Glaciomarine sediments and suspended particulate matter, Weddell Sea Shelf, Antarctica

ANDERS ELVERHØI AND ELEN ROALDSET

Elverhøi, A. & Roaldset, E. 1983: Glaciomarine sediments and suspended particulate matter, Weddell Sea Shelf, Antarctica. *Polar Research 1 n.s.*, 1–21. Oslo.

Samples of glaciomarine sediments and suspended matter from the eastern and central Weddell Sea Shelf were collected during the Norwegian Antarctic Research Expedition (NARE) in 1978/79. Ice-rafted clastic materials are in general the main sediment sources. On the eastern shelf, biogenic materials are abundant (sponges and bryozoan debris). Fine-grained materials, clastic and bioclastic, are additionally supported as fecal aggregates and by currents. The composition of the bottom sediments shows only small variations laterally and within the profiles. Dissolution of the biogenic materials appears to be slight. The suspended matter is dominated by fine silt and clay particles of clastic, biogenic (mainly diatoms) and authigenic (Fe, Mg-rich silicates) origin. Metalliferous particles (Fe, Ti, Zn, Cr, Ni-rich) of possibly anthropogenic and/or cosmic origin are observed. On the upper continental slope and the outer shelf the sedimentation rates are in the range of 2–5 cm/1000 years, which are slightly higher than for the rest of the shelf. The bioclastic glaciomarine deposits grade southward into bioclastic free sediments, showing that glaciomarine deposits outside an ice shelf may form a sequence of alternating bioclastic-rich and bioclastic-free layers. Similarly, late Precambrian carbonate tillite sequences, especially in the case of thin carbonate layers interbedded with tillite layers, may reflect variations in glaciomarine facies rather than interglacial/glacial cycles.

Anders Elverhøi, Norsk Polarinstitutt, Rolfstangveien 12, 1330 Oslo Lufthavn, Norway; Elen Roaldset, Norsk Hydro Research Center, Lars Hillesgt. 30, 5000 Bergen, Norway. *June 1982 (revised October 1982).*

Introduction

Glaciomarine sediments make up a considerable part of Pleistocene and ancient glacial sequences. It is difficult to distinguish between glaciomarine sediments and those deposited by a grounded glacier. This is especially true when the latter sediments are formed by reworking of the former. Furthermore, glaciomarine facies represent a wide group of sediments, ranging from deep-sea sediments with a high content of ice-rafted detritus (IRD) to deposits formed beneath a floating ice shelf. The few available studies present general descriptions of the glaciomarine environment and concentrate on the mechanical compositions of the deposits (Carey & Ahmad 1961; Anderson *et al.* 1977; Drewry & Cooper 1981; Orheim & Elverhøi 1981). For comprehensive reviews of the previous investigations in the Weddell Sea the paper by Anderson and co-workers (i.e. Anderson *et al.* 1979; Anderson *et al.* 1980; Wright & Anderson 1982) may be referred to.

In this paper the emphasis is on the textural, mineralogical and geochemical composition of the sediments on the eastern and central Weddell Sea Shelf, and the relationship of these characteristics to the sedimentary environment.

A close association of carbonate and tillite has been found in late Precambrian glacial sequences (e.g. Schermerhorn 1974). In the eastern Weddell Sea, carbonate-rich bioclastic sediments are a main constituent of the glaciomarine deposits. The present paper will therefore also discuss the recent Weddell Sea deposits in relation to the late Precambrian formations.

Environmental setting

The study area

The southern Weddell Sea Shelf forms a shallow platform with water depths of 300–500 m (Fig. 1). An exception is the Crary Trough running across the continental shelf and providing water depths of more than 1000 m in front of the Filchner Ice Shelf. A ridge of 200–300 m relief at the mouth of the trough is due to accumulation of sediments. West of the Crary Trough the shelf is approximately 500 km wide and underlies the entire southwestern portion of the Weddell Sea.

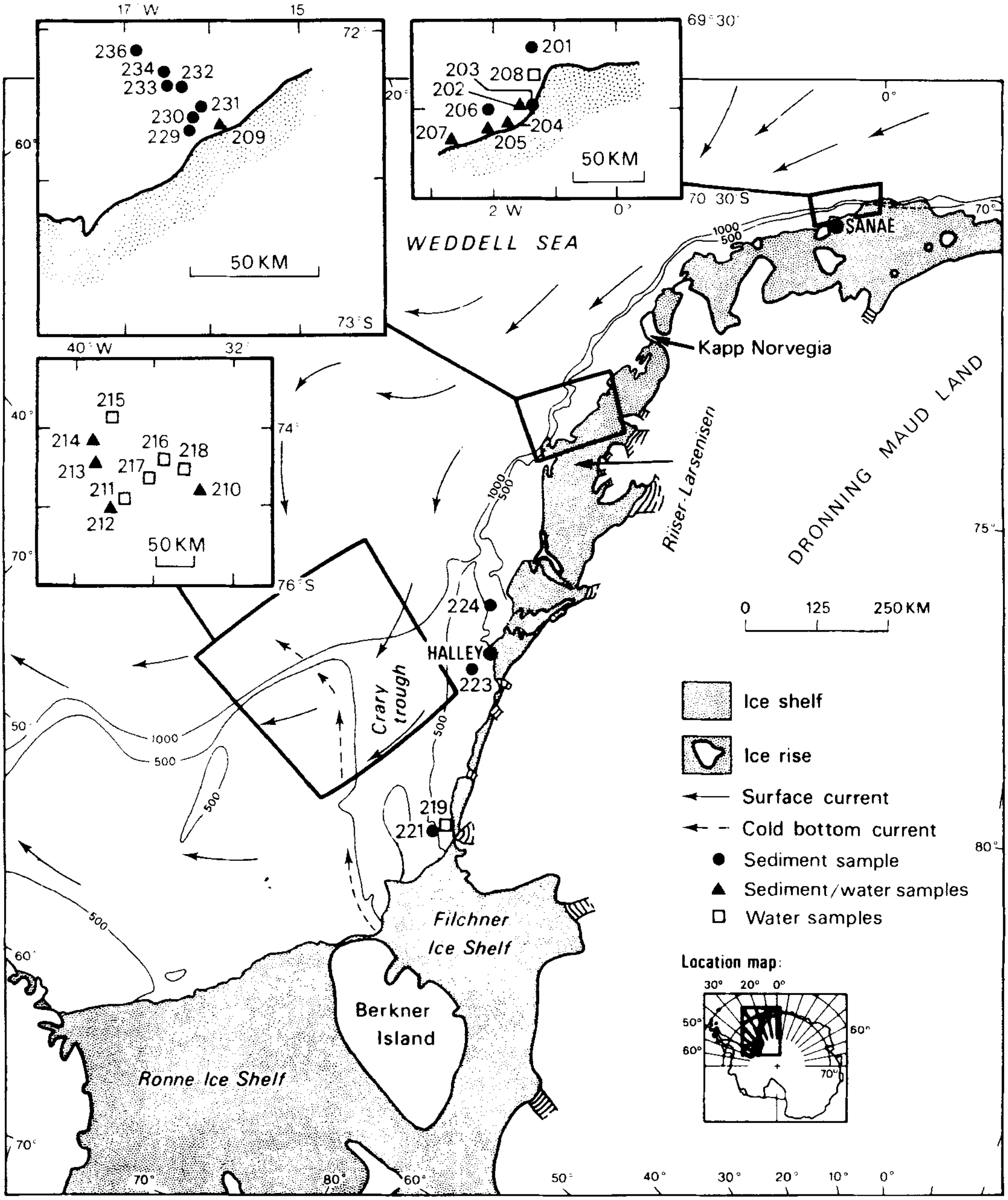


Fig. 1. Regional bathymetry and ice shelves. Southern Weddell Sea, with arrows showing the main current directions, and with sample sites.

At present the Filchner/Ronne Ice Shelves extend 400–600 km seawards off the grounding line, while the distance beyond the ice front to the shelf edge, as defined by the 500 m depth contour, is somewhat less. Along the eastern coast, the ice shelf is more narrow, 50–200 km. In this area the distance from the ice front to the shelf edge is 20–70 km.

Oceanography

The current pattern is characterized by the Weddell Sea Gyro. In the eastern areas, deep Atlantic water flows up onto the shelf, and these water masses are gradually mixed into the shelf water, which flows along the eastern coast into the Weddell Sea (Foster 1978). Because of sea-ice formation, the salinity increases and may cause, especially in the southern and western Weddell Sea Shelf regions, haline convection and mixing of the entire water column leading to the formation of cold saline shelf water (Foster 1978). These water masses flow to the north and mix with warmer deep water as it flows down the continental slope into the South Atlantic.

West of Crary Trough a cold bottom current flows out beneath the Filchner Ice Shelf and continues across the southern Weddell Sea to the shelf edge (Fig. 1), where the current turns westward along the slope (Foldvik 1979).

Long-range current measurements over one year close to stations 212–214 (Fig. 1) show velocities in the range of 10 to 30 cm/s (Foldvik 1979). Similar velocities are also reported from the eastern shelf; here, however, the data are only from short-term measurements (two days) and current velocity calculations (Gill 1973; Foldvik pers. comm. 1980; Kvinge pers. comm. 1980).

Because of the presence of sea ice most of the year and considerable water depths, wave-induced activity on the bottoms is insignificant. In the southern and eastern Weddell Sea the surface current pattern is also believed to account for the intermediate and bottom water (Foster 1978).

Glaciology

The Filchner/Ronne Ice Shelves as well as the ice shelf off Dronning Maud Land are so broad that glacial debris is believed to melt out beneath the ice shelf before reaching the ice front (Fig. 2). South of Halley, however, the ice sheet calves almost directly into the sea, providing sediment-loaded icebergs.

Methods

Sediment sampling

During the Norwegian Antarctic Research Expedition (NARE) 1978/79, bottom sediments, gravity cores (<3 m), grab samples, and dredge hauls were obtained at 22 sites in the eastern and central Weddell Sea (Fig. 1).

Water sampling and filtration

Samples of suspended particulate matter were collected in 30 l polyvinyl chloride Niskin bottles 1, 10, 25, and 100 m above the sea bed at sixteen sites.

Water samples were pressure filtered on board the ship through 142 mm 0.22 μm Nucleopore membrane filters in a teflon filter holder at 3 atm ($3 \times 10^5 \, Nm^{-2}$) pressure on preweighted filters. The filters were immediately rinsed free of salts by at least five repeated flushes with filtered, distilled water, before storage in sealed plastic petridishes wrapped in aluminium foil.

The content of suspended particulate matter was determined gravimetrically at controlled humidity. As the planktonic fauna/flora is to be investigated by biologists, the filters were not heated.

Laboratory methods

The core description is based on visual description, X-radiography, and grain-size analyses.

Grain-size analyses of the <2 mm grades were carried out by standard sieving and settling methods, utilizing Stokes law on the <63 μm fraction. Mineralogical analyses performed by X-ray diffraction (XRD) were obtained on the total sample, <63 μm, 32–4 μm, and <2 μm fractions, which were dispersed in distilled water and sedimented by suction onto a Millipore filter (0.2 μm poresize). The sample was then inverted onto a glass slide and the filter peeled off.

