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Winter Circulation And Hydrography Over the Continental Shelf of the Northwest Gulf of Alaska

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CONTENTS

WINTER CIRCULATION AND HYDROGRAPHY OVER THE CONTINENTAL SHELF OF THE NORTHWEST GULF OF ALASKA[1]

J. D. Schumacher, R. Sillcox,[2] D. Dreves,[3] and R. D. Muench
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ABSTRACT. During winter 1977 temperatures and salinity were measured in the shelf region east of Kodiak Island and in the Shelikof Strait. Two subsurface cores of warm, saline water were observed; one was coincident with the shelf break and one extended northwestward from the break into the Amatuli Trough. The temperatures characteristic of these cores indicated that they were nonlocal, advective features perhaps originating in the Alaska Current and that they reflected a bifurcation of this flow upstream. Current records for Shelikof Strait showed a strong southwesterly flow with no reversals, which suggested a barotropic component driven by an axial pressure difference and resulting in hydraulic flow. The forcing by the Alaska Current was augmented at times by a weak westward baroclinic flow resulting from local freshwater input.

1. INTRODUCTION

Since August 1974 the Pacific Marine Environmental Laboratory (PMEL) has participated in field operations supporting NOAA's Outer Continental Shelf Environmental Assessment Program (OCSEAP) in the Gulf of Alaska. One facet of this program was an exploratory field experiment in the Kodiak Island-Shelikof Strait region (Fig. 1) that included current-meter moorings and conductivity and temperature versus depth (CTD) measurements. In this report we present CTD data collected during two cruises in March 1977. Current records for the period October 1976 to March 1977 are presented and discussed. In addition, satellite imagery is used to help define surface temperature features.

1.1 Previous Studies

Mean circulation in the Gulf of Alaska is dominated by the Alaskan Gyre (Dodimead et al., 1963; Roden, 1969; Ingraham et al., 1976). The northern leg of this gyre is the Alaska Current, which flows westward generally paralleling the coastline. Royer (1975) discussed seasonal changes of hydrographic properties across the Alaskan continental shelf and related these changes to wind forcing. In winter, the Aleutian low pressure system causes storms with southeasterly winds (Danielson et al., 1957). Some evidence indicates that this atmospheric regime is accompanied by a seasonal change in transport of the Alaska Current and the speed of associated flow along the continental shelf (Favorite, 1974; Hayes and Schumacher, 1976). Higher transports and speeds may occur during winter. The flow appears to intensify off Kodiak Island (Favorite, 1967) and a warm surface feature seems to be present along the shelf break (Royer and Muench, 1977). A comprehensive study of hydrographic structure and inferred baroclinic flow on the shelf off Kodiak Island was given by Favorite and Ingraham (1977). Wright (1970) presented a reconnaissance of waters in Shelikof Strait and the shelf region off Kodiak Island.

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[1] Contribution No. 368 from the NOAA/ERL Pacific Marine Environmental Laboratory.
[2] Assigned to PMEL from NOS.
[3] Assigned to PMEL from NOAA Corps.

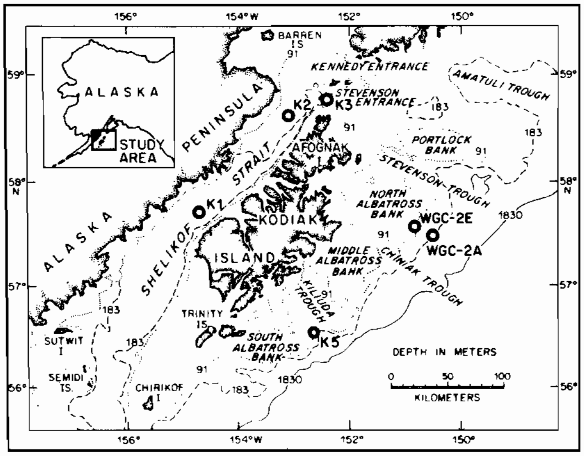

Figure 1. Locations of moored current meters K1, K2, K3, K5, WGC-2A, and WGC-2E.

1.2 Bathymetry

Bathymetry southeast of Kodiak Island is dominated by a series of four relatively shallow (~90 m) shoal areas (Fig. 1). Listed from north to south, these are Portlock Bank and North, Middle, and South Albatross banks. They are separated from one another by narrow channels that cleave the shelf in a direction roughly normal to the coastline.

Stevenson Trough extends from Stevenson Entrance southeasterly, separating Portlock and North Albatross banks. At its shallowest point, in the narrow passage west of Portlock Bank, the Trough is 110 m deep. Chiniak Trough, separating North and Middle Albatross banks, has an apparent sill depth of 145 m. Kiliuda Trough, southernmost of the three cuts, lies between Middle and South Albatross banks and has a sill depth of 150 m. Amatuli Trough, the most northerly feature in the study area, lies north of Portlock Bank and is a large, deep (~200 m) cleft gouging the shelf from east to west. The westward extension of Amatuli Trough bifurcates at the Barren Islands to form Kennedy Entrance north of the Islands and Stevenson Entrance between the Barren Islands and Afognak Island. Kennedy Entrance is the narrower entrance but reaches a depth of almost 200 m; the maximum depth in Stevenson Entrance is slightly more than 120 m.

Shelikof Strait is between Kodiak and Afognak Islands and the Alaska Peninsula. With Kennedy and Stevenson Entrances it connects lower Cook Inlet with the Gulf of Alaska. The northern half of Shelikof Strait, between Afognak Island and the Alaska Peninsula, is generally less than 180 m deep. The southern half is deeper than 200 m. The extension of the Strait southwest of Kodiak Island is bounded on both sides by banks. On the east, the bank extends past the Trinity Islands to Chirikof Island, with depths from 30 to 40 m. To the west, a 100-m shoal area extends southward from the Peninsula to encompass Sutwik Island and the Semidi Islands.

Table 1.
Current-Meter Mooring Summary and Record Statistics

Current-Meter Station	Position	Meter Depth (m)	Observation Period	Record Length (days)	Mean Speed (cm s^{-1})	Variance (cm s^{-2}) U	Variance (cm s^{-2}) V	Mean Flow Speed (cm s^{-1})	Mean Flow Direction (°T)
K1A	57 44.7N 154 43.7W	100	16 October 1976 to 26 March 1977	163	32.9	269.8	332.8	27.1	237
K2A	58 37.2N 153 05.0W	20	15 October 1976 to 27 March 1977	163	42.8	337.7	448.9	38.6	214
		100	16 October 1976 to 27 March 1977	163	30.2	247.2	288.7	26.2	223
K3A	58 45.5N 152 10.4W	20	15 October 1976 to 21 Nov. 1976	37	53.6	2088.5	750.7	30.1	298
K5A	56 33.2N	20	10 October 1976 to 24 March 1977	158	29.8	390.8	424.0	14.7	191
		80	10 October 1976 to 24 March 1977	158	19.1	61.8	235.2	13.3	184
WGC-2A	57 27.1N	20	9 September 1975	68	34.2	322.1	281.5	32.9	225
	150 29.5W	100	to 28 Nov. 1975	68	30.2	233.1	194.6	26.6	235
WGC-2E	57 33.8N 159 49.3W	20	2 October 1976 to 26 March 1977	156	41.2	897.11	016.2	2.5	239

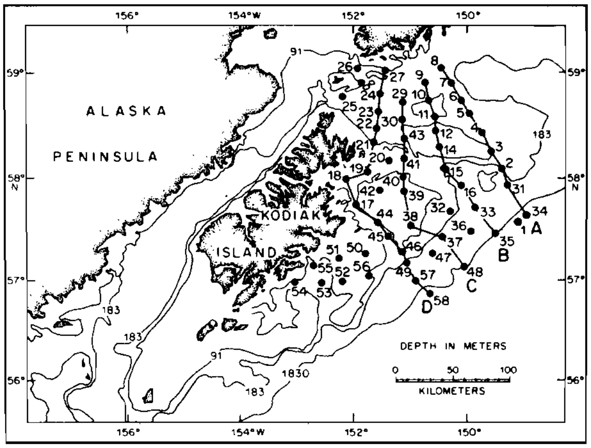

Figure 2. Locations of CTD stations occupied from 2 to 10 March 1977.

2. DATA ACQUISITION AND REDUCTION

Current-meter station locations are shown in Fig. 1. Aanderaa RCM-4 current meters were used in taut wire moorings with an anchor and acoustic release at the bottom and 1,000-lb subsurface buoyancy float above the top current meter. A summary of duration and depth of each station's current meters and current-record statistics is given in Table 1.

The current data were resolved into north and east components and low-pass filtered to remove high-frequency noise. Two new data series were then produced using a Lanczos filter (see Charnell and Krancus, 1976). The first series was filtered such that more than 99% of the amplitude was passed at periods greater than 5 h, 50% at 2.86 h, and less than 0.5% at 2 h. The second series, filtered to remove most of the tidal energy, passed more than 99% of the amplitude at periods of more than 55 h, 50% at 35 h, and less than 0.5% at 25 h. This was resampled at 6-h intervals and was used for examining nontidal circulation.

