1988

PALEOCEANOGRAPHY, VOL. 3, NO. 5, PAGES 551-561, OCTOBER 1988

awi 55

QUATERNARY SEDIMENT PATTERNS IN THE WEDDELL SEA: RELATIONS AND ENVIRONMENTAL CONDITIONS

D. K. Fütterer, H. Grobe and S. Grünig

Alfred Wegener Institute for Polar and
Marine Research, Bremerhaven, West
Germany

Abstract. Sediment patterns such as texture, composition, and facies from three selected areas of the Antarctic continental margin of the Weddell Sea are discussed in relation to environmental variations of the Quaternary hydrosphere and cryosphere. Advance and retreat of ice shelves as well as oscillations in sea ice coverage are reflected by particular sediment facies. The distribution of ice-rafted detritus tracks the Antarctic Coastal Current, and the Weddell Sea Bottom Water contour current can be recognized by its distinctive winnowing and erosion pattern. Distribution and abundance of biogenic sediment components are mainly controlled by the duration of sea ice coverage reflecting the long-term climatic evolution.

INTRODUCTION

The distribution of modern sediments in the Weddell Sea results from a complex interaction between the glacial, oceanographic, and biological processes. In a broad sense, climate is the primary controlling factor. Terrigenous sediment is transported from the Antarctic Continent largely by icebergs calving from glaciers less from ice shelves. Meltwater runoff or fluvial activity is insignificant as is the eolian contribution of terrigenous material and volcanic ash.

The production of biogenic sediments by planktonic organisms is strongly influenced by the distribution of sea ice which undergoes large seasonal growth and decay cycles. During its winter maximum (September) the sea ice of the Weddell Sea expands as far north as 55°S, approaching to the high-productivity zone of the Antarctic Convergence or Polar Front at about 49°S. During its summer minimum (February) a large area of ice still remains in the western part of the Weddell Sea. Biogenic production in the temporarily ice-free areas therefore is reduced and condensed to short time intervals during the year. Observations from long-term time series sediment trap moorings deployed in Bransfield Strait (62°20'S, 58°20'W) and in the central Weddell Sea show the biologically productive season to be condensed to less than 2 months per year [Gersonde, 1986].

Sea ice formation again causes thermohaline circulation by the freeze-out of brines forming dense cold water, which sinks through a complicated mixing process to the deep sea to form bottom water [Foster and Carmack, 1976]. Bottom water directly affects deep-sea sediments by dissolution of carbonate and silica and/or winnows, erodes, and redistributes sediment by current activity.

Paper number 8P0391.
0883-8305/88/008P-0391$10.00

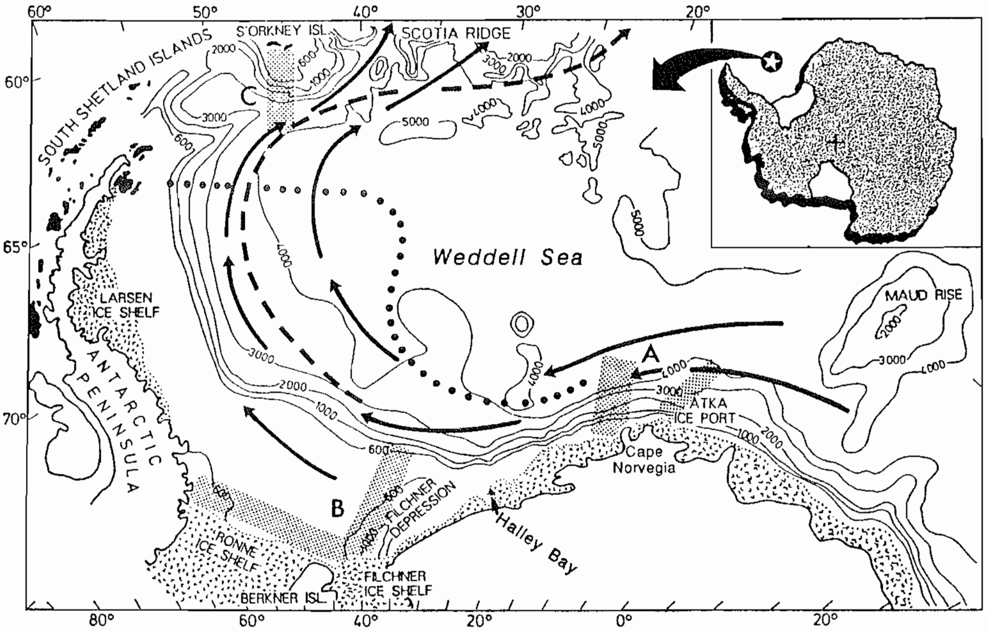

Fig. 1. Schematic map of the circulation patterns in the Weddell Sea. Solid lines denote clockwise surface currents of the Weddell Sea Gyre. The dashed line indicates the tentative contour current of Weddell Sea Bottom Water. The dotted line indicates the average sea ice edge between dense and permanent sea ice to the south and southwest and more loose nonpermanent sea ice to the northeast. A, B, and C mark areas which are discussed in the text [after Johnson et al., 1981, and various sources].

This paper describes the general sediment type formed during the Quaternary in three areas of the Weddell Sea (Figure 1; areas A, B, and C). Each type is formed under different oceanographic, biological, and topographic regimes. Sediment sampling and seismic data acquisition as low-frequency subbottom profiling were carried out during Antarctic expeditions ANT-I, ANT-II, and ANT-IV by R/V Polarstern in austral summers 1983, 1984, and 1985/1986, respectively. Detailed station data and descriptions are provided by Fütterer [1984, 1987] and Hempel [1986].

