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TABLE OF CONTENTS

ABSTRACT

Physical transport processes were studied to provide background information useful in describing the fate and effects of dissolved and suspended contaminants introduced into Elliott Bay. Observations were made during low-river discharge in August 1979 and during high-river discharge in February 1980 using moored current meter arrays and hydrographic surveys. During each study, water properties were measured for about one week, and currents were measured for about two months in Puget Sound, and for about 30 days from near bottom to 30 m in the bay. This paper compares a preliminary interpretation of these studies to earlier hydraulic model studies.

Summer circulation in the deep water of the main basin was dominated by periodic advective inputs of high-salinity, low-temperature water. During winter, analogous events were observed, but the overall water properties of the estuary were much more variable. Also, there was more high-frequency variance in the velocity structure. Both characteristics may be related to external forcing, presumably wind stress and runoff variations.

Currents in Elliott Bay were very weak, dominated by the semidiurnal tide and Duwamish River effluent. Current directions in the outer bay were coupled with the main basin, and average currents suggest a counterclockwise gyre in mid-depths, at about 130 m. Contrary to model findings, the Duwamish River plume appeared on the north side of the bay at all times. Levels of no net motion in the estuarine flow were at about 40-75 m, slightly deeper than in the model. Speeds of 23.5 cm/s, necessary to resuspend bottom sediment, occurred very infrequently in the inner bay, yet suspended sediment was concentrated near the bottom. We inferred residence times for water in the inner bay to range from 1 to 10 days depending upon depth and season.

1. INTRODUCTION

Elliott Bay is one of the major deep-water commercial seaports within Puget Sound. It is located at Seattle on the east side of the Puget Sound main basin, about midway between Admiralty Inlet and the Tacoma Narrows (Figures 1 and 2). It covers an area of about 21.4 square kilometers and is about six kilometers by four kilometers. This gives the bay a rather broad mouth. With the exception of Duwamish Head extending into the bay from the south, the bay has a nearly semicircular shoreline. The principal source of freshwater is the Duwamish River located in the southeast corner of the bay. This river divides into the east and west waterways before entering the bay, and the west waterway carries the majority of the river discharge. Runoff is dominated by rainfall. Thus, high runoff occurs during winter rains, and low runoff occurs during late-summer dry spells.

The bay can be considered to have an inner and outer basin divided by a line from Smith Cove to Duwamish Head. The complete inner shoreline of the bay is dominated by man-made piers and seawalls. Natural shoreline continues west from both Smith Cove in the north and Duwamish Head in the south. The bathymetry of the bay is dominated by a submarine canyon in the outer bay which divides into two canyons in the inner bay. The outer canyon is oriented east-west. The inner canyons diverge with the northern one running northwest-southeast and the southern one near Duwamish Head running almost north-south. Depths in the inner canyons are greater than 75 meters, and in the outer canyon greater than 150 meters. The outer canyon reaches depths of 200 meters where it joins with the axis of the main basin of Puget Sound.

Elliott Bay has become the focus of recent investigation sponsored by the Puget Sound Marine Ecosystem Analysis (MESA) Office of NOAA. Human activities have introduced contaminants into the bay, but there is little environmental information on bay circulation to use in determining the fate of these contaminants. MESA initiated a multidisciplinary study in 1979 to provide background information that would be of use in describing the fate and effects of critical contaminants introduced into the bay. This report describes current meter and hydrographic observations and some preliminary interpretations of physical transport processes within the bay that might affect the transport of dissolved and suspended matter. Description of the particulate studies will be in a separate report (Baker, 1981).

Previous physical oceanography field observations in Elliott Bay have been limited. However, Winter (1977) has carried out a hydraulic model study which showed circulation patterns within Elliott Bay during high- and low-river runoff and for typical flood and ebb tides. In the model, water movement was dominated by the tides and salinity distribution. A depth of 37-55 meters divided the estuarine surface and bottom flows. During flood tides circulation was clockwise and stronger than during ebb tides when the flow was counterclockwise. This tendency for net-clockwise flow resulted in more water flowing out of the bay past Duwamish Head than past Smith Cove. However, water flow was more likely to be outward past Smith Cove when high-river runoff was combined with weak tidal currents. With strong tidal currents and low-river runoff, there was little likelihood of outward flow past Smith Cove. One purpose of these field studies was to see to what degree the hydraulic model results could be verified in the real environment.

Observation of circulation and physical transport processes within Elliott Bay were made using moored current meters and measurements of conductivity and temperature versus depth (CTD). The observations were made both during low- and high-river runoff and at different stages of the tide. Concurrent with this experiment in Elliott Bay, other observations using current meter moorings and CTD surveys were made in the main basin of Puget Sound, Admiralty Inlet, and Hood Canal. Other concurrent observations in Elliott Bay included measurements of suspended sediment and transmissivity (Baker, 1981) and surface salinity and temperature recorded during summer low runoff aboard the Washington State Seattle to Winslow and Seattle to Bremerton ferries (Helseth et al., 1979).

2. OBSERVATIONAL PROGRAM

Because of the marked seasonal changes in precipitation and, thus, in river discharge rates in the Pacific Northwest, this work required field observations to be made at two different periods of the year. Observations in August 1979 were of the effects of low-river discharge and in February 1980 were of high-river discharge effects. During both times, seven subsurface current meter moorings were deployed, and conductivity and temperature versus depth (CTD) surveys were made.

Current Meter Moorings. Four current meter moorings were located within Elliott Bay as shown by the italicized numbers of Figure 2. Each was a taut-wire subsurface mooring with an acoustic release just above the anchor, secondary flotation above the deepest instruments, other flotation just above particularly heavy instrument combinations, and the primary flotation just above the shallowest current meter. The taut-wire-mooring design tends to minimize surface wave noise effect on the Aanderaa rotor. Moorings were all deployed anchor last from the University of Washington vessel RV HOH with the deepest current meter about six meters above the anchor. All current meters used were Aanderaa RCM-4 models, and all had temperature and conductivity sensors. The shallowest current meters on the moorings had to be placed 30 meters below the surface as a compromise between sampling the upper-estuarine flow and avoiding deep-draft vessels and tugboat tow lines. The moorings were maintained for just over a month during each experiment and were recovered using University of Washington vessels. A summary of the moorings including location, duration, depth of current meters, and current record statistics is given in Table 1.

Also incorporated into the current meter moorings were sediment traps, transmissometers and a bottom pressure gauge. Moorings ELLBAY 4A (summer) and 4B (winter) had the bottom pressure gauge mounted on the acoustic release. Transmissometers were located in the vanes of modified current meters and recorded on the original current meter pressure channel. These modified current meters were placed at 92 and 132 m below the surface on moorings ELLBAY 2A and 4A, respectively. During the February, deployment they were at 30 and 90 m on ELLBAY 2B and 130 m on ELLBAY 4B. Sediment traps operated independently of the current meters. They were located just below current meters on ELLBAY 2A at 51 and 93 m and under current meters on ELLBAY 2B at 31 and 91 m and ELLBAY 4B at 131 m. Observations made using the sediment traps and transmissometers are reported elsewhere (Baker, 1981).

TABLE 1

CURRENT METER MOORING and RECORD STATISTICS SUMMARY

Current Meter Station	Position	Current Meter Depth (m)	Observation Period	Record Length (days)	Mean Speed (cm/s)	Variance $(cm/s)^2$	Net Flow Speed (cm/s)	Net Flow Direction (^{o}T)
				A. SUMMER				
ELLBAY 1A	47 36.99N	30	1 Aug 79	41	3.32	4.67	.68	352
	122 22.58W	50	10 Sept 79	41	2.51	3.65	.28	297
		101		26	6.79	31.02	5.06	36
ELLBAY 2A	47 35.98N	30	3 Aug 79	41	3.72	6.25	1.61	336
	122 22.58W	50	12 Sept 79	41	3.43	4.88	.40	239
		92		41	3.01	11.42	.48	340
ELLBAY 3A	47 37.22N	30	1 Aug 79	41	4.62	7.93	.92	12
	122 24.13W	132	10 Sept 79	41	5.69	19.10	.93	284
ELLBAY 4A	47 35.88N	30	3 Aug 79	41	9.12	29.38	3.41	133
	122 24.23W	132	12 Sept 79	41	5.37	9.30	2.98	56
				B. WINTER				
ELLBAY 1B	47 37.04N	30	5 Feb 80	31	2.04	4.49	.59	16
	122 22.65W	50	6 Mar 80	31	2.68	4.16	.38	3
		101		31	4.84	10.37	1.06	296
ELLBAY 2B	47 35.92N	30	6 Feb 80	31	3.32	5.62	1.63	347
	122 22.63W	50	7 Mar 80	31	1.65	3.57	.30	287
		90		31	4.95	14.75	2.41	110
ELLBAY 3B	47 37.29N	30	5 Feb 80	31	4.54	13.40	1.33	325
	122 24.18W	132	6 Mar 80	31	3.57	11.22	.67	348
ELLBAY 4B	47 35.83N	30	6 Feb 80	31	7.27	21.07	2.47	124
	122 24.04W	130	7 Mar 80	31	2.89	7.24	1.45	17

The three additional current meter moorings in August 1979 and February 1980 were deployed at the same time as the Elliott Bay moorings, but were maintained for a duration of two months (Figure 1). The August moorings were located in the center of Puget Sound south of Elliott Bay near the north end of Vashon Island, north of Elliott Bay near Meadow Point, and at the southern end of Admiralty Inlet near Double Bluff. The February deployments were located again in the center of Puget Sound at Meadow Point, on the sill of Admiralty Inlet near Admiralty Head, and in Hood Canal near Anderson Cove. A synopsis of these observations, north and south of Elliott Bay, will be given as related to Elliott Bay and its interaction with the main basin.

Following recovery of the moorings, the current meter observations were reduced as follows. Data were resolved into north and east components, and individual data points exceeding three standard deviations from the mean were removed. Two new data series were then produced using a Lanczos filter (Charnell and Krancus, 1976). The first series was filtered such that over 99% of the amplitude was passed at periods greater than 5 hours, 50% at 2.86 hours, and less than 0.5% at 2 hours. The second series, filtered to remove most of the tidal energy, passed over 99% of the amplitude at periods greater than 55 hours, 50% at 35 hours, and less than 0.5% at 25 hours. The first series is referred to as tidal flow or currents; the second series as subtidal flow or currents. The first series was resampled every hour. The second series was resampled every six hours and was used to examine sub-tidal circulation.

CTD Surveys. CTD measurements were made at thirteen stations within Elliott Bay (Figure 2). A reference station, number 27, was located in the main basin of Puget Sound outside the mouth of the bay. These stations were occupied about the time of current meter deployments, August 7-11, 1979, and February 19-22 and 25-27, 1980. The surveys were conducted from the University of Washington vessel RV ONAR using a Plessey model 9400 CTD system with a model 8400 data logger. This system was configured to sample conductivity, temperature, transmissivity, and depth twice per second. Data were recorded during the down cast using a lowering rate of 30 meters per minute. Nansen bottle samples were taken frequently to provide temperature and salinity calibration data. After each CTD cast was corrected by the Nansen bottle results, one-meter average temperature and salinity values were calculated, from which sigma-t and dynamic depth were then computed.

3. RESULTS--ELLIOTT BAY

Current Meter Data. Very weak speeds characterize all currents observed in Elliott Bay. Instantaneous speeds occasionally attained 30 cm/sec, but there were also frequent periods of less than 1 cm/sec. Mean speeds were typically less than 5 cm/sec (Table 1).

Figures 4, 5, 6, and 7 represent hourly averaged tidal flow about midway between high and low waters (Figure 3). This technique of presentation was chosen so the observations could be related to the hydraulic studies shown in McGary and Lincoln (1977). Despite the inability of the current meters to resolve very low speeds and the corresponding fluctuations in individual direction measurements, a flow pattern did emerge when tidal velocity vectors were averaged over one hour intervals. However, these hourly averaged vectors also can change markedly from hour to hour. This is due to the predominantly clockwise rotary tides of the bay where tidal phase varies with location and depth.

Summer: Tidal currents within the inner bay (0.0-11.0 cm/s) were about half the strength of outer-bay tidal currents (3.0-20.0 cm/s) (Figures 4, 5; A series tidal flow). Tidal flow in the outer bay of 3.0-20.0 cm/s followed bathymetry except for onshore currents during flood tides at mooring 4A. There was also onshore flow at 30 m at mooring 3A during ebb tides. In the inner bay near-bottom tidal currents at mooring 1A were always onshore at 1.5-7.0 cm/s.

Subtidal flow in the outer bay of 1.0-3.0 cm/s paralleled bathymetry except for several onshore periods at 30 m at moorings 3A and 4A (Figure 8). The near-bottom subtidal currents at moorings 3A and 4A were usually directed northwest and northeast, respectively, following bottom contours. The inner-bay moorings showed net currents of about 0.5-2.0 cm/s directed northward out of the bay at 30 m (Figures 9, 10). The near-bottom subtidal flow at mooring 1A was always shoreward, up canyon at 5.0 cm/s. Subtidal flow near the bottom of mooring 2A and at 50 m of moorings 1A and 2A varied between on- and offshore with mean speeds of 1 cm/s or less.

Winter: Tidal flows during winter were often similar to those of summer. The strength of tidal currents in the inner bay (0.0-13.0 cm/s) was about 80% of those in the outer bay (0.0-15.0 cm/s) (Figure 6, 7; B series tidal flow). Tidal flows at moorings 3B and 4B (0.0-15.0 cm/s) followed bathymetry except for greater variability in direction than that shown during the summer. Near-bottom tidal currents at mooring 1B did not show the onshore flow exhibited in summer.

Subtidal currents near the bottom in the outer bay were controlled by bathymetry (Figure 11). At moorings 3B and 4B they were again northwest and northeast, respectively, at about 0.5-2.5 cm/s. At mooring 4B subtidal flow at 30 m had several onshore periods. The inner-bay, near-bottom subtidal flow was onshore at mooring 2B (3.0 cm/s) and offshore at mooring 1B (1.2 cm/s) (Figures 12, 13). At moorings 1B and 2B subtidal flow was directed out of the bay between 0.7-1.8 cm/s, while currents at 50 m alternated between following and opposing the flow at 30 m.

Hydrographic records: Hydrographic data are presented as four sections through Elliott Bay and as surface salinity maps. These include summer and winter observations and, where possible, ebb and flood tidal cycles.

Summer: The three north-south sections showed density principally controlled by salinity as would be expected in the estuarine waters of Puget Sound (Figures 14, 16, 18). The Duwamish River plume was shown by the low salinities located near stations 6,8, and 11 as it left the bay on the north side. The slope of the isopycnals indicated flow inward at the bottom; particularly on the south side, and outflow on the north side of the bay (Figure 14). Isopycnals were horizontal between 40 and 75 m depending on location in the bay. Salinity and temperature records from the summer current meter moorings showed a very slight, 0.2-0.5 $^{o}/oo$ and 0.5°C, uneventful steady rise during the 41 days deployment.

Winter: The only structure in water properties showed in salinity as temperature was uniform top-to-bottom (Figures 15, 17, 19). Rainfall had increased freshwater output from the Duwamish River, and the plume was confined to the north side of the bay as it was in summer. The freshwater lens was about 5 meters thick with salinity differences of 1-3 $^{o}/oo$ from the surface to 5 m. Salinity and temperature records from the winter current meter moorings showed a constant salinity and slight, 0.1-0.5°C, steady decline in temperature.

Surface salinity maps showed river plume characteristics for summer and winter seasons and for flood and ebb tides (Figures 21, 22, 23, 24). Surface salinity indicated that the river was leaving the bay along the north side during all surveys. Comparing the flood and ebb surveys in August (Figures 21, 22), water was 1.0 $^{o}/oo$ fresher near the river mouth, and the 29.50 $^{o}/oo$ contour extended 2.5 kilometers further out along the north shore during the ebb tide. Comparing ebb tides during low- and high-river discharge periods (Figures 20, 22, 24) indicates water at the river mouth can be 6.0 $^{o}/oo$ fresher in winter with average surface salinity 2.0 $^{o}/oo$ fresher in winter at other locations.

4. RESULTS--MAIN BASIN

Current meter arrays were deployed north and south of Elliott Bay in the main basin of Puget Sound during summer '79, and an array was deployed to the north again during the winter '80 study. The north array, hence referred to as mooring 6, contained 8 Aanderaa current meters in 200 m of water. The south array, mooring 5, had 6 current meters in 190 m of water. Water properties recorded by sensors on the current meters were calibrated at one point in the time series with CTD casts. The current meter observations were reduced as outlined above. Subtidal currents were then rotated so that the direction of maximum variance was oriented along-channel. Twenty-five hour averages of temperature and salinity were also computed.

Previous studies of the main basin have indicated that the horizontal gradients tend to be small (Collias et al., 1974), thus mooring 6 is a fair representation of the conditions of the basin as a whole. During the summer '79 time series, the salinity increased uniformly with time between the surface and 122 m (Figure 25). Below this depth, distinct oscillations were superimposed on the increasing trend. The overall increase in salinity over the 40-day record was roughly 0.4 $^{o}/oo$. The temperature signal at mooring 6 during the summer deployment did not manifest a distinct trend, but there seemed to be roughly fortnightly oscillations in the degree of stratification. As with salinity, the deep water showed large variance in temperature, with a visual correlation between temperature and salinity fluctuations.

The along-channel subtidal velocity field at mooring 6 during summer '79 indicated a relatively uniform outflow at the surface and a highly variable inflow at depth (Figure 26). The currents at the deep meters (177, 196 m) showed the greatest variability, ranging from 0 to 20 cm sec^{-1}. There appeared to be a roughly fortnightly periodicity to this oscillation as observed by Cannon et al. (1979). Increased salinity and decreased temperature of the bottom water occurred synchronously with the episodes of strong bottom-water inflow. Mooring 5 showed much of the same water properties as mooring 6 (Figure 27). Again, there was large variance in the temperature and salinity of the deep water.

The currents at mooring 5 showed inflow at all depths (Figure 28). This is evidence of the clockwise net circulation around Vashon Island which arises as a result of nonlinear tidal acceleration at Tacoma Narrows (Farmer and Rattray, 1963). As with mooring 6, the deep meters indicated low-frequency oscillations in the flow. These oscillations were coherent with those at mooring 6 at better than 95% confidence level, with a lag at mooring 5 of approximately two days. This corresponds to an advective velocity of 10-15 cm sec^{-1}, which is consistent with observed deep-water flow. These observations as well as some unpublished flux calculations strongly suggest advection, rather than horizontal dispersion, as the process responsible for deep-water property changes in the main basin.

The winter '80 time series of water properties at mooring 6 indicated a generally decreasing salinity and an almost isothermal temperature profile (Figure 29). The average salinity decreased by roughly 0.3 $^{o}/oo$ over the 60-day interval. Note that the winter '80 salinities were on the order of 1 $^{o}/oo$ less than the summer '79 observations. As with the summer time series, the deep water showed strong oscillation especially near the beginning of the record. The near-surface water showed one major "pulse" of low-salinity water, around 12-15 March. Note that the salinity at 66 m increased during this event.