Temperature and salinity data were collected from the NOAA ship *Discoverer* using a Plessey model 9040 CTD system with model 8400 data logger. This system sampled twice per second for simultaneous values of conductivity, temperature, and depth. Data were recorded during the down cast using a lowering rate of 30 m min^{-1}. Nansen bottle samples were taken at each station to provide temperature and salinity calibration data. The data were averaged to provide 1-m temperature and salinity values from which the other parameters were then computed.

3. CTD OBSERVATIONS

3.1 Hydrography: Kodiak Island Shelf

We present the CTD data (see Fig. 2 for station locations) in a series of surface, bottom, and surface-bottom difference contours for temperature (Figs. 3-5), salinity (Figs. 6-8), and sigma-t (Figs. 9-11). Cross-shelf vertical sections of temperature and salinity are shown in Figs. 12-15.

Surface temperature contours indicate that a tongue of relatively warm (> 6 °C) water extended across Portlock Bank southwestward toward Stevenson Trough. A second band of warm (> 6 °C) surface water extended westward from Amatuli Trough into Kennedy Entrance, roughly paralleling and adjacent to the Kenai Peninsula coastline. Cold (< 5.0 °C) surface waters occurred over North and Middle Albatross Banks and seaward of the 100-fathom depth contour. Warmer waters generally occurred over trough features (e.g., Chiniak and Kiluida troughs) and colder waters occurred over banks. Bottom temperature contours also indicate that the coldest waters tended to lie on the banks and seaward of the 1000-fathom (1830-m) depth contour. The tongue of warm water over southern Portlock Bank was less extensive on the bottom than at the surface. The region of warm water off the Kenai Peninsula was more extensive on the bottom than at the surface and was generally warmer. In addition, these warm bottom waters were closer to shore and extended farther west-southwest than warm surface waters (station 24). The temperature-difference (surface-bottom) contours indicate that little or no thermal stratification was present over North and Middle Albatross banks (Fig. 5). The strongest negative temperature differences occurred in the region west of Amatuli Trough and seaward of the shelf break. Waters over Kiluida and Chiniak troughs and the depression running from Amatuli Trough into Kennedy Entrance showed the strongest negative temperature differences (thermal inversions).

Surface salinity contours indicate that a tongue of low-salinity (32.0 to 32.2 g/kg) water extended west-southwest roughly coincident with the shelf break. A second low-salinity (< 32.0 g/kg) region occurred in a near-coastal band along the Kenai Peninsula. Between these two regions of low salinity the salt content was greater (up to 32.2 g/kg); the highest salinities observed (> 32.6 g/kg) occurred seaward of the shelf-break salinity minima. Bottom-salinity contours show a tongue

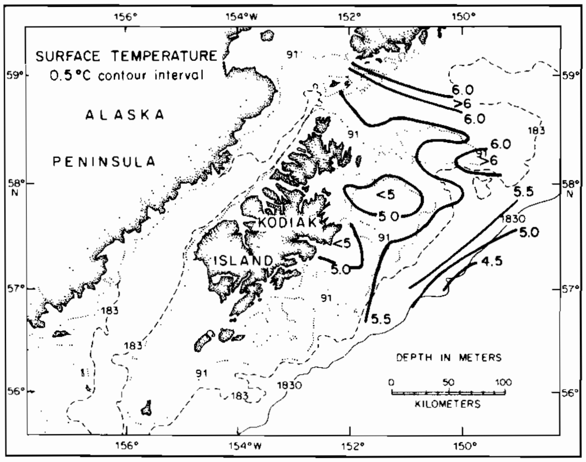

Figure 3. Surface temperature contours for 2 to 10 March 1977.

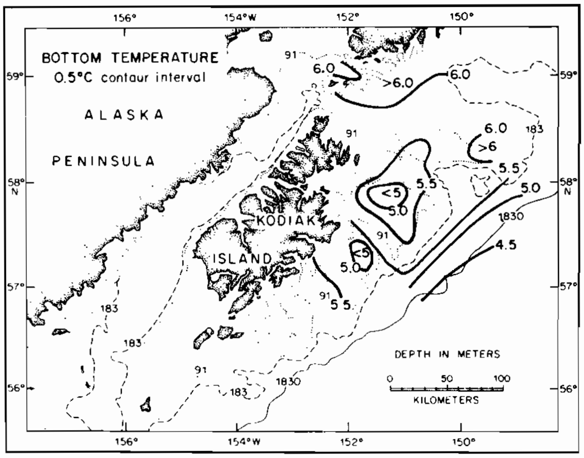

Figure 4. Bottom temperature (or 200-m) contours for 2 to 10 March 1977.

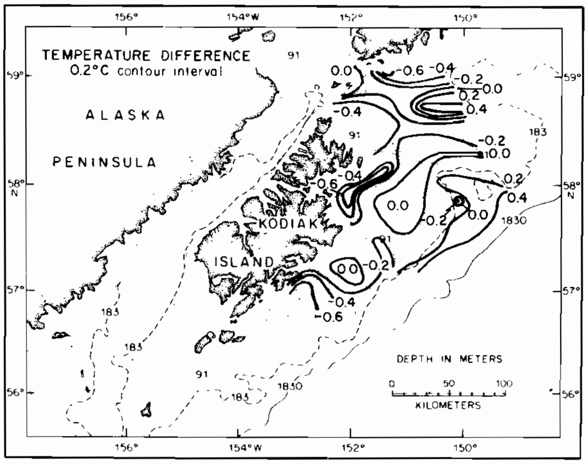

Figure 5. Surface-bottom temperature difference (ΔT) contours for 2 to 10 March 1977.

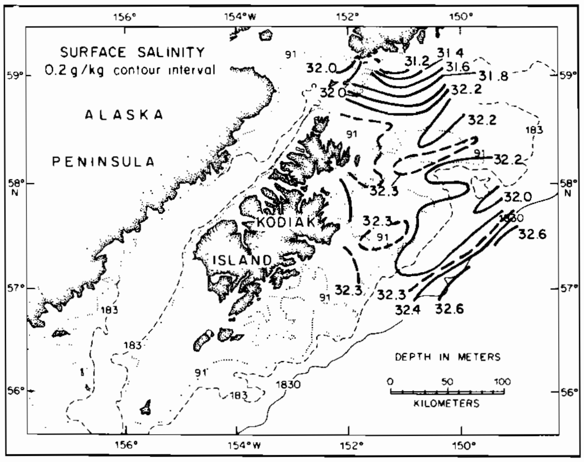

Figure 6. Surface salinity contours for 2 to 10 March 1977.

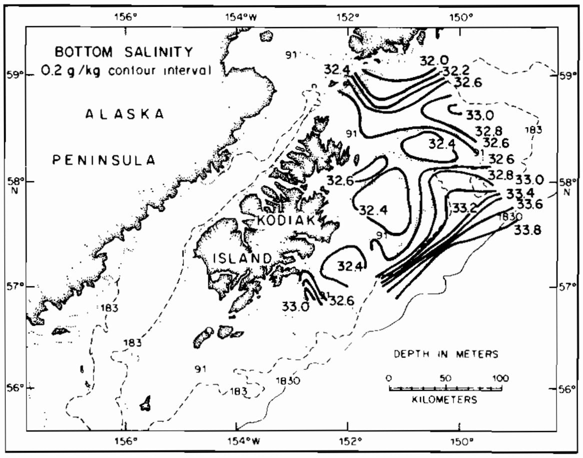

Figure 7. Bottom salinity (or 200-m) contours for 2 to 10 March 1977.

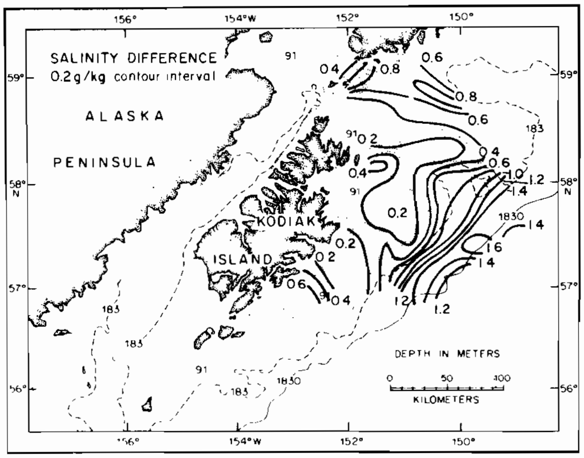

Figure 8. Bottom-surface salinity difference (ΔS) contours for 2 to 10 March 1977.

of high-salinity water (>32.8 g/kg) extending westward from Amatuli Trough. On other side of this tongue, salinity values decreased; hence the 32.6 g/kg contour represents a minimum-salinity band. The 32.6 g/kg to 33.0 g/kg contours indicate tongue-like features protruding into Stevenson, Chiniak, and Kiliuda troughs. Bottom-salinity values also exceeded 32.6 g/kg in the depression off Kodiak. Salinity-difference (bottom-surface) contours indicate nearly vertical homogeneity over the banks. A band of stratified water (ΔS =0.6 g/kg) was present along the Kenai Peninsula; seaward of the banks this band reflects the presence of bottom high-salinity tongues extending into the troughs. Over the shelf break, surface-salinity minima and increased bottom salinities resulted in crowding of the contours.

