UNIVERSITY OF WASHINGTON
DEPARTMENT OF OCEANOGRAPHY

Special Report No. 32

AN OCEANOGRAPHIC SURVEY OF THE BELLINGHAM-SAMISH BAY SYSTEM
Volume II—Analyses of Data

by

Eugene E. Collias, Clifford A. Barnes,
C. Balarama Murty, and Donald V. Hansen

Puget Sound Pulp
and Timber Co.
and
Office of Naval Research
Contracts Nonr-477(10)
and Nonr-477(37)
Project NR 083 012

Reference M66-8
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Research conducted for the Puget Sound Pulp and Timber Company, Bellingham, Washington

This report also incorporates some results of work performed under Office of Naval Research Contracts Nonr-477(10) and Nonr-477(37), Project NR 083 012.

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ABSTRACT

An oceanographic survey of the Bellingham-Samish Bay tidewater system in northwestern Washington was conducted from November 1959 through November 1961. Determinations were made of temperature, salinity, dissolved oxygen, dissolved inorganic phosphate, and spent sulfite liquor by conventional oceanographic methods at selected locations and depths on a total of 14 approximately bimonthly cruises. Current measurements were made at selected locations, and three exploratory diffusion experiments were conducted using Rhodamine B dye. The characteristics of various water properties were described for intervals during the survey period and flushing rates were computed.

The net circulation in this system, which is approximately 11 nautical miles (20 km) by 5 nautical miles (9 km) and 11 fathoms (20 m) in average depth, consists of a surface inflow of freshwater from the Nooksack River that enters the system at the north end and flows south, and a bottom inflow of saline water from Rosario Strait that enters the system at the south end and flows north. Water in the main body of the system is a variable mixture of these two source waters changing with time, position, and depth. Transitory changes in water properties occur at fixed locations, depending primarily on river runoff, tide state, and wind conditions. The difference in properties between the two layers is greater in summer than in winter.

The surface water responds primarily to changes in river discharge, which is greatest in winter and least in late summer. The salinity increases from head to mouth and from surface to bottom in both winter and summer. The temperature does likewise in winter when the river water is colder than seawater, but decreases from head to mouth and from surface to bottom in summer when the river water is relatively warm.

Surface exchanges of mass and energy, including water, oxygen, and heat, directly affect the properties of the layer above a depth of 10 m (33 ft). Below that depth dissolved oxygen decreases and soluble phosphate increases.

The Samish River, which enters Samish Bay near the mouth of Bellingham Bay, is an order of magnitude smaller than the Nooksack, and has little effect on the overall circulation or water properties. Water near the outer edge of the Samish delta differs little from the seawater entering from Rosario Strait, and Samish Bay shows little dilution that can be attributed to water from the Nooksack River and upper Bellingham Bay.

For the observed period the dispersion of industrial and municipal wastes discharged into Bellingham Harbor near the northeastern end of Bellingham Bay was estimated using spent sulfite liquor (SSL) as a tracer. The average concentration of SSL at a distance of 5 miles (9 km) from the outfall was about 1% of that near the outfall. Rarely did the concentration near the mouth of the system and at the outer edge of the Samish delta exceed more than a few parts per million. In general, the SSL tended to remain in the upper few meters and appeared to have little effect on the physical and chemical regimes of the open bay lying between the mouth of the Nooksack River and the entrance from Rosario Strait.

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1. INTRODUCTION

1.1. *Background and Objectives*

In late 1959, representatives of the Puget Sound Pulp and Timber Company[1] of Bellingham, Washington, requested the University of Washington Department of Oceanography to conduct an oceanographic survey of the Bellingham—Samish Bay tidewater system. Under a formal contract the Department of Oceanography agreed to make a survey of the system over an 18-month period, beginning in April 1960, with the following objectives: (1) to determine the distribution of fresh- and seawater in the system and (2) to examine the influence of the adjacent seawater masses upon this system.

This report presents analyses of the data collected during the survey period (April 1960—November 1961) and published in Volume I (Collias and Barnes, 1962). A table of equivalents for conversion of English and metric units used in this report is given in Appendix C.

1.2. *Description of the System*

1.2.1. *Geography:* The Bellingham—Samish Bay system (Fig. 1.1) is a north-south oriented, kidney-shaped body of water located 70 miles (113 km) north of Seattle, Washington. It lies east of Vancouver Island, and is a portion of the larger Puget Sound—Strait of Juan de Fuca—Georgia Strait complex. This system is approximately 11 nautical miles (20 km) in

[1]Now the Puget Sound Division of the Georgia-Pacific Corporation.

length and 5 nautical miles (9 km) in width, and has an average water depth[2] of about 11 fathoms (20 m) at high water. The largest center of population situated near Bellingham Bay is the city of Bellingham (pop. 35,000), located on the northeast corner of the bay. Several smaller communities are located along the south side of Samish Bay and the Lummi Indian Reservation extends along the north and west sides of Bellingham Bay. Much of the remaining area surrounding the system is used for farming. Wooded areas are located close to the water along Point Frances, Lummi Island, and Governors Point.

For this report, the Bellingham-Samish Bay system will be defined as those waters enclosed by the following lines (Fig. 1.2): (1) from the southeastern tip of Point Frances extending southwest to Lummi Island; (2) from Carter Point on the southern tip of Lummi Island extending in a southerly direction to the east side of Vendovi Island; and (3) from Vendovi Island extending southeasterly to William Point Light. Thus the system is separated from Hale Passage by line 1, from Rosario Strait and Bellingham Channel by line 2, and from Padilla Bay line 3.

For portions of the report, Samish Bay will be considered to include the waters situated east of line 4, extending from the northern tip of William Point to Wildcat Cove, while upper Bellingham Bay will be considered to be those waters situated north of line 5, extending easterly from Point Frances to just south of Post Point.

1.2.2. *Bathymetry:* The major bathymetric features (Fig. 1.3) influencing the oceanographic conditions of the system are the tidal flats located at the head of each bay and the four channels connecting the system directly or indirectly with Rosario Strait. The largest of these channels is located south of Lummi Island. It has an average depth of 40 fathoms (73 m), a sill depth of 35 fathoms (66 m) off Lummi Rocks, and deepens to 63 fathoms (115 m) north of Vendovi Island. Inside Bellingham Bay the extension of this channel begins to shoal, bends

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[2]All depths reported in this volume are referred to mean lower low water (MLLW) as established by the United States Coast and Geodetic Survey (USC&GS). The water level at mean higher high water (MHHW) is 8.6 ft (2.6 m) above MLLW.

northward along the east side of Eliza Island, and terminates in a second depression with a depth of 56 fathoms (102 m) directly east of Eliza Island.

The second connecting channel, Bellingham Channel, is located between Cypress and Guemes Islands, and joins the larger channel northwest of Vendovi Island. Bellingham Channel has a 25-fathom (46-m) sill at its southern end, but deepens to 62 fathoms (113 m) in its central portion.

Padilla Bay, the third connecting channel, is located at the southern end of the system. Extensive tidal flats are present in this bay, but a channel over 20 fathoms (36 m) deep is located near Guemes Island. A sill at 10 fathoms (18 m) is located off the southwest tip of Guemes Island.

Hale Passage, north of Lummi Island, provides only shallow access to Rosario Strait. It has a minimum depth of 3 fathoms (5.5 m) at the northern end; but southwest of Point Frances the passage deepens to 20 fathoms (36 m). A ridge at less than 4.5 fathoms (8 m) extends from Point Frances to the north end of Eliza Island and prevents direct access of the deeper water of Hale Passage to upper Bellingham Bay.

Contrasted to the connecting channels, Bellingham and Samish Bays are relatively shallow, with depths of less than 15 fathoms (27 m) in more than two-thirds of the region. Near the head of each bay the water shoals rapidly to large tidal flats created in part by deposition of sediments from the Nooksack and Samish Rivers. The shape and location of the mud flats created by the Nooksack River have changed and sediment has filled portions of the bay near the rivers during the past 50 years (Sternberg, 1961). The extensive tidal flats in Samish Bay, however, were formed originally by the Skagit River, which has since changed course and now empties into Saratoga Passage about 15 miles (27.8 km) to the south.

1.2.3. *Climatology:* The climate found in the system is of a temperate marine nature with relatively mild wet winters and cool dry summers, and is influenced by the Olympic Mountains to the southwest and the Cascade Mountains to the east. Annual precipitation increases from about 10 inches (25 cm) a year near Sequim in the lee of the Olympic

Mountains to over 80 inches (203 cm) on the west side of the Cascades. As much of the precipitation in the Cascades during winter falls as snow, the river runoff is low in winter but high in early summer. A 30-year average annual rainfall of 33.69 inches (86 cm) has been recorded in downtown Bellingham with 76% of this amount falling between early October and late April. Table 1.1 presents the total monthly rainfall data from January 1953 through December 1963 for downtown Bellingham.

Winds have been observed at the Bellingham Airport for more than 20 years but only a small portion of these data have been analyzed. During a four-year period (1950—1954), the prevailing winds were found to be from the south to southeast as shown in Table 1.2. These data indicate only the dominant direction of the wind for the given period and are not averages of the wind vectors. Strong northerly winds of short duration are not reflected in these data. A study of 38 months' wind data (October 1938—December 1941) by the U.S. Weather Bureau indicated a dominant wind direction from the southeast to southwest, but northeast winds were also frequent (Table 1.3)

Records of air temperatures over a 30-year period indicate a yearly average of 49.0°F (9.4°C) with extremes from a low of 3°F (-16.1°C) to a high of 96°F (35.6°C). The lowest temperatures were observed in January and the highest in late July or early August. An average of 151 days elapsed from the last spring freeze to the first fall frost. The mean monthly air temperatures in downtown Bellingham for the period January 1953—December 1963 are presented in Table 1.4.

1.2.4. *Freshwater sources:* The drainage basin supplying freshwater to the Bellingham—Samish Bay system covers 1050 square statute miles of land area (2.71×10^9 m^2) (Fig. 1.4 and Table 1.5). About 36% of this basin extends into the Cascade Mountains and includes portions of Mount Baker and Mount Shuksan; the remaining portion is located in the lowland region surrounding the system. Hence the amount of water being discharged into the system is influenced both by direct precipitation and by snow melt.

Two rivers and five creeks discharge directly into the bays. A sixth creek, Fishtrap Creek, discharges into the Nooksack River near

TABLE 1.1

Monthly precipitation at downtown Bellingham[a]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1953	7.99	2.73	2.59	2.12	1.45	2.02	0.81	0.89	2.08	4.56	6.54	6.62	40.40
1954	5.84	2.77	1.46	2.37	1.17	1.98	1.49	2.32	1.20	1.51	5.05	3.41	33.57
1955	2.67	3.82	2.13	2.40	2.71	1.94	1.77	0.27	1.15	4.52	6.69	5.57	35.64
1956	4.78	2.36	3.22	0.48	0.84	4.55	0.14	1.36	3.32	5.69	2.62	5.96	35.32
1957	2.17	3.07	4.78	2.59	0.72	1.65	1.97	0.69	0.92	2.55	1.91	3.53	26.55
1958	4.00	4.20	1.35	2.52	1.39	0.77	0.00	0.29	1.91	6.52	7.27	4.86	35.08
1959	5.87	3.28	2.07	4.42	2.32	1.37	0.51	1.33	4.26	3.80	5.07	4.53	38.83
1960	3.89	2.38	2.21	2.41	4.15	1.25	0.00	2.70	2.12	2.88	4.68	2.36	31.03
1961	4.12	6.17	4.30	2.67	2.07	0.91	1.34	1.20	1.62	4.31	2.74	4.44	35.89
1962	2.70	1.45	2.73	2.29	2.11	1.48	0.38	4.70	2.37	2.58	5.02	3.73	31.54
1963	1.20	3.05	1.78	3.37	0.99	1.26	2.08	0.43	1.03	4.27	6.78	6.92	33.16
30-year average	4.14	3.22	3.11	2.26	1.92	1.93	0.99	1.10	1.98	3.64	4.51	4.89	33.69
30-year average Seattle	5.73	4.24	3.79	2.40	1.73	1.58	0.81	0.95	2.05	4.02	5.35	6.29	38.94

[a]From U.S. Weather Bureau records (in inches).

TABLE 1.2

Prevailing winds at Bellingham Airport[a]

Time of day	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
04	SE/13	SE/8	N/7	SE/6	SE/5	SE/6	S/6	S/6	S/6	SE/6	SE/8	SE/9
10	SE/12	SE/9	S/10	S/9	S/9	S/9	S/8	S/9	S/8	S/8	SE/8	SE/9
16	SE/11	S/9	S/10	S/9	S/9	S/8	S/8	S/9	S/7	S/7	SE/8	SE/9
22	SE/11	S/7	SE/6	SE/5	SE/5	SE/5	S/5	S/5	SE/5	SE/6	SE/8	SE/10

[a] For the period 1950–1954. True wind direction over speed in mph. Personal communication from Mr. Earl Phillips, U.S. Weather Bureau, Seattle, Washington.

TABLE 1.3

Frequency of occurrence of wind directions at Bellingham Airport[a]

Direction	Percentage of occurrences	Remarks
N	1	
NNE	2	5 cases over 32 mph
NE	8	
ENE	3	
E	6	
ESE	2	
SE	7	
SSE	12	
S	6	
SSW	7	37 cases over 32 mph
SW	11	
WSW	8	
W	4	
WNW	1	
NW	1	
NNW	1	
Calms	21	

[a]For the period October 1938—December 1941. Personal communication from Mr. Earl Phillips, U.S. Weather Bureau, Seattle, Washington.

TABLE 1.4

Monthly mean air temperatures at downtown Bellingham[a]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Avg.
1953	43.9	40.9	43.5	48.4	54.9	56.3	61.9	62.6	57.5	51.7	48.1	42.4	51.0
1954	33.2	42.1	40.4	45.1	52.8	55.3	58.3	59.9	57.3	49.4	48.7	41.4	48.6
1955	38.8	37.5	38.1	44.2	49.6	56.7	58.6	58.8	55.4	49.7	36.9	36.2	46.7
1956	37.9	35.2	40.7	48.4	55.0	56.8	62.4	60.4	57.0	48.8	41.3	39.4	48.6
1957	28.6	36.8	43.8	48.9	56.8	59.7	59.9	60.2	60.3	49.8	42.1	43.0	49.2
1958	43.1	47.0	43.8	48.7	58.5	64.4	67.5	63.9	58.1	50.7	41.7	41.8	52.4
1959	38.7	39.4	43.7	48.4	53.6	60.1	63.8	60.2	56.8	49.6	41.2	39.4	49.6
1960	37.1	41.0	42.9	49.5	53.3	58.6	64.1	61.5	56.2	51.8	43.1	38.0	49.7
1961	41.4	44.9	45.7	48.1	55.5	60.9	64.6	64.5	55.4	48.2	40.1	38.8	50.7
1962	37.5	41.9	40.6	49.1	51.3	57.6	60.7	60.8	57.4	51.8	46.0	41.8	49.7
1963	32.4	44.6	43.7	48.0	54.4	58.6	60.7	62.8	60.8	52.8	44.6	40.0	50.3
30-year average	36.8	39.5	43.0	48.6	53.2	57.8	61.0	60.6	56.7	50.1	43.1	39.6	49.0
30-year average Seattle	38.2	41.6	45.4	51.3	57.4	62.2	66.7	65.6	60.5	52.6	44.2	40.4	52.2

[a]From U.S. Weather Bureau records (in degrees Fahrenheit).

TABLE 1.5

Summary of the Bellingham—Samish Bay system land-drainage basin

Freshwater source	Areas in square statute miles		
	Gaged[a]	Ungaged	Total
Nooksack River[b]	640	140	780
Fishtrap Creek[b]	23	2	25
Samish River[b]	90	15	105
Squalicum Creek[c]	20		20
Whatcom Creek[c]	63		63
Chuckanut Creek—Colony Creek—Edison Slough		44	44
Lummi Peninsula—Lummi Island—Eliza Island		13	13
Totals	753	297	1050

[a]A gaged river is one on which flow measurements have been made. The gaged area listed is that amount of land upstream from the gage.

[b]A continuously recording water-level recorder is installed at some convenient location on the river to record river level and the the flow is computed from these data.

[c]Intermittently gaged.

Lynden, below the last downstream water-stage recorder on the Nooksack. The Nooksack River enters the northern end of Bellingham Bay. At one time the Lummi River received a portion of the Nooksack flow, but dikes now keep the Nooksack confined to its main channel. The Samish River discharges into the southeast corner of Samish Bay and its average discharge rate is about 10% of that of the Nooksack. Two creeks, Squalicum and Whatcom, enter the northeast side of upper Bellingham Bay. The former drains a small land area between the Nooksack River and the city of Bellingham, whereas the latter is the outlet to Lake Whatcom and discharges into a dredged waterway along the west side of the Georgia-Pacific mill. Sewers from the pulp mill enter along the side of this waterway and the main sewer of the city of Bellingham[3] enters at its head. The remaining three creeks (Chuckanut, Oyster, and Colony) have small drainage basins and are affected only by local rainfall and land drainage. Chuckanut Creek enters the north end of Chuckanut Bay while the other two creeks discharge into the north side of Samish Bay.

Of the several freshwater sources discharging into the system, only the Samish River, Nooksack River, and Fishtrap Creek have been gaged on a continuing annual basis; but the other creeks have been gaged occasionally. The total gaged area is 753 square statute miles (1.95×10^9 m^2), leaving about 25% of the drainage basin ungaged. Runoff from the ungaged areas can be estimated because most of these areas are immediately adjacent to the system and are influenced primarily by local precipitation.

The Nooksack River discharge basin extends into the mountains and the river has two periods of high runoff, one in late fall and winter in response to direct precipitation, and the other in June as a result of snow melt from the mountains. In contrast to this, the Samish River drainage basin is confined to the lower coastal area; the river is influenced primarily by direct precipitation, and has a single high runoff period from late fall through winter.

Runoff data for the Nooksack River, Samish River, and Fishtrap Creek are presented in Table 1.6 for the period January 1958 through December 1962.

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[3]The average discharge rate of the City of Bellingham's sewage-treatment plant was 7.9×10^6 gal (3.0×10^5 m^3) per day or a rate of 0.35 m^3/sec.

TABLE 1.6

Monthly mean runoff of the Nooksack and Samish Rivers, and Fishtrap Creek[a]

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Yearly mean
Nooksack River at Lynden (Gage located at 48°55.2' N, 122°29.2' W)													
1958	4767	5040	2400	2854	4451	3580	2338	1515	1614	3677	5441	6220	3641
1959	6057	2609	3169	5900	5634	5778	4109	2113	4035	3972	5772	4892	4509
1960	3253	4105	2631	3935	4604	5002	3126	2141	1719	3365	4173	3456	3461
1961	5997	7724	4192	3771	4488	5109	2821	1859	1639	2685	2926	3923	3903
1962	5109	3229	1736	3408	3170	3884	2650	2833	2028	2605	5211	5335	3434
Fishtrap Creek at Lynden (Gage located at 48°57.8' N, 122°26.0' W)													
1958	64.1	71.1	33.0	31.1	13.9	7.6	4.2	2.6	3.0	7.8	37.8	66.0	28.3
1959	91.3	57.7	55.4	70.1	47.3	20.9	10.3	6.4	11.1	22.5	59.8	74.2	43.8
1960	71.7	73.4	50.9	41.3	46.7	22.8	9.1	6.6	10.0	34.5	53.8	56.5	39.7
1961	86.5	142.	95.0	50.1	39.8	16.8	10.3	8.2	8.2	16.1	27.4	78.7	47.7
1962	98.4	51.2	42.1	36.7	34.7	18.4	11.1	12.0	11.8	17.7	45.6	66.3	37.2
Samish River near Burlington (Gage located at 48°32.8' N, 122°20.3' W)													
1958	404	445	205	199	84	41	23	19	22	206	594	389	217
1959	603	376	373	477	262	121	50	31	134	214	548	487	306
1960	401	475	266	304	235	128	43	37	41	82	286	192	206
1961	372	988	503	364	199	88	44	30	34	105	220	418	276
1962	465	244	254	239	174	87	36	60	52	126	379	404	210

[a]Values are averages in cubic feet per second (cfs).

1.2.5. *Seawater Sources:* The local seawater comes originally from the Pacific Ocean, entering the Strait of Juan de Fuca at depth off Cape Flattery. As this water progresses toward Rosario Strait, it is mixed with less saline water being discharged from the Puget Sound–Strait of Juan de Fuca–Georgia Strait complex. Rosario Strait, a connecting channel between the eastern end of the Strait of Juan de Fuca and Georgia Strait, contains a mixture of more saline water from the former and less saline water from the latter. The strong tidal currents in Rosario Strait are usually effective in mixing the waters top to bottom but not along channel. Thus the water found off the entrance to Bellingham Bay is nearly homogeneous vertically, however its properties change continuously along the channel and throughout the tidal cycle.

1.2.6. *Tides:* The tides in the Bellingham–Samish Bay system are of the mixed type, nominally with two unequal highs and two very unequal lows per tidal day. At certain times of the month the two semidiurnal tides are of nearly equal height, while at other times the low high and high low become nearly the same so that for about 6 hours there is no significant change in tide height. Continuous measurements of tide height were made at Bellingham by the U.S. Coast and Geodetic Survey from September 1934 through August 1935. Published predicted tide heights, however, are based on Port Townsend as the reference station. The normal maximum tide range is 13 ft (4.0 m) with a normal high spring tide of 9.5 ft (2.9 m). Mean tide height is 5.2 ft (1.6 m) above MLLW but extremes of 11.5 ft (3.5 m) and -4.5 ft (-1.4 m) have been reported. In addition to the normal astronomical effects, meteorological conditions can produce significant changes in water height. A strong southerly wind superimposed on a high tide tends to raise the water level above normal, whereas a northerly wind may cause a decrease in water level at the same location. Changes in atmospheric pressure also affect the tide height, the tides being slightly higher during periods of low pressure.

In consequence of the continuously changing water level, the waters in the various channels and in the bays move with tidal periodicity. The direction and magnitude of the movement depend in large part upon the tide state, tide range, and bathymetry of the location under consideration. Tidal currents are important in transporting water from one part of the system to another and also govern the mixing processes, particularly in narrow channels.

1.3. *Location of Oceanographic Stations*

Twenty-seven stations were established within the Bellingham-Samish Bay system and approaches (Fig. 1.5 and Table 1.7). On most cruises, additional stations were occupied in Rosario Strait and other adjacent channels to aid in characterizing the water entering the system. From this network of stations it was possible to: (1) determine the annual cycles in water characteristics; (2) define the water masses; (3) calculate the amount of freshwater in the system; and (4) evaluate the flushing rate of the system.

Samples were taken at selected depths to within 5 m (16 ft) of the bottom. In all cases, the samples were more closely spaced in the upper 20 m (66 ft) than in the deeper water. On a typical survey, 235 water samples were collected.

1.4. *Summary of Cruises*

Fourteen cruises were conducted by personnel of the University of Washington Department of Oceanography during this survey of Bellingham and Samish Bays. The first cruise (BB-243) was made in November 1959 prior to the beginning of the intensive survey period. On each cruise water samples from selected depths were collected for chemical analysis. Bottom samples and biological specimens were obtained on the first three cruises, dye-tracer studies using Rhodamine B dye were made on three cruises, and current measurements were made on two other cruises. A tabular summary of these surveys is presented in Table 1.8.

1.5. *Previous Investigations*

Prior to November 1959 several agencies including the University of Washington had conducted oceanographic surveys of the area. The Washington State Department of Fisheries, in a series of cruises from September 1955 to September 1959 (Westley, 1957, 1958; Westley and Tarr, 1959, 1960; Lindsay, Westley, and Woelke, 1960) obtained two to four water samples at each of 18 stations near the periphery of the bays. During the summer of

TABLE 1.7

Positions of oceanographic stations

Name	Lat N 48° + (')	Long W 122° + (')	Nearest landmark
A-1	44.6	36.2	
A-2	45.1	34.0	
A-3	45.5	32.0	Cement plant
B-1	44.0	36.0	
B-2	44.3	32.9	
B-3	44.6	30.3	Pulp mill
C-1	42.8	36.0	
C-2	42.8	33.9	
C-3	42.8	31.8	Post Point
D-1	41.6	35.3	Point Frances
D-2	41.5	33.1	
D-3	41.4	31.0	
E-1	41.4	37.9	Hale Passage, south end
F-1	40.0	36.3	Reil Harbor
F-2	40.0	33.7	
F-3	40.0	31.0	Governors Point
G-1	37.7	37.8	Viti Rocks
G-2	38.2	34.1	Eliza Rocks, southeast of
G-3	38.3	31.7	
G-4	37.1	32.4	
G-5	35.9	33.1	
G-6	35.0	35.0	Point Williams, west of
H-1	38.2	29.3	Samish Bay, north end
H-2	36.7	29.5	Samish Bay, middle
H-3	35.5	31.0	Samish Bay, south end
J-1	33.0	34.5	boat Harbor
K-1	35.0	40.0	Bellingham Channel

TABLE 1.8

Cruises made during the oceanographic survey of the Bellingham–Samish Bay system

Cruise number	Cruise[a]	Date	Number of stations: System	Number of stations: Adjacent waters	Remarks
1	BB-243	2–4 November 1959	22	25	Surface trace[b]
2	BB-257	19–21 April 1960	23	19	Surface trace[b]
3	BB-262	20–22 May 1960	26	18	Surface trace[b]
4	BLL-04	21–22 June 1960	22	4	
5	BLL-05	18–19 July 1960	24	3	Current measurements
6	BLL-06	23–24 August 1960	23	4	
7	BLL-07	28–29 September 1960	23	4	
8	BLL-08	2–4 November 1960	22	4	
9	BB-272	16–17 December 1960	22	6	Part of a general Puget Sound survey
10	BB-276	6–7 February 1961	22	14	Dye study
11	BLL-11	20–23 March 1961	24	4	Dye study
12	BLL-12	15–16 May 1961	23	6	
13	BLL-13	10–14 July 1961	15	1	Dye study and current measurements
14	BB-296	15 November 1961	14	6	Part of a general Puget Sound survey

[a]The prefix BB designates a *Brown Bear* cruise and BLL signifies a survey made using a charter vessel.

[b]Indicates that a detailed distribution of the surface temperature and salinity was made using a Salinity-Temperature-Depth recorder (Jacobsen, 1948).

1957 the Washington State Pollution Control Commission studied the area near the pulp mill, taking samples at the surface, mid-depth, and bottom (Wagner, Ziebell, and Livingston, 1957). The Puget Sound Pulp and Timber Company in private studies frequently observed the distribution of water properties in selected areas and depths. Tollefson (1959, 1962) has studied the biology and Sternberg (1961) the sediments.

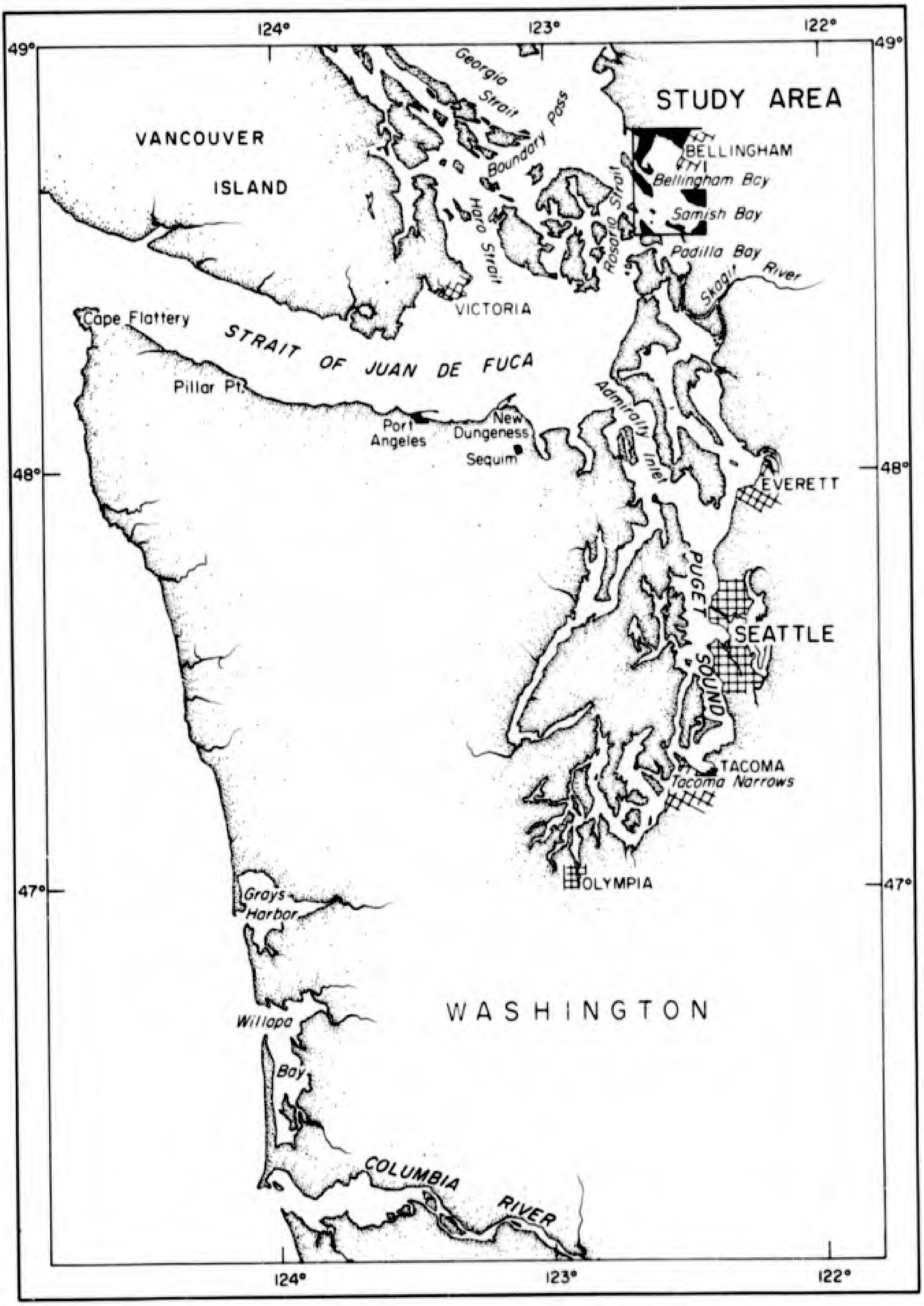

Fig. 1.1. Location of Bellingham and Samish Bays.

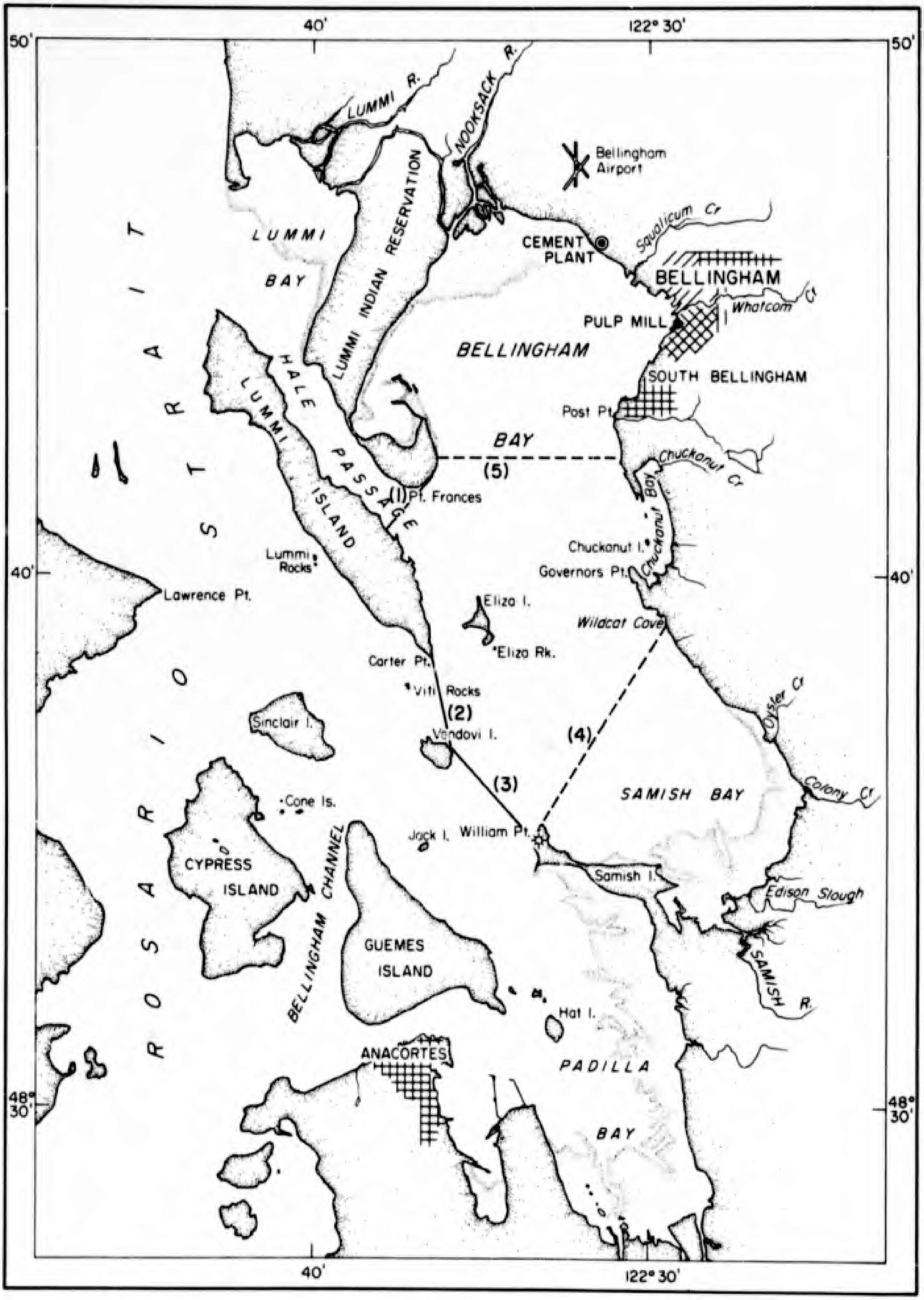

Fig. 1.2. Details of the Bellingham-Samish Bay system.

