Iceberg scouring and sea bed morphology on the eastern Weddell Sea shelf, Antarctica*

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A detailed shallow seismic and side scan sonar study, combined with vibrocoring on the continental shelf off Riiser Larsenisen ice shelf, East Antarctica, has provided information on the different morphological patterns present in the area. Features related to the motion of grounded icebergs prevail, with relatively narrow iceberg plough marks being predominant. A 'washboard pattern' probably results from a wobbling motion of grounded, tabular icebergs under influence of direct push by the advancing ice shelf, and a hummocky disturbed sea bed morphology results from small scale sediment slumping, often triggered by iceberg action. Narrow, elongate depressions incise the sea floor sediments, which are composed of glacigenic diamictons. Formation of the depressions is not fully understood, but erosion by subglacial meltwater under an expanded East Antarctic ice sheet is a possibility, although this requires a different glacier thermal regime than that of the present-day. Although this study is restricted in area, the processes of the region are typical of the Antarctic continental shelf. The results may hence have a more regional significance.

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Iceberg ploughing and its effect on the sea floor are extensively reported from most Arctic shelf regions (Goodwin et al. 1985), but little is published from the Antarctic. The Antarctic ice shelves are major producers of large, tabular icebergs and between 1981 and 1985, 70,000 icebergs (>10 m wide) were registered around the continent. The total iceberg population south of the Antarctic Convergence is estimated to be around 300,000 (Orheim 1987a). The icebergs have a long residence time in continental shelf waters due to the circum-Antarctic current system (Foster 1978), and extensive iceberg scouring can be expected.

Increased knowledge of iceberg ploughing in an ice shelf environment is important also in the northern hemisphere, as this environment may have existed, to a greater extent than at present, during previous glacial cycles.

A local area of the continental shelf outside the Riiser-Larsen ice shelf (Fig. 1) was surveyed with echo sounder and side scan sonar during the Norwegian Antarctic Research Expeditions 1976/77 and 1978/79 (NARE 76/77 and 78/79). Although the line coverage was sparse and somewhat random, a wide range of sea bed features was discovered, most of which were related to iceberg ploughing, a presently ongoing process (Lien 1981). A more comprehensive study, which also included shallow seismic equipment and coring, was carried out in the same area during NARE 84/85. This paper presents an interpretation of the sea bed features found in the region, based on all three surveys, but emphasizing data from NARE 84/85.

Data acquisition

Acoustic profiling was carried out along a grid of lines trending NW-SE (Fig. 2), partly determined by the sea ice conditions. Due to the sea ice conditions and inaccurate navigation, particularly during previous expeditions, no older lines were repeated, but a limited overlap with the previous surveys exists. The vessel (K/V 'Andenes') was navigated by means of a Motorola mini ranger system with an accuracy of approximately 10 m. Transponders were placed on the ice shelf and positioned by a Marconi satellite navigator utilizing the Transit satellite system. Thus, relative navigation was within 10 m accuracy, while absolute geographical coordinates were considered accurate to within 200 m.

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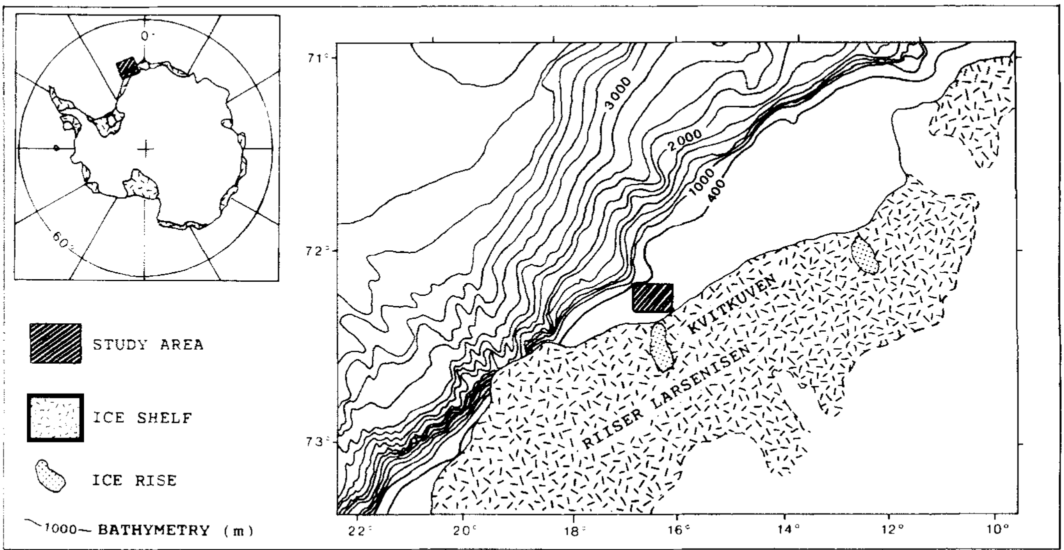

Fig. 1. Location of the survey area on the eastern Weddell Sea shelf. The 400 m contour approximates the shelf edge.

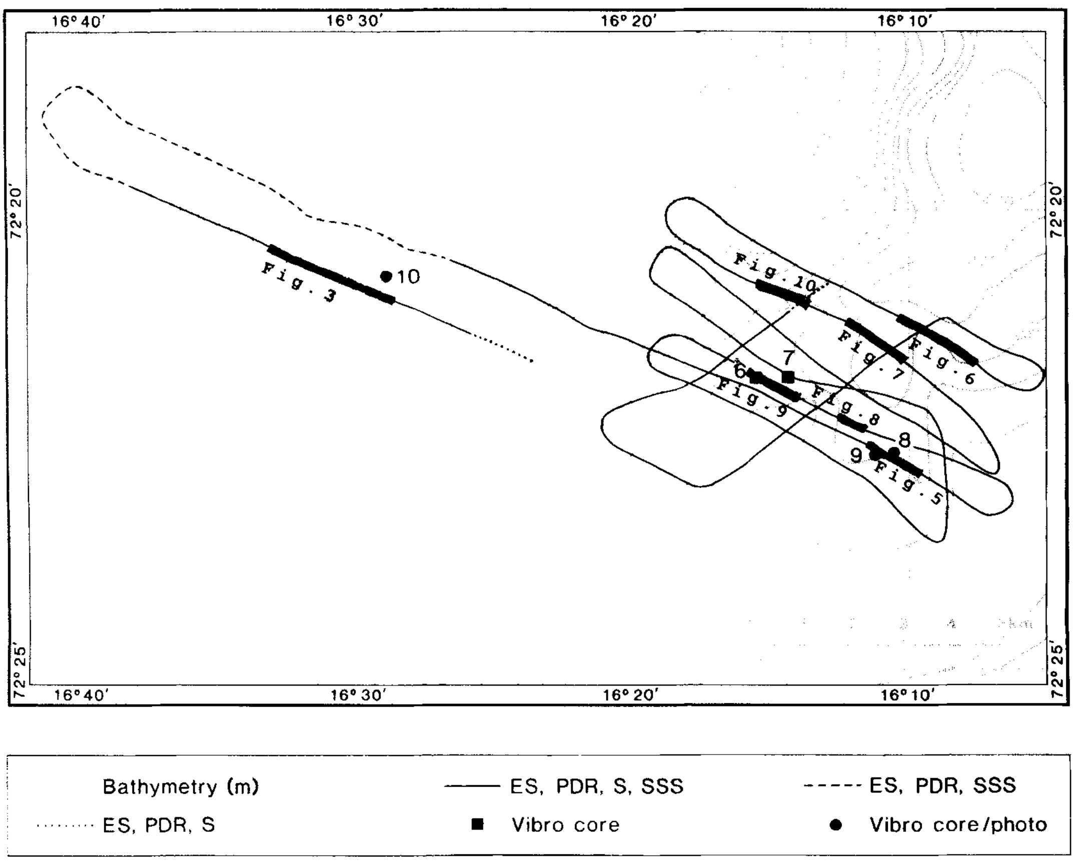

Fig. 2. Bathymetry of the study area with location of acoustic profiles, samples and profile sections used in later figures (heavy lines). Use of the different acoustic systems is shown by different profile signature. The bathymetry is based on data from NARE 76/77, 78/79 and this study. ES: echo sounder, PDR: 3.5 kHz echo sounder, S: sparker, SSS: side scan sonar.

