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Distribution and Dispersal Pattern of Suspended Particulate Matter in Maxwell Bay and Its Tributary, Marian Cove, in the South Shetland Islands, Antarctica

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Abstract: SPM (suspended particulate matter) and CTD (CTDT) casting data obtained from Maxwell Bay and its tributary, Marian Cove, in the South Shetland Islands, Antarctica have been compiled to describe SPM distribution in detail and to elucidate the dispersal pattern of the fine-grained sediments in the areas. Of the primary pathways for the dispersal of sediment in ice-influenced fjords, only ice-contact processes are unique to fjord. The effect of glaciofluvial discharges have been overwhelmed by the influences of subglacial discharge and ice-front melting. Fluvial discharges from side-entry glaciers that commonly end on land is, however, more responsible for the overflow plumes in Maxwell Bay and Marian Cove. Submarine discharge, which is almost always in the form of vertically rising buoyant jets, is considered rare, and no direct evidence exists to support their importance or even existence.

Active glaciofluvial input from Marian Cove causes most suspended particulate matter to be concentrated near the mid-point of Maxwell Bay. Thus, even though closer to fjordhead trunk glaciers, SPM concentration in Collins Bay is comparatively low, largely due to clean tidewater glaciers and absence of meltwater streams around the Collins Bay.

Strong bottom current flowing along the continental shelf off the South Shetland Islands may import and export sediment from the out side of Maxwell Bay, influencing the distribution of bottom sediment as well as benthic community, although no direct evidence of currents exists in the area.

Key words: suspended particulate matter, glaciofluvial discharge, overflow plume, Maxwell Bay, Marian Cove

INTRODUCTION

Maxwell Bay is one of the deep (up to 500 m), glacially-eroded fjords along the southern margin of the South Shetland Islands, West Antarctica (Fig. 1). The bay is arbitrarily bounded by the King George and Nelson Islands, and is rimmed by the ice cliffs descending from the highly flattened ice cap of Fildes Peninsula and Nelson Island on the northeast and southeast, respectively. Tidewater and/or valley glaciers are essentially confined to embayments and the surfaces of these glaciers are covered by eolian debris (Fig. 1). The bay comprises a central basin and several tributaries, Marian Cove, Potter Cove to the northeast and Collins Bay to the north. Marian Cove is bounded by the Weaver Peninsula to the northwest and the Barton Peninsula to the southeast, and is bathymetrically separated from Maxwell Bay by a shallow (less than 20 m) submarine sill at the mouth (Yoon *et al*, 1995). Small valley glaciers, draining southwest from the cove heads, debouch large amount of icebergs and turbid meltwater into the cove during the summer months. Meltwater streams are common on the coast, forming small outwash fan (Fig.2).