A Phillips diffractometer was used with a scanning speed of 1° per minute. For more detailed scanning the speed was reduced to $\frac{1}{4}$ or $\frac{1}{8}$° per minute. Each sample was analysed air dried, after ethylene glycolation and after heating.

The methods of mineral identification followed standard criteria (Brindley & Brown 1980) with additional reference to the zeolite d-spacings given by Deer *et al.* (1963) and Berry (1974). Chemical analyses of <2 μm and <63 μm fractions were performed by means of X-ray fluorescence (Kraeft 1972).

The nature and composition of the suspended particulate matter were analysed by JEOL JSM 3 scanning electron microscope with an energy dispersive X-ray spectrometer probe (EDAX). Mean chemical composition of the suspended matter was determined semi-quantitatively by scanning the filters. Elemental intensities measured in the Nucleopore filters are generally less

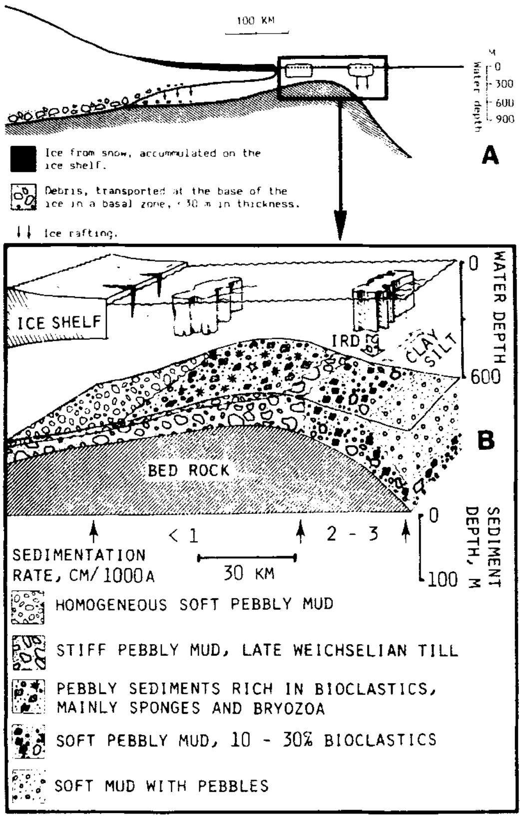


Fig. 2. □ A. Schematic section through an ice shelf showing the principal depositional sites. Because of (i) sub ice shelf melting and (ii) glacial erosion products within an ice sheet are primarily concentrated in the basal layer, icebergs calving off an ice shelf are almost free of detritus. For narrow ice shelves the melting is less extensive and icebergs may contain debris. Sediment loaded icebergs most likely form where the ice sheet calves directly into sea. This is illustrated by icebergs on the outer shelf drifting along the shore with the coastal current. (From Orheim and Elverhøi 1981; Drewry and Cooper 1981.) □ B. Illustration of the sediment distribution on the continental shelf outside Riiser-Larsenisen. Sediment thicknesses are based on shallow seismic records and sediment cores. (From Orheim and Elverhøi 1981.)

than 10–20 per cent of the lowest elemental intensities encountered in the samples, with the exception of Mn, for which the filter may contribute significantly to the measured intensity in the samples.

Sedimentary environment

Sediment composition

Overconsolidated (30–100 kN/m^2) pebbly mud is exposed at the seabed on the outer shelf (Fig. 3). The most common type of sediment, however, both on the shelf and on the upper continental slope, is soft pebbly mud. With the exception of core 214, the sediments were homogeneous. In core 214 laminations were seen. Rock fragments within the samples included basalt, gabbro, granite, gneiss, and schist. The quartz grains frequently displayed a rounded and frosted morphology.

The origins of the sediments have previously been discussed by Anderson *et al.* (1980), Orheim & Elverhøi (1981) and Elverhøi (1981) (see also Fig. 2). The overconsolidated pebbly mud is interpreted as a till, probably of late Weichselian age, while the soft pebbly mud is mainly formed from ice rafting. The lower part of the latter deposits on the shelf is suggested to represent materials frozen on to the grounded late Weichselian Ice Sheet and later melted out as the ice started to float (Orheim & Elverhøi 1981). According to Wright & Anderson (1982), the sediment on the upper continental slope may locally have been reworked by gravity flow.

Of special interest are the bioclastic-rich sediments recovered on the shoals outside Riiser Larsen-isen and SANAE (Figs. 3 and 4a). The bioclastics are confined to the eastern shelf with very low content in the central regions (Fig. 4b). In the sediments the diatoms show signs of dissolution (Fig. 4c).

Lumps of sponges were found at station 229. These sponges were similar to the 'volcano' type assemblage previously described from the Ross Sea area (Dayton *et al.* 1974). Bryozoan debris and corals were the main constituents in samples 230 and 231. In sample 204 the sediment consisted mainly of sponge needles. Underwater photographs showed that the sea bottom outside Halley is covered with living organisms, mainly corals.

Depositional rate

On the shallow shelf outside Riiser Larsen-isen, a depositional rate of 1 cm/1000 years has been postulated (Orheim & Elverhøi 1981), mainly reflecting accumulation of bioclastic materials. ^{14}C-dating of three cores on the shelf and upper slope revealed depositional rates in the range of 2–5 cm/1000 years (Fig. 5). In two cores from the eastern coast (206 and 234), sand and gravel-sized carbonates made up 10–30 per cent of the samples, which means that the clastic depositional rate is lower than the above values suggest. Cores

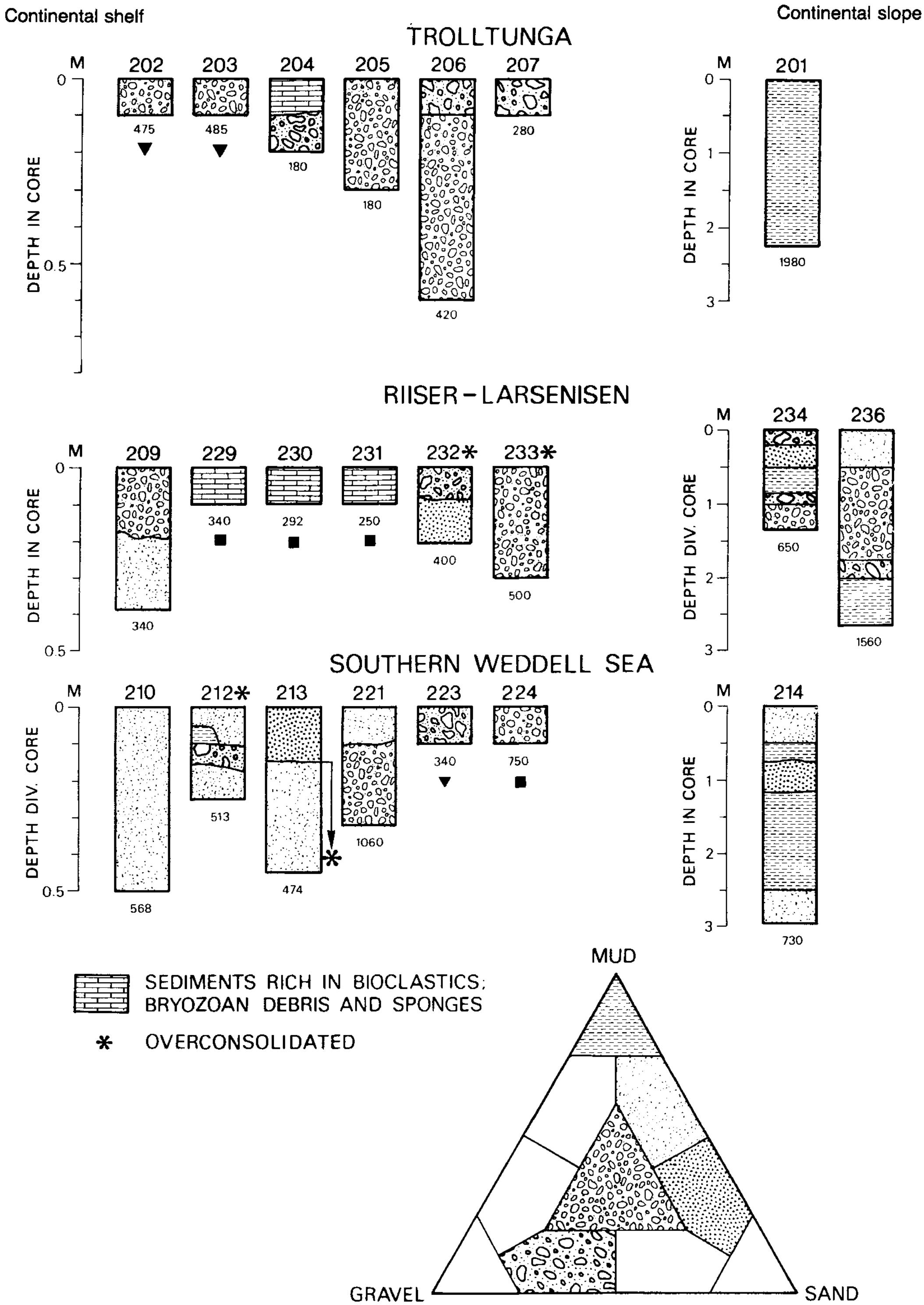
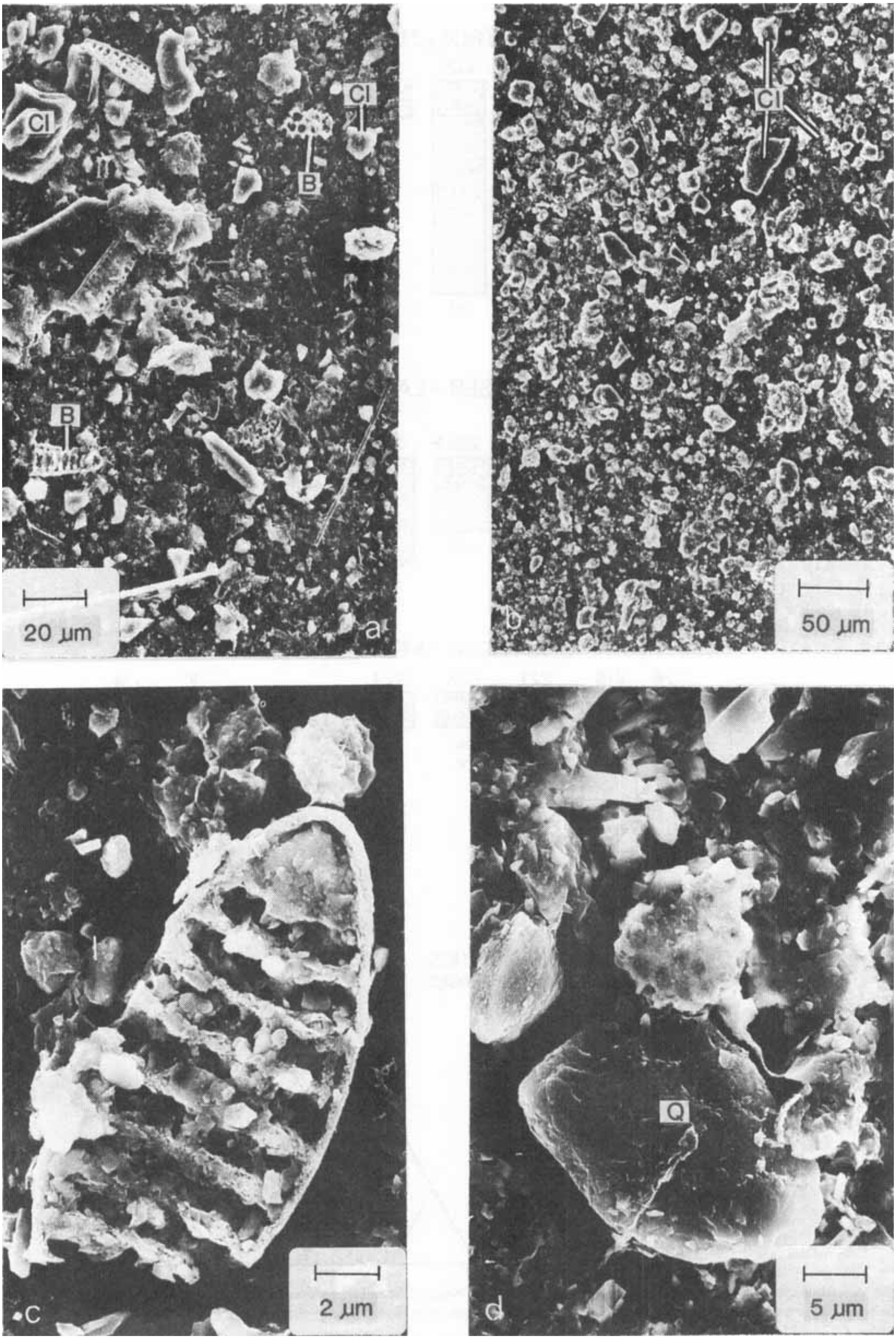