The following acoustic equipment was used:
—Klein Model 400 side scan sonar with 100 kHz transducers (SSS).
—E.G.&G. sparker system with 3-electrode array, 1 kJ energy and band pass filter setting 80–500 Hz (S).
—O.R.E. 3.5 kHz, hull mounted echo sounder (PDR).
—Simrad 50 kHz, hull mounted echo sounder (ES).

The ship's 50 kHz echo sounder was run continuously, but due to operational problems, the whole survey (100 km) was not continuously covered with all acoustic equipment (Fig. 2). Vibrocoring (barrel length 3.5 m, diameter 0.09 m) was carried out with vibration times of 20 min at five sites (Fig. 2). At three of the sites a Benthos deep sea camera was used for sea floor photography.

Bathymetry

Water depths in the survey area (Fig. 2) range

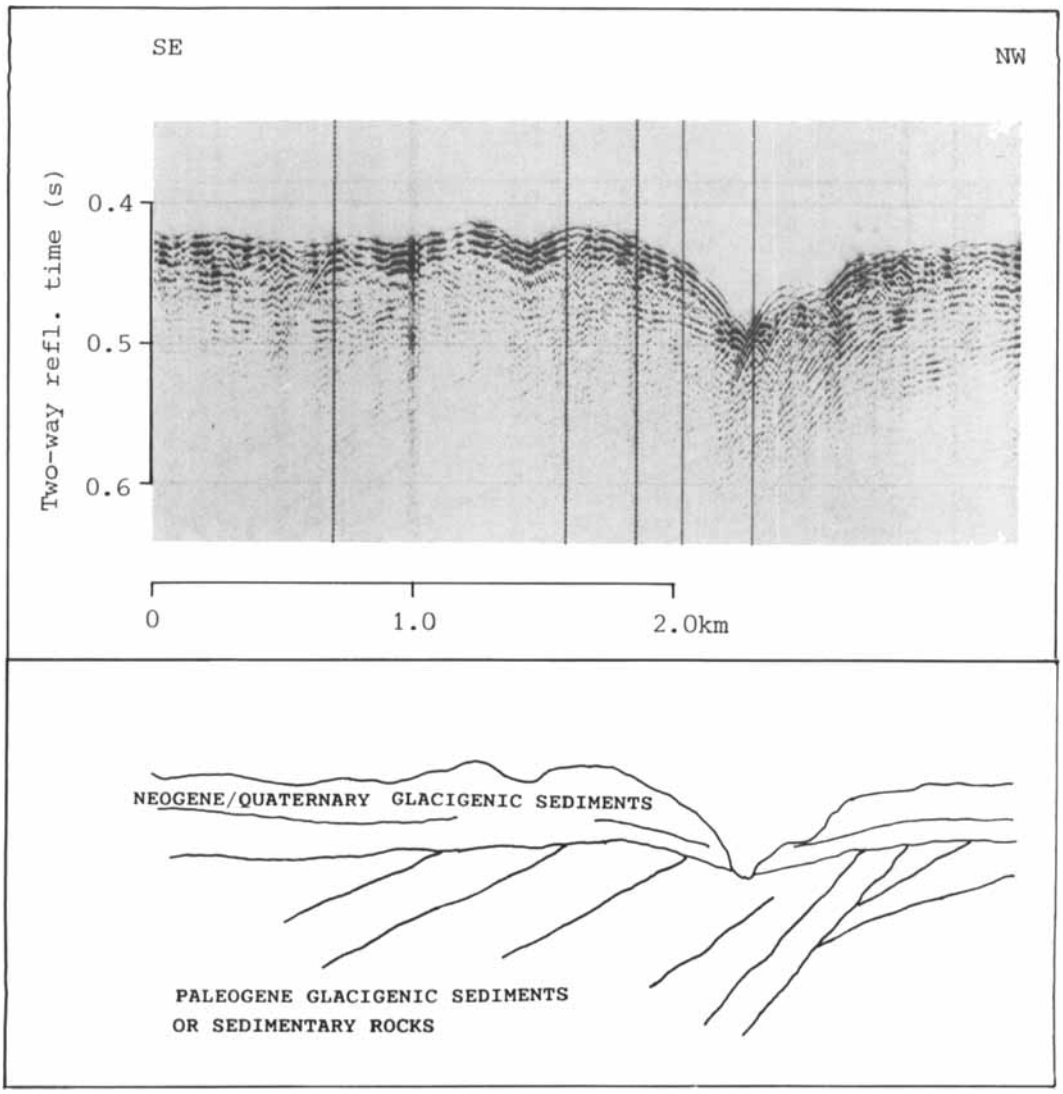

Fig. 3. Sparker record across one of the narrow channels. The angular unconformity is recognized over large parts of the Weddell Sea shelf. For location, see Fig. 2.

from 250 to 400 m, with an average depth of 300–320 m. A major trough runs west-northwesterly in the northern part of the area, with a relief of up to 150 m. The bank area to the south of this trough is incised by elongated, canyon-like depressions (Figs. 2 and 3), with relief generally varying from 15 to 30 m, but with a maximum relief of 60 m. These features seem to form passages across the bank area, to the deeper trough in the north, and they generally follow a NNE-SSW direction.

In the southeast, a NE-SW trending ridge connects the two most shallow areas and bisects the study area (Fig. 2). With the exception of a marked depression down to approximately 350 m water depth to the south, the southeastern slope of this ridge is rather gentle and regular, and generally the area forms a part of the regional slope towards the continent. Water depths exceed 340 m close to the ice shelf front in the southeast (Figs. 1 and 2).

Southeast of the study area, the ice sheet is grounded at the Kvitkuven ice rise (Fig. 1). The shallowing towards the south is most likely a part of the larger shoal that causes the ice-rise.

Sea bed features

The different sea bed features recorded in the survey area have been mapped (Fig. 4) using Lien's (1981) classification:

—Iceberg plough marks (termed unsystematic furrows by Lien (1981)).