THE WEDDELL SEA EMBAYMENT

The Weddell Sea (Figure 1) is the southerly part of the South Atlantic Ocean, bounded on the east and southeast by the east Antarctic Craton, to the south by the Filchner-Ronne Ice Shelves, to the west by the Antarctic Peninsula, and to the north by the South Shetland Islands and the Scotia Ridge, which exhibits sill depths of more than 3000 m (Figure 1).

The width of the continental shelf, which is up to 600 m deep, increases from 90 km off the east Antarctic Craton to more than 500 km off the Filchner-Ronne Ice Shelf. At 40°W a deep trough (more than 1000 m), the Filchner Depression (or Crary Trough) cuts the gently dipping shelf. It extends several hundred kilometers south beneath the ice shelf and is believed to have formed by action of a grounded glacier or ice shelf during the Weichselian [Haugland et at., 1985] or may mark the position of a major fault system [Elliot, 1972]. The Filchner Depression is closed to the north by a sill with depth of approximately 700 m. The western shelf area off the Antarctic Peninsula is poorly known, since permanent pack ice cover makes this region nearly inaccessible to research vessels.

The Weddell Sea deep basin is a gently sloping (toward the northeast) abyssal plain broken by seamounts and fracture zone ridges to the north and northeast. At 03°E, 65°S, the north-south trending aseismic ridge of the Maud Rise, most probably of volcanic origin, reaches a water depth of up to about 2000 m.

However, our present knowledge of even the large-scale topography of the Weddell Sea basin is inadequate, and the reliability of the existing bathymetric data base is still a problem in this remote and hostile region. For example, recent bathymetric survey in the central Weddell Sea [Fütterer, 1987] demonstrated that a chain of seamounts, the Islas Orcadas Seamounts, shown on earlier bathymetric maps [e.g. Canadian Hydrographic Service, 1981] for the central Weddell Sea from 65°S to 67°S and 23°W to 26°W, does not exist and should be removed from future compilations.

HYDROGRAPHY AND SEA ICE

The main hydrographic feature of the Weddell Sea (Figure 1) is its cyclonic circulation pattern of surface waters, the Weddell Gyre [Deacon, 1937]. Surface waters flow toward the southeast, as the Antarctic Coastal Current (ACC), following the contours of the east Antarctic continental margin down to Berkner Island (Figure 1), passing the broad shelf area off the Filchner-Ronne Ice Shelves and then northwestward to the Antarctic Peninsula and the Larsen Ice Shelf. The gyre then turns northeast along the South Orkney Islands block and finally flows along the Scotia Ridge to as far as 40°E [Gordon et al., 1981]. Along the shelf break off Cape Norvegia the coastal current is 100 km wide and reaches velocities of up to 40 cm/s near the surface [Carmack and Foster, 1977].

The Weddell Sea is one of the principal sources of oceanic bottom waters. The mode of formation of present-day Weddell Sea Bottom Water (WSBW) is complex, variable, and in may details poorly understood. Commonly, it is assumed that it is a multiple mixing process of surface and intermediate waters. During sea ice formation over the broad shelf areas of the inner Weddell Sea, the freeze-out of brines produces very cold and more saline water, the Western Shelf Water (WSW) that mixes with modified warm deep water near the shelf break to from WSBW. This water sinks along the continental slope and flows cyclonically as a contour current around the western and northwestern perimeter of the Weddell Sea basin [Foster and Carmack, 1976]. Further mixing of WSBW with warm deep water (WDW) gives typical values for temperature and salinity traditionally described for Antarctic Bottom Water (AABW) [Foster and Carmack, 1976; Carmack, 1977].

WSW flows beneath the Filchner-Ronne Ice Shelf, where it is cooled, due to melting of shelf ice, to the in situ freezing point and forms Ice Shelf Water (ISW) [Carmack and Foster, 1975, 1977]. Minimum temperatures down to -2.2°C have been observed in the Filchner Depression where the maximum draught of the ice shelf is 400 m [Foldvik et al., 1985]. This very cold ISW spills over the sill of the Filchner Depression and can be traced as a narrow bottom current downslope. Current velocities of 1 to 1.5 m/s are assumed based on currentmeter mooring data [A. Foldvik, personal communication, 1987]. Mixing of ISW and WDW on the slope produces additional WSBW.

Observations by Gordon [1982] indicate that additional bottom water formation can take place in the area of the Weddell Sea Polynya (open water areas in the ice covered ocean) by deep convection north of Cape Norvegia (Figure 2). This suggests a possible component of the postulated bottom current further to the east than indicated in Figure 1.

Another important feature of Weddell Sea hydrography is the sea ice cover which exhibits an extreme seasonal as well as long-term annual variation in area and thickness [Zwally et al., 1983]. Large parts of the inner and western Weddell Sea are permanently covered with dense and compact sea ice. Minimum coverage is observed during February, whereas the northernmost extension of the sea ice edge in the Weddell Sea reaches the South Sandwich Islands (at about 56°S, 26°W) in August [Deutsches Hydrographisches Institut, 1981]. The retreat of the sea ice edge begins by mid-September and proceeds rapidly during November and December. Slight modifications of the general pattern of sea ice coverage are made by small nonpermanent coastal polynyas off the Filchner-Ronne Ice Shelves and sometimes as far to the northwest as the Antarctic Peninsula. These coastal polynyas are caused by katabatic winds blowing down the Antarctic continental ice cap and pushing the newly formed sea ice away from the Antarctic coast to form ice-free waters [Hellmer and Bersch, 1985].