Fig. 3. Lithological description of sediment samples from the Weddell Sea. The grab samples and the dredge hauls are identified as ▼ and ■, respectively. Numbers at top and bottom of columns refer to station and water depth, respectively. Note that different scales are used for cores from the continental shelf (left) and cores from the continental slope (right).


Cl
Cl
B
B
20 µm
a
Cl
b
50 µm
c
2 µm
Q
d
5 µm

214 and 234 are from the uppermost part of the continental slope, an area where gravity flows may be initiated according to Wright & Anderson (1982). However, the increasing ^{14}C-age down-core and fossil in living position in the cores, suggest an autochthonous sediment sequence.

Very few data are available on depositional rates outside ice shelves. The results obtained are of the same order as those previously reported from the Ross Sea area (Fillon 1977). The results thus seem to confirm that the clastic sediment supply outside ice shelves is rather low.

Grain-size distribution and ice rafting

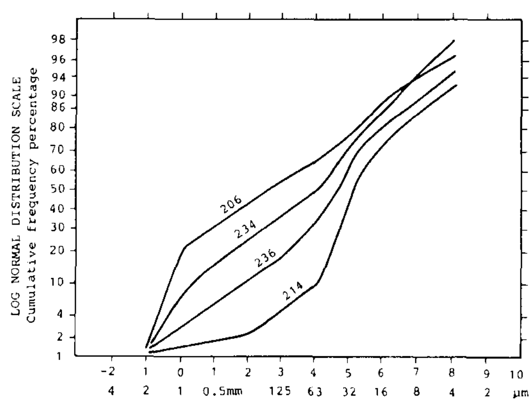
The surface sediments are relatively rich in coarser clastic material on the outer shelf and upper slope along the eastern coast (Fig. 6, samples 206 and 234). A similar pattern was also found for 17 samples taken by NARE 1977 (Elverhøi & Maisey, in prep.). The relative deficiency in the finer grades in the samples from the eastern areas may (1) be caused by removal of the finer material by winnowing, as suggested by Anderson *et al.* (1980); (2) be a primary feature of the ice-rafted material, where clay and finer silt have been kept in suspension while the coarser grades have settled; and (3) be a combination of both these processes.

Accurate data for the critical boundary shear stresses or critical erosion velocities for cohesive sediments are limited (e.g. Postma 1967; Enger 1968; Graf 1971; Drake 1976; Nowell *et al.* 1981). Additionally, knowledge on the current velocities on the eastern shelf is very limited; however, they are probably within the range of 10–30 cm/s. The possibilities of bottom erosion have to be discussed very briefly, therefore.

The water content of sediments may provide a rough estimate of the resistance of erosion of muddy deposits. Experiments have shown that for fine-grained silt the critical velocity is 30 cm/s at 80 per cent water content, increasing to 50 cm/s at 60 per cent water content of dry weight (e.g. Postma 1967). The water content of the surface sediments on the Weddell Sea Shelf is in the range 55–75 per cent (25–35 per cent water content was found in the overconsolidated mud/

SAMPLE/ DEPTH IN CORE (CM)	WATER DEPTH (M)	TYPE OF MATERIAL	^{14}C-AGE	SEDIMENTATION RATE, CM/1000 YEARS (0 2 4 6 8)
206/16	420	coral	3950 ±160 (T-3836) 4700 (adjusted 750 yr)	
234/35	650	bryozoan debris	21240 ±760 (T-3617)	
234/85		"	28130 ±1410 (T-3618)	
234/105		"	37830 ±3110 (T-3332)	
214/175	730	shell bivalves in situ	> 35100 (1σ) (T-3835)	(max.)

Fig. 5. ^{14}C datings for three Weddell Sea cores. The vertical bars show the average sedimentation rates as calculated on a wet sediment basis. Sample 206/16 is corrected for ^{14}C deficiency in Antarctic waters (e.g. Harkness 1979). Numbers in parentheses refer to radiocarbon lab. no.



Sample nr.	Material >2mm	Median grain size	Water depth
206	66%	200 µm	420 m
234	30%	63 µm	650 m
236	10%	50 µm	1560 m
214	5%	32 µm	730 m

Fig. 6. Grain-size characteristics for four surface samples from the sand–silt–clay fractions.

Fig. 4. (a, b) Scanning electron micrographs of surface sediments from the eastern region (a) station 234 and central region (b) station 210. Cl: clastics. B: bioclastics. (c) Diatom, partly dissolved (station 234, top sediment). (d) Detail of sample 209 with 20 µm quartz particle (Q).

till). Considering the current velocities, 10–30 cm/s, the probability of extensive erosion of the Weddell Sea Shelf/upper slope sea bed seems low.

In the Weddell Sea the coarser clastic debris is brought in by icebergs, extending down to water depths of 200–300 m, giving a settling depth for the ice-rafted debris of 100–200 m on the outer shelf, increasing to 1000 m on the continental slope. The ice-rafted materials are unsorted, ranging from gravel to fine grained silt and clay. The latter materials are easily kept in suspension by current velocities greater than 1 cm/s (Hollister & Heezen 1972). This leads to a separation of the coarser-grades from the finer ones during settling. Taking into consideration the low sedimentation rate, it seems evident that a 2 cm pebble may be exposed on the surface for a period of 1000 years.

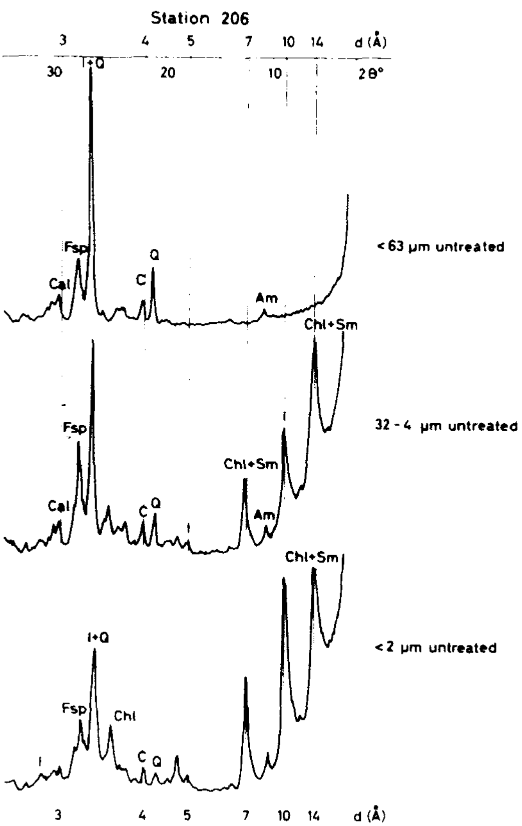


Fig. 7a. Characteristic X-ray diffraction curves for the coarse silt/medium silt and of the clay fraction. Chl = chlorite. I = illite. Q = quartz. Sm = smectite. Am = amphibole. C = christobalite (and albitite?). Fsp = feldspar (mainly albite). Cal = calcite.

Relatively frequent rafting of coarser materials may thus have given rise to the pebble-rich surface of the eastern shelf.

Although the possibilities for bottom erosion seem limited, this process cannot be excluded, especially with respect to episodic events.

According to the above, the primary grain size of the ice-rafted material is essential for the sea floor sediment composition. The sediments may be modified during settling, however, and additional modification may also occur by the action of bottom currents.

The bioclastic sediments in relation to the sedimentary environment

Recent years' investigations have shown that the Antarctic shelf areas support a prolific bioclastic fauna of high diversity (Knox 1970). The bioclastic accumulations are of Holocene age, as during the late Weichselian the shelf regions were covered by grounded ice (Stuvier *et al.* 1981). The fauna is characterized by suspension feeders which have accumulated to thicknesses of up to 0.75 m. The dominance of silica organisms is related to the high abundance of silica (Arnaud 1977). On the other hand, calcium availability is a limiting factor for the carbonate producing organisms, resulting in a predominance of fragile species (e.g. bryozoans).

The benthic life is further related to (1) high productivity, (2) low sediment input, and (3) available substrata (Arnaud 1977). In the Weddell Sea these factors have been found to be caused by (1) intrusion of deep Atlantic water up onto the eastern shelf, (2) presence of an ice shelf, and (3) ice rafting of pebbles.

Mineralogical and chemical composition

General description

The coarse silt fraction consists mainly of quartz, albitic feldspar and, additionally, calcite and traces of dolomite and cristobalite (Fig. 7a). The fine silt and clay fractions, however, are dominated by smectite, illite, and chlorite (Fig. 7a, b and 8a), besides minor amounts of amphibole, quartz, cristobalite, albite, K-feldspar, and carbonates. Kaolinite was not detected by slow scan XRD analysis nor after HCl-treatment.

The mineralogical composition differs only slightly between the different areas (Table 1). The biogenic carbonate and cristobalite contents are highest in the eastern areas. In the central parts of the Weddell Sea, with formation of cold shelf water, the content of bioclastic material is low. Zeolites (Fig. 8a), possibly of the clinoptilolite, stilbite and/or phillipsite type, were recorded in the 32–4 μm fractions in two cores. No zeolite was observed in the corresponding clay fractions. This is in accordance with previous investigations (Biscaye 1965; Czyscinski 1973; Corliss & Milliman 1981).

