OCEANOGRAPHIC INFLUENCES ON SEDIMENTATION ALONG THE ANTARCTIC CONTINENTAL SHELF

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Abstract. Continental shelf surface sediment samples from the Ross Sea west to the George V Coast are examined in relation to the ocean circulation. The relative concentrations of ice-rafted debris, biogenic phases, and current-reworked material in modern surface sediments are controlled by the interaction of glacial, biological, and oceanographic processes. Ice rafting is presently an important sedimentary process only within a few tens of kilometers of the coast where outlet glaciers drain. Ice-rafted debris is a minor component of surface sediments near the front of the Ross Ice Shelf, consistent with basal melting landward of the northern edge of the shelf ice. Siliceous biogenic material is a significant component of surface sediments in shelf basins. Its distribution is strongly influenced by marine currents, which generally decrease with depth and transport material onshore and east to west on the inner shelf. Marine currents rework relict glacial and glacial-marine deposits, leaving residual glacial marine sediments on shallow banks and on the outer shelf. Reworking of these very cohesive relict deposits is facilitated by biological mixing of surface sediments. Maximum sustained current velocities (1 meter off the bottom) indirectly derived from grain-size data range from < 8 cm/s in shelf basins and troughs to 20-25 cm/s on the outer shelf/upper slope. Pelagic sedimentation and reworking by marine currents appear to be the prime contributors of sediment to the shelf today, a sitution that differs dramatically from that of the last glacial maximum when glacial and glacial-marine sedimentation were predominant on the shelf.

Introduction

The Antarctic continental shelf is unique in its great depth, rugged topography, and glacial setting. Glacial loading and erosion have produced an average shelf depth of about 500 m [Vanney and Johnson, this volume]. In many areas the shelf deepens in the onshore direction. Most of the coastline and nearshore region is covered by floating or grounded glacial ice, so that beaches are uncommon. This limits the potential roles of pack ice and anchor ice in supplying ice-rafted debris to deeper regions of the shelf. Antarctic glaciers supply sediment directly to the sea by subglacial sedimentation or by ice rafting of material entrained in icebergs or floating ice shelves and ice tongues. In contrast to the Arctic seas, where meltwater streams supply large amounts of sediment to the coastal zone, modern sediment input by meltwater is considered to be minimal in the Antarctic. Biogenic sedimentation rates are high on the deeper areas of the shelf, and in some areas aeolian deposition may be significant.

Given its great depth, absence of meltwater run-off, and lack of a wave-dominated coastal zone, marine currents and mass flow processes are likely to be key sedimentary agents on the continental shelf. Reworking of shelf sediments by glacial ice, an important process in the Arctic, is of minor importance in the Antarctic because relatively little of the shelf is sufficiently shallow (< 150-200 m) to be scoured by sea ice and icebergs. Because of these unique features, models for sediment accumulation on other continental shelves, including other high latitude areas, do not adequately depict sedimentation on the Antarctic shelf.

In this paper we describe the distribution patterns of surface sediments on the continental shelf from 150°W west to 140°E. This sector includes those portions of the Antarctic coastline where a sufficient sample density exists for such studies. Both compositional and textural sediment properties are examined and interpreted, along with the distribution patterns, in terms of present-day sedimentary processes.

Modern sediment supply to the Antarctic shelf is dominated by ice rafting, pelagic

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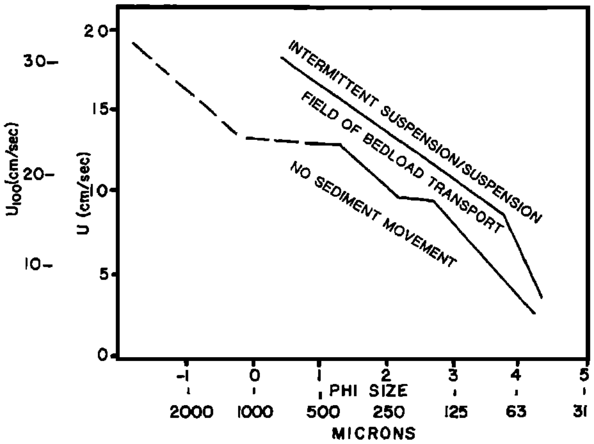

Fig. 1. Relationship between bottom current velocity and sediment transport by traction and saltation (bed load field), and intermittent suspension and suspension for particles of varying size. Field boundaries were derived from flume experiments [Singer and Anderson, 1984] utilizing poorly sorted sediments, mechanically mixed to simulate the effects of bioturbation. Velocities (U) measured between 1 and 3 cm above the bed are equivalent to those measured at higher levels in the flume and are thus taken as mean flow velocities. The current velocity 1 meter off the bottom in an oceanic setting (U_{100}) is calculated from mean flow velocity in the flume experiment following the procedure of Southard et al. [1971].

production and deposition, and the redistribution of material reworked from relict units on the seafloor. These processes involve vertical and/or horizontal transport of sediment through the shelf water column. Physical processes that control the structure and chemistry of the shelf water column will influence the nature of sedimentation. Therefore, we briefly discuss what is known about shelf circulation and currents in relation to sedimentology. For the Pennell Coast region, we show how current directions may be inferred from mineralogical patterns in surface sediments. Our ultimate goal is to integrate knowledge of shelf water column processes with surface sediment distribution patterns in order to formulate accurate models of sediment deposition on the Antarctic shelf.

Although links between the oceanography and sedimentology of the Antarctic shelf are not well defined at this time, the sediments provide a potential proxy record of shelf water column conditions. Sediment textural and compositional data can be used to derive bottom current intensity and direction as well as information about biological productivity in surface waters. Once the credibility of such proxy techniques is more firmly established, they will become an additional tool for examining the response of the Antarctic marginal seas to past global climatic perturbations.

Estimation of Relative Bottom Current Intensity

A variety of interrelated physical parameters influence the supply of terrigenous and biogenic sediments and their distribution on the Antarctic shelf. The current and wind regimes, light intensity, water column stability, seasonal ice coverage, and wave energy are among the most important. One principal variable which will be discussed in this paper is bottom current intensity, which can be determined at least qualitatively from textural and compositional analysis of surface sediments. Sediment grain-size distribution can provide important information about suspension versus bottom transport mechanisms and maximum velocities of bottom currents. Our approach to grain size/current speed relationships is based upon results from flume experiments by Southard et al. [1971] and Singer and Anderson [1984], so some discussion of the method is warranted.

Shields [1936] and Hjulstrom [1939] experimented with particle transport versus flow conditions, and published curves that are still widely cited. Those experimenters measured the bottom shear stress or velocity at which particles of a given size experienced initial transport. Their studies have limited application to sedimentology, in part because threshold velocities were defined by the initial movement of uniform sediment grains in equigranular (well-sorted) beds. In the marine environment, sediments are often poorly sorted, and complex sediment transport mechanisms include traction, saltation, intermittent suspension and suspension [e.g., Middleton and Southard, 1977]. These transport mechanisms operate simultaneously on grains of different sizes, with each mechanism involving a quantum increase in transport rate. At any given velocity, different size particles are thus transported and deposited by various mechanisms, and different size populations may be segregated through time. The velocity required to transport particles of a given size can only be determined by knowing how those particles were transported.

Visher [1969] and Middleton [1976] recognized that grain-size distributions of sand samples consist of discrete modes which represent the different transport populations. Although the polymodal nature of many marine sediments renders a strict Visher-type analysis difficult, useful information on transport mode can be acquired by examining specific regions of the grain-size spectrum that show evidence of current influence, e.g., near truncation points. Assuming that transport modes

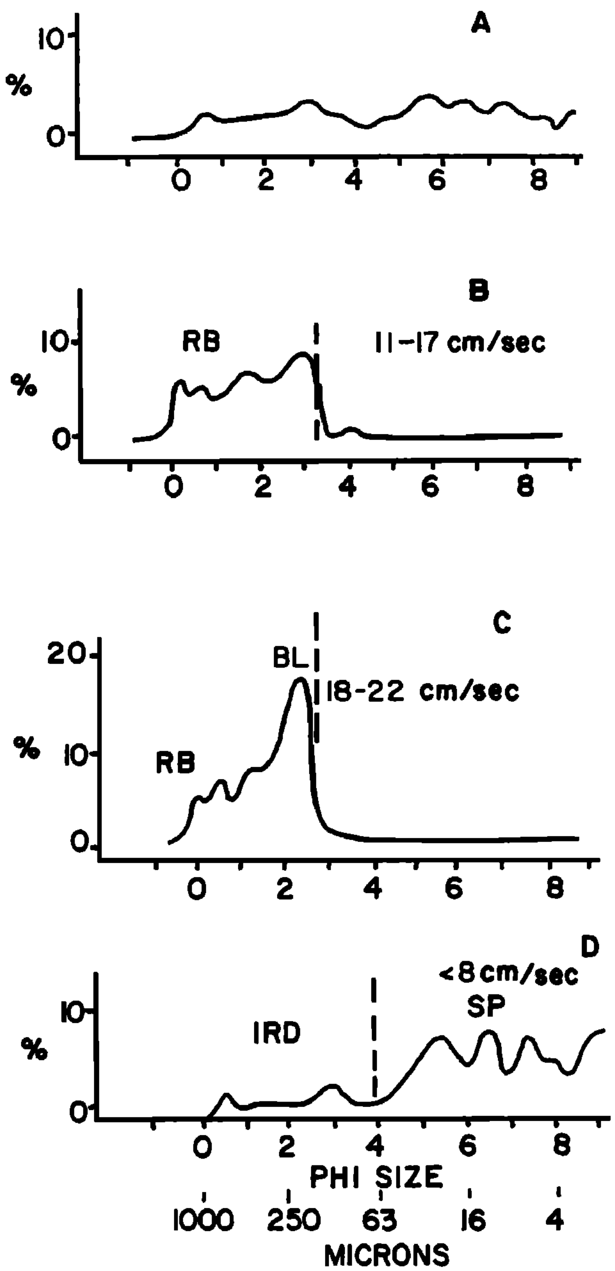

Fig. 2. Examples of typical grain-size curves for Antarctic surface sediment samples and the inferred current velocites. Sample A is a typical unsorted glacial-marine sediment similar in size distribution to starting material used in flume experiments of Singer and Anderson [1984]. Sample B is a residual bed (RB) resulting from winnowing of material finer than 90 μm (3.5 ϕ). Sample C shows a bed load mode (BL) resulting from winnowing of material finer than 150 μm (2.75 ϕ) and associated residual bed. Sample D consists of unsorted ice-rafted debris (IRD) in a typical fine-grained basin deposit where most material has settled out of suspension (SP).

could be discerned by grain size analysis, Singer and Anderson [1984] conducted a series of experiments to measure critical transport velocities for different particle sizes, by various transport mechanisms. Their experiments differed from previous flume studies in that they used an initially unsorted bed, designed to resemble glacial and glacial-marine sediments of the Antarctic continental shelf.