The temperature structure of the water column weakened during the time of the observations, becoming virtually isothermal by the middle of March. A sharp cooling of the deep water occurred around 18 February, concurrently with a decrease in salinity. This is in contrast with the inverse correlation observed during the summer at mooring 6. It is, however, consistent with observations in winter 1973 when cooler water appeared to enter without any apparent increase in bottom density (Cannon and Ebbesmeyer, 1978).

The velocity field observation at mooring 6 during winter showed more high-frequency energy and more irregularity in the baroclinic field than in the summer observations (Figure 30). As in the summer, the deep-water inflow was correlated with changes in salinity. There were several periods of significant deep-water outflow, indicating a characteristic of the normal baroclinic regime. Several episodes of relatively high-frequency baroclinic oscillation were evident, with a period of about 2.5 days. The most distinct such episode is from 8 to 15 March, coincident with the low-salinity "pulse" in the upper-water column. Whether the motion is forced at the observed frequency, or whether the oscillation is a resonant response of the estuary is yet to be determined.

5. DISCUSSION AND CONCLUSIONS

Observations of currents and water properties have been made in Elliott Bay and in the main basin of Puget Sound during both summer low runoff and winter high runoff. The primary purpose of this work was to provide a better description of circulation features that would affect the movement and dispersion of dissolved and suspended substances within the bay. The main circulation features were the semidiurnal tidal currents and the river effluent shown by the near-surface salinity distributions. Both tidal and subtidal currents were weak, on the order of 5 cm/sec, with no large differences between summer and winter. Variations in other aspects of the flow, however, could be seen between the inner and outer embayments, and between summer and winter runoff conditions.

Circulation in the outer bay west of Duwamish Head was closely linked to that in the main basin. Flood and ebb tidal currents near the bottom ran south and north, respectively, following the bathymetry. Currents at 30 m followed the same general pattern, except for some indication of a shoreward component to the flow. For longer than tidal periods the average flow was predominantly to the north, particularly near the bottom. However, main basin average flow at this same depth of about 130 m was to the south, thus suggesting a counterclockwise, subtidal flow at middepth in outer Elliott Bay (Figures 8 and 11). The above was observed both in summer and winter. Density and salinity profiles across the mouth of the bay indicated water flowing into the bay at depth, particularly on the south side during summer (Figure 14).

Inner-bay circulation showed several contrasts with the outer bay. Tidal currents were weaker. Flow in the inner bay oscillated with each tide, except that near-bottom currents in the northeast part of the bay (mooring 1) had an onshore component during the summer (Figures 4 and 5). Subtidal flow was weakest in the northeast during both seasons, but was generally outward at 30 m and inward at depth. One exception occurred during summer at the southeastern mooring, 2A, where subtidal currents appeared to flow weakly northward. During winter high runoff, near-bottom subtidal flow in the southeast was stronger and almost always steadily inward (Figure 13). This would seem to be a manifestation of the estuarine flow, except that subtidal currents at 30 m were of the same order of magnitude during both seasons. At the northeastern mooring, near-bottom flow during summer was steadily onshore, but generally offshore during winter.

Surface salinity and temperature surveys showed that the Duwamish River plume was always located on the north side of the bay. In the winter during high runoff, water at the river mouth was lower in salinity by about 6 $^{o}/oo$ than in summer, and in the outer bay by about 2 $^{o}/oo$. Winter results showed most of the freshwater to be leaving the bay in the north, with a small amount passing Duwamish Head. Summer results showed all water leaving by the north side of the bay on ebb tides as in winter. During flood tides in the main basin, river flow was suppressed and isohalines were moved 1-2 km back toward the river mouth (Figures 21 and 22).

Variations in the plume during summer low runoff were also distinguishable from surface observations made from the Washington State ferries (Helseth et al., 1979). The standard deviation of mean salinity increased sharply in the inner bay, and the mean temperature increased into Elliott Bay from a minimum in the main basin. Even though runoff was extremely low, a salinity front was observed across the bay in the general vicinity of Duwamish Head. Unfortunately, no observations of this nature were possible during high runoff.

When these results were compared with the Puget Sound hydraulic model, there were some similarities as well as differences. The estuarine flow in the inner bay showed reversal between inflow and outflow at 37-55 m in the model. CTD and current meter data from the field experiment seemed to suggest a depth range of 40-75 meters, although this was hard to determine accurately because of the few current measurement points distributed vertically in the water column. The model suggested a predominance of river water leaving the bay past Duwamish Head in the south, with the only exception being during periods of high runoff coupled with weak tides (Winter, 1977). Other dye studies in the model also have suggested that water from the west waterway is flushed outward around Duwamish Head (Rogers, 1955). Field data, however, seem to show the opposite. During low runoff, the river plume was on the north side of the bay for both flood and ebb tides. High runoff results also showed most of the river plume on the north.

Inner Elliott Bay is also a dredge spoil site for Duwamish River sediment, which is possibly contaminated with pollutants. If this dredge spoil were resuspended, bottom currents might transport it onshore. Previous studies of this dredge site (Dexter et al., 1979; personal communication with E. A. Quilan) showed bottom sediments consisting of consolidated silt with organic content. Unconsolidated course silt can be resuspended when water speeds are about 23.5 cm/s at 2 m above the bottom. However, the Elliott Bay silt would require greater speeds due to the consolidation and organic content of the silt. Bottom currents measured 6 m above the bottom in these studies were greater than 23.5 cm/s only infrequently, and only at two sites. This current speed was never exceeded during the winter observations. During summer from 5-10 September at mooring 1A, this speed was exceeded for periods ranging from 10 minutes to 2 hours with maximum speeds ranging from 24.0 - 48.0 cm/s. The mean maximum speed was about 34.0 cm/s for a duration of about an hour. The other summer mooring was 3A, where the flow exceeded 23.5 cm/s on only four occasions from 8-10 September. On two of those occurrences, mean maximum speeds were 33.0 cm/s for almost 2 hours. Thus, these studies show few times when speeds seem large enough to resuspend bottom sediments in the inner bay. However, the companion suspended sediment observations made by Baker (1981) show relatively high concentrations near the bottom.

Flushing rates or water residence times cannot be calculated from these data, partly because no observations could be made in the water from 30 m to the surface. However, some idea of these rates may be obtained using the progressive vector diagrams (PVD) from the current observations to indicate possible water excursion during the observation period. The inner bay is about 4 km wide in each direction. Combining this with the implied excursion from the PVD gives an idea of the time necessary to move water completely into or out of the inner bay for various currents (Table 2).

In the inner bay these net flows at 30 m and near the bottom were most illustrative (Figures 31 and 32). During the summer and winter deployment currents at 30 m at both inner moorings were to the north out of the bay. The implied excursion of these currents was about 15-50 km, which is about 4-12 times the north-south length of the bay. The time required to traverse the length of the bay would be about 3 days at mooring 2 and 7 days at mooring 1 for both summer and winter. Flow near the bottom changed direction with season. At mooring 2, flow was north out of the bay during the summer, and

TABLE 2

INFERRED WATER RESIDENCE TIMES FOR INNER ELLIOTT BAY

Mooring	Duration (days)	Net Flow (cm/s)	Implied Excursions (km)	Direction (°T)	Transit Time of 4-km bay (days)
			A. Summer		
ELLBAY 1A					
30m	39.63	0.68	23.18	352	6.84
101m	24.25	4.77	99.48	78	0.98
ELLBAY 2A					
30m	37.21	1.61	51.52	336	2.89
92m	39.50	0.48	16.31	340	9.69
			B. Winter		
ELLBAY 1B					
30m	29.54	0.59	14.99	16	7.88
101m	29.54	1.06	26.93	296	4.39
ELLBAY 2B					
30m	29.50	1.63	41.35	347	2.85
90m	29.50	2.41	61.14	110	1.93

southeast into the bay during the winter. Flow was also stronger in the winter. The implied excursions and corresponding times to transit the inner bay in summer and winter were 16 and 61 km and about 10 and 2 days, respectively. Near bottom flow at mooring 1 was to the east into the bay during summer, and west out of the bay during winter. Here, summer flow was about four times stronger than winter flow. Summer transit time across the bay was about one day, but into the bay. Winter transit was several days. During all of these, however, speeds were usually not large enough to resuspend sediment. Thus, these implied excursions apply to sediment already in suspension.

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FIGURES

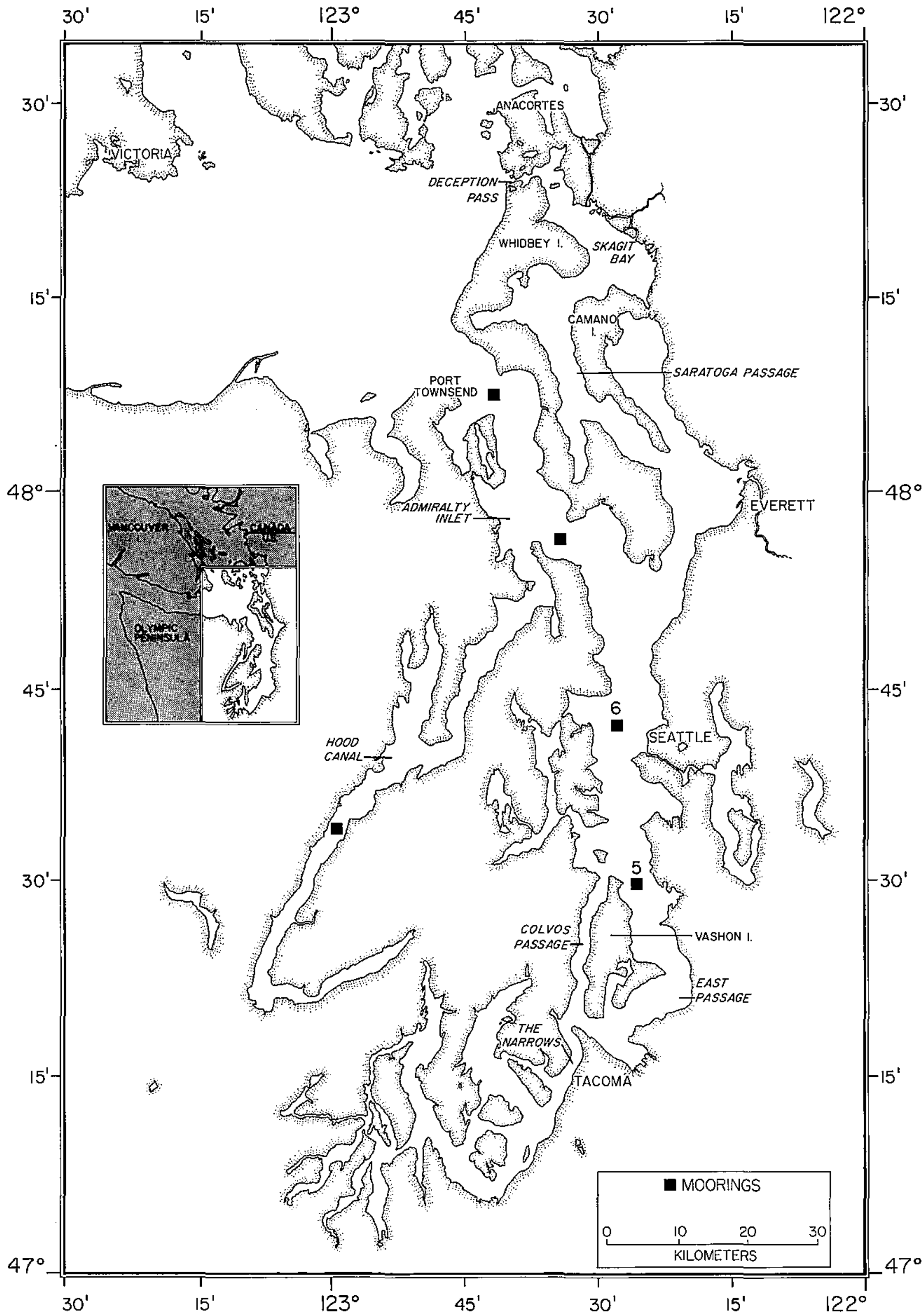

Figure 1. Puget Sound region showing Elliott Bay and the current meter moorings in the main basin.

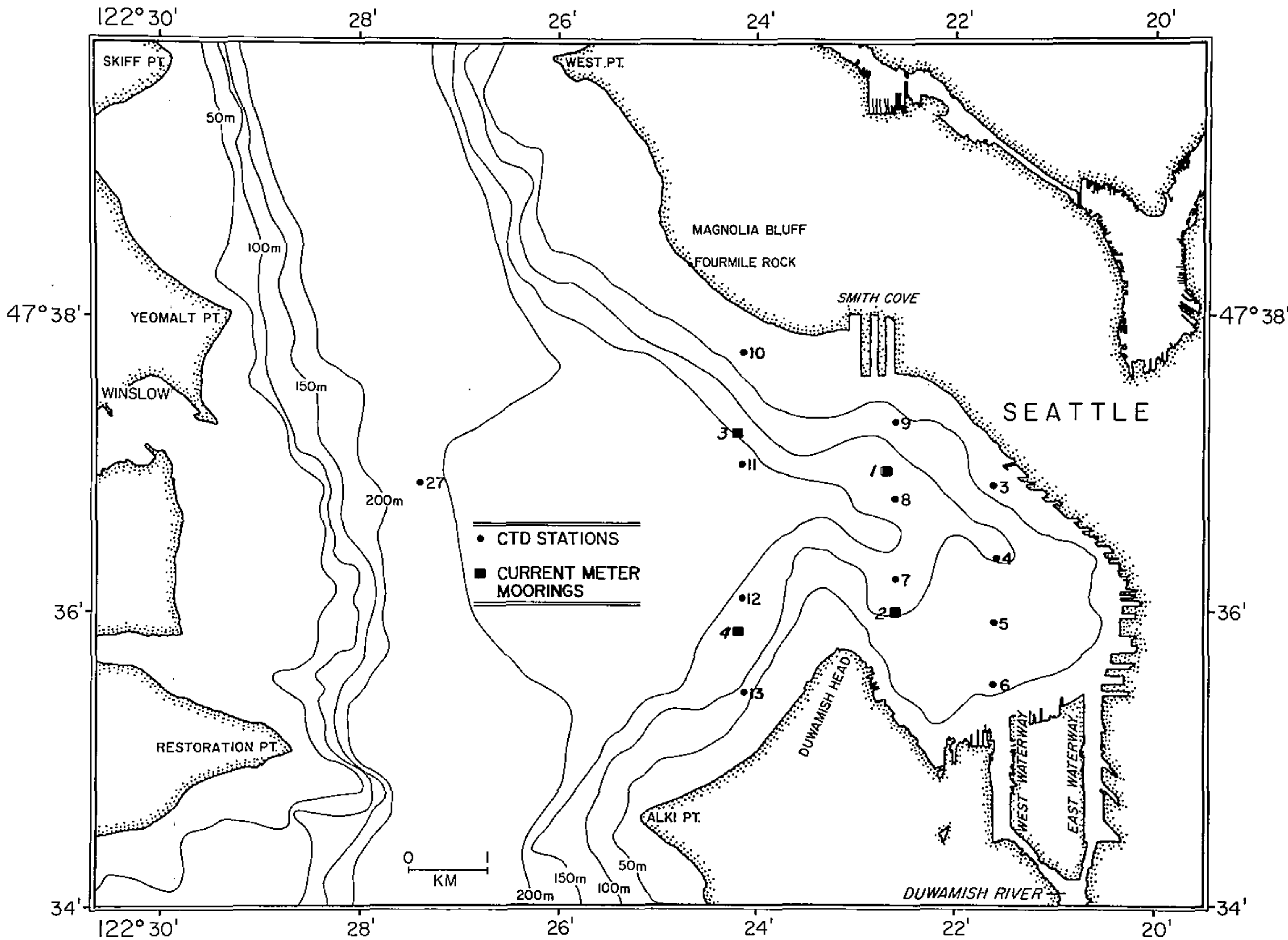

Figure 2. Elliott Bay showing current meter moorings and CTD stations.

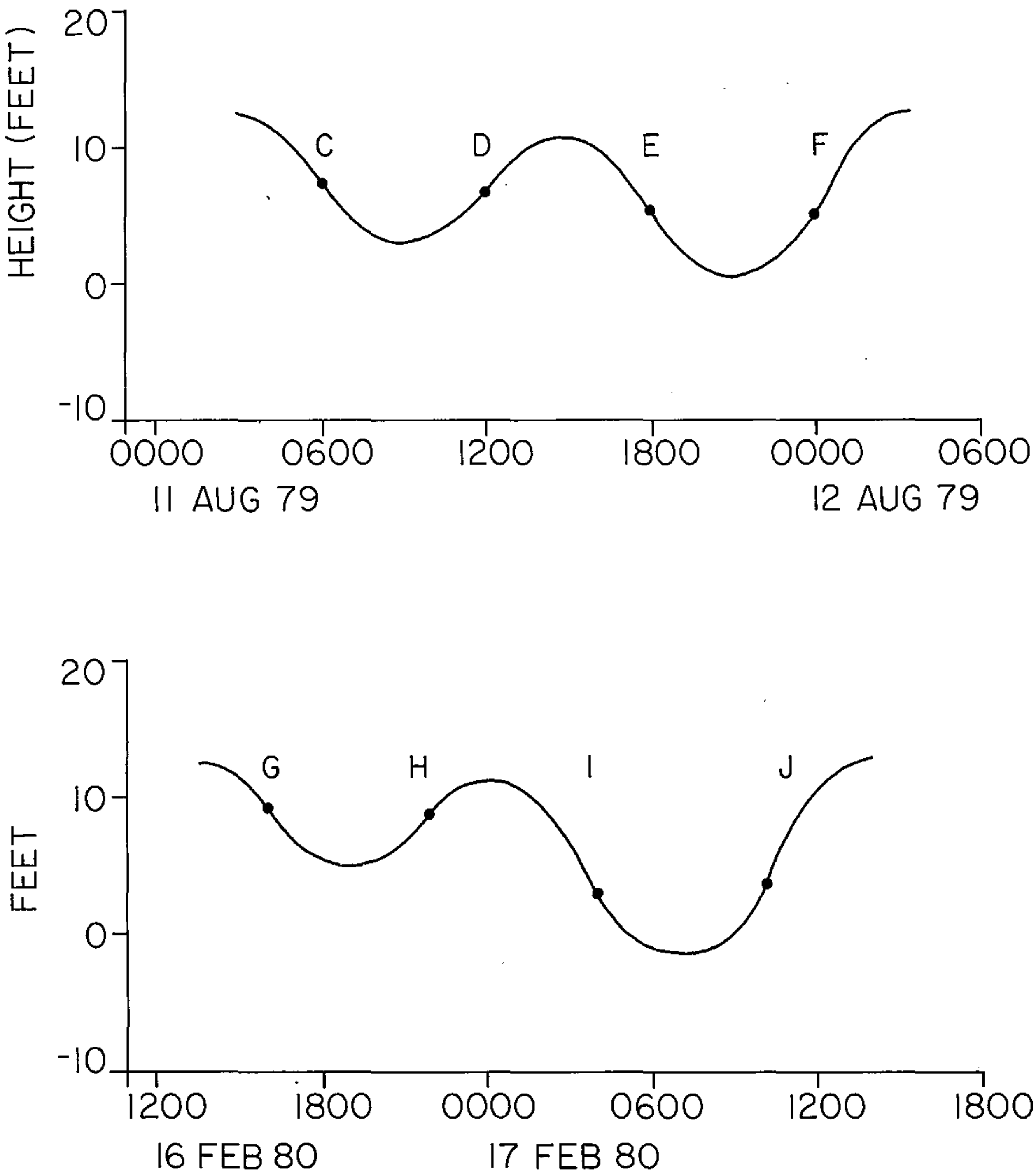

Figure 3. Times and heights of tides in Elliott Bay corresponding to tidal currents shown in Figures 4, 5, 6, 7.