Surface sigma-t contours resembled salinity contours. The region extending westward across Portlock Bank was of relatively low density as indicated by the 25.5 sigma-t contour. As expected from the salinity distribution, a surface density minimum paralleled the shelf break, and denser bottom waters appeared in the trough and valley features. Sigma-t difference (bottom-surface) contours further substantiate the vertically homogeneous nature of waters over the banks and the contrasting presence of vertical stratification over troughs (Fig. 11). Greatest stratification in the upper 200 m of the water column was over the slope.

We present vertical sections (Figs. 12–15) of temperature and salinity to further clarify the extent of various features. At the "upstream" boundary of the region (Fig. 12), warm water (>6.0°C) was observed from the surface to a depth of approximately 125 m over the shelf edge, with maximum temperatures (>6.3°C) at depths of 60 to 70 m. The apparent bimodal temperature distribution over the shelf edge at stations 3 and 31 may be a result of sampling; stations 2 to 8 were occupied consecutively from 2 to 3 March, whereas 31 and 34 were occupied on 7 March. The apparent configuration therefore may represent a seaward meander of the warm core. However, a subsurface temperature maximum certainly did occur over the shelf edge. Coincident with the more seaward portion of the shelf-edge warm core (at station 31) was a shallow (<40 m) salinity minimum.

A second warm core at about 75 m extended 50 km seaward from station 8 (~25 km from the Kenai Peninsula). Maximum temperatures (>6.0°C) extended from the bottom to ~50 m. Seaward of this location, the warm core narrowed to a 10- to 15-m thick region at a depth of 70 m. Low salinity was observed only at station 8, and

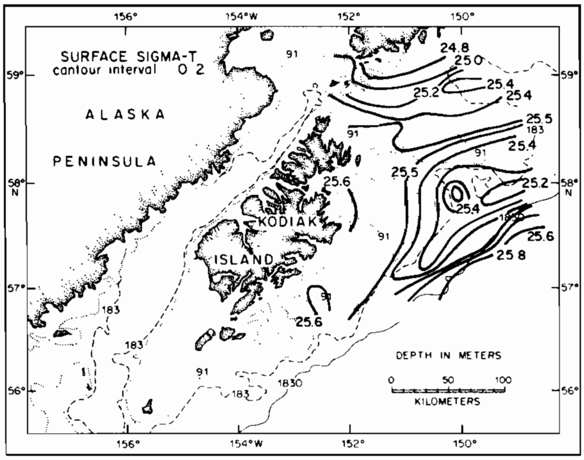

Figure 9. Surface sigma-t contours for 2 to 10 March 1977.

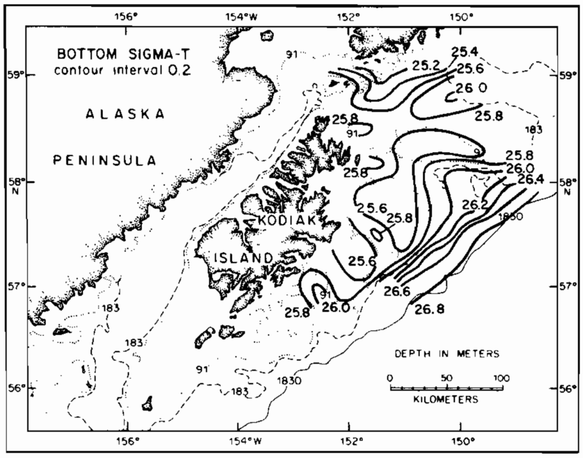

Figure 10. Bottom sigma-t (or 200-m) contours for 2 to 10 March 1977.

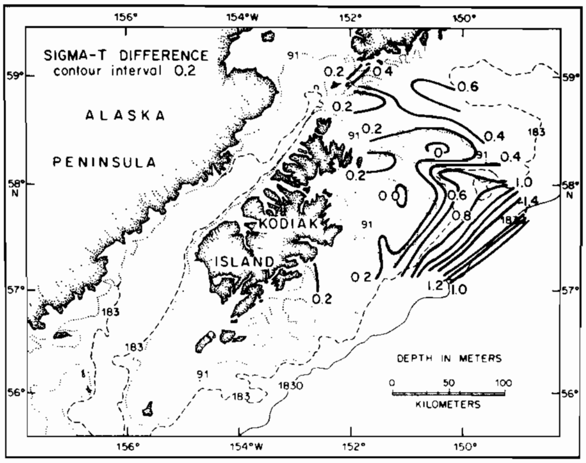

Figure 11. Bottom-surface sigma-t difference ($\Delta\sigma_t$) for 2 to 10 March 1977.

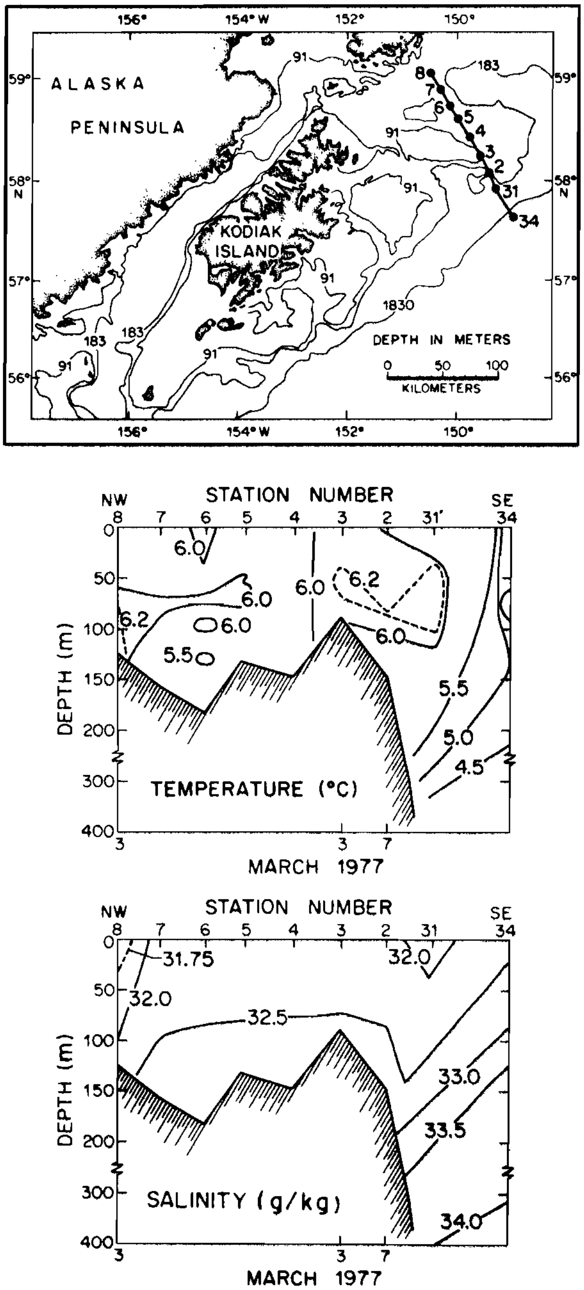

Figure 12. Temperature and salinity section for stations 2-8, 31, and 34.

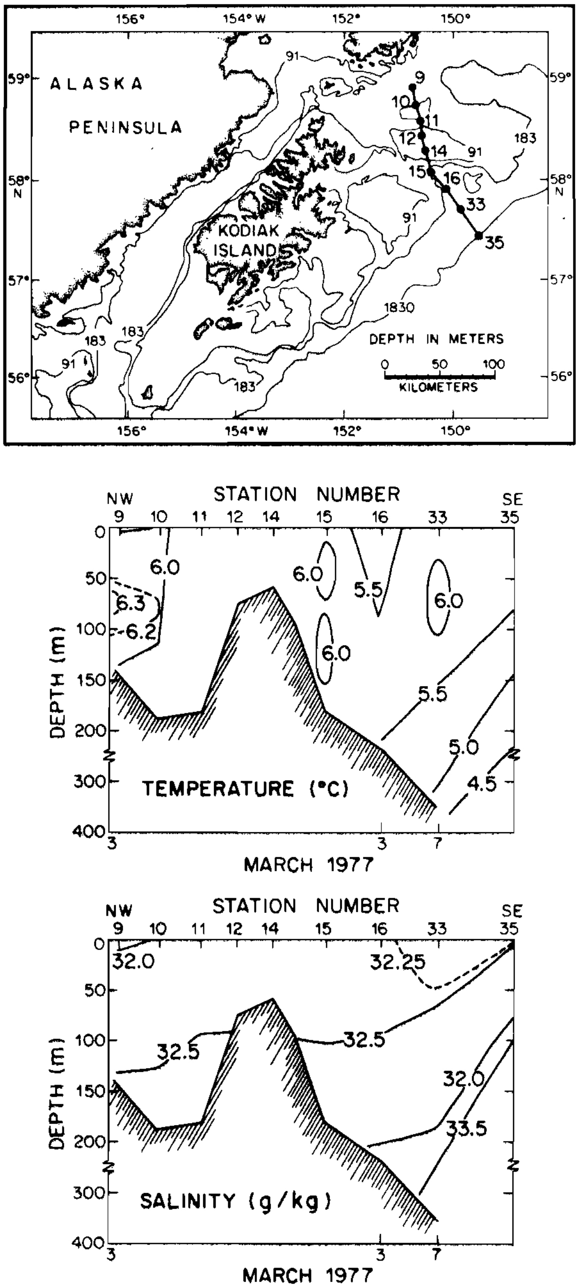

Figure 13. Temperature and salinity section for stations 9-12, 14-16, 33, and 35.