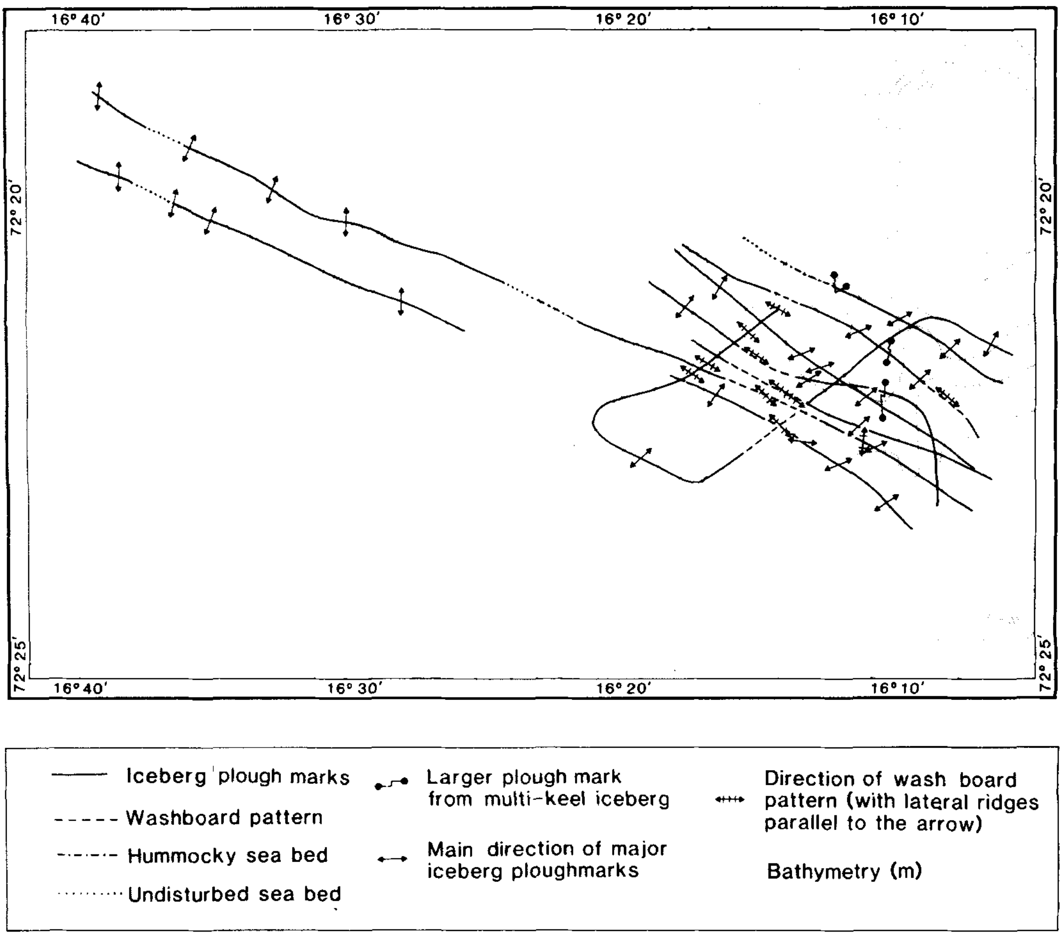

Fig. 4. Map showing the distribution of the different sea bed morphologic features recorded along ship's track.

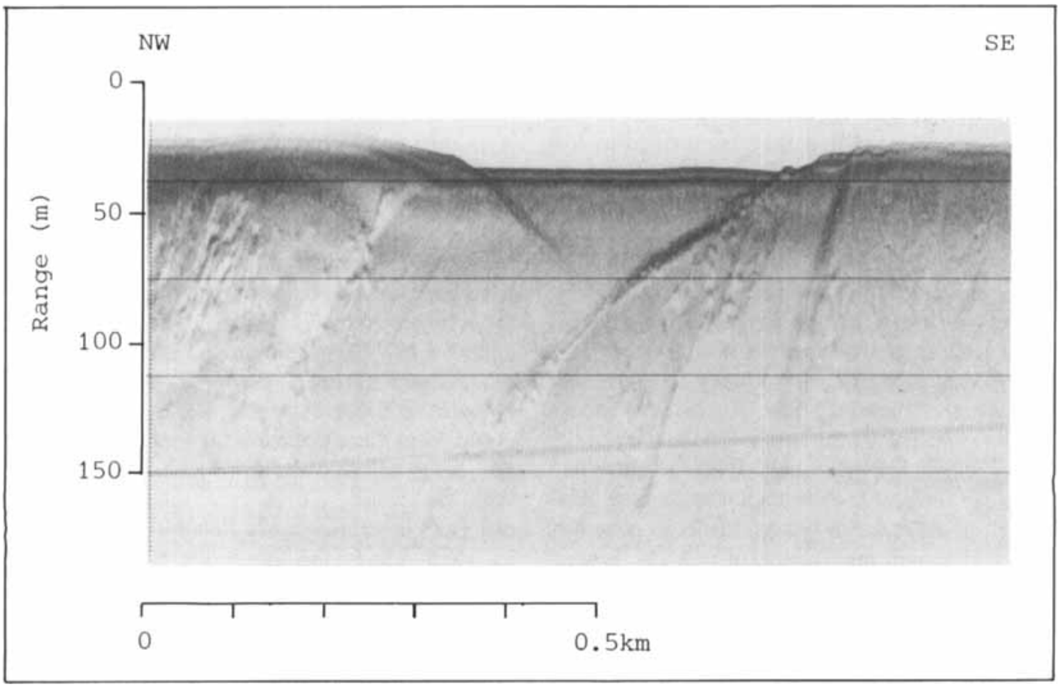

Fig. 5. Side scan sonograph running obliquely across a large plough mark formed by a tabular iceberg. The relief is 9 m, the shortest distance from berm to berm nearly 300 m and the real width of the flat bottom is approximately 170 m. For location, see Fig. 2.

—Washboard pattern.
—Hummocky sea bed.
—Undisturbed sea bed.

The iceberg plough marks are by far the most common features (Fig. 4). They characterize most of the area, except some of the troughs and slopes. The cross-sectional shapes, dimensions and orientation may vary considerably between plough marks, but most often the characteristics within individual marks are rather persistent. Plough

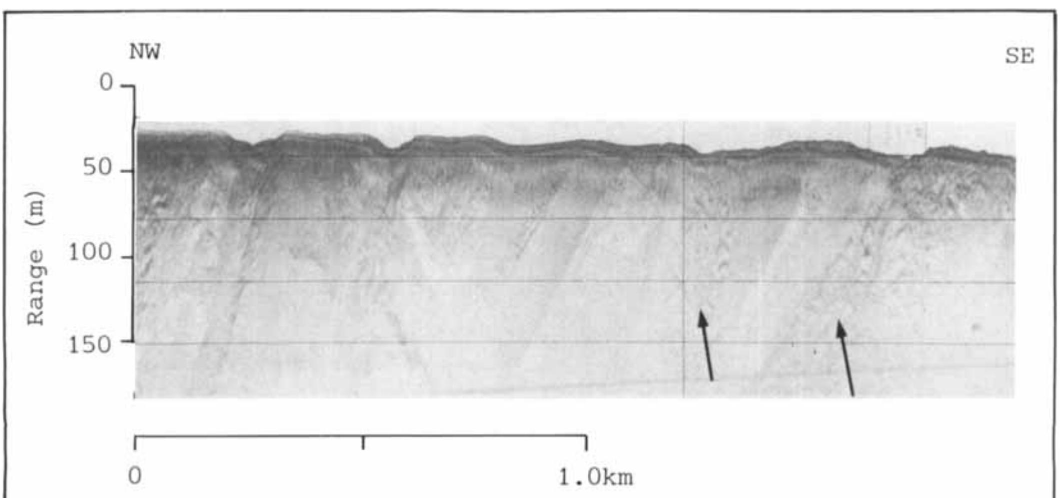

Fig. 6. Side scan sonograph from an area where hummocky sea bed (arrows) is found in association with iceberg plough marks. The sonograph also shows typical cross-sectional shapes of plough marks. For location, see Fig. 2.