In poorly sorted, cohesive sediment beds only the very surface of the bed is eroded in the absence of sediment mixing. After fine grains are removed from the top of the bed, a surficial lag of coarser particles protects (armors) the bed from further erosion. In the marine environment armoring is prevented by biological mixing, thus rendering bottom sediments more susceptible to current erosion. The high standing stock of benthic organisms on most areas of the Antarctic continental shelf [e.g., Bullivant and Dearborn, 1967; Everson, 1977] and analyses of box cores [Nittrouer et al., 1984] suggest that sediment mixing by bioturbation is important. Singer and Anderson [1984] simulated the effects of bioturbation by mechanically mixing the sediment bed. They justify using a much faster mixing rate than occurs in the marine environment on the grounds that the rate of mixing only influences the efficiency of bed erosion; shear velocity (or shear stress) influences the size of particles eroded from the bed. Their results demonstrate that without thorough mixing of the bed, unsorted sediments are not sufficiently eroded to produce measurable grain size differences at mean velocities less than 15 cm/s (measured to within 1 to 3 cm of the bed). With sediment mixing, silts and clays were resuspended at velocities less than 5 cm/s to produce a residual bed consisting of unsorted sand and gravel. These results are consistent with theoretical treatments of the subject of sediment suspension processes [Blatt et al., 1980; Middleton and Southard, 1977; Anderson and Kurtz, 1985]. Singer and Anderson also measured the mean current speeds at which different size sand grains moved along the floor of the flume by either traction or saltation, using sampling trays placed at various levels on or above the floor of the flume, one meter downstream of the bed. Their field for bed load transport is shown in Figure 1. The critical transport velocities derived through their experiments are lower than those obtained in previous studies [e.g. Shields, 1936]. These differences are ascribed to the fact that Singer and Anderson used a rough unsorted bed (made to resemble glacial marine sediment of the Antarctic shelf) whereas previous workers have dealt mainly with smooth, well sorted beds. The actual shear velocity acting on the bed will be greater for a current of given velocity passing over a rough (unsorted) bed than over

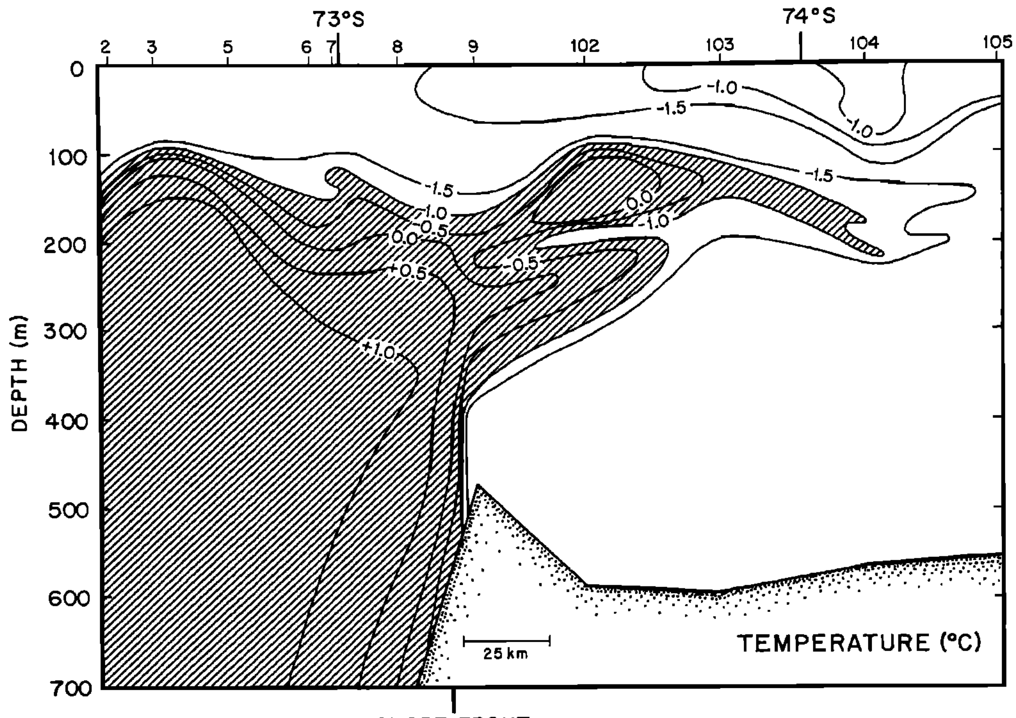

Fig. 3. Temperature section across the continental shelf break in the northwest Ross Sea near 178°E, December 19-20, 1976. Temperatures were measured by a salinity-temperature-depth instrument (STD 2-9) and by expendable bathythermographs (XBT 102-105) from the U.S. Coast Guard icebreaker Northwind [Jacobs and Haines, 1982]. Relatively warm water (T > -1.0°C) intrudes onto the continental shelf above the slope front that separates very cold (-1.9°C) shelf water from deep water (>+1.0°C) north of the shelf.

a smooth bed [Middleton and Southard, 1977]. Because of these differences, the Singer and Anderson curve was used to derive current speed for samples containing bed load transport fractions. Singer and Anderson measured mean flow velocity which, in the case of flume experiments involving shallow uniform flow, can be converted to the current velocity one meter off the bed using

$$\frac{U_y}{U_*} = 5.6 \log_{10} \frac{\rho U_* y}{\mu} + 4.9$$

[Daily and Harleman, 1966], where U_y is the velocity at distance y above the bed, U_* is shear velocity, ρ is fluid density, and μ is fluid viscosity. The shear velocity (U_*) is derived from the mean flow velocity using

$$\frac{U_{mean}}{U_*} = 5.75 \log_{10} \frac{\rho U_* h}{\mu} - 4.72$$

[Rouse, 1949], where h is flow depth. See Southard et al. [1971] for a justification of these computations when dealing with shallow uniform flow in flume experiments. The method used in deriving current speed from sediment grain size data is illustrated in the following set of examples. For a more detailed description of this method see MacDonald and Anderson [1985].

Sample A in Figure 2 is a typical unsorted glacial sediment. Material finer than 90 μm (3.5 Ø) has been eroded from sample B relative to sample A, resulting in the formation of a residual bed (RB). This implies either sediment mixing and removal of fines via bed load transport by currents with velocities (U_{100}) of at least 11 cm/s, the lowermost line in Figure 1, or winnowing via intermittent suspension at current velocities of at least 17 cm/s, the boundary between the bed load and intermittent suspension fields. Sediment finer than 150 μm (2.75 Ø) has been removed from sample C, and a sorted bed load (BL) population (177 μm, 2.5 Ø) is clearly illustrated. Traction is a slow process, and the traction mode coexists with the residual bed material (1000 to 250 μm, 0 to 2 ϕ) in sample C. Here, implied current speeds 1 meter off

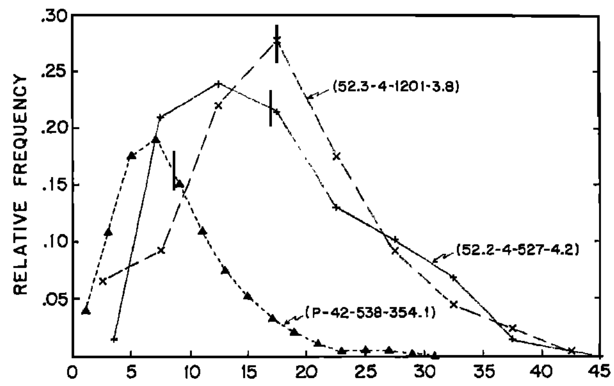

Fig. 4. Current speed frequency records from three instruments moored near bottom in the Ross Sea. Vertical bars denote mean currents. Within the brackets, read (mooring designator-height above bottom (m)-water depth (m)-record length (days)). The moorings were located at 72°55'S, 177°20.2'E on the continental slope (52.3), 73°21'S, 176°57.9'E on the outer shelf (52.2), and 78°05.5'S, 175°30'W near the Ross Ice Shelf (P). Data from Jacobs et al. [1974] and Pillsbury and Jacobs [this volume].

the bottom are between 18 and 22 cm/s, the range of the bed load field for particles 177 µm in diameter. Sample D shows a typical fine grain size population (SP) associated with unsorted ice-rafted debris (IRD), and reflects sedimentation under quiescent bottom conditions (< 8 cm/s).

There are several limitations to this technique. The original grain size distribution of the source material influences the distribution of respective transport modes. If the input material were well sorted, e.g. recycled beach sands, this kind of analysis would be of little use. However, the diverse sediment sources and unique supply mechanisms on the Antarctic continental shelf make it difficult to model the formation of an extensive well-sorted modern deposit, except via bottom current influences and aeolian transport. The latter has been shown to be important in McMurdo Sound [Barrett et al., 1983]. Regional variations may exist in the grain-size distributions of terrigenous sediments supplied from the continent, but our underlying assumption is that all of this source material is poorly sorted. This assumption is supported by the poorly sorted nature of glacial sediments in the area (e.g., sample A in Figure 2).

Following the procedure of Southard et al. [1971] we have calculated ocean bottom velocities at one meter above the seabed (U_{100}) using the flume data of Singer and Anderson [1984]. The transformation is sensitive to a number of factors that influence erosion velocity (bed cohesion, roughness, and fluid turbulence) which we are unable to precisely evaluate in the field. Calibration of sediment textural data to absolute velocity within the water column is hampered by the absence of boundary layer studies and the scarcity of direct current measurements near the seafloor on the Antarctic continental shelf.

Methods

Samples used in this study include trigger core tops, Dietz-La Fonde grab samples, and samples taken from the tops of box cores. Grain-size analyses were performed using an automated settling tube for sand-sized material (> 63 µm, 4 ϕ), and a hydrophotometer [Jordan et al., 1971] for fine-grained (< 63 µm) sediments. For samples collected on the George V shelf, the amount of terrigenous material within the very fine sand and coarse silt fraction of siliceous oozes (31 µm to 125 µm, 8.5 ϕ to 3 ϕ) was based on 300 point counts on each of 15 processed slides.