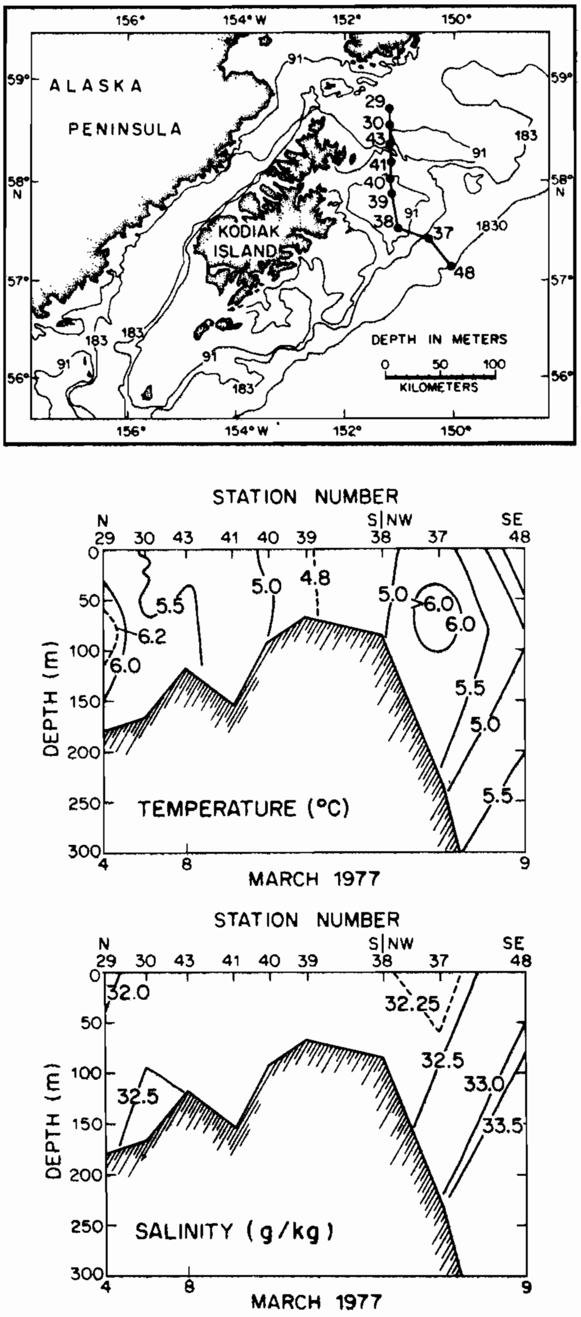

Figure 14. Temperature and salinity section for stations 29–30, 37–41, 43, and 48.

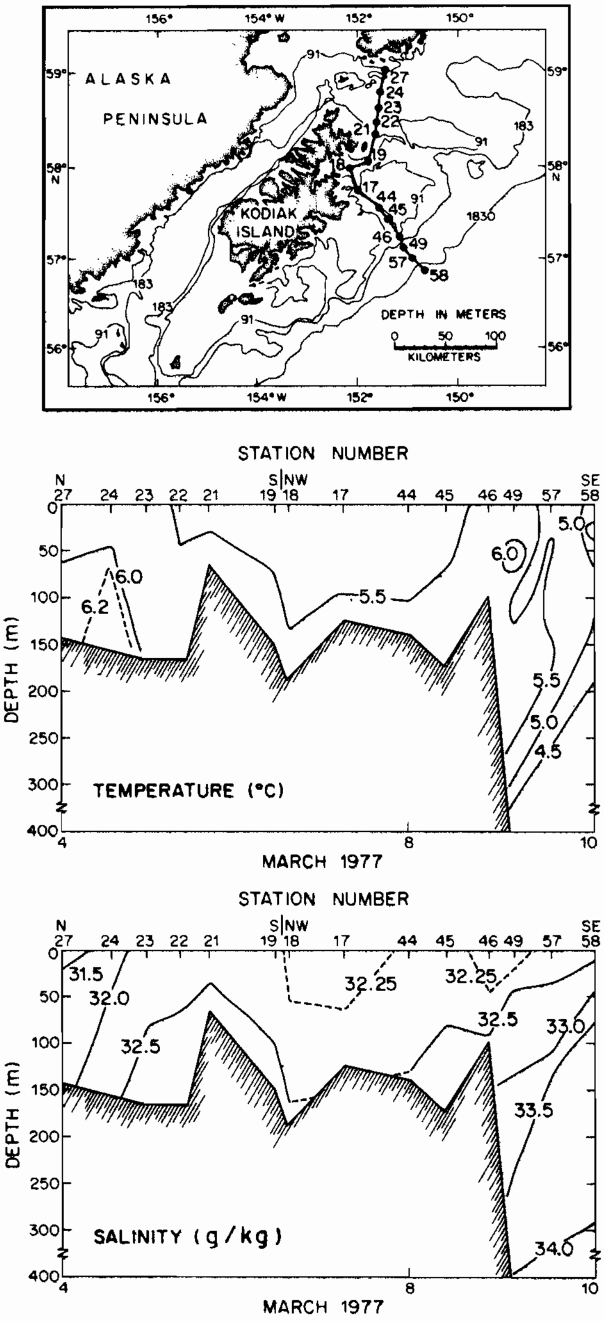

Figure 15. Temperature and salinity section for stations 17–19, 21–24, 27, 44–46, 49, and 57–58.

salinities below 32.0 g/kg occurred to a depth of 105 m. Salinity values observed over Amatuli Trough were equivalent to those at a similar depth over the shelf edge.

In the three "downstream" sections (Figs. 13, 14, and 15) the salient features were a shallow (<50 m) salinity minimum (<32.5 g/kg), a subsurface temperature maximum (>6.2°C) located over the shelf-edge region, and a warm subsurface core along the Kenai Peninsula. In addition, vertical structure was attenuated on the shoal bank regions, leading to near-homogeneity.

3.2 Hydrography: Shelikof Strait

Three closely-spaced sections of CTD stations (Fig. 16) were occupied from 28 to 30 March 1977 in the Shelikof Strait–Lower Cook Inlet region. We present composites of temperature and salinity (Figs. 17 and 18).

Temperature observations from Kennedy and Stevenson Entrances (Fig. 17) indicated little thermal stratification; typical values had a magnitude less than 0.25°C over the water column with a maximum ΔT = −0.62°C observed at station K4.3. In general, water temperatures were lower (<5.0°C) in Kennedy than in Stevenson Entrance; however, a warmer (>5.5°C) bottom layer was present on the Kenai Peninsula side of the entrance. Salinity observations also indicated little stratification. A maximum ΔS = 0.39 g/kg was measured at station K4.3 on the northeast side of

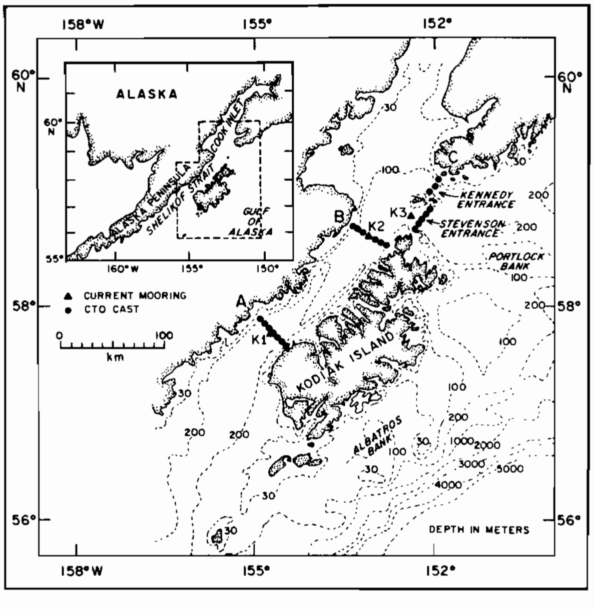

Figure 16. Locations of CTD stations occupied in Shelikof Strait from 28 to 30 March 1977.

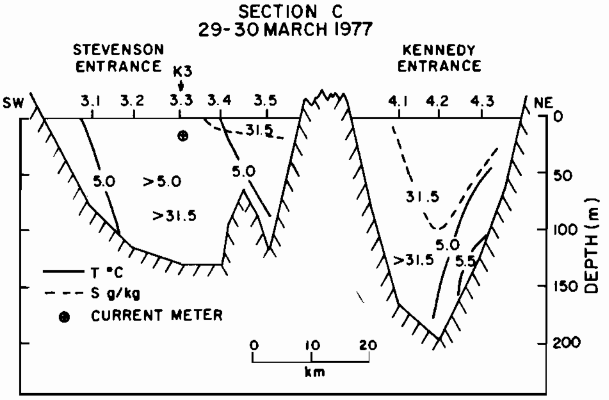

Figure 17. Composite temperature and salinity section across entrances to Shelikof Strait. Location of current-meter mooring K3 is also shown.

