MODEL FOR SUBMARINE GLACIAL DEPOSITION*

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ABSTRACT
        Present-day sedimentary environments in
the eastern Weddell Sea confirm low clastic
sediment input from wide (> 100 km) ice shelves.
Mainly bioclastic sediments are formed *in situ*
on the inner and shallow central-shelf areas
(250 to 350 m water depth), with sedimentation
rates probably < 0.01 m ka^{-3}.   Ice-rafted
debris   (IRD) is mainly deposited on the outer
shelf and upper continental slope, with a
sedimentation rate of 0.02 to 0.07 m ka^{-3}.
The coarse-grained texture of these deposits is
caused by removal of finer grades in suspension
during settling of IRD sediments.   Overconsoli-
dated till was deposited < 31 ka BP during
expansion of grounded ice to the shelf break.
Subsequent eustatic rise caused grounded ice to
float. Frozen-on sediments melted out of the
base of the ice, depositing soft pebbly mud
above the till. Marine conditions similar to
present-day conditions were found for the
interval 30 to 40 ka BP.
        IRD variation is an indicator of ice-shelf
coverage and changes in relative sea-level, and
is, in low latitudes, probably inversely
related to the degree of ice cover.

INTRODUCTION
        Unsorted or bimodal muddy sediments with a
variable content of pebbles make up the main
part of the Quaternary continental-shelf sedi-
ments in high-latitude areas (Emery 1968).
Similar sediments have also been recovered in
ancient rock sequences. The primary glacial
origin of these sediments is well documented;
however, a detailed interpretation may fail,
due to lack of adequate models of depositional
processes (Edwards 1978). Recent progress in
studies of models of glacial facies has been
made on terrestrial deposits (e.g. Boulton 1975).
For the glaciomarine environment, the model of
Carey and Ahmad (1961), based on data from the
Antarctic, is still mistakenly applied. The
terms "wet-based" and "dry-based" ice shelves,
with corresponding sedimentary facies, have been
based on incorrect field data, and should not be
used.
        In the present paper, glaciological and
oceanographic observations and sediment samples
from the Weddell Sea are used to characterize
sedimentation outside an ice shelf and show how
it is influenced by sea-level rise and fall.

THE PHYSICAL ENVIRONMENT
Ice-shelf flow
        The Weddell Sea is surrounded by mostly
100 km-wide ice shelves on the eastern side,
while the combined 500 km-wide Filchner and
Ronne ice shelves confine the sea in the south
(Fig. 1). Figure 2 shows ice-shelf flow and
mass balance for ice shelves such as those on
the eastern side. The ice shelves exhibit
internal temperatures well below freezing,
increasing with depth to pressure-melting point
(p.m.p.) at the ice/sea-water interface. No
basis exists for making major thermal distinc-
tions between ice shelves, such as use of terms
"warm" and "cold". Erosion products from an
ice sheet are primarily concentrated in a rela-
tively thin basal zone some metres in thickness
(Gow and others 1979). A 10 m-thick basal
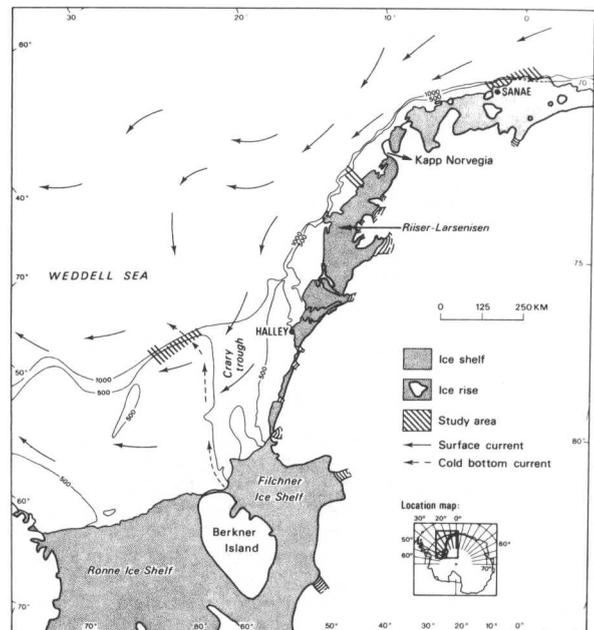sediment layer at the grounding line of the ice