The objective of this study is to reasses SPM

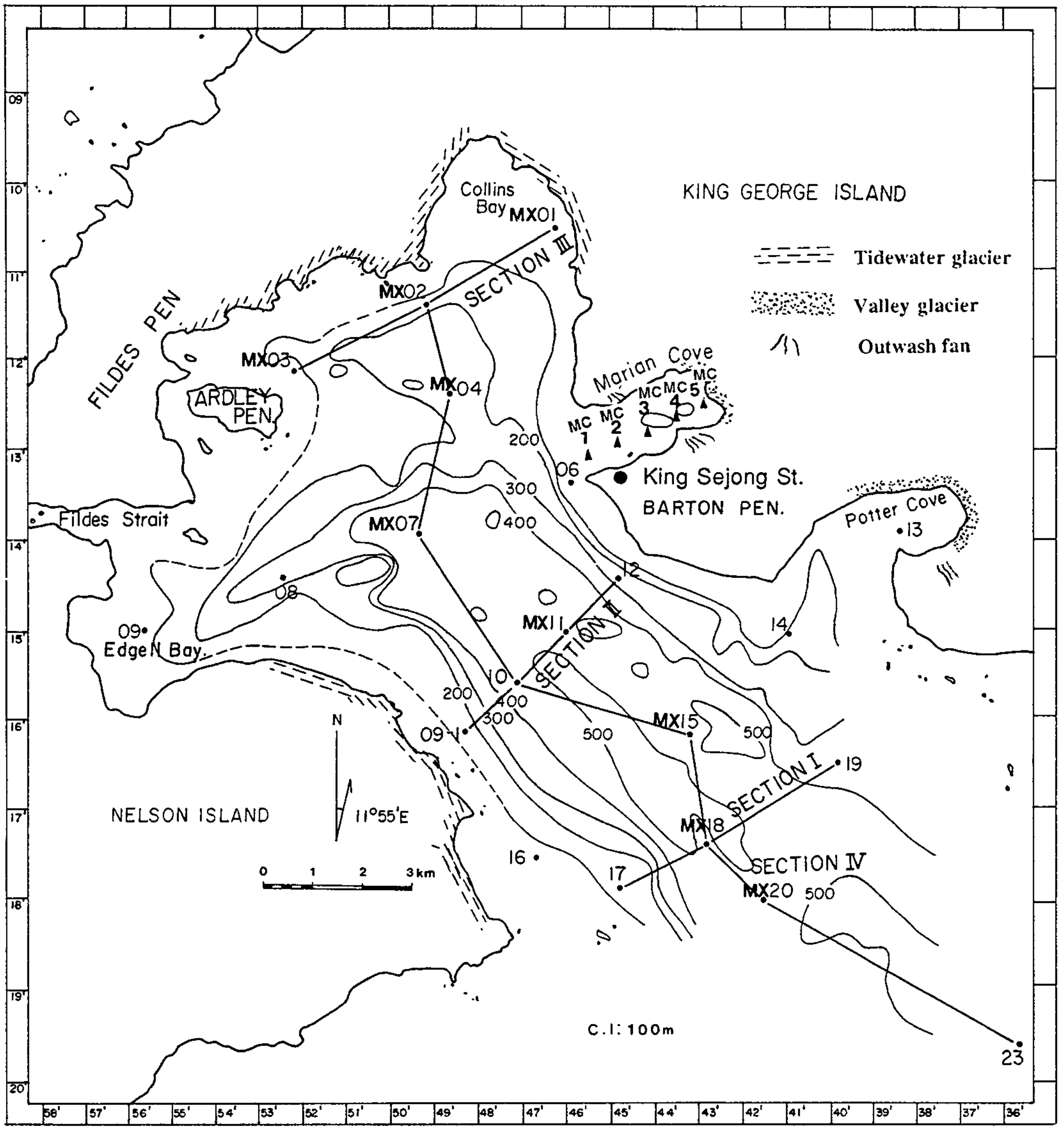

Fig. 1. Positions of CTD castings (dark circle) occupied during January 27-28, 1989 in Maxwell Bay and CTDT castings (dark triangle) occupied during January 16, 1994 in Marian Cove. Contours in meters.

(suspended particulate matter) distribution in detail and to elucidate the dispersal pattern of the fine-grained sediments in Maxwell Bay and its tributary, Marian Cove. For this purpose, pertinent CTDT data were obtained in 5 stations in Marian Cove on February, 1993, and SPM data from the surface water of Marian Cove were obtained in twenty stations on December, 1992 (Fig. 1). In addition, previous data of SPM and CTD collected from Maxwell Bay and its vicinity during January 27-28, 1989 were compiled into a distribution map.

SPM MEASUREMENTS AND CTD (CTDT) CASTING

The observations presented here are based on the CTD and SPM (suspended particulate matter) data obtained from seven stations in Maxwell Bay on

Fig. 2. Turbid meltwater streams developed along the land glacier around Marian Cove. They somtimes form numerous outwash fans or small deltas on the coastal areas.

February 1989, SPM data from twenty stations in Marian Cove on December, 1992 and CTDT data from five stations in Marian Cove on February 1993 (Fig.1).

Seventy water samples were collected at depths of 0,10, 20, 30, 40, 50,100,150, 200, 300 and 400 m from 7 stations in Maxwell Bay (Fig. 1). A known volume (between 1.0 and 1.5 l) of the samples was vacuum-filtered through pre-weighed nuclepore filters having a nominal pore size of 0.4 μm. Filters were air dried and reweighed in the laboratory on board. Total suspended sediment concentration was then calculated using the sample volume and sediment weight.

CTD (conductivity/temperature/depth) profiles were obtained with an EG & G Smart CTD at Stations 1 (near the bay head), 18 (bay mouth) and 23 (off the bay mouth) in Maxwell Bay (Fig. 1) and we used the CTD data that were obtained during downcasting at a lowering rate of 1 m/sec. The data were despiked from the continuously increasing depth to remove extreme values, and then averaged over 1m intervals to obtain temperatures and salinity. The data are considered to be corrected ± 0.01°C in temperature and +0.01‰ in salinity.

CTDT (conductivity/temperature/depth/transmissometer) profiles were obtained with a SEABIRD model SBE-25 profiler and model 11 deck unit that had a sampling rate of 24 Hz. Four channels recorded simultaneous values of conductivity, temperature, pressure (depth), and light transmission. The conductivity cell was flushed by a pumping system so that no artificial spikes were generated. Salinity was derived from temperature and conductivity data and after using calibration measurements made both before and after the cruise. Salinity results are accurate to within ± 0.02. Light transmission was determined from a SEATECH transmissometer with a monochromatic red-light source (660 nm wavelength) and a 10 cm beam path length. The salinity, temperature, depth, and transmissivity data were averaged over a 1.0 m depth interval representing between 25 and 30 measurements of each value.

For the surface distribution of SPM, water samples were collected in a 5 l plastic bottle at twenty stations in Marian Cove. Four liter water samples were filtered through preweighed millipore filter papers with aperture of 0.45 μm.

ENVIRONMENTAL SETTING

Maxwell Bay, typically U-shaped fjord, is approximately 14 km long and 6 km to 14 km wide, separated from the Bransfield Strait. Water depth increases gently from the coastline to 200 m depth, but it shows steep slope from 200 m to 400 m depth (Fig. 1). While the shallow areas (<200 m) show irregular topography, the central basin of the bay is relatively flat with depth ranging from 400 m to 550 m. The maximum depth in the central basin is 520 m. Between King George and Nelson Islands lies Fildes Strait forming a unique channel which connects the bay with Southern Drake Passage.

The strait is very narrow, 400 m to 800 m wide, and there have been no sounding data available because of inaccessibility to the strait due to glaciers and big icebergs. Active iceberg calving from a glacier snout is found in Collins Bay and Marian Cove during the cruises.