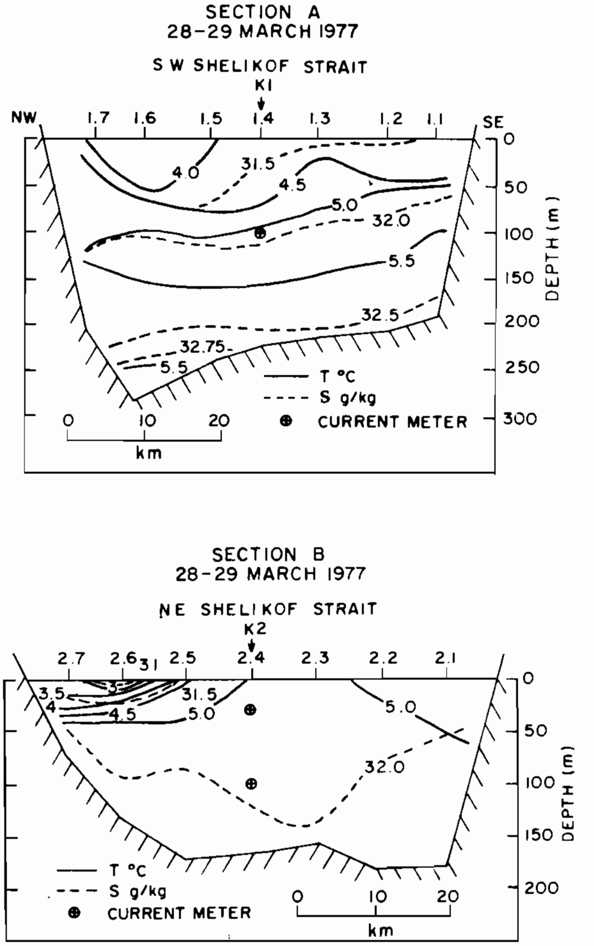

Figure 18. Composite temperature and salinity sections for southwestern (section A) and northeastern (section B) Shelikof Strait. Locations of current-meter moorings K1 and K2 are also shown.

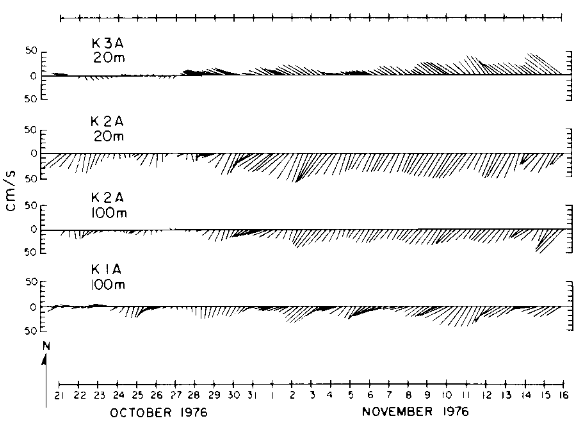

Figure 19. Low-pass filtered current records from Stevenson Entrance (K3A) and Shelikof Strait (K1A and K2A) for October and November 1976.

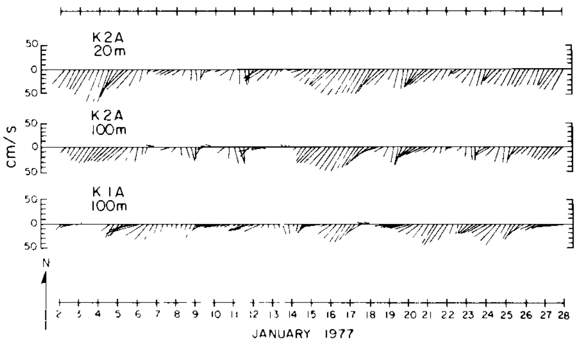

Figure 20. Low-pass filtered current records from Shelikof Strait (K1A and K2A) for January 1977.

Kennedy Entrance, and values typically were ~0.25 g/kg. In general, waters in Kennedy Entrance were less saline than in Stevenson Entrance, with a maximum salinity of 31.98 g/kg observed near the bottom at two stations on the southwest side of the latter. Density differences were generally <0.15 sigma-t units, with a maximum of 0.30 at station K3.3.

In Fig. 18, we present data from both the northeast (section B) and the southwest end of Shelikof Strait (section A). Only the upper 50 m of the water column on the northwestern or Alaskan Peninsula side of the Strait in section B exhibited significant thermal structure. At station K2.6, surface temperature was 2.31°C; a bottom temperature of 5.41°C yielded $\Delta T = -3.10°C$. In the center of the Strait (~18 km toward the southeast), an observed value of 5.01°C at the surface and 5.40°C at the bottom yielded $\Delta T = -0.39°C$. The colder water was associated with the lowest observed salinities; surface values were <31.00 g/kg centered at station K2.6. In general, salinity values for the entire section were below 32.00 g/kg with a maximum value 32.19 g/kg observed at station K2.2. The maximum $\Delta S = 1.11$ g/kg was observed at station K2.6, whereas $\Delta S = 0.20$ g/kg was typical of values for the entire southeastern half of the section. The ensuing density difference values (σ_t bottom - σ_t surface) were $\Delta\sigma_t = 0.66$ units at station K2.6, with values of less than 0.20 units on the southeastern side.

Surface temperatures from the southwestern end of Shelikof Strait (section A) were warmer than those noted for the northeastern end, with a similar horizontal distribution; e.g., a minimum of T = 3.80°C was observed at station K1.6. Vertical thermal structure was observed across the entire section; however, this structure was not as strong as noted for section B (i.e., the maximum $\Delta T = -1.87°C$, with values generally > -1.50°C). Salinity values exhibited small horizontal gradients, minimum surface values (31.38 g/kg) obtained along the Alaska Peninsula, and slightly higher values (31.50 g/kg) off Kodiak Island. Near-bottom (200 m) isohalines (e.g., 32.5 g/kg) were not inclined and attained a maximum value of 32.84 g/kg at station K1.6. Thus values of $\Delta S > 1.0$ g/kg pertain throughout this section. Density differences were ~0.80 units with a maximum of $\Delta\sigma_t = 1.01$ unit at station K1.6. We note the lack of inclination of the isopycnals as indicated by the isohaline structure.

4. DIRECT OBSERVATIONS OF CURRENT

We present representative segments of the low-pass filtered current records from Stevenson Entrance and Shelikof Strait in Figs. 19 and 20. As indicated in these records, net flow generally entered Shelikof Strait through Stevenson Entrance (K3A). From 28 October to 15 November, flow was consistent in direction and appeared to increase in magnitude with a maximum speed of approximately 70 cm s^{-1}. The mean velocity for this 37-day record was 30 cm s^{-1} directed toward 298°T.

The two current records from the northeastern end of Shelikof Strait (K2A) indicated that flow was predominantly axial (where the axis of Shelikof Strait was taken to be 230°T toward the southwest). During the period when flow was exiting eastward from Stevenson Entrance, the flow at K2A (Shelikof Strait) was weaker than usual. The two time series from K2A were well