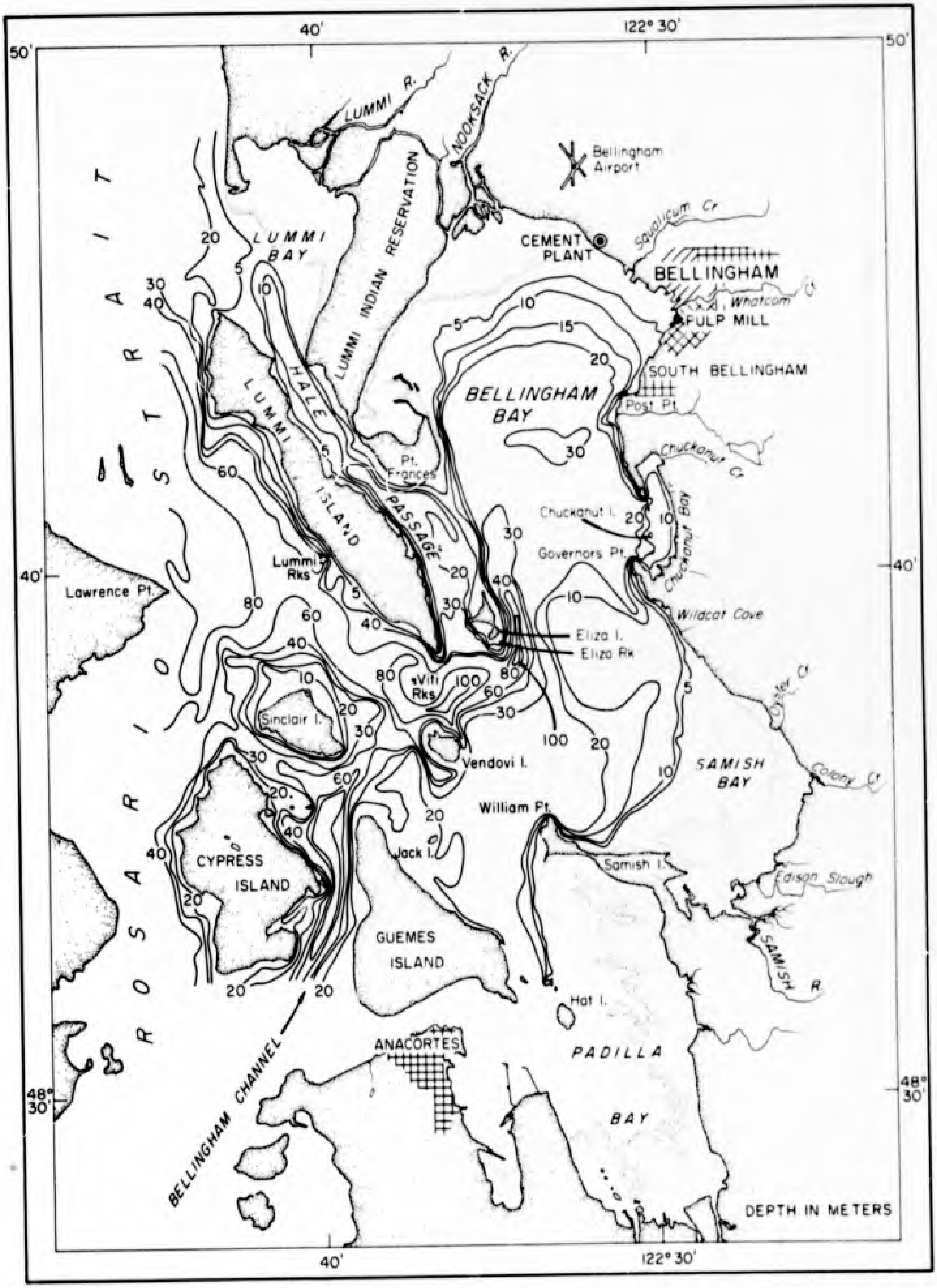

Fig. 1.3. Bathymetric features of Bellingham and Samiı Bays.

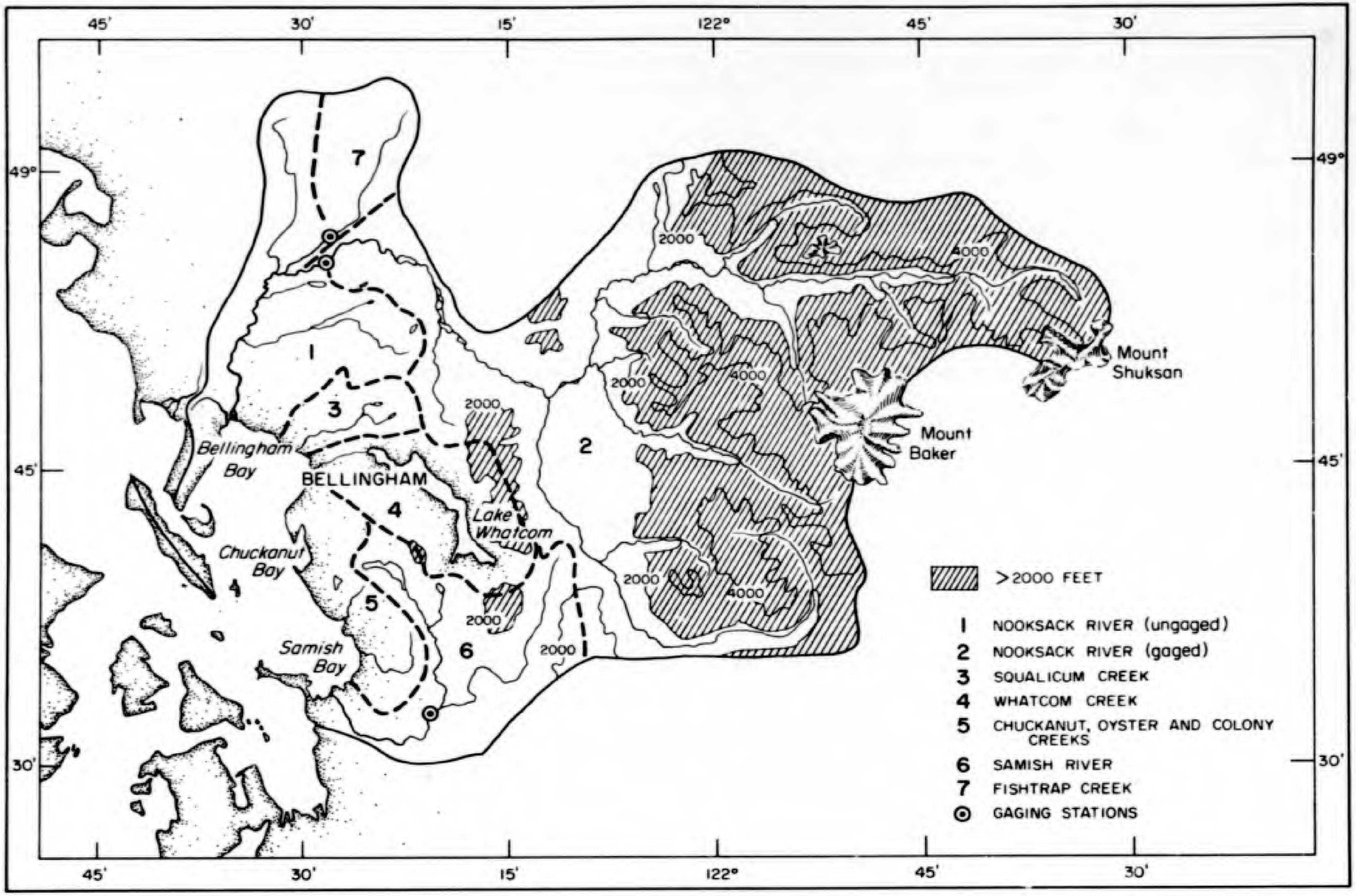

Fig. 1.4. Drainage basin feeding into Bellingham and Samish Bays.

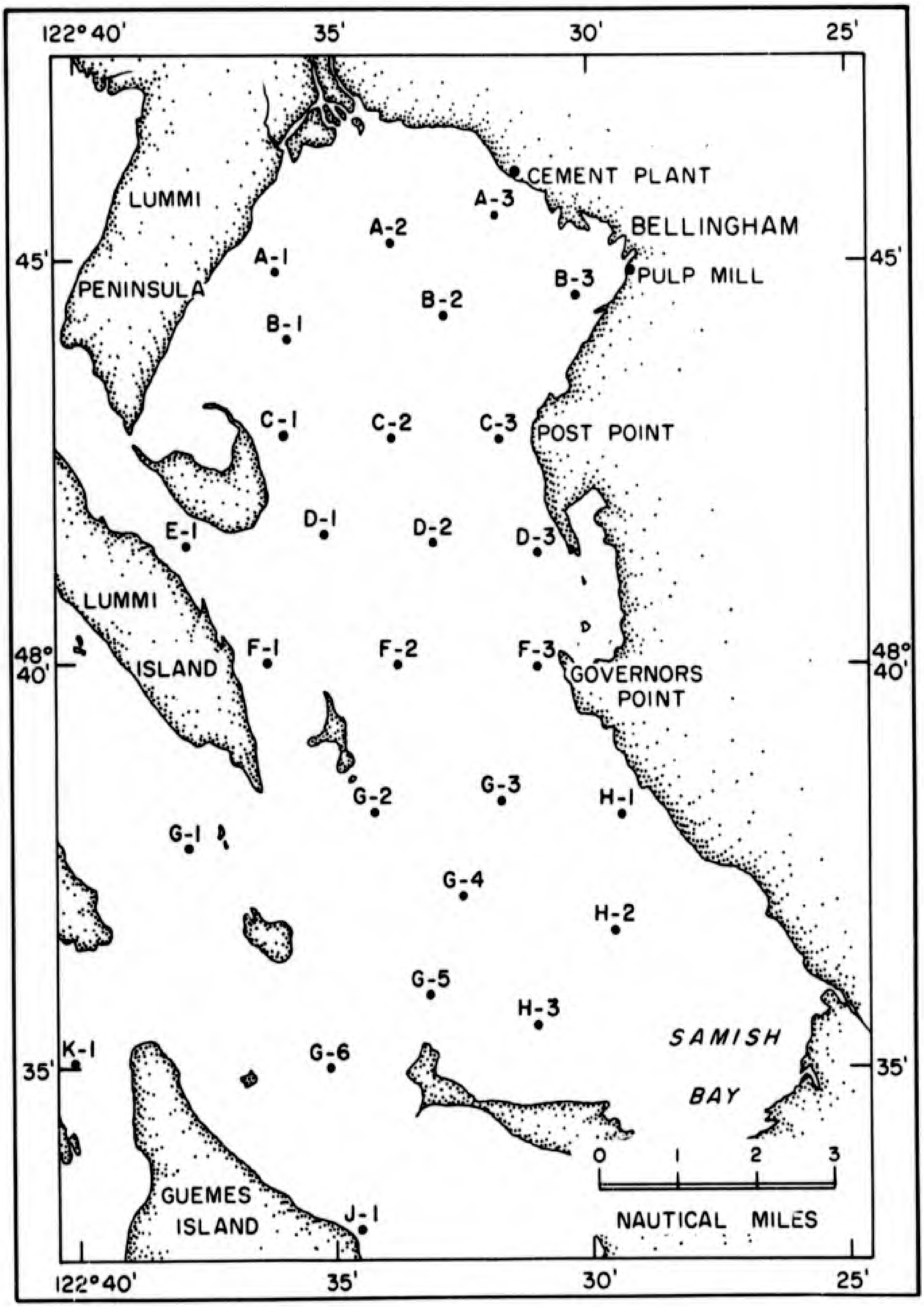

Fig 1.5. Location of oceanographic stations occupied in Bellingham and Samish Bays.

2. WATER CHARACTERISTICS

2.1. *Introduction*

Water characteristics in this study were determined from samples obtained with deep-sea reversing bottles of the Fjarlie (1953) and Nansen type. The Fjarlie bottle, essentially a straight, open tube to permit rapid flushing, was used in the upper 20 m (66 ft), and the Nansen bottle at greater depths. Each reversing bottle was equipped with a pair of deep-sea protected reversing thermometers to register the water temperature at the particular sampling depth. Upon retrieval of the reversing bottle from depth, the thermometers were read and samples of water were withdrawn for the determination of salinity, dissolved oxygen, and spent sulfite liquor.[4] On seven of the fourteen cruises, additional samples were obtained for determination of dissolved inorganic phosphate. The resulting data and a detailed description of the analytical methods employed are presented in Volume I of this report (Collias and Barnes, 1962).

Although water characteristics and water movements in this system are interdependent, certain aspects of each can be discussed separately. In this chapter, the observed water characteristics, selected computed parameters of the Bellingham—Samish Bay system, and factors affecting them will be examined. The important factors affecting the oceanography of the system include bathymetric features, runoff, seawater characteristics, climatic conditions, and tides.

The Puget Sound—Strait of Juan de Fuca—Georgia Strait complex is basically a two-layer system consisting of a surface layer of lower salinity water flowing seaward over a deeper inflowing layer of higher salinity water. The surface layer contains freshwater added locally from

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[4]Spent sulfite liquor (SSL) was determined by a modified Pearl-Benson method (Barnes *et al.*, 1963). This method is not specific for SSL, but responds to many phenolic-type compounds. Sources other than the pulp mill may at times contribute significantly to concentrations below 5 ppm, but not to concentrations above 10 ppm. "Pearl-Benson index" would be a better term for the values reported.

direct precipitation, river runoff, and other land drainage. The deeper, more saline layer has its origin in the Pacific Ocean off Cape Flattery and has a net flow landward in response to pressure forces associated with the density difference between freshwater and seawater. The boundary between the layers is most distinct near a major river or on either side of a constriction having strong tidal currents. The boundary usually becomes diffuse toward the ocean as a consequence of vertical mixing by wind and the entrainment of the deeper more saline water into the surface layer. The oceanic water in the bottom layer, which enters the Strait of Juan de Fuca off Cape Flattery, flows through most of the strait with little modification until it reaches the mixing zones. These zones include the eastern end of the Strait of Juan de Fuca, Haro Strait, Rosario Strait, and Admiralty Inlet.

2.2. *Annual Cycles*

2.2.1. *General Features:* The characteristics of local water continuously change in response to currents, mixing, exchange of mass and energy across the sea surface, and biological processes. These changes in properties vary from short-term random fluctuations as found in turbulent mixing to longer-term changes with definite cycles, such as seasonal changes.

The characteristics of the inflowing Pacific Ocean water forming the deeper layer change throughout the year primarily in response to seasonal changes of offshore winds. During summer months the northerly coastal winds cause upwelling along the Washington coast. This upwelled water is relatively cool, highly saline, nutrient rich, and low in oxygen. In August it flows strongly landward at depth throughout the Strait of Juan de Fuca. As a result, most parts of Puget Sound and Georgia Strait exhibit a salinity maximum and oxygen minimum in late summer and autumn. By late autumn, following a shift of the coastal winds to the south, the deeper water entering the Strait of Juan de Fuca decreases in salinity and nutrient content, and increases in temperature and oxygen content. Concurrently, the surface layer is more dilute and cooler. Hence a seasonal or annual cycle of water characteristics is developed in response to the meteorological cycle. To illustrate the annual cycles in water characteristics for water entering the Strait of Juan de Fuca, semimonthly averages of temperature, salinity, dissolved oxygen, and density for selected depths at a station off Pillar Point[5] are presented in Fig. 2.1 (after Megia, 1956). Somewhat similar annual cycles of water characteristics are observed elsewhere in Puget Sound and Georgia Strait but their timing and magnitude vary with distance from the Pacific Ocean and with local conditions.

The cycles of temperature, salinity, dissolved oxygen, and density[6] observed in Bellingham and Samish Bays during the survey period are more directly affected by variations of these respective properties found in Rosario Strait. In addition they are affected by runoff entering the system from the Nooksack and Samish Rivers, local winds, and local air temperature.

2.2.2. *Salinity Cycle:* For water below 5 m (16 ft) at all stations in the system, a salinity maximum (Fig. 2.2B through 2.8B) occurred in late autumn, rather than in August as observed off Pillar Point. This lag reflects in part the time required for the more saline oceanic water to flow landward toward Georgia Strait, and for the local accumulation of runoff water to flow seaward. From August the salinity decreased to a minimum in April, near the end of the rainy season. The salinity then began to increase but dropped to a second minimum in July in response to an accumulation of runoff water from the Nooksack and Fraser Rivers. Subsequently, in step with diminishing runoff and the continued transport seaward of accumulated river water, the salinity increased to the autumn maximum.

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[5]This station is located at 48°18.2'N and 124°02.1'W, about 30 miles (56 km) east of Cape Flattery. The data were obtained over a ten-year period from July 1932 to February 1942 by the Oceanographic Laboratories of the University of Washington under the leadership of Dr. Thomas G. Thompson.

[6]Densities in this report are expressed as sigma-*t* (σ_t). Sigma-*t* is an expression for the density of seawater, at atmospheric pressure and at its *in situ* temperature and salinity, as defined by the equation:

$$\text{sigma-}t = (\text{density} - 1) \times (1000)$$

Seasonal variations occurring in the upper 5 m (16 ft) of water are difficult to separate from the effects of wind, tidal currents, and short-term variations in discharge from the Nooksack River. These transient effects cause rapid changes in the surface characteristics that obscure long-term changes, but in general the surface waters are freshest in winter and most saline in late autumn.

2.2.3. *Temperature Cycle:* The temperature of the deeper water entering the Strait of Juan de Fuca was lowest in July and August, when the surface-water temperature was at its annual maximum (Fig. 2.1A). As the deeper water flowed landward it mixed with surface water in the connecting channels to Georgia Strait and Puget Sound. This mixed water, which supplies the deeper water in the many interior basins and arms, is coldest in winter and warmest in late summer. The result is that, in general throughout most of the Puget Sound region, water temperatures at all depths are lowest in winter and highest in late summer, but lag behind the air temperature cycle at any given location.

In the Bellingham-Samish Bay system the lowest temperatures (Fig. 2.2A through 2.8A) occurred between December and February at all stations. The temperatures of surface water increased from March to a maximum in July, but the maximum at depth was not reached until late August or September. By the time the bottom water reached its maximum temperature, the surface had begun to cool. On the cooling portion of the cycle, the surface water cooled more rapidly than the deeper water and was cooler than that at depth during the winter months. Hence the water column became isothermal twice during the year, once in late autumn and again in early spring.

Although the annual temperature cycle is similar at all stations, the annual range of surface temperatures decreases from the head of upper Bellingham Bay toward Rosario Strait. In upper Bellingham Bay the water currents are weaker, vertical mixing is less, and the Nooksack River has a strong influence on density stratification. These effects permit the same water to remain at the surface for a longer time in upper Bellingham Bay and to receive more solar heating. Toward the mouth of the system the Nooksack River has less influence, the water currents become stronger, vertical mixing increases, and solar heat is distributed over a greater depth. The maximum range of surface temperature was observed at station A-1 (see Fig. 1.5 for location) off the Nooksack River and the minimum toward the mouth at station H-2 in Samish Bay, which is directly influenced by the fairly strong currents injecting mixed water from Rosario Strait. Below 5 m (16 ft) the temperature range was only about one-third that of the surface but followed a similar seasonal trend.

2.2.4. *Oxygen Cycle:* The dissolved oxygen content at any location, depth, and time is dependent upon several factors. In the surface layer and in the photic zone, oxygen is added by direct exchange across the sea surface and by phytoplankton photosynthesis. Oxygen utilization occurs at all depths due to respiration, to decomposition of detritus, and to chemical oxygen demands of certain contaminants; but in water below the photic zone oxygen cannot be added except by diffusion and advection. The result is that the water usually decreases in oxygen content after it has left the surface layer. An average rate of decrease for selected deeper basins in the Puget Sound region has been determined to be about 0.023 ppm/day (Barnes and Collias, 1958), but a rate of about four times this value was found on one occasion in Dabob Bay (Kollmeyer, 1965).

In addition to affecting the salinity and temperature cycles, the intrusion of Pacific Ocean water into the Strait of Juan de Fuca in summer influences the oxygen content of the waters of Puget Sound and Georgia Strait. During summer and early fall the oxygen content of the deeper water is low because of the low oxygen content of the intruding oceanic water, relatively slow circulation at depth, and continuing oxidation of naturally produced organic material. During the winter months the oxygen content of the intrusive oceanic water increases and the interchange and mixing of the deeper water with newly oxygenated surface waters is more rapid. In spring photosynthesis by phytoplankton is at a maximum, so the surface waters are frequently supersaturated.

The oxygen cycles in Bellingham and Samish Bays (Fig. 2.2C through 2.8C) show that water of lowest oxygen content occurred below 5 m (16 ft) in September and October. The oxygen content increased until March and then began to decline. Phytoplankton blooms are indicated by the high oxygen values found in the upper 2 m (6 ft) from April through July. The effect of contaminants, noticeable in upper Bellingham Bay, is to decrease the oxygen content in the upper few meters below that which would normally prevail. This was evident from the vertical distribution of SSL concentration shown in Fig. 2.33 and 2.34.

2.2.5. *Density Cycle:* The density of the water in the Bellingham Bay region is controlled primarily by salinity and secondarily by temperature, the pressure effects being almost negligible over the depth range in the bay. At all stations the density was at a maximum from November through January (Fig. 2.2D through 2.8D). Subsequently the density at depth decreased to a minimum in July and August, whereas that at the surface was minimal in March and again in early summer. In the north end of Bellingham Bay the surface density responds quickly to variations in runoff from the Nooksack River.

2.3. *Salinity Distribution*

The surface salinity distribution in the Bellingham-Samish Bay system is controlled by the Nooksack River while the salinity distribution at depth is controlled by water entering from Rosario Strait. As previously discussed, each of these source waters undergoes annual changes that profoundly affect the system (see sections 1.2.4, 1.2.5, and 2.2). The dispersion of Nooksack River water discharged into upper Bellingham Bay depends upon wind, tidal action, and rate of river discharge. Consequently, the distribution of surface salinity was quite variable and less predictable than that observed in the deeper water.

Figures 2.9 through 2.21 present the surface salinity observed on each cruise. Because the data used to prepare each figure were not obtained simultaneously, the distributions present a gross pattern rather than an instantaneous picture. On three cruises the surface salinity in upper Bellingham Bay (Fig. 2.22 through 2.25) was measured using a Salinity-Temperature-Depth recorder (Jacobsen, 1948) within a 3-hr period, to give a more nearly synoptic picture.

The least saline surface water in the system was always observed near the mouth of the Nooksack River and along the head of upper Bellingham Bay, from station A-1 to station B-3. From the river mouth toward Rosario Strait the surface water became more saline, with a marked increase frequently observed near a line between Post Point and Point Frances (line 5 in Fig. 1.2). South of this line the surface salinity approached that of the water entering the system from Rosario Strait. Surface salinities in Samish Bay were usually about the same as those observed off Viti Rocks, except for the waters over the tidal flats. These waters reflected the runoff of the Samish River, having lowest salinity during the winter months when rainfall was greatest.

The thickness of the surface layer in upper Bellingham Bay varied with the rate and duration of discharge from the Nooksack River. During periods of high river discharge, a shallow surface layer of low salinity covered most of upper Bellingham Bay. The surface layer deepened and became more saline with low river runoff in late summer. This change in depth from cruise to cruise was evident in the vertical salinity distributions observed along a longitudinal section extending from the Nooksack River (station A-2) to station G-1 off Viti Rocks (Fig. 2.26B through 2.39 B).

Observations were made during two periods of high Nooksack River discharge. In June 1960 the Nooksack River discharge for the 20 days preceding the cruise averaged 5545 cfs (157 m^3/sec) and produced a thin, low salinity surface layer extending from the mouth of the Nooksack River to Eliza Island (Fig. 2.12). Although low salinity water covered all of upper Bellingham Bay, the depth to the 26‰ salinity isopleth averaged less than 2 m (6 ft) (Fig. 2.29B). The second period of high Nooksack River discharge occurred in February 1961, when the average discharge rate for the 20 days prior to the cruise was 6915 cfs (195 m^3/sec) and the discharge for the two days immediately preceding the cruise was 7080 and 15,200 cfs (200 and 430 m^3/sec), respectively, which was 21% greater than in June 1960. The resulting surface layer covered about three-fourths of upper Bellingham Bay, and was very muddy and of very low salinity (Fig. 2.18). Above the B-line of stations, the surface salinities were less than 5‰ and the 26‰ salinity isopleth was at a depth of less than 2 m (6 ft). Because of this large discharge, the 29‰ salinity isopleth was 11 m (36 ft) deep as far south as Post Point (see Fig. 2.35B).

When the Nooksack and Samish River flows decreased to a minimum in late summer, the surface layer practically disappeared and the salinities observed throughout the entire bay approached that of Rosario Strait.

In September 1960 the combined Nooksack River and Fishtrap Creek flow diminished to 1600 cfs (45 m^3/sec) and no pronounced surface layer was evident (Fig. 2.15). Also, the highest overall surface salinity was observed at this time and the 29‰ isopleth came within 3 m (10 ft) of the surface (Fig. 2.32B).

In July 1960 the combined Nooksack River and Fishtrap Creek discharge approached the average annual discharge rate of 3730 cfs (106 m^3/sec). The surface layer at this time extended southward from the head of Bellingham Bay to William Point but did not intrude into Samish Bay or west of Vendovi Island (Fig. 2.13 and 2.30B).

The influence of wind upon Bellingham and Samish Bays is dependent upon the speed, direction, and duration of the wind. In November 1959 the winds recorded aboard ship were from the north to northeast at 8–18 knots (4–9 m/sec) with gusts up to 30 knots (15 m/sec). This wind pushed the less saline surface layer from the central portion of upper Bellingham Bay toward Point Frances (Fig. 2.9) and confined it to a narrow band near Lummi Peninsula. As the less saline surface water moved away from the vicinity of station B-3, its replacement by more saline water became evident as shown by a comparison of two sets of observations made about 10 hr apart (Fig. 2.9 and 2.22). The surface salinity along a line extending southwest from station B-3 increased nearly 2‰ while the spent sulfite liquor (SSL) content in the central portion of the bay decreased by more than 30 ppm (Fig. 2.26 and 2.53). At the end of the 10-hr period a narrow band of fresher water with relatively high SSL content extended from the pulp mill to Post Point. It was also noted that the surface salinity contours over the entire system tended to orient themselves parallel to the wind. At the same time a core of colder water, more saline, of lower oxygen content, and of low SSL content, entered upper Bellingham Bay at depth and moved from station G-3 toward station B-3, counter to the wind, compensating for the outward movement of surface water.

The effect of strong southwest winds of 10–20 knots (5–10 m/sec) was observed in April 1960. This wind pushed the surface layer toward station B-3, causing a deepening of the surface layer in that vicinity. Higher salinity water appeared along Lummi Peninsula and extended into the center of upper Bellingham Bay, resulting in an eastward bulge of the 26‰ isopleth so that the surface salinity distribution assumed a crescent shape (see Fig. 2.10). Another crescent-shaped distribution of surface salinity was observed in June 1960 (Fig. 2.12), when the winds were from the southwest to northwest at speeds up to 10 knots (5 m/sec). These winds also caused the less saline water in Samish Bay to be confined near the mouth of the Samish River.

Southerly winds observed in August 1960 deepened the surface layer and confined it to an area near the mouth of the Nooksack River (Fig. 2.14 and 2.31B). This was accompanied by the appearance of higher salinity water in the southern portion of Bellingham Bay and in Samish Bay.

Vertical salinity gradients existed all year, but were strongest during the spring and early summer months when river runoff was at a maximum, and least during months of minimum runoff. The strongest vertical gradients were observed in the upper 10 m (33 ft), decreased between 10 and 20 m (33 and 67 ft), and were very small between 20 m and the bottom. Below 20 m the changes in salinity over the entire Bellingham-Samish Bay system were less than 0.5‰.

2.4. *Temperature Distribution*

The surface distribution of temperature (Fig. 2.40 through 2.52) did not always parallel the surface salinity distribution. The best correlation between temperature and salinity distributions was observed from May through September. At this time the less saline surface layer in upper Bellingham Bay was warmer than the underlying water so that the position of this layer could be defined by either temperature or salinity. Also during this period upper Bellingham Bay was considerably warmer than Samish Bay. Throughout the remainder of the year the surface waters exhibited so little variation of temperature that a marked change of salinity could not be detected readily by a corresponding change in temperature.

The vertical temperature distributions (Fig. 2.26A through 2.39A) indicated that most of the temperature gradient was confined to the upper 10 m (33 ft) and decreased from the head of Bellingham Bay to the entrance. This observation was similar to that for salinity. The largest temperature gradients occurred in June and July when summer heating was at a maximum and the Nooksack River was high. In late fall and early spring the entire system became nearly isothermal. A temperature inversion with colder water at the surface than at depth was evident in late winter just before the beginning of the warming cycle. Remnants of water remaining in the system from late autumn were observed during late winter and spring. These were indicated as pockets of slightly warmer or colder water below the surface and were confined to upper Bellingham Bay (see Fig. 2.34 and 2.36).

2.5. *Spent Sulfite Liquor Distribution*

The source of spent sulfite liquor (SSL) in Bellingham and Samish Bays is the Georgia-Pacific Corp. pulp mill. The average amount of effluent discharged per day by the mill is 42×10^6 gallons (0.159×10^6 m^3), the equivalent to a flow of 65 cfs (1.8 m^3/sec). This effluent is mostly freshwater containing dissolved and suspended solids from the pulping process and has an average Pearl-Benson index of 27,000 ppm (Edwin H. Dahlgren, personal communication, 1962). Because the effluent from the mill is discharged at a fairly uniform rate, the SSL may be considered to be a unique property originating from a continuous point source. The amount of SSL discharged into upper Bellingham Bay was dependent upon the activity of the mill and did not change in a cyclic fashion as did salinity or temperature. Hence the three-dimensional distribution of SSL gives some indication of the gross movement of the waters in the system. In general the highest concentrations of SSL were found in the inner harbor near the pulp mill and out to station B-3. Beyond this region the concentrations of SSL declined rapidly.

The surface distributions of SSL are presented in Fig. 2.53 through 2.64. The figures represent neither instantaneous distributions nor average concentrations; but surface SSL values were obtained on two cruises at closely spaced intervals over a short period of time, for correlation with the salinity distribution (Fig. 2.65 and 2.66).

The vertical distribution of SSL (Fig. 2.26D through 2.39D) tended to follow the salinity distribution. Most of the SSL was confined above the 10-m (33-ft) level but values of less than 10 ppm SSL were usually observed at all depths.

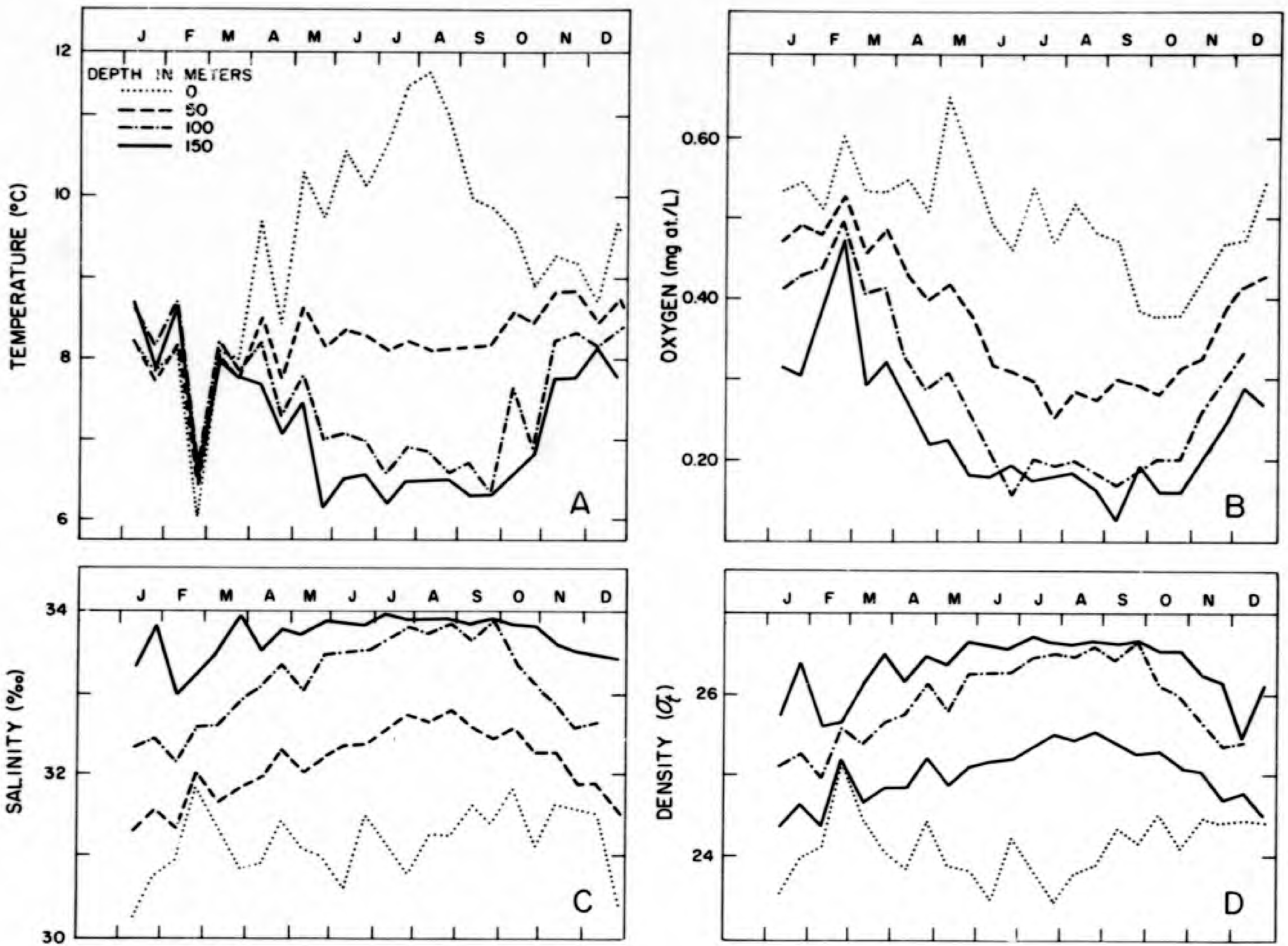

Fig. 2.1. Water characteristics at Pillar Point.