Fig.1. Eastern Weddell Sea with the main
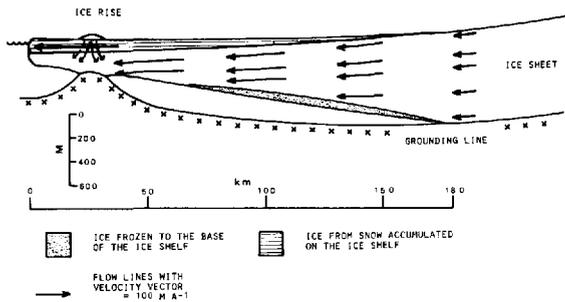current system and study areas referred to in
the text.

Fig.2. Section of an ice shelf showing flow lines and mass balance. The ice flows radially from the ice rise, the crossing velocity vectors indicate the ice shelf flowing past the ice rise. Flow rates and ice thicknesses are generalized from observations at Riiser-Larsenisen during NARE 1976/77 and 1978/79. Based on data from other ice shelves, the basal melting rate is taken as 1 m a^{-1} at the ice front, decreasing linearly to 0 at 100 km from the barrier. A freezing rate increasing linearly to 0.1 m at the grounding line is assumed for the remaining section.

shelf in Figure 2 will melt out in a zone 60 to 70 km from the ice front. Thus these ice shelves are too wide to give rise to icebergs containing continental sediments. Basal melting may also take part nearer the grounding line. Currents flowing down-slope will have temperatures higher than at p.m.p. (Robin 1979); thus basal ice can be stripped of sediments especially where deeper ice, such as ice streams, enters the ice shelf.

Currents in the Weddell Sea

The Weddell Sea opens to the north into the South Atlantic (Fig. 1). The current pattern is characterized by the westward-flowing Antarctic coastal current and a series of gyres in the central Weddell Sea. The water masses have a low vertical stability which suggests that the surface currents mirror the intermediate and bottom currents (Foster 1978). On the western side of the Crary trough, a cold bottom current flows out beneath the Filchner Ice Shelf and continues across the shelf to the shelf break from where the current flows westward along the slope (Foldvik 1980). Long-term current measurements made during 1968 and 1977-79 at eight moorings on the shelf break (Fig. 1) (Foldvik and Kvinge 1974, Foldvik 1979, Foldvik, personal communication) showed that maximum velocities 25 m above the bottom were 0.4 m s^{-1}. Usually the maximum ranged about 0.2 m s^{-1}, with a mean velocity at about 0.09 m s^{-1}. The flow pattern beneath the Filchner-Ronne ice shelves is not known, but the outflowing cold bottom water is believed to be related to the tidal influx from the Weddell Sea (Foldvik, personal communication). Iceberg drift tracks in the eastern Weddell Sea suggest that the velocities of the coastal current are not significantly greater than those measured on the shelf break. Measurements by Kvinge (personal communication) near Halley at 140 m water depth over 2 d showed maximum velocity of 0.3 m s^{-1} and a mean at 0.15 m s^{-1}. Wave-induced bottom currents are not important, because of the presence of sea ice which hinders wave generation for most of the year and because of the depth of the continental shelf (250 to 550 m).

SEDIMENTARY ENVIRONMENT

Data acquisition and laboratory procedures

The sedimentological data discussed in this paper were obtained during the Norwegian Antarctic Research Expedition (NARE) 1978/79 (Fig. 1). The programme consisted of taking gravity cores and grab samples at 30 sites, and water samples from 1, 10, and 100 m above the sea bottom at 12 sites, as well as under-water photographs, shallow seismic-reflection profiles, and side-scan sonar records. Supporting data from NARE 1976/77 are also included.

Complete particle size analyses of grades < 2 mm in size were carried out on the samples by standard procedures. X-ray analyses were made of all cores. Water samples were filtered on 142 mm 0.2 μm Nuclepore filters at 3 x 10^5 Pa pressure on pre-weighed filters. The texture and chemical composition of the suspended matter were studied by means of an electron microscope with an energy dispersive unit.