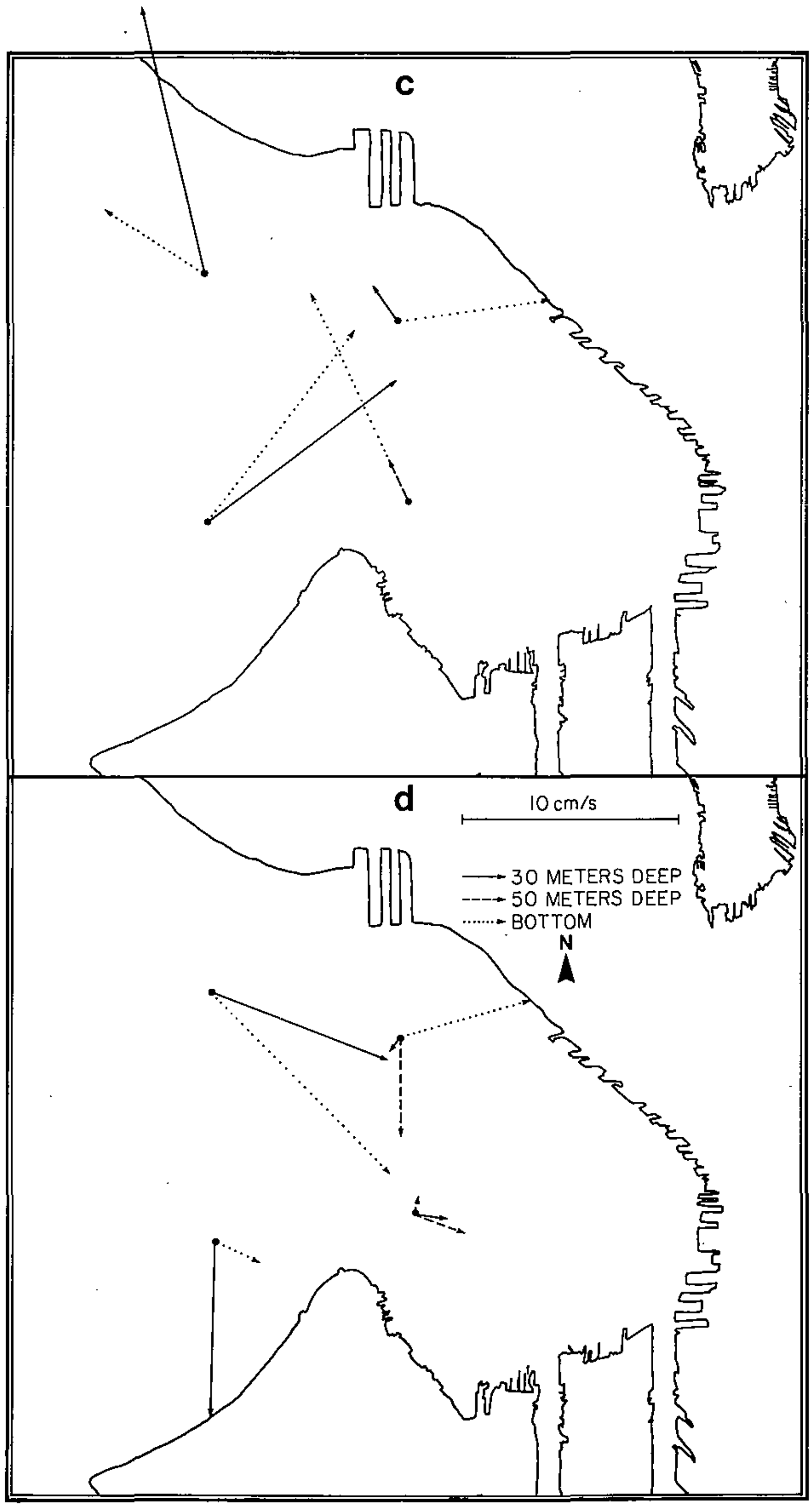

Figure 4. Summer tidal currents at the four current meter moorings in Elliott Bay for small ebb (panel C) and small flood (panel D) tides.

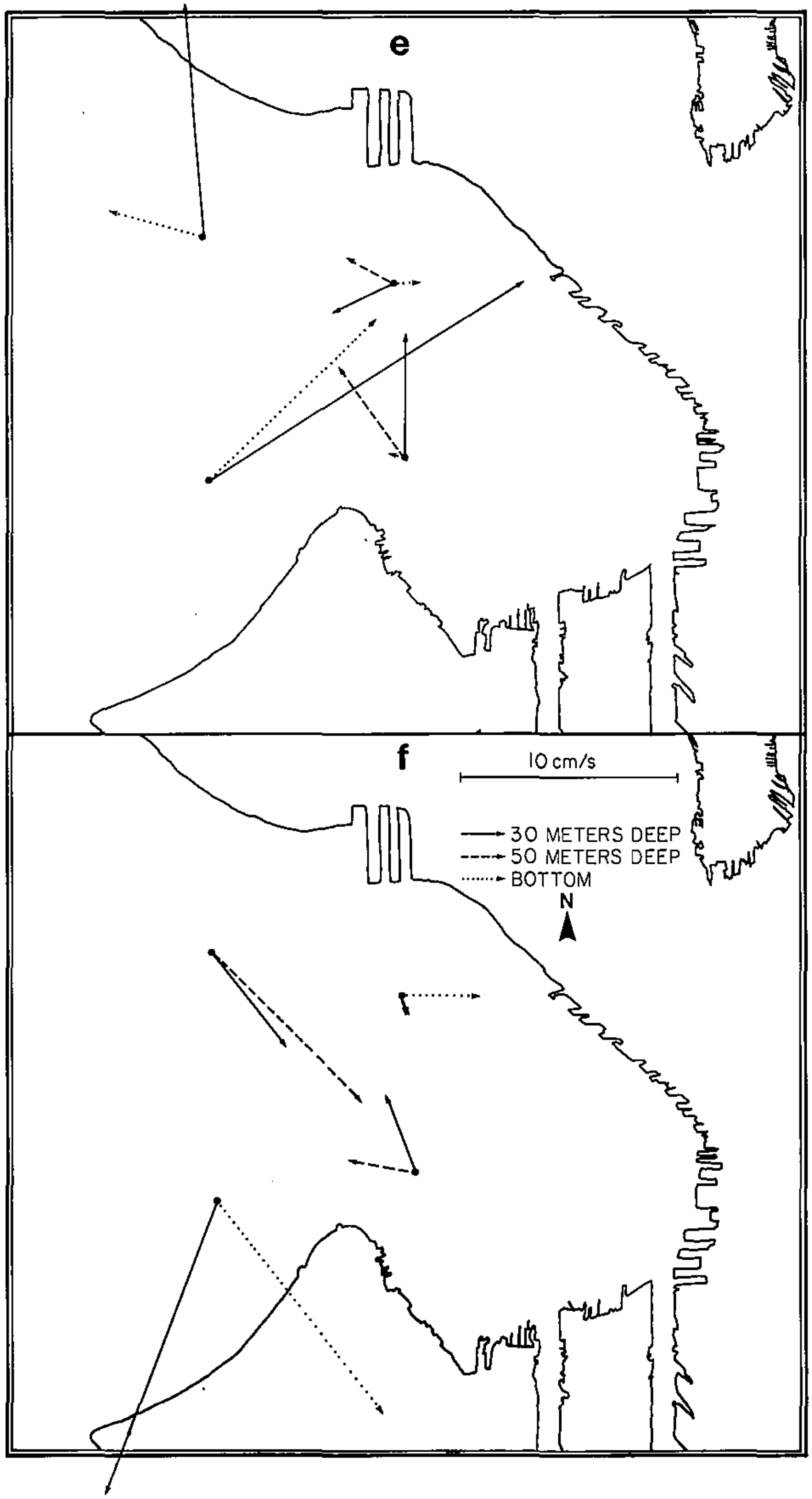

Figure 5. Summer tidal currents at the four current meter moorings in Elliott Bay for large ebb (panel E) and large flood (panel F) tides.

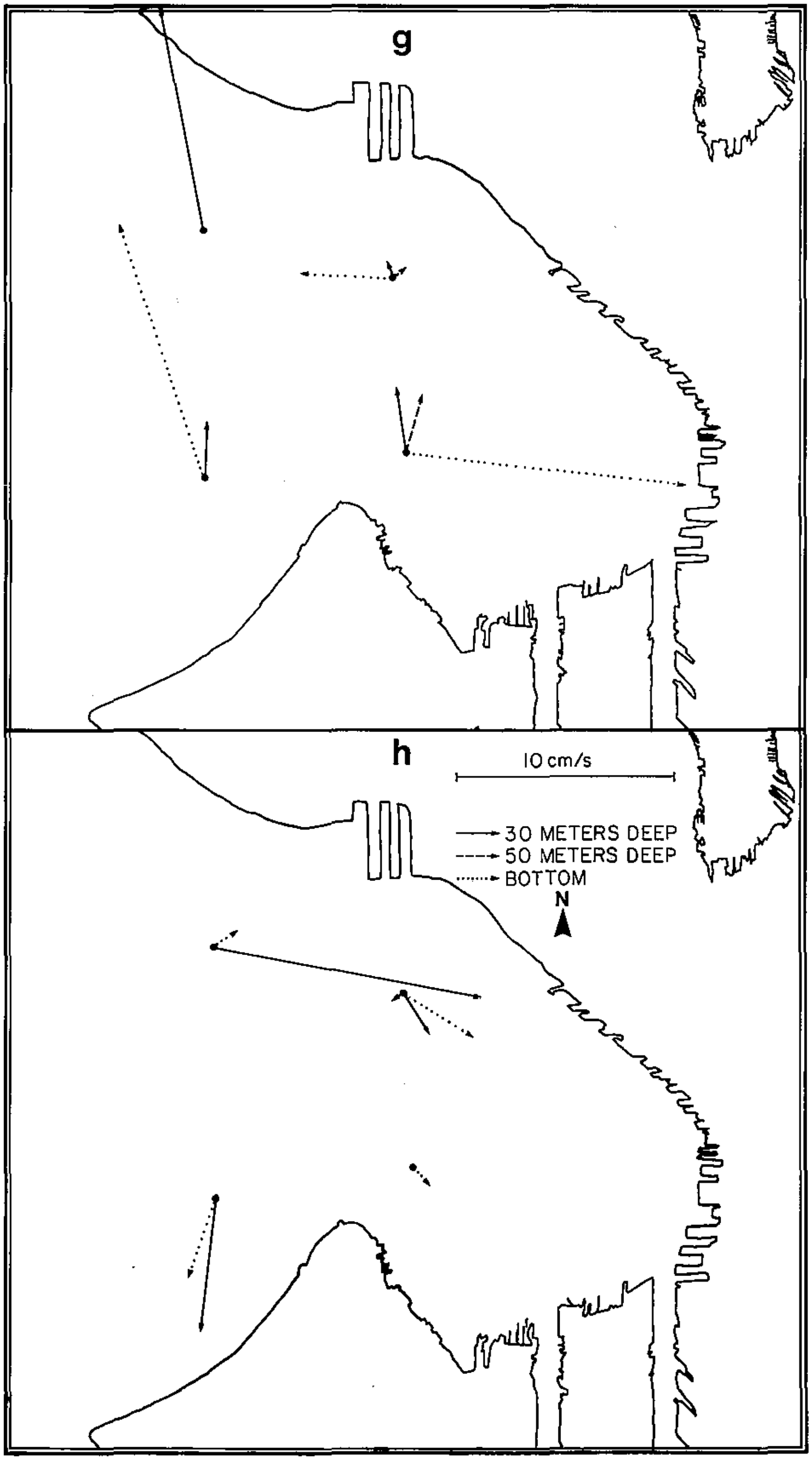

Figure 6. Winter tidal currents at the four current meter moorings in Elliott Bay for small ebb (panel G) and small flood (panel H) tides.

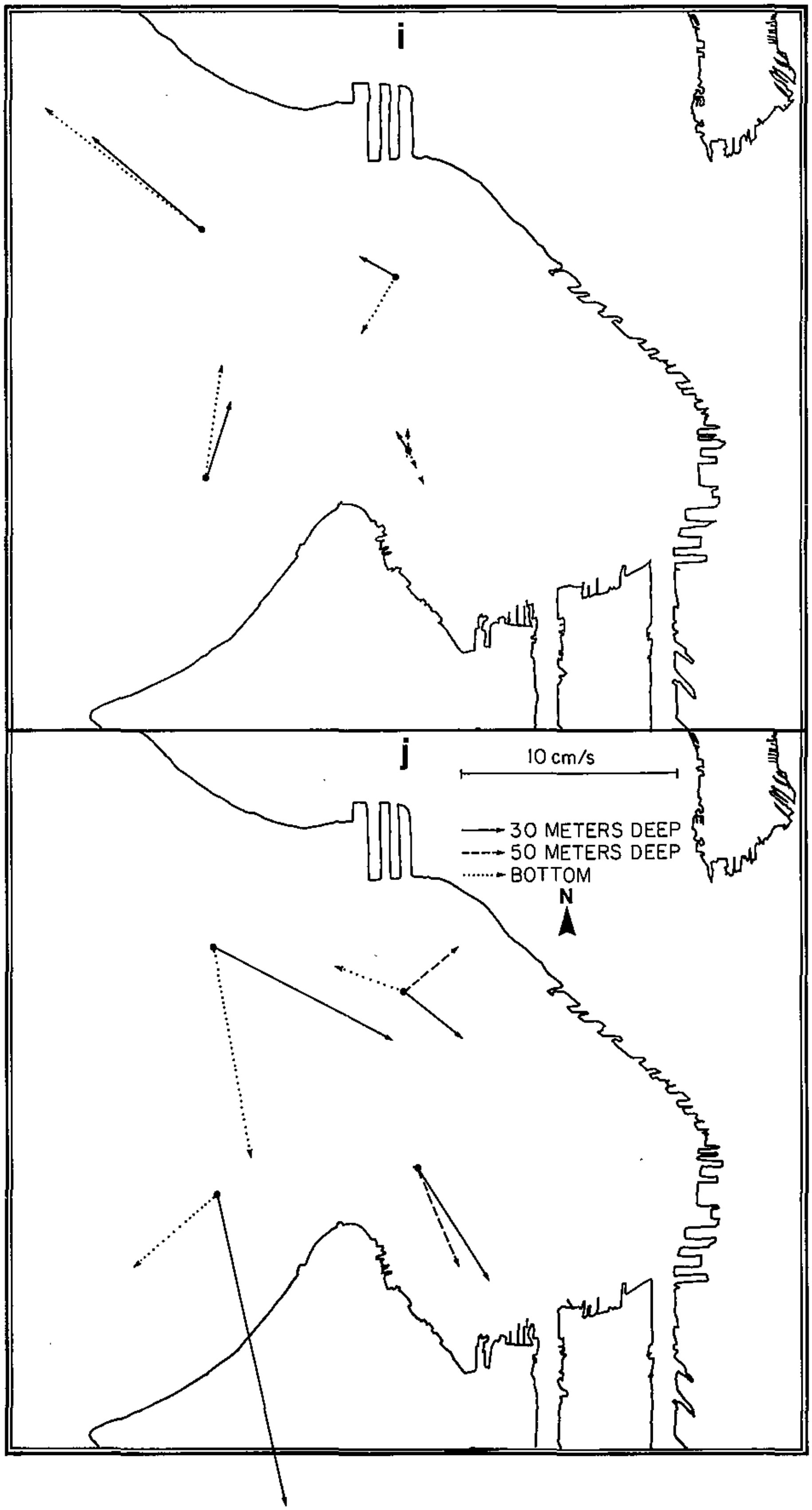

Figure 7. Winter tidal currents at the four current meter moorings in Elliott Bay for large ebb (panel I) and large flood (panel J) tides.

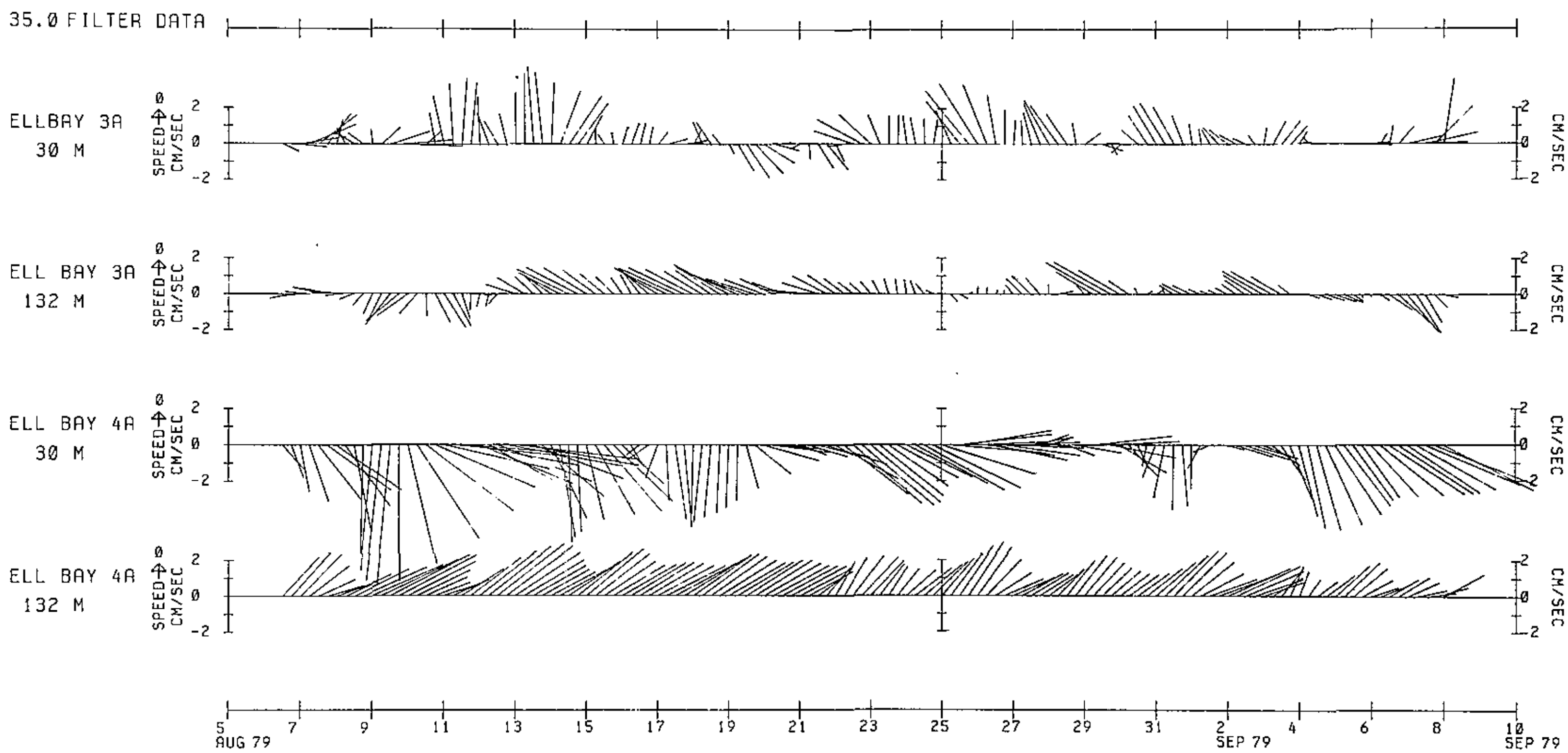

Figure 8. Summer subtidal flow in outer Elliott Bay for moorings 3A and 4A.