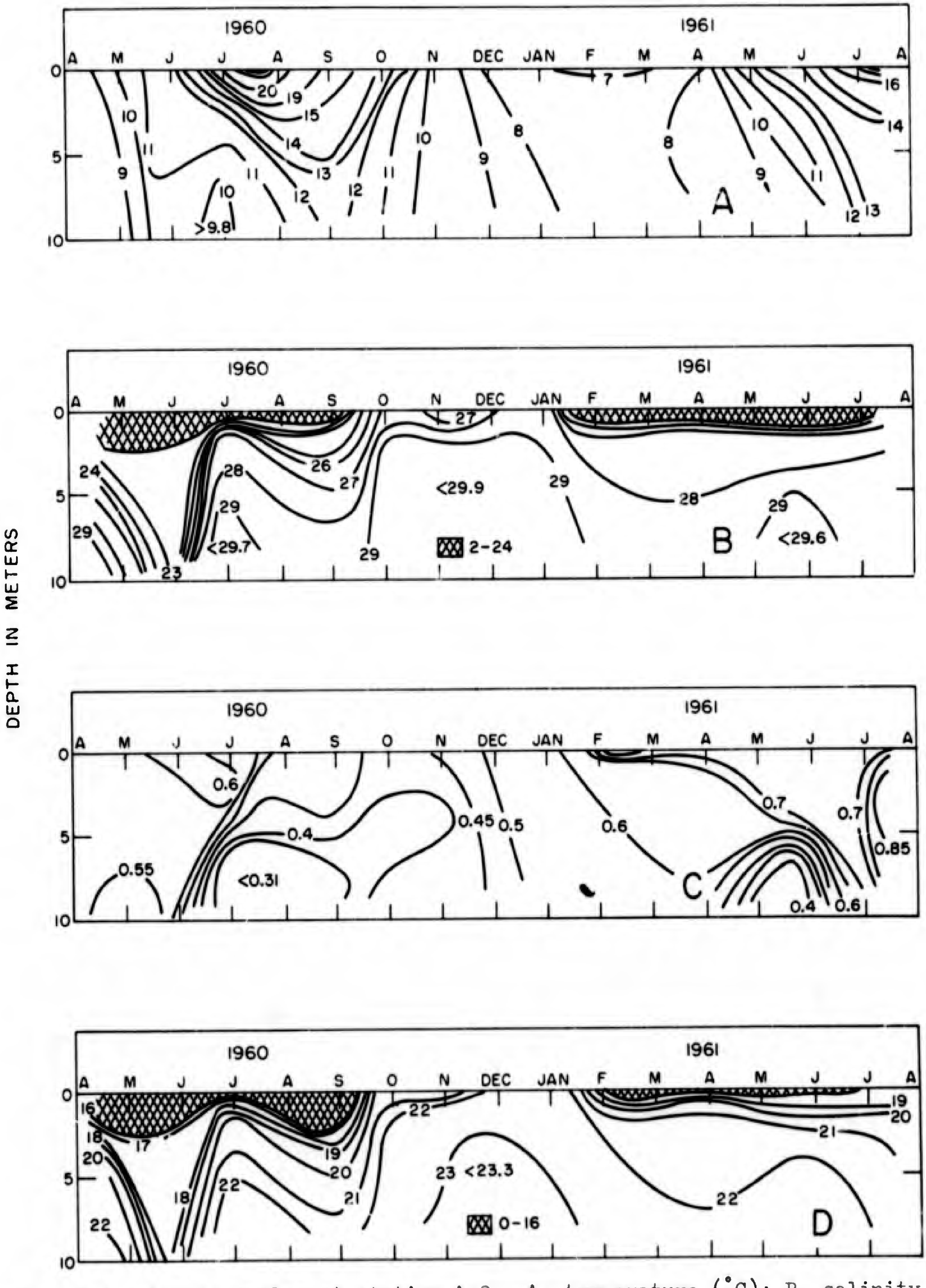

Fig. 2.2. Annual cycles at station A-3. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

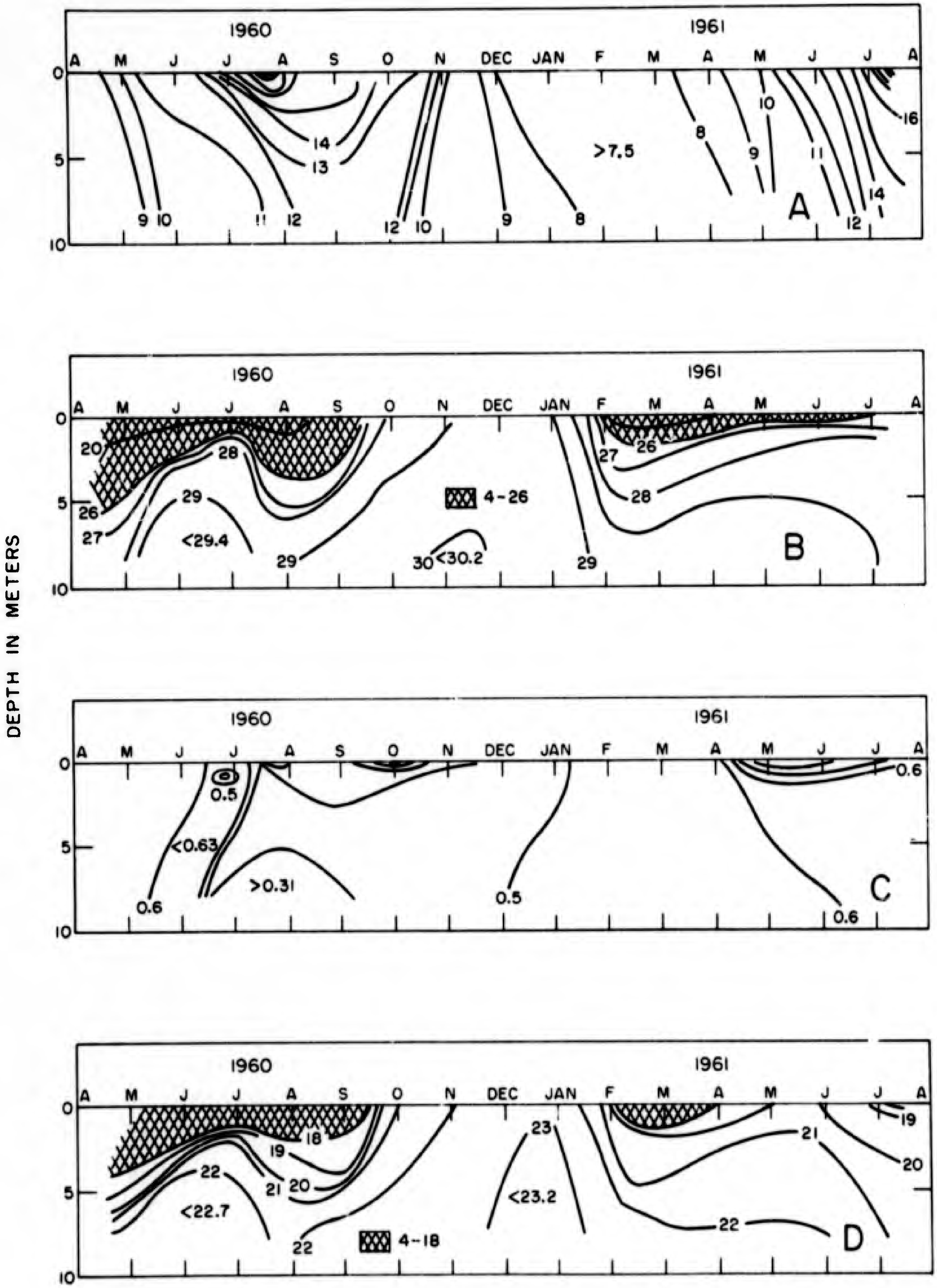

Fig. 2.3. Annual cycles at station B-3. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

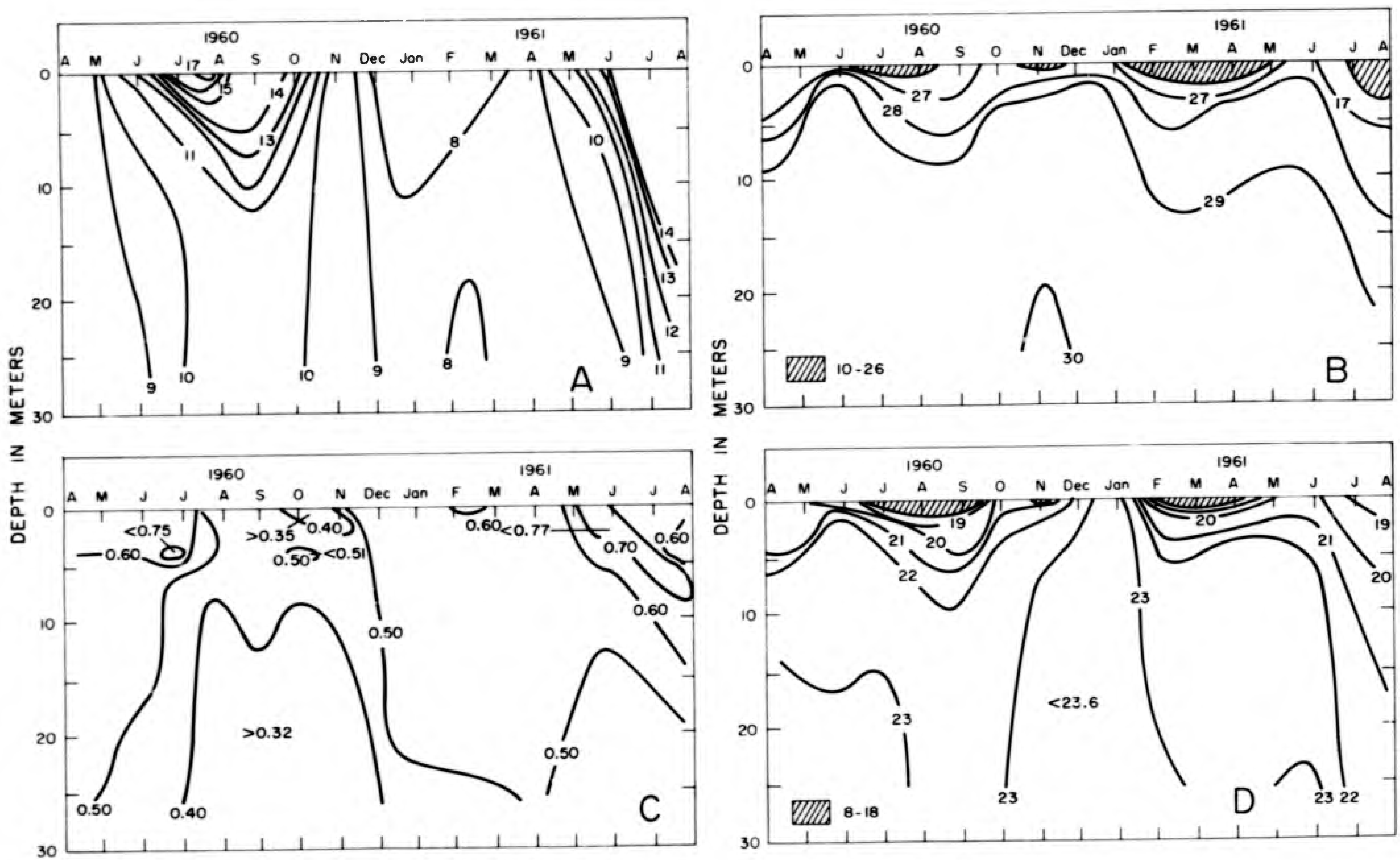

Fig. 2.4. Annual cycles at station C-2. A, temperature (°C); B. salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

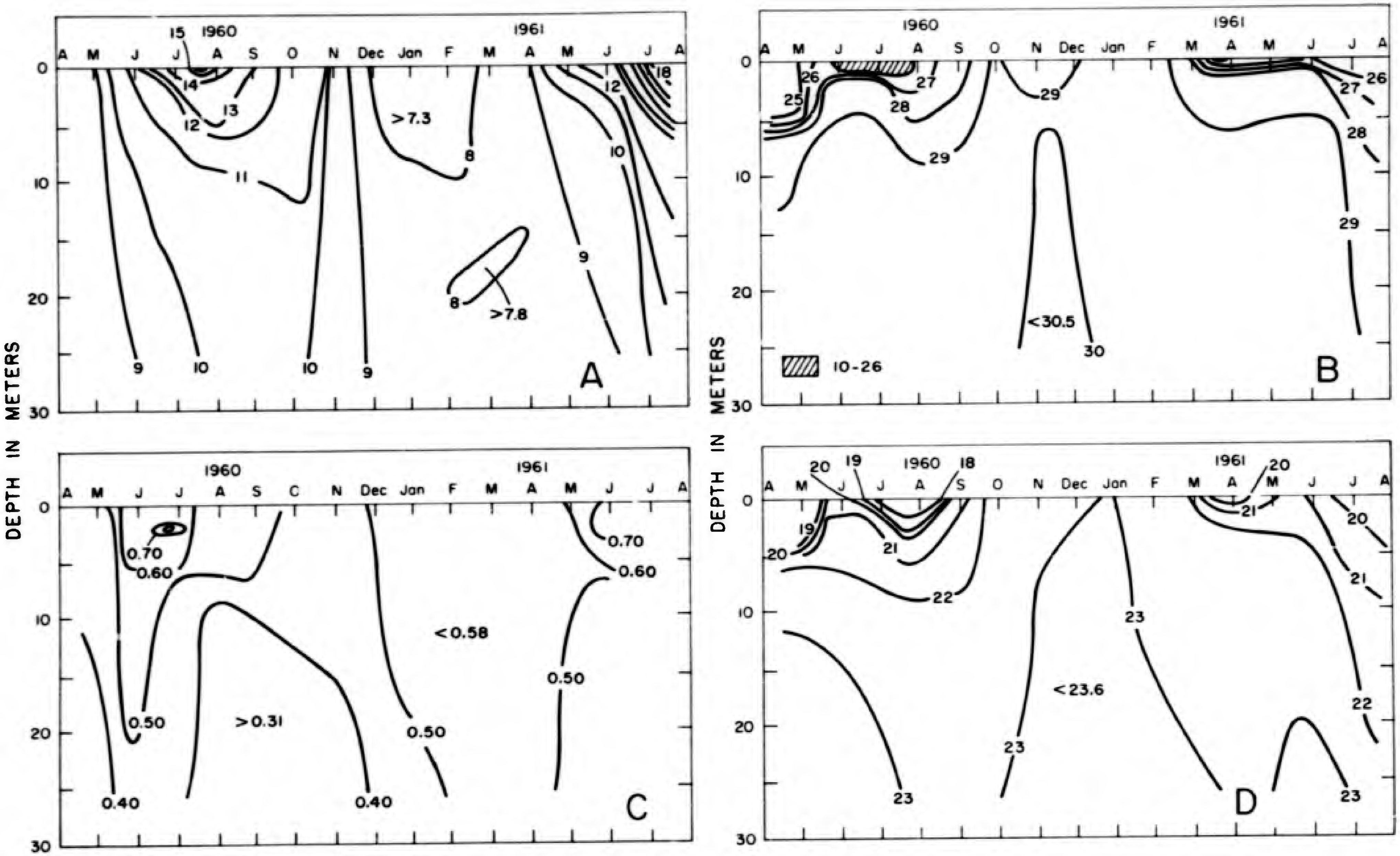

Fig. 2.5. Annual cycles at station D-2. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

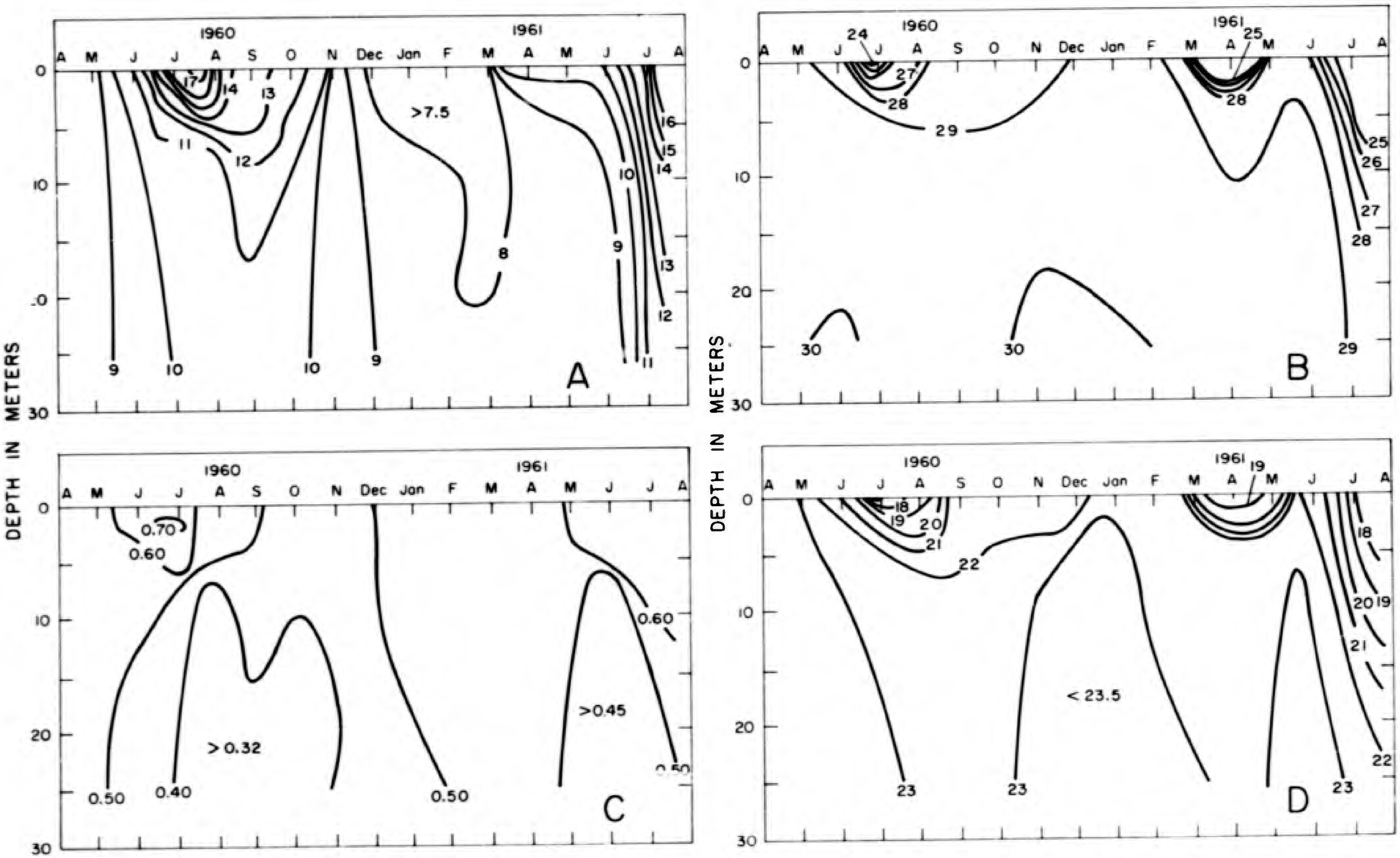

Fig. 2.6. Annual cycles at station F-2. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

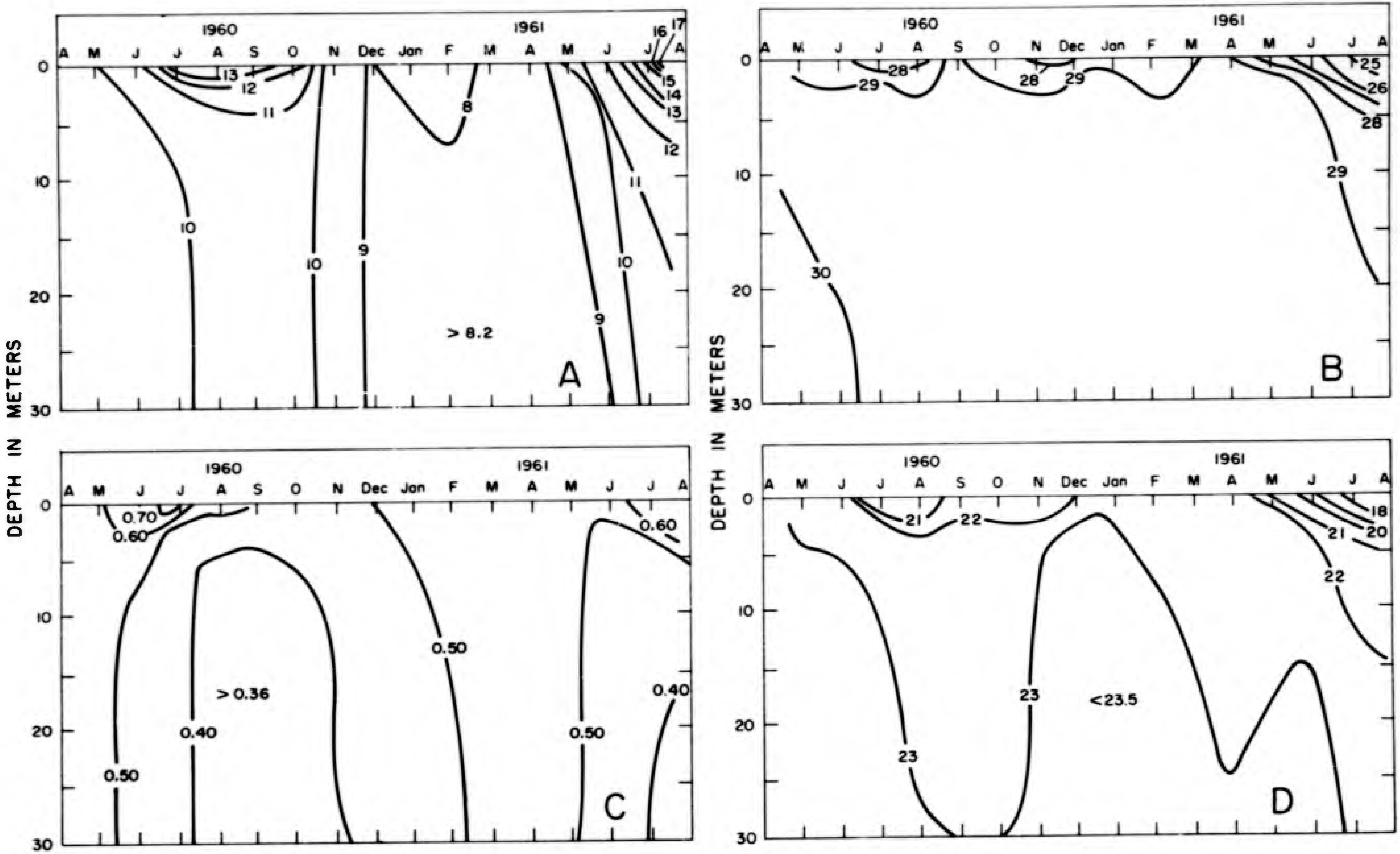

Fig. 2.7. Annual cycles at station G-2. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

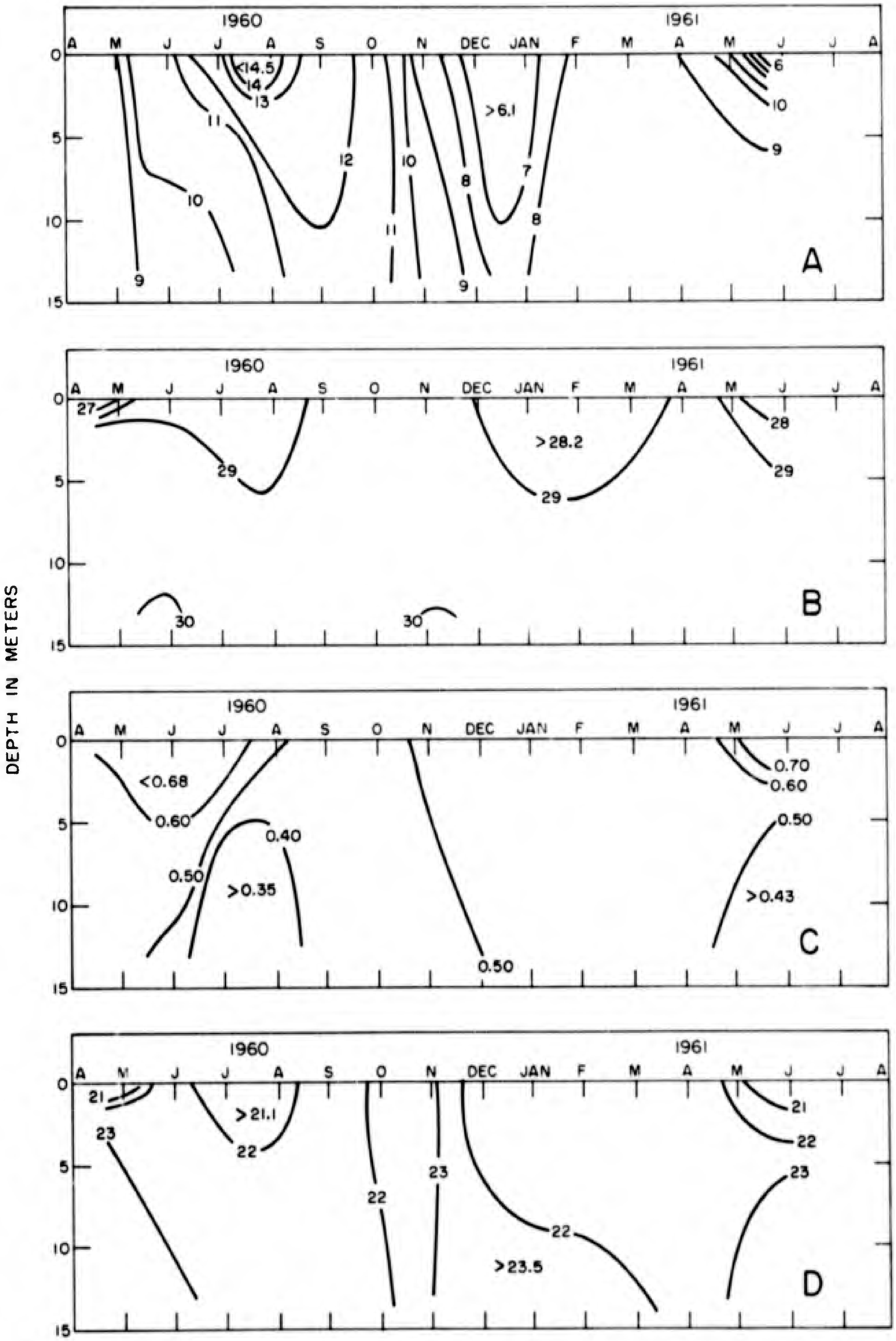

Fig. 2.8. Annual cycles at station H-2. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, density as σ_t.

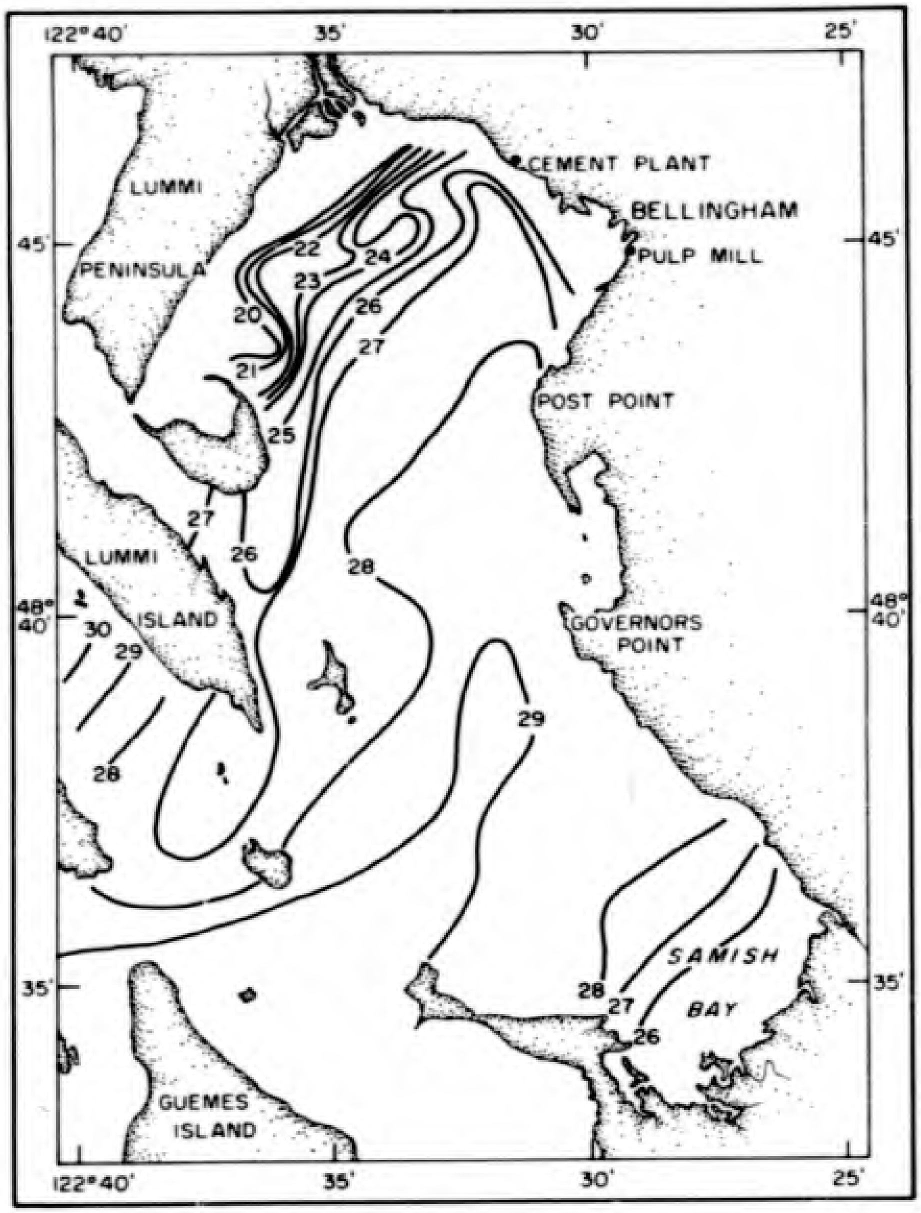

Fig. 2.9. Surface distribution of salinity for 2-4 November 1959.