For our studies of biogenic silica and organic carbon distribution, we utilized 230 sediment grab samples that we collected and another 25 samples taken from the tops of box cores collected in the southern Ross Sea by DeMaster et al. [1983]. The sediment samples were dried, gently ground with mortar and pestle, and sieved through a 425 µm (1.25 ϕ) screen to remove coarse crystalline particles. Biogenic silica was determined by a kinetic dissolution experiment in 0.1 molar NaOH at 85°C following the procedures of DeMaster [1979, 1981]. We modified his technique by measuring silica concentrations at 4 hours and using data from the 3-, 4-, and 5-hour samplings to determine the clay mineral influence. As described by DeMaster [1981], grinding produces a slight increase in weight percent biogenic silica calculated for sediment samples with < 4% biogenic silica. Organic carbon contents were determined using a LECO analyzer following standard techniques [Boyce and Bode, 1972]. Weight percent biogenic silica and organic carbon values reported here are not corrected for sea salt content of the dried samples, which ranges from 1 to 5%.

Continental Shelf Circulation and Currents

Ocean circulation near the Antarctic continental margin is marked by seasonal waxing and waning of sea ice, prevailing winds off the ice sheet, large lateral property gradients combined with upwelling and sinking over the continental slope, net melting of the large floating masses of glacial ice, and currents dominated by a westward drift and diurnal tides. The continental shelf is largely ice covered from April through October, and portions of it remain beneath the sea ice and glacial ice year-round [Naval Polar Oceanography Center, 1974-1985]. Even during the winter period, however, leads and polynyas along the coastline constitute more than 15% of the shelf area north of the ice shelves, and sea ice that forms in these open water areas is rapidly moved offshore [Kurtz and Bromwich, this volume; Zwalley et al., this volume]. Winter brine drainage increases the salinity of shelf waters, the densest of which accumulate on the western sides of the wider shelves and in depressions along the coastline [Jacobs et al., 1970, this volume; Gordon and Tchernia, 1972; Killworth, 1974]. In combination with surface winds, the resulting density field leads to a cyclonic (clockwise) circulation pattern in the large embayments, with onshelf flows at shallow to intermediate depths east of and above the high density regions (Figure 3).

Near the continental shelf break, some of the denser shelf waters flow along and down the slope, mixing with, entraining and modifying the deep water or producing Antarctic Bottom Water [Carmack and Killworth, 1978; Foldvik et al., this volume]. At some locations, deep water or its derivatives upwell onto the continental shelf and subsequently provide heat for melting glacial ice [Jacobs et al., 1979]. Over the upper continental slope, a well-developed subsurface frontal zone (Figure 3) is characterized by sharp horizontal thermohaline gradients, evidence of deep vertical mixing and relatively high levels of biological productivity [Ainley and Jacobs, 1981].

Few current measurements have been made very near bottom on the Antarctic continental shelf. From a number of brief (5-10 min) direct current observations about 1 m above the seafloor in the Ross Sea, Jacobs et al. [1970] reported currents in excess of 15 cm/s on the outer shelf and generally less than 10 cm/s on the inner shelf. More recent measurements, some for a full year, also show stronger near-bottom currents near the continental shelf break. Two of the curves in Figure 4 show current speed distributions for 4-day moorings near 1200 m on the continental slope and 525 m on the outer shelf in the Ross Sea. The left-hand curve in Figure 4 displays similar data from a 354-day record at 508 m near the Ross Ice Shelf. Mean current speed at the inner shelf site, 42 m above the seafloor, is only half that at the outer shelf and slope sites, 4 m above bottom. The 4-day records were obtained during the austral summer, a time when both higher and lower energy levels have been noted in yearlong records on the Antarctic continental shelf [Foldvik et al., this volume; Pillsbury and Jacobs, this volume]. Bimodal current speed distributions could result in the formation of fine laminations in some shelf sediments, even without seasonal variations in productivity. More importantly, the frequent incidence of high current speeds, particularly on the outer shelf (Figure 4) raises the prospect that high-energy events may play as important a sedimentologic role as sustained, slower drifts much as described by Hollister and McCave [1984].

Most current measurements at intermediate depths have been taken beneath the sea ice, either in McMurdo Sound [Tressler and Ommundsen, 1962; Heath, 1977; Carter et al., 1981; Lewis and Perkin, this volume] or along and under the ice shelves [Jacobs et al., 1979; Jacobs and Haines, 1982; Pillsbury and Jacobs, this volume; Potter and Paren, this volume]. These measurements revealed currents that are dominated by diurnal periods, and commonly range up to half a knot ($\approx$ 25 cm/s). The mean directions for several year-long observations near the ice shelf show significant southward and westward components. Currents associated with vertical overturning during winter sea ice formation events are likely to reach the seafloor at some locations, particularly beneath coastline leads associated with katabatic winds off the ice sheet [Kurtz and Bromwich, this volume; Cavalieri and Martin, this volume].

The near-surface circulation, seasonal sea ice distribution, and water column stratification all influence biological productivity and the resulting concentrations of biogenic components in shelf sediments. Surface currents are variable, but appear to be strongest (in excess of 1 knot ($\approx$ 50 cm/s)) near the coastline or ice shelf [U.S. Naval Oceanographic Office, 1960]. Substantial currents have also been measured directly beneath the sea ice [Mitchell and Bye, this volume]. Geostrophic currents are not large, but there are indications from the density field and from ship drift that surface flows set to the east on the south side of the shelf break/slope front, and to the west on its north side [Ainley and Jacobs, 1981].

Nutrient levels are of minor concern in surface waters on the shelf, since abundances seem to be rarely depleted below relevant thresholds by phytoplankton blooms. The most stable surface layers will be those longest exposed to summer insolation, specifically in the southwest Ross Sea. Sea ice usually persists throughout the austral summer over the slope and outer shelf in the eastern Ross Sea, along the Victoria Land coast, the Pennell Coast west of 167°E, and on the George V Coast east of 147°E [Naval Polar Oceanography Center, 1974-1985].

Ross Sea (150°W to 163°E)

Physiography

The bathymetry of the Ross Sea north of the Ross Ice Shelf has been described and mapped by Lepley [1966], Hayes and Davey [1975], Vanney et al. [1981] and Vanney and Johnson [this volume]. The shelf has an average depth around 500 m and slopes toward the continent (Figure 5). It is bounded on the east by Sulzberger Bay, which contains several small basins with depths as great as 900 m. The central Ross Sea shelf is characterized by a series of elongate, north to northeast trending banks (≈ 300 m) and basins (> 500 m). The western shelf is more rugged and deeper, particularly near the Victoria Land coast where outlet glaciers have eroded the seafloor to create narrow transverse troughs, down to 1200 m in the case of Drygalski basin. The irregular topography of the western Ross Sea shelf is further accentuated by volcanic islands and seamounts of the McMurdo Sound complex, which extends along a roughly north-south line from McMurdo Sound to Cape Adare.

Sediments

The Ross Sea was sampled as part of Eltanin cruises 27, 32, and 52 and during "Deep Freeze" cruises on U.S. Coast Guard icebreakers (DF 76, 78, 80, 83, and 84). Sedimentological studies have been conducted by Stetson and Upson [1937], Kennett [1966], Chriss and Frakes [1971], Glasby et al. [1975], Kellogg et al. [1979], Barrett et al. [1983], and Anderson et al. [1984]. Fifty-nine surface grab samples collected in the Ross Sea during DF 84 provide an important basis for this discussion.

Surface sediments in the Ross Sea are composed of mixtures of unsorted ice-rafted debris, siliceous biogenic material (mainly diatom frustules), calcareous shell debris, and terrigenous silts and clays that have been transported in suspension by marine currents. The concentrations and distributions of these various components (Figure 6) reflect the relative influence of glacial, oceanographic, and biological processes. Sediments consisting of greater than 20% ice-rafted debris and associated with fine-grained current-derived terrigenous material are referred to as Compound Glacial Marine (CGM) after Anderson et al. [1980a]. These are common in Sulzberger Bay and in a relatively narrow zone along the Victoria Land coast. Compound glacial marine sediments with > 10% diatoms (dCGM) occur on the central shelf east of 180°. Current-winnowed sediments containing abundant calcareous shell debris are referred to as Residual Glacial Marine (RGM), also after Anderson et al. [1980a]. These sediments blanket most of the outer continental shelf and upper continental slope and the tops of banks in the western Ross Sea. Terrigenous silts and clays (cZ and zC) make up more than 80% of the surface sediments collected along the front of the Ross Ice Shelf east of approximately 180°. To the west of 180°, the silts and clays contain 10-50% by weight biogenic silica and are labeled SiM (siliceous mud) and SiO (siliceous ooze). Sands and muddy sands were sampled in western McMurdo Sound and off the Edward VII Peninsula.

The concentration of coarse (larger than 63 μm, 4 ϕ) ice-rafted debris (IRD) in surface sediments increases in an offshore direction from the Ross Ice Shelf (Figure 7). The low concentrations near the calving line of the ice shelf suggest that melt-out of most basal debris occurs landward of the barrier, consistent with the oceanographic data [Jacobs et al., this volume; MacAyeal, this volume].

Grain-size data from central and outer shelf samples exhibit a prominent mode between 125 and 177 μm (3 ϕ to 2.5 ϕ, Figure 7). At this time we are unable to evaluate the contribution of aeolian debris to this mode. Aeolian material is known to be of importance in some coastal areas [Barrett et al., 1983], especially in regions affected by katabatic winds. We would expect some size sorting to occur during the aeolian transport process. We note that, although the absolute concentration of ice-rafted material (aeolian and glacial) varies across the shelf, sands from different areas exhibit consistent truncation points at 125 μm (3 ϕ, Figure 7). This implies that the maximum sustained velocity (U_{100}) of bottom currents on the shelf is greater than 18 cm/s, the minimum velocity required to transport this size material by intermittent suspension and suspension (Figure 1), therefore removing it from the bed. At this velocity, sands in the 125 to 177 μm range are transported as bed load (Figure 1) and the occurrence of a sorted mode in many samples implies that bottom currents are indeed acting on these sediments.

An increase in the relative proportion of fine-grained material (finer than 125 μm, 3 ϕ) in an onshore direction reflects a lower frequency of high velocity (> 18 cm/s) bottom current events. These general trends are supported by bottom current records from the shelf (Figure 4). Also important is the observation that the frequency of low velocity (<8 cm/s) events that will facilitate sedimentation of fine-grained components is significantly greater on the inner shelf (Figure 4).