A large polynya, the Weddell Sea Polynya (Figure 2), observed from satellite images was present during austral winter 1973 through 1977 in the open ocean of the Weddell Sea at 63°S to 71°S and 30°W to15°E [Martinson et al., 1981]. The cause and mechanism for the origin of this polynya are not yet known nor are the types and sources of water masses forming it. It is speculated that deep convection and/or perturbations originating from the Maud Rise at 65°S, 3°E (Figure 1) might be responsible

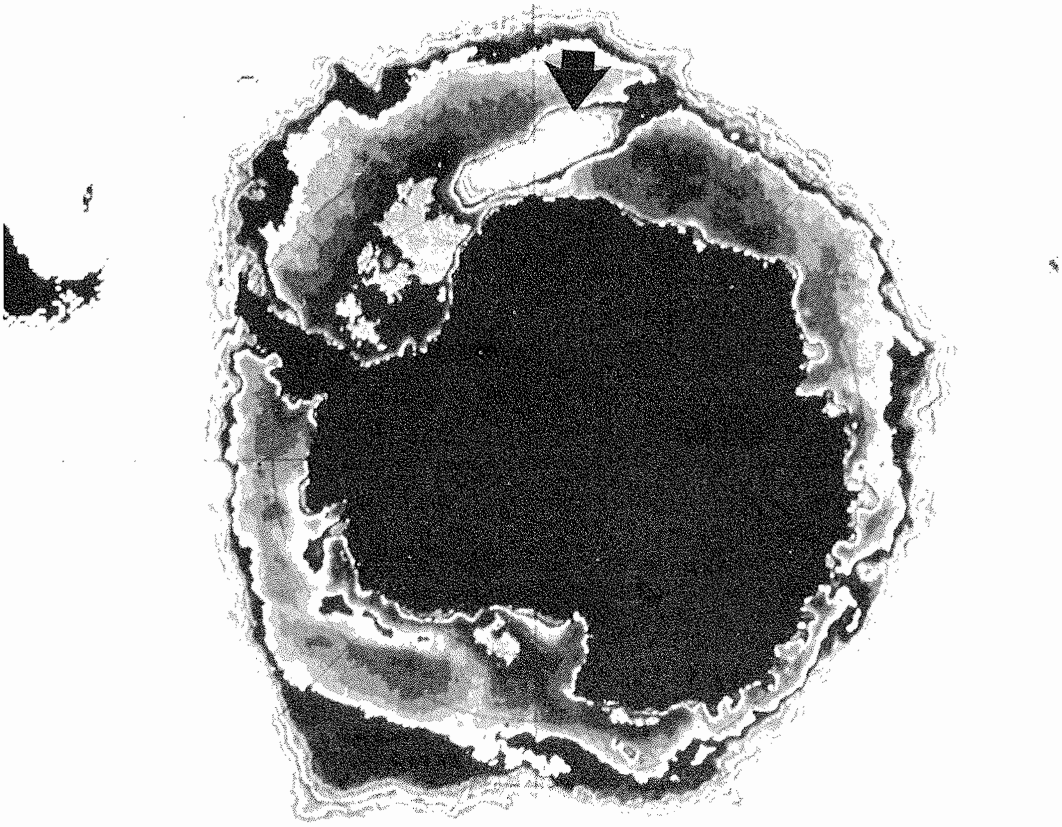

Fig. 2. Distribution of sea ice around the Antarctic Continent and location and extension of the Weddell Sea Polynya (arrow) during August 1974. The microwave satellite image is from Zwally et al., [1983].

for the occurence of this striking oceanographic feature [Martinson et al., 1981; Hellmer and Bersch, 1985]. If the Weddell Sea Polynya is a persistent phenomenon, its influence on regional productivity should be enormous and should be documented by a geological signature in the underlying sedimentary record [Defelice and Wise, 1981].

SEDIMENTATION AT CAPE NORVEGIA

The continental margin off Cape Norvegia at 13°W (Figures 1 and 3) is divided morphologically into a shelf (shelf break at about 500 m), upper continental slope (500-2000 m), slope terrace (2000-3000 m), which is crossed by the deep erosional incision of the Alfred Wegener Canyon, and lower continental slope. The latter feature is formed by the steep Explora Escarpment, which is interpreted to represent an outer basement high [Hinz and Krause, 1982].

Sediments on the shelf, upper slope, and slope terrace consist in general of silty and clayey muds with various amounts of coarse sand and gravelly dropstones. The sediment sequence on the slope terrace shows cyclic fluctuations in color, structure, and degree of bioturbation as well as in content of ice-rafted detritus (IRD), clay minerals, and biogenic components. Carbonate-rich horizons

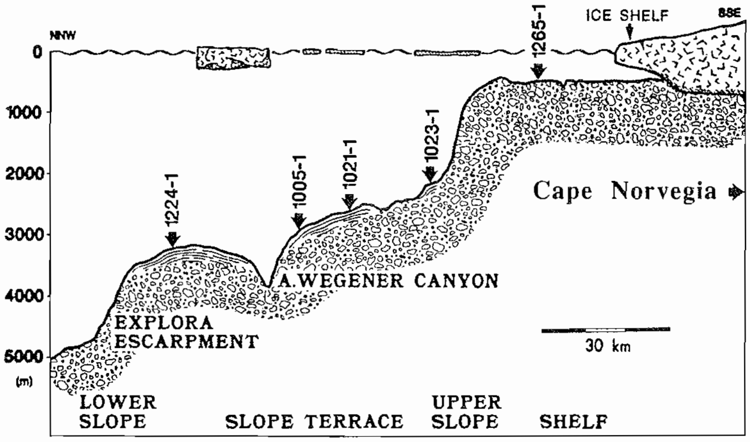

Fig. 3. Bathymetric structure of the continental margin off Cape Norvegia based on high-precision echo sounding and low-frequency subbottom profiling (3.5 kHz).

correlate positively with increased sand and gravel sized IRD content, bioturbation, and coarser grain sizes as does biogenic silica which contributes up to 20 % of the sand-sized fraction. Radiolarians and sponge spicules are the main biosiliceous components, whereas diatoms are present in low abundances in surface sediments only. Within the uppermost meter of the sediment, diatom preservation drops significantly due to dissolution of biogenic opal [R. Gersonde, personal communication, 1987].