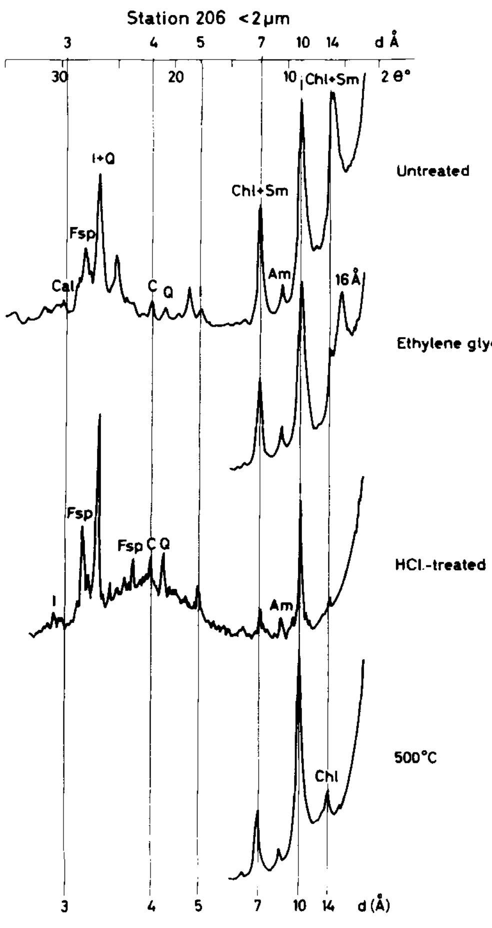


Fig. 7b. Characteristic X-ray diffraction curves for the clay fraction after ethylene glycol, acid and heat treatments. Chl = chlorite, I = illite, Q = quartz, Sm = smectite, Am = amphibole, C = christobalite (and albite?), Fsp = feldspar (mainly albite), Cal = calcite.

Distribution and source of smectite

The smectite and illite distribution seems to depend on regional features (Table 1).

Smectite dominates in samples from outside Riiser Larsenisen and from the central Weddell Sea, while illite is the major clay mineral in samples from outside SANAE. High illite content is also observed in the samples from outside the ice front of the Filchner Ice Shelf.

The smectite referred to here has strong basal reflection of 15 Å, expanding to about 18 Å with ethylene glycol treatment and collapsing on heating to 450°C. Occasionally the smectite reflection is asymmetric and irregular, as illustrated in Fig. 8b, showing similarities to saponite as described by Brindly & Brown (1980). The smectite in the finer silt and clay fractions shows a similar behaviour. This type of smectite may be similar to the smectite-like aggregates frequently recorded in the above water masses, which by EDAX-analyses are shown to be Fe-, Ti-rich (i.e. trioctahedral). This, and the chemical analyses of the clay fraction of the bottom sediments showing a high content of Fe, make it reasonable to assume that the smectites of the sediments are mainly trioctahedral.

Airborne dust has been found to contribute significantly to the sediments of the Central Atlantic (Delaney *et al.* 1967; Parkin *et al.* 1967; Folger 1970). At Barbados and in the South Atlantic, 80 per cent of the wind-blown particles are within 5–30 μm in size, and consist mainly of micaceous minerals, chlorite, talc, anatase, rutile, hematite, goethite and gibbsite. Illite and chlorite dominate relative to smectite, kaolinite and quartz. Delaney *et al* (1967), Chester *et al.* (1971), Prospero & Carlson (1972), and Goldberg & Griffin (1964) found the airborne supply and composition to be similar to the sediments accumulating in the deep ocean. A certain supply to Weddell Sea waters and sediments of airborne dust supplied from desert regions in Antarctica and South America with prevailing northerly and easterly winds is therefore to be expected.

The smectite content of the Weddell Sea fine silt and clay fraction is high, however, compared to eolian dust.

In oceanic sediments the formation of sepiolite and trioctahedral smectite is often related to submarine volcanism (Wollast 1974, 1977; Brindley & Brown 1980). Such processes may account for the high smectite content in the Weddell Sea

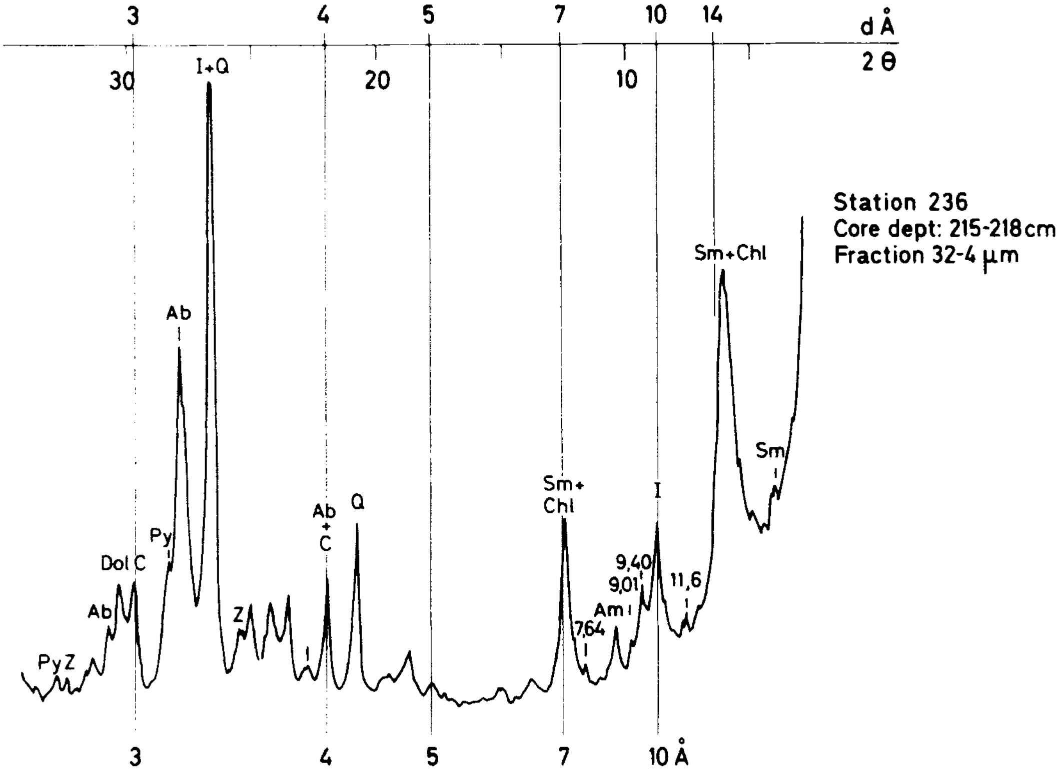


Fig. 8a. X-ray diffractogram of a sample from sediment depth of 215–218 cm in core 236. Smectite, illite, chlorite, and albite are the predominant minerals. Early diagenetic/zeolite minerals (z) (9.40 Å and 9.1 Å) are also shown.

sediments. Alteration of volcanic material by palaeogonitization and halmyrolysis includes loss of Ca and Mg and gain of alkalies. Authigenic smectite has been described in association with albite and zeolite (Bonatti 1963; Hay 1966; Buehmann & Ritzkovski 1976).

Vertical mineralogical variations

In general the observed vertical mineralogical composition is rather uniform (Table 2). In core 233, which consists of till-like material, the content of carbonate and cristobalite shows these sediments in part to be made up of older marine deposits. The mixed nature invalidates any strong emphasis on the observed variations. Although the depositional environment changed during deposition of the sediments in cores 214, 234, and 236, with closer proximity to the ice front during the late Weichselian, this environmental change is not reflected in the mineralogy.

Chemical analyses

Average chemical analyses for the <63 µm and <2 µm fractions and the corresponding variation ranges are listed in Table 3. The sponge-rich sediments which are completely dominated by Si are not included in the chemical analyses. The differences between the eastern and central regions are illustrated in Fig. 9, where, in addition to the differences in content of 'bioclastic elements' such as Ca, the eastern regions show a higher Fe content, a fact related to the higher content of smectite.

Angino & Andrews (1968) have previously analysed sediment samples from the shelf south of Halley. Their data show lower Al and somewhat higher Ti content than our data. The area south of Halley is probably supplied with sediments from the adjacent land areas, in contrast to the rest of the eastern shelf which receives IRD from eastern Dronning Maud Land. The observed

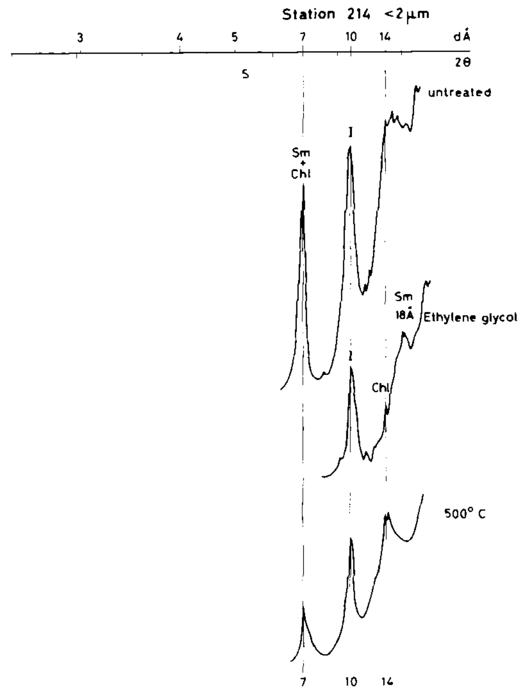


Fig. 8b. X-ray diffractogram illustrating the characteristic saponite reflections in the 14–16 Å interval which expand to 18 Å after glycolation and collapse with heating.

Table 1. Mineralogical composition of surface sediments, based on XRD analyses of <63 µm and <2 µm fractions (clay minerals).

	SAMPLE NR:	QUARTZ	CRISTOBALITE	AMPHIBOLE	K-FSP	ALBITE	PYRITE	CALCITE	DOLOMITE	CLAY MINERALS: SMECTITE	CLAY MINERALS: CHLORITE	CLAY MINERALS: ILLITE
SANAE	201	●	○	○	+	◐	○			◐	○	●
	202	●	○	○	+	●		○		◐	○	●
	203	●	○	○	+	●		○		◐	◐	●
	205	●	○		+	●		◐	+	◐	○	●
	206	●	○	○	+	●		◐	+	◐	○	●
	208	●	○	◐	+	●	+	◐	+	◐	○	●
RIISER-LARSEN ISEN	209	●	○			◐		○		●	○	◐
	232	●	○			●		◐	+	●	○	○
	233	●	○		+	●		◐	○	●	○	○
	234	●	+			◐		◐	○	●	○	◐
	236	●	○	+		●		◐	+	◐	◐	●
SOUTHERN WEDDELL SEA / CENTRAL WEDDELL SEA	210	●	+		+	●		+		●	○	◐
	212	●	○		+	●		+	+	●	○	◐
	214	●	○		◐	●		+		◐	○	●
	220	●	○	+	+	●		+		◐	○	●
	221	●	○		+	●		+	+	◐	○	●

● MAJOR COMPONENT ○ MINOR COMPONENT
◐ SECOND MAJOR COMPONENT + TRACE
NOT DETECTED

Table 2. Mineralogical variation with depth for gravity cores, based on XRD analyses of <63 µm and <2 µm fractions (clay minerals).