We attribute the increased concentration of residual ice-rafted and current derived sands along the outer shelf and tops of shallow banks to more efficient winnowing of fine sediments. Increased winnowing efficiency would result from more frequent strong flow events, more extensive sediment mixing by bottom dwellers, and/or reduced sediment input. The winnowed sediments, including diatom frustules, are probably transported both north across the continental shelf break into the deep ocean and south toward the deeper basins on the in-

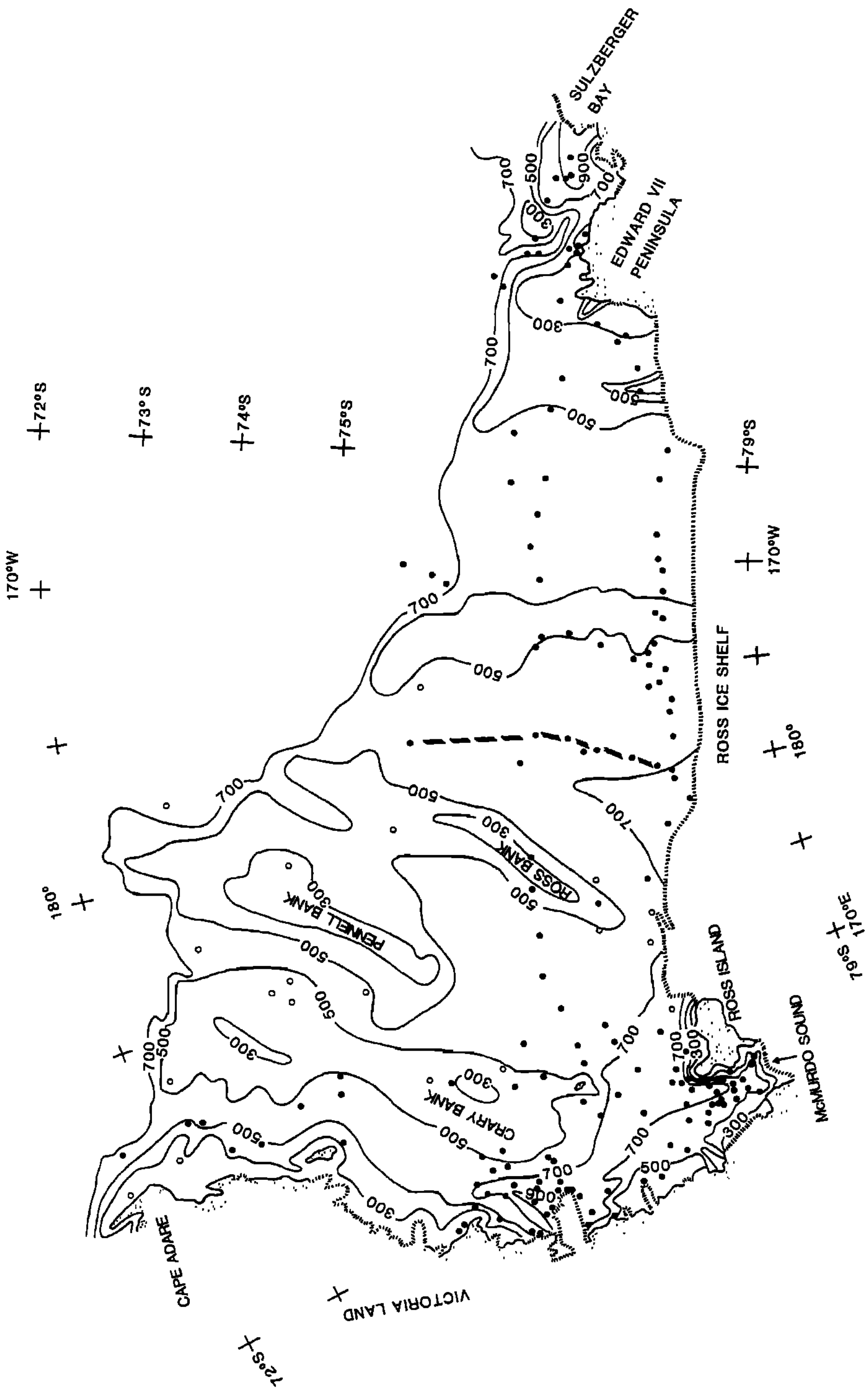

Fig. 5. Bathymetry of the Ross Sea (in meters, modified from Vanney et al., [1981]) and location of sediment samples used in this study. Samples at locations shown by solid circles were used for grain size, biogenic silica, and organic carbon measurements. Those at locations shown by open circles were used only for grain size analyses. The dashed line shows the location of the sediment composition transect in Figure 14.

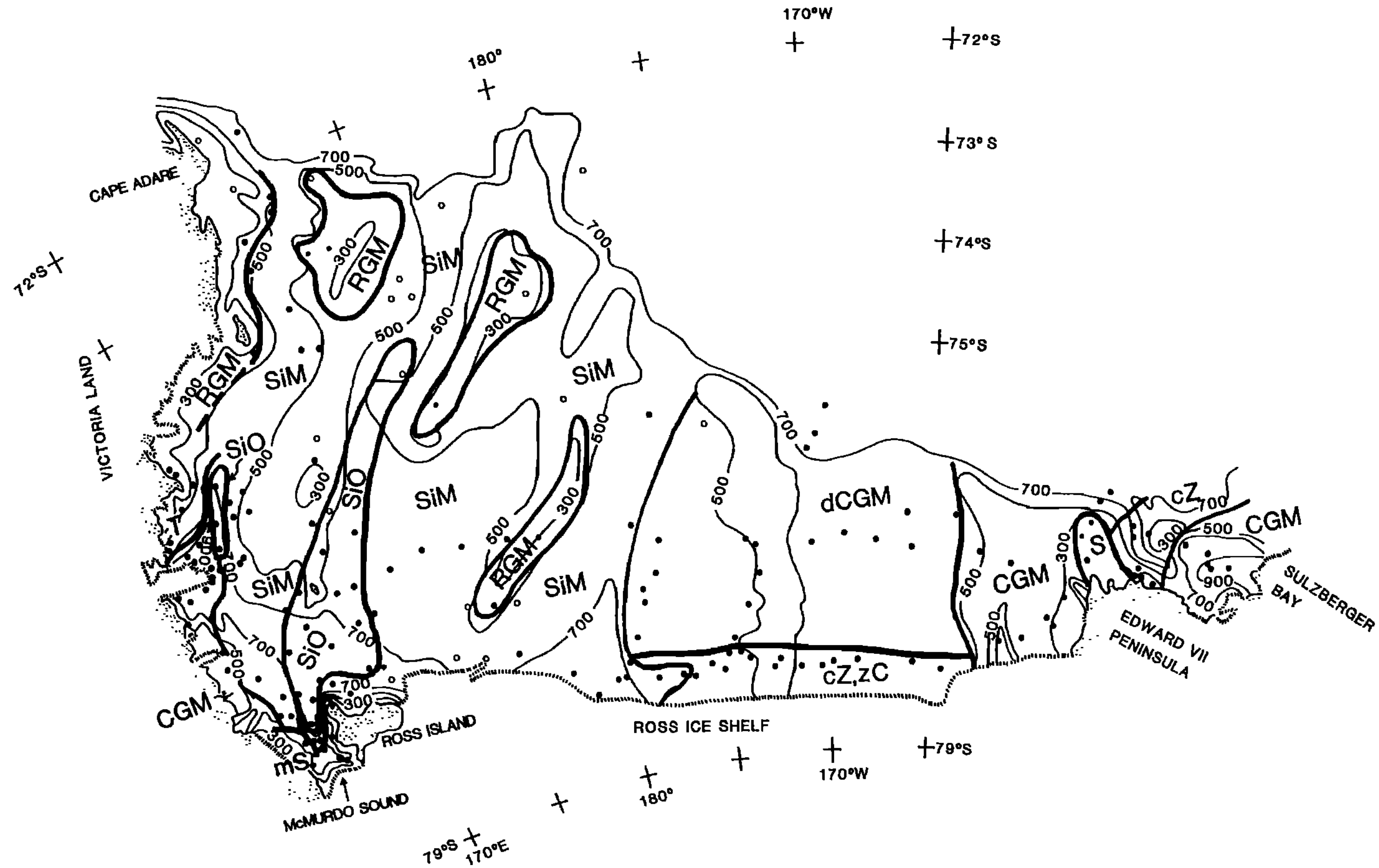

Fig. 6. Ross Sea sediment distribution map. CGM, compound glacial-marine; dCGM, diatomaceous compound glacial-marine; RGM, residual glacial-marine; S, sand; T, turbidite; cZ, clayey silt; zC, silty clay; SiO, siliceous ooze; SiM, siliceous mud. Group assignments are based on grain counts made during microscopic examination of sediment.