Sedimentary facies. On the basis of the data summarized above, the apparent sedimentary cycles are attributed to different sediment facies. These reflect different environmental conditions which are mainly due to changing hydrographic regimes caused by the retreat and advance of ice shelves and sea ice [Grobe, 1986a, b].

The paratill facies [Grobe, 1986b] is deposited only on the shelf during an interglacial period with melting and retreating ice shelves. The sediment consists typically of a mostly ice-rafted gravelly diamicton with a varied admixture of benthic biogenic carbonate (mainly bryozoans) and opaline silica (sponge spicules). Sedimentation rates are up to 3 cm per1000 years [Grobe, 1986b]. A significant portion of the fine fraction is winnowed by the Antarctic Coastal Current (ACC), and the remaining clay fraction is dominated by chlorite.

The morainic facies [Grobe, 1986b] occurs at the base of the upper continental slope only and reflects the advance of grounded ice to the shelf break and floating ice beyond during peak glacial periods. The sediments are characteristically dark green (N3, Munsell color chart) and lack bioturbation. They show varied textures, fine- and coarse-grained laminations and graded bedding (turbidites up to a few centimeters in thickness), a high abundance of lithic fragments, in the sand-sized fraction, and a typically high chlorite to illite ratio.

Three main facies types occur on the slope terrace and are classified as cold or glacial, warm or interglacial, and transitional facies, respectively. The cold facies [Grobe, 1986a, b] is interpreted to be deposited during glacial intervals and is characterized by light olive-gray (5YR 4/4) sediments with little IRD and an increased amount of fine-grained material with smectite as the dominant clay mineral. Biogenic components such as planktonic foraminifers, diatoms, and radiolarians are rare and may reflect a reduced biogenic production due to permanent sea ice cover. The input of IRD is also low because the grounded ice shelves do not permit calving of icebers to carry terrigenous material to the sea.

The transitional facies [Grobe, 1986a, b] is deposited during a transition from a glacial to an interglacial period. Its sediment texture is very similar to the cold facies. Silt and clay with smectite as the dominant clay material and a low IRD content generally are representative of the transitional facies. Grain size, however, may become slightly coarser, since near the continent the IRD content increases significantly due to increased end glacial iceberg calving from rapidly refloated ice shelves. The most significant difference from the cold facies, however, is among the biogenic components. A high abundance of radiolarians is exclusively limited to this facies type and may indicate more favorable environmental conditions. Planktonic foraminifers peak significantly later in the warm facies but are also present in the transitional facies.

The warm facies is marked by a light olive-gray (5Y 5/2) sediment color, increased IRD content, and coarser grain size as well as by more intensive bioturbation. Carbonate content is up to 28 % and is almost exclusively made up of planktonic foraminifer sinistral *Neogloboquadrina pachyderma*. Illite is the dominant clay mineral, and smectite is less abundant. This facies forms during warmer episodes when calving glaciers and ice shelves supply numerous icebergs that are transported by the ACC. The pathway of the ACC along the continental margin is therefore marked by increased IRD content from melting icebergs. The retreat of sea ice coverage in this warmer episode enhances biogenic production which is documented by the high content of planktonic foraminifera preserved in the sediments. Diatom silica is present in minor amounts in surface sediments only and decreases rapidly by dissolution downcore.

Fluctuations in the calcite compensation depth (CCD) seem to follow the long-term cyclicity of sea ice coverage which is related to variations in hydrography, and biogenic production and consequently to sediment facies. During deposition of the warm facies type to Cape Norvegia, the CCD is at 3500-4000 m water depth and shallows to 2000-3000 m during formation of the cold facies type.

Sedimentation rates off Cape Norvegia, obtained from ^{14}C and ^{230}Th analyses, reach up to 4 cm per 1000 years [Grobe, 1986b]. In the central part of the slope terrace, the average sedimentation rate is about 2-3 cm per 1000 years. It increases up to 3-4 cm per 1000 years toward the continent due to increased accumulation of terrigenous material and with increased distance from the continent. In addition, in this region there is an increased supply of planktonic foraminifera that produces an abvious increase in carbonate content. A similar pattern of carbonate distribution (increasing amounts of carbonate with increased distance from the ice shelf edge toward the open water of the coastal and/or Weddell Sea Polynya) has been observed farther northeast off Atka Iceport at 8°W [H. Grobe, unpublished data, 1988].

The high carbonate content is presumed to be an effect of the ice-free waters of the Weddell Sea Polynya that probably strongly favors planktonic productivity. The apparent cyclicity in carbonate content in all sediment cores off Cape Norvegia as well as off Halley Bay to the southwest and Atka Iceport to the northeast is inferred to represent the presence and absence of the Weddell Sea Polynya through time. Preliminary dating of sediment cores off Atka Ice port by magnetostratigraphy may make it possible to trace back the history of the Weddell Sea Polynya beyond the Brunhes/ Matuyma boundary (at 730,000 years B.P.) into the Pliocene [Grobe and Kuhn, 1987; see also Defelice and Wise, 1981].

SEDIMENTATION OFF THE FILCHNER-RONNE ICE SHELF

Surface sediments on the broad shelf off the Filchner-Ronne Ice Shelves (Figure 1, area B), which is speculated to be one of the primary source areas of bottom water formation [Carmack and Foster, 1977; Hellmer and Bersch, 1985], show changes in sediment texture along the ice shelf edge from the southeast to the northwest [Anderson, 1971; Haase 1986]. Sediments in the southeast, on the Berkner Shelf near the Filchner Depression, consist primarily of clean, well-sorted sands. In the central part off the Filchner-Ronne Ice Shelf, muddy sands occur, whereas in the northwest near the Antarctic Peninsula, gravelly muds (glacial marine diamicton) including abundant large dropstones dominate. In northeasterly direction off the edge of the Ronne Ice Shelf over the large shelf area, the textural composition of the sediments shows a continuous decrease in grain size from gravelly muddy sand to sand, sandy mud, and mud, the latter of which covers most of the shelf area.