The climate of Maxwell Bay areas has a considerable effect on environmental conditions. Monthly mean air temperature varies from −8.4°C (August) to 2.4°C (February), and annual mean air temperature is −2.2°C. The surface layer of Maxwell Bay freezes up in winter, from late July to mid-September. Maximum ice thickness reaches 60 cm in Marian Cove in late August. Once free from ice cover, Maxwell Bay is soon invaded by drifting ice. During the open water season ice floes have been always observed (KORDI, 1989). Annual total pre-

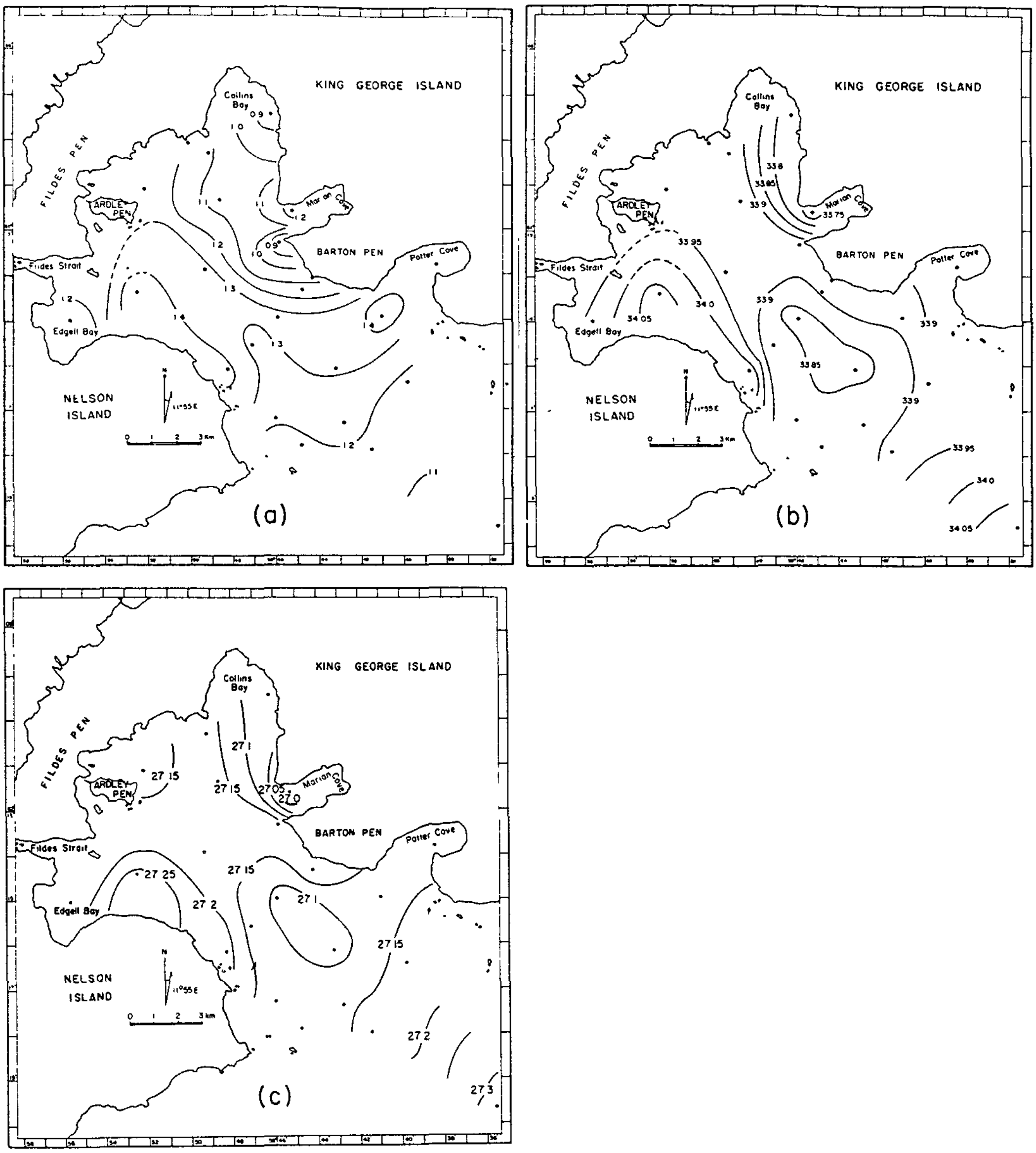

Fig. 3. Horizontal distributions of (a) temperature, (b) salinity and (c) density at 1 m water depth from hydrographic stations (represented by dots) occupied during January 27-28, 1989.

cipitation is approximately 17 cm and precipitation during summer (from December to February) counts for 73% of the total annual precipitation. Annual total snow fall is approximately 460 cm, and monthly total snow fall shows its maximum value of 230 cm in June.

WATER COLUMN STRUCTURE

Horizontal distributions of water properties show that surface salinity and density are generally higher in the western part of Maxwell Bay than in the east, and surface temperature is lower in the eastern part than in the west (Fig. 3). In particular, the lowest surface salinity was observed in Collins Bay