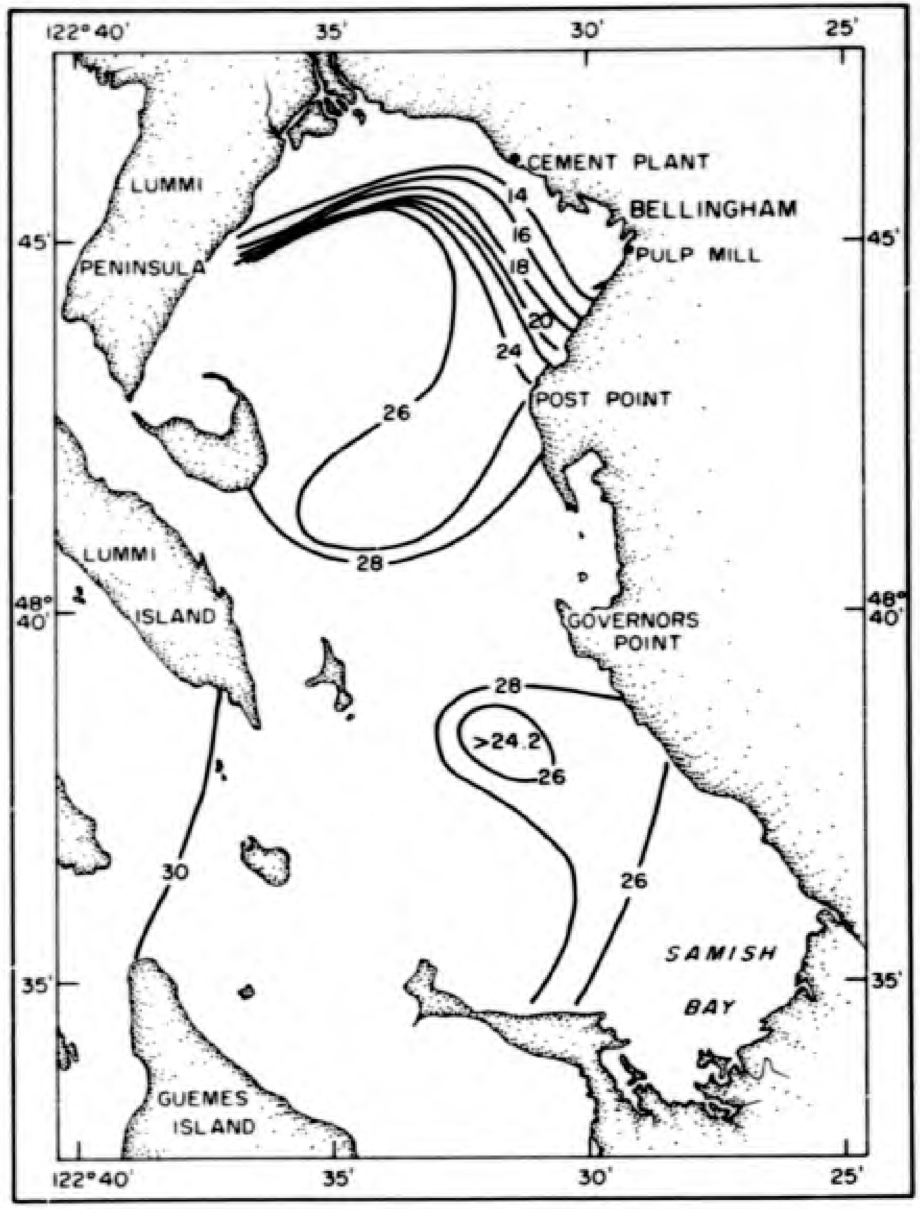

Fig. 2.10. Surface distribution of salinity for 19-21 April 1960.

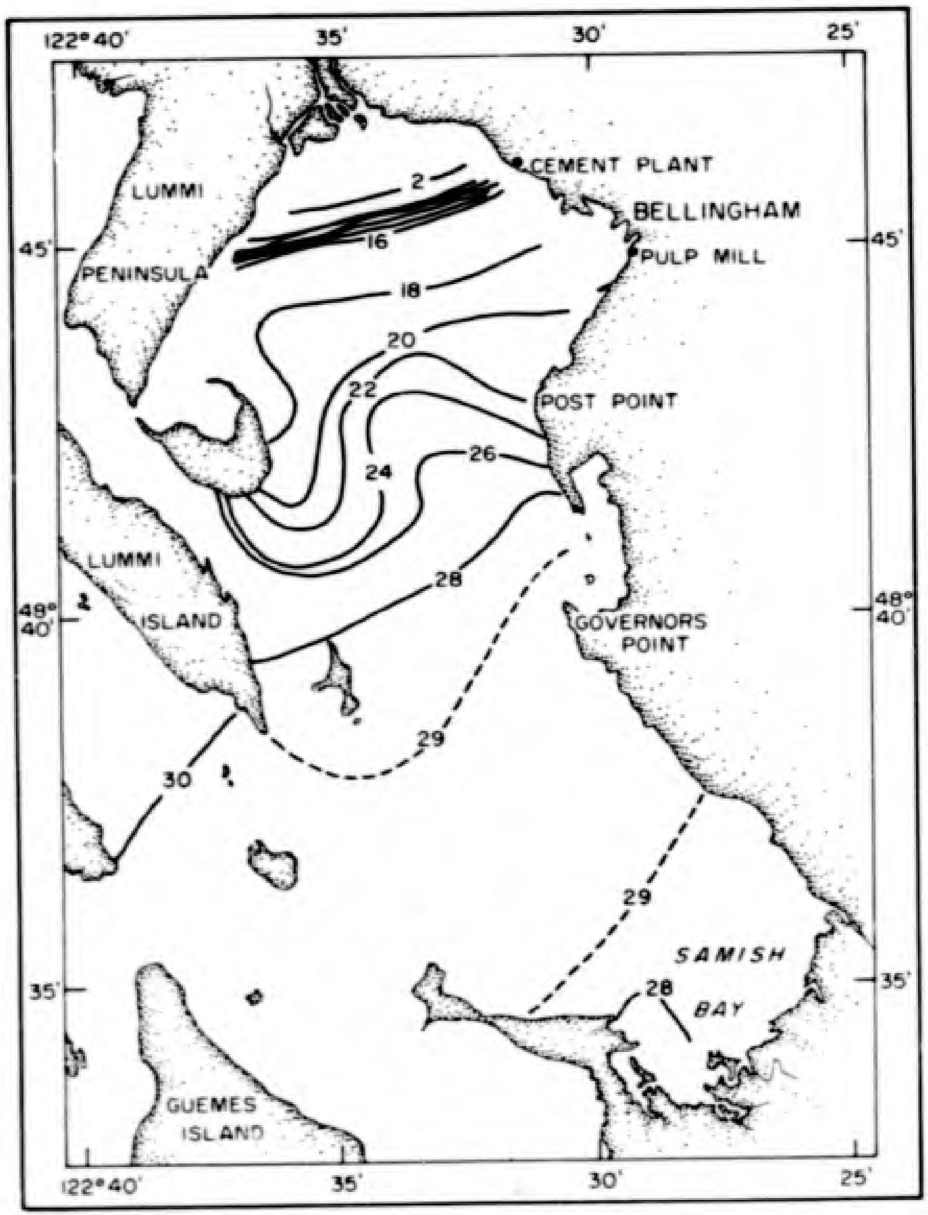

Fig. 2.11. Surface distribution of salinity for 20-22 May 1960.

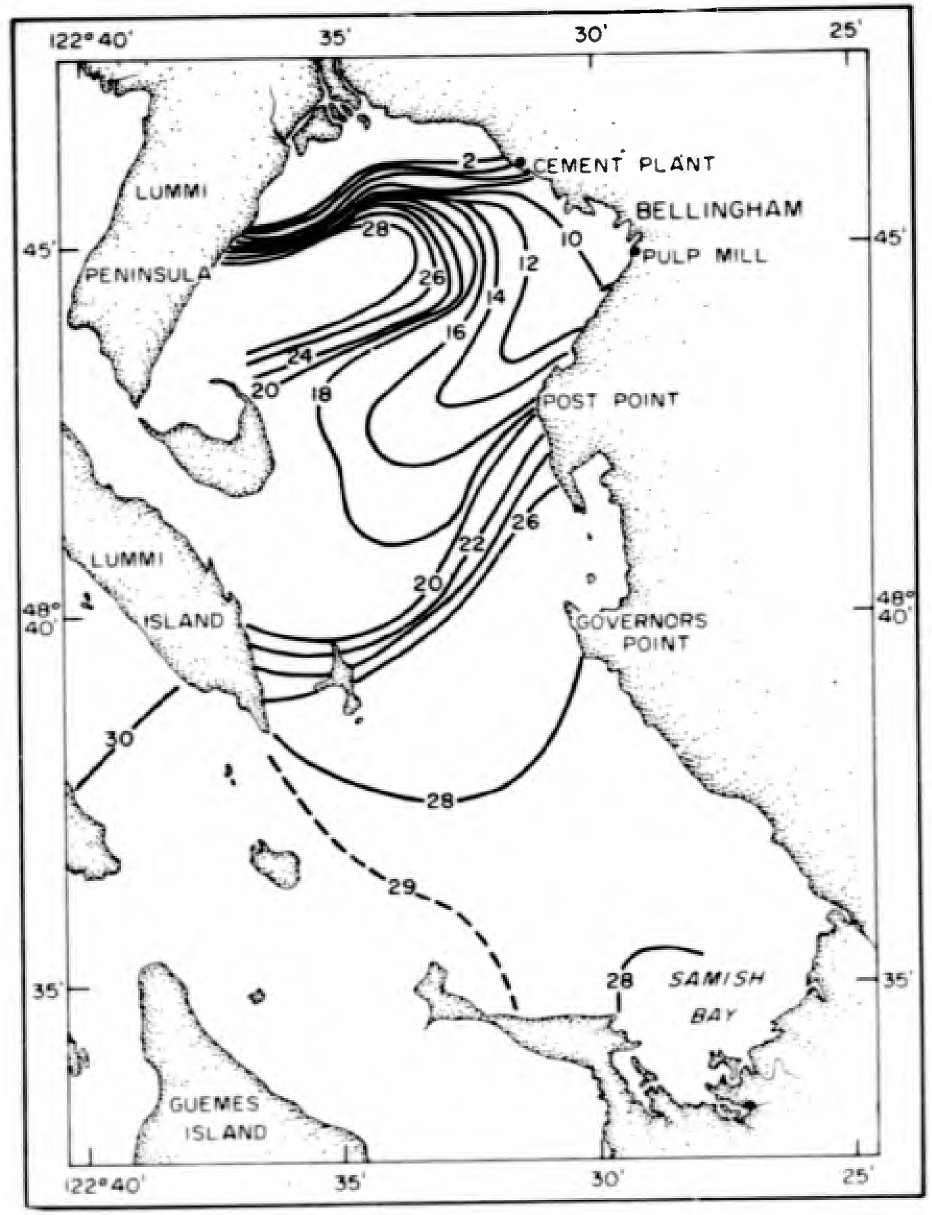

Fig. 2.12. Surface distribution of salinity for 21-22 June 1960.

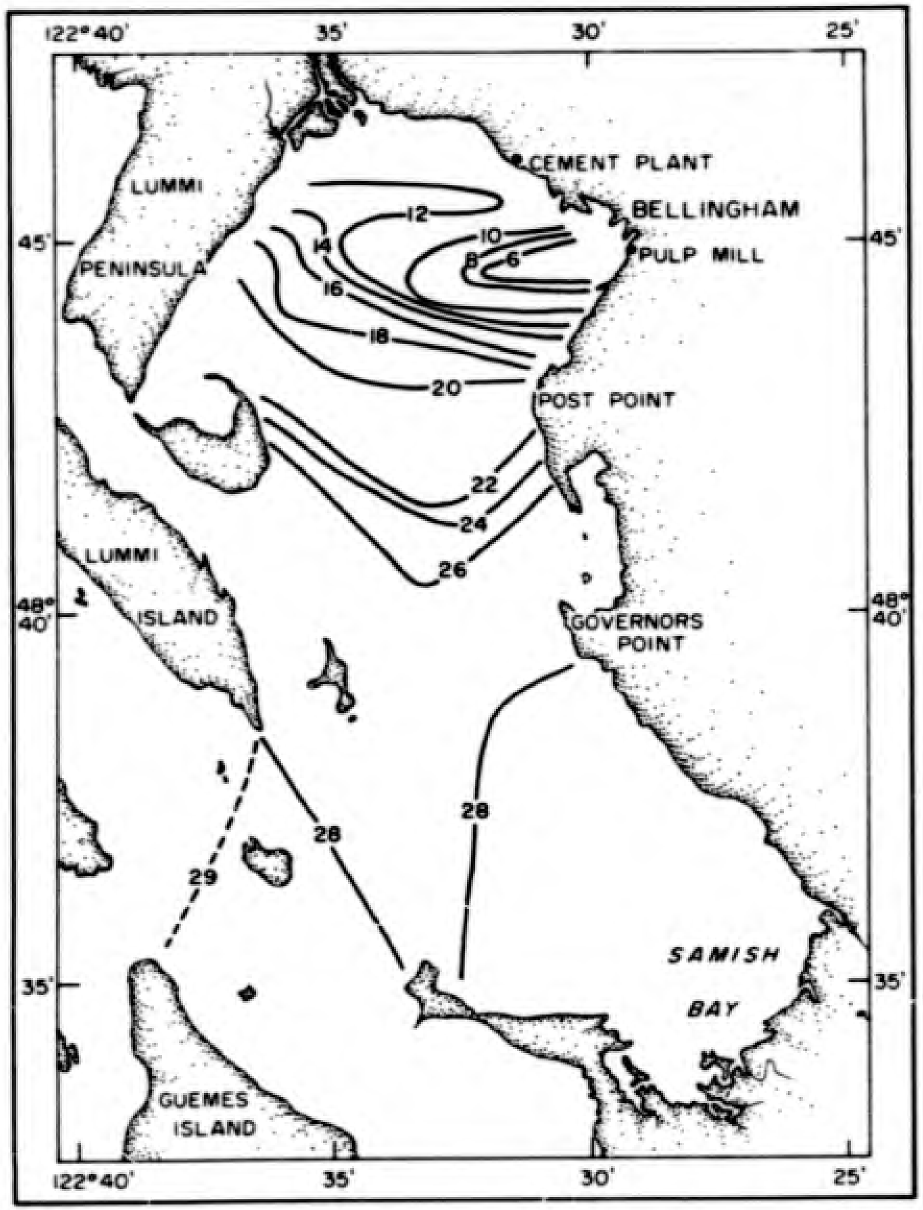

Fig. 2.13. Surface distribution of salinity for 18-19 July 1960.

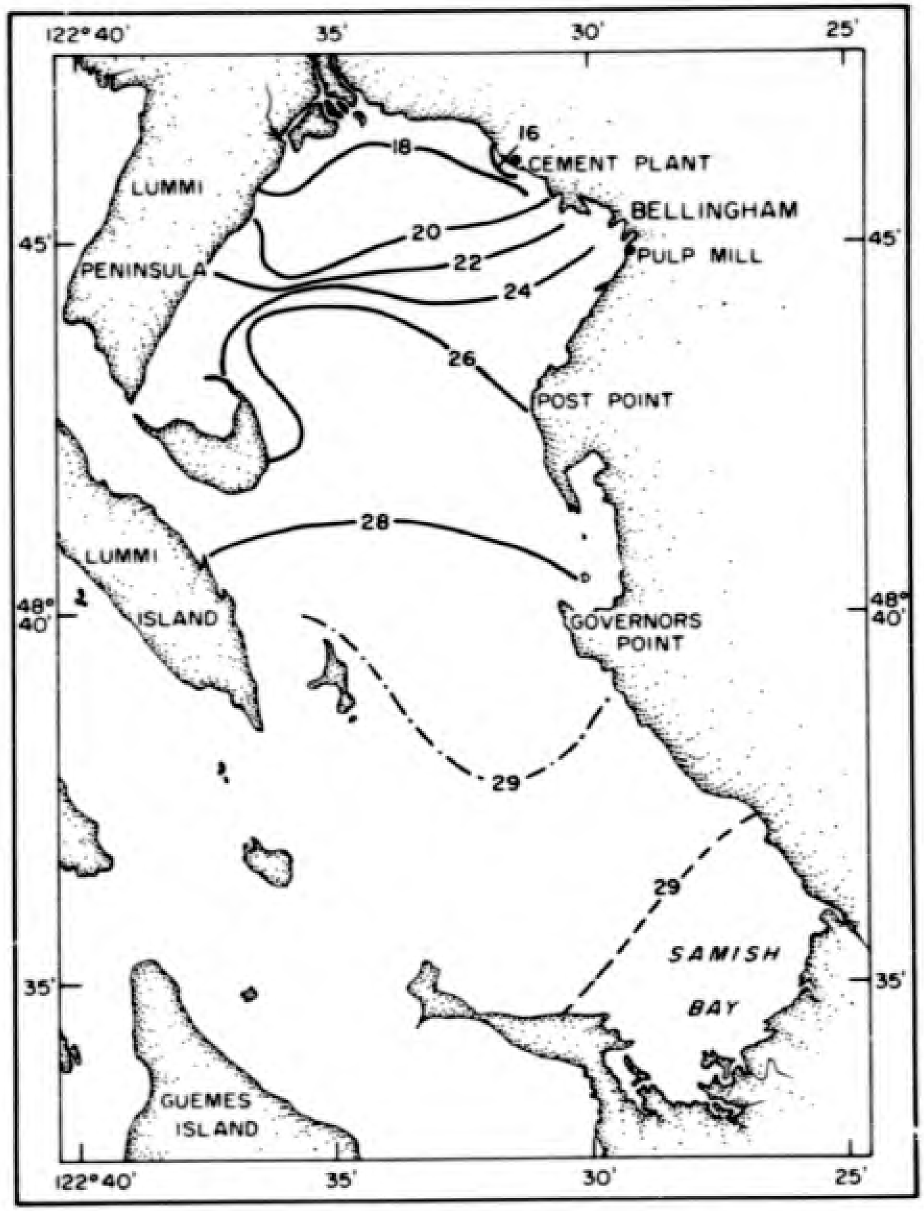

Fig. 2.14. Surface distribution of salinity for 23-24 August 1960.

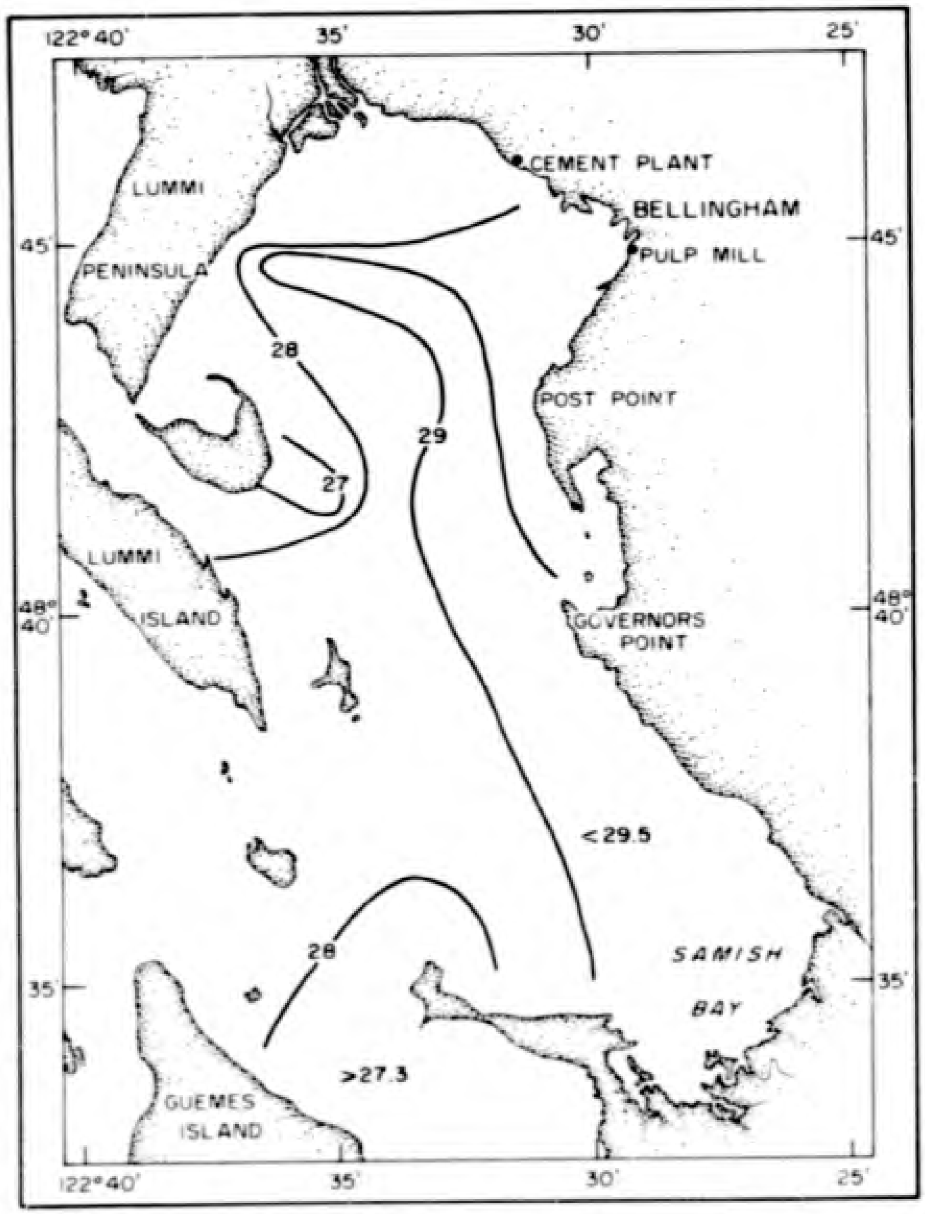

Fig. 2.15. Surface distribution of salinity for 28-29 September 1960.

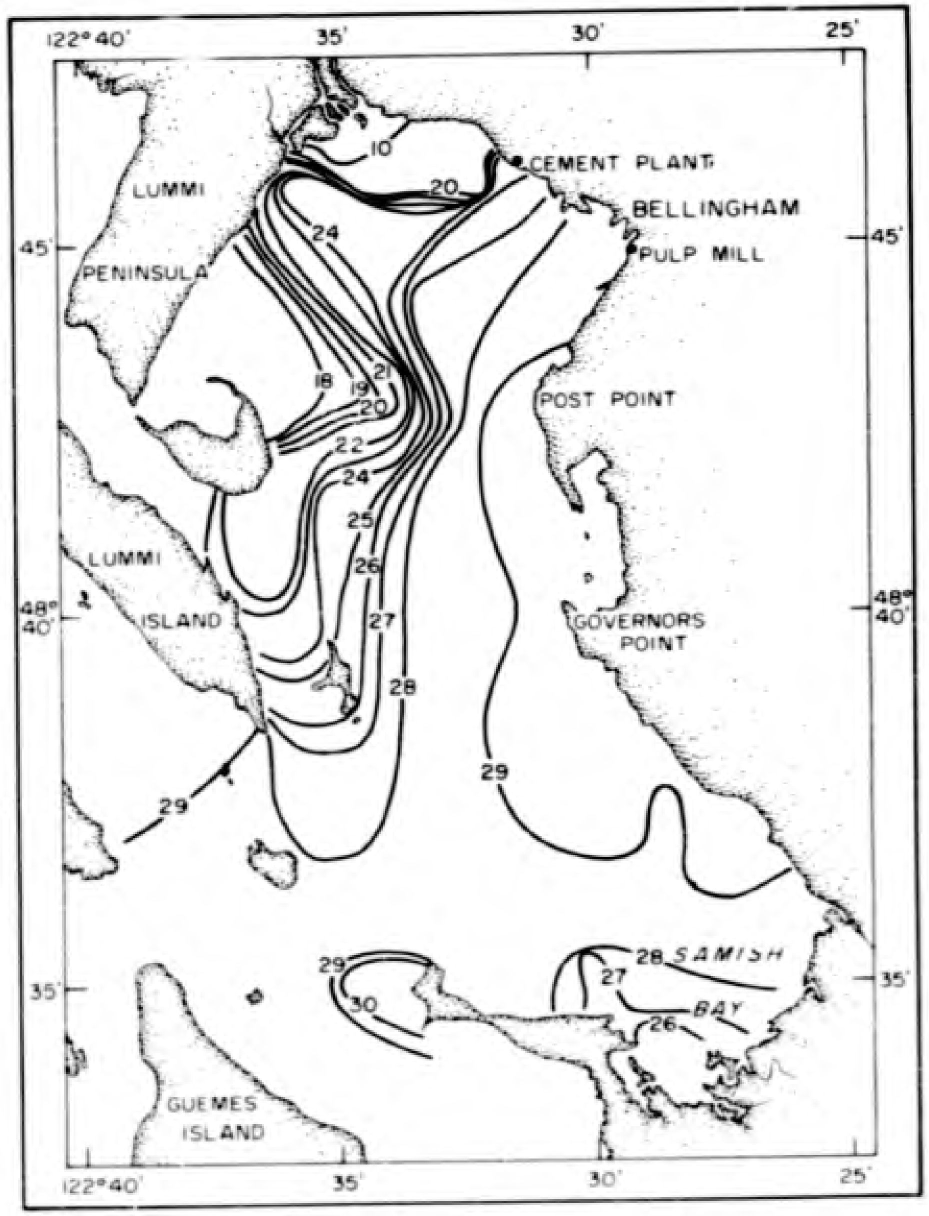

Fig. 2.16. Surface distribution of salinity for 3-4 November 1960.

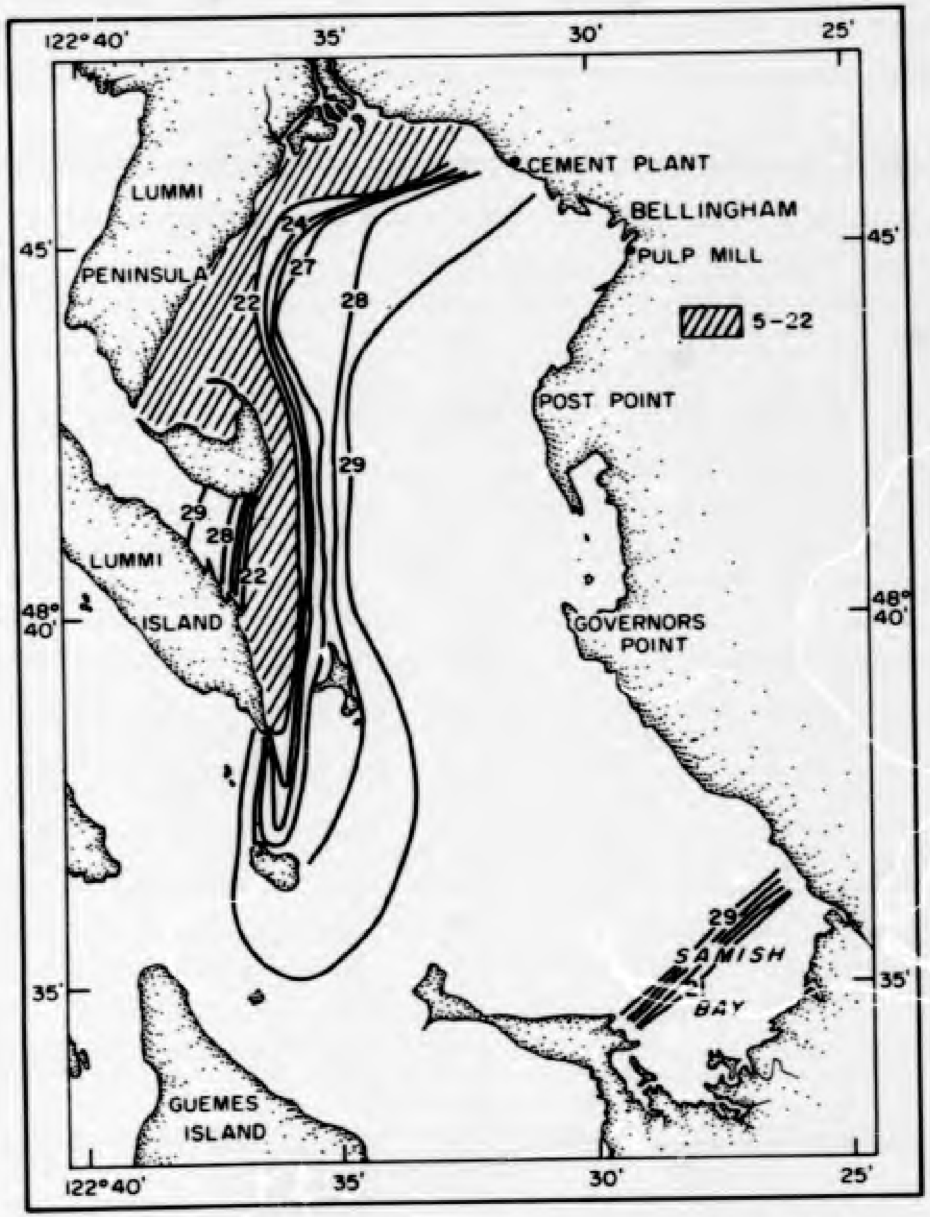

Fig. 2.17. Surface distribution of salinity for 16-17 December 1960.

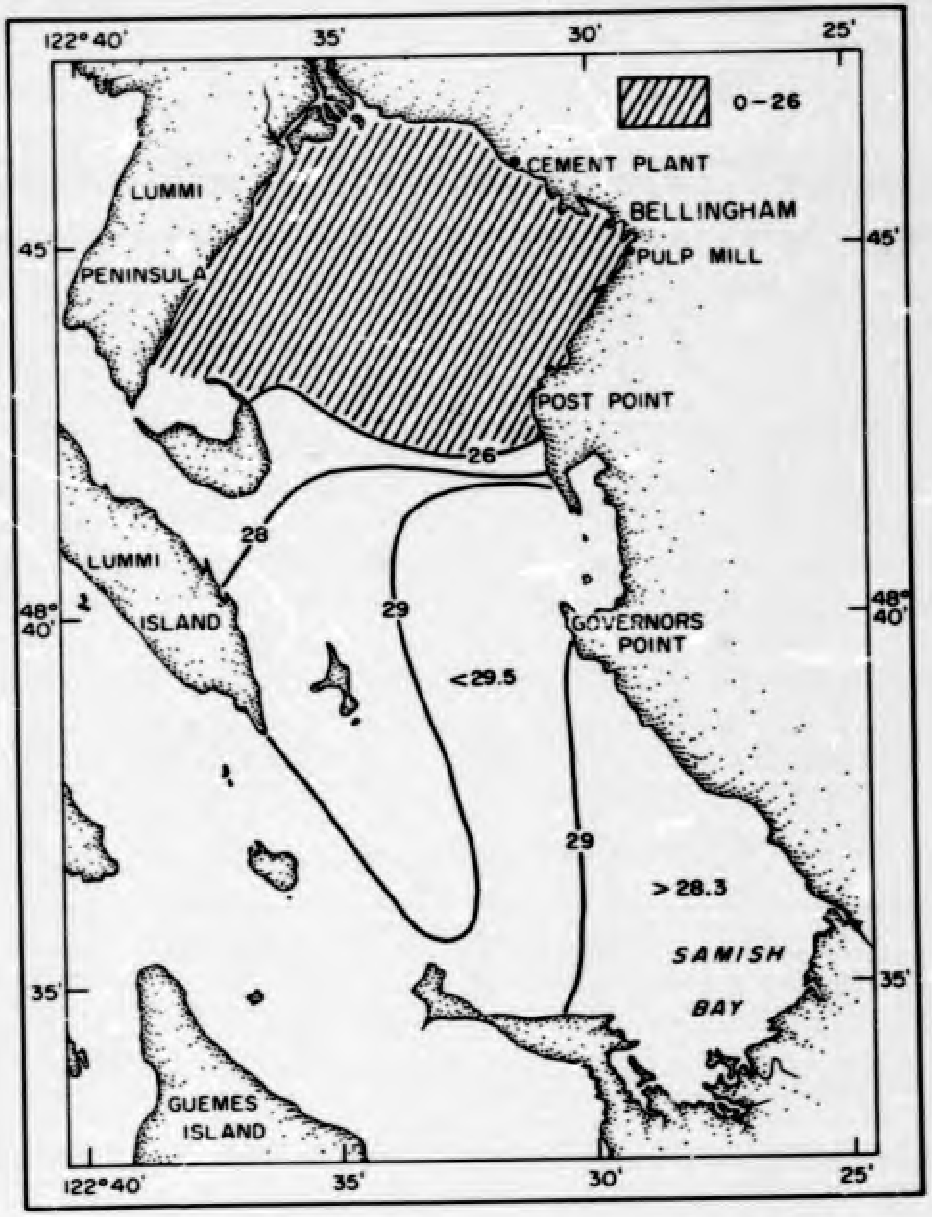

Fig. 2.18. Surface distribution of salinity for 6-7 February 1961.

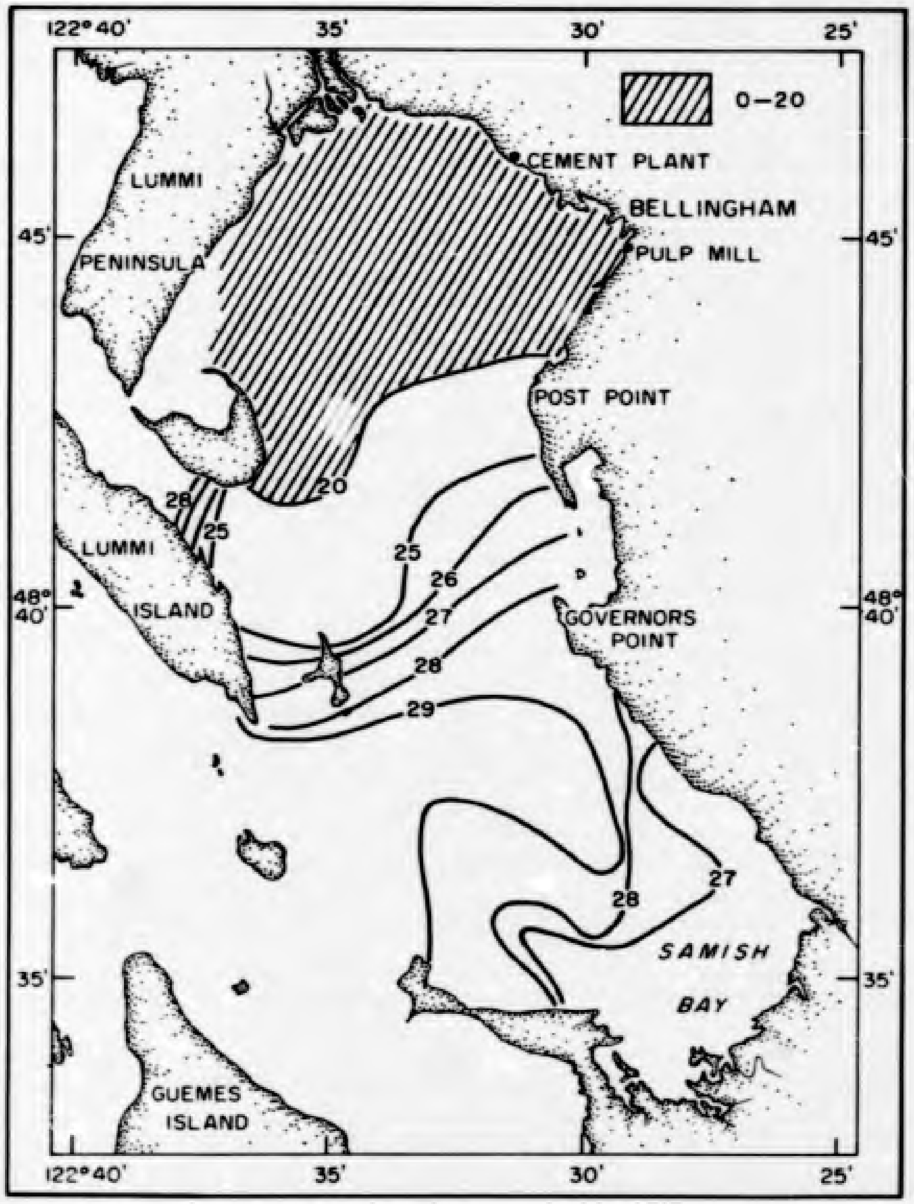

Fig. 2.19. Surface distribution of salinity for 20-22 March 1961.