marks with relief of 10 m and width of nearly 300 m have been recorded (Fig. 5.). Most commonly, the cross-sections are U- or V-shaped (Fig. 6), but the widest ones often have flat bottoms, indicating that they are formed by icebergs with tabular bases (Fig. 5). Infill of sediments may flatten the bottom of smaller plough marks, but this is an unlikely cause for the flat shape of the wider ones. Plough marks formed by multi-keeled icebergs are also common (Fig. 7). Directional trends of the large features (Fig. 4) are approximately N-S in the northwestern part of the area, but change gradually to more NE-SW in the southeastern part. The side scan sonographs indicate that the transport direction of the icebergs most likely has been from the north and northeast (Fig. 8). Although the iceberg drift direction, indicated by plough marks, is generally rather persistent and consistent with the general circulation pattern, the bergs occasionally change direction or rotate (Figs. 7 and 8).

The washboard pattern (Fig. 9) consists of alternating parallel grooves and ridges with a typical wavelength of 15–20 m and a relief of <1–2 m. These are cut sub-perpendicularly by lateral ridges of a similar relief, dividing the washboard area into narrower units. The pattern may cover areas of more than 2 km^2. The grooves and ridges forming the washboard pattern are persistent in shape and size within the same region, but often vary from region to region (Fig. 9). The pattern is mainly concentrated in a wide topographic embayment in the southeast, where the iceberg plough marks seem to be absent (Fig. 4). In the central part of this embayment the washboard patterns are predominant, while they seem to have been obscured by iceberg plough marks at the embayment flanks (Fig. 10). The lateral ridges define a NW-SE trend on the majority of the records, which is nearly perpendicular to the main plough mark direction (Fig. 4), but slight deviations from these directions are seen, and in one area the pattern is observed to turn. Furthermore, the washboard pattern is most commonly observed in gentle slopes that face towards the ice shelf. Here, the directions of the pattern, defined by the lateral ridges, are sub-perpendicular to the local bathymetric contours.

The hummocky sea bed (Fig. 6) comprises a dense pattern of smaller mounds or ridges which may cover large areas. It is usually found adjacent to plough marks, and may cover large areas along the plough mark rims (Fig. 6), but is also recorded independently of plough marks on the south-

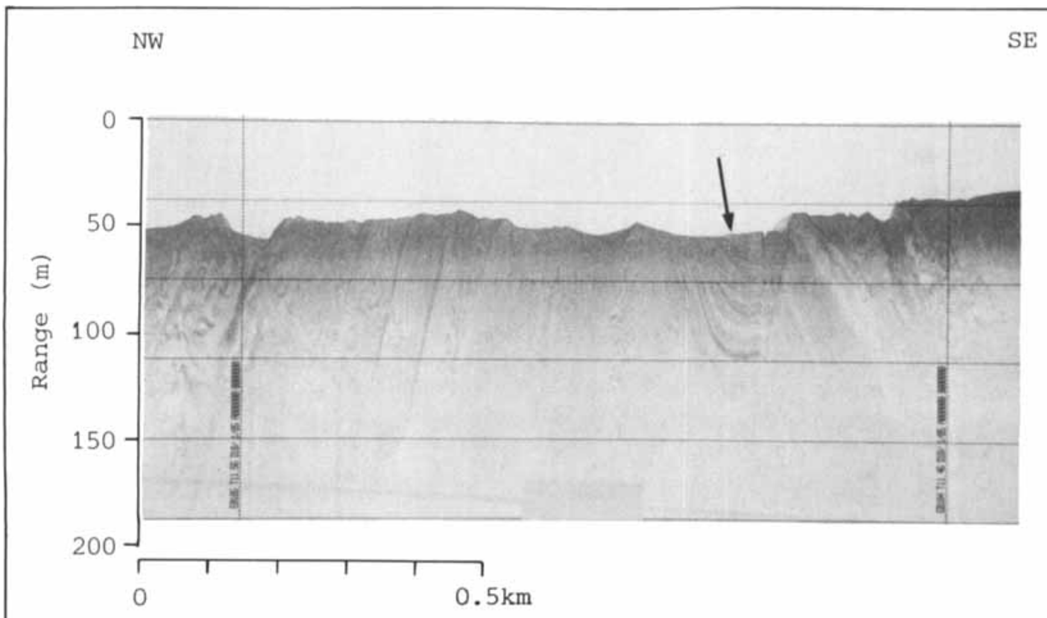

Fig. 7. Side scan sonograph showing the plough mark after a multi-keel iceberg that has rotated (arrow). For location, see Fig. 2.