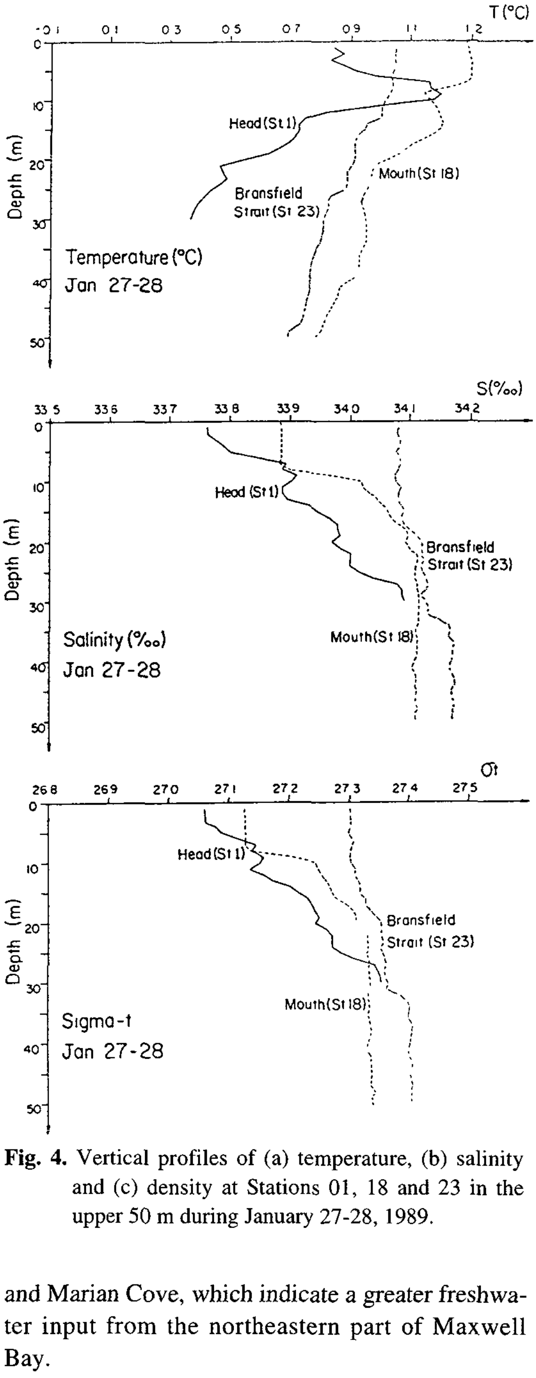

Fig. 4. Vertical profiles of (a) temperature, (b) salinity and (c) density at Stations 01, 18 and 23 in the upper 50 m during January 27-28, 1989.

and Marian Cove, which indicate a greater freshwater input from the northeastern part of Maxwell Bay.

Vertical profiles of temperature, salinity and sigma-t measured at three stations (the head, the mouth and outside the fjord) of Maxwell Bay are shown in Figure 4. Halocline generally occurs within the upper 50 m of water depth. The halocline is an important feature of the water structure in terms of transport and deposition of sediments, and its depth is dependent on freshwater discharge and morphology of the fjord. At the head the surface mixed layer is very thin with sharp salinity gradient, forming a stronger halocline between 1 and 3 m water depths. This shallow halocline is not so conspicuous compared with other high-runoff fjord (Pickard and Stanton, 1980), and probably results from a small amount of freshwater input from nearby tidewater glaciers. As the mixing and entrainment increase seaward the layer becomes thick with higher salinity and reduced gradient at the mouth. Density profiles are similar to salinity profiles, indicating that density is controlled mainly by salinity than by temperature. Vertical stability becomes stronger at the head due to the decrease of surface salinity caused by more meltwater input while the stability becomes more homogeneous at the mouth and outside fjord.

At the head of the fjord, where meltwater input and active iceberg calving occur, surface salinity is lowest (33.8‰) (Fig. 4), which is much higher than that (1 6.4%o) of near the runoff glacier of Admiralty Bay (Szafranski and Lipski, 1982), indicating a small amount of freshwater input into Collins Bay. Vertical profile of water temperatures shows their maximum near 10 m water depth (Fig. 4), indicating a temperature inversion from surface to 5 m subsurface. Convective cooling by the atmosphere cannot account for the low temperature of surface water, because surface waters at other station are warmer than the underlying water. Considering the low surface salinity, the temperature inversion results from the influx of meltwater derived from nearby tidewater glaciers surrounding Collins Bay.

DISTRIBUTION OF SUSPENDED PARTICULATE MATTER (SPM)

Maxwell Bay

The concentrations of SPM in the waters of Maxwell Bay generally range between 0.1 and 1.0 mg/l (Fig.5), which corresponds approximately to those in Bransfield Strait where the concentration is usually less than 1 mg/l in the surface water (Leventer and Dunbar, 1985). Maximum concentration, greater than 1.6 mg/l, occurred near the mouth of Marian Cove (St. MX 11 in fig.1) where