Sediment distribution and sea-floor erosion

Usually a thin veneer (up to 1 m thick) of soft pebbly mud is underlain by similarly composed sediment; however, the latter unit is characterized by a high degree of compaction (Fig. 3). The overconsolidated sediments are
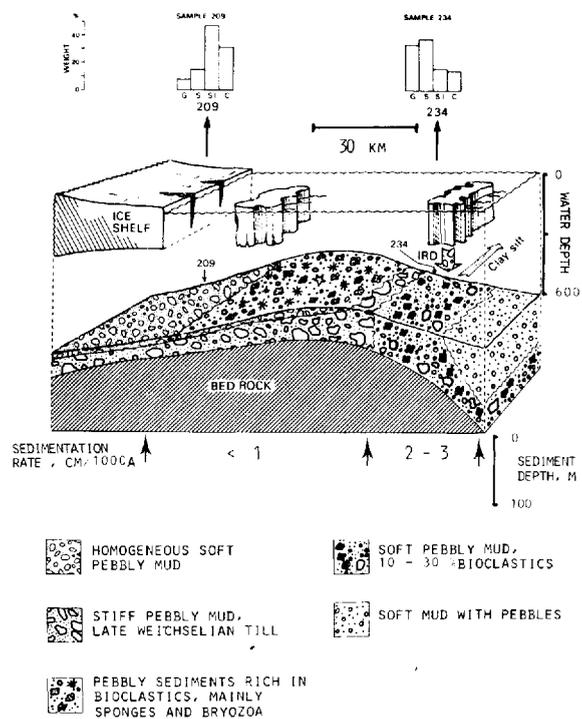

Fig.3. Sediment distribution and processes on the continental shelf outside Kapp Norvegia. Sediment thicknesses are based on shallow seismic records. The overconsolidated till (shear strength 50-120 kN m^{-2}) was formed during a period of low sea-level and grounded ice shelf. At this time sediments were frozen into the ice shelf and subsequently melted out to give the homogeneous soft mud. The two outermost units are both IRD facies with successively decreasing content of coarser materials seaward. The histogram shows grain-size distribution of two samples south-west of Kapp Norvegia. C: clay, SI: silt, S: sand, G: gravel (2-16 mm). Sample 209 is from a location that was underneath the ice shelf until < 2 a previously.

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confined to the shelf, and on the upper slope they continue into soft mud with a variable content of pebbles. A similar lithology for the Weddell Sea area was also found by Anderson and others (1980).

The sea floor, especially on the outer shelf and upper slope, was apparently enriched with pebbles and gravels (Fig. 3, sample 234). The observed bottom currents cannot, however, erode the underlying clayey sediments extensively, but they can maintain suspended clay and silt melted out from the icebergs, thus causing selective deposition of the coarser fractions.

A concentration of 0.1-1.0 mg ℓ^{-1} of clay and fine-grained silt is common in bottom water as well as in intermediate parts of the water column, both in the coastal current and in the cold current on the shelf break. Similar values are also observed farther east along the Antarctic coast (Lisitzin 1972). The suspended matter consists of quartz, feldspar, and illitic clay minerals with additional iron-rich aggregates, and is also rich in bioclastic silica, mainly diatom fragments, settled from the surface water. Magnesium-rich bioclastic carbonate detritus and sponge needles were not observed in the bottom-water samples. These components are frequent in the sea-floor sediments, and they should have been present in the suspended matter if there had been extensive erosion.

Anderson and others (1980) ascribe the presence of coarse-grained sea-floor sediments on the shelf to winnowing by bottom currents. However, it follows from the above that the sediment texture is instead mainly inherited from the primary englacial sediments.

Sedimentation rates and transport

Bryozoa fragments from three levels in a core on the upper slope (650 m water depth) south-east of Kapp Norvegia have been ^{14}C-dated giving an average sedimentation rate of 0.027 m ka^{-1} (Fig. 4). The core site is outside the estimated position of the late Pleistocene grounding line and, because of the decreasing age upward in the core, the sedimentary sequence is believed to be intact. Bryozoa are found in the surface sediments at the core site, indica-

ting *in situ* origin. In the core, the bioclastics account for 10 to 30%, implying a clastic sedimentation rate of 0.02 m ka^{-1}. Similar rates have also been calculated for the glacio-marine deposits in the Ross Sea area (Fillon 1977).