SAMPLE NR.	DEPTH IN CORE (CM)	QUARTZ	CRISTOBALITE	AMPHIBOLE	K-FSP	ALBITE	PYRITE	CALCITE	DOLOMITE	CLAY MINERALS: SMECTITE	CLAY MINERALS: CHLORITE	CLAY MINERALS: ILLITE
206	0-2	●	○	○	+	●		◐	+	◐	○	●
	12-14	●	○	○	+	●	+	○		◐	○	●
	23-25	●	○	◐	+	●	+	◐		◐	○	●
	44-48	●	○	○		●		◐	+	◐	○	●
	60-63	●	○	◐	+	●	+	◐	○	●	○	◐
233	0-2	●		◐	+	●		◐	○	●	○	○
	9-10	●	○	○		●		◐	○	●	○	○
	19-20	●	○	○		●	+	◐	○	●	○	○
	27-30	●	+	+		●	+			◐	○	◐
234	0-2	●	+	+		◐		+	○	●	○	◐
	33-35	●				○		●		●	○	◐
	78-81	●	+		+	○		●		●	◐	○
	102-136	●	+		+	○	+	●		●	◐	◐
	134-136	●	+		+	●		+		◐	○	●
236	0-2	●	○	+		●		◐	+	◐	◐	●
	100-103	●	○	+		◐		○		●	○	○
	200-203	●	○	+	+	●		○		●	○	○
	250-253	●	○	+		●		○		●	○	○
214	0-2	●	+		○	●	+	+	+	◐	○	●
	64-66	●			+	○	+	+	+	◐	○	●
	103-105	●				○		+		◐	○	●
	172-175	●				○	+	+		◐	◐	●
	245-247	●	+	+	+	○		+		●	○	●

~~LEGEND~~
● MAJOR COMPONENT ○ MINOR COMPONENT
◐ SECOND MAJOR COMPONENT + TRACE
NOT DETECTED

differences may thus be related to differences in the source area.

The high phosphate content in the clay fraction of some samples is of special interest. The highest content (7.6 per cent) was observed in sample 212, which is regarded as a late Weichselian till (Elverhøi 1981). Shell fragments in the same sequence have been dated to $31{,}290^{+1880}_{-1520}$ B.P., and the phosphate content is presumably related to biogenic production. High phosphate content may thus be applied for recognizing till deposits formed from reworking of primary marine sediments.

Suspended matter

Suspended load

The shelf waters contain 0.1 to 2.0 g/m^3 of suspended matter (Table 4). This concentration range is common for the bottom, as well as for the intermediate parts of the water column, and is close to the range of 0.5 to 1.5 g/m^3 reported

Table 3. Average chemical composition of surface sediments.

Oxide	Average <63 µm	Range	2 µm	Range	<63 µm 1	<63 µm 2	<2 µm 1	<2 µm 2
SiO_2	61.7	(53.8 -70.2)	49.1	(40.8–55.3)	61.9	67.0	46.9	57.0
TiO_2	1.12	(1.86– 0.71)	0.84	(1.2– 0.6)	0.95	0.79	0.94	0.69
Al_2O_3	12.1	(14.4 -10.9)	14.6	(17.6–11.1)	12.4	12.3	13.5	16.7
$Fe_2O_{3(T)}$	6.81	(9.3 - 4.3)	9.73	(13.4– 6.2)	5.88	4.93	10.3	7.75
MgO	3.18	(5.1 - 1.4)	4.65	(6.6– 2.1)	2.76	1.73	5.25	2.59
CaO	4.18	(7.7 - 1.1)	1.68	(4.3– 0.6)	5.91	1.71	2.59	0.85
Na_2O	2.46	(3.7 - 1.5)	3.25	(7.2– 1.0)	3.01	2.10	4.63	1.44
K_2O	2.28	(2.8 - 1.7)	3.42	(4.3– 2.6)	2.32	2.64	3.55	3.73
P_2O_5	0.46	(1.5 - 0.14)	2.12	(7.6– 0.16)	0.57	0.21	2.50	2.12[3]
LOI	4.75	(7.4 - 1.9)	7.78	(10.8– 5.0)	3.75	5.69	7.40	8.01

1) 202, 203, 205, 206, 208 Eastern region (upwelling)
2) 210, 212, 214, 220, 221 Central region (downwelling)
3) of which sample 212 'disturb' average of the 4 others: 0.77%
Average: 32 samples.

by Lisitzin (1972) for suspension concentrations in the oceans, and also like those observed on open shelves in low latitude areas (Emery & Milliman 1978). The values, however, are considerably lower than those found in some other glaciomarine environments, such as the Bering Sea (up to 13–15 g/m³, Lisitzin 1972), and off the Kongsfjorden glacier, Svalbard (up to 500 g/cm³, Elverhøi *et al.* 1980), where glacial streams have high sediment yields.
is close to the range of 0.5 to 1.5 g/m³ reported

Composition and texture

Antarctic surface waters have been found to be

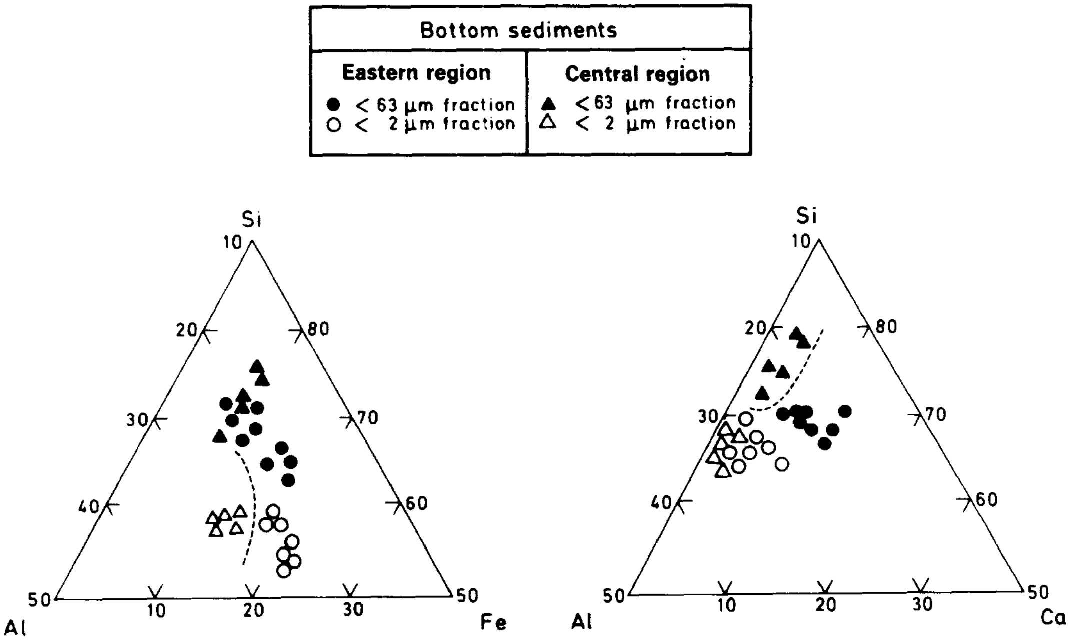


Fig. 9. Triangular plot illustrating the chemical composition of the bottom sediments.

rich in nutrients and blooming with planktonic species (Lisitzin 1972:149–155; Emery & Honjo 1979). Generally the proportion of biogenic to clastic particles is higher in the upper part of the water column than in the lower. Detrital grains are mostly concentrated in nearshore regions and in the bottom layer (Fig. 10a–d).

The clastic fragments range in size from 5 μm up to 50–70 μm, and seem to represent at least two different populations:

1. A mainly glacially derived phase, with fragments from 15 to 20 μm, and up to 50 to 70 μm (Table 5). The occurrence of detrital zircon may be noted.
2. Fine-grained material (silicates and metalliferous particles) of eolian, volcanic and/or cosmic origin, 10 μm in size, and particle aggregates with individual grains generally below 5 μm (Table 5).

The biogenic particles are predominantly diatoms which vary in size from 20 to 30 μm up to 150 to 170 μm, and occasionally have thin threads of 300 μm length. The diatoms are well preserved and are without sign of dissolution. Aggregates similar to fecal pellets are common.

In addition to these particles, presumably authigenic mineral aggregates 50–70 μm in size with individual particle size smaller than 5 μm have been observed (Fig. 10c and d, Table 5).

Metalliferous particles

Of special interest are the metalliferous particles grouped in Table 5 (Group B) generally around 5 μm in size. Particles with high contents of Fe, Ti, Zn, Mn, Cr, Ni, and Cu are found at most of the stations. Approximately one out of ten particles are metalliferous, and among these, the iron particles by far dominate (70–80 per cent). The particles must consist of pure metal, metal oxides/hydroxides, or possibly in some cases sulphides. Characteristic compositions and energy dispersive spectral analyses are given in Table 6 and Fig. 11.

Magnetic iron spherules of cosmic origin (cryoconites 4 μm in diameter) have been recorded in Atlantic deep-sea sediments (Lisitzin 1972). Landy & Peel (1981) report heavy metal concentrations (Cd, Pb, Zn) in snow from the Antarctic Peninsula. Relatively large and erratic concentrations suggested that contamination had occurred. Landy & Peel (1981) suggest that their analyses include aerosols from the major pollutant sources: mining, base metal melting and refining, and automobile exhaust. This could also explain these Weddell Sea metal anomalies.

A cosmic contribution to the metalliferous particles may also be anticipated, in particular since the Antarctic glaciers are considered to be excellent natural traps for cosmic material. Of the total amount of mineral material in Antarctic ice, nearly 67 per cent is black magnetic spherules 10–170 μm in size (Nishibori & Ishizaki 1959; Tiel & Schmidt 1961; Schmidt 1964).

Meteorites and cosmic dust that fall on the Antarctic ice sheet are preserved by and carried along with the ice and delivered into the sea.

Authigenic mineral aggregates

Iron silicate aggregates are recorded in many of the water samples. From their morphology an authigenic origin is suggested (Fig. 10c). Analyses give the following composition for an iron silicate particle of sample 206 (atomic percentage): Si: 32, Ti: 0.2, Al: 5.4, Fe: 47, Mg: 6, and Ca: 8. This composition may correspond to an iron-rich sepiolite or smectite.

Sepiolite forms mainly as biogenic opal (diatom and radiolarians), dissolve and absorb cations (preferentially Mg^{++}) in pore and/or sea water (Wollast 1974, 1977). This process is further enhanced by low temperatures (Christ *et al.* 1973).

In authigenic smectite formed by basalt–sea water interactions, the Fe-rich component is predominant at low temperatures (Hawkins & Roy 1963; Elderfield 1977). As the Weddell Sea waters have low temperatures, below 0°C, this may favour the formation of Fe-sepiolite and/or Fe-smectite.