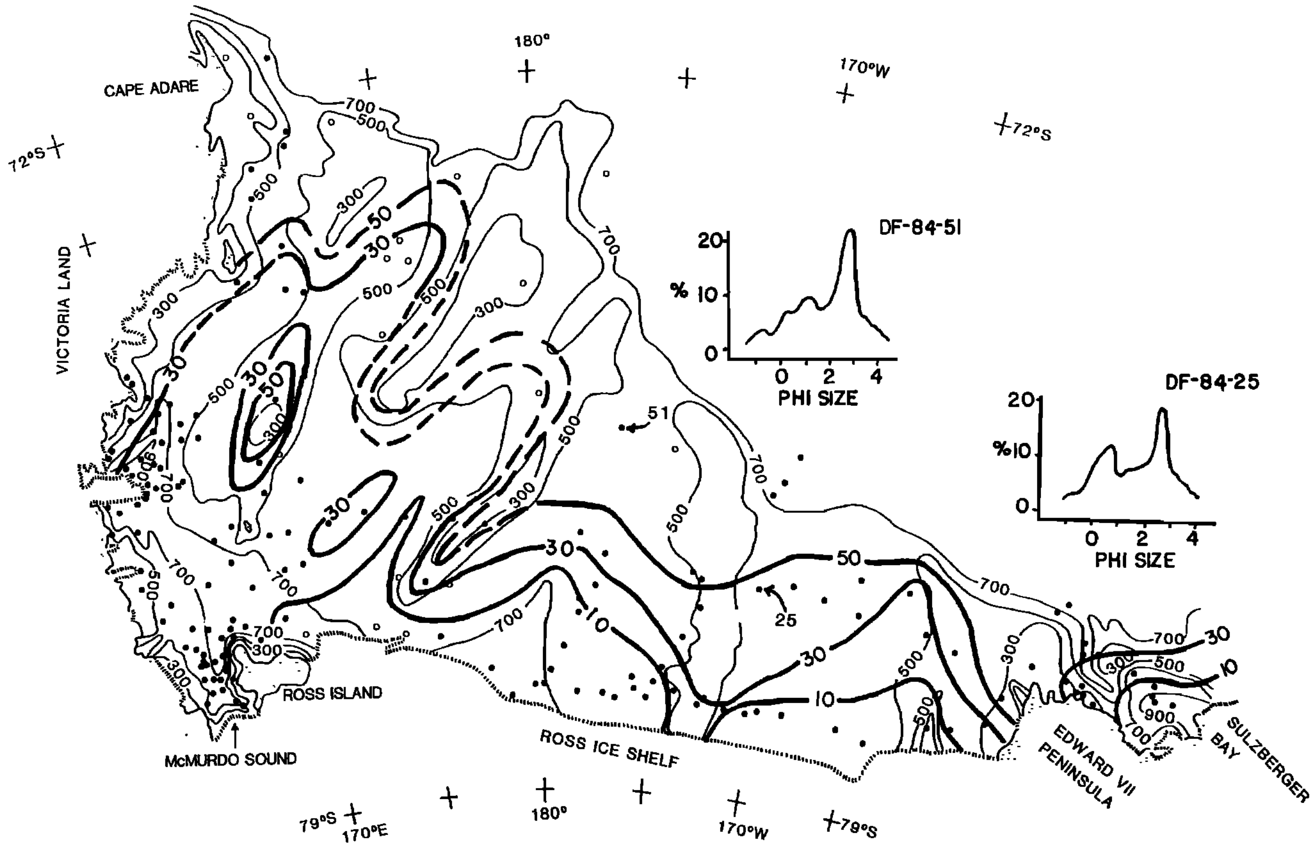

Fig. 7. Bold contours show weight percent of coarse (> 63 μm) ice-rafted debris in Ross Sea surface sediments. Light contours show bathymetry in meters. Also shown are two representative sand fraction grain-size frequency curves for surface sediments from the central Ross Sea. All samples show clear evidence of winnowing, with the finer than 125 μm (3 ϕ) component partially removed. The sorted 125 μm to 150 μm (3ϕ-2.5ϕ) mode is possibly of aeolian origin.

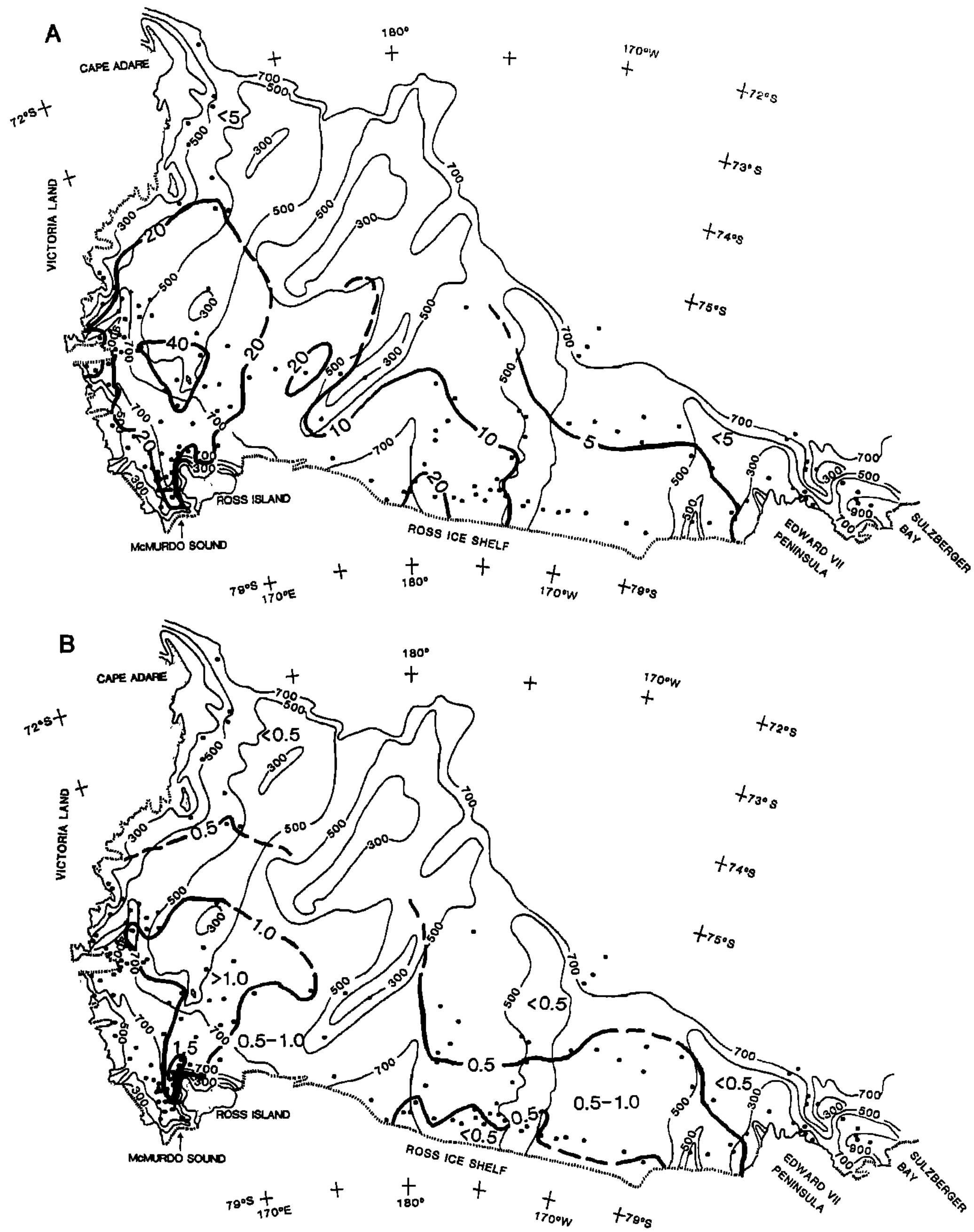

Fig. 8. Bold contours of weight percent concentrations of (a) biogenic silica and (b) organic carbon in surface sediments of the Ross Sea. Light contours show bathymetry in meters.

ner shelf where more quiescent bottom conditions are probable. It is possible that some portion of the IRD maximum along the outer continental shelf results from a higher frequency of iceberg tracks there [e.g., Tchernia and Jeannin, 1983], specifically via deposition from valley glacier icebergs that are more likely than ice shelf icebergs to be sediment laden.

The distribution of biogenic silica in surface sediments increases in the onshelf and east-to-west directions (Figure 8a). This pattern agrees with the observations of Truesdale and Kellogg [1979], who attributed variability in the diatom content of surface sediments to less extensive summer sea ice cover in the western Ross Sea. The highest concentration of biogenic silica (40% by weight) oc-

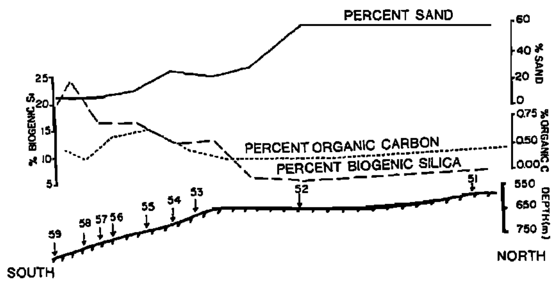

Fig. 9. Concentrations of sand, organic carbon and biogenic silica, along a north-south transect on the Ross Sea continental shelf (dashed line, Figure 5).

curs on the southern and western flanks of Crary bank. This is approximately the region where Smith and Nelson [1985] reported extremely high biogenic silica concentrations (up to nearly 1600 mmol/m^2 integrated from 0 to 150 m) in a surface layer stabilized by meltwater from the receding pack ice edge. The high accumulation rates (1-3 mm/yr) of sediments in the western Ross Sea and their potential importance to the global silica budget are discussed by DeMaster et al. [1983] and Ledford-Hoffman [1984].

Other factors also regulate the distribution of siliceous material on the seafloor. For example, open water is present during the austral summer along much of the Ross Ice Shelf, and some of the highest levels of primary production have been measured in the southeastern Ross Sea [El-Sayed et al., 1983]. High concentrations of opaline material also occur in the surface waters of Sulzberger Bay (R. Dunbar and A. Leventer, unpublished data, 1983), although the sediments of this region are depleted in biogenic components. Organic opaline debris from these locations and from regions of high productivity near the continental slope is likely to be transported westward and onshelf by the mean current flow. Diatom oozes on the Ross Sea shelf are mainly in the 16 µm to 63 µm (6 ϕ to 4 ϕ) range, a size that can be maintained in suspension by weak currents (a few centimeters per second). The opal distribution is thus strongly influenced by the hydrographic regime, especially for diatom frustules that settle through the water column as discrete particles rather than in fecal pellets. Fecal pellets accounted for only a minor portion of the total opal flux collected in sediment traps from the central Ross Sea and McMurdo Sound [Dunbar, 1984; Dunbar et al., 1984]; most material was transported as small aggregates of organic opaline debris. The westward drift of surface and subsurface water on the southern half of the shelf will serve to concentrate biogenic silica in that direction.

The mean circulation, the general decrease in current speed with depth, and the deeper water in the southwest Ross Sea will together concentrate fine grained sediments there. Samples from a transect taken across the central Ross Sea (Figure 9) illustrate the effects of winnowing and redeposition. From the outer shelf to the inner shelf there is a threefold decrease in sand content, while the opal content increases from less than 10% to greater than 20% by weight.

The organic carbon content of sediments also increases from east to west and, to a lesser degree, from north to south in the Ross Sea (Figure 8b). Despite relatively high opaline silica content (> 20%), sediments from depressions in the central Ross Sea tend to be depleted (< 0.50%) in organic carbon (Figure 9). We believe this reflects a more rapid degradation of organic carbon relative to dissolution of silica in the cold well-oxygenated waters of the Antarctic shelf. Thus, as winnowing and transport continue, the organic carbon/opal ratio of a reworked sediment is decreased. Sediments with > 1% organic carbon by weight blanket approximately 50,000 km^2 of the western Ross Sea. Higher organic carbon/opal ratios in these biogenic sediments indicate a lesser degree of reworking via resuspension in the water column there than in the central Ross Sea.