The described textural differences result from deposition in areas with different current velocities [Haase, 1986], especially in areas with tidal currents flowing under the ice shelf. The highest current velocities have been inferred for the shelf off Berkner east of 55°W. This, however, is the area where, at 500 to 600 m water depth, Ice Shelf Water (ISW) with extrememly low temperatures (potential temperature -2.2°C) flows northward from beneath the ice shelf to later form Weddell Sea Bottom Water [Foldvik et al., 1985]. Thus the clean, well-sorted, fine- to medium-grained sands on the upper western flank and shelf of the Filchner Depression represent residual sands resulting from strong currents related to the outflow of ISW [Haase, 1986], from beneath the ice shelf rather than to tidal currents.

The sandy sediment sequence along the

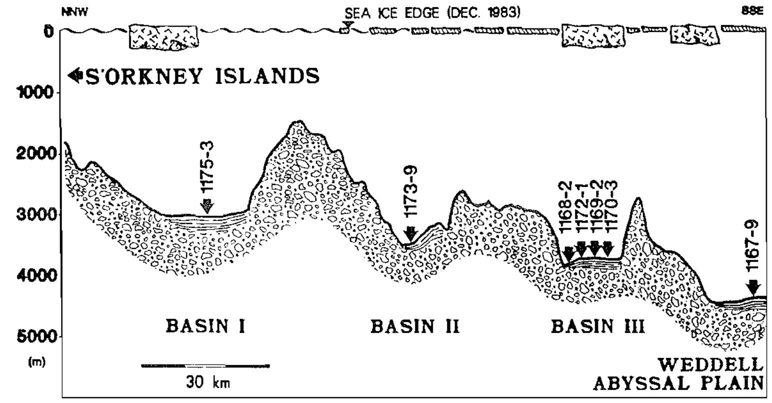

Fig. 4. Morphology of the continental slope of South Orkney Islands (Figure 1, area C) and location of sediment cores.

western flank of the Filchner Depression (= Crary Trough) has been interpreted by Anderson and Wright [1982] to represent a turbiditic sequence. This interpretation is rather unlikely not only because of topographic constraints but because of strong bioturbation in certain horizons of the "graded" sequence [Melles, unpubl. Theses, 1987].

To the north of the Filchner Depression, current meter measurements show the outflow of ISW on the upper continental slope [Foldvik et al., 1985; A. Foldvik, personal communication, 1987]. In this region the continental slope is most probably swept or winnowed of fine-grained sediment, leaving a hard, dropstone-paved sediment surface, an interpretation which is deduced from sub-bottom profiling. The further course of the newly formed WSBW as a contour current along the foot of the continental slope of the Weddell Sea can simply be traced from the distribution pattern of sediment textures [Anderson, 1975, Figure 7] which shows sandy muds and muddy sands indicative of the winnowing activity of the WSBW. Additional evidence for strong contour current circulation of the WSBW comes from compass-oriented bottom photographs showing a consistent orientation of lineations and deflection directions of sessile organisms [Hollister and Elder, 1969].

SEDIMENTATION SOUTH OF SOUTH ORKNEY ISLANDS

Sedimentation in the northwestern Weddell Sea to the south of the South Orkney Islands (Figure 1, area C) is strongly influenced by a distinct slope topography. The continental slope consists of steplike fault blocks separated by sediment-filled basins (Figure 4), a structural pattern which is also indicated in the tectonic map of the Scotia Arc [British Antarctic Survey, 1985].

Sediment cores from these basins typically show cycles of sandy silty muds alternating with clayey muds (Figure 5). Positively correlated with the sandy silty muds is the occurence of diatoms and radiolaria [R. Gersonde, personal communication, 1987] and increased ice-rafted detritus (IRD). With increasing water depth, siliceous material diminishes and is completely missing from sediments on the Weddell Sea Abyssal Plain. Sediments at all depths sampled are barren of carbonate microfossils. The present-day calcite compensation depth in the South Orkney area is reported to be as shallow as 500 m [Pudsey et al., 1988]. Volcanic ash material is finely dispersed throughout all sediment cores. One remarkable, dark ash layer, clearly discernable in all cores, provides a reliable intercore correlation of the sediment sequences revocered, as has been confirmed by paleomagnetic investigations (Figure 5).

The apparent cyclicity of coarse and fine sediments is interpreted to represent alternations of warm and cold facies, such as those shown off Cape Norvegia. The IRD cyclicity might document the path of melting icebergs carried by the ACC or the northern branch of the Weddell Sea Gyre (Figure 1).

The disappearance of siliceous material with increased water depth to the south may be caused by two different mechanisms which presently cannot be distinguished.