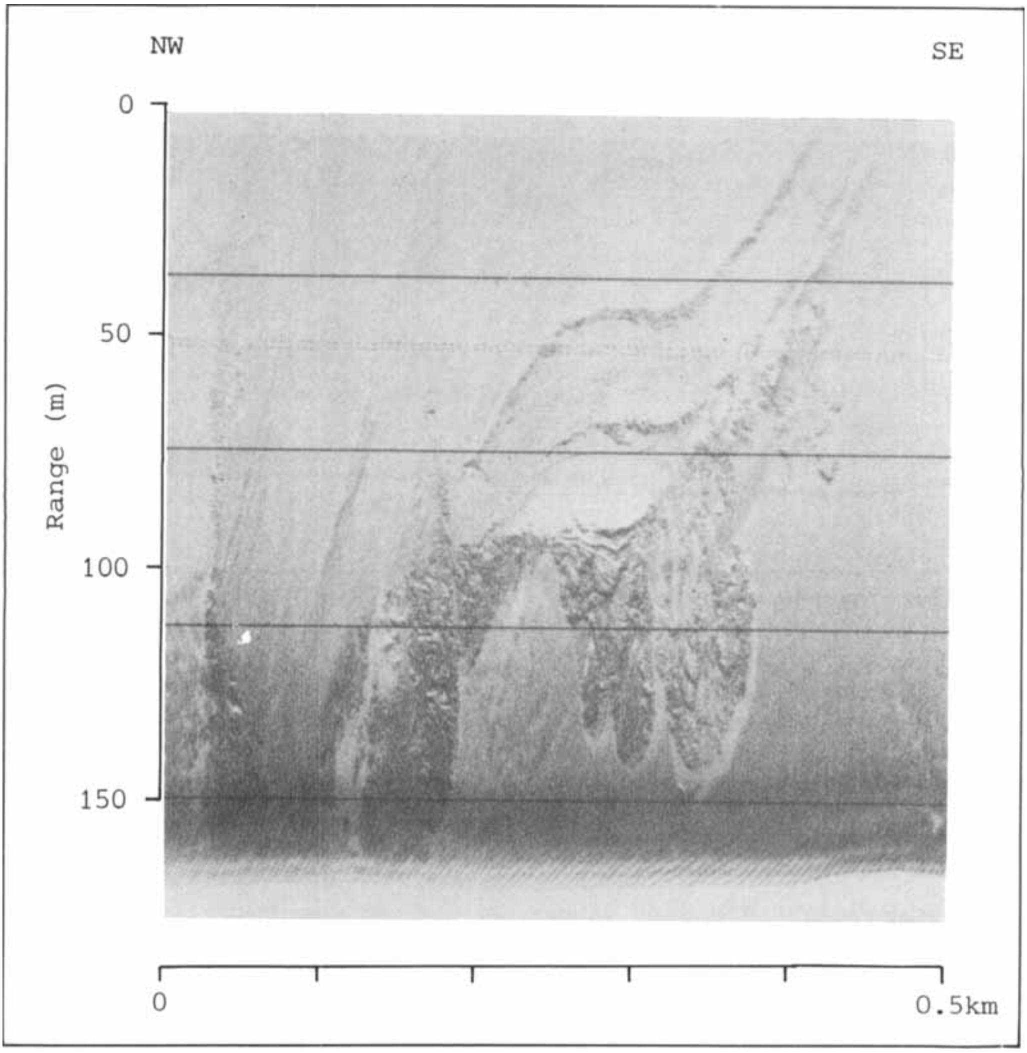

Fig. 8. Side scan sonograph showing a plough mark with changing direction. Note local debris slides off the plough mark berms. For location, see Fig. 2.

eastern slope of the main, northwesterly trending trough (Fig. 4). Generally, the hummocky sea bed is most typically found on slopes.

The undisturbed sea bed is observed in only one area, on the southeast flank of the major trough (Fig. 4), and has a cover of soft sediments which show few irregularities on the side scan sonographs. However, in some embayments of the same trough, there are only few iceberg plough marks, and the sea bed is classified as undisturbed. These undisturbed conditions are mainly found in water depths greater than 330–340 m (Fig. 4).

Sediment distribution and composition

An angular unconformity (Fig. 3) has previously been interpreted to represent the boundary between the pre-glacial sedimentary bedrock and the overlying glacigenic sediments (Elverhøi & Maisey 1983). However, new information from drill holes on the East Antarctic continental shelf showed glacial diamictites both above and below a similar unconformity (ODP Leg 119 Shipboard Scientific Party 1988). Despite poor biostratigraphic control, the drilled unconformity may

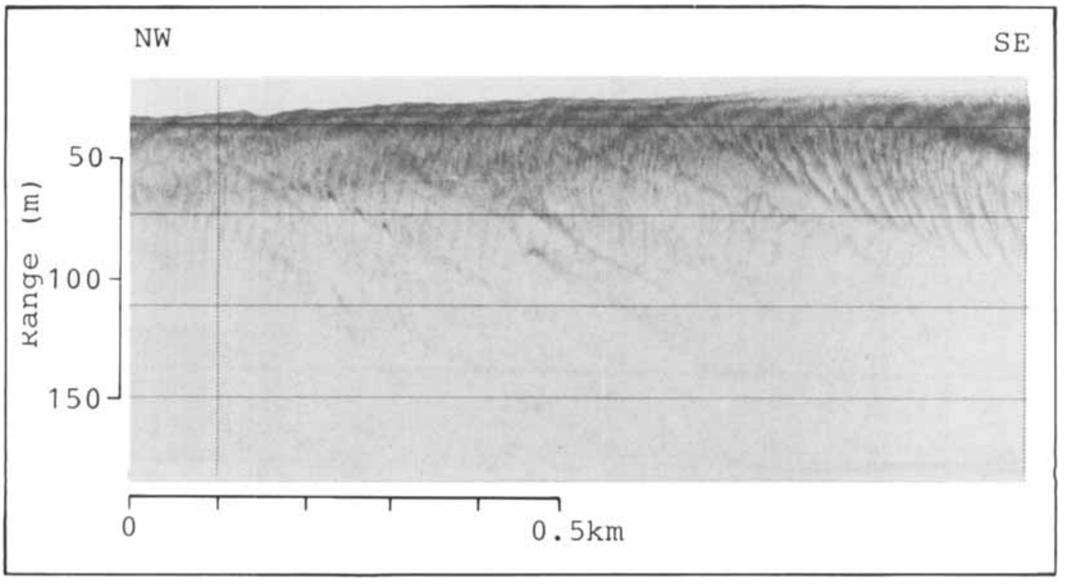

Fig. 9. Side scan sonograph over an area of washboard pattern. For location, see Fig. 2.

represent a lower Oligocene–upper Miocene hiatus. Although correlation can only be tentative, such a large hiatus is likely to be of regional extent, and we therefore suggest that the angular unconformity of the present study area also represents a mid-Tertiary hiatus, and that glacigenic sediments can be found below it as well as in the upper part of the section. The thickness of the

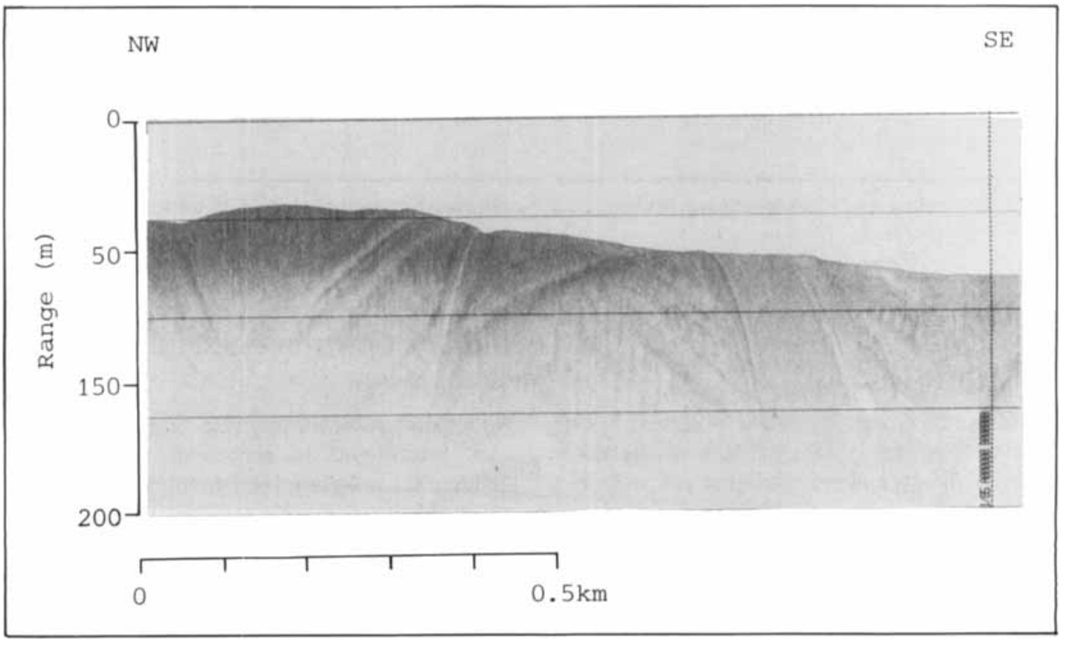

Fig. 10. Side scan sonograph showing transition between the washboard pattern and other features. This profile shows that the washboard pattern is overprinted by the other features. For location, see Fig. 2.