A persistent polynya is present in Terra Nova Bay [Kurtz and Bromwich, this volume] and might be expected to be accompanied by higher levels of illumination, surface warming, and higher annual productivity. However, the greatest enrichment in opal content of these sediments occurs not beneath the polynya but immediately to the east on the western flank of Crary bank (Figure 10a). The region of greatest organic carbon enrichment appears slightly west of the area of maximum opal content (Figure 10b). Surface productivity in the bay may in fact be low because of frequent deep mixing by strong winds and as a result of brine drainage from newly formed sea ice. Alternatively, freshly produced biogenic debris may be rapidly removed to the north and east by surface currents generated by offshore winds. In addition, biogenic sediments in the Drygalski basin may be diluted by terrigenous material arriving as wind-blown debris [Barrett et al., 1983], or rafted from the Drygalski Ice Tongue. It is not known to what extent the transport of terrigenous components into the basin might be facilitated by high density plumes sinking as a result of sea ice formation. Detailed analyses of biogenic components and sediment accumulation rates are needed to further elucidate controls on sedimentation in the region.

Pennell Coast (166°E to 171°E)

Physiography

The continental shelf of the Pennell Coast region of north Victoria Land has an average

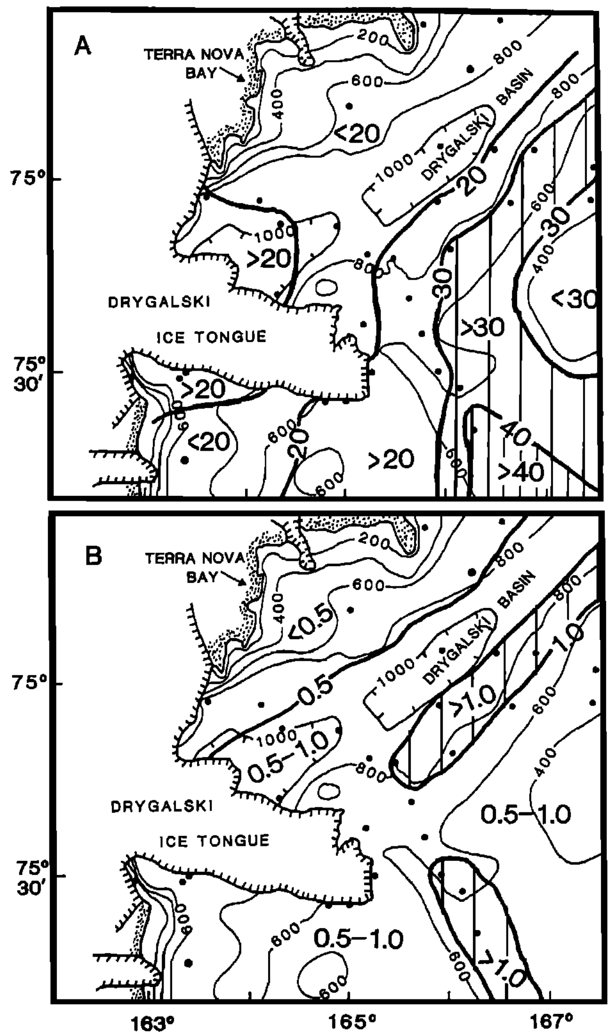

Fig. 10. Bold contours show weight percent concentrations of (a) biogenic silica and (b) organic carbon in surface sediments of the Terra Nova Bay region of the western Ross Sea. Light contours show bathymetry in meters. The polynya in Terra Nova Bay [Kurtz and Bromwich, this volume] lies directly north of the Drygalski Ice Tongue and commonly occupies a 1000-km^2 area, roughly equivalent to 1° longitude by 20' latitude.

depth just over 200 m, which makes it one of the shaOlowest areas of the Antarctic continental margin (Figure 11) [Vanney and Johnson, this volume]. The inner shelf is rugged, while the outer shelf exhibits relatively smooth topography [Brake and Anderson, 1983]. Transverse troughs are associated with large outlet glaciers.

Sediments

The following discussion is based upon analyses of grab samples and piston cores acquired during DF 80. Sands, muddy sands, and residual glacial marine sediments blanket the outer shelf, and finer-grained sediments occupy the inner shelf (Figure 11). Diatomaceous oozes, muds, and sandy muds are accumulating below about 350 m in glacial troughs. These deposits consist of a mixture of diatom frustules, terrigenous silts and clays, and very fine volcanic sand. Trough sediments contain less than 10% by weight ice-rafted sand and gravel. Perennial sea ice may limit the source of biogenic material west of about 167°E, assuming ice-edge productivity enhancement does not outweigh the effect of ice cover.

Poorly sorted glacial-marine sediments (CGM) are confined to a narrow (<20 km) coastal zone between Cape Adare and Dennistoun Glacier (71°11'S, 168°00'E), and to the region west of Yule Bay (70°44'S, 166°40'E). Residual glacial-marine sediments (RGM) occur on the shallower (<250 m) portions of the shelf between Dennistoun Glacier and Yule Bay. The distribution of sands and muddy sands on the outer shelf suggest a continuation of the sand unit toward the northwest Ross Sea (Figure 6).

There are two distinctly different sources of terrigenous sediment along the Pennell Coast of north Victoria Land, the quartz-rich Robertson Bay Group which outcrops along the entire coastline west of Robertson Bay, and

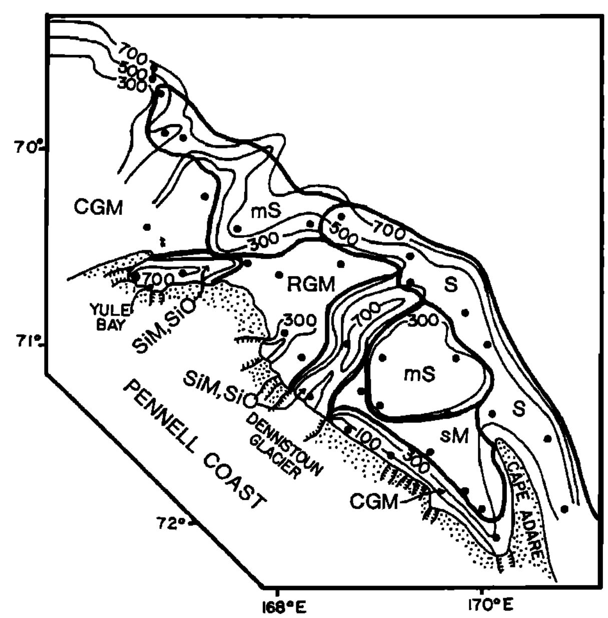

Figure 11. Bathymetry (in meters, from Brake and Anderson [1983]) and surface sediment distribution map for the Pennell Coast continental shelf. RGM, residual glacial-marine sediment; CGM, compound glacial-marine sediment; S, sand; mS, muddy Sand; sM, sandy Mud; SiM, siliceous mud; and SiO, siliceous ooze. Dots show station locations.

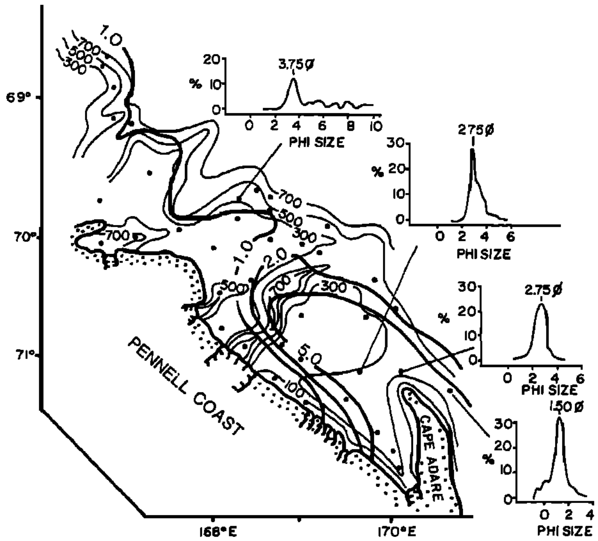

Fig. 12. Bold contours show volcanic sand/quartz sand ratios for sands and muddy sands of the Pennell Coast continental shelf [from Brake, 1982]. Light contours show bathymetry in meters. Also shown are representative grain-size frequency curves.

the McMurdo Sound Volcanic Group, restricted to the Cape Adare region [Brake, 1982]. Sediment transport paths can thus be determined through mineralogical analyses, such as the volcanic sand/quartz sand ratio (Figure 12). Volcanic sands comprise the major fraction of terrigenous sediment accumulating on the central and outer shelf, and are transported as far as 60 km west of Cape Adare. Bottom current velocities may be estimated from the grain size distributions in Figure 12. East of Cape Adare, bottom current velocities (U_{100}) of up to 25 cm/s are indicated by relatively coarse bed load fractions (175 μm to 350 μm, 2.5 ϕ to 1.5 ϕ). Current speeds of 16 to 22 cm/s to depths of 350 m would be needed to transport the volcanic sands to the west of Cape Adare. The deep basins adjacent to the coast are accumulating diatomaceous muds with opal contents up to 35% and are therefore characterized by more sluggish circulation.

George V Continental Shelf (140°E to 150°E)

Physiography

The bathymetry of the George V Coast is typical of other portions of the East Antarctic continental shelf in that it is characterized by a rugged and deep inner shelf (Figure 13) [Vanney and Johnson, this volume]. The inner shelf is dominated by the George V Basin, which attains depths greater than 1000 m parallel to the coastline and apparently extends beneath the Mertz and Ninnis Glacier tongues. The rest of the shelf is smoother, with alternating banks (≈ 200 m) and depressions (≈ 500-700 m). The continental shelf break occurs abruptly at 400-500 m. The continental slope exhibits two distinct morphologies. The area west of 143°30'E is characterized by highly irregular topography and a gentle slope. The eastern region is very steep along the upper slope, but marked by several large (> 300 km^2) isolated banks and knolls at depths of 2000 to 3000 meters on the lower slope, not shown in Figure 13.

Sediments

Fifty-six grab samples and piston cores were acquired from the George V continental shelf in early 1979 from the USCGC Glacier (Figure 13). Initial accounts of the surface sediments and fauna were given by Domack [1980, 1982], Milam and Anderson [1981], and Anderson et al. [1983]. A detailed description of relict glacial and glacial-marine deposits of the area can be found in the works by Anderson et al. [1980a] and Domack [1982]. Surface sediments obtained during the 1911-1914 Australasian Expedition to this region were examined for composition [Chapman, 1922], mineralogy [Von der Borch and Oliver, 1968], and palynology [Trueswell, 1982].