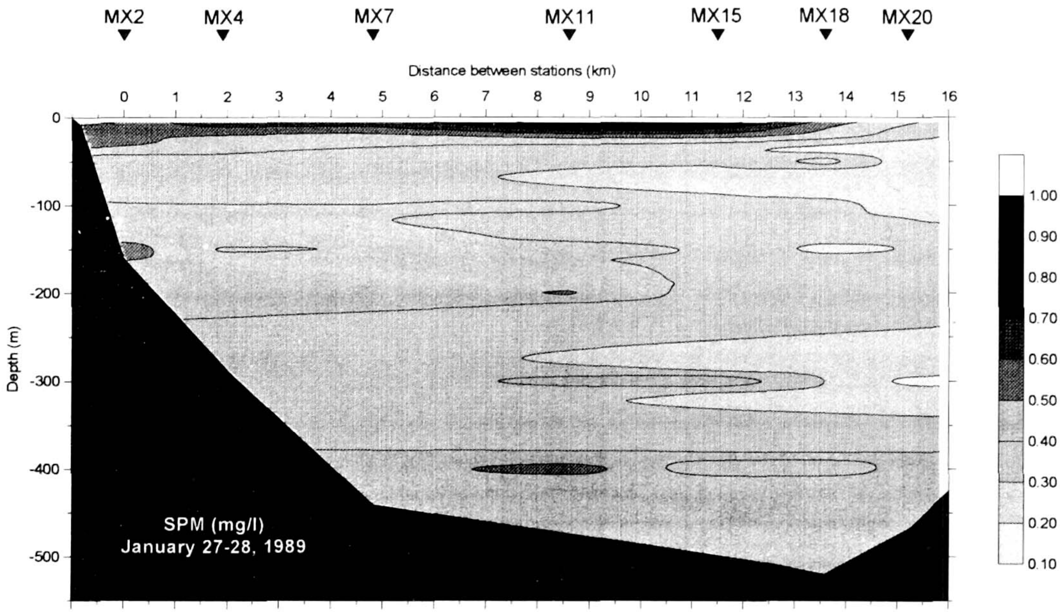

Fig. 5. Vertical distribution of suspended particulate matter (SPM) in Maxwell Bay. Refer the stations to Figure 1.

glaciers commonly end on land, developing numerous meltwater streams, whereas the lowest quantity of less than 0.4 mg/l was recorded in fjord-head (Collins Bay) surrounded by tidewater glaciers. Hence, horizontal distribution of SPM in Maxwell Bay reveals that there is no systematic down-fjord decrease in concentration (Fig. 5), as might be expected where the dominant source of greater sediment discharge is present.

Figure 6 shows vertical profiles of SPM in Maxwell Bay. The concentrations are generally highest (more than 0.5 mg/l) at the surface water and gradually decrease with depth, in good accord with low salinity at the surface water and gradual increase with depth. However, vertical profile of suspended sediment concentration near Collins Bay (St. MX2) represents a concentration maximum at a water depth of 25 m, indicating an interflow that extended at least 3 km from nearby tidewater glaciers (Fig. 6). The concentrations in the interflow ranges from 0.5 to 0.6 mg/l but these values are not likely higher than those of overflow measured at outside of Collins Bay. Locally, in the region (St. MX20) where waters of Maxwell Bay and Bransfield Strait mixed, vertical profile of SPM have slightly high values in surface and bottom waters, and lower value in the intermediate depths (Fig.6).

SPM concentrations of the surface water in Marian Cove range from 4.0 mg/l to 28 mg/l, which is much higher than those of Maxwell Bay proper water (Fig. 7). Highest concentration, greater than 28 mg/l, occurs on the northern side of Marian Cove (Fig. 7), where valley glaciers are heavily crevassed and commonly end on land, whereas the lowest quantity of less than 4.0 mg/l was recorded in the cove-head surrounded by tidewater glaciers. The maximum SPM concentration in the cove gradually decreases southeastward to a value as low as 12 mg/l on the coast off the Korean Antarctic Station, indicative of advection of turbid plumes southeastward along the southern coast of the Barton Peninsula (Fig.7).

Figure 8 shows the vertical profiles of temperature, salinity and beam attenuation coefficient (BAT) at Stations MC5 (near the cove head), MC3 (mid-point of the cove) and MC1 (near the mouth). BAT commonly shows a highest value at the surface water and rapid decreases with depth, indicating a development of overflow plume in Marian Cove. Surface mixed layer is characterized by low temperature and salinity, and high BAT value. The mixed layer is thin (less than 3 m) with well-stratification at the cove head (MC4 and MC5) and ver-