The sedimentation rates from the upper continental slope may be higher than average for the continental shelf in the Weddell Sea. In the shallower regions (250 to 350 m), the sea floor is covered by sponges and bryozoa debris. This flourishing organic life suggests a low sedimentation rate. Low sedimentation rate on the shelf area is also supported by exposure of the overconsolidated pebbly mud of late Pleistocene age (discussed later) at 350 to 550 m water depth. A deposition rate of < 0.01 m ka^{-1} is suggested for this area (Fig. 3).

Recognizable plough marks with varying sharpness in topography were observed by side-scan sonar on the shelf and at the shelf break at 400 to 600 m water depth (Fossum and Klepsvik, personal communication). This is below ice ploughing caused by present-day icebergs. The good preservation of the plough marks also confirms low sedimentation rates in this glacio-marine environment.

The lack of clastic sedimentation on the shelf areas is probably due to lack of sediment in the icebergs calving from the adjacent ice shelf (Fig. 2). Furthermore, the shallow water depths on the central shelf hinder entry of thick icebergs from other areas. Suspended sediment transport from the bordering ice shelf may occur in addition to the deposition of ice-rafted debris (IRD). Direct observations are not available, but information can be obtained indirectly from suspended matter in the current flowing out from beneath the Filchner Ice Shelf. Our sediment data for the cold bottom current are based only on samples on the shelf break, which is a considerable distance from the ice shelf. The observed sediment concentrations indicate weak currents with low sediment discharge beneath the ice shelf. This is confirmed by the observations of only a very thin cover of soft sediment above seismic high-velocity bedrock at 1 200 m depth in the centre of the Crary trough, immediately in front of the Filchner Ice Shelf, and without any evidence of erosion (Maisey, personal communication).

SEA-LEVEL CHANGES AND ICE EXTENT
Sea-level lowering, ice advance, and sedimentation

Overconsolidated pebbly mud (Fig. 3) was recovered on the shelf break outside Kapp Norvegia (3 samples) and on the shelf break in the central Weddell Sea (6 samples). We conclude that these are till deposits on the basis of geographic distribution, sediment texture, and especially the degree of compaction (Fig. 3), these latter factors being similar to those of basal till deposits on the Norwegian continental shelf (Rokoengen and others 1978). Anderson and others (1980) also suggest that these are till deposits. Presence of crushed shell fragments and sponge needles further show that the sediment has a primary marine origin.

One date is available from the overconsolidated sediment in the central Weddell Sea, located 400 km from the present ice front. Shell fragments from the lower part of a shallow core were ^{14}C-dated to

31 920 $^{+1\ 820}_{-1\ 520}$ (1σ) $^{+4\ 330}_{-2\ 880}$ (2σ) [14]Ca BP (not

corrected for ^{14}C-age of sea-water (Harkness 1979)). The overloading must be younger than
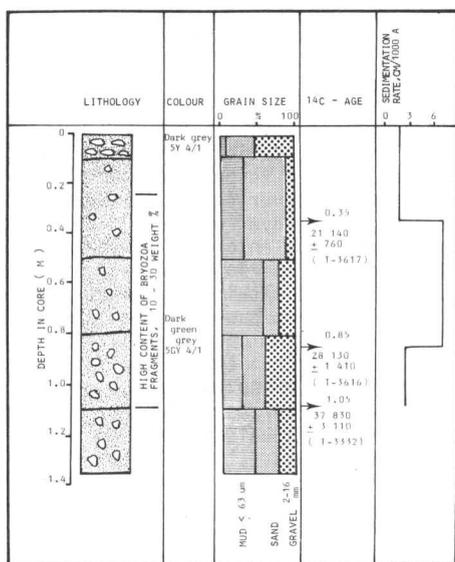

Fig.4. Characteristic lithological section of a core from the shelf break/upper slope outside Dronning Maud Land. X-ray analyses did not show any sign of lamination. Position: 72°19' S, 16°11' W, water depth 650 m.

the original marine sediments, thus indicating a major expansion of the combined Filchner-Ronne ice shelves less than 31 ka BP. We believe that the sea-level lowering of 100 to 130 m at the end of the late Pleistocene led the Filchner-Ronne ice shelves and western Dronning Maud ice to ground and expand to the shelf break.