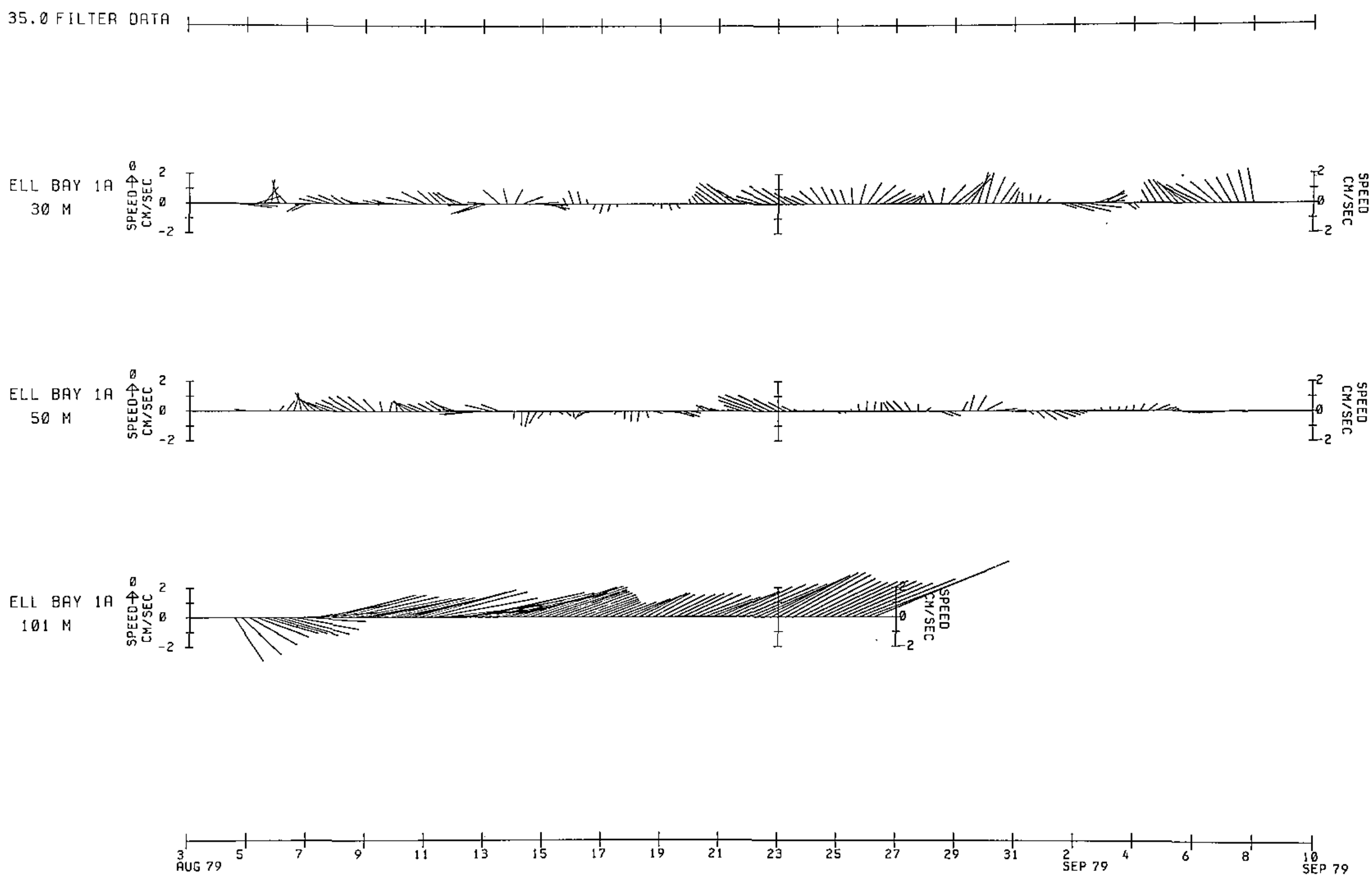

Figure 9. Summer subtidal flow in inner Elliott Bay, mooring 1A.

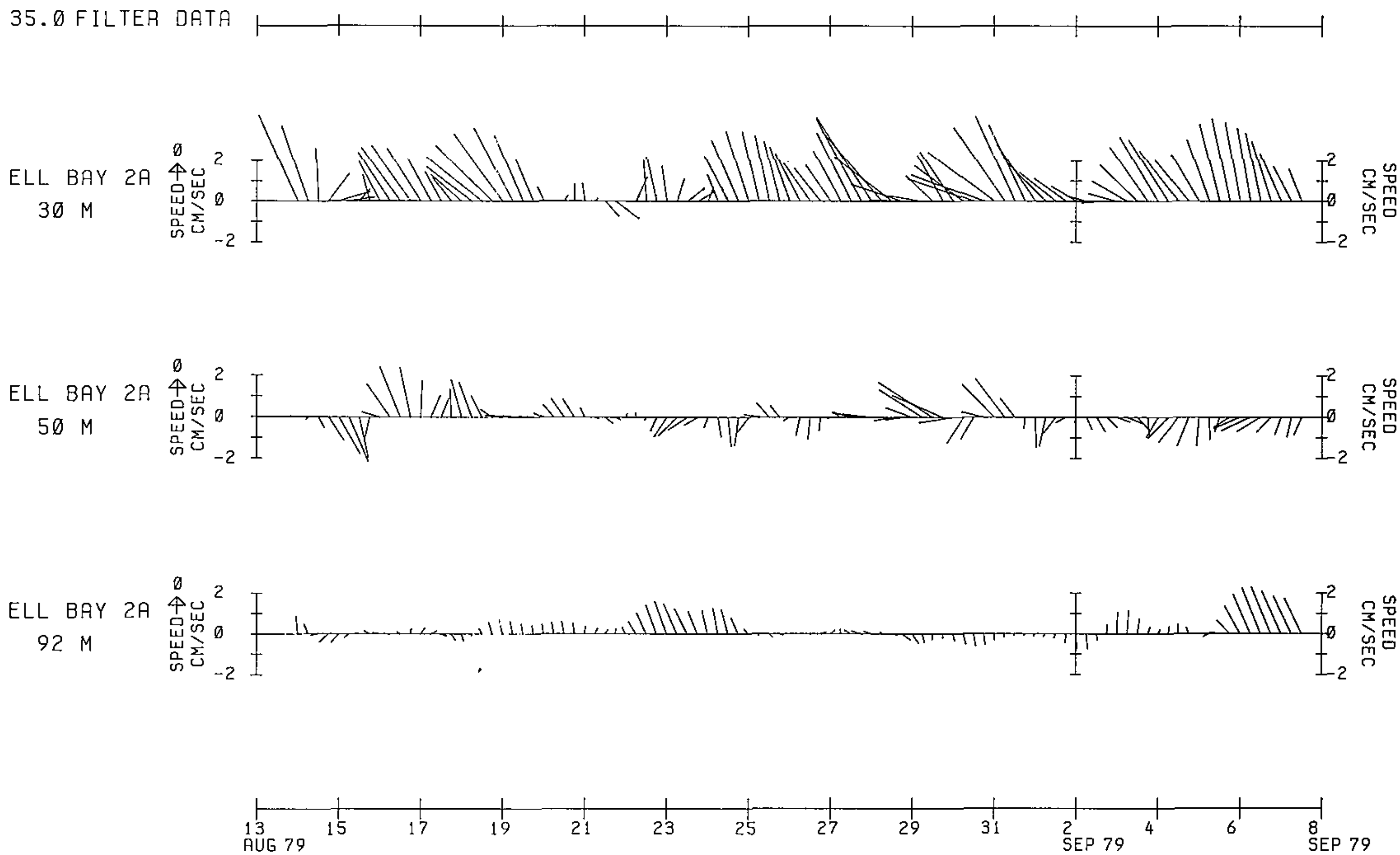

Figure 10. Summer subtidal flow in inner Elliott Bay, mooring 2A.

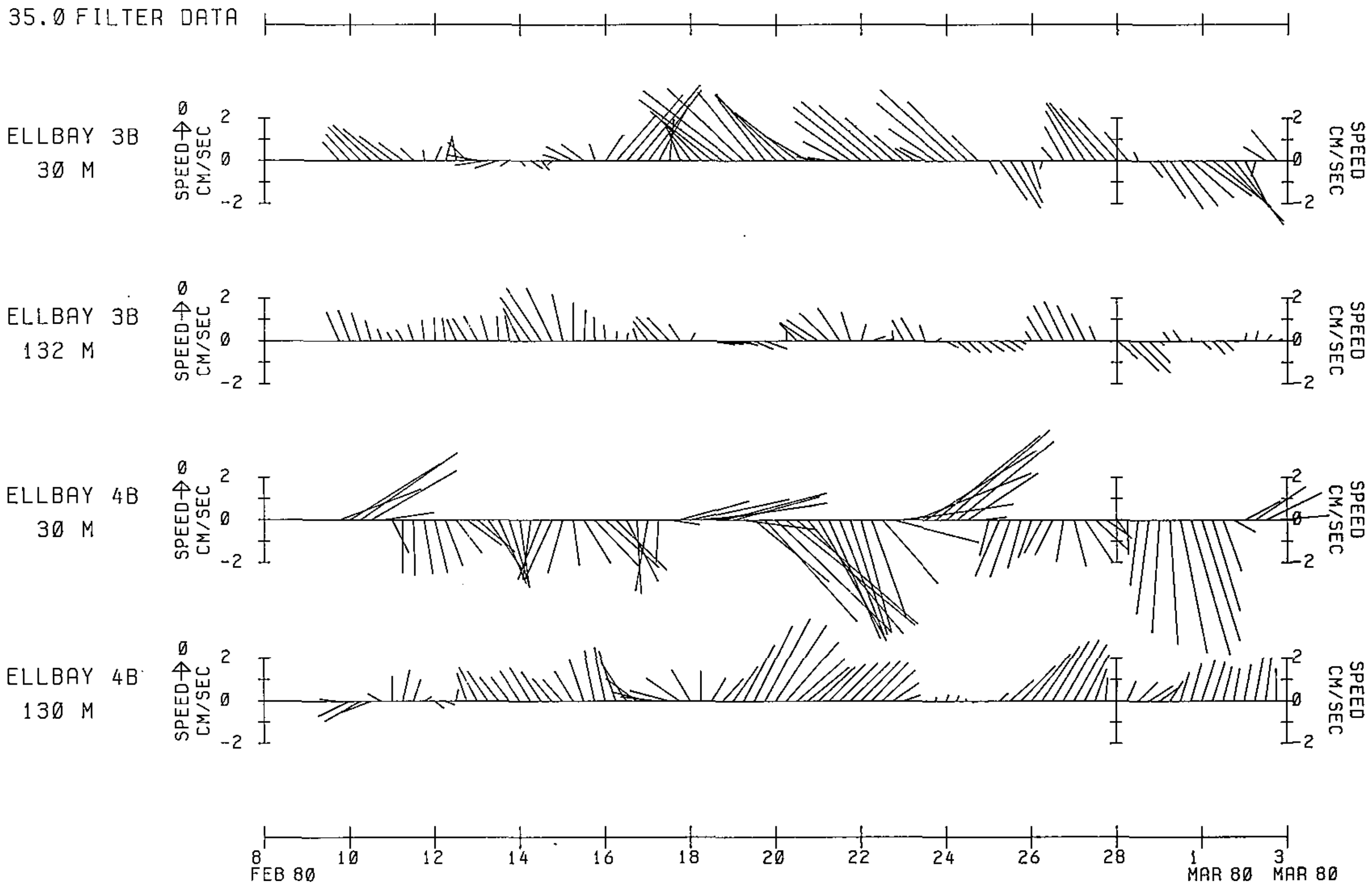

Figure 11. Winter subtidal flow in outer Elliott Bay for moorings 3B and 4B.

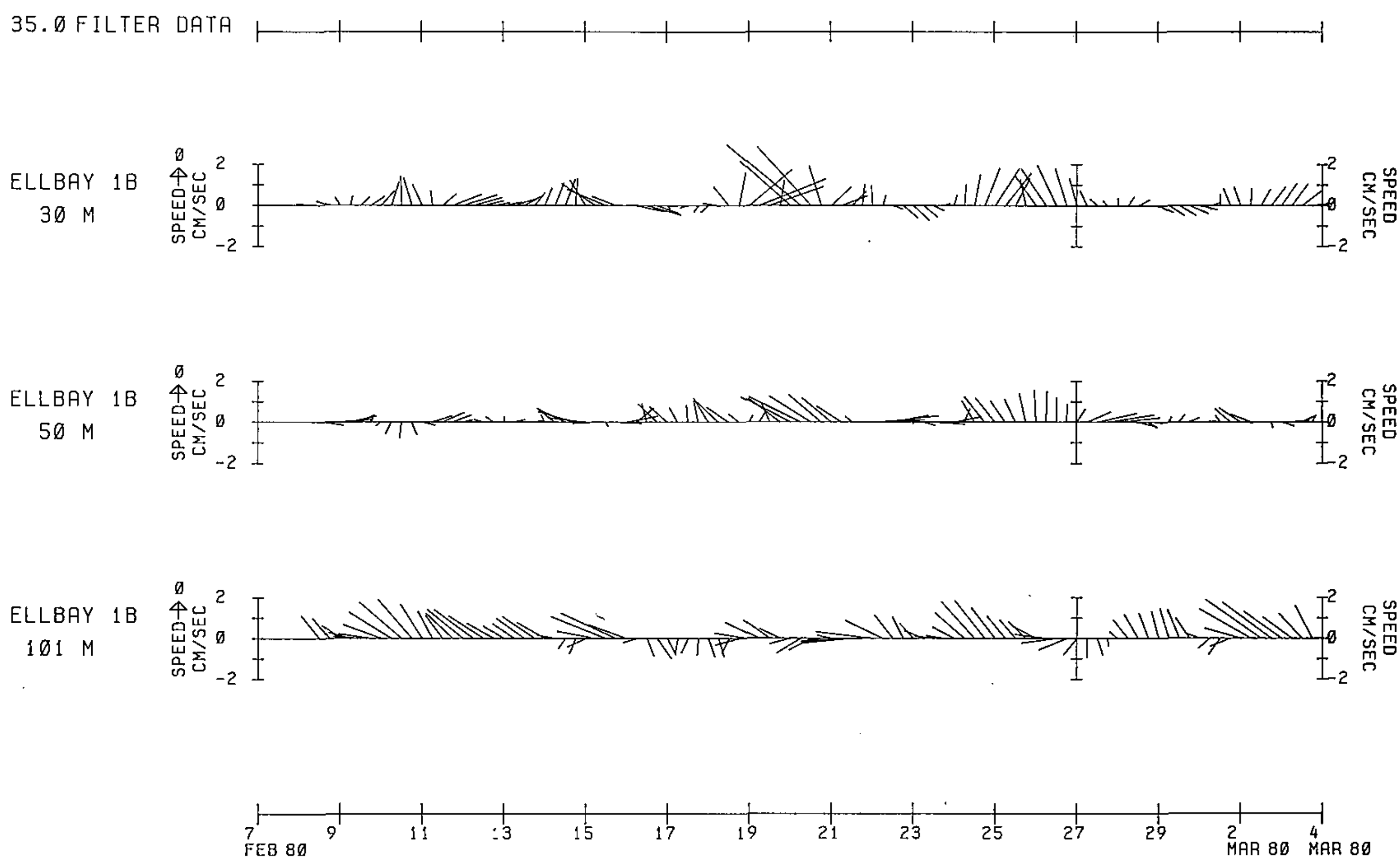

Figure 12. Winter subtidal flow in inner Elliott Bay, mooring 1B.