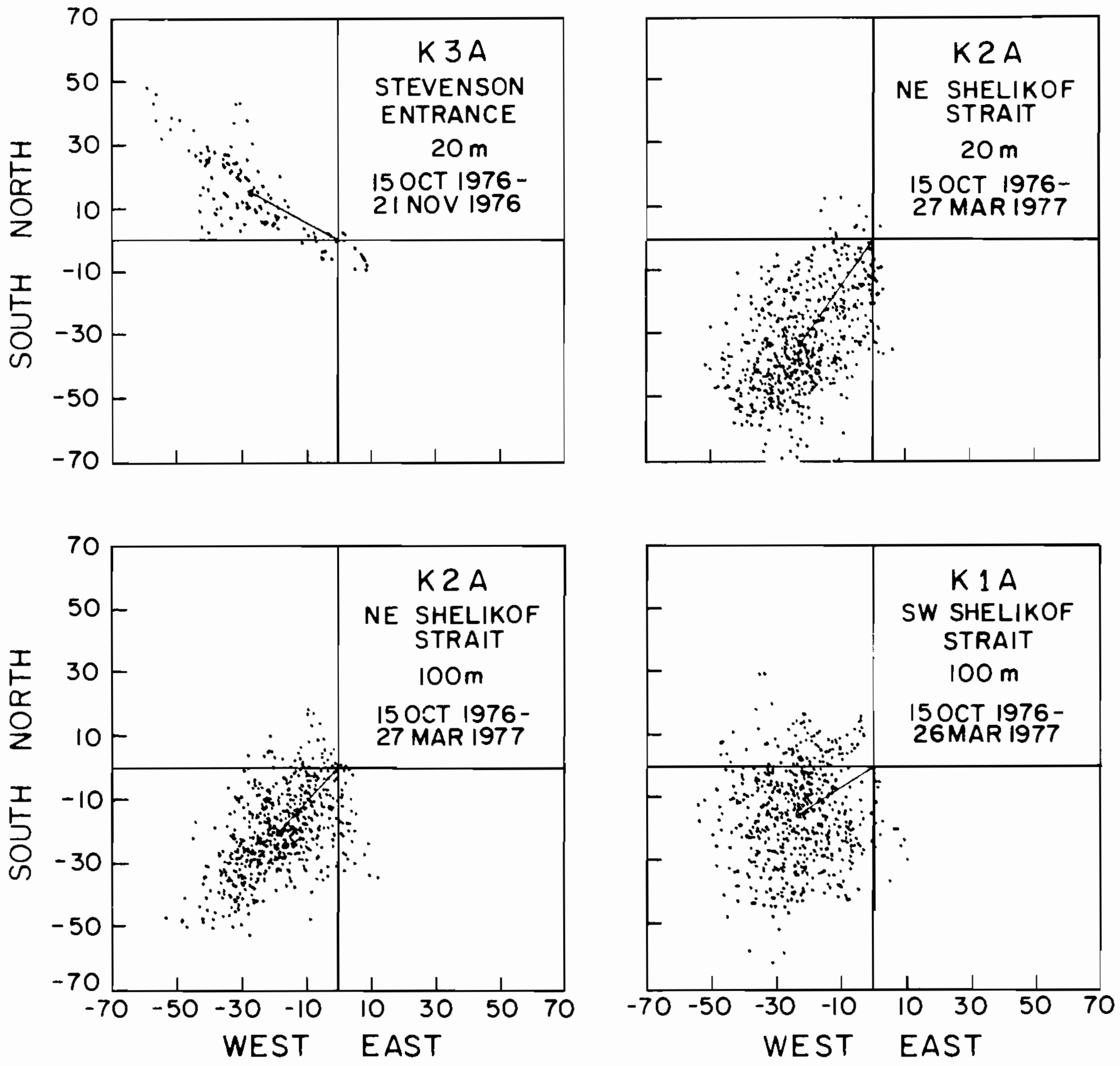

Figure 21. Scatter diagrams for low-pass filtered current records at stations K1A, K2A and K3A. Note that vector on each plot represents net current.

correlated visually. Net flow at 100 m was 9° to the right of the mean flow at 20 m; net speed at 100 m was 12 cm s^{-1} less than at 20 m (Table 1). These values indicated a mean vertical shear along the axis of the Strait of $-1.11 \times 10^{-3}s^{-1}$. The 100-m record from K1A (southwestern end of the Strait) was similar to that at K2A; i.e., there was a strong tendency for low-frequency flow along the major axis. There appeared, however, to be a somewhat greater degree of cross-channel variation.

To further examine variability of the subtidal flow, we present scatter plots of the Shelikof Strait current data (Fig. 21). Each point represents the head of a single vector created on a 6-h time base. The plots show that winter flow was predominantly into Stevenson Entrance and southwest through Shelikof Strait. Scatter about the mean was greater at K1A than at K2A, as suggested by the stick diagrams.

In contrast to the consistent, strong, subtidal flow observed in Shelikof Strait, the current record from North Albatross Bank, mooring WGC-2E, indicated weaker flow with a substantial number of reversals (Fig. 22). From 22 October to 8 November 1977, flow was consistent with speeds of the order of 15 cm s^{-1}. A more complex flow mode was evident in the 7 to 26 February record segment. During this period, several intervals occurred when flow was reversed from the mean direction (239°T). During this 156-

day record 12 clockwise rotations of the current vector were distinguishable, lasting 2 to 3 days. The scatter plot for this record (Fig. 22) clearly shows the high degree of variability superimposed on the mean flow toward the southwest. The maximum speed events $(\sim 30 \text{ cm s}^{-1})$ tended to parallel the local bathymetry (235°T).

Current records from the western flank of Kiliuda Trough (K5-A) indicated that mean currents at both depths tended to parallel the local bathymetry (north-south orientation) and flow seaward. We note a 7° turning to the left of the near-bottom mean flow with respect to flow at 20-m depth, and a mean shear along the axis of the Trough of $1.98 \times 10^{-4}\text{s}^{-1}$. Subtidal flow was relatively consistent; however, in 5 instances, lasting 1 to 2 days, flow at both levels had northerly components (into the Trough).

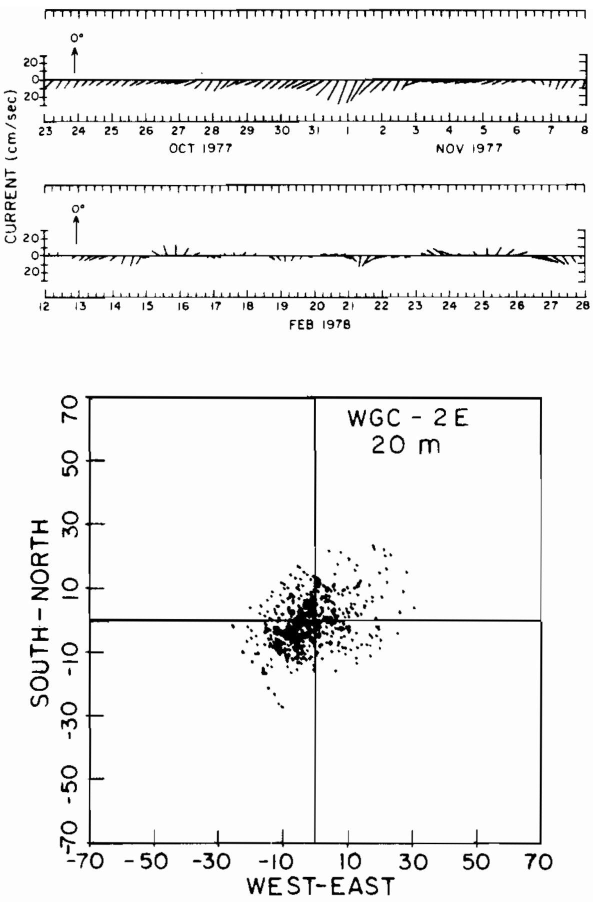

Figure 22. Representative portions of 20-m depth current record from North Albatross Bank (WGC-2E) showing periods of constant (October and November) and highly variable (February) flow. Also shown is scatter diagram for entire record.

5. DISCUSSION

5.1 Stratification

Over Middle Albatross, North Albatross, and Portlock banks we observed little or no stratification with $\Delta\sigma_t < 0.2$ (see Fig. 11). This lack of vertical structure was also noted by Favorite and Ingraham (1977) during late April and early May 1973. Winter thermohaline convection, coupled with turbulence resulting from currents impinging on the banks, probably contributed to this vertical mixing. During summer, heating and freshwater addition would be expected to result in substantial stratification over all but the shallowest bank regions.

Over the troughs, along the Kenai Peninsula, and seaward of the shelf edge, stratification was stronger ($\Delta\sigma_t > 0.4$.) This stratification was caused primarily by salinity, which exerts dominant control over density (Royer and Muench, 1977). Occurrence of high-salinity water in the troughs (e.g., $S > 33.0$ g/kg at station 53 in Kiliuda Trough) was also noted by Wright (1970). The apparent source of these waters was the shelf-edge portion of the Alaska Current. This current advected water whose temperature and salinity at 150-m depth (the sill depth of Kiliuda Trough) were similar to those observed inside the sill. Seabed drifter data suggested a net onshore flow of near-bottom waters shoreward of midbank (Favorite and Ingraham, 1977). Current records from K5A indicated that flow events occurred which might transport shelf-edge waters shoreward into Kiliuda Trough. The greater duration and strength of such events in the upper water column (Fig. 23b) suggested that forcing was initially applied at the surface by winds. Northeasterly winds could reverse the generally offshore flow and force the entire water column shoreward. Sea-level setup would then require a deep return flow which is suggested by the 80-m current records. Similar reversals of mean flow in a trough across the continental shelf off the coast of Washington State have been reported (Cannon, 1972; Cannon et al., 1972). These authors offer a similar explanation. We suggest that deep, shelf-edge water episodically flows shoreward in the troughs, providing the observed high-salinity bottom waters.