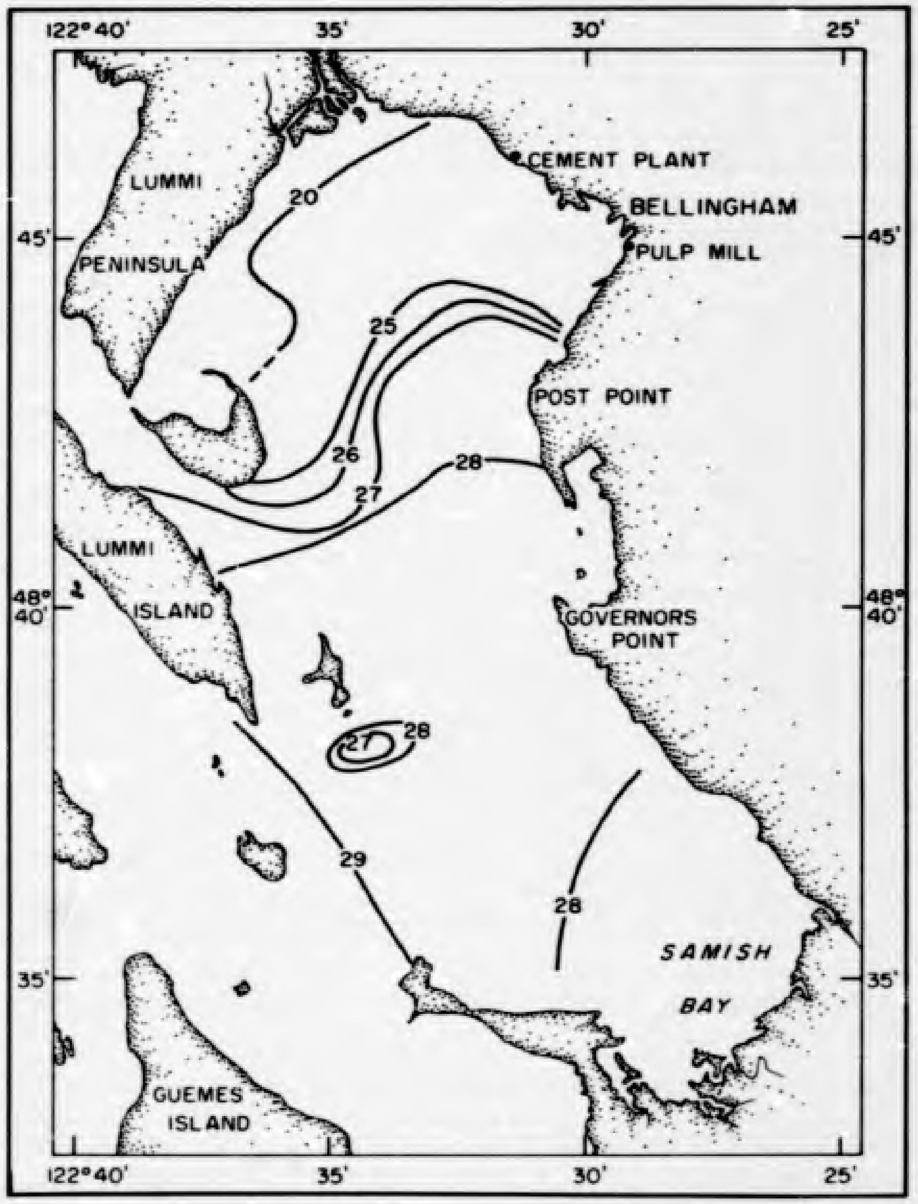

Fig. 2.20. Surface distribution of salinity for 15-16 May 1961.

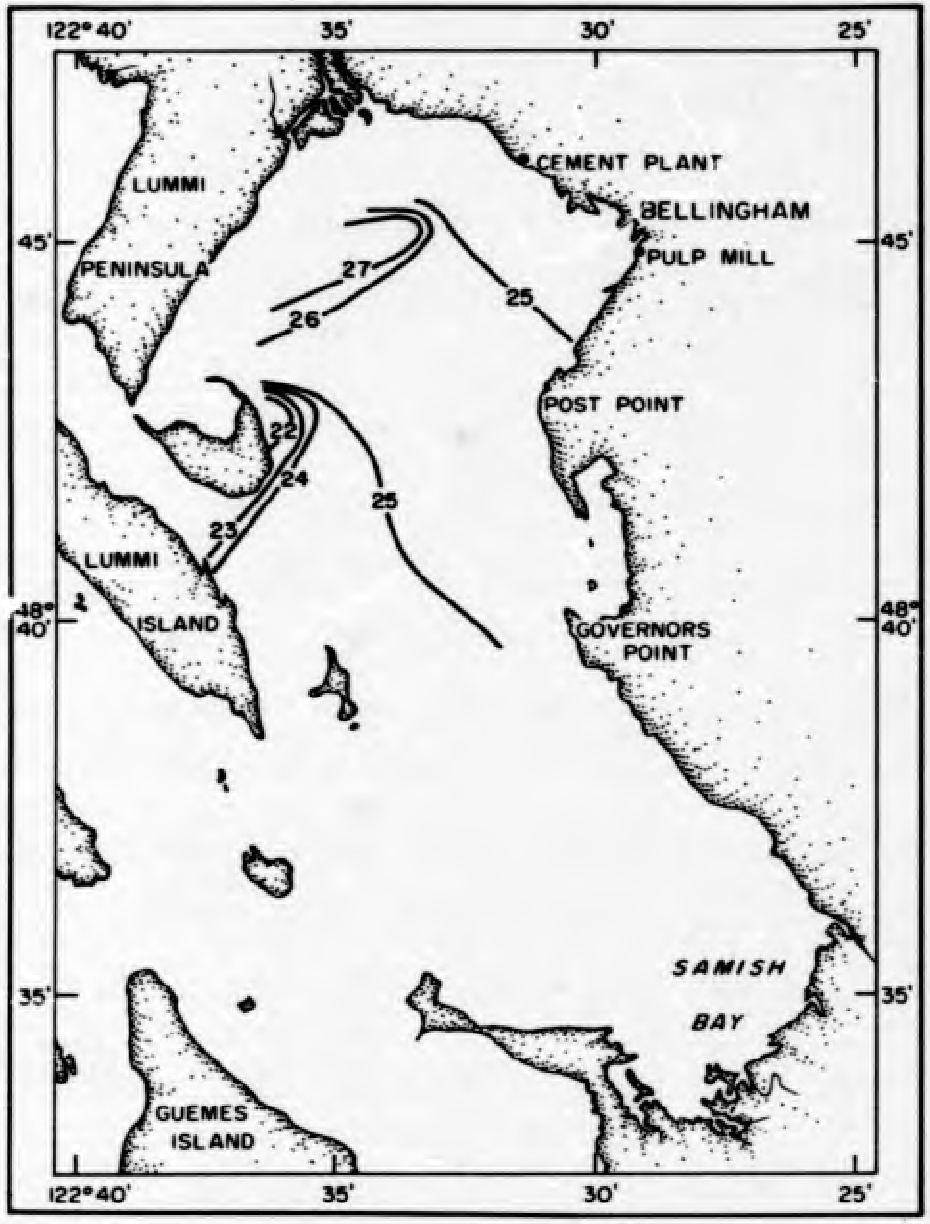

Fig. 2.21. Surface distribution of salinity for 10-11 July 1961.

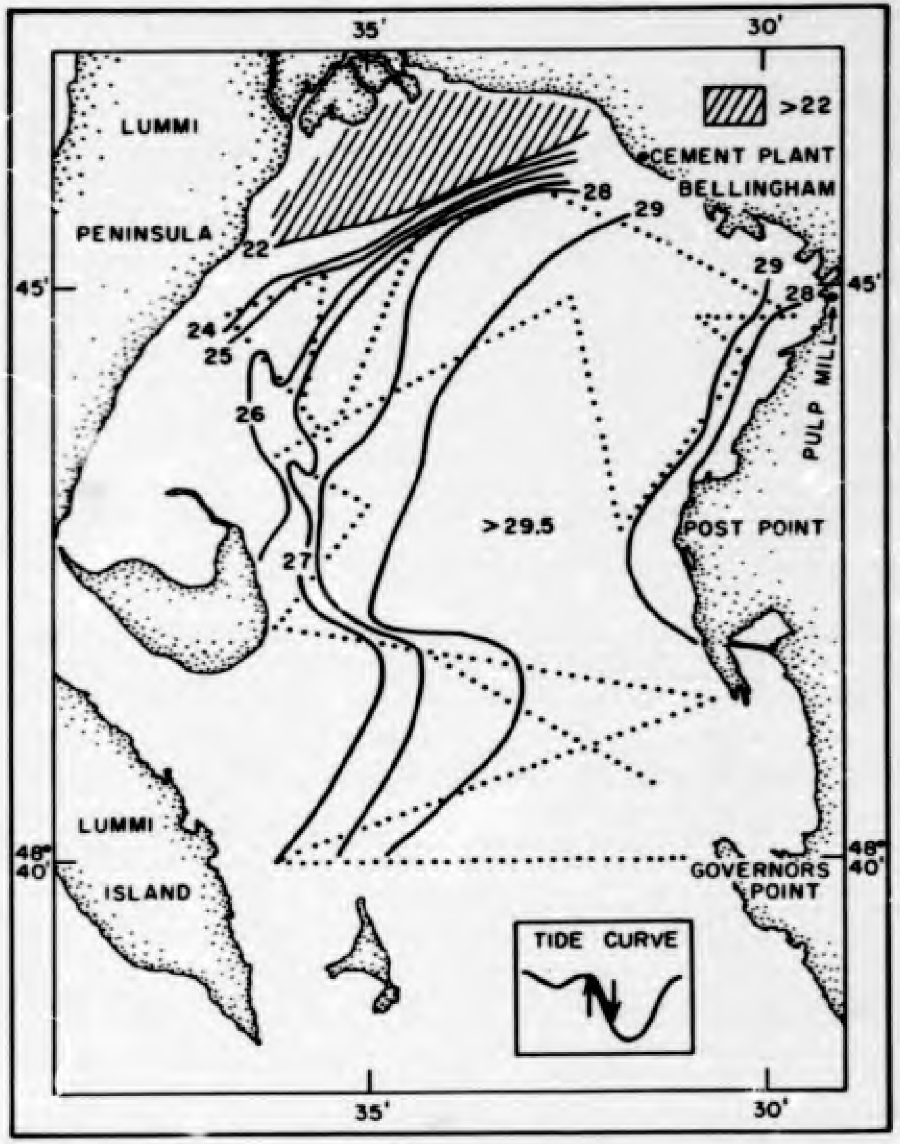

Fig. 2.22. Surface distribution of salinity in upper Bellingham Bay, 4 November 1959, 0744-1130.

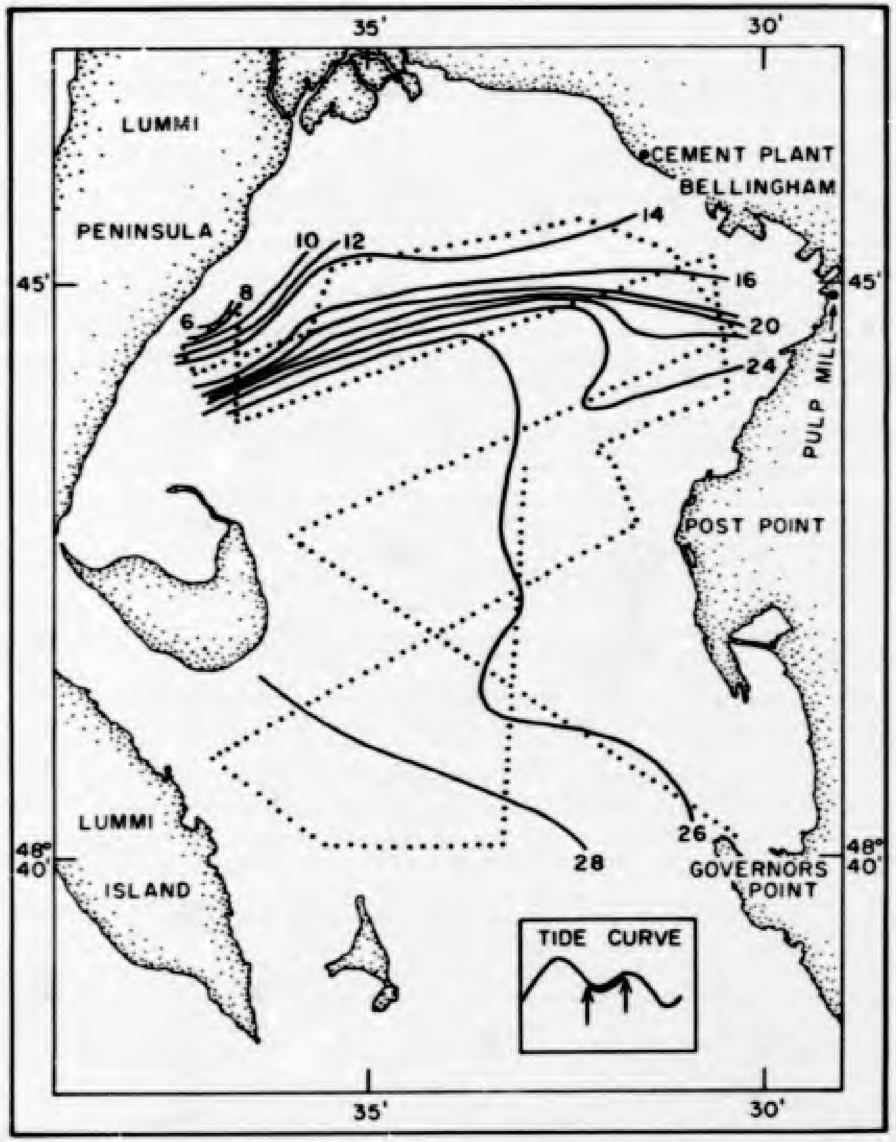

Fig. 2.23. Surface distribution of salinity in upper Bellingham Bay, 21 April 1960, 0845-1237, small flood tide.

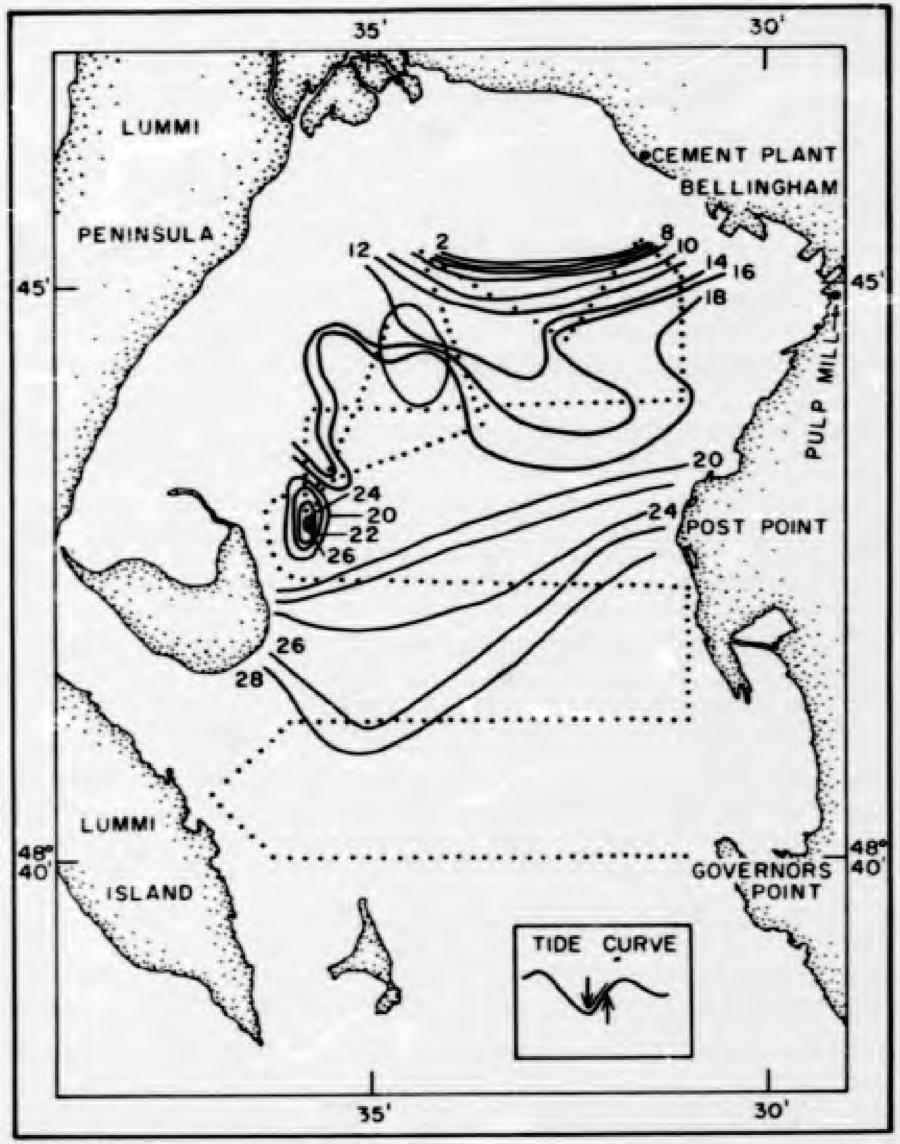

Fig. 2.24. Surface distribution of salinity in upper Bellingham Bay, 21 May 1960, 0943-1338, flood tide.

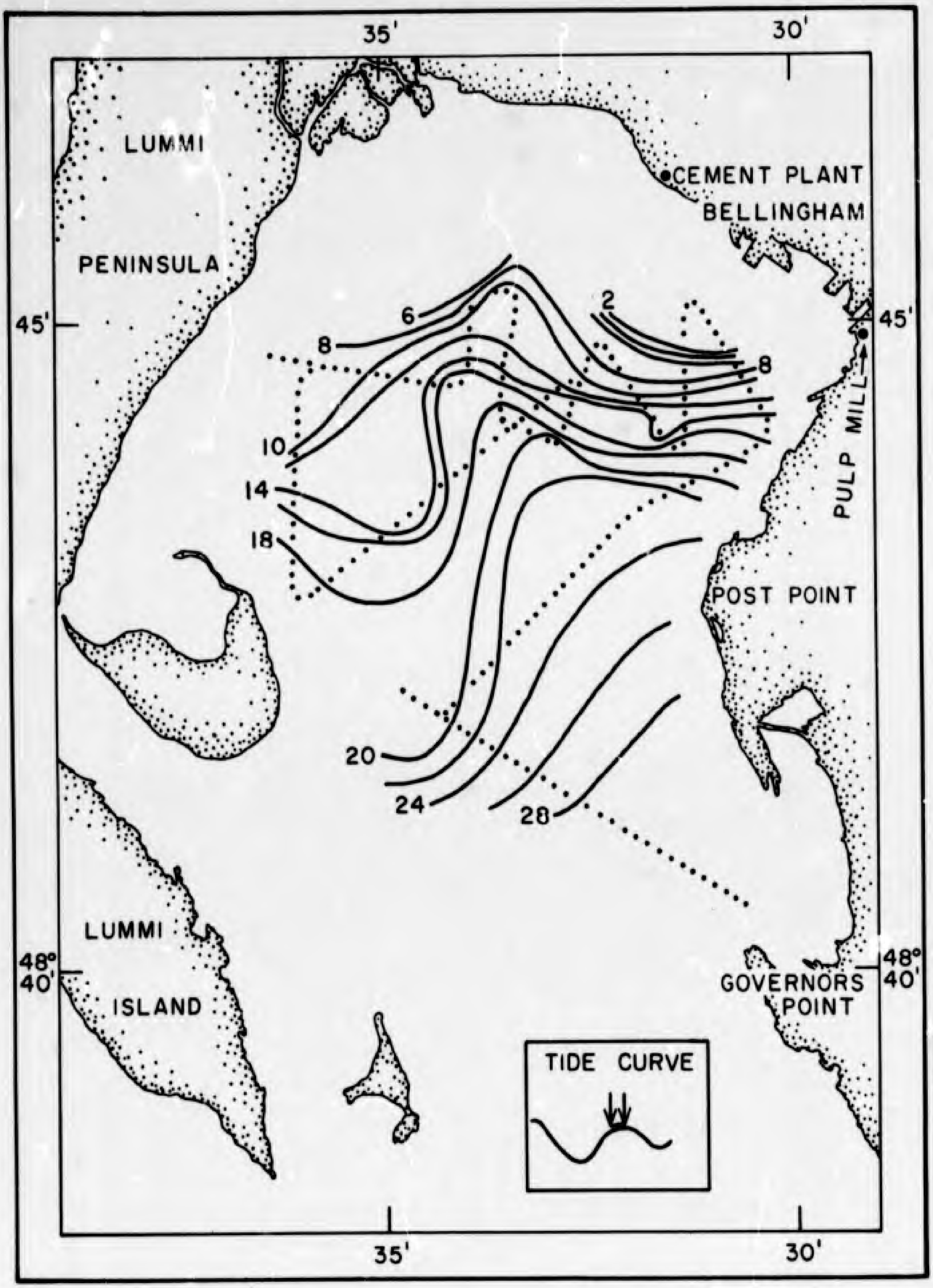

Fig. 2.25. Surface distribution of salinity in upper Bellingham Bay, 21 May 1960, 1410-1632, ebb tide.

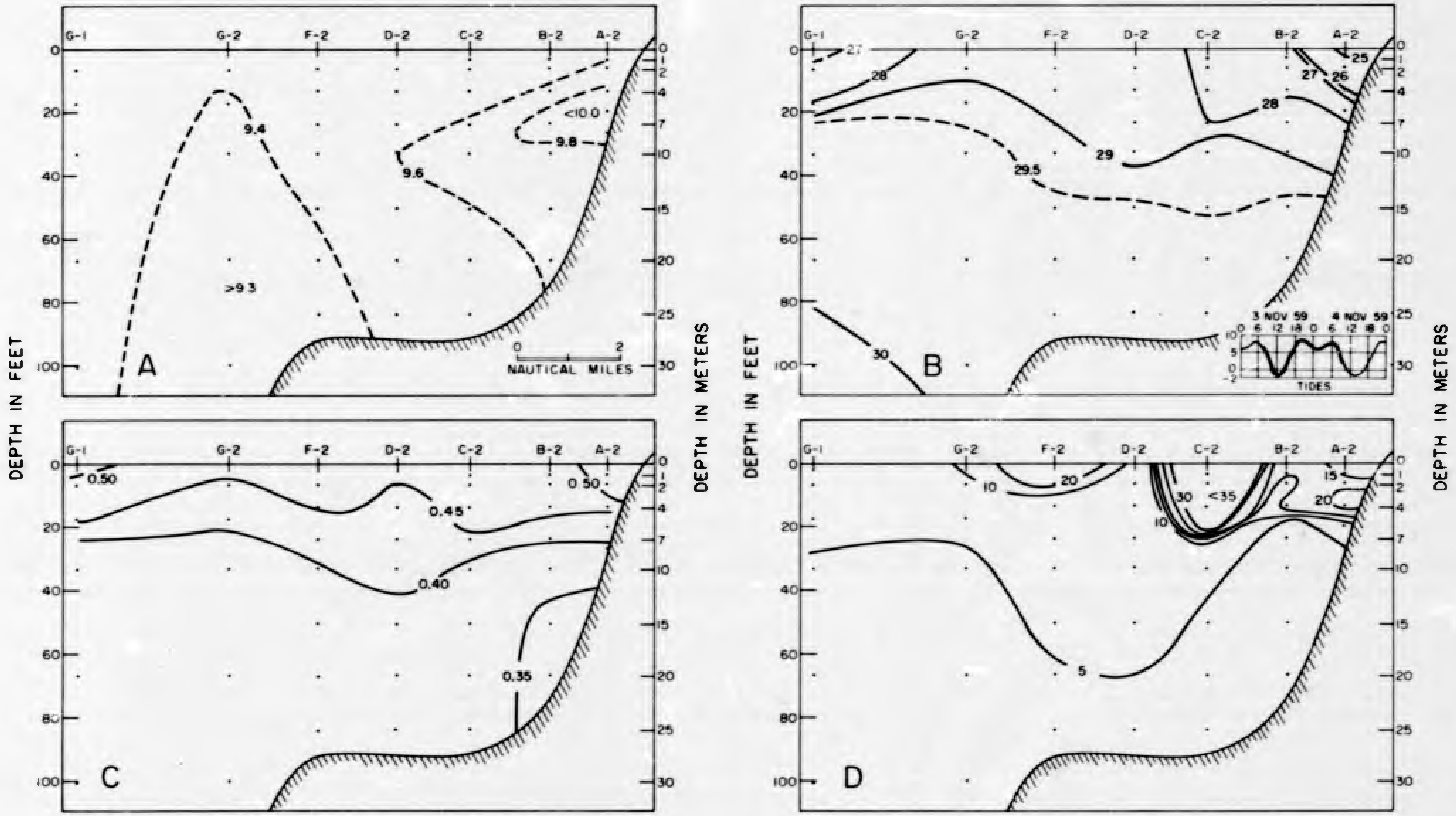

Fig. 2.26. Vertical distributions of water characteristics for November 1959. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

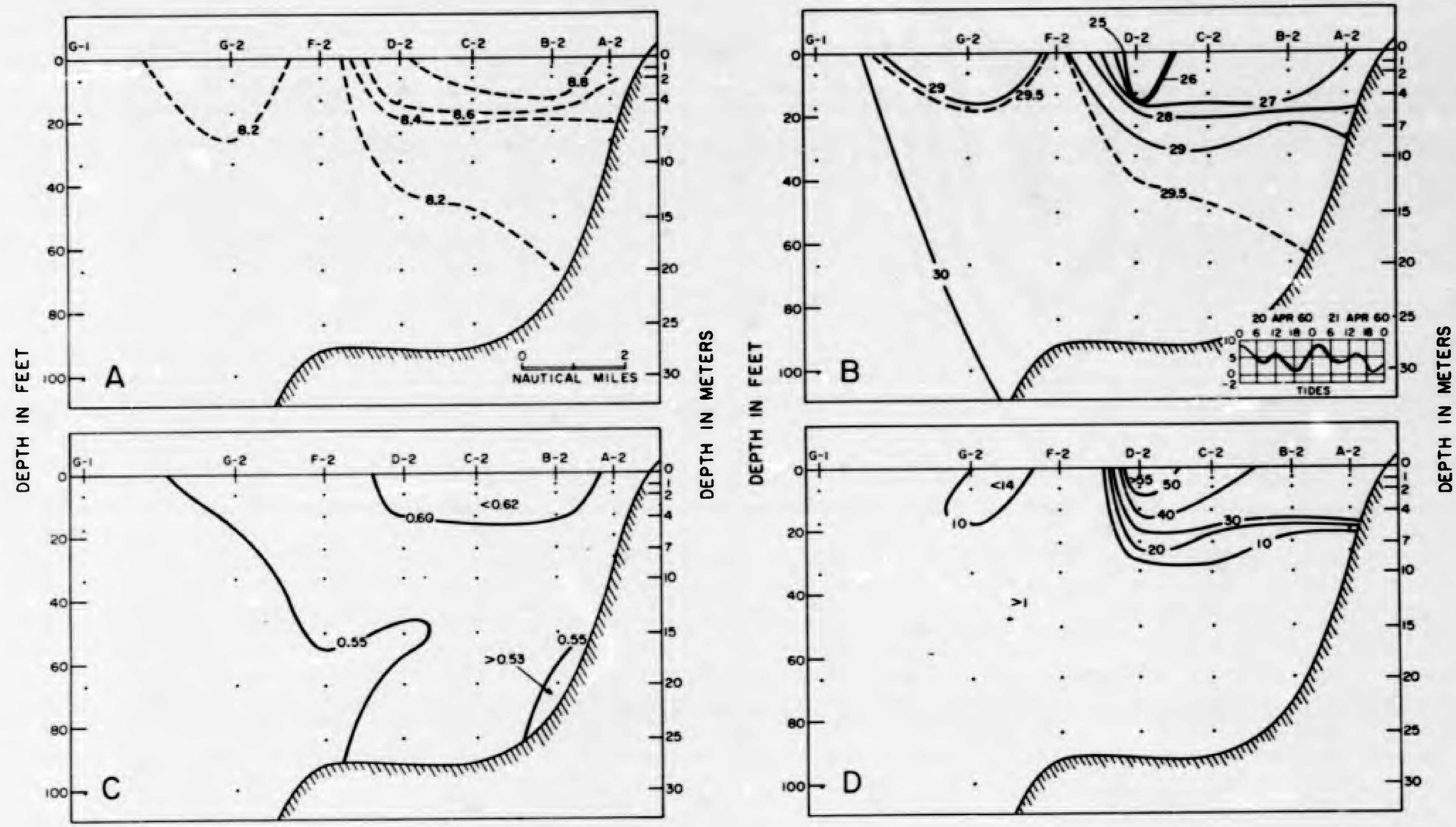

Fig. 2.27. Vertical distributions of water characteristics for April 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

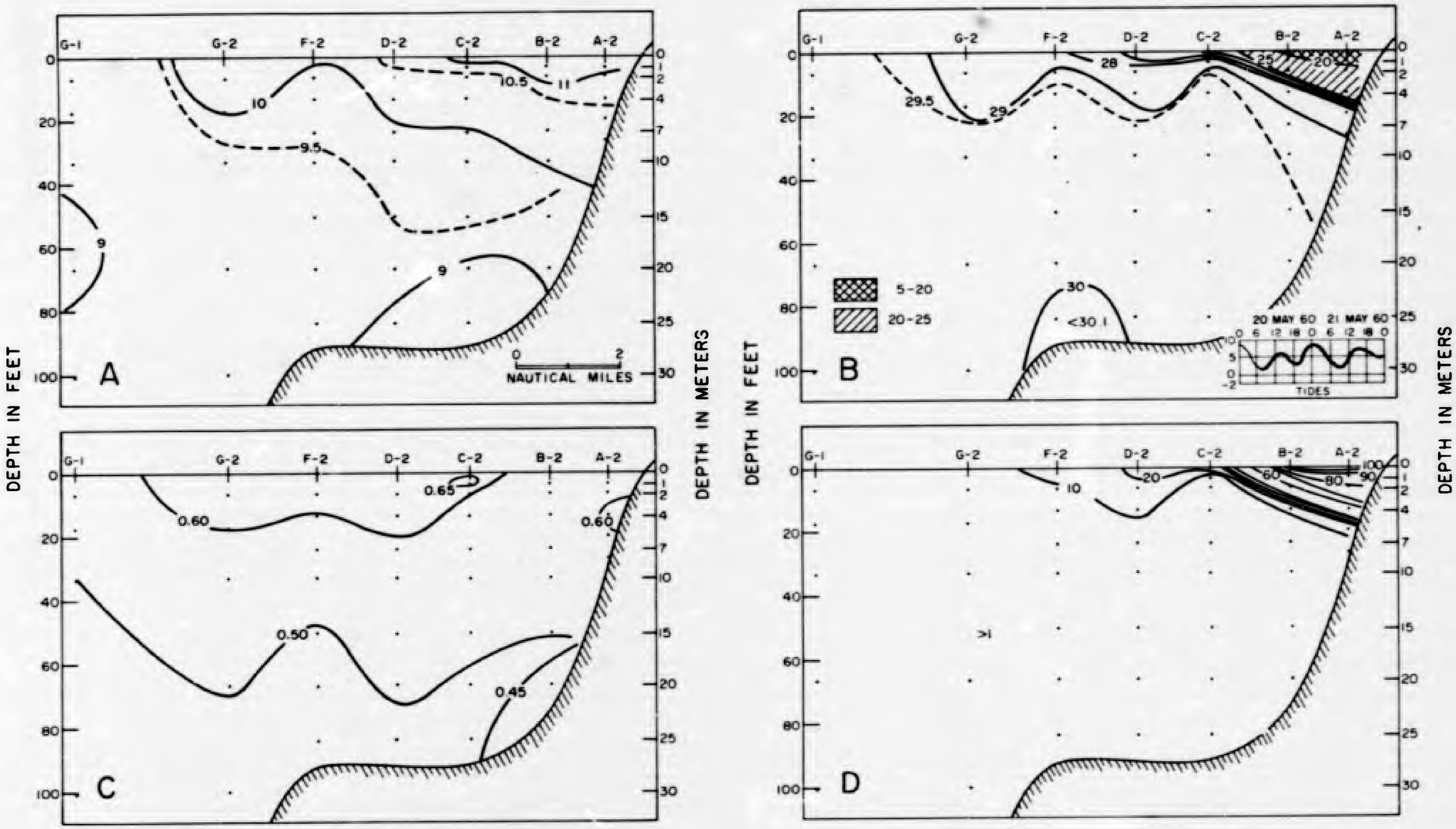

Fig. 2.28. Vertical distributions of water characteristics for May 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); C, spent sulfite liquor (ppm).