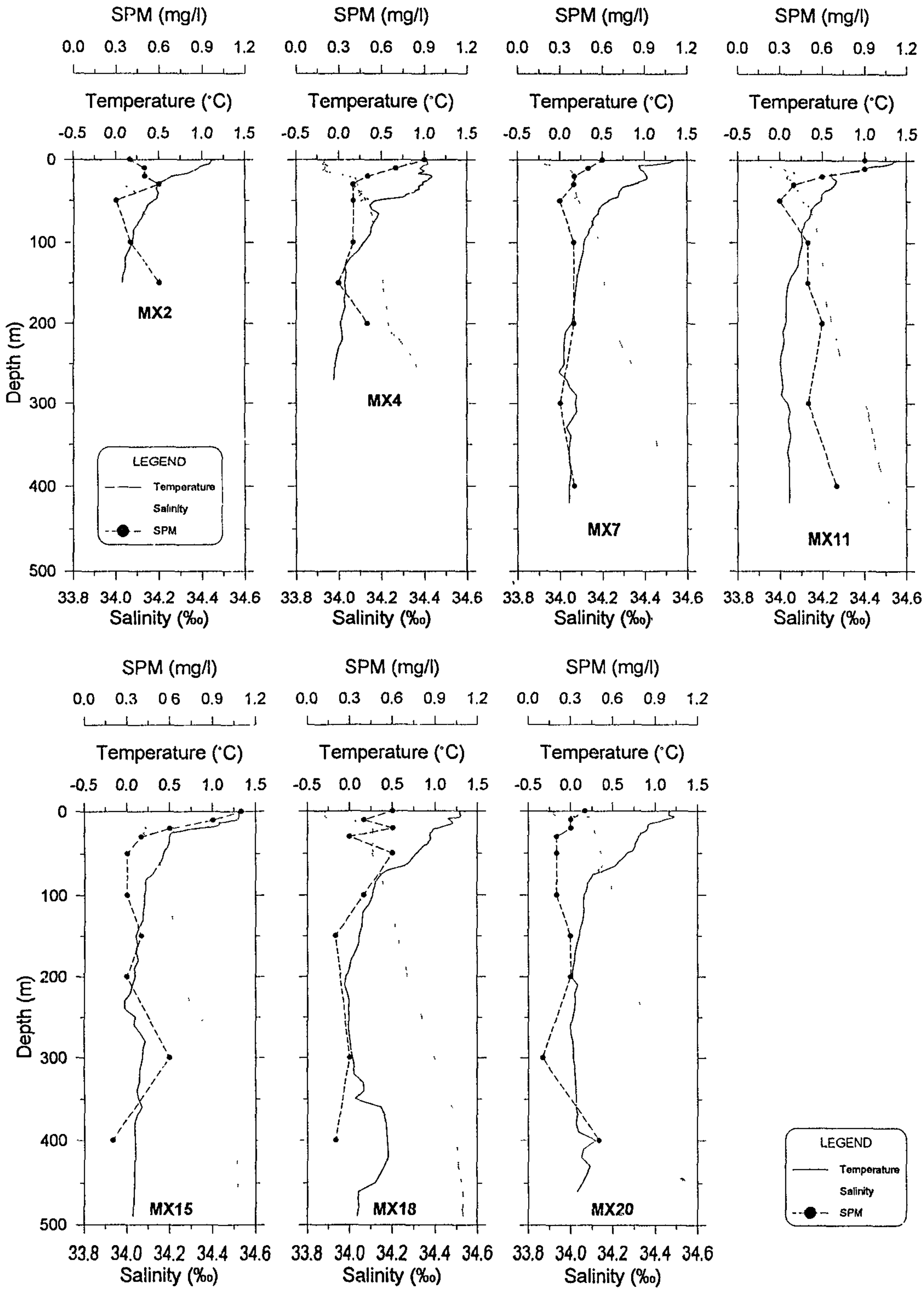

Fig. 6. Vertical profiles of SPM (mg/l) in Maxwell Bay during January 27-28, 1989.

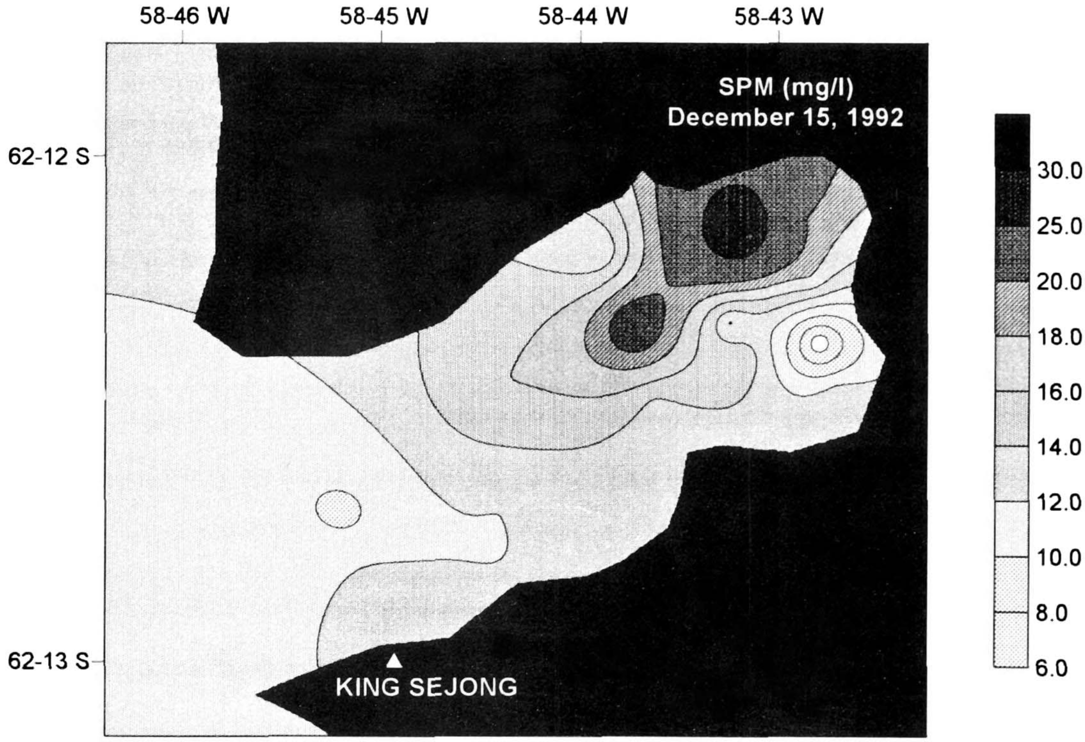

Fig. 7. Horizontal distribution of SPM (mg/l) in Marian Cove on December 15, 1992.

tical water stability is strong. On the other hand, toward the mouth the mixed layer becomes thicker (up to 10 m) with surface salinity decreasing at the mouth of the cove (MC1) and vertical stability becomes weaker.

DISPERSAL PATTERN OF SUSPENDED PARTICULATE MATTER

From the results presented above it is clear that the circulation pattern within Maxwell Bay is dominated by week estuarine-type surface outflows, characterized by surface plumes of warm and turbid water.