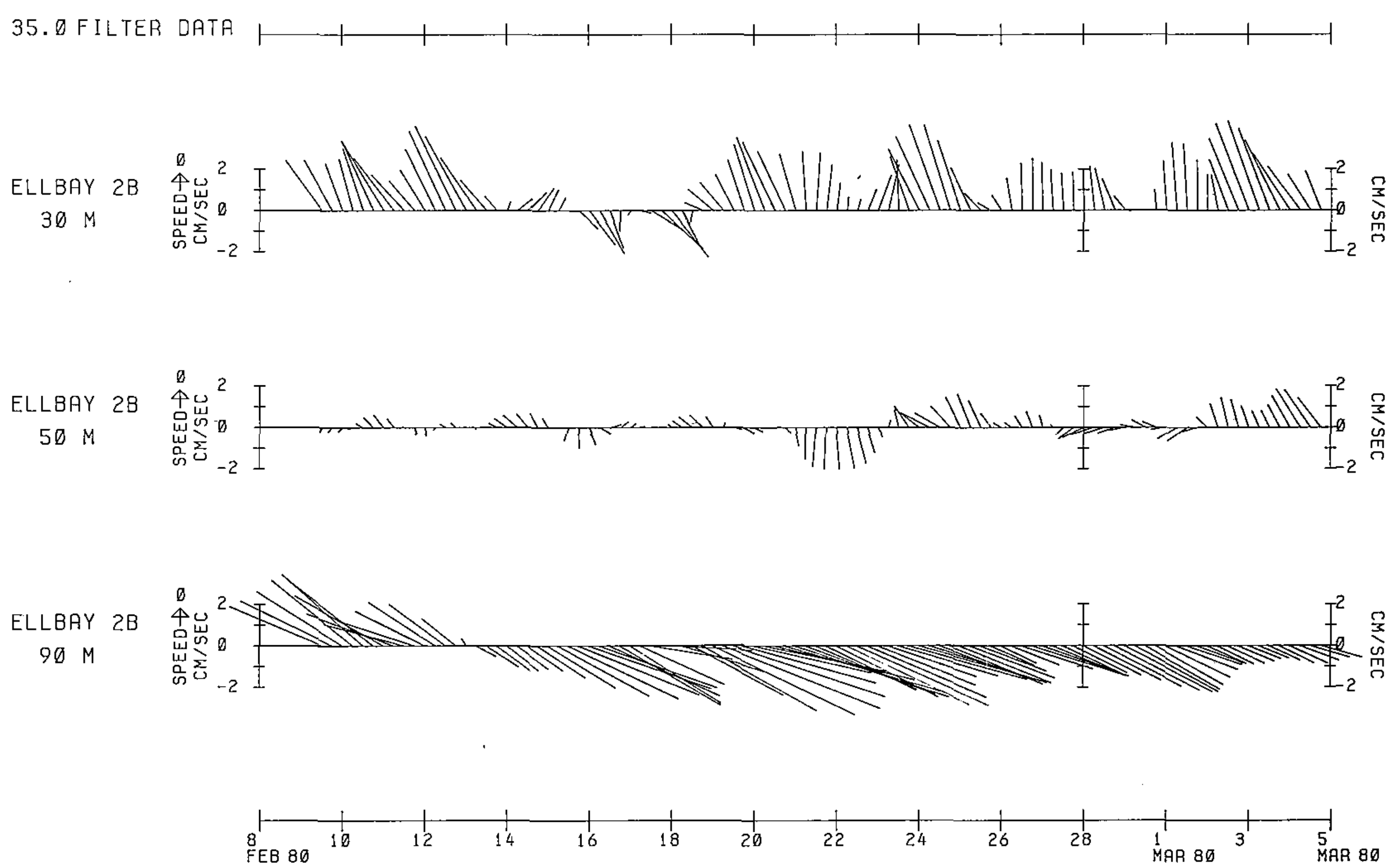

Figure 13. Winter subtidal flow in inner Elliott Bay, mooring 2B.

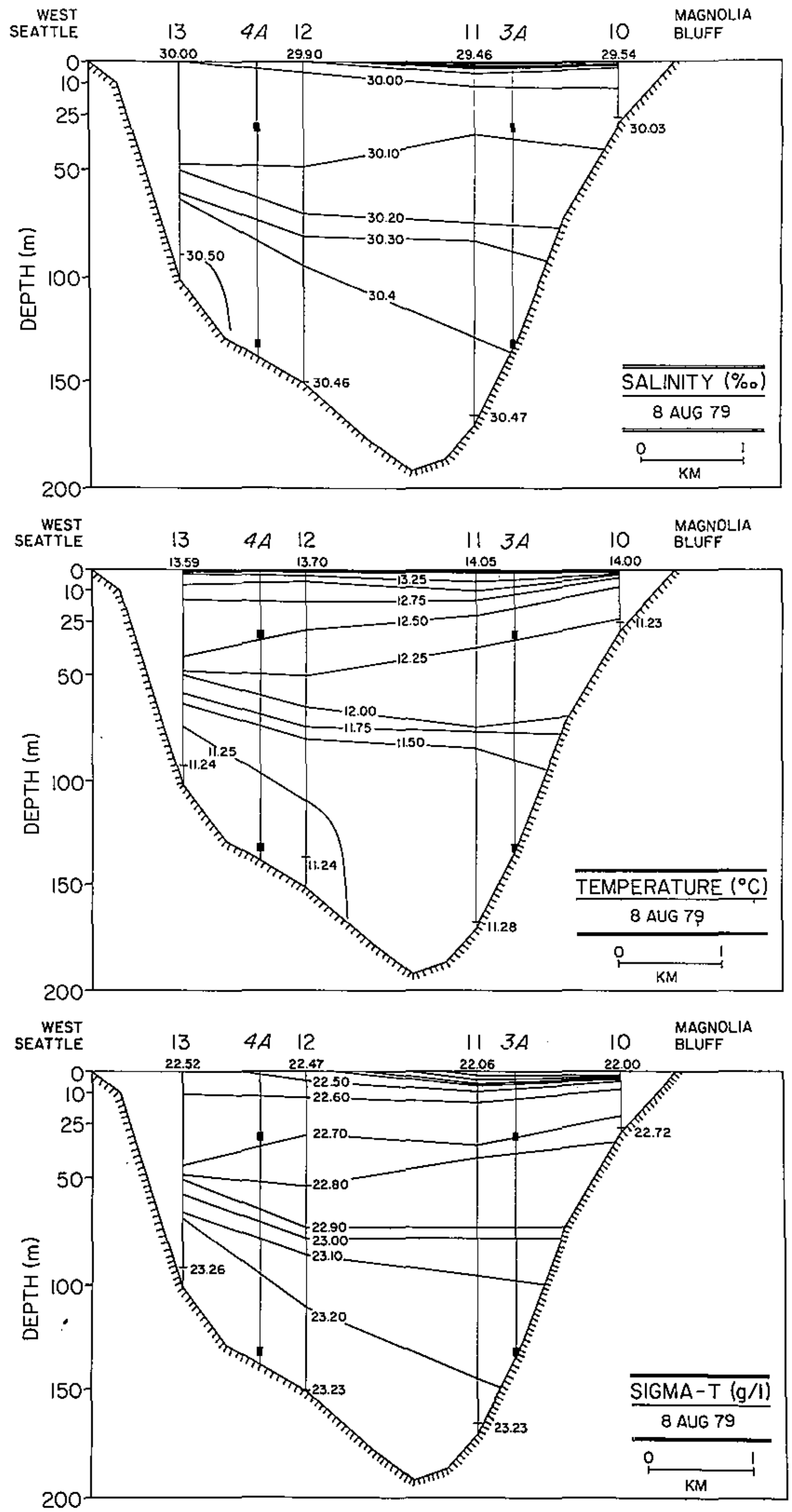

Figure 14. Summer south-north section across outer Elliott Bay.

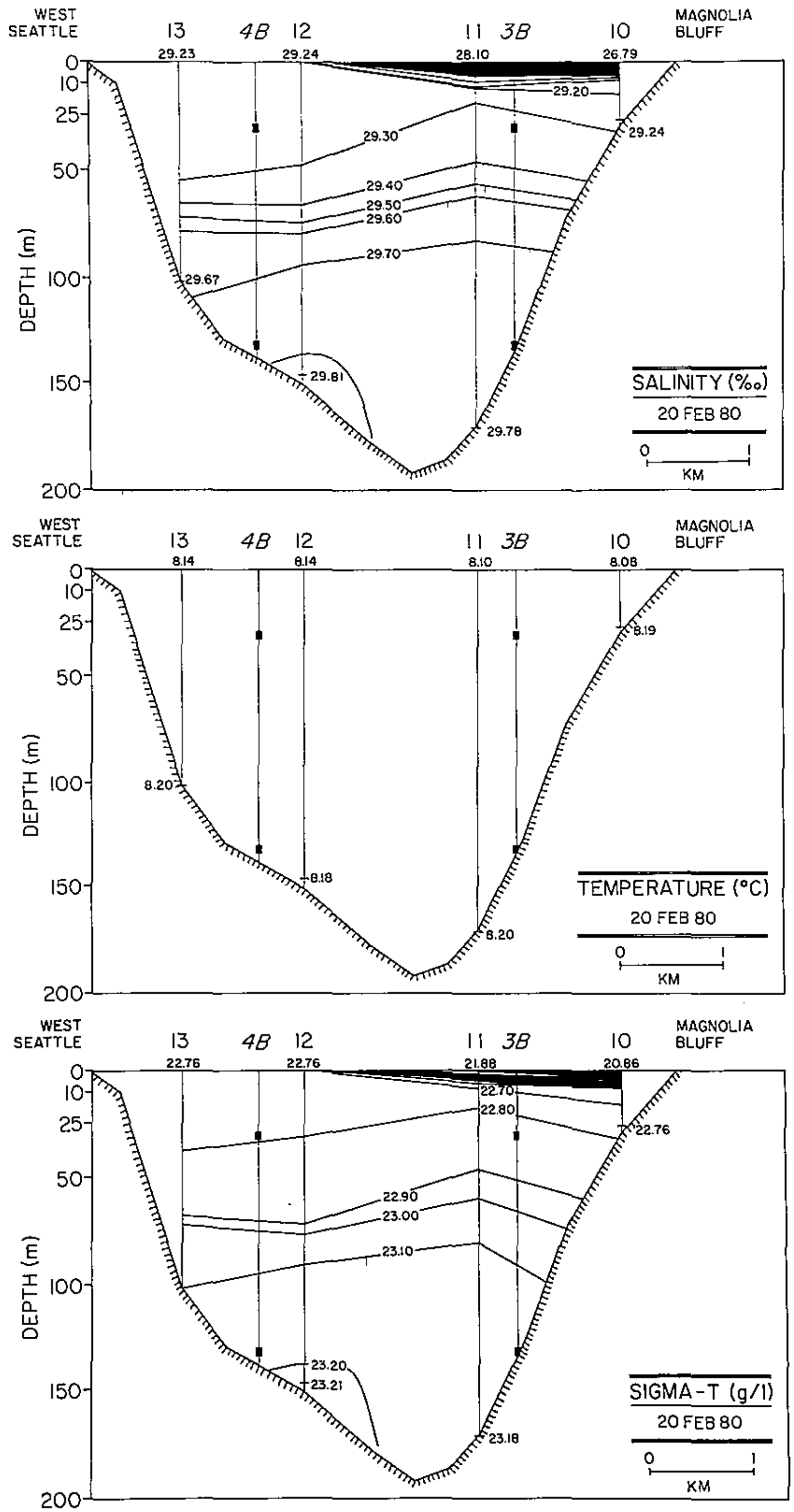

Figure 15. Winter south-north section across outer Elliott Bay.

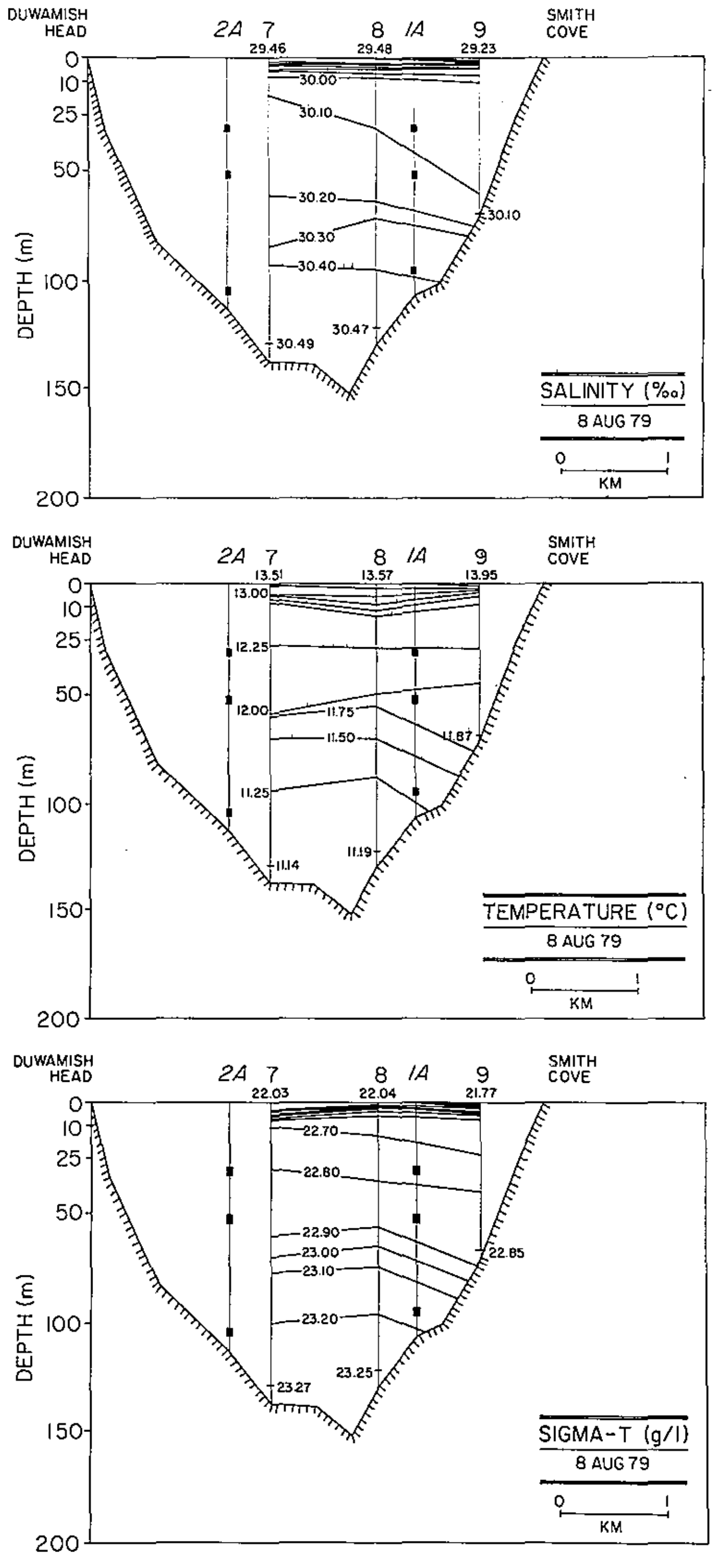

Figure 16. Summer south-north section across inner Elliott Bay.

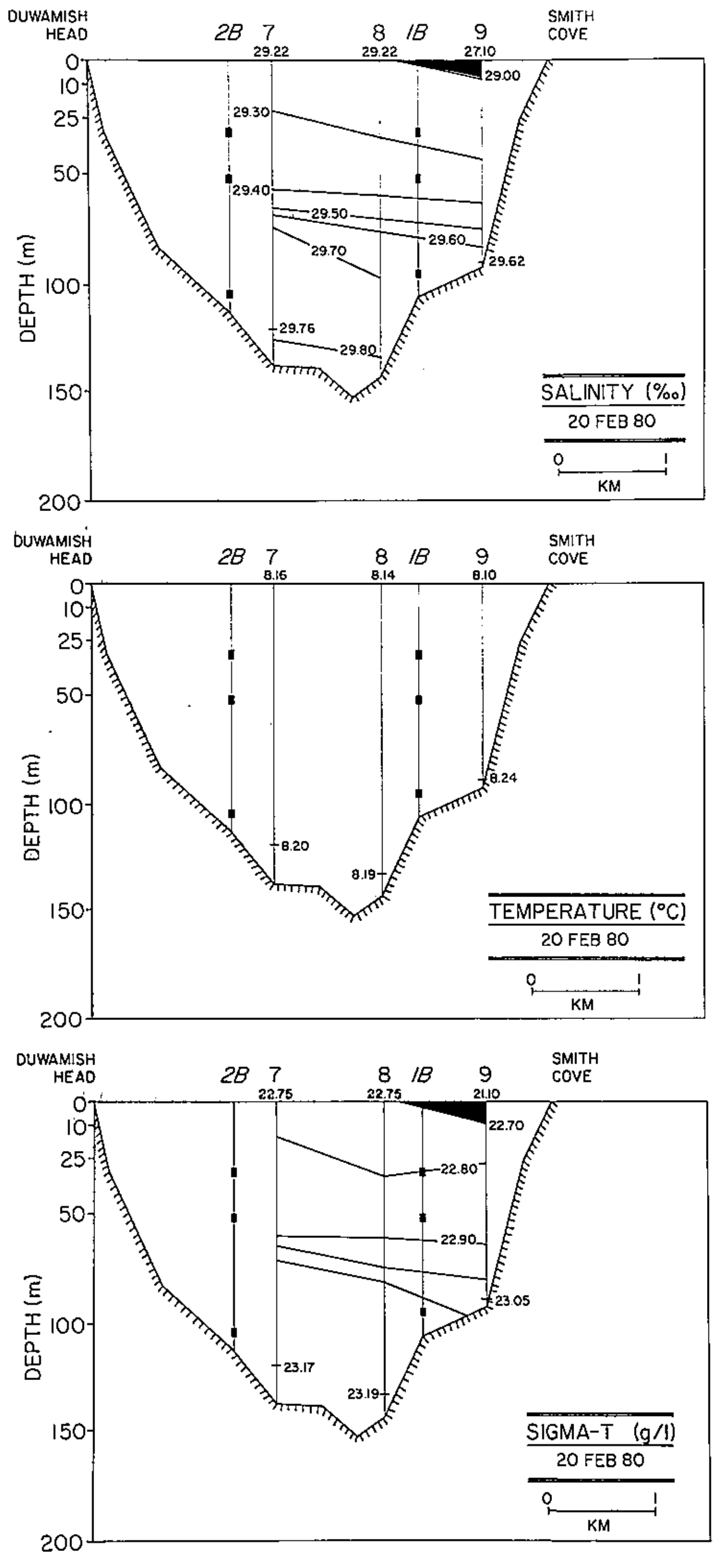

Figure 17. Winter south-north section across inner Elliott Bay.