Stratification over the shelf edge results from the presence of a shallow (< 50 m), low-salinity feature. This is probably an extension of the freshwater filament noted by Royer and Muench (1977) which lies over the shelf edge approximately 500 km to the east. The source of such water is

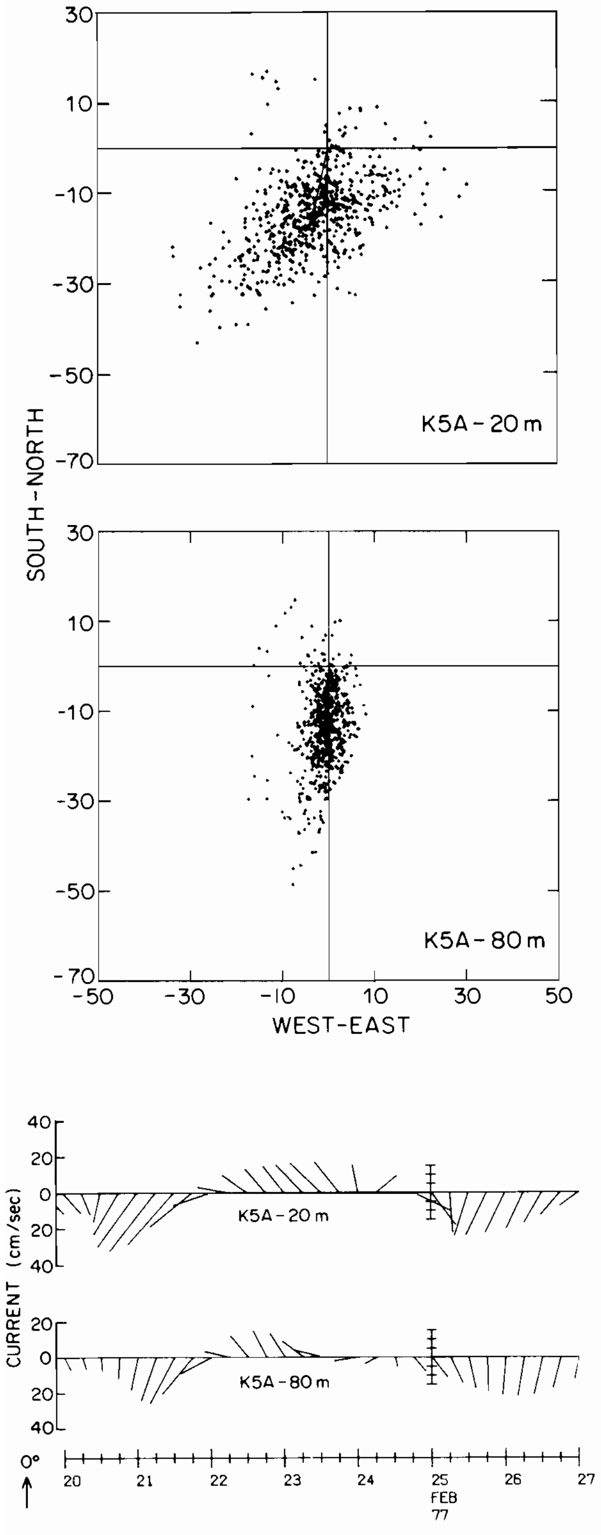

Figure 23. Representative portions of current records from Kiliuda Trough (K5A) indicating flow events into trough. Also shown are scatter diagrams for entire record.

runoff which accumulates around the perimeter of the northeast Gulf of Alaska and is diverted seaward by topography. Favorite and Ingraham (1977) observed a similar feature. During summer, we suspect that increased freshwater input reduces the salt content over the entire shelf and thereby masks the filament. The effect of the filament on circulation will be discussed later.

The stratified region along the Kenai Peninsula again demonstrates the pronounced effect of salinity on density. Although a negative ΔT (see Fig. 5) or thermal inversion occurred, the observed low-salinity band of coastal water resulted in relatively strong stratification. The probable sources of this low-salinity water were Prince William Sound and the Copper River. Enhancing stratification along the Kenai Peninsula were the high-salinity (33.06 g/kg at station 6) bottom waters observed at the western end of Amatuli Trough. As these waters flow into upper Shelikof Strait via Stevenson and Kennedy Entrances, vigorous tidal mixing (71% of the record variance from K3A or 2027 cm s^{-1} was contained in tidal frequency bands) resulted in reduced stratification.

Stratification at the northeastern end of Shelikof Strait was generally similar in magnitude to that observed in the Barren Island section; however, a more highly stratified band was observed on the northern side of the Strait. The low salinity and temperature of this ~50-m deep band appeared to be related to outflow from Lower Cook Inlet. In this region, ice formed from river water in Upper Cook Inlet melted, thus providing the observed water characteristics. The low-salinity cold band appeared to have been laterally diffused across the southwestern portion of the Strait, reducing stratification in the upper 50 m; however, more saline (>32.75 g/kg) bottom waters compensated for the reduced stratification in the upper water column. At the southwestern end of Shelikof Strait, stratification generally increased by a factor of three above that observed in the northeastern end.

5.2 Horizontal Distribution in Shelikof Strait

As shown in Fig. 18, surface waters in northeastern Shelikof Strait were colder and less saline than those at the southwestern end. Advection of temporally changing source water may have caused the difference. Current records indicated a consistent mean flow speed of 25 to 40 cm s^{-1} toward the southwest in the upper 100 m of the water column. The origin of these waters was the shelf region off the Kenai Peninsula. During February and March 1977, a thermistor record from K2A (100 m), three CTD casts over the shelf edge, and reoccupation of three CTD stations in the Barren Island region indicated a ~0.025°C/day temperature decrease (Fig. 24). If we assume a net speed of ~30 cm s^{-1}, water from K2A would reach K1A in 8 days. CTD casts were conducted at K1A 2 days before those near K2A, so the total time difference was 10 days. Using the observed change of temperature with time and time difference, the longitudinal temperature gradient at 100 m would be ~0.25°C, which was essentially the difference observed from CTD data.

A similar but less detailed signature appeared in the salinity measurements. A ~0.02 g/kg salinity difference was observed between the locations with a 10-day time lag between K2A and K1A; this gradient would have resulted in longitudinal salinity differences of ~0.2 g/kg, as observed in the upper 100 m. Royaer (1975) reported that subsurface salinities and temperatures give evidence of an annual cycle independent of local insolation and freshwater addition. Our data indicated such a signal; we suggest that an annual temperature cycle is associated with subsurface waters transported by the Alaska Current.

An annual signal associated with the Alaska Current may explain the longitudinal difference in water properties observed in Shelikof Strait; however, below about 150 m temperature and salinity values are greater than can be accounted for by considering the seasonal signal (see Fig. 18). Indeed, values from the near-bottom layer closely resemble those observed at the shelf edge. (Fig. 15). In concert with the lack of sufficiently saline waters near the Barren Islands, we suggest that this observation implies that shelf-edge waters enter Shelikof Strait at depth via its southern terminus (sill depth ~200 m). The entrainment of such waters by the strong southwesterly flow in the upper waters would require a net flow into the Strait of near-bottom waters.

5.3 Circulation

Advection of warm cores and the shelf-edge salinity minima into the study area by the westward-flowing Alaska Current was a prominent feature. Infrared satellite imagery shows the surface manifestation of the warm cores (Fig. 25). Such data combined with hydrographic data (Fig. 26) suggest that the Alaska Current bifurcated in the vicinity of Amatuli Trough; one branch flowed axially into the trough toward the Barren Islands and the other branch continued southwest along the shelf edge and offshore. The

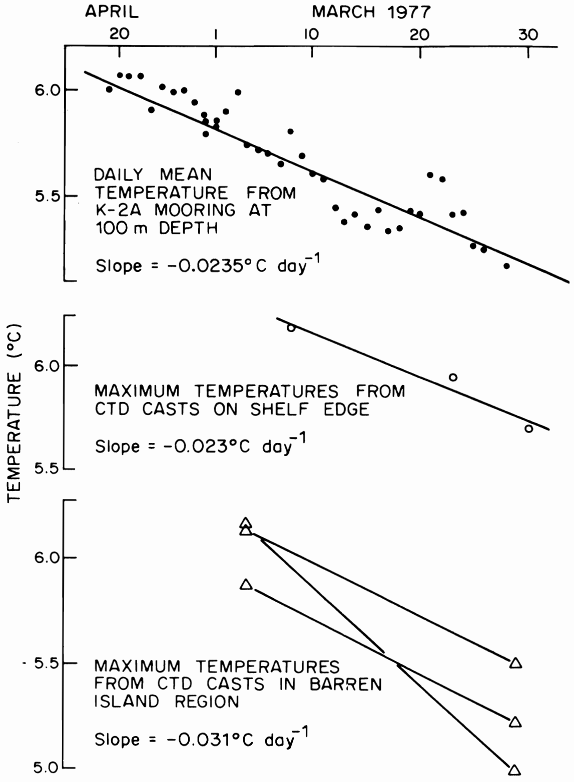

Figure 24. Temperature gradients observed in waters around Kodiak Island during February and March 1977.

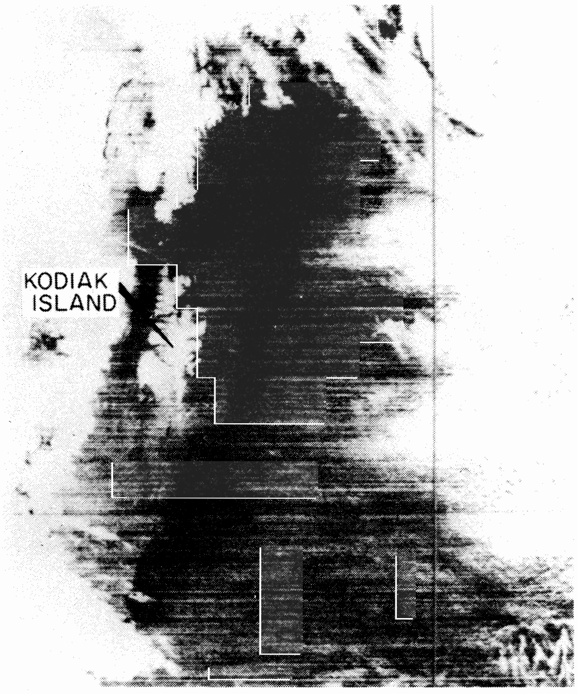

Figure 25. Infrared satellite image of surface waters in vicinity of Kodiak Island. Darker areas indicate warmer water.