Surface sediments in this sector vary widely in texture and composition (Figure 14). Siliceous muds and oozes predominate below 500 m. Relict glacial and glacial-marine sediments occur on the westernmost shelf and along the flanks of Mertz and Ninnis banks. Residual glacial-marine sediments, sands, and muddy sands, often containing calcareous debris, blanket the upper slope and outer shelf and the easternmost shelf along the Ninnis bank. Calcareous biogenic sediments are found nearshore at depths of less than 200 m.

Siliceous muds and oozes are poorly to very poorly sorted, are typically laminated, and contain a low diversity arenaceous foraminiferal assemblage [Milam and Anderson, 1981]. The concentration of coarse ice-rafted material is low in both sediment types, but tends to be more concentrated in oozes (Figure 14).

Sediment-laden icebergs are rarely sighted in Antarctic waters, and this form of ice rafting probably supplies only a small amount of material to the modern sediments of the shelf. However, during Deep Freeze 79, several sediment laden icebergs were observed and sampled along the George V Coast (Figure 15). The material recovered from these icebergs was very poorly sorted, ranging in size from 1000 to < 4 μm (0 to 8 ϕ) [Anderson et al., 1980b]. Approximately 50% of the entrained debris was finer than 63 μm (4 ϕ).

Sediments with biogenic silica content greater than 10% and organic carbon content greater than 0.5% are generally restricted to

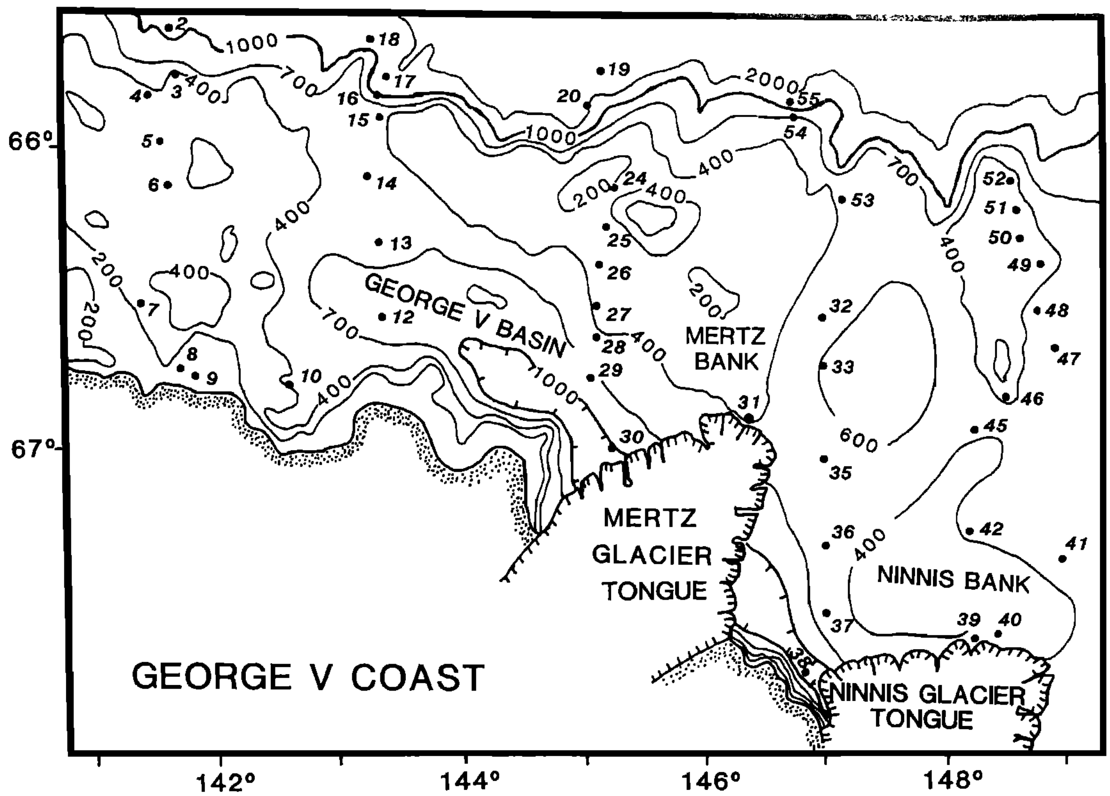

Fig. 13. Bathymetry (in meters, modified from Vanney and Johnson [1979] and Domack [1980]) of the George V continental shelf and locations of Deep Freeze 79 sediment sample stations (black dots).

depths below 500 m (Figure 16). There is an east to west increase in the thickness of biogenic units as well as in the biogenic silica and organic carbon concentrations of sediments within the George V basin. Up to 40 meters of diatomaceous ooze with a biogenic silica content greater than 30% has accumulated in the western end of the George V basin (Figure 16a). From 12 kHz subbottom profiler data, Domack and Anderson [1983] estimated the average thickness of these deposits to be 6 m and the areal extent to exceed 625 km^2. The accumulation rate for these sediments is about 0.3 cm/yr, based on ^{210}Pb analyses of the piston core at site 12 in Figure 13 (K. Cochran and D. DeMaster, personal communication, 1981).

The biogenic sediment distribution pattern results in part from the east to west transport of freshly produced opaline debris by surface water moving along the coastline. Sediment enrichment in opal and organic carbon is lower in the central and eastern portions of the George V basin, perhaps due to lower productivity related to the persistent sea ice cover east of 147°E. In addition, some sediment accumulating at deeper levels, such as in the western end of the George V basin, must be derived from the adjacent shallow banks where opaline sediments are absent. Information about winnowing on the shelf and upper slope is provided by grain-size data.

Residual glacial-marine sediments, sands, and muddy sands occur on the upper slope and shallow regions of the shelf and only differ in relative concentration of fine-grained matrix, i.e., mean grain size and sorting (Figure 14). These sediment types tend to be highly bioturbated and are in gradational contact with underlying glacial sediments. These stratigraphic and grain-size relationships indicate that these modern sediments are the by-products of reworked glacial sediments.

The efficiency with which fine-grained sediment is winnowed from a bed is primarily a function of mixing of the bed, whereas the size material eroded from the bed is velocity dependent, as demonstrated by Singer and Anderson [1984]. The size material being winnowed from these modern surface sediments is 125 μm (3 ϕ) and finer, which implies that they are subject to currents in the range of 18 to 22 cm/s. An offshore transition from residual glacial marine sediment to muddy sand and finally to well-sorted sands of the shelf break/upper slope is attributed to more efficient mixing by benthic organisms, lower sedi-

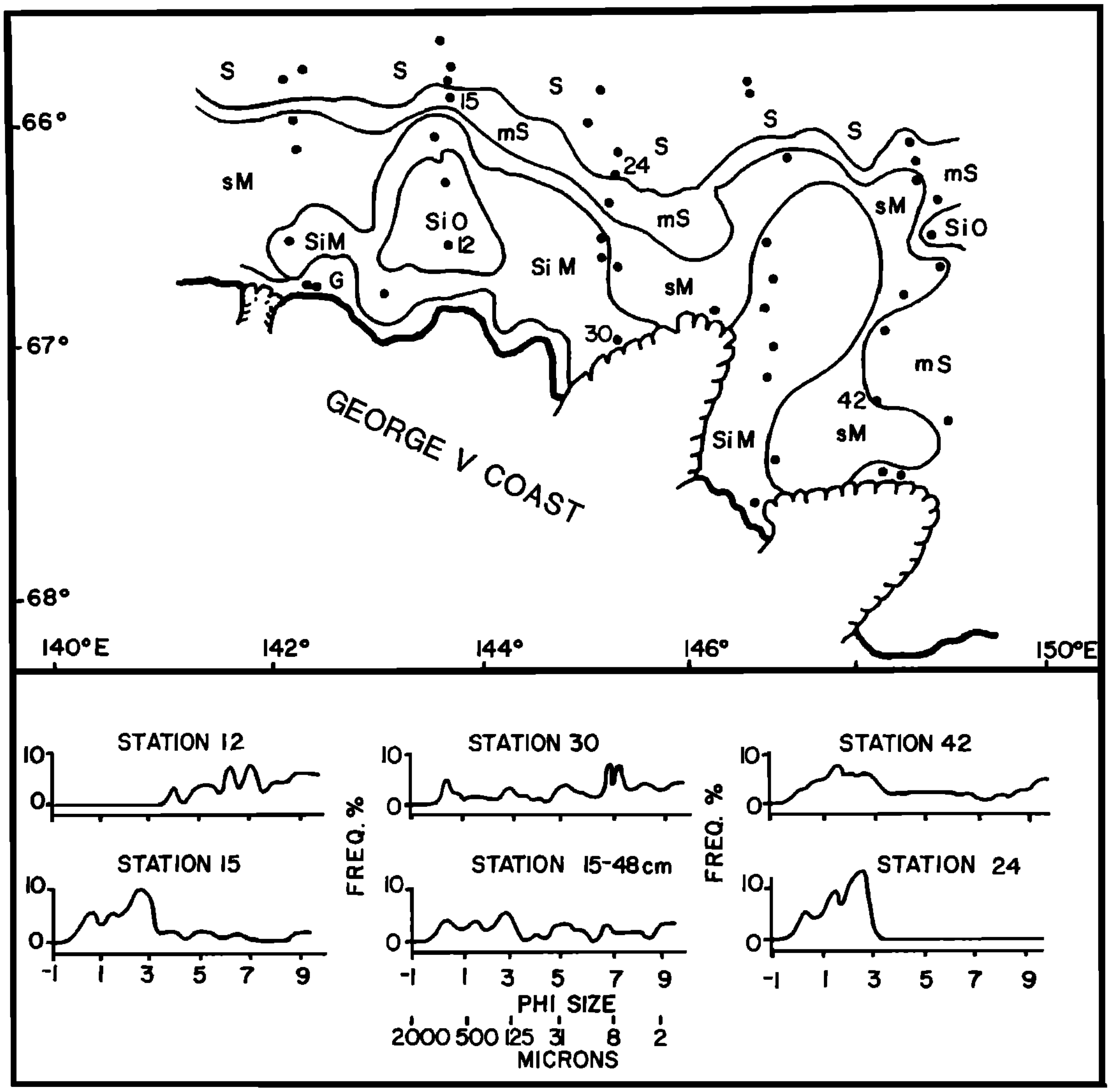

Fig. 14. Surface sediment distribution map for the George V continental shelf and representative grain size frequency curves for major sediment types. Grain-size data from an ice-rafted glacial marine unit (station 15 at 48 cm) illustrates the unsorted nature of sediment deposited on the shelf during the Pleistocene. SiM and SiO, siliceous mud and ooze, respectively. These two differ only in the relative concentration of siliceous biogenic material. The frequency curve for station 12 is representative of these poorly sorted, polymodal sediments. Sand (S), includes both well sorted saltation modes and poorly sorted residual sands with associated traction modes (cf. station 24). Poorly sorted sandy muds (SM) resemble compound glacial marine sediments but are more the product of reworking of relict glacial sediments than modern ice rafting and settling from suspension. The frequency curve for station 30 is representative of this group. Muddy sands (mS) exhibit evidence of winnowing (e.g., the frequency curves for stations 15 and 42) and therefore resemble residual glacial marine sediments, except that they lack significant amounts of gravel. Gravel (G) occurs in a shallow (< 150 m) nearshore zone.

mentation rates, or to more persistent, but not necessarily stronger, currents in that direction. Any of these factors would result in more efficient winnowing. In contrast, coarser sands on the continental slope imply stronger currents (U_{100} up to 25 cm/s).