Vertical profile (Fig. 8) of beam attenuation coefficient in Marian Cove reveals maximum value at the surface and gradual decrease with depth. This maximum value at the surface water typically reflects a development of overflow which can be developed in temperate and subpolar regions during the melt season. The overflow is characterized by low salinity and low temperature (Fig. 8), indicating a greater meltwater input from the adjacent sources. Based on the study on ice-contact processes in sub-polar setting (Syvitski, 1989), submarine discharge can create turbid meltwater plumes in the form of vertically rising buoyant jets. However, it seems unlikely that the submarine discharge plays an important role in dispersal of suspended sediments in Marian Cove. Rather, fluvial and supraglacial discharges through the meltwater streams and/or water falls appears to be more important for carrying suspended sediments. Unlike those of Collins Bay, the glaciers of Marian Cove are not directly in contact with marine waters except for the trunk fjord-head glaciers where calving processes are active during the melt season. The glaciers end mostly on land, resulting in the broad beach with a lot of meltwater streams through which snow melt waters enter into the cove. Based on the visual observation on the ship, well-defined turbulent plumes occur along the surrounding nearshore area, indicating that large volumes of fine particles are discharged directly into the cove during the melt season, developing overflow over the stratified surface waters.

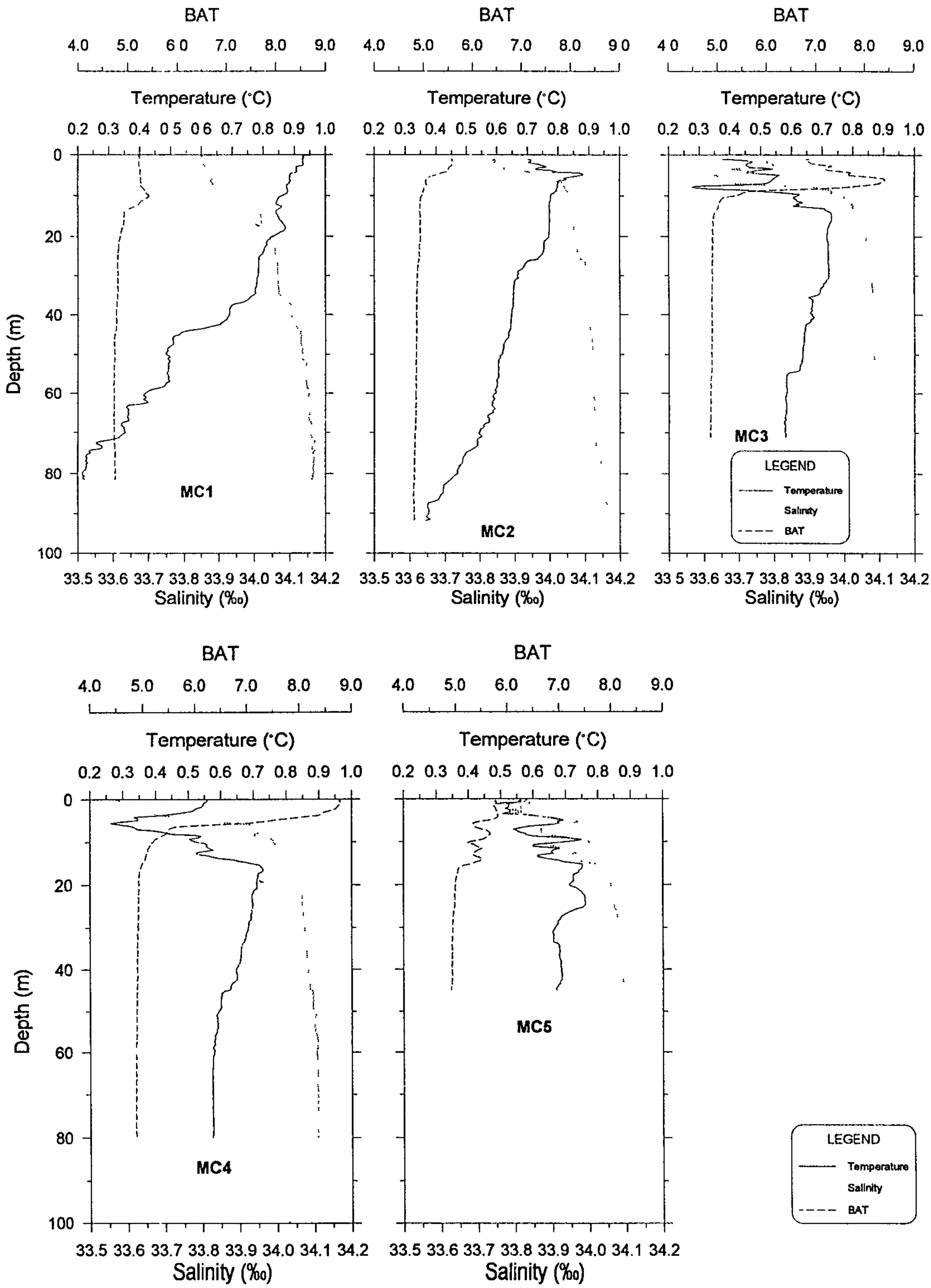

Fig. 8. Vertical profiles of temperature, salinity, and beam attenuation coefficient (BAT) in Marian Cove on January 16, 1994.

Strong wind and resulting surface water could resuspend sediment at nearshore area and cause the highly turbid layer at the surface water. During the period of investigation, the maximum wind speed was 39 m/sec with an average speed of 9.0 m/sec. Predominant wind direction was northerly which can generate surface waves propagating shoreward. Although storm-wave events are not important on Maxwell Bay, the prevailing northerly wind and resulting surface waves are persistent during the survey and represent a significant amount of energy when integrated over the period of investigation (Chang *et al.*, 1990).