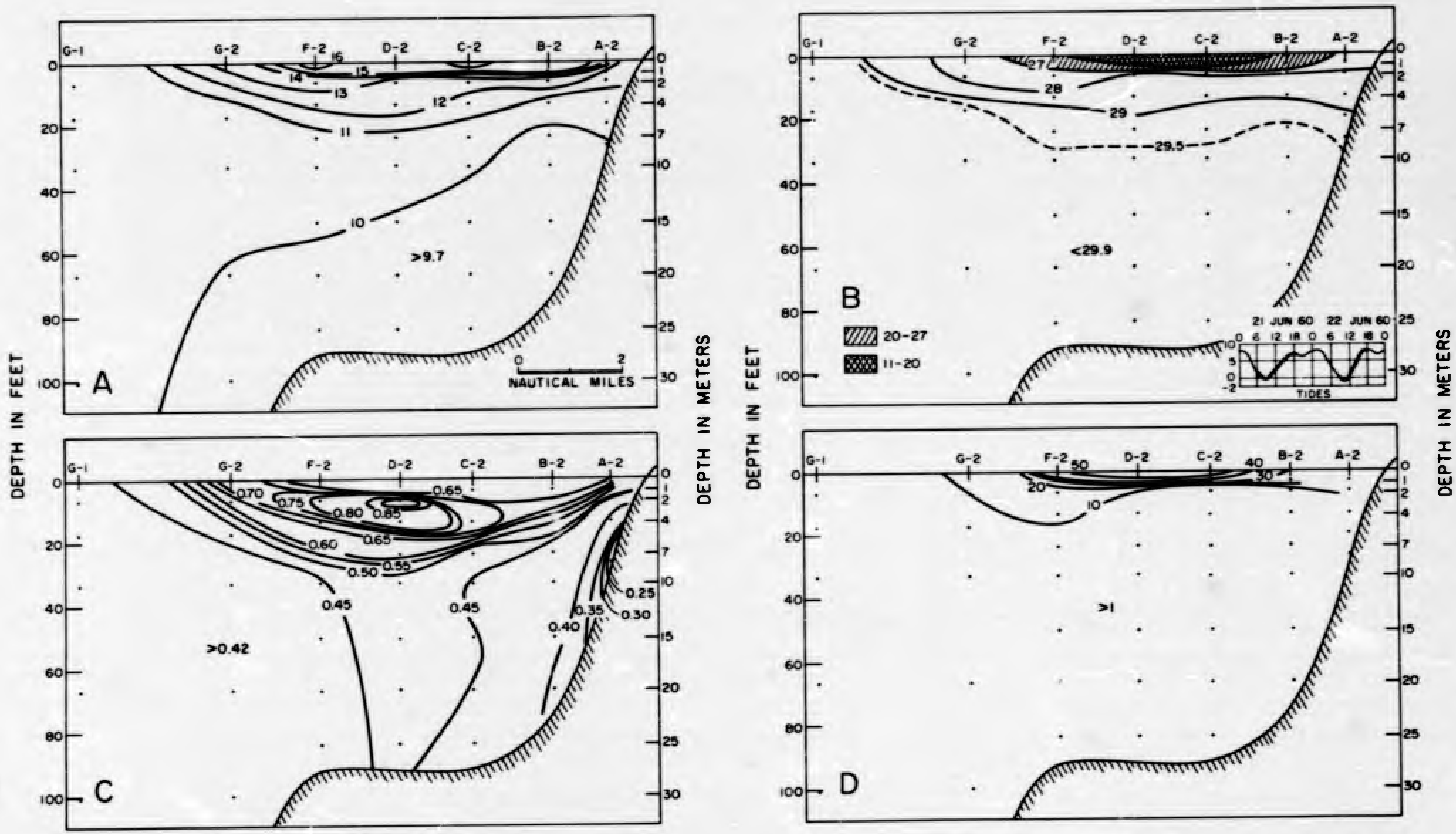

Fig. 2.29. Vertical distributions of water characteristics for June 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

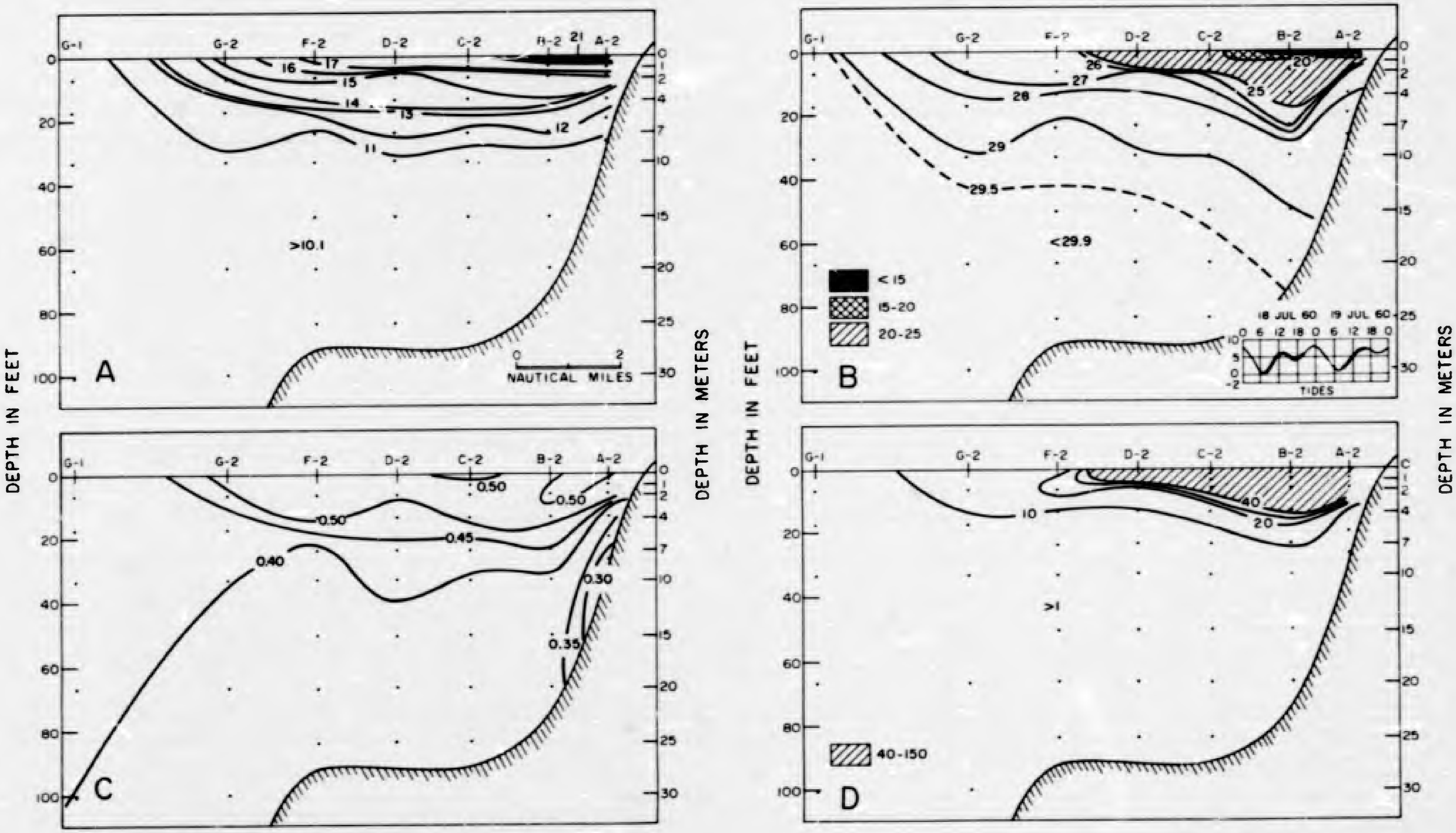

Fig. 2.30. Vertical distributions of water characteristics for July 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

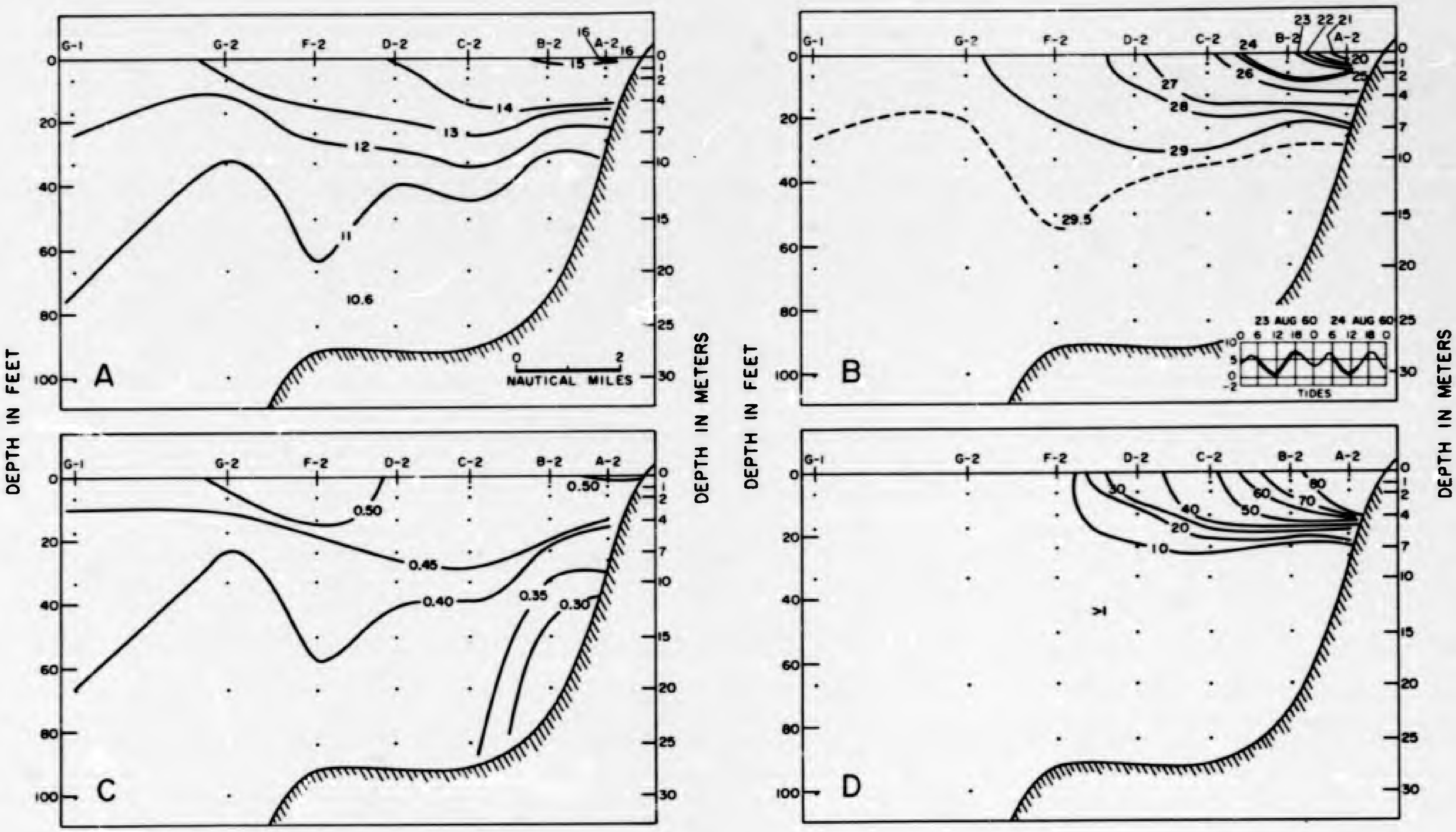

Fig. 2.31. Vertical distributions of water characteristics for August 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

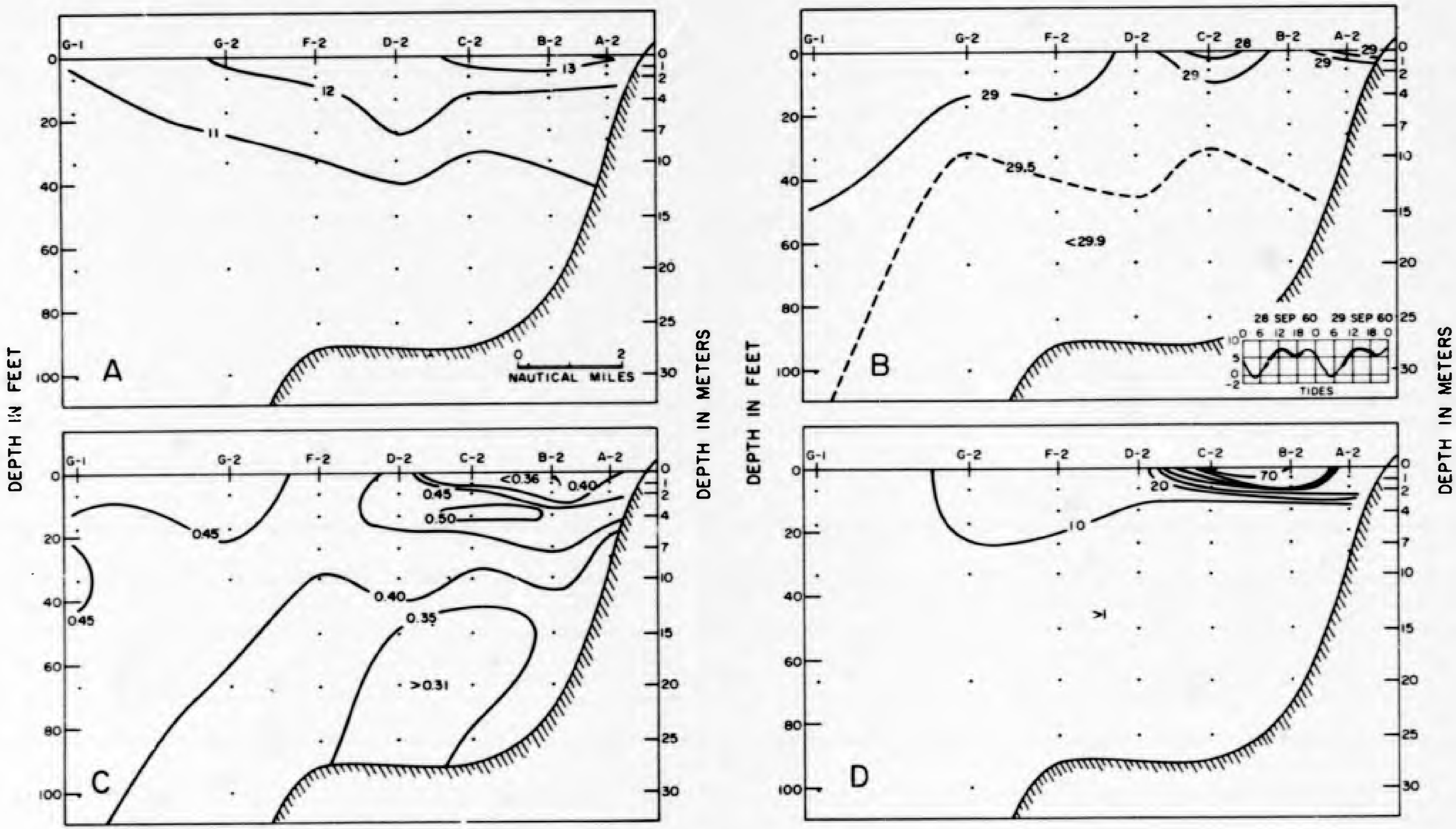

Fig. 2.32. Vertical distributions of water characteristics for September 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

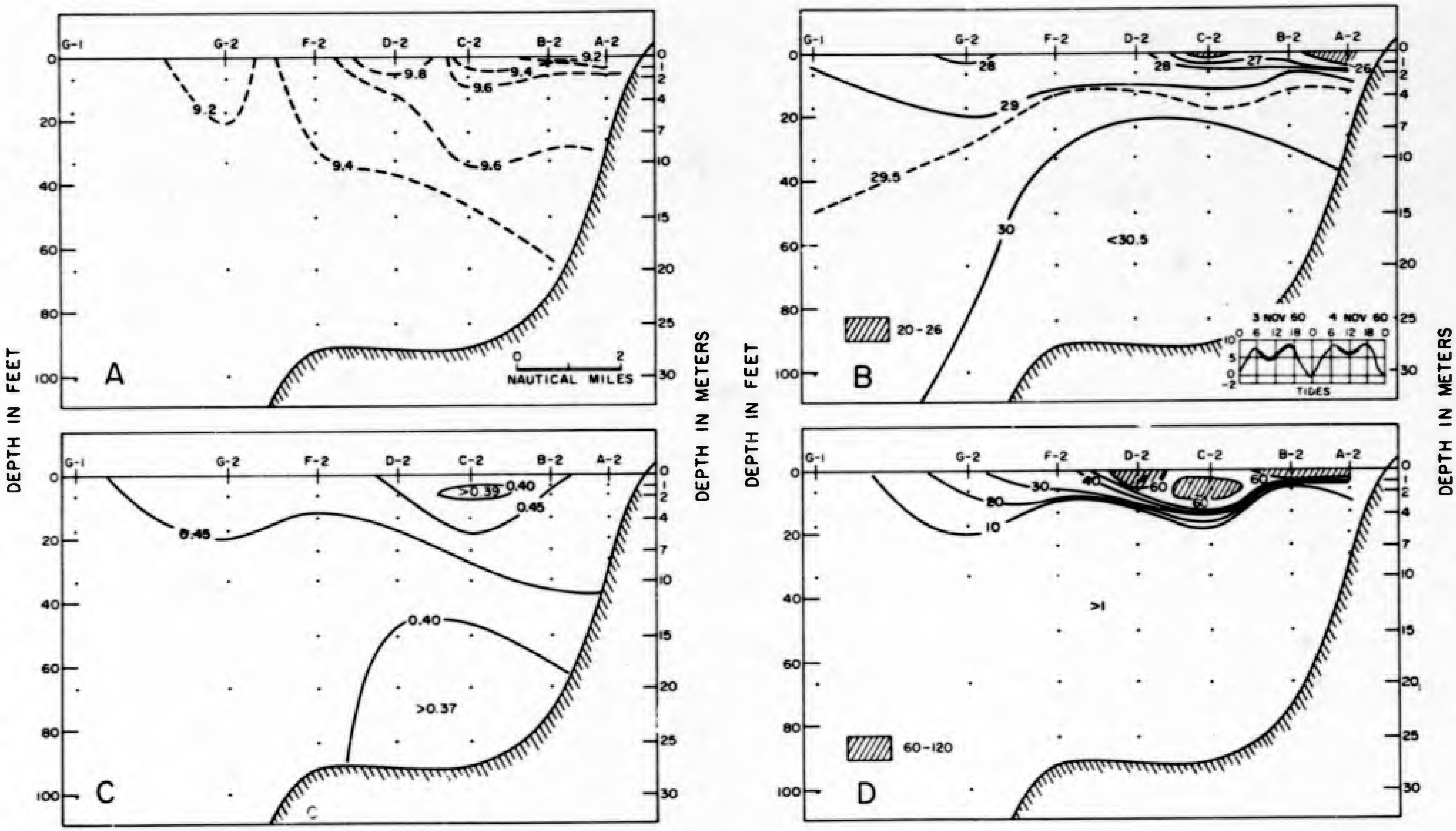

Fig. 2.33. Vertical distributions of water characteristics for November 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

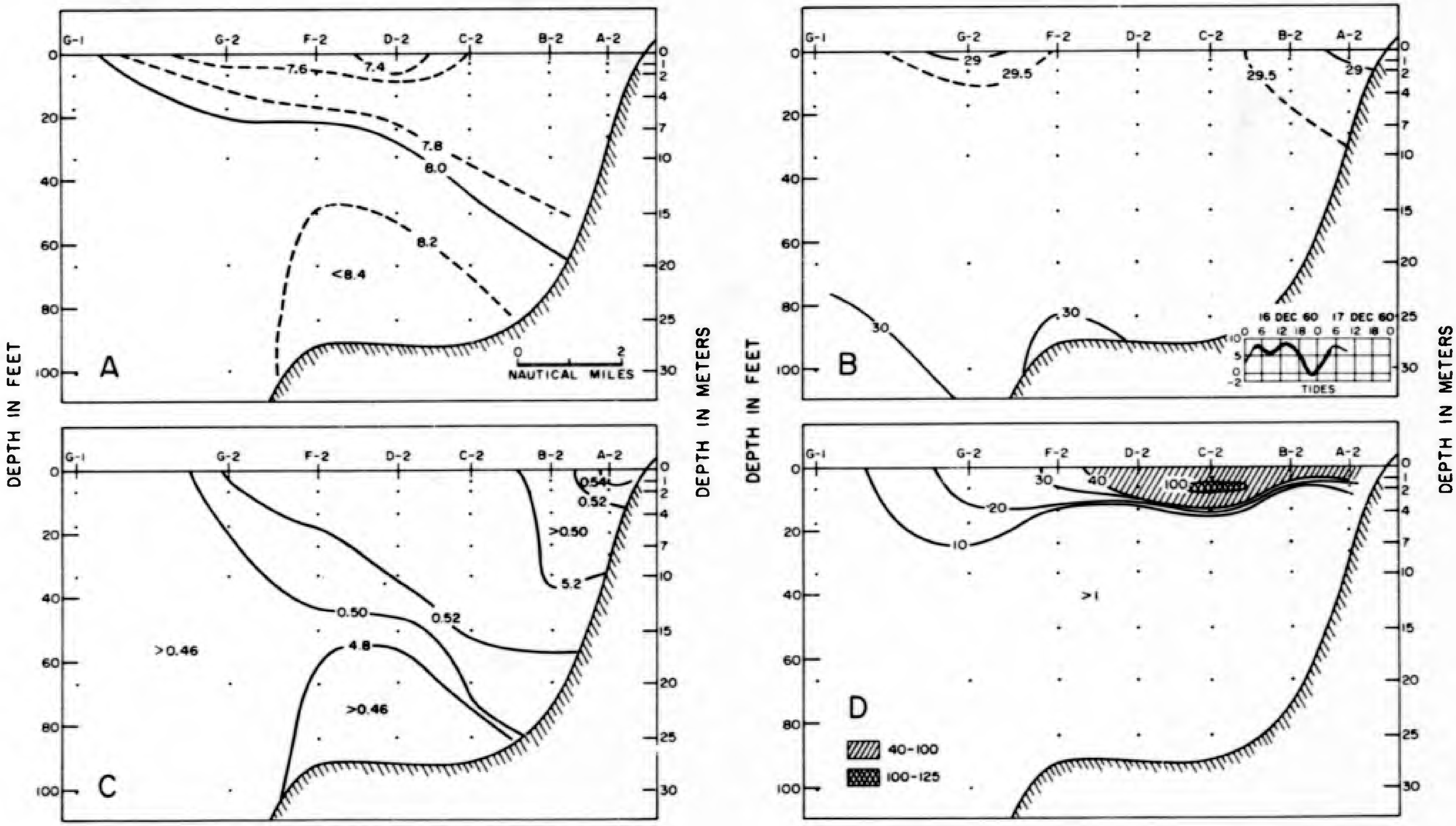

Fig. 2.34. Vertical distributions of water characteristics for December 1960. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

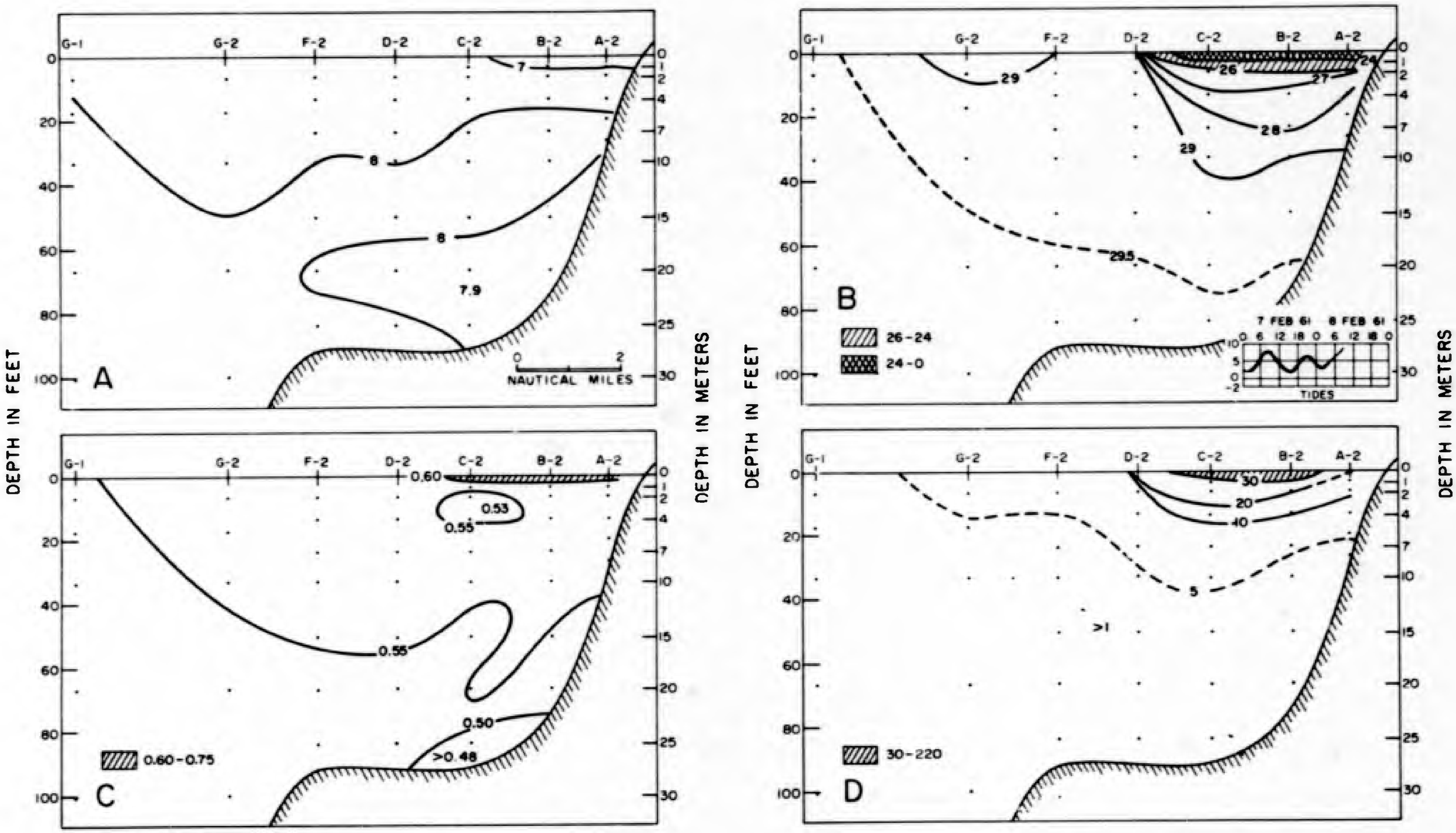

Fig. 2.35. Vertical distributions of water characteristics for February 1961. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

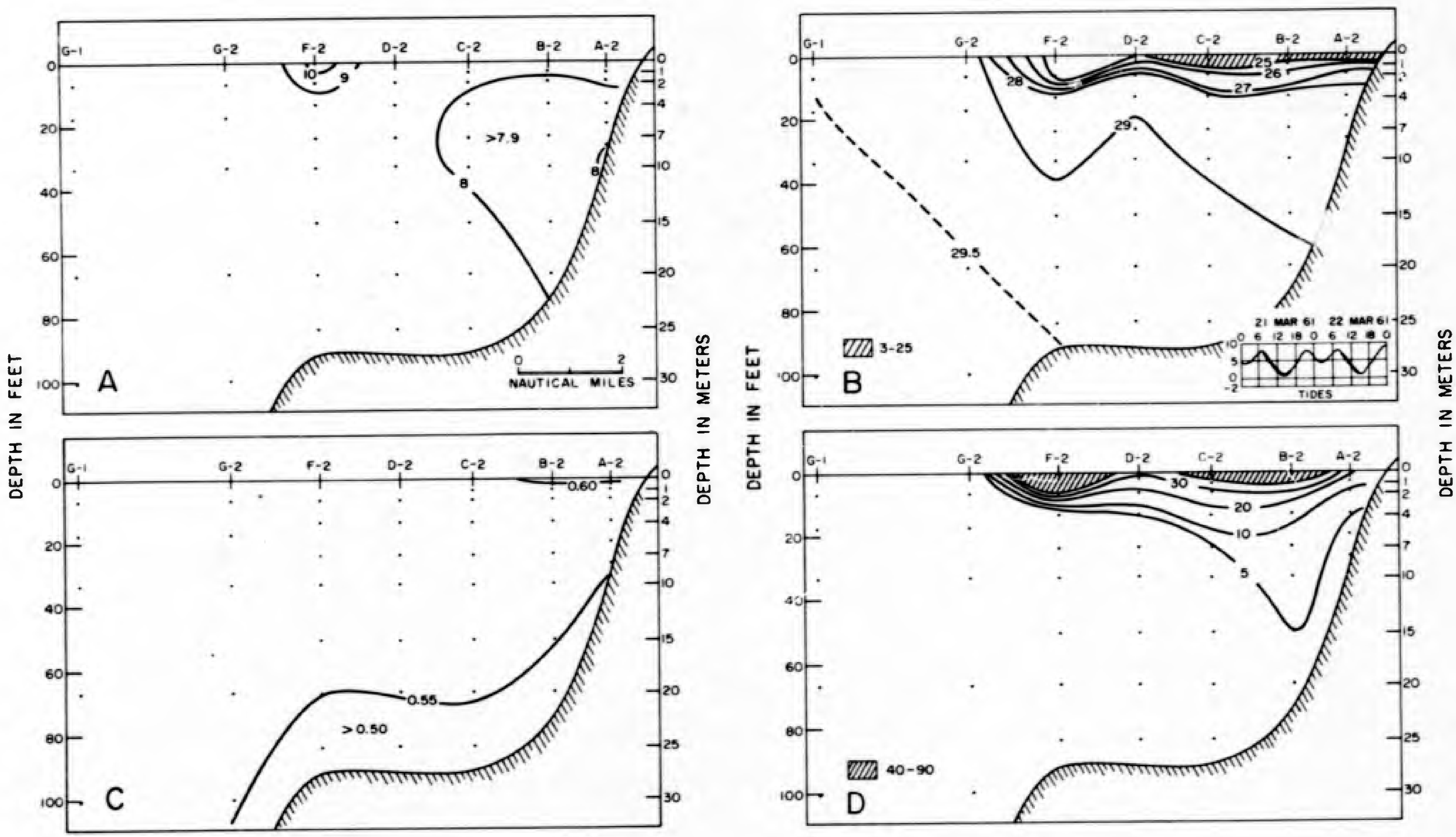

Fig. 2.36. Vertical distributions of water characteristics for March 1961. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

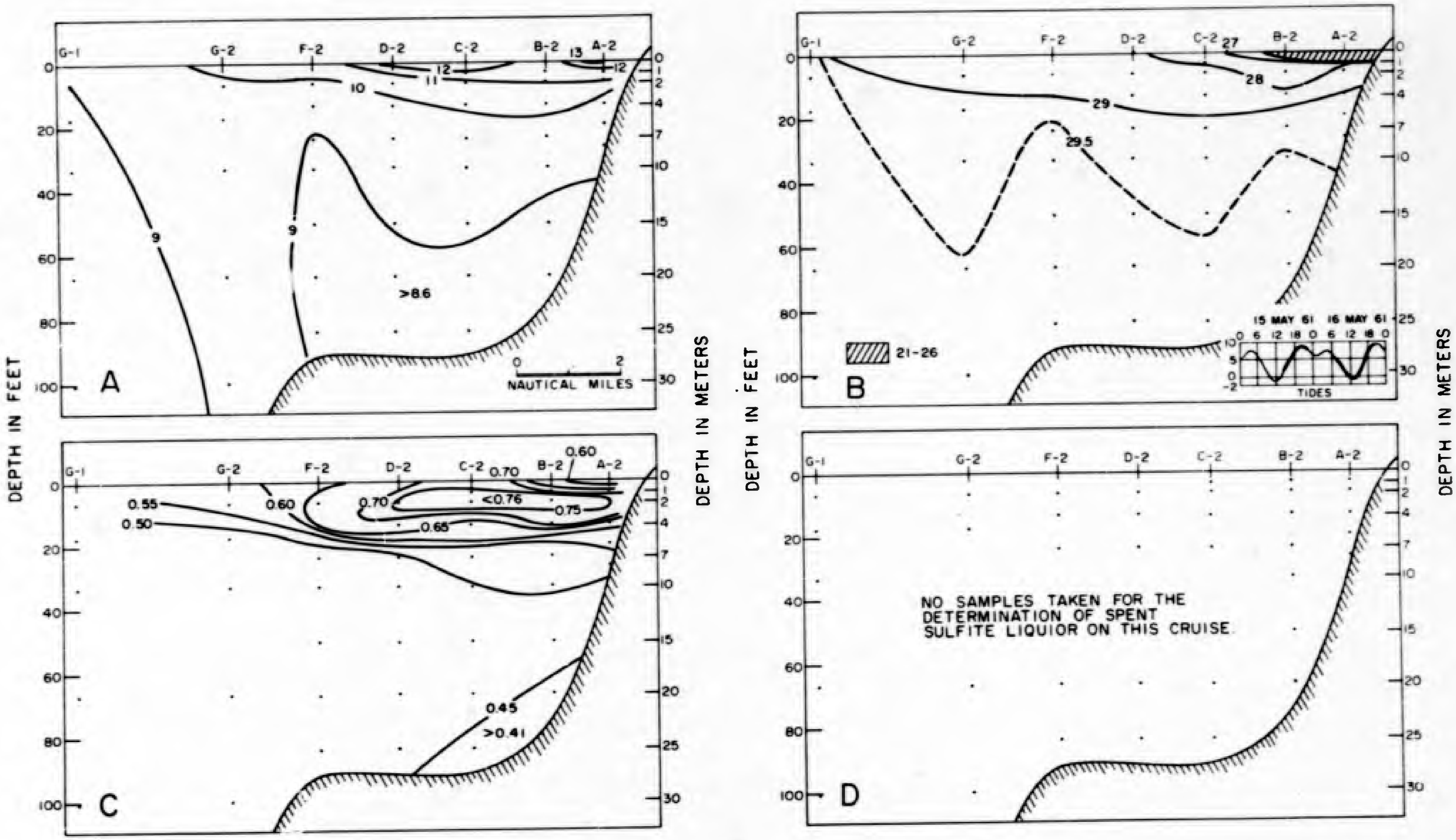

Fig. 2.37. Vertical distributions of water characteristics for May 1961. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