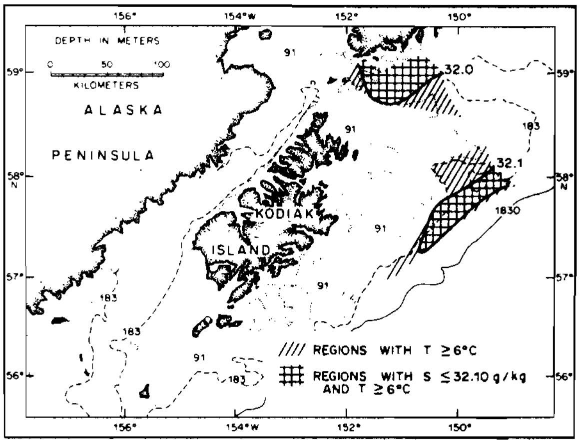

Figure 26. Spatial distribution of warm less-saline waters observed during March 1977.

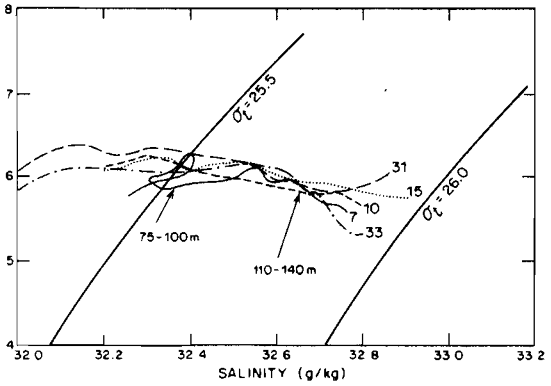

Figure 27. Temperature-salinity curves for selected CTD stations over shelf edge (stations 15, 31, and 33) and along the Kenai Peninsula (stations 7 and 10). Station locations are shown on Fig. 2.

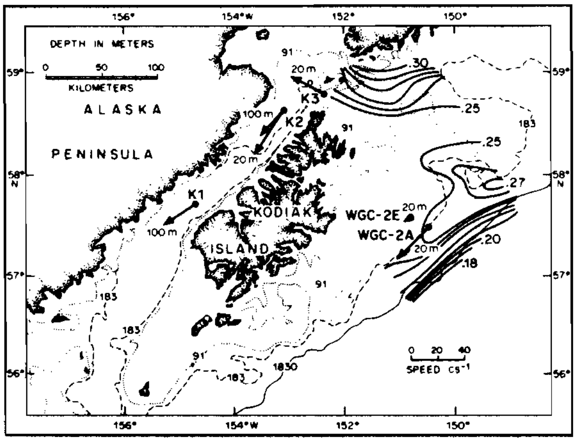

Figure 28. Dynamic topography (0/100 dB; 0.01 dynamic meter contour interval) for observations during March 1977. Arrows indicate observed net flow for periods in Table 1.

spatial distribution of warm, less saline water (Fig. 26) clearly demonstrates the impact of nonlocal advection due to the Alaska Current. Temperature-salinity curves from selected stations along the shelf break and along the nearshore region off the Kenai Peninsula demonstrate that waters at these locations had essentially the same T-S characteristics (Fig. 27). This supports our contention that the current had split upstream from this region; hence, waters at these stations have the same source and consequently the same T-S characteristics.

Dynamic contours (Fig. 28) indicated the baroclinic, geostrophic component of flow in response to the cross-shelf, bimodal distribution of mass. A reference level of 100 dB was used so that the majority of CTD data could be included. Over the slope the highest geostrophic speeds (e.g., the relative flow to the southwest between station 58 and 57) were calculated to be 24 cm s^{-1} (0/100 dB), 34 cm s^{-1} (0/200 dB), and 66 cm s^{-1} (0/1200 dB). The tendency for warmer, less saline waters to extend into Stevenson Trough resulted in a clockwise flow with relative speeds of about 2 to 3 cm s^{-1}. Along the Kenai Peninsula, 0/100 dB dynamic contours indicated another region of relatively strong flow between stations 8 and 7; calculated westward speed (0/118 dB) was of the order of 20 cm s^{-1}. Inflow speed through Stevenson Entrance was calculated to be about 8 cm s^{-1} (0/116 dB), and through Kennedy Entrance the estimate was about 9 cm s^{-1} (0/181 dB). The stations used above do not entirely span the two entrances, and calculated values seaward of these features indicated values of 15 cm s^{-1} (0/116 dB between stations 23 and 24) and 11 cm s^{-1} (0/116 dB between stations 24 and 27). The two bands of relatively strong baroclinic, geostrophic flow (i.e., along the Kenai Peninsula and coincident with the slope) were separated by a region of weak flow with a clockwise tendency. Current records from North Albatross Bank (WGC-2E), the shelf edge (WGC-2A), and Stevenson Entrance (K3A) supported these geostrophic calculations.

Baroclinic, geostrophic calculations for the northeastern end of Shelikof Strait indicated weak flow. Between stations K2.5 and K2.3, the 0/150 dB speed was ~5 cm s^{-1}, and the 30/110 dB speed was ~3.6 cm s^{-1}, with both speeds representing flow toward the northeast. This flow was in the opposite direction from the net flow and represented approximately ⅓ of the observed vertical shear. At the southwestern end of the Strait, calculated geostrophic flow was ~10 cm s^{-1} (0/215 dB) toward the southwest. These geostrophic, baroclinic speeds were all much less than those observed. The lack of strong baroclinicity and little evidence for wind forcing leads us to believe that a dominant, driving mechanism was a bifurcated branch of the Alaska Current augmented by freshwater addition which created a pressure gradient and downslope hydraulic flow.

6. SUMMARY

Observations from moored current meters, recording conductivity/temperature/depth (CTD) units, and satellite imagery have been used to describe temperature, salinity, and flow fields for a region extending from the banks east of Kodiak Island westward through Shelikof Strait. These measurements were obtained during winter 1976-77. The temperature-salinity field was dominated by the presence of two subsurface cores of warm (>6.0°C), saline (~32.5 g/kg) water, one roughly coincident with the shelf break and one extending northwest from the shelf break into Amatuli Trough. The region between these bands, generally overlying Albatross Bank, was characterized by lower temperatures and salinities. The bands themselves were of the appropriate temperature and salinity to have originated in the Alaska Current, which suggests that this current bifurcated near the southeastern end of Amatuli Trough and consequently some Alaska Current water flowed northwest through the Trough. Infrared satellite imagery supports the concept of such a bifurcation. A shallow band of relatively low salinity (<31.6 g/kg) water, manifesting fresh water input from continental drainage to the east, paralleled the Kenai Peninsula coast.

Current records from northern Shelikof Strait indicated consistent southwesterly flow during the entire October 1976 to March 1977 mooring period. Mean currents at 20-m depth were ~39 cm s^{-1} toward the southwest, and mean currents at 100 m were ~26 cm s^{-1} toward the southwest. Few flow reversals were observed; only 1% of the low-pass filtered records indicated a northeasterly flow component, and a 37-day current record from Stevenson Entrance indicated a strong mean flow (~30 cm s^{-1}) westward into Shelikof Strait. Presence of these strong flows with no reversals, coupled with a lack of density structure in the water column, indicated a barotropic driving mechanism for the flow. We suggest that a longshore pressure gradient set up by the westward flowing branch of the Alaska Current was sufficient to drive the observed flow through Shelikof Strait. The forcing due to the Alaska Current was augmented in some instances by a westward baroclinic flow resulting from freshwater input along the coastline.

Flow over the banks northwest of Kodiak Island was less well defined than in Shelikof Strait. Low-temperature, weakly stratified water was observed over the banks, whereas in the troughs water was stratified with warmer, more saline water near the bottom. The deep water in the troughs may indicate that a net onshore flow of bottom water was occurring, or that shelf-edge water episodically was driven across the sills into the troughs. Dynamic topography suggested a weak tendency for cyclinic flow over North Albatross Bank, in sharp contrast to the distinct westward flows to the north (along the Kenai Peninsula) and south (the Alaska Current). A current record from northern Albatross Bank indicated weak (~3 cm s^{-1}) flow. Only 7% of this record's variance was contained in subtidal frequencies, and flow reversals were frequent with direction changing in an anticyclonic sense.

Clearly, more saline waters lie in Kiliuda Trough and the deep depression to the southwest. Current records from the shelf edge of the Trough suggest that the source for more saline waters may be at the shelf edge. The physical processes for trough flow, discussed here, may be similar to those reported for other cross-shelf trough features. An understanding of water renewal is critical to our knowledge of why this region is so productive and to our ability to estimate the impact of water-borne contaminants. We are examining the velocity field at five sites in the Kiliuda Trough region and will present the results in subsequent reports.

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