Higher concentrations of suspended sediments occur in Marian Cove, embracing the northeastern tip of the Barton Peninsula. These turbid plumes appear to be associated with the bulk of fluvial input or transportation derived from Marian Cove. This interpretation is supported by the fact that the highest concentrations of SPM in Maxwell Bay occur near the mouth (MX11) of the Marian Cove, rather than near the trunk glacier (MX2) of Maxwell Bay (Fig. 6). Preliminary hydrographic surveys (Fig. 3) additionally reveal that a low-salinity cold surface water plume extends from the mouth of Marian Cove and is subsequently deflected to the southeast. These facts all suggest that Marian Cove would be a most probable source to the bulk of suspended particulate matter in Maxwell Bay.

In Collins Bay (MX2 in Fig. 6), comparatively low quantity of SPM, even though closer to fjord-head trunk glaciers, results probably from small supply of terrigenous detritus because the glaciers surrounding Collins Bay are very clean, showing only faint debris bands along the ice cliffs, and because meltwater streams are not common so that turbid outflows may be not developed; the bottom sediments have been reported to be much thinner in Collins Bay herein compared to Marian Cove (Hong *et al.*, 1991).

Off the mouth of Maxwell Bay (MX20 in Fig. 6), the development of turbid layer near the sea floor is probably related to resuspension by strong bottom current activity which occurs along the northwestern continental shelf of Bransfield Strait. Grain-size analyses for the surface sediments off the mouth of Maxwell Bay reveal that well-sorted sandy sediments predominate, indicating bottom shear stress keeping particles in suspension (Anderson and Smith, 1989; Yoon *et al.*, 1990). Benthic community study of Polychaetes for the surface sediments between Maxwell Bay and Bransfield Strait supports this aerial distinction in bottom shear stress, showing that soft bottom species, typically *Maldane sarsi antarctica*, are restricted to inshore muddy sediments, whereas hard bottom species, represented by *Pista spinifera* and *Neoamphitrite affinis* antarctica, predominate offshore (Ahn and Kang, 1991).

Vertical profile of SPM in Collins Bay (MX2) represents an development of shallow interflow at a water depth of 25 m (Fig. 6). The interflow is characterized by relatively low salinity, indicating a meltwater plume derived from nearby glacier (Fig. 6). Interflow processes may be inferred under conditions of reduced salinity which occurs near glacially-influenced fjord. The tidewater glaciers in Collins Bay debouch large amounts of fresh water into the bay (Fig. 3), so that well-developed estuarine circulation has shallow-surface layer of reduced salinity flow outward over deeper, normal salinity waters. This process would result in the greatest dilution of nearshore waters above the pycnocline. Thus, lower concentrations of suspended sediment would be required to form interflow.

Another possible process for the interflow may be a combination of tidal action and subice melting; ambient seawater and suspended particulate matter are entrained by tidal rectification beneath the ice, and results in basal melting with consequent low density turbid meltwater. Movement of the water up from the base of the glacier would be driven by the buoyancy of the meltwater until density equilibrium is reached between the meltwater and ambient seawater. Interflow plume would be finally generated as lower density in ambient water is encountered by the rising meltwater. Vertical profile (MX2 in Fig. 6) which shows, below concentration maximum, gradual increase in SPM concentration with depth reflects upward diffusion of turbid meltwater from beneath the glacier. During the survey of Maxwell Bay, Griffith and Anderson (1989) have observed a calving event in which debris-laden ice bobbed to the surface in bays and suggested that these materials may be flushed from beneath the glacier by diluted turbid meltwater.

CONCLUSIONS

Surface waters of Maxwell Bay and Marian Cove are characterized by low salinity, temperature and high turbidity, indicating a development of overflow plume that resulted from the increase of terrigenous input during the melt season. No direct evidence exists to support the subglacial discharge which is almost always in the form of vertically rising buoyant jets, suggesting that ice-contact processes, such as subglacial discharge, are considered rare. Rather, glaciofluvial discharges from the side-entry glaciers which commonly end on land, can be more effective for the overflow plumes compared to fjord-head trunk glacier. Strong wind and resulting waves could cause the highly turbid layer at the surface water because of the prevailing northerly wind which represent a significant amount of energy when intergrated over the period of investigation.

Higher SPM concentrations, embracing the northeastern tip of the Barton Peninsula appear to be associated with the bulk of fluvial input or transportation derived from Marian Cove, suggesting that Marian Cove would be a most probable source to the bulk of suspended particulate matter in Maxwell Bay. Low SPM concentration in Collins Bay, even though closer to fjord-head glaciers, results probably from negligible terrigenous input due to clean glaciers surrounding the fjord-head, and partly due to the poor development of meltwater streams in the fjord-head.

Strong bottom current which occurs along the continental shelf off the South Shetland Islands seems to play an important role in developing of turbid bottom layer off the mouth of Maxwell Bay. This interpretation is supported by the predominance of well-sorted sandy sediment and the presence of hard bottom species, *Pista spinfera* and *Neoamphitrite affinis antarctica* off the mouth of Maxwell Bay, indicative of bottom shear stress keeping particles in suspension.

In Collins Bay, comparatively less-saline, -turbid interflow may result from the input of large amounts of freshwater, so that the dilution of nearshore waters above the pycnocline would be greatest, allowing for the development of less-turbid interflow in the bay.

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