Chemical composition

The suspended matter generally has a lower Si and Al content and a higher TiO_2, Fe_2O_3 and CaO content than the bottom sediments (Table 7, Fig. 12). In particular the Fe_2O_3 content differs strikingly from values obtained in the sediments. No clear differences in the composition of particules from the different stations could be observed.

Extreme Fe-contents were recorded for filters from stations 205 (52 per cent) and 215 (72 per

Table 4. Suspended load and particle characteristics (obtained from SEM investigations).

	Station	Water depth (m)	Sample above bottom (m)	Suspended particulate matter (mg/l)	Max. clastic particle diam. (um)	Median particle diam. (um)	Particle characteristica
Eastern regions							
	202	475	1	0.2	170[2]	<10	biog. > chem. ≈ clastic
	204	180	50		80 (>200)[1]	50	biog. >> clastic
			30		70	<10	clastics > biog.
	205	180	30	0.6	40 (100)[1]	<10	clastics > chem. >> biog.
			1	0.8	60	<10	clastics >> chem. > biog.
	207	280	50	0.5	50	< 5	clastics >> biog. > chem.
			1		50	<10	clastics >> biog. > chem.
	208	1800	1100	0.8	20 (40)[1]	<10	clastics > chem. > biog.
			1	0.4	20	< 5	clastics >> biog. > chem.
	209	340	150	1.1	10 (>100)[1]	< 5	clastics > biog. >> chem.
			1	2.2	50	ca.10	clastics >> biog.
Central regions							
	210	568	200	1.4	40	<10	chem. > clastic >> biog.
			1	0.6			
	211	548	25		50	<10	chem. > biog. > clastic
			1	0.4	25	< 5	chem. > clastic > biog.
	212	513	1	0.3	40	< 5	clastics > chem. ≈ biog.
	213	474	100	0.9	40	ca. 5	
			1	1.1	20	< 5	clastics > chem. > biog.
	214	730	10	0.3	5 (70)[1]	< 5	clastics > biog. > chem.
			1	1.1	30	< 5	clastics > biog. > chem.
	215	1540	1000	0.5	20	ca. 5	biog. > chem. > clastics
			10	0.6	10 (100)[1]	< 5	chem. >> biog. > clastics
			1	0.2	30	< 5	biog. > clastic chem.
	216	705	10	1.0	20	< 5	clastics > biog. chem.
			1	0.3	20 (100)[1]	< 5	biog. > clastic >> chem.
	217	420	10	0.3	30	< 5	clastics > chem. > biog.
			1	0.3	15	< 5	clastics > biog. > chem.
	218	500	10	0.1	15 (100)[1]	<10	clastics ≈ biog. > chem.
			1	0.6	20	< 5	clastic > chem. ≈ biog.
	219	570	100	1.1	20	< 5	clastics >> chem. > biog.
			10	0.4	30	< 5	clastics >> chem. ≃ biog.
			1	0.5	25	< 5	clastics >> chem.

1) Clastic particles maximum diameter with size of biogenic particles in paranthesis

2) Fe particle diameter. Clastic particles 15 um.

biog. = organic materials, mainly diatoms.

chem. = inorganic aggregates probably formed in the water masses (including the Fe-rich particles).

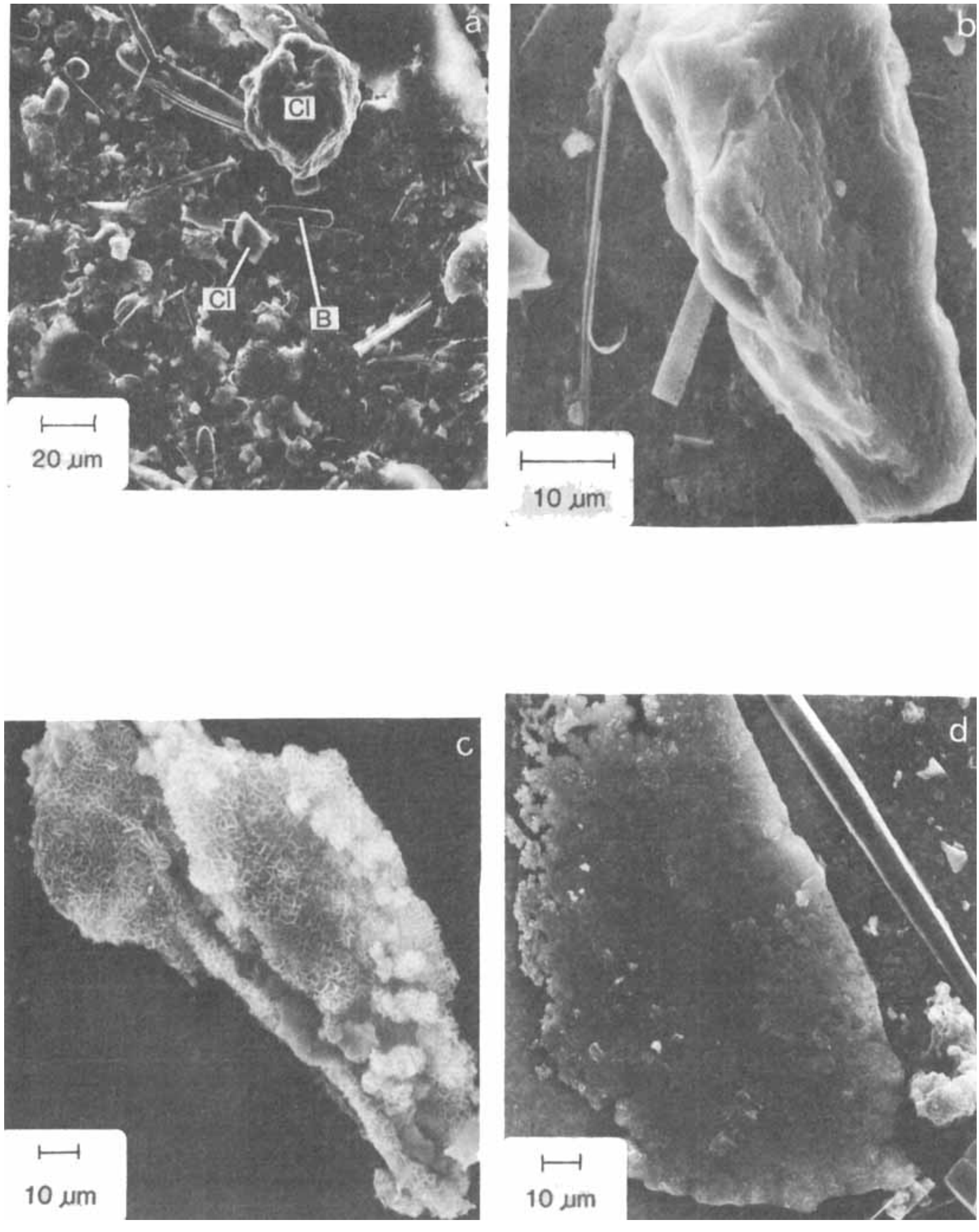


Fig. 10. Scanning electron micrographs of suspended matter from Cl: clastics. B: bioclastics. (a) Station 210, 1 m above sea bottom. (b) Feldspar grain, station 211, 1 m above sea bottom. (c) Fe–Si particle, Fe-sepiolite (?) Station 211, 25 m above sea bottom. (d) Fe-rich particle, hematite (?) Station 218, 10 m above sea bottom.

Table 5. Minerals identified in the clastic and authogenic mineral phases.

Clastic fragments

Group (A):

Quartz, K-feldspar, plagioclase (oligoclase–albite), pyroxene (diopsidic), zircon, rutile (or another TiO_2 polymorph), chlorite, muscovite, biotite, mixed layered illite/chlorite/smectite, kaolinite, metalliferous particles (magnetite; hematite, ilmenite).

Group (B):

Quartz, kaolinite, smectite (trioctahedral), albite, goethite, limonite (and hematite?), gibbsite.

Anthropogenic, volcanic and/or cosmic metalliferous particles: ZnS, Ti-oxides, Fe-oxides, (Fe, Cr, Ni, Cu, Zn)-, (Fe, Cu, Zn)-, (Fe, Zn, Ti, Cu)-, (Zn, Cu, Fe)-, and (Ti, Cu, Zn)- particles.

Autigenic minerals

Iron sepiolite/chamosite (?), ankerite, dolomite, calcite, Fe-rich aggregates (limonite/hematite) (up to 170 μm)

Secondary on the filtre- gypsum: Mg-sulphate.

cent). These values are not included in the averages.

As previously noted, the bottom sediments mainly consist of materials coarser than the major part of the suspended matter. The chemical analyses also indicate this material to be of minor importance for the total sediment input. Fine-grained materials have, however, been found to settle as fecal aggregates (McCave 1975; Landing & Feely 1981). Such aggregates are identified and are thus likely to play an important role in the sedimentation of the finer grades of the sea floor sediments, as the bottom currents may keep the true clay sized material in suspension.

Table 6. Metalliferous particles and their semiquantitative composition in per cent as measured from energy dispensive spectra.

	Fe	Ti	Cr	Ni	Cu	Zn	Mo	Si 1)	Ca
ZnS					20	80			
Ti - oxide/hydroxide	5	95							
Fe - oxide/hydroxide	90-100								0-10 2)
(Fe,Cr,Ni,Cu,Zn) - particle	60		20	10	5	5		tr.	
(Fe,Cu,Zn) - particle	60				35	5		tr.	
(Fe,Zn,Ti,Cu) - particle	65	10			5	20			
(Zn,Cu,Fe) - particle	10				20	70		tr.	
(Ti,Cu,Zn) - particle		70			20	10			
(Mo,Fe) - particle	5						95		

1) The small size of the particles in some cases make it impossible to avoid background contamination

2) May reflect the presence of Ca-bearing coating

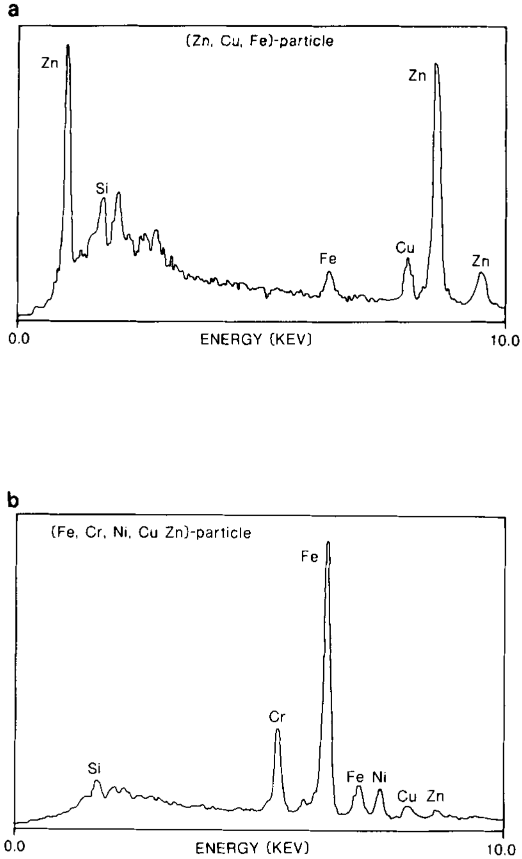


Fig. 11. Energy dispersive spectra of metalliferous particles, station 202, 1 m above seabed. (a) (Zn, Cu, Fe) – particle. (b) (Fe, Cr, Ni, Cu, Zn) – particle.