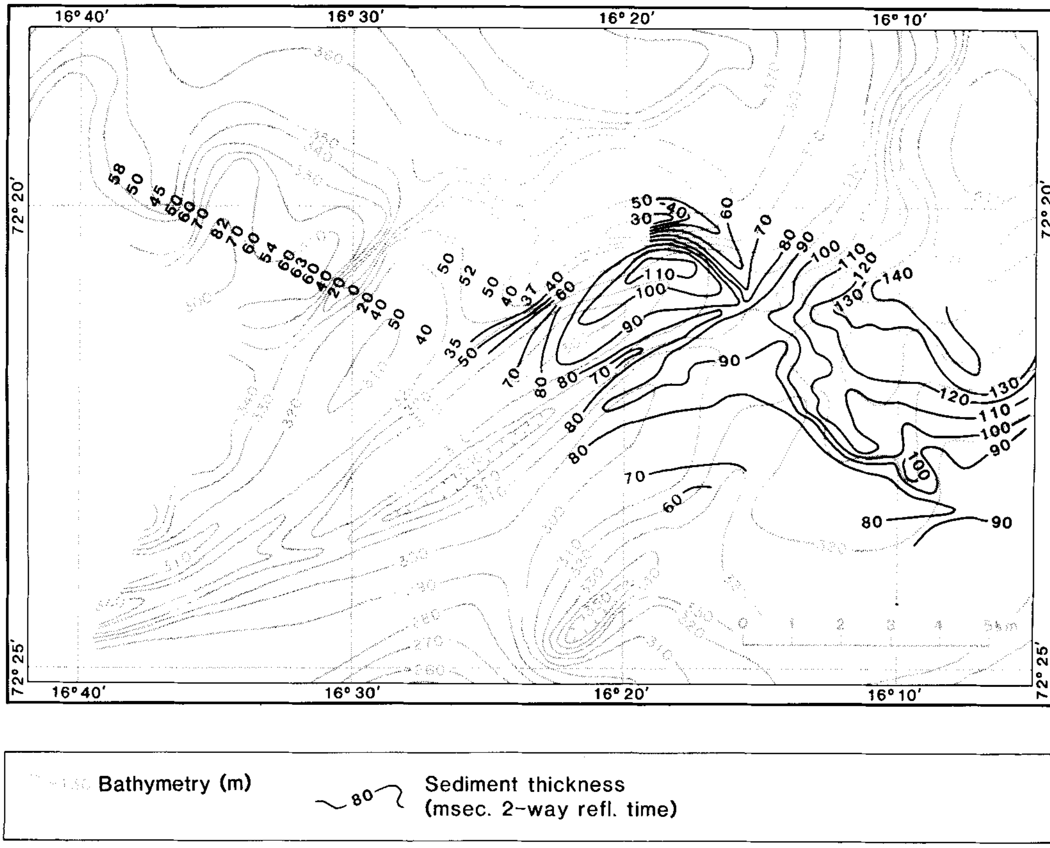

Fig. 11. Map of sediment thickness above the upper angular conformity.

sediments above the unconformity (Fig. 11) vary from zero in one of the major longitudinal depressions to more than 140 msec. (two-way reflection time) on the northeastern bank. As the angular unconformity is relatively regular and only gently sloping, variations in sediment thickness are reflected in the surface topography.

Vibrocores from five locations (Fig. 2) revealed a sandy diamicton with varying content of gravel and pebbles (Fig. 12). Core lengths were between 2.6 and 3.5 m, with the exception of AN85-6 (0.5 m). Lithologic variability seems unsystematic, although intervals in which finer and coarser sediments predominate do occur, in particular in core AN85-10 (Fig. 12). The lower 20 cm of this core also contain clasts consisting of unlithified sediment aggregates. According to Powell (1984), this may imply release of basal debris from glacier ice. Physical properties profiles (Fig. 12) indicate essentially normally consolidated sediments, with the exception of AN85-9, where the shear strength increases to over 110 kPa in the lower part of the core. This location is in the bottom of a large plough mark (Fig. 5). Other fluctuations in the physical properties are small and can be attributed to variations in grain size distribution, superimposed on the main down-core trend of increased bulk density and decreased water content, caused by compaction. From the Atterberg limits the sediment mostly classifies as an inorganic sandy, gravelly clay of medium plasticity (Lambe & Whitman 1979). Relative to Boulton & Paul's (1976) 'T-line', defined from lodgement tills from Iceland and Spitsbergen, the sediments from the present study area mainly plot in a position slightly towards the left of the diagram and below the line (Fig. 13), indicating depletion of the finest grain fractions, or that these fractions consist mostly of rock flour. A combination of the two causes is considered likely here.

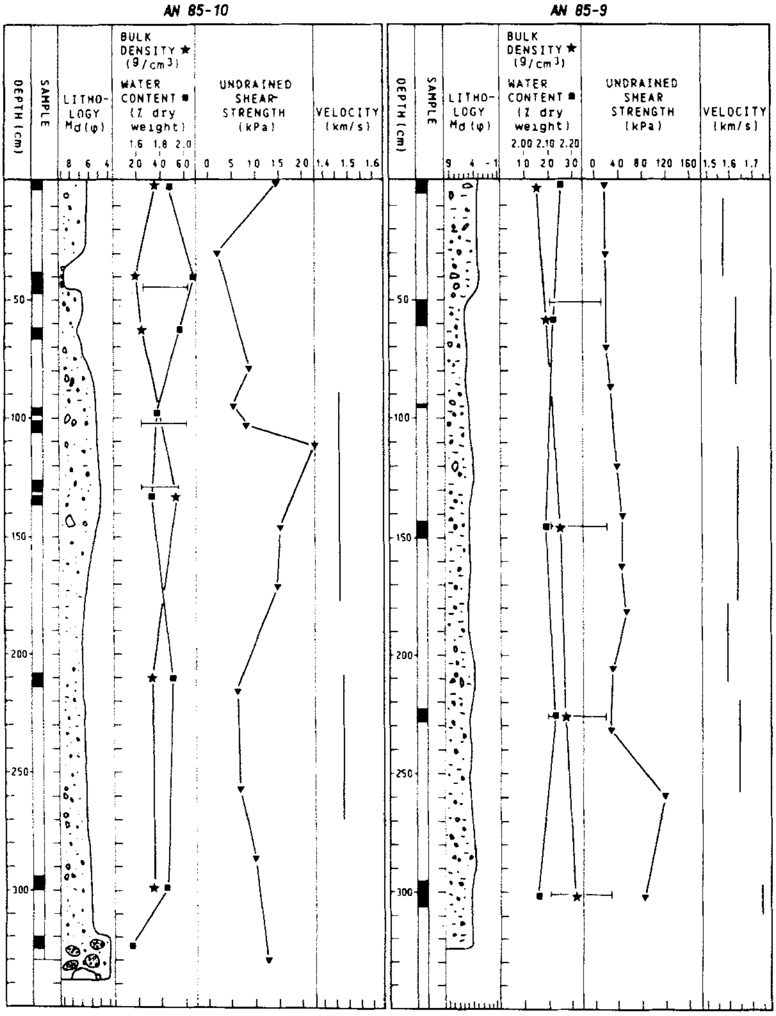

Fig. 12. Vibrocores AN85–9 and 10, with physical properties. Horizontal bars in the bulk density/water content column mark the plastic and liquid limits of the sediment.