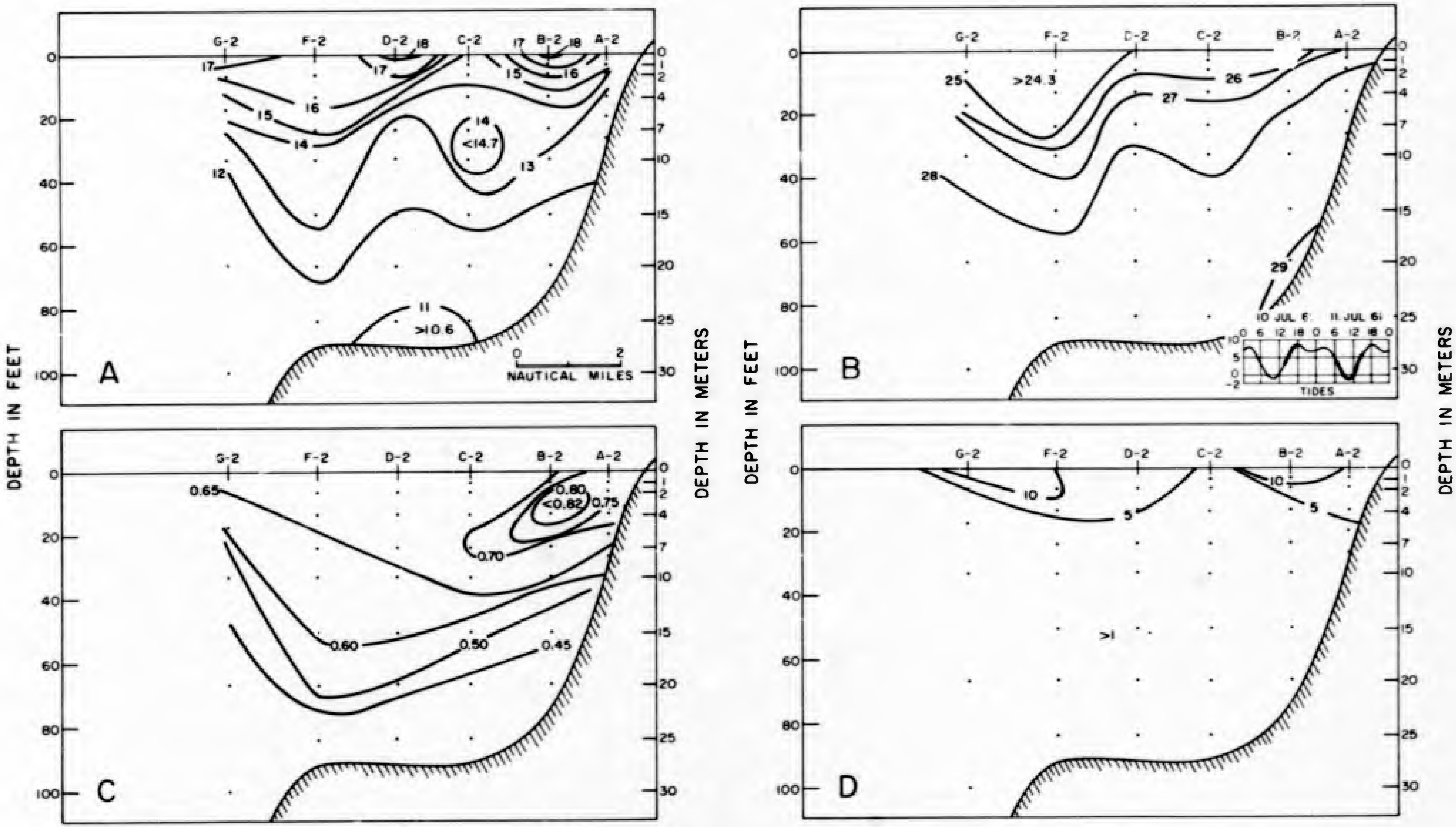

Fig. 2.38. Vertical distributions of water characteristics for July 1961. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

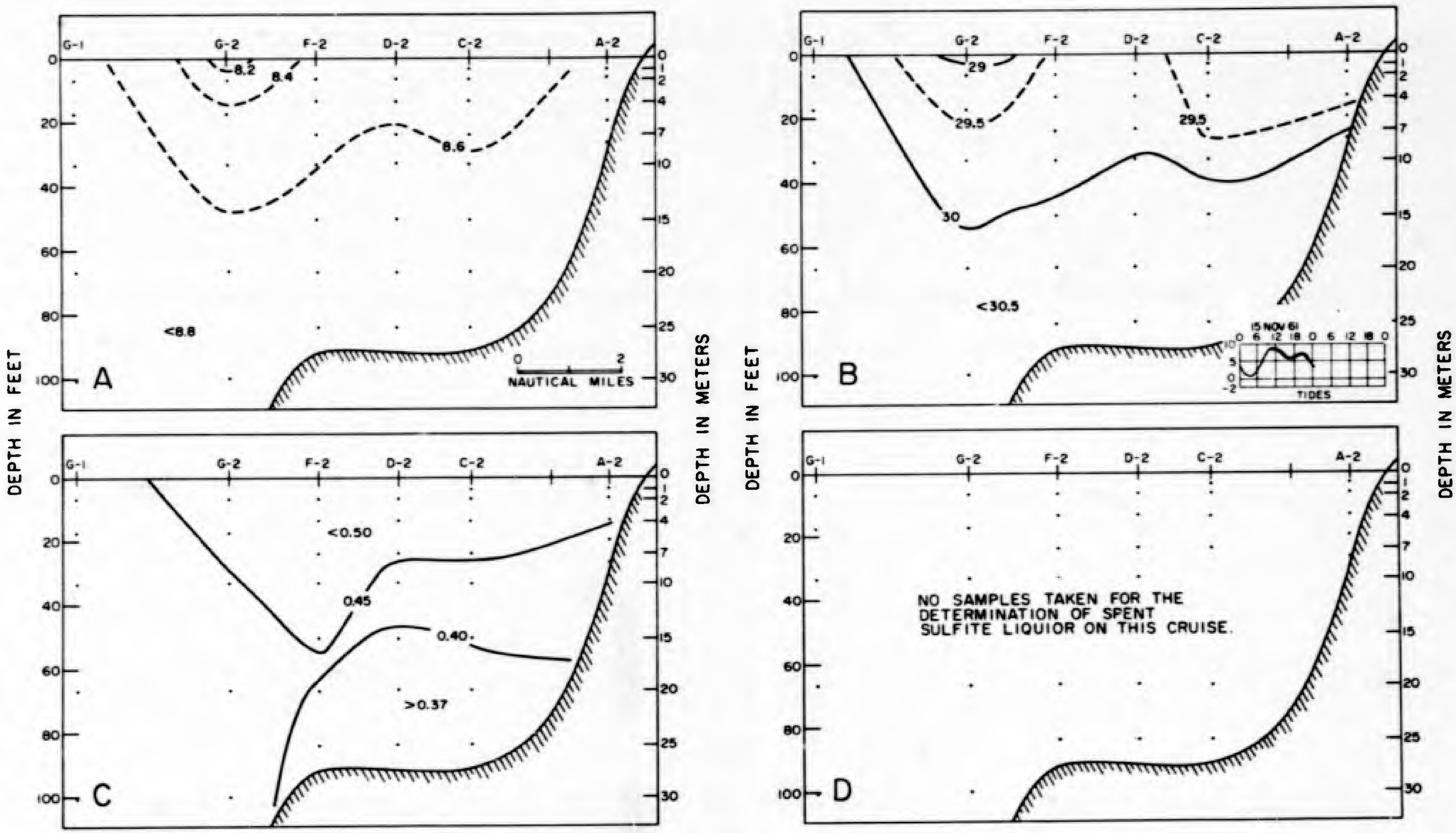

Fig. 2.39. Vertical distributions of water characteristics for November 1961. A, temperature (°C); B, salinity (‰); C, oxygen (mg-atom/liter); D, spent sulfite liquor (ppm).

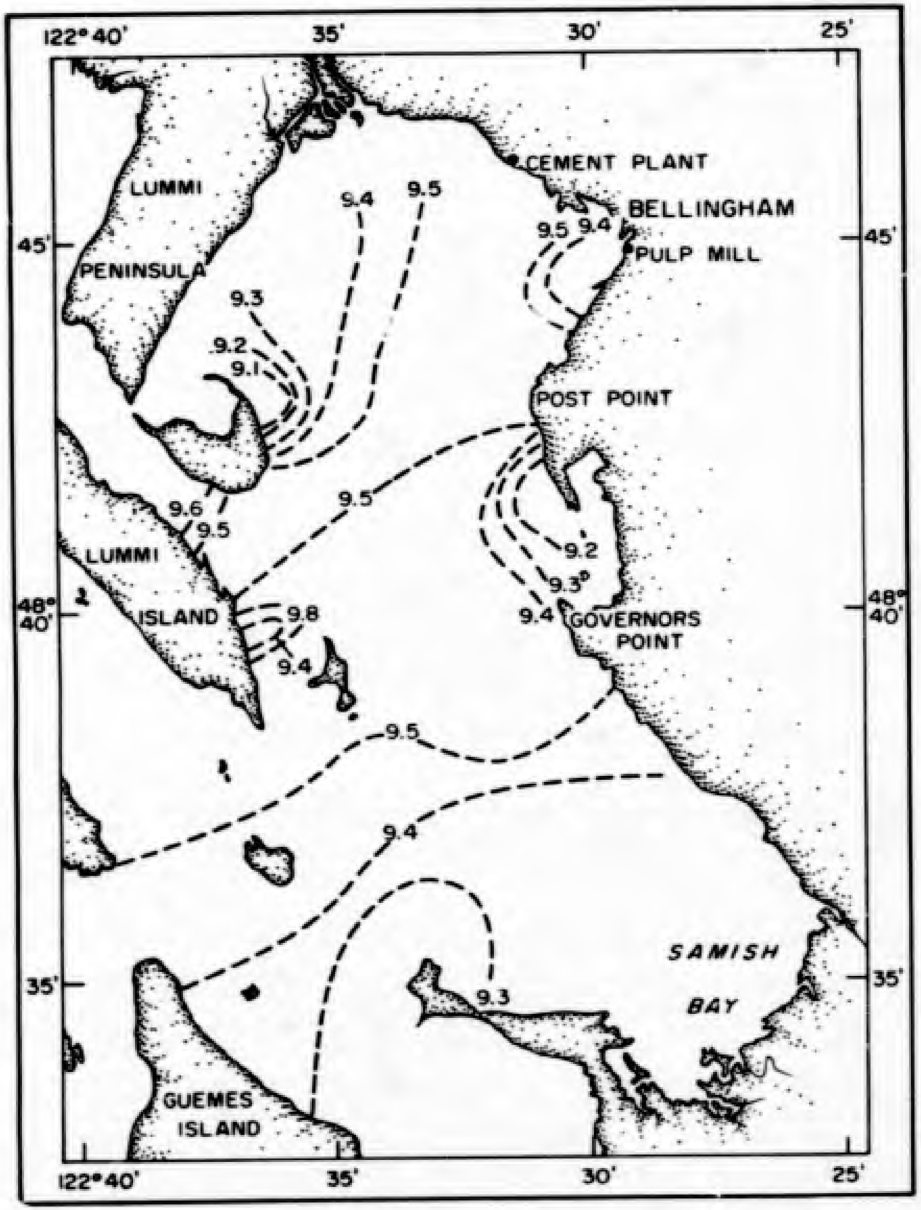

Fig. 2.40. Surface distribution of temperature for 2-4 November 1959.

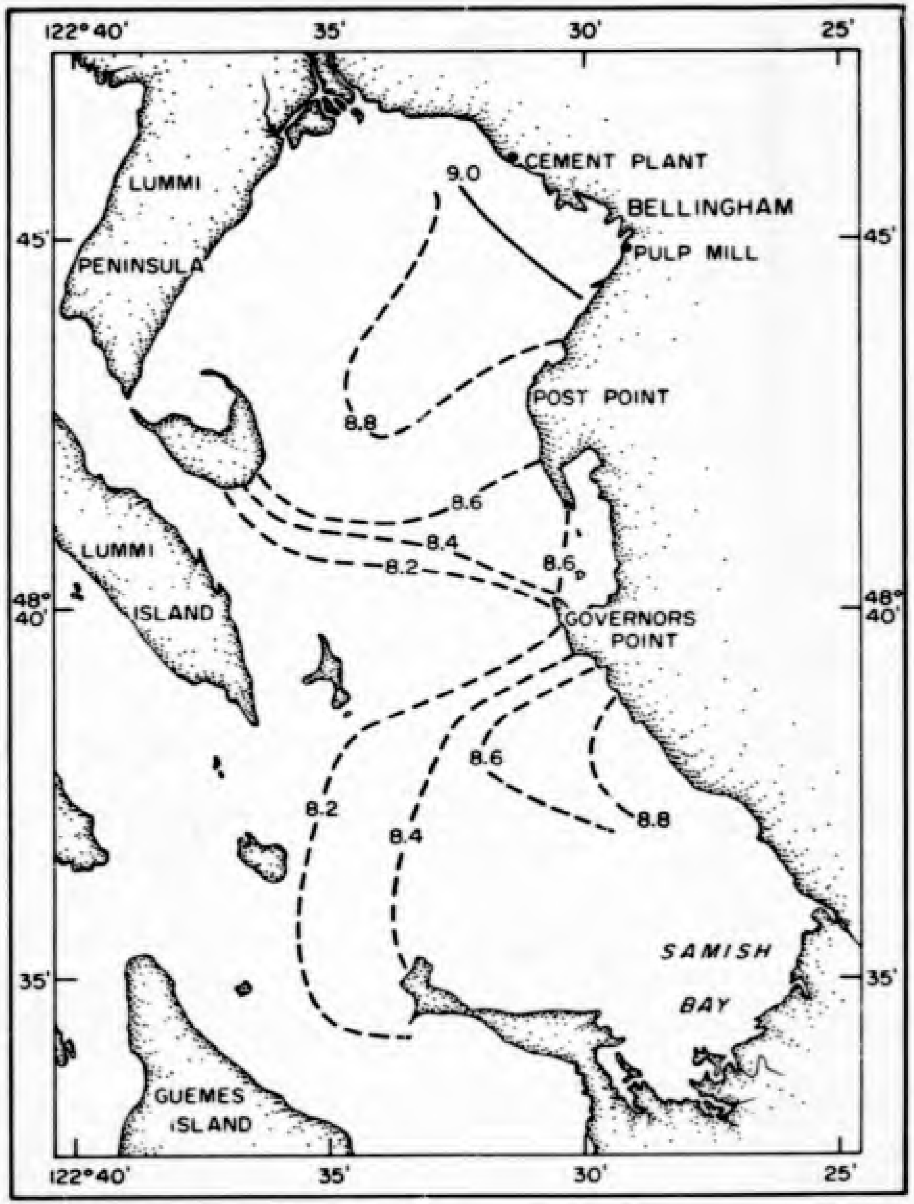

Fig. 2.41. Surface distribution of temperature for 19-21 April 1960.

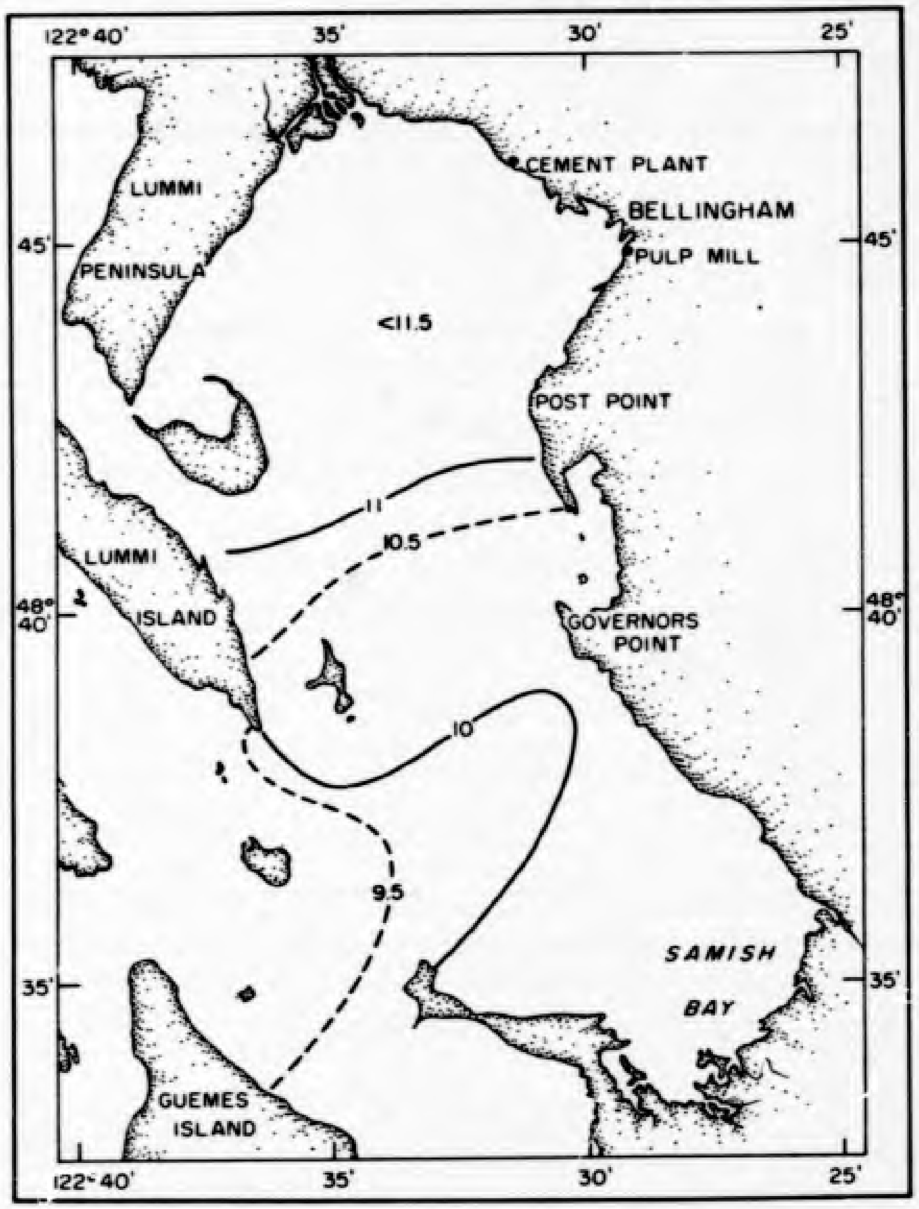

Fig. 2.42. Surface distribution of temperature for 20-22 May 1960

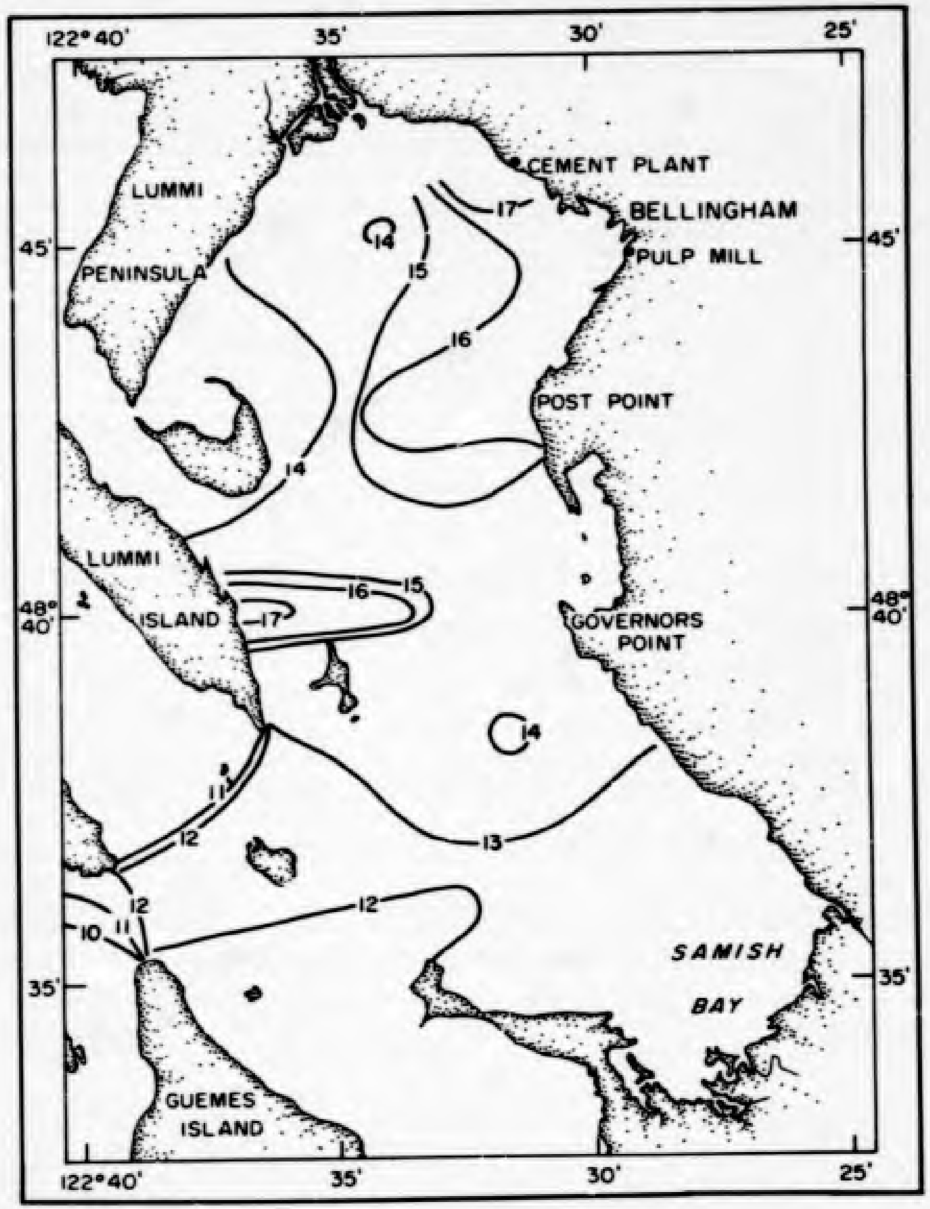

Fig. 2.43. Surface distribution of temperature for 21-22 June 1960.

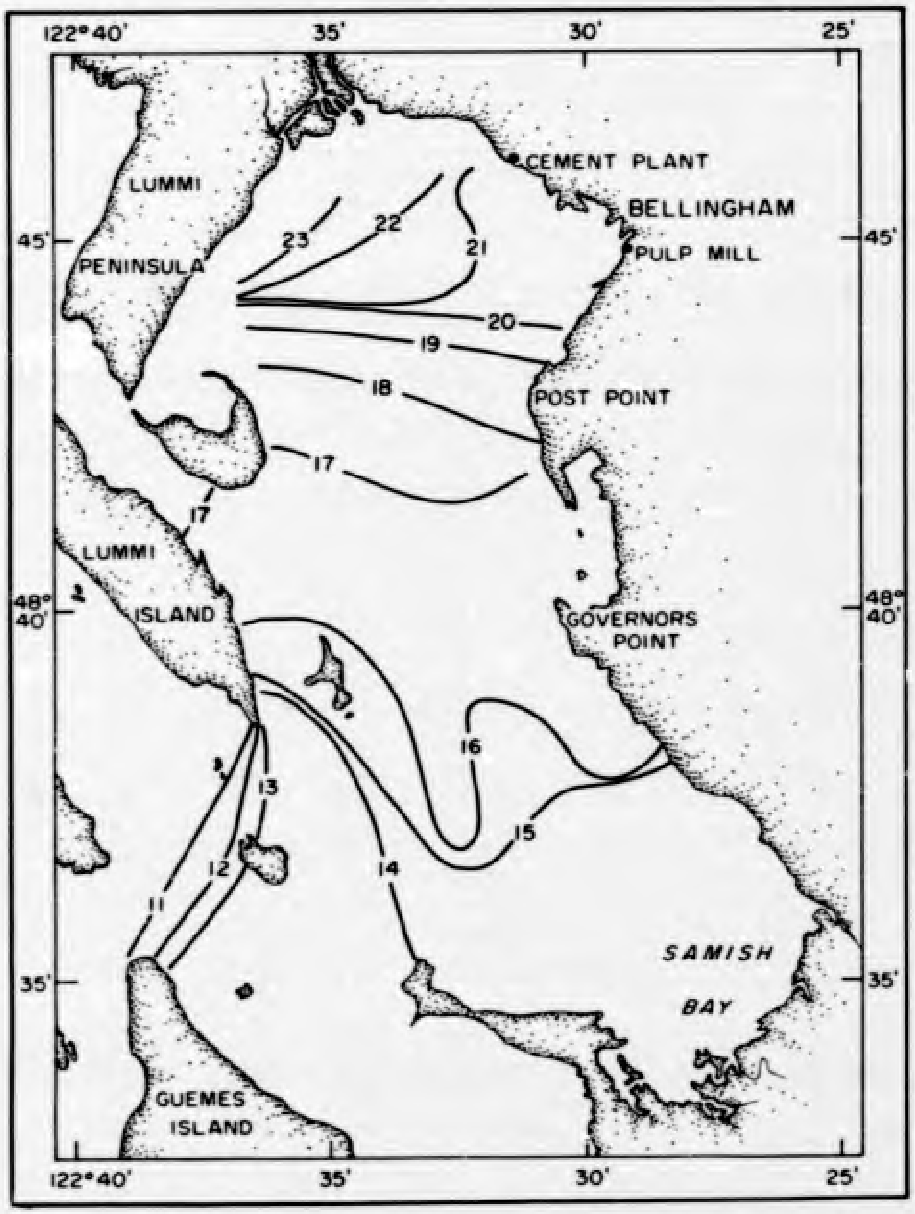

Fig. 2.44. Surface distribution of temperature for 18-19 July 1960.

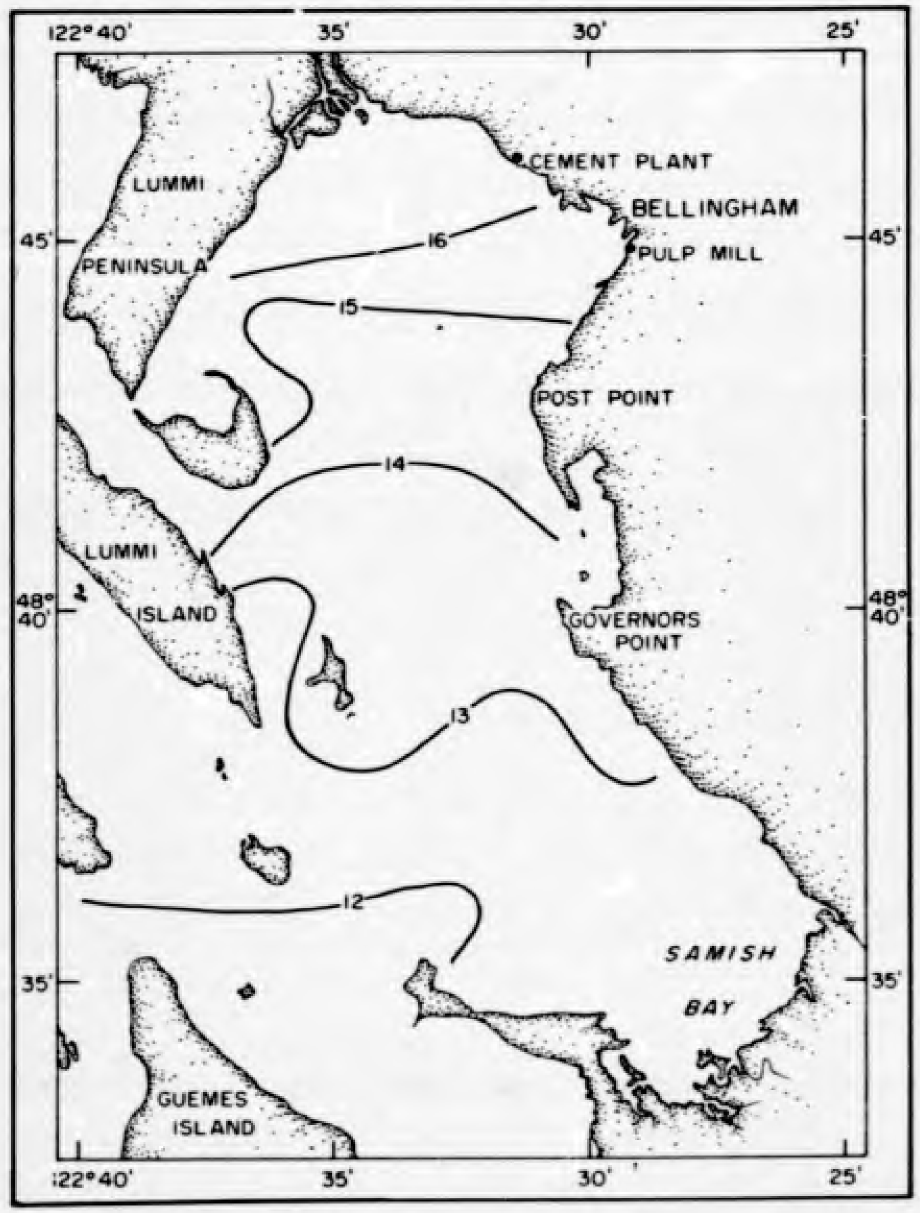

Fig. 2.45. Surface distribution of temperature for 23-24 August 1960.

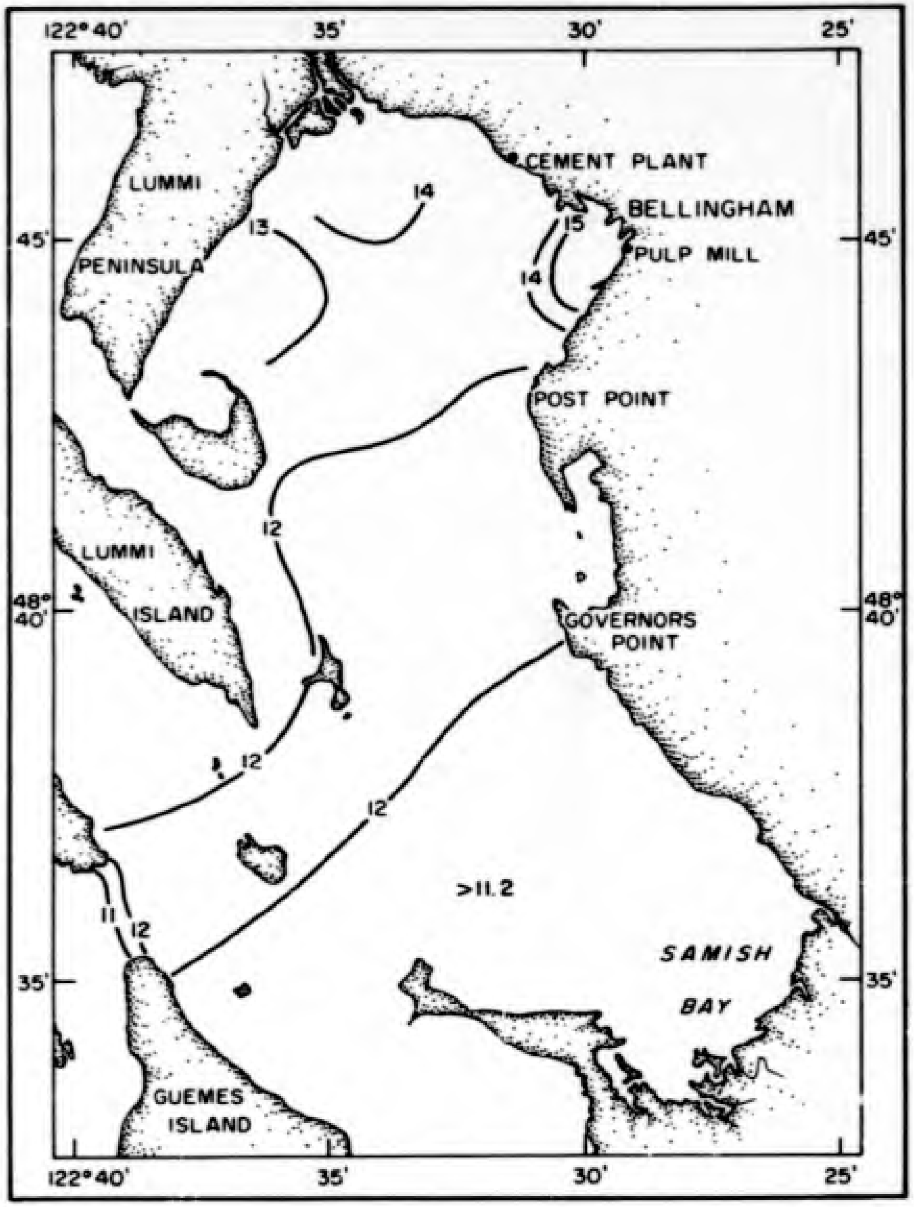

Fig. 2.46. Surface distribution of temperature for 28-29 September 1960.