Glacial and bioclastic sediments – recent and late Precambrian time

Late Precambrian glacial sediments commonly occur in association with carbonates. The carbonates are found (1) to overlie the glacial deposits conformably as a cap ('cap-carbonate') or (2) to be interbedded with the glacial deposits. The origin of such sequences has been greatly disputed (e.g. Schermerhorn 1974; Spencer 1975; Deynox & Trompette 1976). The discussion has been impeded by lack of adequate models and also by the fact that carbonates traditionally have been interpreted as warm-water formations. Cold-water carbonates, however, have been reported from several sites: Labrador Shelf (Müller & Milliman 1973), NW Barents Sea (Bjørlykke *et al.* 1978), and outside Tasmania (Rao 1981).

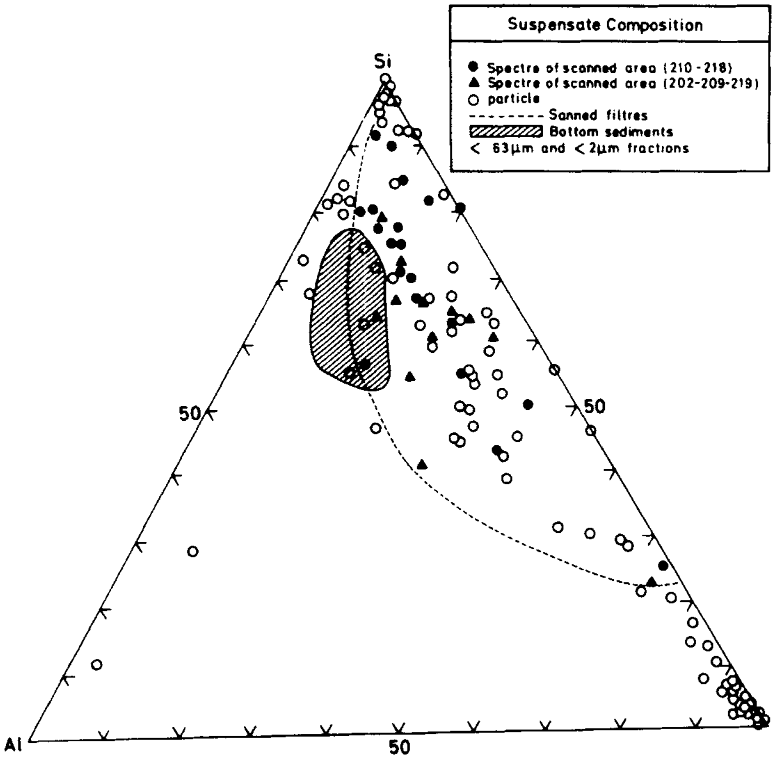
The carbonate (mollusc and barnacle) formation in the Barents Sea is realated to the late Weichselian glacio-eustatic rise, which left the Barents Sea starved of clastic supply (Bjørlykke *et al.* 1978). The carbonates are conformably underlain by late Weichselian till, thus forming a sequence similar to type 1, where the carbonates represent an interglacial formation.

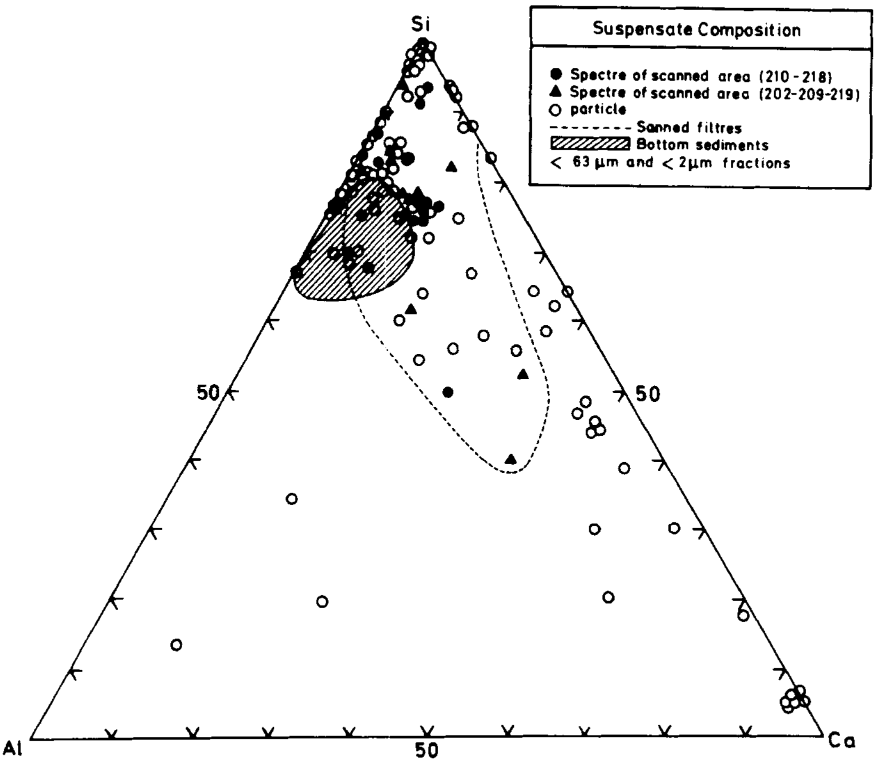
Similarly, several authors have proposed that carbonates associated with the late Precambrian glacial deposits represent interglacial or postglacial deposits, formed in response to glacio-eustatic transgression of vast shelf areas (Deynox & Trompette 1981; Plumb *et al.* 1981). The late Precambrian carbonates are mainly shallow-marine stromatolites and also early diagenetic dolomite, and therefore differ strongly from the bioclastic material accumulating on the Weddell Sea Shelf at 300–500 m of water depth. Some of the late Precambrian carbonates, both type 1 and 2, contain striated pebbles, demonstrating ice rafting (Plumb *et al.* 1981). These observations indicate (1) that carbonate formation may occur at water depth allowing the passage of icebergs, i.e. water depths of at least 80–100 m and (2) that carbonates can accumulate in glacial environments.

In the Weddell Sea, bioclastic material has been found to form as an integral part of the glaciomarine sediments. Essential for its formation is the low clastic supply outside an ice shelf and supply of nutrient-rich water due to intrusion of deep Atlantic water onto the shelf. A similar situation may also have occurred in ancient times. In late Precambrian rocks, the commonly thin interbedded carbonate sequences in particular may be interpreted as facies variations within a glaciomarine environment instead of glacial/interglacial cycles.

Table 7. Comparison between the chemical composition of bottom sediments and suspended particulate matter (31 samples).

Element Oxide	Suspended matter	Bottom sediments <63 μm	<2 μm
SiO_2	53.8	66.7	55.0
TiO_2	2.61	1.21	0.94
Al_2O_3	9.1	13.1	16.4
Fe_2O_3	15.6	7.35	10.9
MgO	6.34	3.43	5.21
CaO	6.28	4.51	1.88
K_2O	5.80	2.46	3.83


Suspensate Composition
Spectre of scanned area (210 - 218)
Spectre of scanned area (202-209-219)
particle
Sanned filtres
Bottom sediments
< 63µm and < 2µm fractions
Si
Al
Fe
50
50
50


Suspensate Composition
Spectre of scanned area (210 - 218)
Spectre of scanned area (202-209-219)
particle
Sanned filtres
Bottom sediments
< 63 µm and < 2µm fractions
Si
Al
Ca
50
50
50

Conclusion

The sediments and sedimentary environment outside an ice shelf can be characterized by the following:

- The sediments are mainly supplied by ice rafting.
- During settling, clay and fine silt are kept in suspension, leading to an enrichment of the coarser grades in the bottom sediments.
- The suspended matter is of minor importance for the total sediment budget. The main part of the clay and fine silt materials may settle as fecal aggregates.
- Bioclastic sediments constitute an integral part of the glaciomarine deposits.
- The sedimentation rate is relatively low, 1–5 cm/1000 years.

The sedimentary environment outside an ice shelf forms a striking contrast to the environment outside a tide-water glacier (Elverhøi *et al.* 1980; Powell 1981), where the sediments are mainly supplied from suspension at a high depositional rate (e.g. 10 cm/year) in Kongsfjorden, Svalbard. In such areas, high turbidity effectively prohibits organic deposition (Gulliksen & Taasen, in press).

Glaciomarine sediments may often be hard to distinguish from a basal till in a rock sequence. Sediments from outside an ice shelf may be recognized by their content of such bioclastic elements as Ca, Si, and also P.

The environment outside an ice shelf provides suitable conditions for bioclastic accumulations. In previous geologic times similar conditions may have prevailed, indicating that the carbonate layers in between tillite beds in late Precambrian rocks may reflect glaciomarine facies variations instead of glacial/interglacial cycles.

Acknowledgements. – We are grateful to colleagues at the Norwegian Antarctic Research Expedition 1978/79, especially George H. Maisey, for their help in the field, and to Sven Bäckström and Arnfinn Andersen for their assistance with the sample analyses. K. Bjørlykke, J. D. Milliman, H. Dypvik and C. F. Forsberg kindly reviewed the manuscript.

References

Anderson, J. B., Clark, H. C. & Weaver, F. M. 1977: Sediments and sediment processes on high latitude continental shelves. *Proc. Offshore Tech. Conf.* 91–95.

Anderson, J. B., Kurtz, D. D. & Weaver, F. M. 1979: Sedimentation on the Antarctic continental slope. *SEPM Special Publ. 27,* 265–283.

Anderson, J. B., Kurtz, D. D., Domack, E. W. & Balshaw, K. M. 1980: Glacial and glacial marine sediments of the Antarctic Continental Shelf. *J. Geol. 88,* 399–414.

Angino, E. E. & Andrews, R. S. 1968: Trace element chemistry, heavy minerals, and sediment statistics of Weddell Sea sediments. *J. Sed. Pet. 38,* 634–642.

Arnaud, P. M. 1977: Adaptations within the Antarctic marine benthic ecosystem. Pp. 135–157 in Llano, G. A. (ed.). Adaptations within Antarctic ecosystems. *Proc. Third SCAR Sypm. on Antarctic Biology.*

Berry, L. G. (ed.) 1974: *Selected Powder Diffraction Data for Minerals.* First edition, Publ. by Joint Committee on Powder Diffraction Standards. Philadelphia, Pa.

Biscaye, P. E. 1965: Mineralogy and sedimentation of Recent deep-sea clay in the Atlantic Ocean and adjacent Seas and Oceans. *Bull. Geol. Soc. Am. 76,* 803–832.

Bjørlykke, K., Bue, B. & Elverhøi, A. 1978: Quaternary sediments in the northwestern part of the Barents Sea and their relation to underlying Mesozoic bedrock. *Sedimentology 25,* 227–246.

Bonatti, E. 1963: Zeolites in pelagic sediments. *New York Acad. Sci. Trans. Ser. II, V. 25,* 938–948.