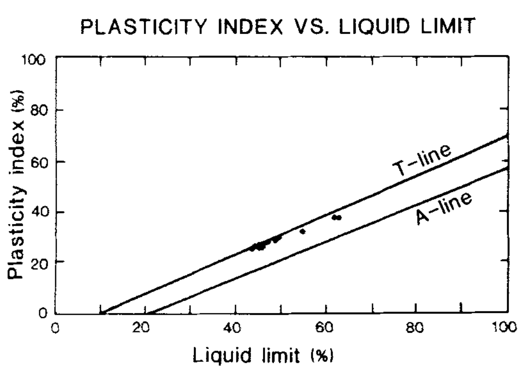

Fig. 13. Plot of plasticity versus liquid limit for sediments from the study area (dots). The A-line (Casagrande 1948) marks the division between sediments of a broadly inorganic nature (above the line) and those with a significant organic content (below the line). The T-line is defined for lodgement tills from Iceland and Spitsbergen (Boulton & Paul 1976).

Formation and distribution of iceberg related features

Iceberg plough marks and general characteristics

The main transport mechanism for icebergs in the region is the southwesterly running coastal current (Foster 1978). The distribution of iceberg plough marks seems to be topographically dependent, with few plough marks on slopes on lee sides (relative to the main iceberg transport direction) and a general absence of ice related features in the deepest areas. Klepsvik & Fossum (1980) reported the ice shelf in this region to extend 200 m below sea level, hence defining the average draft of icebergs from the area. Even if the draft increases by as much as 50% through rolling and overturning, as reported from the Arctic (Bass &

Peters 1984), the deepest waters of the study area would be too deep to be scoured by recent, locally derived icebergs. Bergs of considerably deeper drafts (>400 m) have, however, been reported from other parts of the Antarctic (Keys 1984). The shallow bank area in the northeastern part of the study area (Fig. 2) is a barrier for larger icebergs drifting in from the east. Deeper waters along the ice shelf, however, offer a possible passage. Thus, the changes in directional trends of the plough marks, from NE to N in the eastern and the western part of the study area, respectively (Fig. 4), are most likely also topographically determined.

Despite the fact that many icebergs observed in this region are tabular, and usually have widths greater than 100 m, most of the plough marks are relatively narrow, with widths in the order of 30–70 m. This indicates that the submarine parts of the icebergs are rapidly degraded to more irregular shapes, although some icebergs also clearly are tilted. The most important deterioration processes for icebergs in general are calving, melting and wave erosion (Kristensen 1983; Hamley & Budd 1986; Venkatesh 1986). Calving will produce successively smaller icebergs that will be more susceptible to overturning and melting. However, the calving will normally not have a keel-shaping effect on icebergs with a tabular appearance. Orheim (1987b) showed that the melting rate of an ice front may reach the order of 10 m/year at 200 m water depth, while there is a minimum melting rate at around 50–100 m depth. This type of differential melting will have a keel-forming effect on the icebergs. Josenhans et al. (1985) reported ice fragments embedded in sediments of the floor of a freshly formed plough mark off northern Canada. The ice fragments originated from degradation of the grounded iceberg. This type of ice shedding may not be important for the general deterioration of Antarctic icebergs, but it may have significance as a keel-shaping process on grounded icebergs. The different deterioration processes lead to a decrease in iceberg stability, and increase the likelihood of tilting. Tilting may also give rise to narrow, V-shaped plough marks.

Washboard pattern

The washboard pattern is only recorded below 300 m water depth in the present study. Lien (1981) recorded the pattern also further to the east, but only below 280 m water depth. In shallower water it is overprinted by the iceberg ploughing (Fig. 10). Furthermore, the overlap with previous surveys (Lien 1981), although limited, seems to indicate that areas which were then dominated by washboard patterns now have a predominance of iceberg plough marks. Thus, the distribution of preserved washboard pattern is clearly depth and time dependent. The pattern seems to predate most of the ploughing, which is the dominating process at present.

A formation of the washboard pattern as bedforms caused by current activity is considered unlikely in this area, due to the character of the cored sea floor sediments and the generally low current velocities (15–30 cm/s) of the region. Furthermore, as washboard pattern is also observed with a distinct bend, a mode of formation related to the action of grounded icebergs seems more likely.

Lien (1981) proposed a model for the washboard pattern, where the features are formed by the wobbling motion of grounded, tabular icebergs. The force necessary to move the icebergs is exerted by current, wind or direct push by the ice shelf proper, which currently moves with an average velocity in the order of 200–500 m/year (Orheim 1986). The wobbling is caused by small rotations around an equilibrium position, possibly assisted by tidal movements that are approximately 1 m in the region (Lutjeharms et al. 1985). A similar model was suggested by Reimnitz et al. (1973) for smaller, similar features in the Arctic. The lateral ridges may result from irregularities in the iceberg sole, or from spacing between individual icebergs that move as a group, for instance packed together by sea ice. The directions of the washboard pattern (Fig. 4) indicate that wind or direct push by the ice shelf are more plausible driving forces than currents. Direct push is favoured by the fact that the washboard pattern seems to be older than the other sea bed features. Grounded icebergs may have been pushed by the advanced ice shelf before calving left the area under open, marine conditions, again susceptible to the action of freely floating and grounding icebergs. The fact that the washboard pattern at present seems to be most common where the sea floor slopes gently towards the ice shelf gives further support to the direct push hypothesis. Evidence of variations in the ice front position is given by Orheim (1986), who reported that three large segments of the ice shelf in this region broke off between 1974 and 1987. However, deviating directions from the general trend (Fig. 4), as well as bending patterns, indicate that other mechanisms of movement may also be active.

Similar patterns from Hudson Bay (Josenhans et al. 1988) are interpreted as being formed by the base of the grounded Laurentide ice sheet. Although a similar process cannot be excluded in the present study area, we favour the iceberg formation process, described above, as this provides an explanation for both the lateral ridges and the parallel grooves and ridges. Directions of the pattern would be similar in both mechanisms, as this would be determined by the general flow of glacier ice. However, formation by the base of an ice sheet would not allow any deviations from parallelism within such a restricted area.

Hummocky and undisturbed sea bed

The location of the hummocky and undisturbed sea bed in the trough area is dependent on the distribution of soft sediments, the slope of the sea bed and the current conditions in the area. The accessibility of icebergs is also important.

The hummocky sea bed is most prevalent in the steeper slopes of the eastern part of the study area. Also, the hummocky pattern found in connection with plough marks seems to be most pronounced in sloping areas. Lien (1981) interpreted this pattern to be formed by movement of unstable sediments. The present data confirm this interpretation, and further data indicate that where the features cover larger areas the formation is more dependent on gravitational forces (i.e. steeper slopes) than where the hummocky sea bed is formed only locally, adjacent to plough marks.