However, prior to this event the bioclastic content in the till shows marine conditions. Additional evidence for conditions similar to the present, e.g. a retracted ice shelf, is also found in the ^{14}C-dated core (Fig. 4). During the period 30 to 40 ka BP, the lithology is similar to the present surface sediments, i.e. depleted in the finer grades.

The sedimentary environment on the upper slope during the period of a lower sea-level and an expanded ice shelf is also shown by this core (Fig. 4). At 21 ka BP, corresponding to the probable time of an expanded and grounded ice shelf, an increase in muddy sediments and decrease in pebble content is noted. The increased content of the finer grades reflects sedimentation in a sub-ice-shelf environment, being different from the present open continental shelf and slope where the clay and silt are removed during settling (Fig. 3).

Sediment incorporation by a grounded ice shelf

Soft pebbly mud overlies overconsolidated late Pleistocene deposits on the shallower parts of the shelf outside Kapp Norvegia. X-ray analyses of cores show that the sediment is not laminated. This thin unit was limited on its seaward side to water depths < 300 m. A similar unit was found in the central Weddell Sea down to 400 to 500 m water depth (Maisey, unpublished, Anderson and others 1980). This sediment cannot have been deposited by currents, because it is not found at greater depths, nor is it likely to be IRD which has been selectively deposited. Instead, we propose that these elevated parts of the sea bed were shoals on which ice shelves have been grounded in connection with a lower sea-level and/or thicker ice. The ice shelf/ice rise will freeze to the bed after grounding, and permafrost will form. This is discussed by Orheim* where it is shown that grounding for the order of 10^3 a will develop some tens of metres of permafrost. The frozen sediment will become part of the ice shelf when the sea-level rises, and the ice shelf may become partially afloat depending upon the amount of sediment, and its dimensions and flow. Melting of the frozen-in sediments would lead to the observed sequence of soft deposits overlying overconsolidated sediments.

Sedimentation near the grounding line

The position of the grounding line will be affected by (1) changes in sea-level, whether from iso- or eustatic effects, (2) thickening or thinning of the ice sheet, including long- and short-term deviations from steady state, and (3) changes in flow pattern. Advance or retreat of the grounding line will cause a complex interbedding of sediments because most sediments are deposited near it. Our concept of the resulting sequence is shown in Figure 5. Recognition of such sequences should be important in the reconstruction of former ice margins.

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* In preparation: "Permafrost under grounded ice shelves".
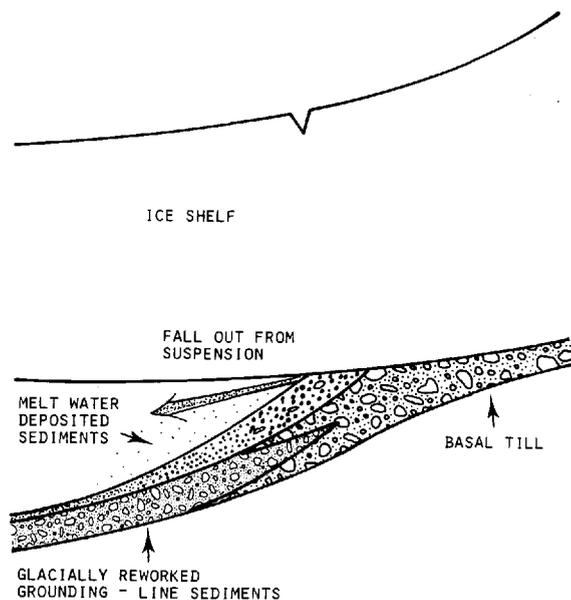

Fig.5. A concept of the sediment distribution at the grounding line with outflowing melt water. Advance of the grounding line leads to glacial reworking of the melt-water deposits with mixing-in of basal till sediments.