1. It may simply be the result of decreased biological productivity because of permanent sea ice coverage to the south and only seasonal coverage to the north. The sea ice edge, as observed in December 1983, is

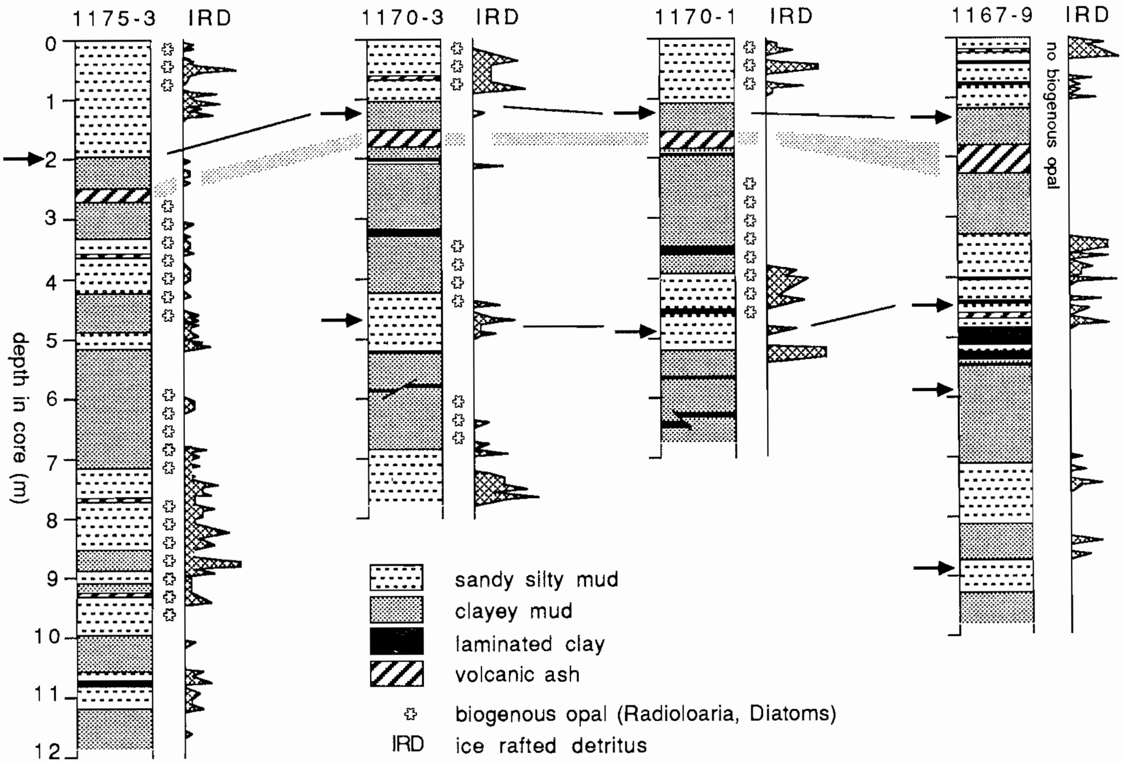

Fig. 5. Sediment texture and composition of gravity cores from the continental slope of South Orkney Islands block (for location, see Figure 4). Arrows mark paleomagnetic events within Brunhes Normal Epoch used for intercore correlation.

just north of the boundary between biosiliceous-rich sediments to the north and biosiliceous-poor to barren sediments to the south (Figure 4). This position of the ice edge is in agreement with long-term observations of sea ice distribution [Zwally et al., 1983]. During cold phases, when the sea ice edge moves far to the north, this area is permanently ice-covered, and the sediments beneath are barren of siliceous microfossils.

2. The disappearance of siliceous microfossils may be due to dissolution within WSBW. This seems to be the case for the sediments of the Weddell Sea Abyssal Plain. Similar water masses have been observed at the bottom of Basin III (Figure 4) by Rohardt [see Fütterer, 1984], and they may be responsible for dissolution of siliceous material. The fluctuations of coarse and fine sediments and warm and cold sediment facies in this area could then be the result of a rise of WSBW or a similar corrosively aggressive water mass to 3000 m water depth to cause siliceous dissolution in basins I and II (Figure 4).

On the northwestern margin of the Weddell Sea Abyssal Plain and the basin III (Figure 4), subbottom profiling records show evidence of major erosion or reduced sedimentation by bottom water flow (Figure 6). A 10 to 15 km wide erosion channel marks the flow of the WSBW as a contour current along the foot of the northern continental slope of the Weddell Sea. In box-core samples and gravity cores the "normal" sediment sequence of more than 80 m (Figure 6, site b) is reduced to a thin pavement of gravel-sized dropstones (Figure 6, site a). Similar patterns were described at the foot of the Walvis Ridge in the northernmost Cape Basin and have been interpreted as scour patterns induced by the Antarctic Bottom Water (AABW) current [Bornhold and Summerhays, 1977].

CONCLUSIONS

Some features of the Weddell Sea hydrography (its surface and bottom circulation pattern) are recorded in the bottom sediment and can be deduced from analyses of