As the study area is adjacent to both grounded ice (Kvitkuven) and floating shelf ice, enhanced sedimentation may have occurred because of grounding line movement. If the ice shelf grounds and refloats sediment may freeze to the sole and subsequently be redeposited (Powell 1984; Orheim & Elverhøi 1981). However, the sampled sediments would most likely be stable in the slopes of the study area (<2 degrees) unless disturbed by some external force. The action of icebergs is a likely mechanism. Impact during the calving process, during overturning or by vertical movements induced by waves or tides may trigger small scale failures in unstable sediments, as well as producing a cratered surface over a period of time. Moving icebergs, however, may themselves also create instability. During the ploughing, large amounts of sediments are transported through a combination of squeezing and push from the plough mark to the berms on each side (Lien 1986). Furthermore, minor movements of the iceberg may have a pumping effect that sets up strong local currents (Fig. 14), and the process may initiate a 'continuous debris slide source' as the iceberg moves. The pumping effect may be important for sediment transport and winnowing on a local scale, but the extent to which this takes place will depend on iceberg shape and stability and sediment characteristics. The relatively non-cohesive sediments cored in this area are likely to be affected by the pumping process. The general absence of hummocky morphology in some of the shallower bank areas may result from a different sediment character (for example higher compaction) than the normally consolidated, unsorted sediments cored elsewhere (Fig. 12). The iceberg pumping mechanism may thus not be efficient here. Another effect, however, that could be of importance, is that hummocks and plough mark berms in shallow water may be more subject to current and biologic reworking, and thus less apparent on side scan sonographs.

The undisturbed sea bed is found in relatively flat areas and in local embayments of the major trough in water depths greater than 330–340 m. Most likely, the ice related processes described earlier have not affected these areas because of

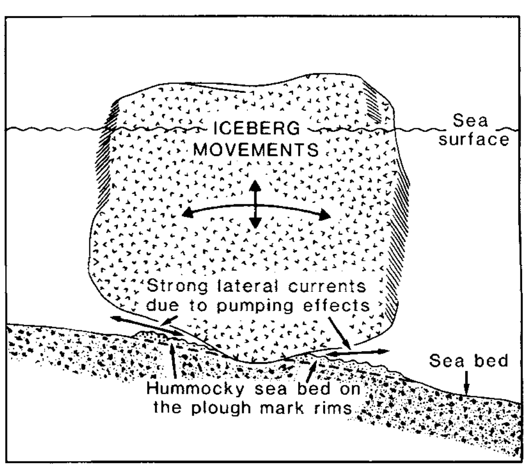

Fig. 14. Sketch of iceberg movement causing local debris slides to the sides of its path.

their protected locations and their local topography. These factors probably also give rise to current conditions that favour deposition of fines brought into suspension by the other processes. Hence, patterns formed in such areas may be obliterated more easily. However, direct evidence for burial of ice related features in sediments is not observed.

Formation of sediment properties

Of the five vibrocores recovered (Fig. 2) only AN85–9, which was taken at the bottom of a plough mark with a relief of nearly 10 m (Fig. 5), had overconsolidated material in the lower part of the core (Fig. 12). Holocene sedimentation rates are as low as 2–5 cm/ky on the Weddell Sea shelf (Elverhøi & Roaldset 1983), and from previously dated samples in the same region the sediments sampled date back to Weichselian time. Most likely, the East Antarctic ice sheet was grounded out to the shelf edge during Late Weichselian time (Elverhøi 1981; Elverhøi & Maisey 1983) and overconsolidated sediments would be expected, either as basal till or as ice-loaded glaciomarine deposits. The process of iceberg ploughing, however, will most likely reduce an initial overconsolidation in the uppermost sediments rather than having a consolidating effect (Lien 1983, 1986). The duration of the loading is normally too short to allow drainage of porewater, but the process will disturb the sediment considerably and nearly normally consolidated sediments may result. Vorren et al. (1983) proposed the term 'iceberg turbate' for this type of sediment. The iceberg turbate will also be depleted in fines, brought into suspension by the ploughing process. Thus, much of the upper few metres of sediments found in the study area are probably affected by intense iceberg ploughing during most of the Holocene, and as such classify as an iceberg turbate.

The elongated depressions

Sparker records (Fig. 3) show that the elongated, canyon-like depressions are erosional, cut into the unlithified sediments, locally down to the underlying unconformity. The dimensions of the depressions preclude iceberg ploughing as a mode of formation. Possible mechanisms include:

a) Erosion by glacier ice.
b) Subglacial meltwater activity.
c) Current activity.

The present state of information is sparse, particularly as there are no cores from within the depressions, and only general aspects of the different possibilities can be discussed.

Erosion by glacier ice seems the least likely mechanism, because the directions of the depressions are sub-perpendicular to the expected ice flow pattern of an expanded ice sheet. Furthermore, known mechanisms of glacier erosion (Drewry 1986) are unlikely to produce such narrow, elongated features.

Subglacial meltwater activity during a period of an expanded East Antarctic ice sheet may be the most likely mechanism of formation, considering the shape of the features. Subglacial meltwater streams follow, in general, the directions of ice movement, but may deviate from this due to topographic effects and boundaries in the ambient pressures in the ice (Shreve 1972; Sugden & John 1976). The depressions lead towards the deeper waters of the west-northwesterly running trough in the northern part of the study area. The main problem with this explanation is that it implies extensive subglacial meltwater flow, which is different from the present-day situation, where signs of meltwater are sparse or essentially lacking around the margins of the East Antarctic ice sheet (Anderson et al. 1983; Molnia 1983).

Little is known about current velocities necessary to erode unsorted, cohesive sediments. Studies based on non-cohesive sediments find critical current velocities in the order of 20/40 cm/s, varying with bed roughness and sediment water content, to resuspend material of <63 μm (Postma 1967; Butman & Moody 1983). Based on present-day current velocities in the order of 15–30 cm/s and the character of the cored sediments, currents under hydrographic conditions similar to those of today do not seem capable of forming the elongated depressions. An ice shelf nearly aground in front of an expanded ice sheet would be a possible way of canalizing currents. Currents enter under present-day ice shelves (Foldvik et al. 1985), but how currents of the required velocities could develop remains an open question.

A problem common to both b) and c) is the formation of a protective lag deposit that would soon prohibit further erosion. Absence of cores within the depressions prevents a thorough discussion of this. However, given the present state of information, we favour subglacial meltwater as the most likely mechanism. This would have the capability of creating the highest current shear. However, large amounts of subglacial meltwater require a different glacier thermal regime than what is known at present from the region, and therefore remains problematic.

Conclusions

Despite the local nature of this study, the investigated area may physiographically be considered representative of large parts of the Antarctic continental shelf. The conclusions drawn may thus be valid for large regions, at least in water depths shallower than 400 m:

—Most sea bed features recorded are closely related to the action of grounded icebergs, with iceberg plough marks of similar appearance to those described from Arctic regions being predominant.

—Hummocky sea bed resulting from sediment movement is dependent on sediment stability. The sediment movement, however, is often triggered by the action of grounded icebergs. Point contacts between icebergs and the sea floor may also add to the hummocky appearance.

—The advancing ice shelf exerts a direct push on grounded icebergs, which may form a washboard pattern on the sea floor when moving with a wobbling motion, in particular in slightly up-sloping areas. Thus, most washboard patterns are probably formed during periods of relatively little calving activity, and are partly overprinted by other patterns when re-exposed to open marine conditions.

—Elongated canyon-like depressions with a relief of up to 60 m are eroded into the sediments. A possible explanation for their formation is subglacial meltwater activity during a period of an expanded East Antarctic ice sheet. This, however, requires a glacier thermal regime different from the one known from the region today.

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