IRD DISTRIBUTION: CONCLUDING REMARKS

IRD is a diagnostic element of glaciomarine sediments. As noted, the erosion products from the continental ice sheets are concentrated in a basal ice zone of a few metres thickness, and, because of basal melting under ice shelves, coasts free of ice shelves will represent the major source of IRD around Antarctica.

Data on iceberg drifts and melt rates (Tchernia 1974, Morgan and Budd 1978, Orheim 1980, Vinje 1980) and on ocean temperatures in the Southern Ocean (Gordon and Goldberg 1970) have been used to construct Figure 6, showing probable iceberg paths and melt rates. From this, it appears that IRD deposits are confined to coastal areas, although deposits have been found beyond these limits (Tolstikov 1966). Keeping the geography of Antarctica unchanged, it is difficult to envisage former water properties and circulation that would allow IRD from the basal layer to be deposited far north of the Antarctic Convergence. At some longitudes a 10 m basal layer would melt before the icebergs reached the Antarctic Convergence even if the temperature was lowered by 5° C. Nor is preservation of the basal sediment because of overturning likely, because an overturned iceberg will normally continue to roll. We therefore conclude that IRD at low latitudes and outside the main IRD zone (Fig. 6) must originate from thicker basal layers, or from sediment in higher levels of the ice sheet eroded from nunataks. It follows that the IRD patterns will be more accidental, and outside the main IRD zone the deposition rate will become very low. Thus, models that relate an increase in IRD in cores to glacial expansion can be expected to fail. This has been recognized by several authors in recent years (Keany and others 1976). Following from the previous section, sea-level changes can clearly assist entrainment of sediments onto the base of an ice shelf. Subsequent calving may produce
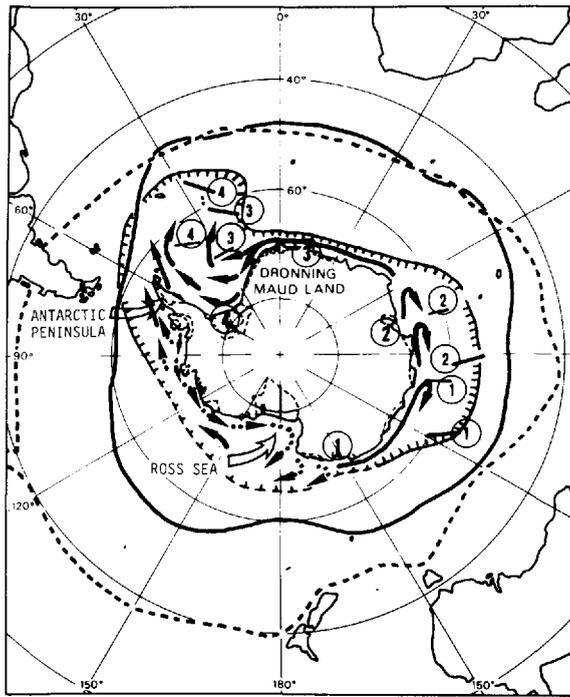
Fig.6. IRD distribution. Arrows show "probable" iceberg paths, based mostly on tracks of instrumented icebergs. Drift tracks in the sector from the Antarctic Peninsula to the western Ross Sea are constructed from mean surface currents (e.g. Treshnikov 1964). Thin and thick numbered lines give approximate locations for melting of 5 and 10 m of basal ice of icebergs from corresponding locations. Solid line: Antarctic Convergence, hatched line: outer limit of IRD from sediments in the basal ice, dashed line: outer limit of IRD (Tolstikov 1966).

debris-rich icebergs which could contribute to IRD found at lower latitudes.

Obviously the above cannot be applied directly to the northern hemisphere. Here the circulation is more meridional, and icebergs can drift farther towards the Equator before losing their basal load. However, high iceberg melt rates must have prevailed in warmer seas, and caution should be used in equating variations in glaciation with IRD sedimentation rates far from iceberg sources.

ACKNOWLEDGEMENTS

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