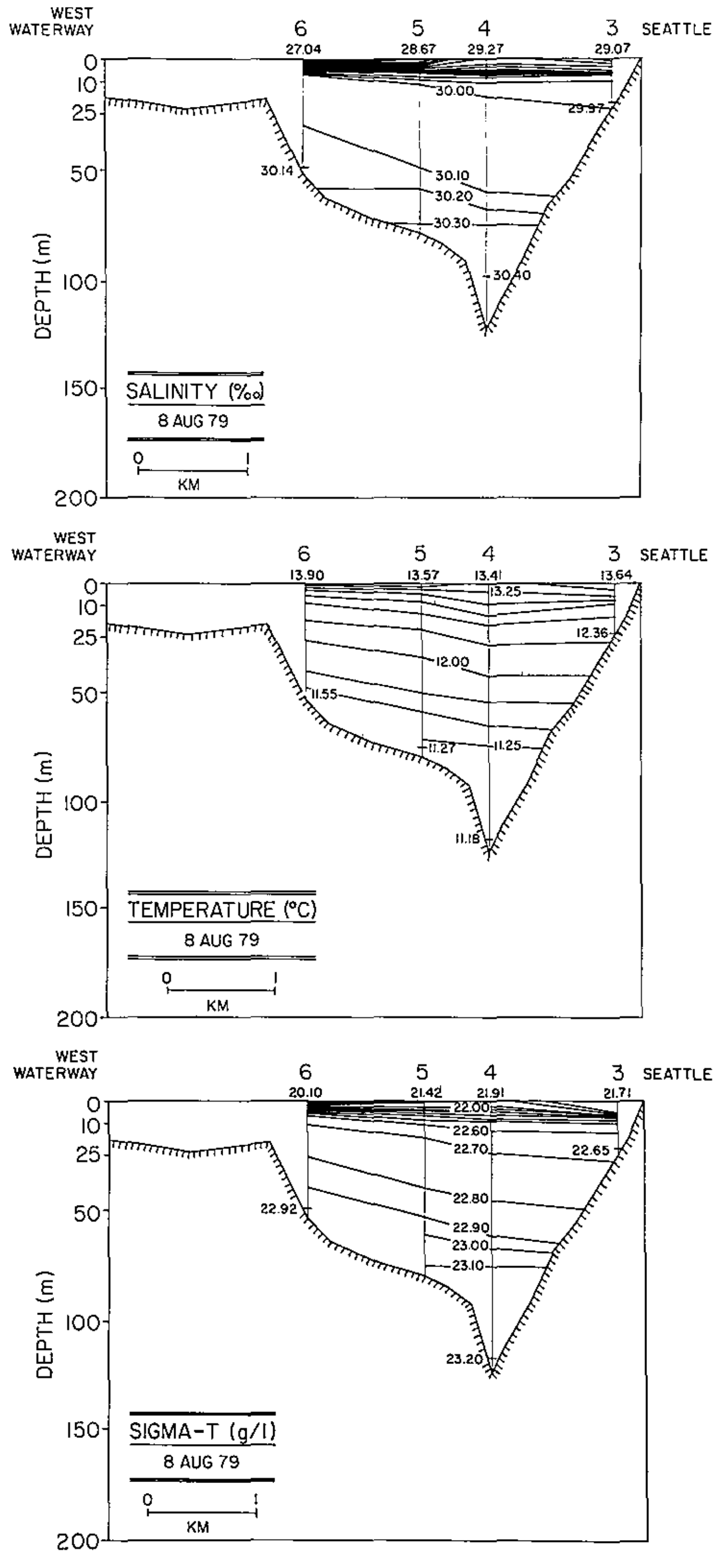

Figure 18. Summer south-north section from the mouth of the Duwamish River northward across Elliott Bay.

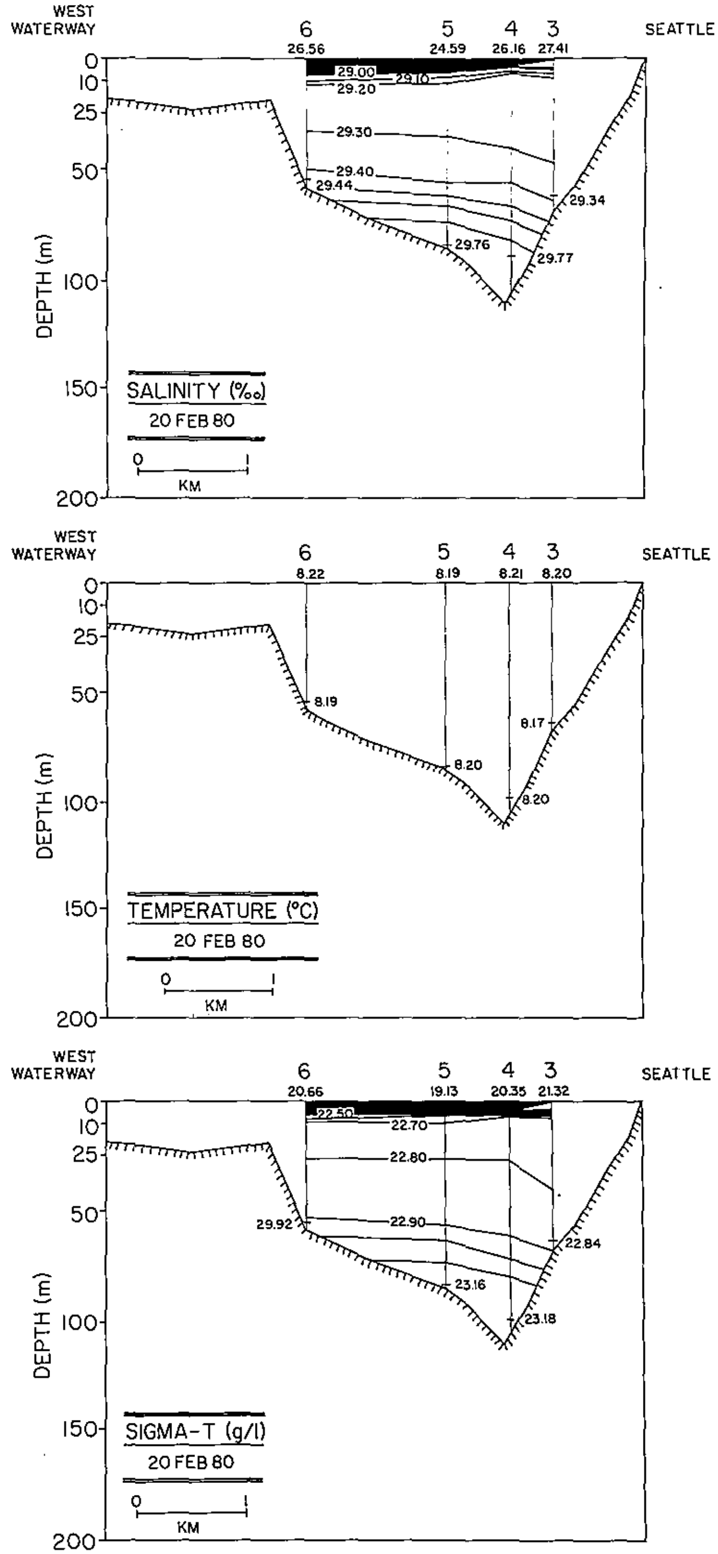

Figure 19. Winter south-north section from the mouth of the Duwamish River northward across Elliott Bay.

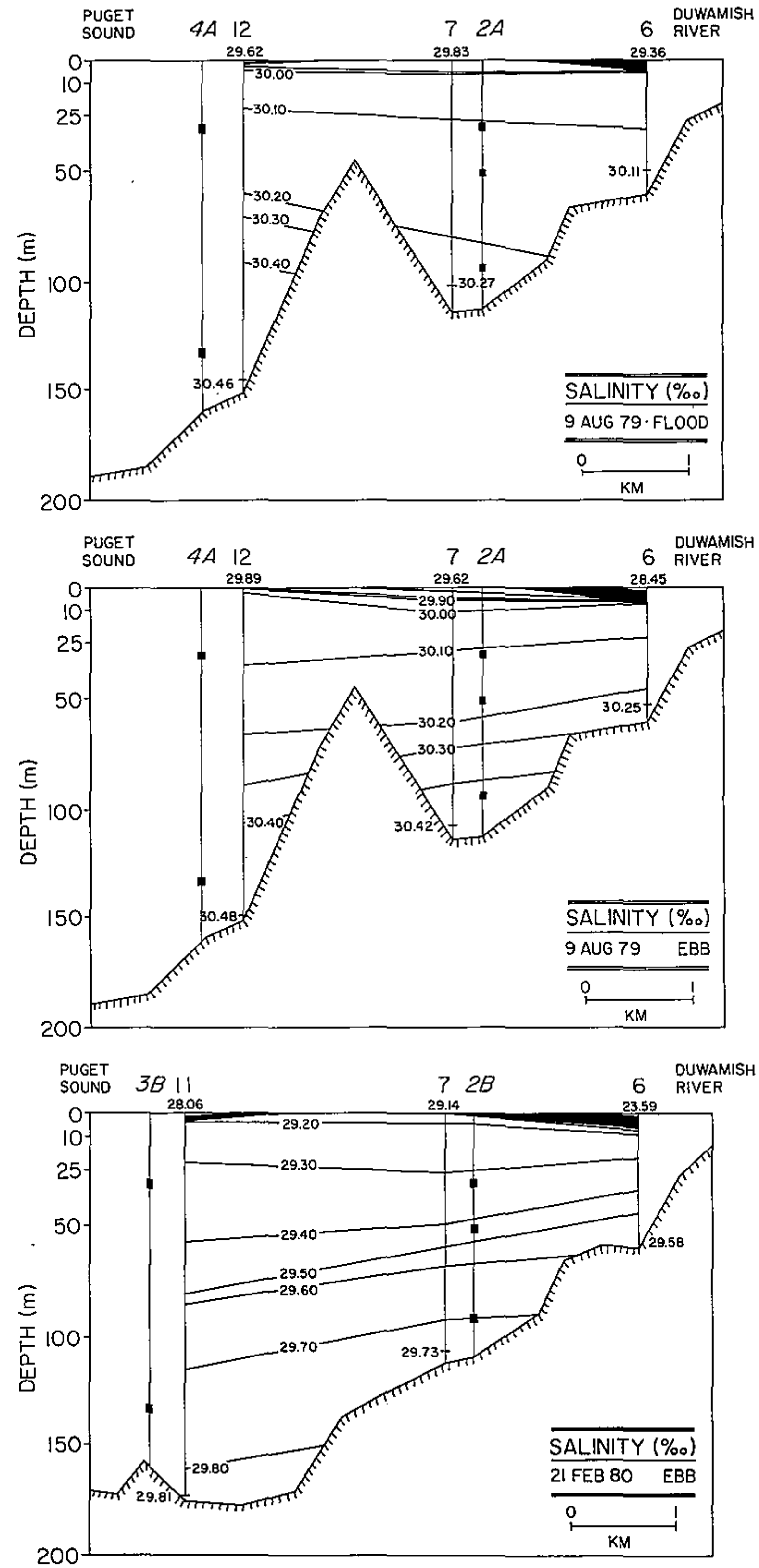

Figure 20. Axial section of salinity along Elliott Bay from the mouth of the Duwamish River to outer Elliott Bay for summer flood and ebb and winter ebb.

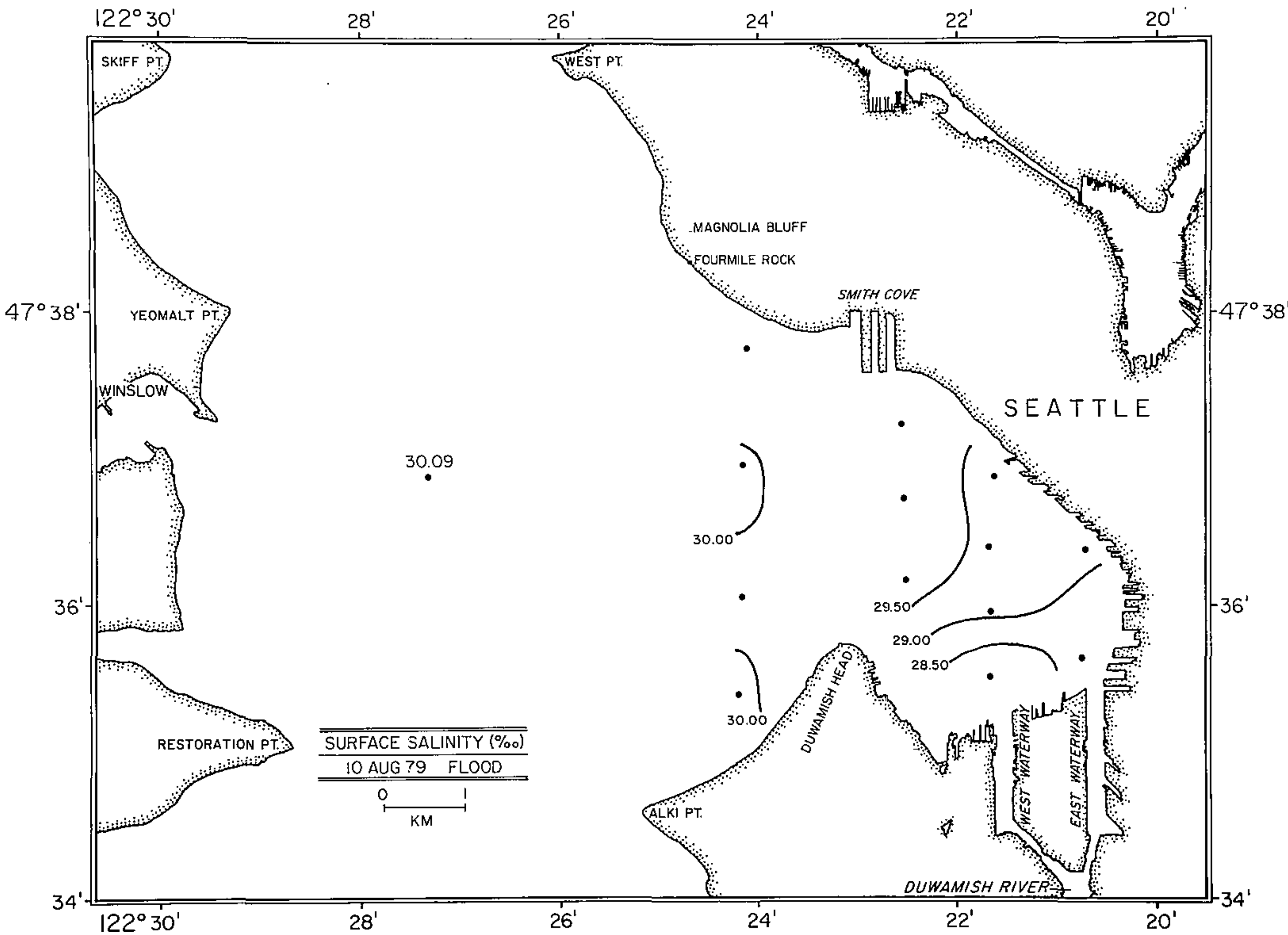

Figure 21. Summer surface salinity in Elliott Bay during flood tide.

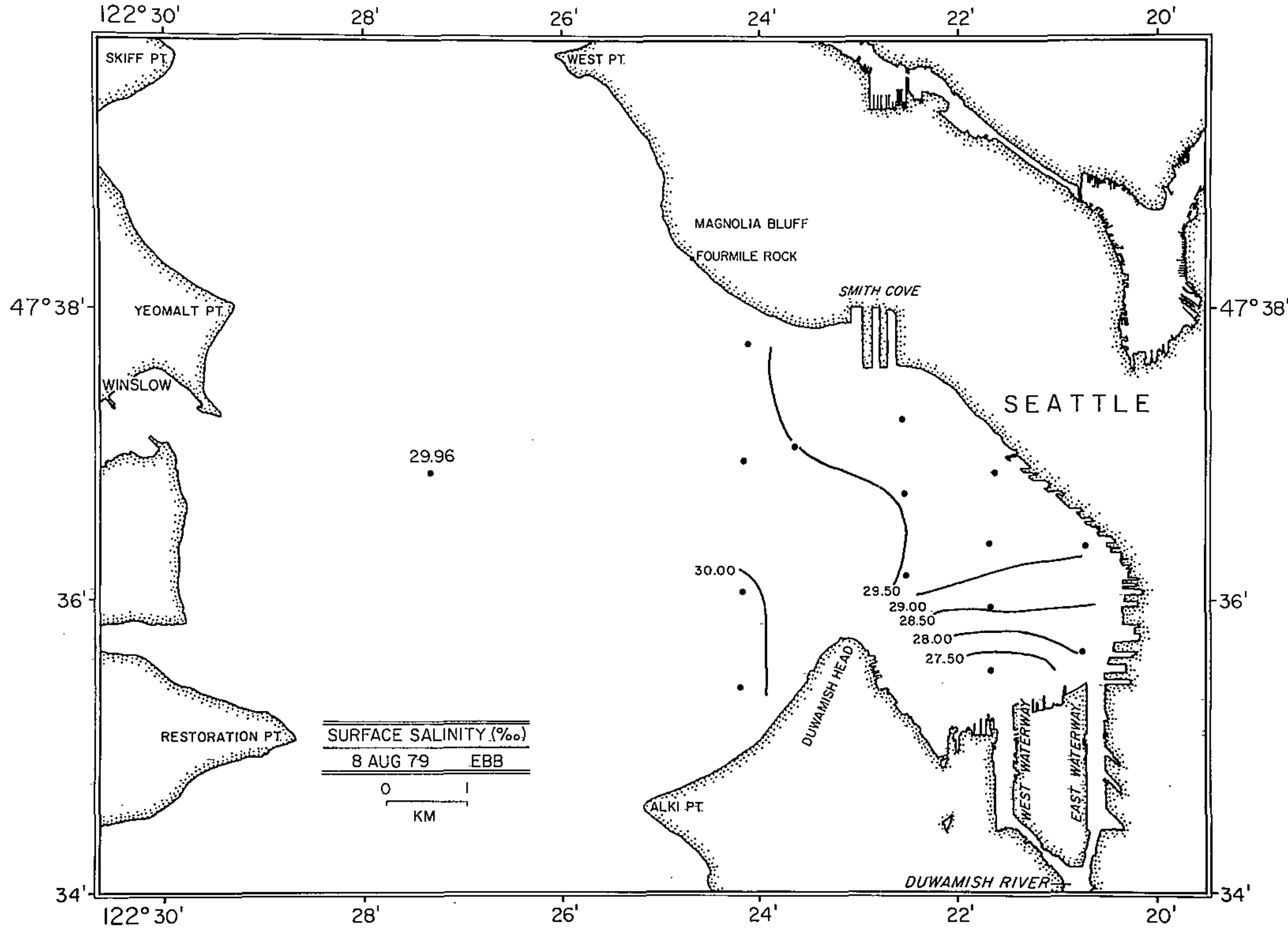

Figure 22. Summer surface salinity in Elliott Bay during ebb tide.