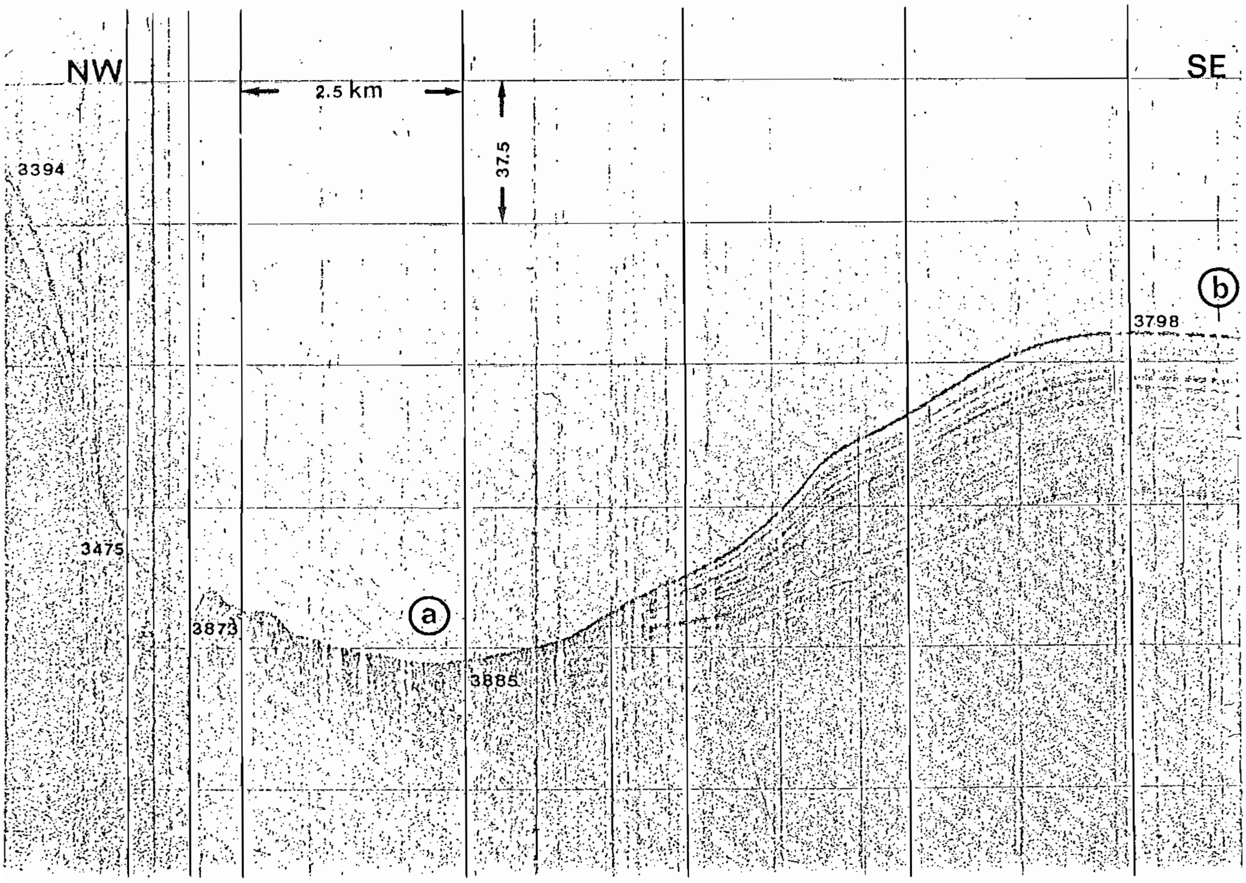

Fig. 6. Effect of erosion by Weddell Sea Bottom Water (WSBW) flow within basin III at the continental slope of South Orkney Islands (for location, see Figure 5). Winnowing of the WSBW contour current wedges the complete sequence from site b to a thin lag pavement of glacial marine dropstones at site a. The figure is a 3.5-kHz subbottom profiling record from R/V Polarstern 1983.

sedimentary facies preserved in cores.

1. The Antarctic Coastal Current (ACC) can be traced with reasonable reliability in the sediments along the continental margin of the eastern Weddell Sea as well as along the South Orkney Islands in the north of the Weddell Sea by an increase in ice-rafted detritus (IRD).
2. The regional extent of the Weddell Sea Polynya and its presence or absence during the Quaternary and Pliocene can probably be determined by abundance fluctuations of planktonic foraminifera.
3. The outflow of Ice Shelf Water (which most likely contributes significantly to the formation of Weddell Sea Bottom Water) off the Filchner-Ronne Ice Shelf is reflected by clean, well-sorted sands on the shelf and most probably by lag deposits on the continental slope of the southern Weddell Sea at 40°W.
4. The cyclicity in abundance of siliceous microfossils in the sediments of the northwestern Weddell Sea may reflect either changes in the position of the northern edge of permanent sea ice or dissolution by Weddell Sea Bottom Water (WSBW) through time.
5. The flow of Weddell Sea Bottom Water as a contour current is documented along the continental slope of the western and northwestern Weddell Sea. It forms erosional channel structures some 10 to 15 km wide and up to 80 m deep showing coarse lag deposits in the center of the channel and condensed but stratigraphically complete sediment sequences at the channel's margin.

Acknowledgements. We are grateful to R. Gersonde for providing unpublished data and information as well as for stimulating discussions and critically reading the paper. The paper was significantly improved by critical discussions with J. Kenneth, who carefully read an earlier version of it. We thank L. Burkle, N. Hamilton, S. O'Connell, and S. W. Wise for their careful reading, criticism, and discussion of the paper. Much support was given at sea by the captain and crew of R/V Polarstern wich is gratefully acknowledged as well as the help of the colleagues of the scientific parties during the sometime harsh conditions on the ANT-I, ANT-II, and ANT-IV expeditions.

Contribution No. 55 of the Alfred Wegener Institute for Polar and Marine Research.

REFERENCES

Anderson, J. B., Marine origin of sands in the Weddell Sea, *Antarct. J. U.S.*, *6*, 168-169, 1971.

Anderson, J. B., Factors controlling $CaCO_3$ dissolution in the Weddell Sea from foraminiferal distribution patterns, *Mar. Geol.*, *19*, 315-332, 1975.

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

Bornhold, B. D., and C. P. Summerhays, Scour and deposition at the foot of the Walvis Ridge in the northernmost Cape Basin, South Atlantic, *Deep Sea Res.*, *22*, 743-752, 1977.

British Antarctic Survey, *Tectonic map of the Scotia Arc*, scale 1:3,000,000, *Misc. Map 3*, Cambridge,1985.

Canadian Hydrographic Service, General bathymetric chart of the oceans (GEBCO), scale 1:10,000,000, sheet 5.16, Ottawa, 1981.

Carmack, E. C., Water characteristics of the southern ocean south of the Polar Front, A Voyage of Discovery, edited by M. V. Angel, *Deep Sea Res.*, *24*, suppl., 15-41, 1977.

Carmack, E. C., and T. D. Foster, Circulation and distribution of oceanographic properties near the Filchner Ice Shelf, *Deep Sea Res.*, *22*, 77-90, 1975.

Carmack, E. C., and T. D. Foster, Water masses and circulation in the Weddell Sea, in *Polar Oceans*, edited by M. J. Dunbar, pp. 151-165, Arctic Institute of North America, Calgary, 1977.