Brindley, G. W. & Brown, G. 1980: *Crystal Structures of Clay Minerals and their X-ray Identification,* Mineralogical Society, London.

Buehmann, D. & Ritzkowski, S. 1976: Clay minerals of the Northwest German Tertiary Basin. Pp. 56–62 in Tobien, H. (ed.), *The Northwest European Tertiary Basin. Report – International Geological Correlation Programme. Project 124,* 1.

Carey, S. W. & Ahmad, N. 1961: Glacial marine sedimentation. Pp. 865–894 in Rasch, G. O. (ed.), *Geology of the Arctic,* Univ. of Toronto Press, Toronto.

Corliss, B. H. & Milliman, J. D. 1981: The use of phillipsite in test construction of agglutinated deep sea benthonic foraminifera. *Sedimentology 28,* 401–406.

Czyscinski, K. 1973: Authigenic phillipsite formation rates in the Central Indian Ocean and the Equatorial Pacific Ocean. *Deep Sea Res. 20,* 555–559.

Chester, R., Elderfield, H. & Griffin, J. J. 1971: Atmospheric dust transportation by the Atlantic northeast and southeast trade wind. *Nature 233,* 474–476.

Christ, C. L., Hostetler, P. B. & Siebert, R. M. 1973: Studies in the system $MgO–SiO_2–H_2O$ (III): The activity product constant of sepiolite. *Am. J. Sci. 273,* 507–525.

Dayton, P. K., Robillard, G. A., Paine, T. R. & Dayton, L. B. 1974: Biological accommodation in the benthic community at McMurdo Sound, Antarctica. *Ecological Monographs 44,* 105–108.

Deer, W. A., Howie, R. A. & Zussmann, J. 1966: *An Introduction to the Rock Forming Minerals,* Longmans, Green & Co. Ltd., London.

Delaney, A. C., Parkin, D. W., Griffin, J. J., Goldberg, E. D. & Reidmann, B. E. F. 1967: Airborne dust collected at Barbados. *Geochim. Cosmochim. Acta 31,* 885–909.

Deynoux, M. & Trompette, R. 1976: Late Precambrian mix-

Fig. 12. Triangular plot illustrating the chemical composition of the suspended matter. Composition of bottom sediments is also shown (shaded).

tites: Glacial and/or non glacial? Dealing especially with the mixtites of West Africa. *Am. J. Sci. 276,* 1302–1315.

Deynoux, M. & Trompette, R. 1981: Late Precambrian tillites of the Taocedeni Basin, West Africa. Pp. 123–131 in Hambrey, M. J. & Larlund, W. B. (eds.), *Earth's Pre-Pleistocene Glacial Record,* Cambridge University Press.

Drake, D. E. 1976: Suspended sediment transport and mud deposition on continental shelves. Pp. 127–158 in Stanley, D. J. & Swift, D. J. (eds.), *Marine Sediment Transport and Environmental Management,* New York.

Drewry, D. J. & Cooper, A. P. R. 1981: Processes and models of Antarctic Glaciomarine sedimentation. *Ann. Glaciol. 2,* 117–122.

Elderfield, H. 1977: Authigenic silicate minerals and the magnesium budget in the oceans. *Phil. Trans. R. Soc. London A. 286,* 273–281.

Elverhøi, A. 1981: Evidence for a Late Wisconsin glaciation of the Weddell Sea. *Nature 293,* 641–642.

Elverhøi, A., Liestøl, O. & Nagy, J. 1980: Glacial erosion, sedimentation and microfauna in the inner part of Kongsfjorden, Spitsbergen. *Norsk Polarinstitutt Skrifter,* nr. 172, 33–58.

Emery, K. O. & Honjo, S. 1979: Surface suspended matter off western Africa: relations of organic matter, skeletal debris and detrital minerals. *Sedimentology 26,* 775–794.

Emery, K. O & Milliman, J. D. 1978: Suspended matter in surface waters: Influence of river discharge and up welling. *Sedimentology 25,* 125–140.

Enger, D. F., Smerdson, E. T. & Masch, F. D. 1968: Erosion of cohesive sediments. Report of the task committee on erosion of cohesive materials. Committee on Sedimentation. Proc. Am. Soc. Civ. Eng. *J. Hydraul. Div. 94* (HY4), 1017–1049.

Fillon, R. H. 1977: Ice rafted detritus: Late Cenozoic relationships in the Ross Sea Region. *Marine Geology 25,* 73–93.

Foldvik, A. 1979: Current and tidal measurements from the Weddell Sea. In: *International Union of Geodesy and Geophysics. XVII General Assembly, Canberra 1978. Abstracts and timetable for the inter-disciplinary Symposia:* 158.

Folger, D. W. 1970: Wind transport of land-derived minerals, biogenic and industrial matter over the North Atlantic. *Deep Sea Res. 17,* 337–352.

Foster, T. P. 1978: Polar Oceans: Similarities and differences in their physicle oceanography. Pp. 117–140 in McWhinnie, M. A. (ed.), *Polar Research: To the Present and the Future,* Am. Assoc. Adv. Sci. Westview Press, Boulder, Co.

Gill, A. E. 1973: Circulation and bottom water formation in the Weddell Sea. *Deep Sea Res. 20,* 111–140.

Goldberg, E. D. & Griffin, J. J. 1964: Sedimentation rates and mineralogy in the South Atlantic. *J. Geophys. Res. 69,* 4293–4309.

Graf, W. 1971: *Hydraulics of Sediment Transport,* McGraw-Hill, New York. 513 pp.

Gulliksen, B. & Taasen, J. P. in press: Effect of an oil spill in Spitsbergen in 1978. *Marine Pollution Bulletin.*

Harkness, D. D. 1979: Radiocarbon dates from Antarctica. *Br. Antarct. Surv. Bull. 47,* 43–59.

Hay, R. L. 1966: Zeolites and zeolitic reactions in sedimentary rocks. *Geol. Soc. Am. Spec. Pap. 85,* 130 p.

Hawkins, D. B. & Roy, R. 1962: Experimental hydrothermal studies on rock alteration and clay mineral formation. *Geochim. Cosmochim. Acta 27,* 1047–1054.

Hollister, C. D. & Heezen, B. C. 1972: Geologic affects of ocean bottom currents. Pp. 37–66 in Gordon, A. L. (ed.), *Studies in Physical Oceanography 2,* Gordon & Breach, New York.

Knox, G. A. 1970: Antarctic marine ecosystems. Pp. 69–96 in Holdegate, M. W. (ed.), *Antarctic Ecology, Scientific Comm. Antarctic Research,* Academic Press, London.

Kraeft, U. 1972: Preparation für die Rontgenspektranalyse nach neuen und bewahrten Gesichtspunkten. *G-I-T-, Fachzeitschrift für das Laboratorium 16 C 473,* 1–61.

Landing, W. M. & Feely, R. A. 1981: Chemistry and vertical flux of particles in the northeastern Gulf of Alaska. *Deep Sea Res. 28,* 19–37.

Landy, M. P. & Peel, D. A. 1981: Short term fluctuations in heavy metal concentrations in Antarctic snow. *Nature 291,* 144–146.

Lisitzin, A. P. 1972: Sedimentation in the world ocean. *Spec. Publ. Soc. Econ. Paleont. Minerals. 17.*

McCave, I. N. 1975: Vertical flux of particles in the ocean. *Deep Sea Res. 22,* 491–502.

Müller, J. & Milliman, J. D. 1973: Relict carbonate rich sediments on southwestern Grand Bank, Newfoundland. *Can. J. Earth Sci. 10,* 1744–1750.

Nishibori, E. & Ishisaki, M. 1959: Meteoritic dust collected at Syowa Base, Ongul Island, east coast of Lutsow-Holm Bay: Antarctic Repts. *Japan Antarct. Res. Exped. (Antarct Rec.) 7.*

Nowell, A. R. M., Jumars, P. A. & Eckman, J. M. 1981: Effects of biological activity on the entrainment of marine sediments. Pp. 133–153 in Nittrouer, C. A. (ed.), *Sedimentary Dynamics of Continental Shelves. Developments in Sedimentology 32,* Elsevier, Amsterdam.

Orheim, O. & Elverhøi, A. 1981: Model for submarine glacial deposition. *Ann. Glaciol. 2,* 123–128.

Parkin, D. W., Phillips, D. R., Sullivan, R. A. L. & Johnson, L. 1970: Airborne dust collections over the North Atlantic. *J. Geophys. Res. 76,* 1782–1793.

Plumb, K. A., Denrick, G. M., Needham, R. S. & Shaw, R. D. 1981: The Proterozoic of northern Australia. Pp. 205–307 in Hunter, R. D. (ed.), *Precambrian of the Southern Hemisphere. Developments in Precambrian Geology 2.* Elsevier, Amsterdam.

Postma, H. 1967: Sediment transport and sedimentation in the estuarine environment. Pp. 158–179 in Lauff, G. H. (ed.), *Estuaries.* Am. Assoc. Adv. Sci., Washington D.C.

Powell, R. D. 1981: A model for sedimentation by tidewater glaciers. *Ann. Glaciol. 2,* 129–134.

Prospero, J. M. & Carlson, T. N. 1972: Vertical and areal distribution of Sahara dust over the Western Equatorial North Atlantic Ocean. *J. Geophys. Res. 77,* 5255–5265.

Rao, C. P. 1981: Cementation in cold-water bryozoan sand, Tasmania, Australia. *Mar. Geol. 40,* 23–33.

Schermerhorn, L. J. G. 1974: Late Precambrian mixtites. Glacial and/or non-glacial. *Am. J. Sci. 274,* 673–824.

Schmidt, R. A. 1964: Microscopic extraterrestrial particles from the Antarctic Peninsula. *Ann. no. 4, Nat. Acad. Sci. 19.*

Spencer, A. M. 1975: Late Precambrian glaciation in the North Atlantic region. Pp. 217–240 in Wright, A. E. & Newall, G. (eds.), *Ice Ages: Ancient and Modern,* Geol. Jour. Special Issues.

Stuiver, M., Denton, G. H., Hughes, T. J. & Fastook, J. L. 1981: History of the marine ice sheet in west Antarctica during the Last Glaciation: A working hypothesis. Pp. 319–436 in Denton, G. H. & Hughes, T. J. (eds.), *The Last Great Ice Sheets,* John Wiley & Sons, New York.

Tiel, E. & Schmidt, R. 1961: Spherules from the Antarctic ice cap. *J. Geophys. Res. 66,* 307–310.

Wollast, R. 1974: The silica problem. Pp. 359–392 in Goldberg, E. D. (ed.), *The Sea.* Vol. 5. *Mar. Chem.,* John Wiley & Sons, New York.

Wollast, R. 1977: Factors affecting the composition of sediment pore waters. *Proc. 2nd Int. Symp. on Water-Rock Interaction, Strassbourg,* 295–313.

Wright, R. & Anderson, J. B. 1982: The importance of sediment gravity flow to sediment transport and sorting in a glacial marine environment, Eastern Weddell Sea, Antarctica. *Geol. Soc. Am. Bull. 93,* 951–963.