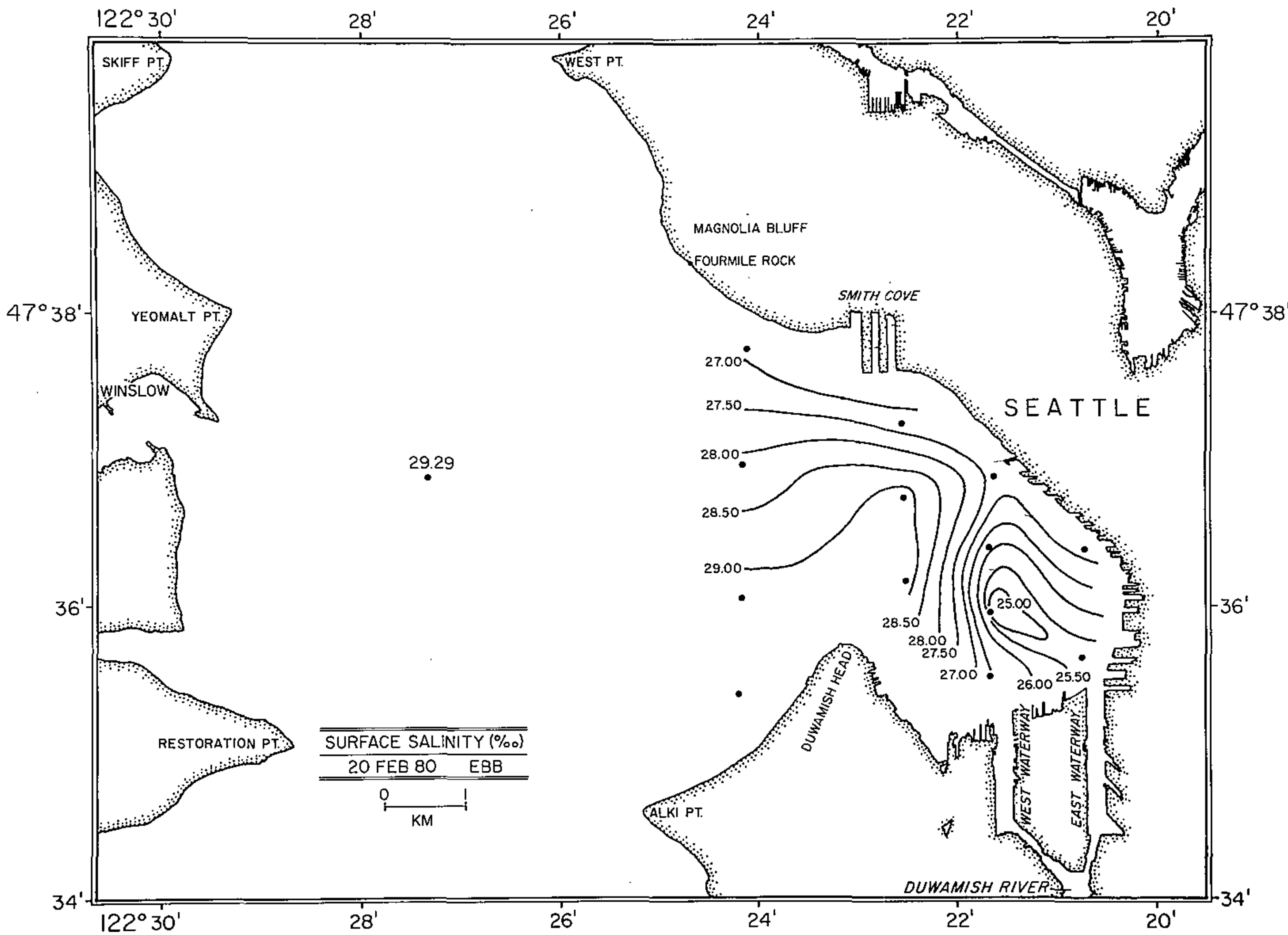

Figure 23. Winter surface salinity in Elliott Bay during ebb tide.

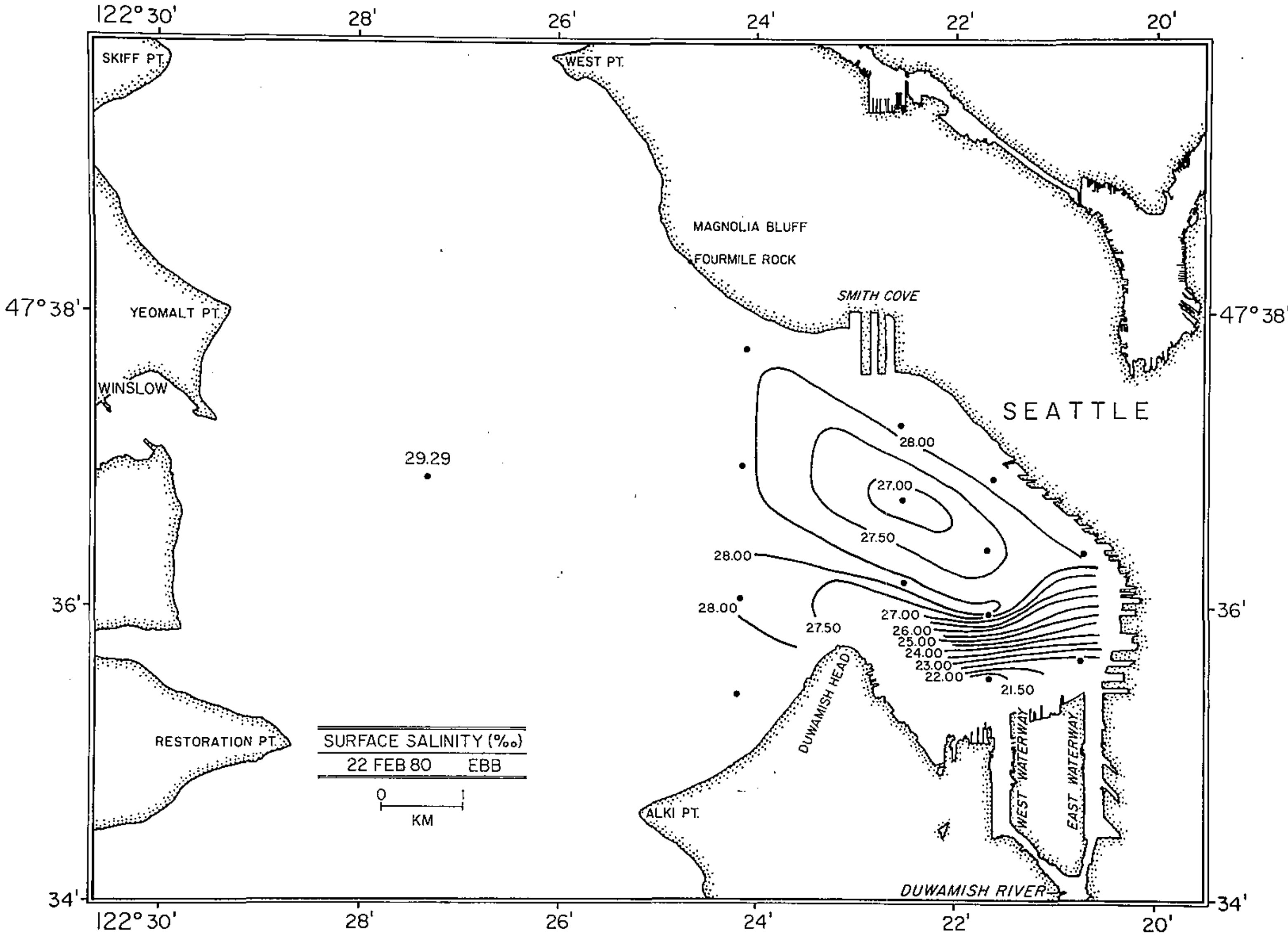

Figure 24. Winter surface salinity in Elliott Bay during a second ebb tide.

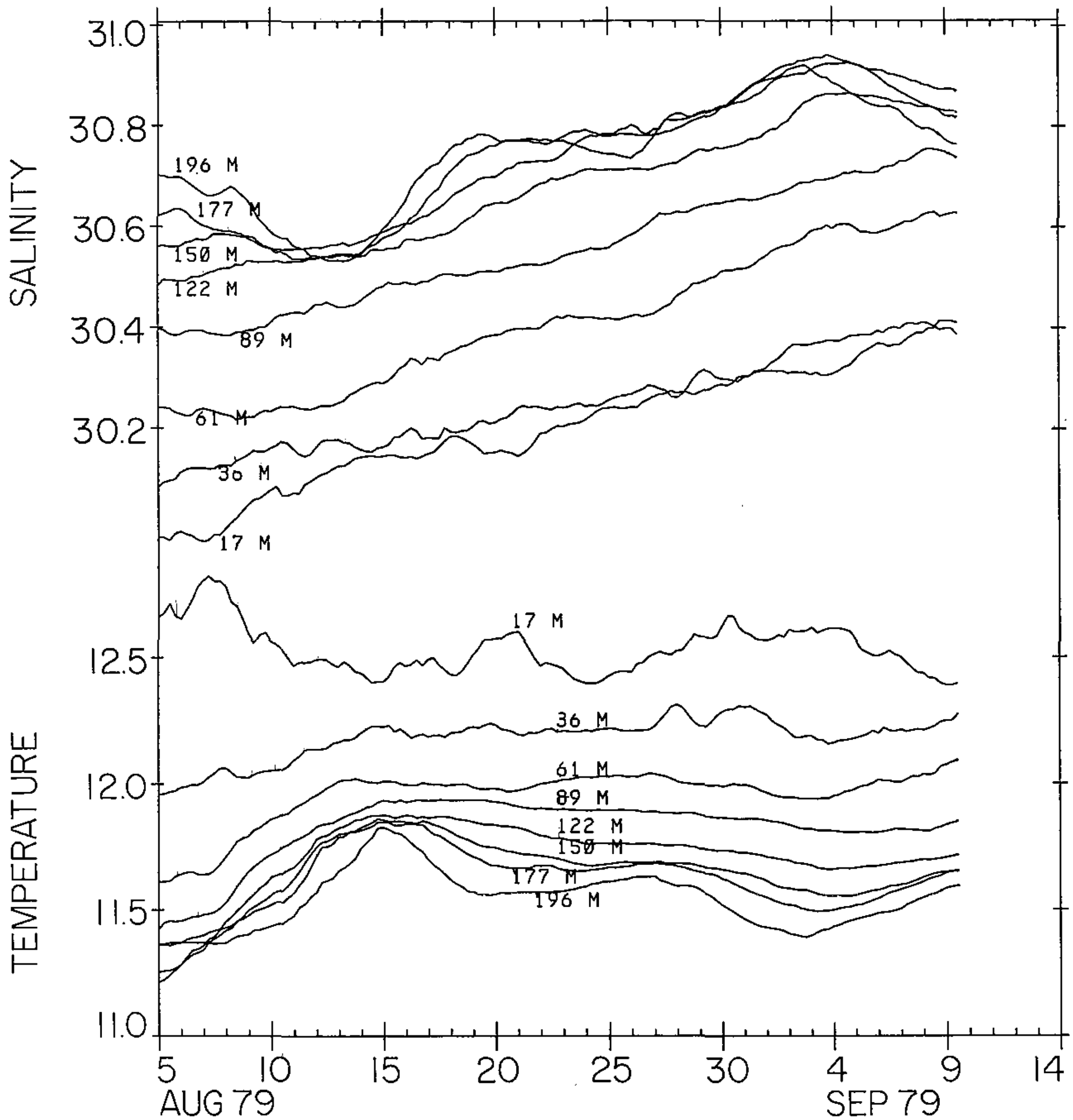

Figure 25. 25-hour averaged salinity and temperature at mooring 6, summer'79. (Depths of meters are indicated.)

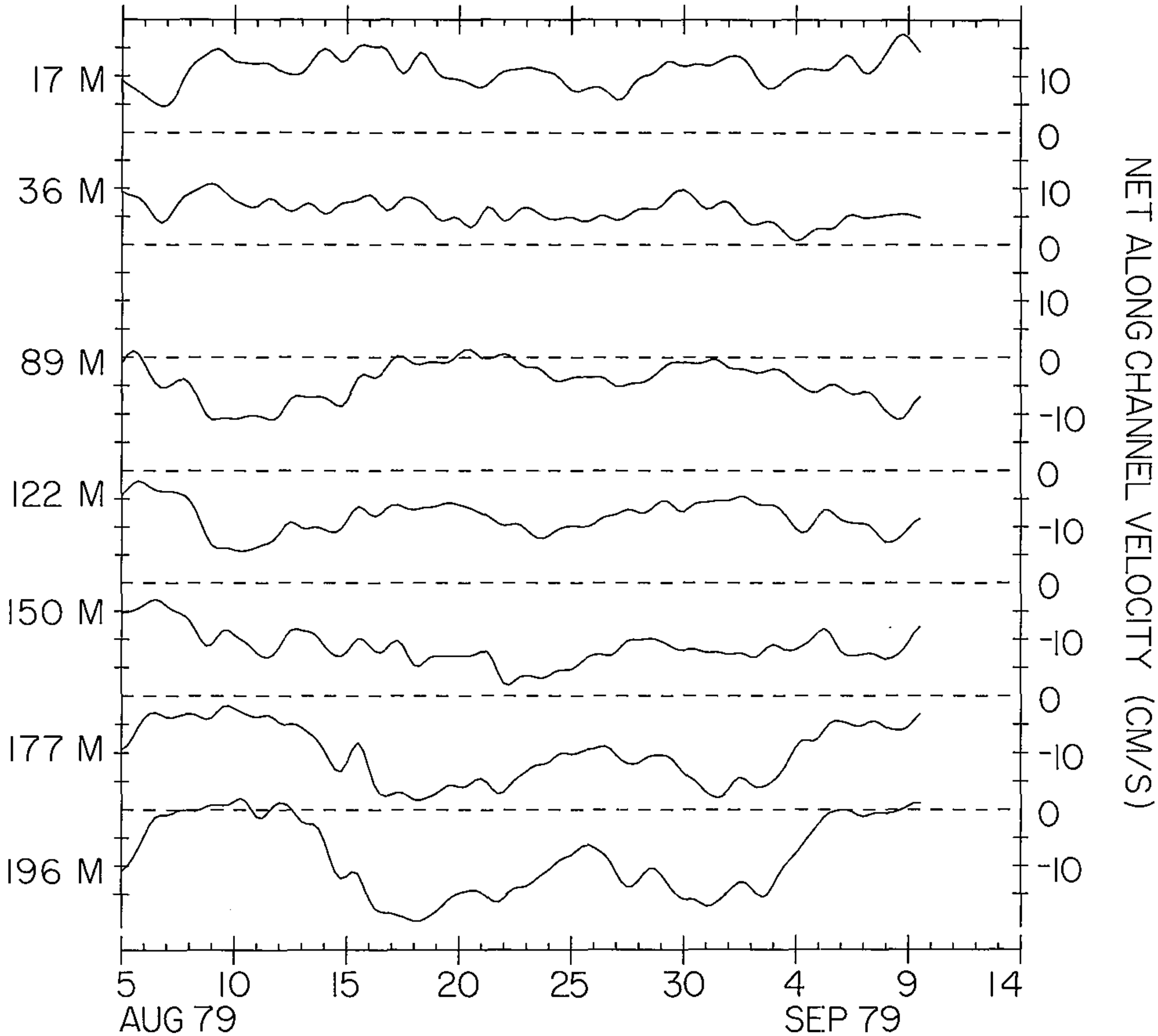

Figure 26. 35-hour filtered along-channel velocity at mooring 6, summer '79. (Positive currents indicate out-estuary flow.)

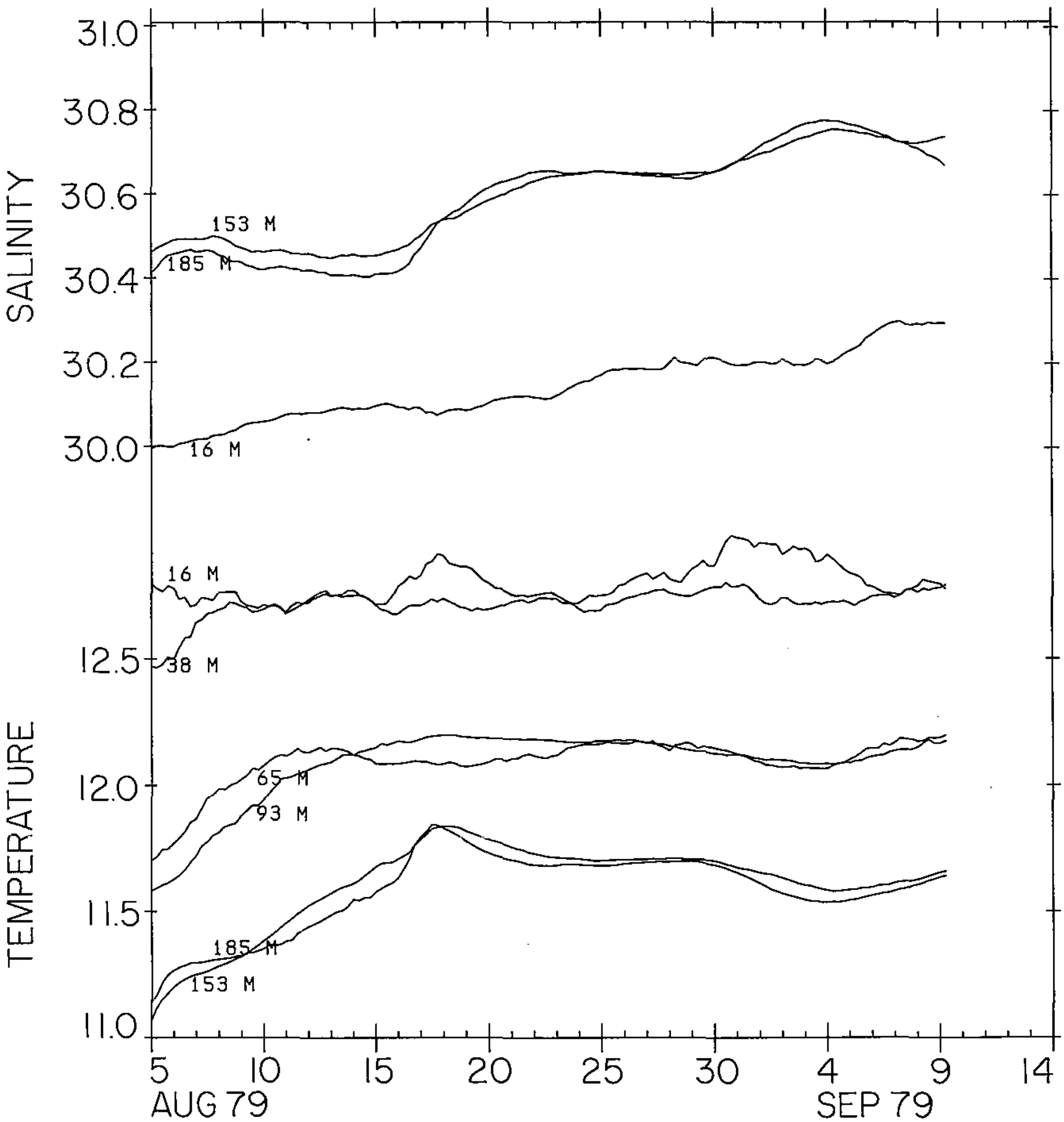

Figure 27. 25-hour averaged salinity and temperature at mooring 5.