The fine-grained fraction eroded from relict glacial sediments is redeposited in shelf basins along with freshly produced and reworked diatomaceous material to comprise siliceous muds and oozes. This locally derived fine-grained terrigenous material (very fine

Fig. 15. Large iceberg with thick debris zones observed during Deep Freeze 79 off the Ninnis Glacier, George V Coast. After Anderson et al. [1980b].

sand and coarse silt) comprises no more than 30% of the total sample weight of siliceous oozes. This would represent a mass of approximately 5×10^{14} g within our estimated volume for the present distribution of ooze (625 km^2 and 6 m thick). Reworking during the Holocene of a 20-cm surface layer of relict glacial and glacial-marine sediment over that portion of the shelf shallower than 500 m ($\simeq$ 8000 km^2) would provide 4 to 10×10^{14} g of fine-grained terrigenous sand and silt. Therefore, the terrigenous component of fine-grained basin sediments can be derived via scouring of relict glacial and glacial-marine sediments on the adjacent shallower portions of the shelf. Ice rafting and meltwater run-off may also supply material to the shelf, but significant sediment input by these processes is not needed to produce a balanced sediment budget.

Conclusions

Surface sediments of the Ross Sea, Pennell, and George V continental shelves are similar in composition and texture and have distribution patterns that indicate similar processes are active in these areas. Sedimentation on the shelf is presently dominated by the production and settling of biogenic material and reworking by bottom currents. An aeolian-derived component may be important in some areas.

Compound glacial-marine sediments, which consist of unsorted ice-rafted debris and fine-grained terrigenous and biogenic material, occur in nearshore areas drained by outlet glaciers and across much of the central and eastern Ross Sea shelf. There appears to be a relatively limited input of terrigenous material by glaciers and meltwater at the present time. By contrast, the Antarctic continental shelf was blanketed with glacial and glacial-marine sediments during the last glacial maximum [Anderson et al., 1980a].

Residual glacial-marine sediments are very poorly sorted glacial-marine deposits from which fine-grained components have been winnowed by marine currents. They occur on shallow banks and on the outer continental shelf and typically display physical and textural evidence of bottom current reworking. Biological mixing of relict glacial and glacial-marine sediment is believed to decrease the cohesive properties of these deposits and ren-

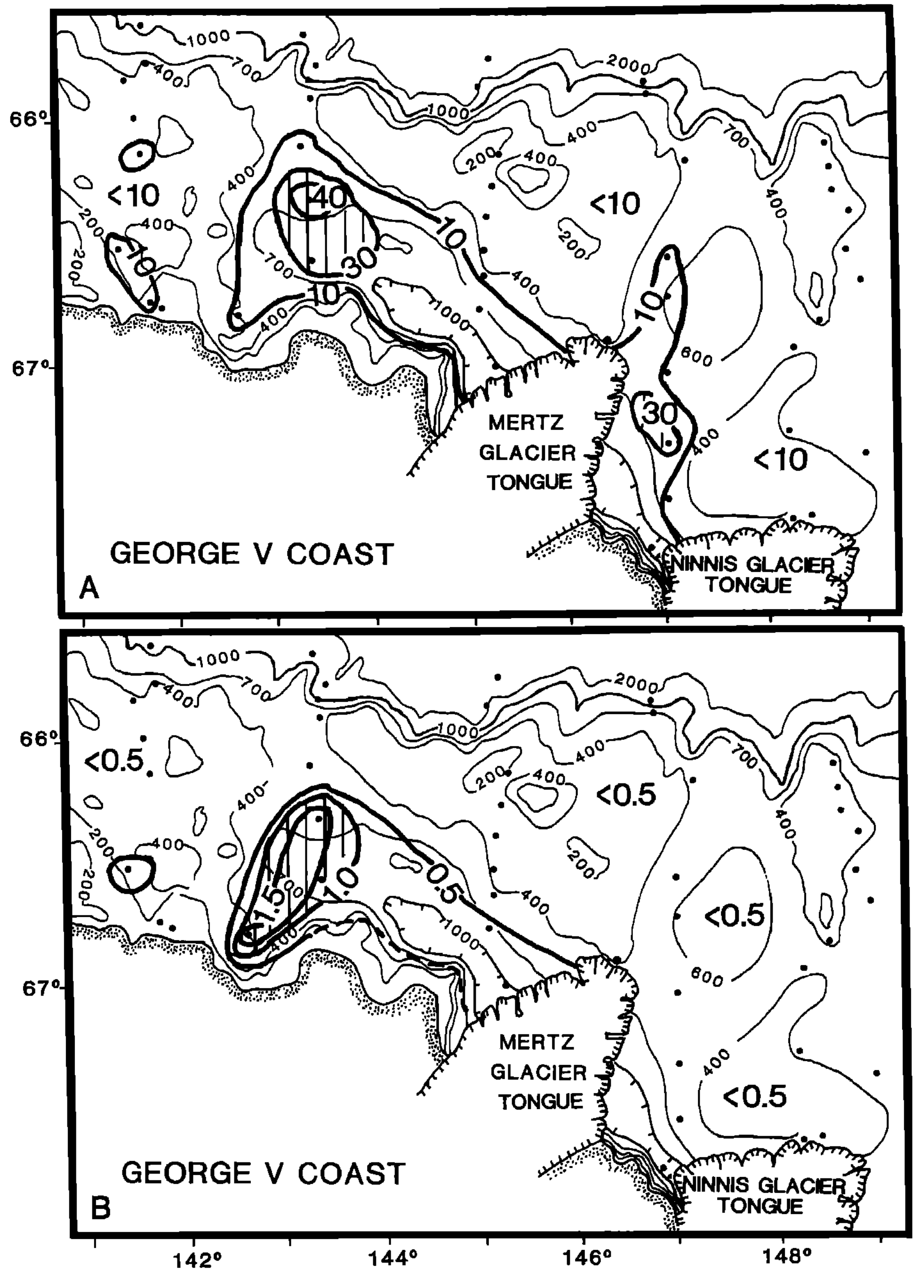

Fig. 16. Bold contours show weight percent concentrations of (a) biogenic silica and (b) organic carbon in surface sediments of the George V continental shelf. Light contours show bathymetry in meters. The concentrations of biogenic opal and organic carbon are high at the western end of George V trough and low on banks and ridges.

der them more susceptible to marine current influence.

Sediments containing up to 45% biogenic silica and up to 2% organic carbon are found in shelf basins. They frequently contain only minor amounts of ice-rafted debris and coarse terrigenous silt, due to rapid accumulation rates and/or limited input of terrigenous material via ice rafting and meltwater streams. These biogenic sediments are redistributed by marine currents, which tend to erode fine-grained sediments from shallow portions of the shelf and redeposit some portion of this material in shelf basins. These biogenic components are especially enriched in areas where reduced sea ice conditions prevail during summer months. Siliceous sediments of the Antarctic have anomalously low organic carbon/opal ratios compared to other continental shelf deposits. This may result from more rapid oxidation of organic carbon relative to dissolution of biogenic silica in the cold, oxygenated waters of the Antarctic, abetted by reworking of the shelf sediments.

In all of the areas studied, bottom currents are effectively reworking relict glacial and glacial-marine deposits on unobstructed regions of the outer and central shelf to depths of about 500 m, i.e., to about the depth of the continental shelf break. The degree of winnowing decreases in an onshore direction and with increasing depth. Grain size data suggest that sustained current speeds one meter off the bottom range from less than 8 to 25 cm/s. Maximum sustained velocities appear to be highest (20-25 cm/s) on the outer shelf and somewhat lower and more uniform on the central shelf. Seabed current velocities of only a few centimeters per second are inferred from the characteristics of material being deposited in shelf basins and troughs. These inferred velocities are in agreement with available current meter data in the Ross Sea.

Most sediments winnowed from Antarctic continental shelf deposits fall within the very fine sand to clay size range. Some experiments with flumes and observations of fluvial systems have indicated that cohesive beds comprised of material in this size range can only be winnowed and transported by currents with speeds in excess of 20 to 30 cm/s, measured or calculated 1 m above bottom [Hjulstrom, 1939; Sundborg, 1967]. We infer that lower threshold speeds (U_{100} < 20 cm/sec) will transport this size material on the Antarctic shelf, based, in part, upon the flume experiments of Singer and Anderson [1984]. Those experiments suggest that low velocity currents (< 8 cm/s) may be competent for erosion and transport of silts and clays, consistent with the work of Rees [1966]. Heezen and Hollister [1971] suggested that many previously determined relationships between erosion velocity and grain-size were not valid for abyssal sediments consisting of grains finer than medium sand (350 μm, 1.5 ϕ), because of variability in the degree of sediment cohesion. On the Antarctic shelf, sediment cohesion is reduced by bioturbation, and fine-grained sediment may thus be winnowed by relatively low-velocity currents.

In all three study areas, we infer onshore and east to west transport of surface sediments from compositional and textural variations. Sediment transport across the shelf break and down the continental slope also occurs, as evidenced by light-scattering observations and by shelf water on the slope and rise [Jacobs et al., 1970; Eittreim et al., 1972; Foldvik et al., this volume]. Estimates of current velocity based on grain-size analysis are reasonably consistent with the limited current meter data available in the Ross Sea. A more precise calibration of grain size data to bottom water current velocity must await detailed benthic boundary layer studies on the Antarctic continental shelf.

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