Deacon, G. E. R., The hydrology of the southern ocean, *Discovery Rep.*, *15*, 1-124, 1937.

Defelice, D. R., and S. W. Wise, Jr., Surface lithofacies, biofacies, and diatom diversity patterns as models for delineation of climatic change in the southeast Atlantic Ocean, *Mar. Micropaleontol.*, *6*, 29-70, 1981.

Deutsches Hydrographisches Institut, *Handbuch des Atlantischen Ozeans*, Hamburg, 1981.

Elliot, D. H. Aspects of Antarctic geology and drift reconstructions, in *Antarctic Geology and Geophysics*, edited by R. J. Adie, pp. 849-858, Universitetsforlaget, Oslo, 1972.

Foldvik, A., T. Gammelsrod and T. Torresen, Circulation and water masses on the southern Weddell Sea shelf, in *Oceanology of the Antarctic Continental Shelf*, *Antarctic Res. Ser.*, *vol. 43*, edited by S. S. Jacobs, pp. 5-20, AGU, Washington, D. C., 1985.

Foster T. D., and E. C. Carmack, Frontal mixing zone and Antarctic Bottom Water formation in the southern Weddell Sea, *Deep Sea Res.*, *23*, 301-317, 1976.

Fütterer, D. K. (Ed.), Die Expedition Antarktis-II mit FS "Polarstern" 1983/84: Bericht von den Fahrtabschnitten ANT-II/1, ANT-II/2, ANT-II/3 mit Beiträgen der Fahrtteilnehmer, *Ber. Polarforsch.*, *18*, 92 pp., Alfred Wegener Institute, Bremerhaven, 1984.

Fütterer, D. K. (Ed.), Die Expedition Antarktis-IV mit FS "Polarstern" 1985/86: Bericht von den Fahrtabschnitten ANT-IV/3 und ANT-IV/4 mit Beiträgen der Fahrtteilnehmer, *Ber. Polarforsch.*, *33*, Alfred Wegener Institute, Bremerhaven, 210 pp., 1987.

Gersonde, R., Biogenic siliceous particle flux in Antarctic waters and its palaeoecological significance, *S. Afr. J. Sci.*, *82*, 499-501, 1986.

Gordon, A. L., Weddell Deep Water variability, *J. Mar. Res.*, *40*, Suppl. 199-217, 1982.

Gordon, A. L., D. G. Martinson and H. W. Taylor, The Wind-driven circulation in the Weddell-Enderby Basin, *Deep Sea Res.*, *28*, 151-163, 1981.

Grobe, H. Sedimentation processes on the Antarctic continental margin at Cape Norvegia during the late Pleistocene, *Geol. Rundsch.*, *75*, 97-104, 1986a.

Grobe, H. Spätpleistozäne Sedimentationsprozesse am antarktischen Kontinentalrand vor Cape Norvegia, östliche Weddell See, *Ber. Polarforsch.*, *27*, 128 pp., Alfred Wegener Institute, Bremerhaven, 1986b.

Grobe, H. and G. Kuhn, Sedimentation processes at the Antarctic continental margin, *Ber. Polarforsch.*, *33*, Alfred Wegener Institute, Bremerhaven, pp. 83-87, 1987.

Haase, G. M., Glaciomarine sediments along the Filchne/Ronne Ice Shelf, southern

Weddell Sea - First results of the 1983/84 Antarktis-IV/4 expedition, *Mar. Geol.*, *72*, 241-258, 1986.

Haugland, K., Y. Kristoffersen, and A. Velde, Seismic investigations in the Weddell Sea embayment, Tectonophysics, 114, 293-313, 1985.

Hellmer, H. H., and M. Bersch, The southern ocean: A survey of oceanographic and marine meteorological research work, *Ber. Polarforsch.*, *26*, 115 pp., Alfred Wegener Institute, Bremerhaven, 1985.

Hempel, G., (Ed.), Die Expedition Antarktis III mit FS "Polarstern" 1984/85, *Ber. Polarforsch.*, *25*, 209 pp., Alfred Wegener Institute, Bremerhaven, 1986.

Hinz, K., and W. Krause, The continental margin of Queen Maud Land/Antarctica: Seismic sequences, structural elements, and geological developement, *Geol. Jahrb.*, *Reihe E, 23*, 17-41, 1982.

Hollister, C. D., and R. B. Elder, Contour currents in the Weddell Sea, *Deep Sea Res.*, *16*, 99-101, 1969.

Johnson, G.L., G.R. Vanney, A. Elverhoi, and J. Labrecque, Morphology of the Weddell Sea and Southwest Indian Ocean, *Dt. hydrogr. Z.*, *34*, pp. 263-272, 1981.

Martinson, D. G., P. D. Killworth and A. L. Gordon, A convective model for the Weddell Polynya, *J. Phys. Oceanogr.*, *11*, 466-488, 1981.

Melles, M., Sedimentation in der Filchner-Depression, südöstlicher Weddellmeer-Shelf, Antarktis, unpubl. Diplom Thesis, Univ. Göttingen, 180 pp., 1987.

Pudsey, C. J., J. W. Murray, and P. F. Ciesielski, Late Pliocene to Quaternary sedimentation on the South Orkney shelf, *Br. Antarct. Surv. Bull.*, 1988.

Zwally, H. J., J. C. Comiso, D. L. Parkinson, W. J. Campbell, F. D. Carsey, and P. Gloersen, Antarctic sea ice, 1973-1976: satellite passive microwave observation, NASA Spec. Publ., *NASA SP-459*, 206 pp., 1983.

D. K. Fütterer, H. Grobe, and S. Grünig, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, West Germany.

(Received November 27, 1987;
revised May 12, 1988;
accepted May 23, 1988.)