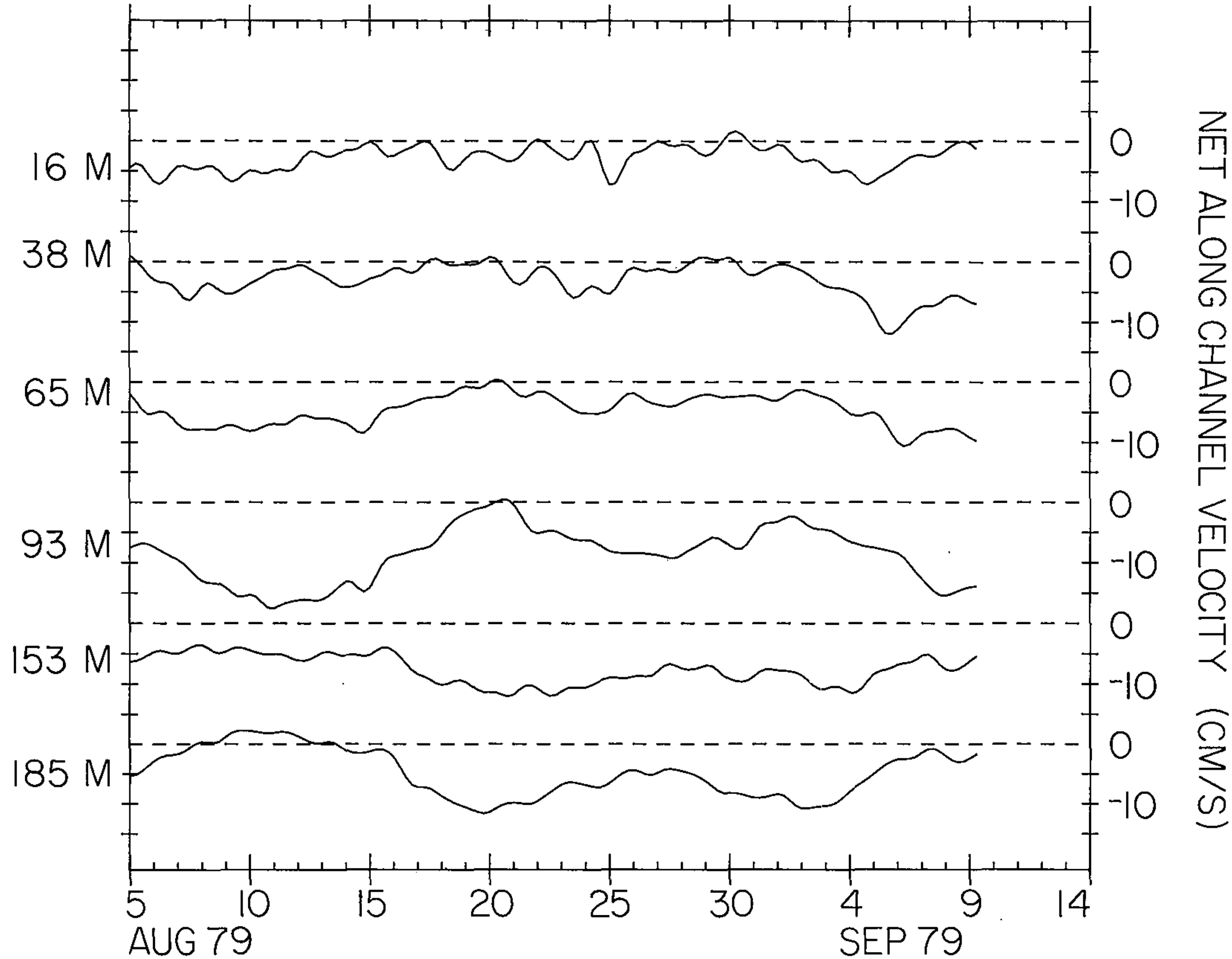

Figure 28. 35-hour filtered along-channel velocity at mooring 5.

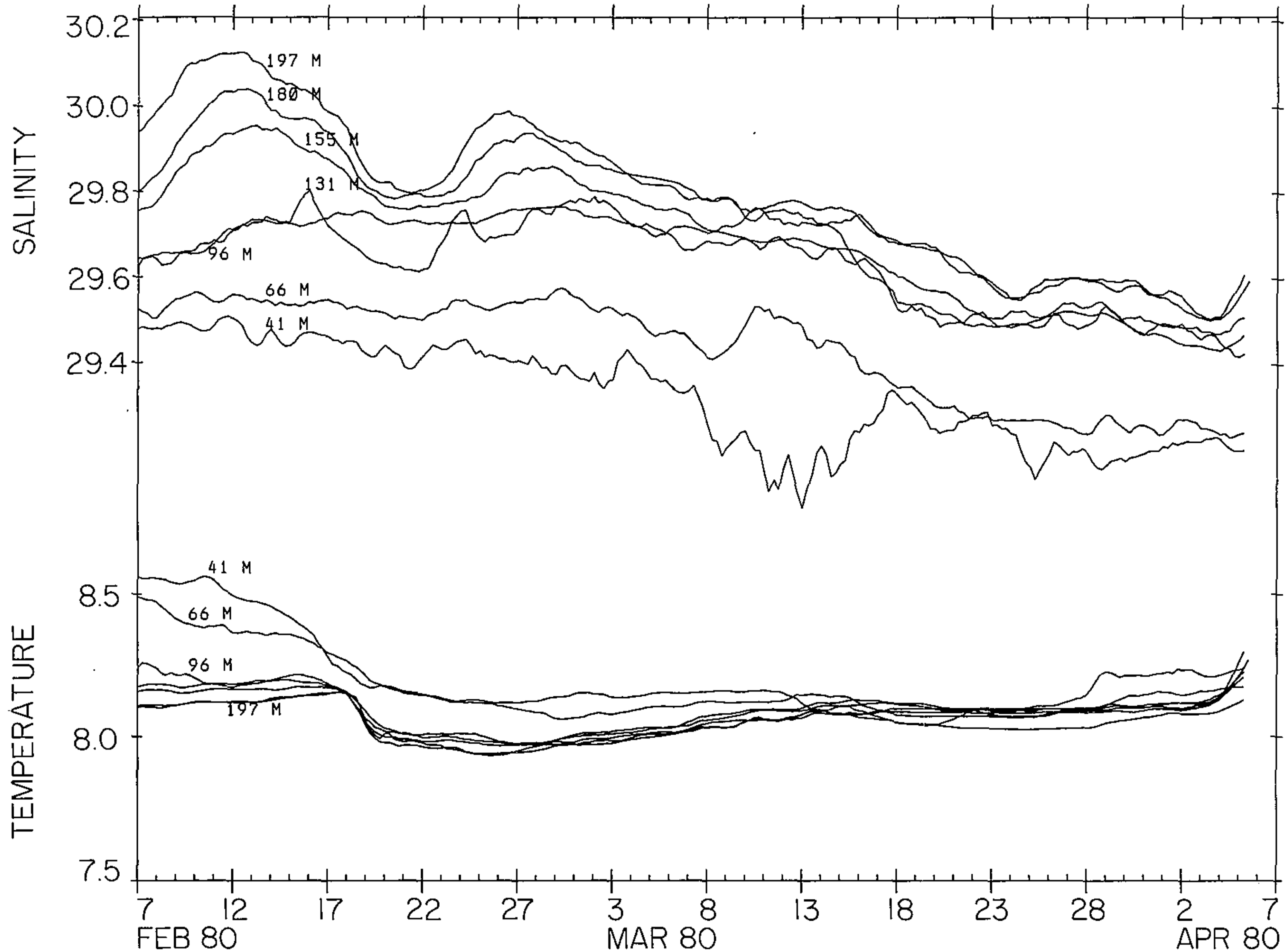

Figure 29. 25-hour averaged salinity and temperature at mooring 6, winter '80.

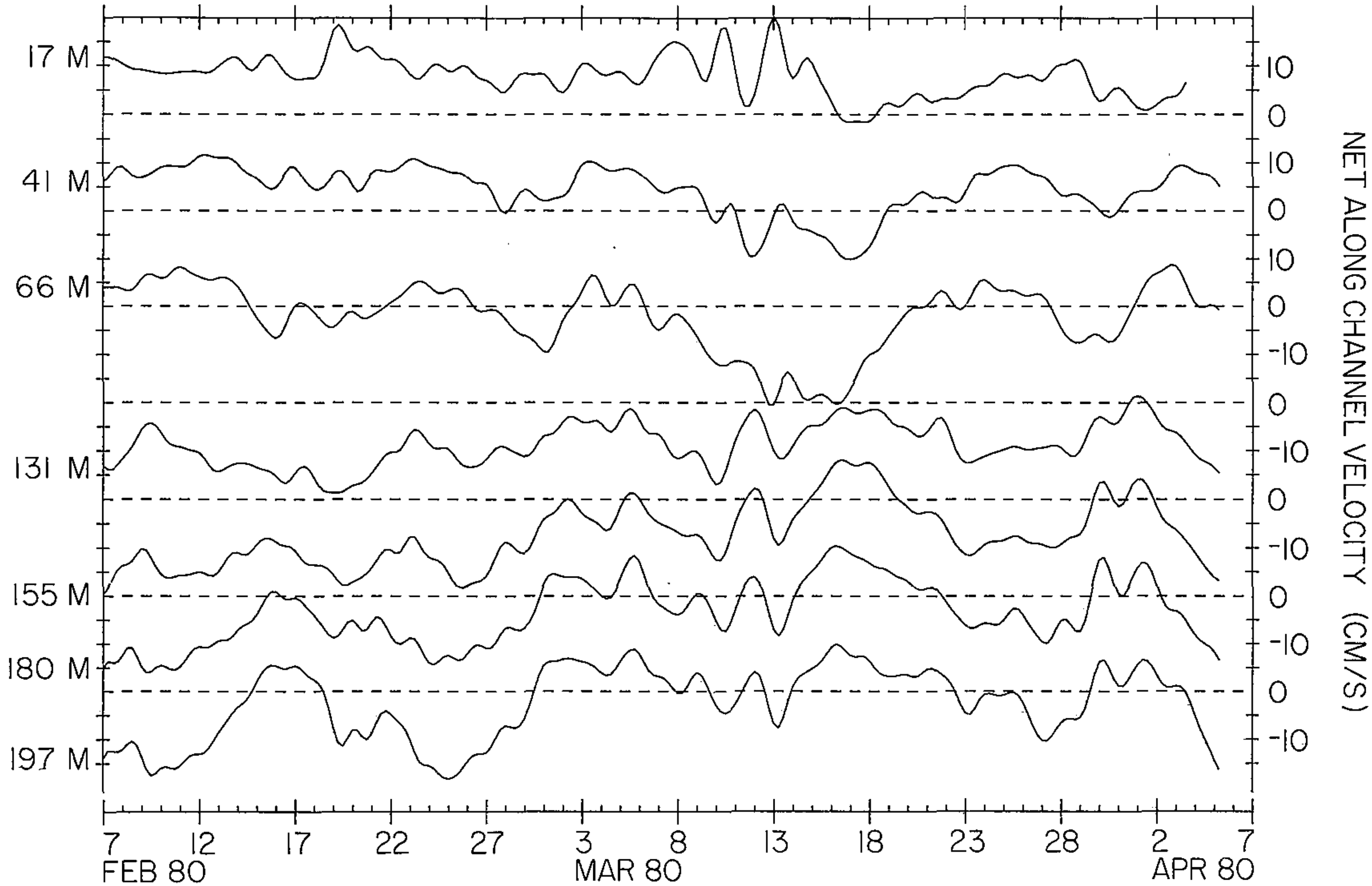

Figure 30. 35-hour filtered along-channel velocity at mooring 6, winter '80.

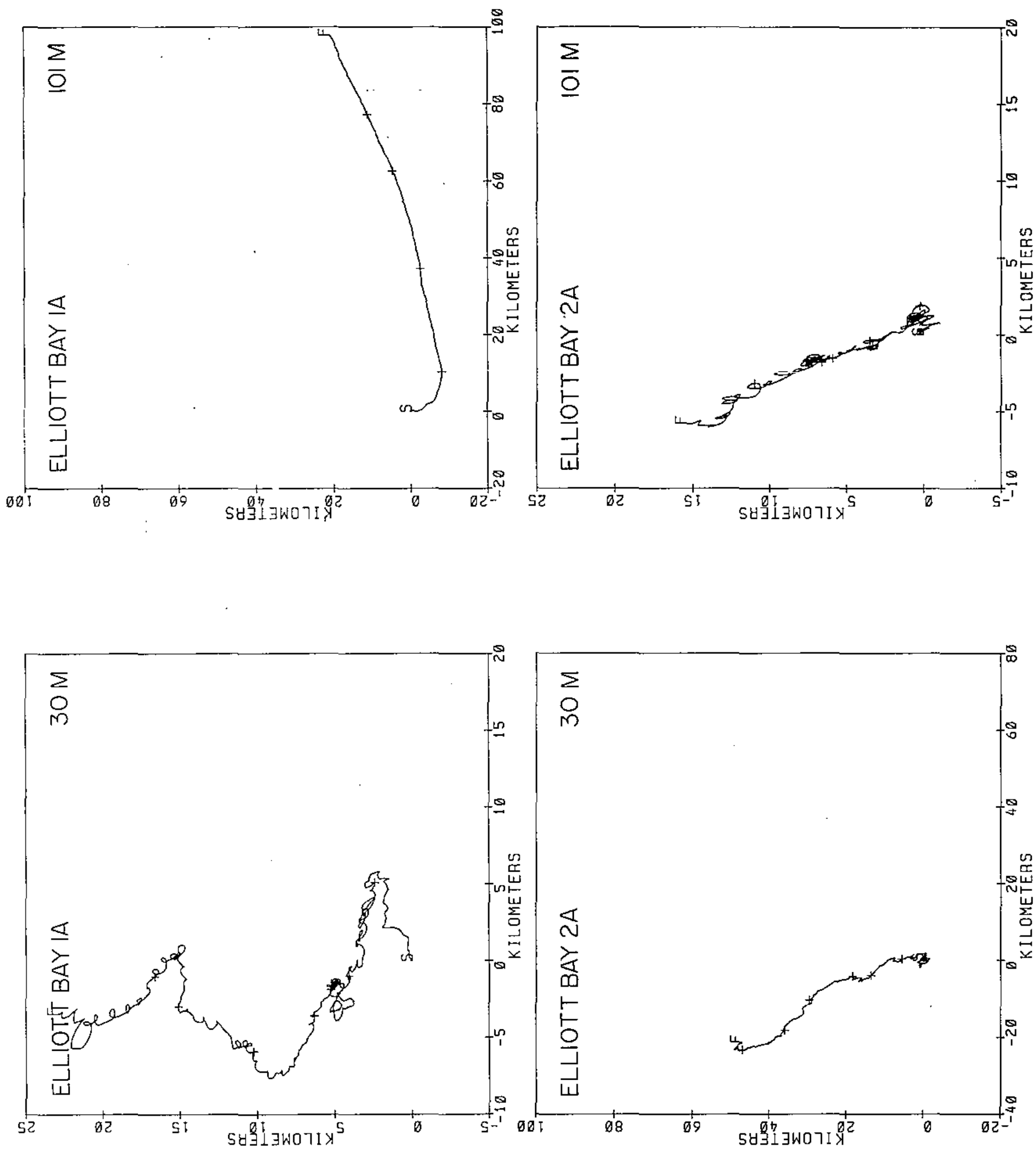

Figure 31. Summer progressive vector diagrams at moorings ELLBAY 1A and 2A. (S is start, F is finish, + symbol indicates 5-day interval.)

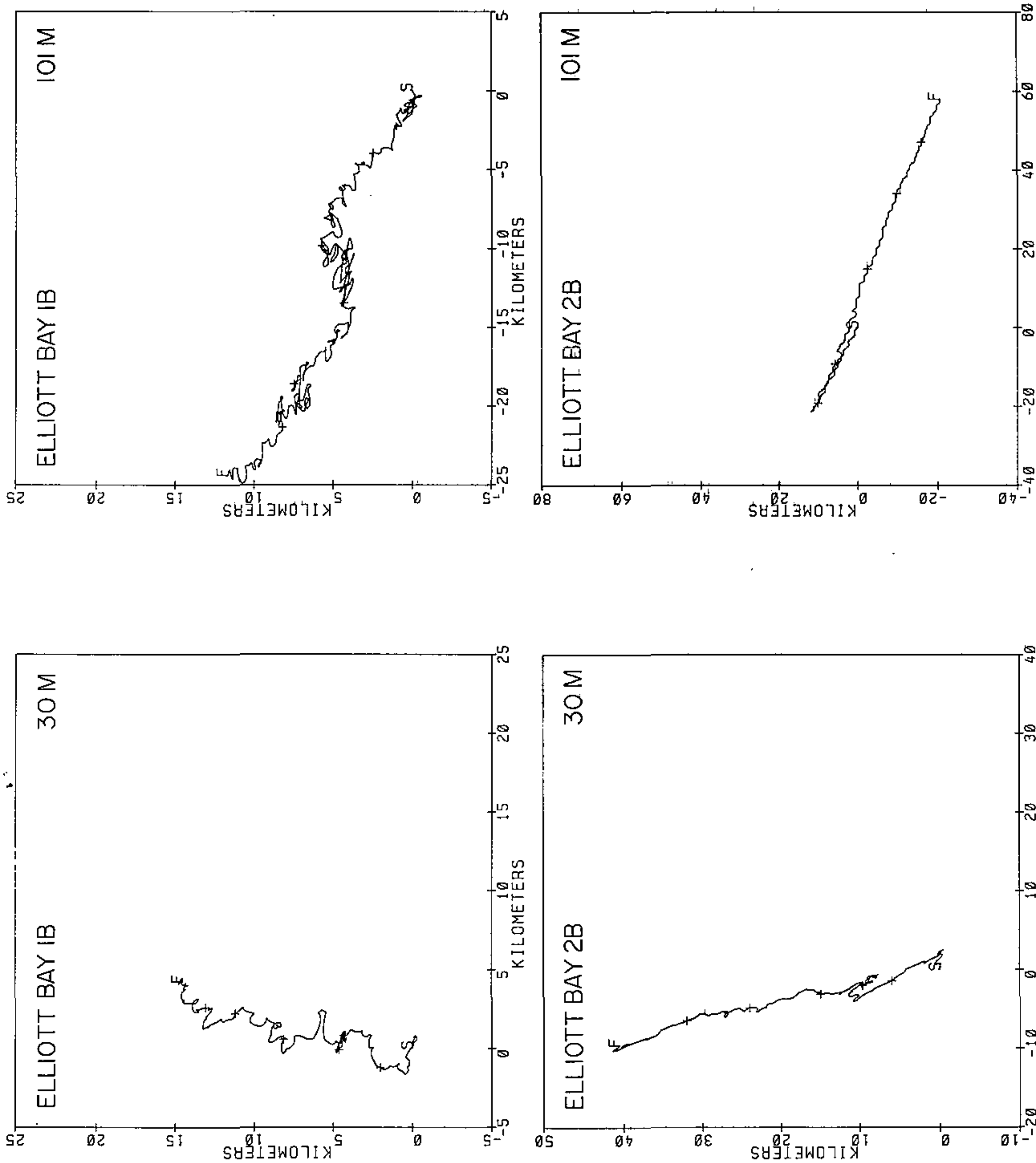

Figure 32. Winter progressive vector diagrams at moorings ELLBAY 1B and 2B.

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