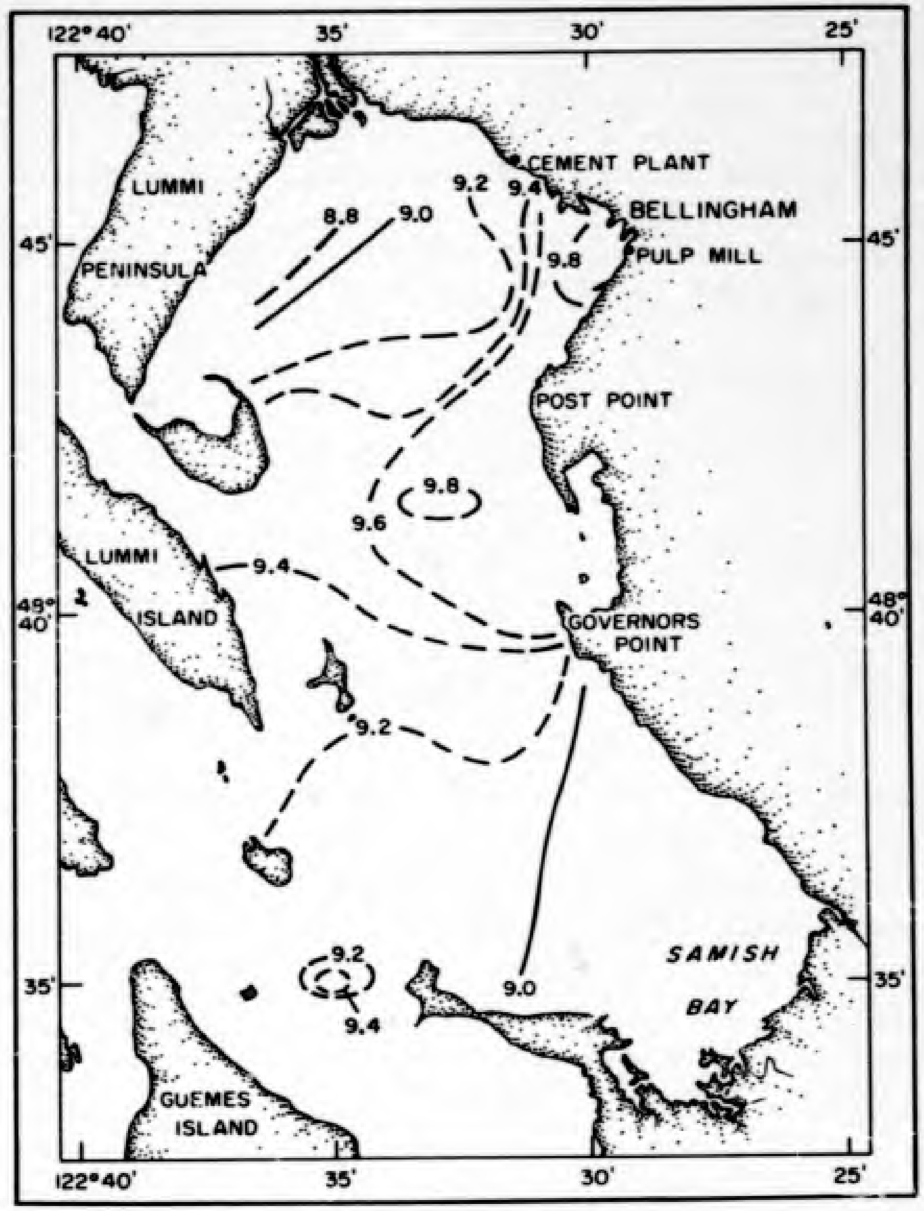

Fig. 2.47. Surface distribution of temperature for 3-4 November 1960.

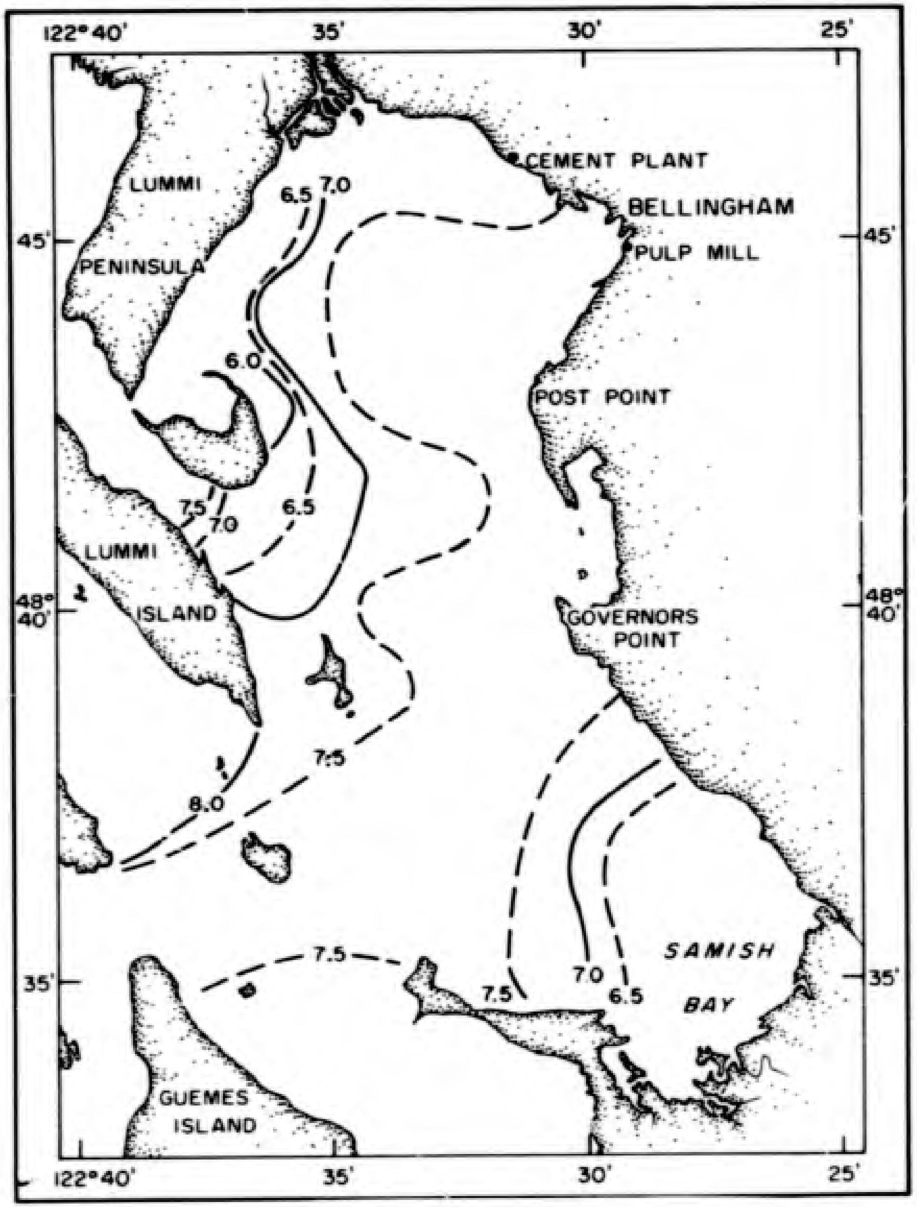

Fig. 2.48. Surface distribution of temperature for 16-17 December 1960.

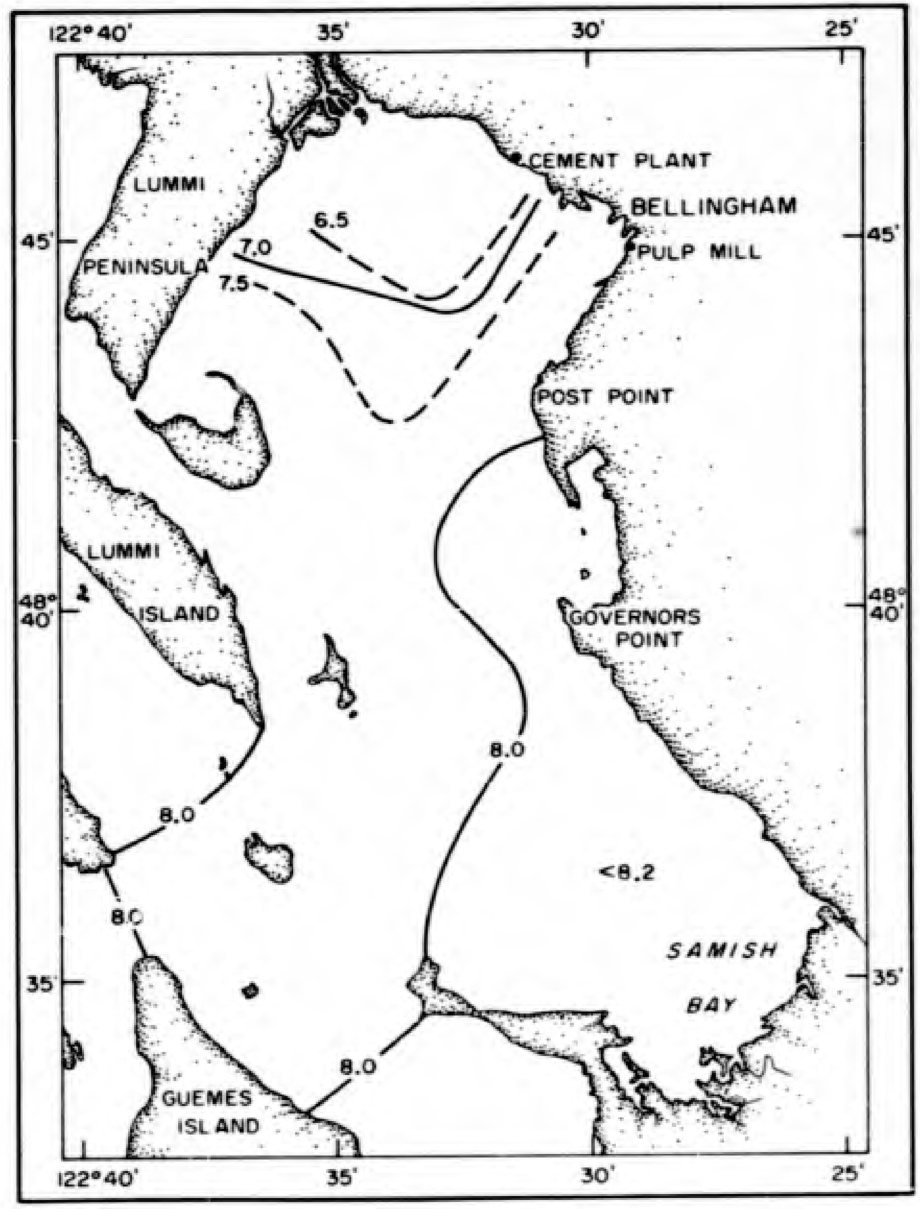

Fig. 2.49. Surface distribution of temperature for 6-7 February 1961.

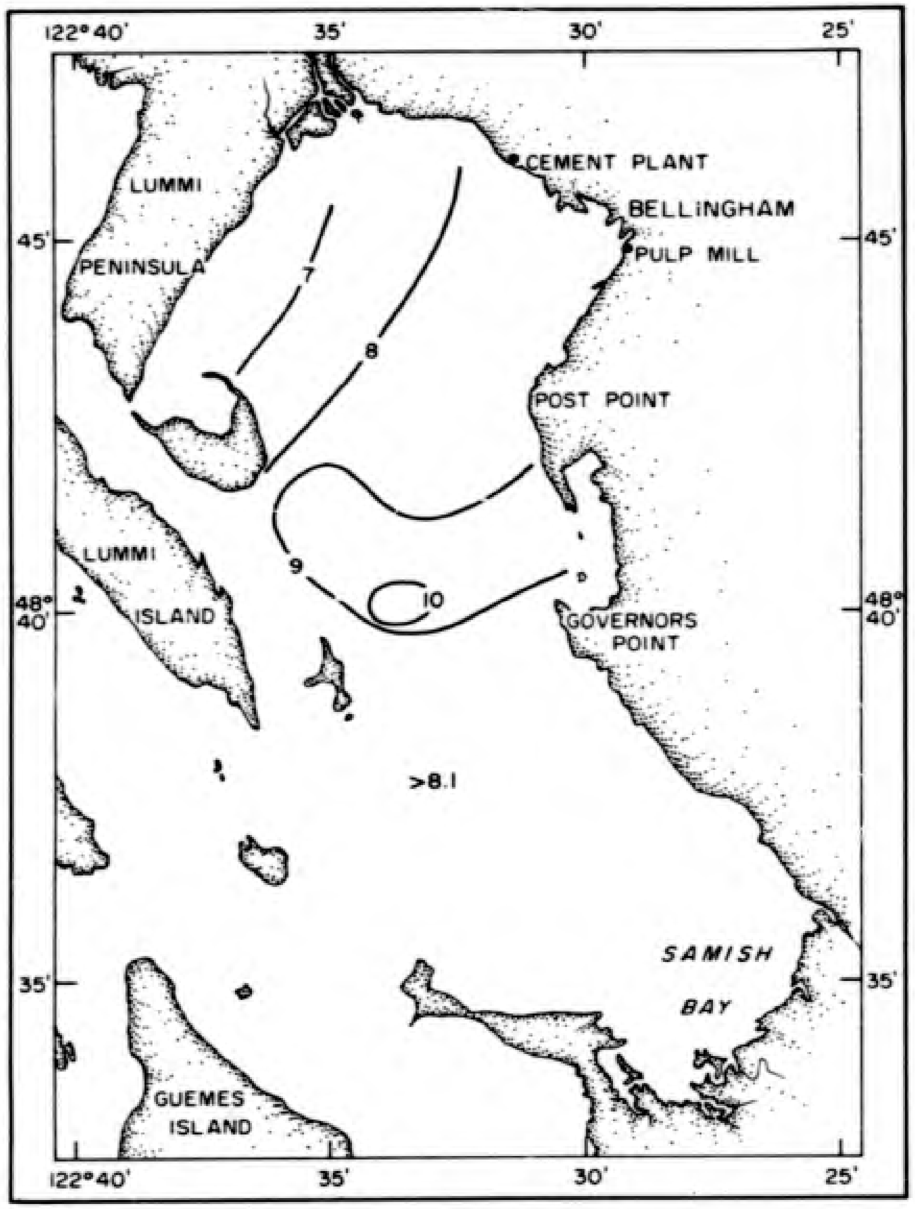

Fig. 2.50. Surface distribution of temperature for 20-22 March 1961.

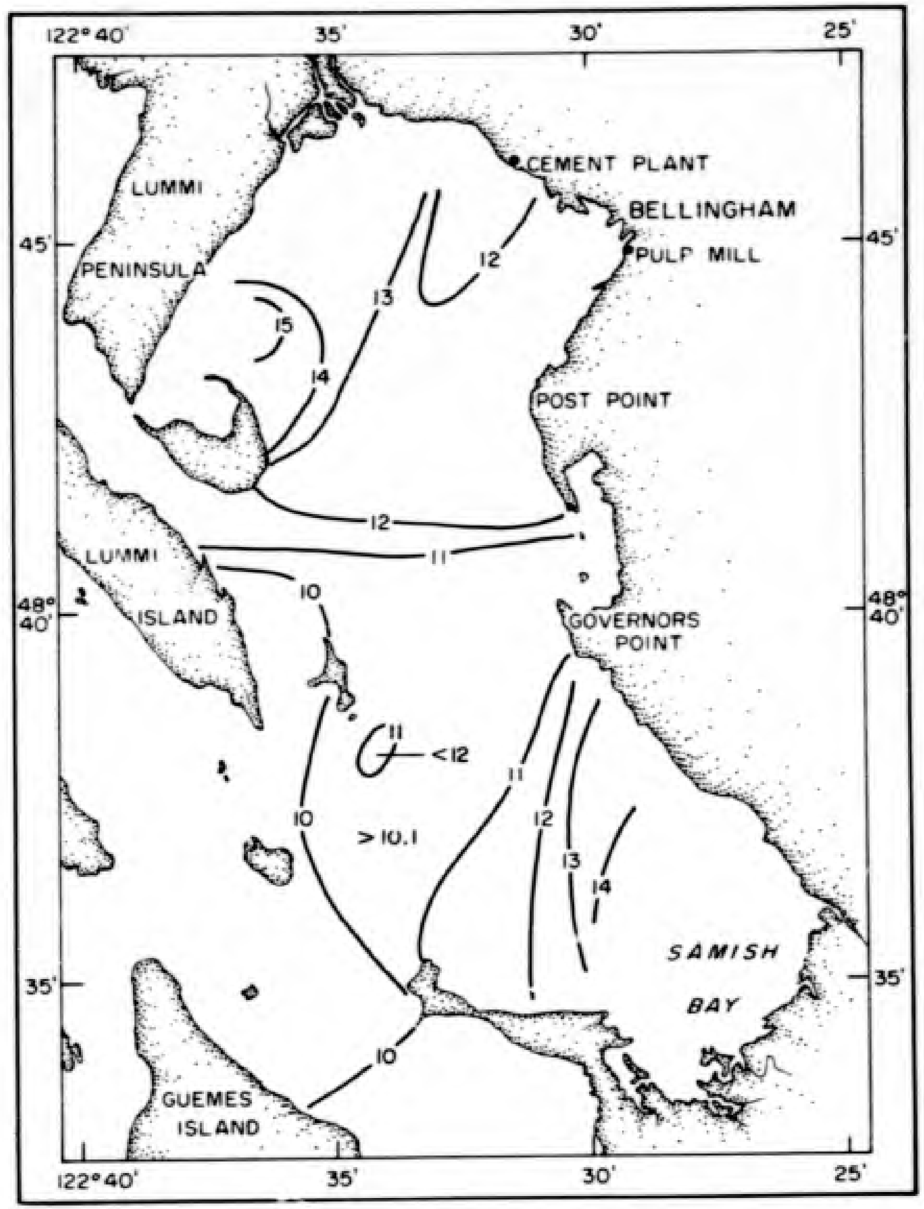

Fig. 2.51. Surface distribution of temperature for 15-16 May 1961.

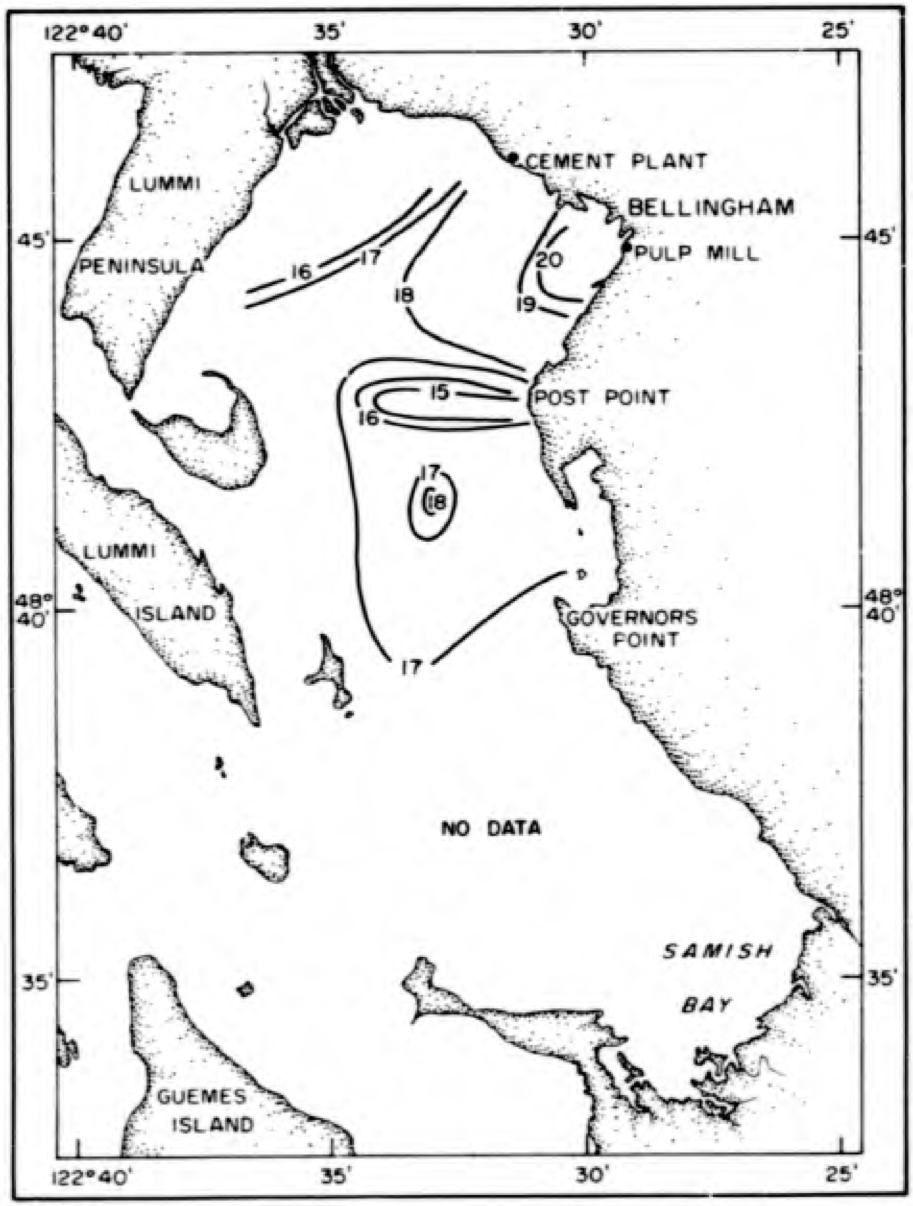

Fig. 2.52. Surface distribution of temperature for 10-11 July 1961.

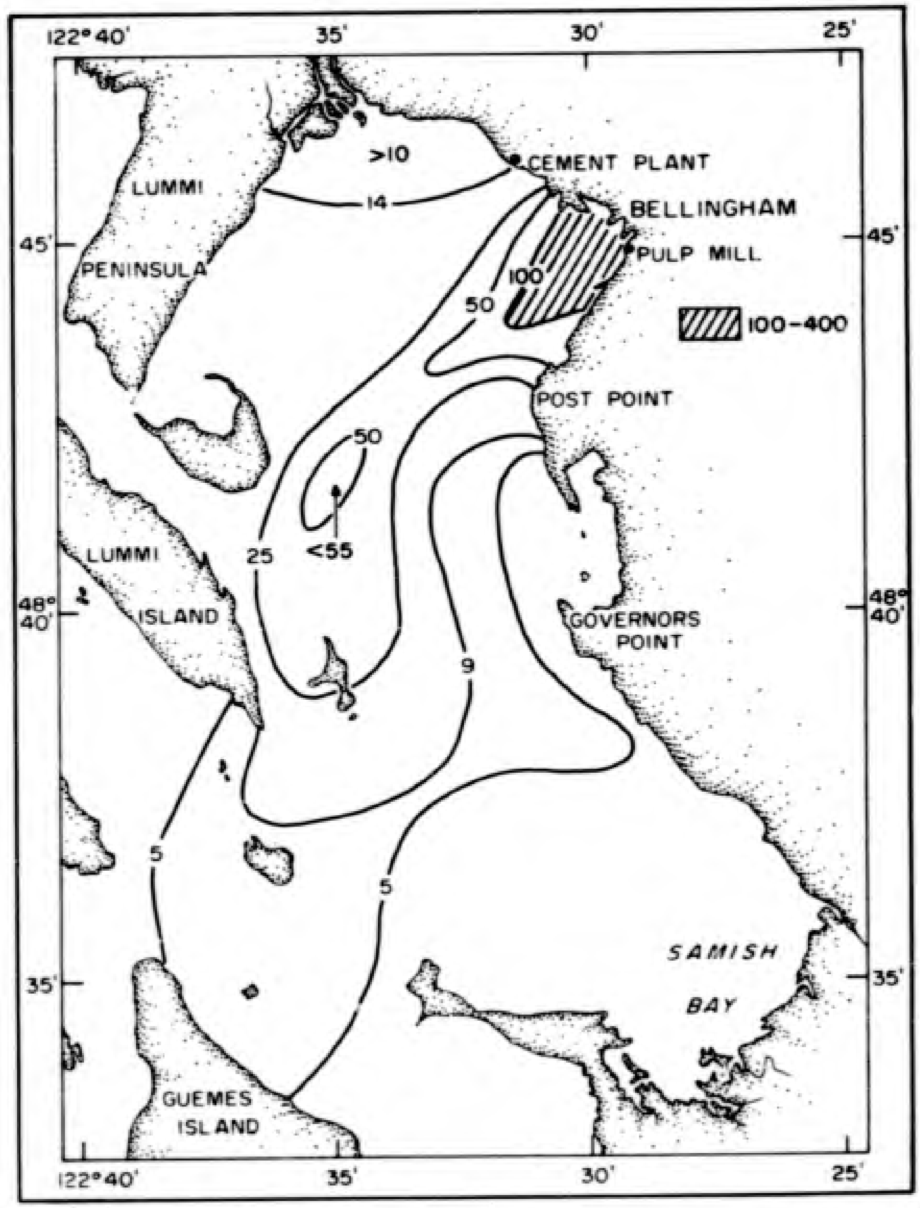

Fig. 2.53. Surface distribution of spent sulfite liquor for 2-4 November 1959.

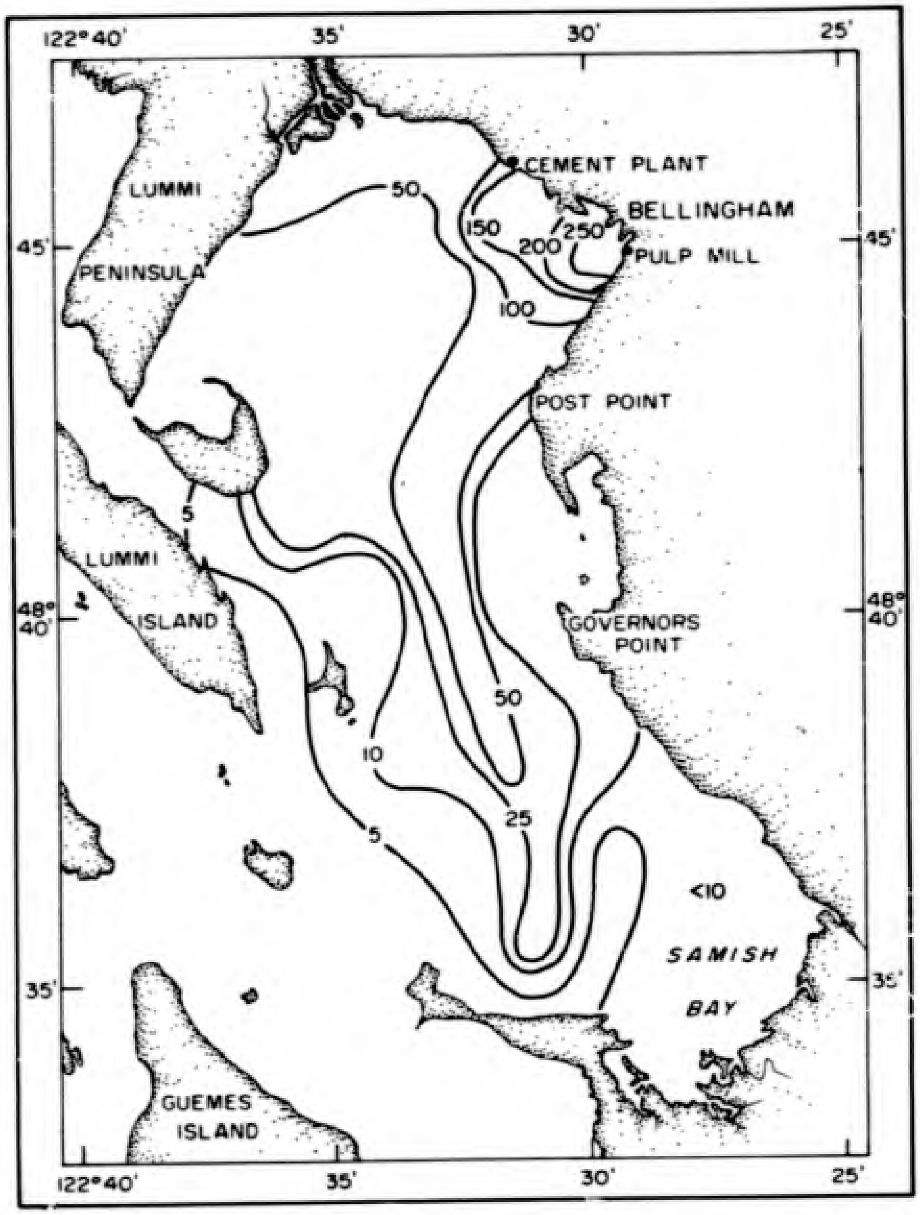

Fig. 2.54. Surface distribution of spent sulfite liquor for 19-21 April 1960.

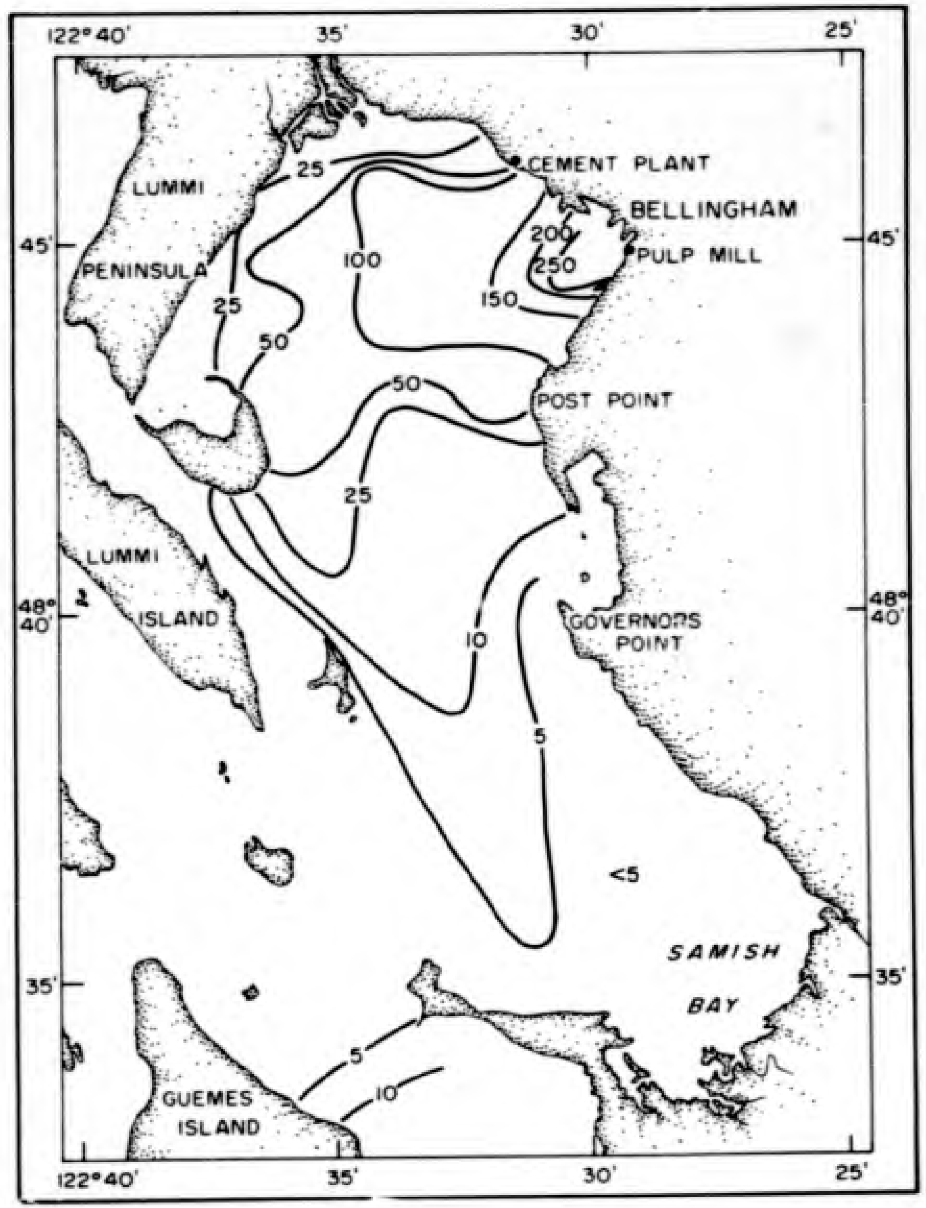

Fig. 2.55. Surface distribution of spent sulfite liquor for 20-22 May 1960.

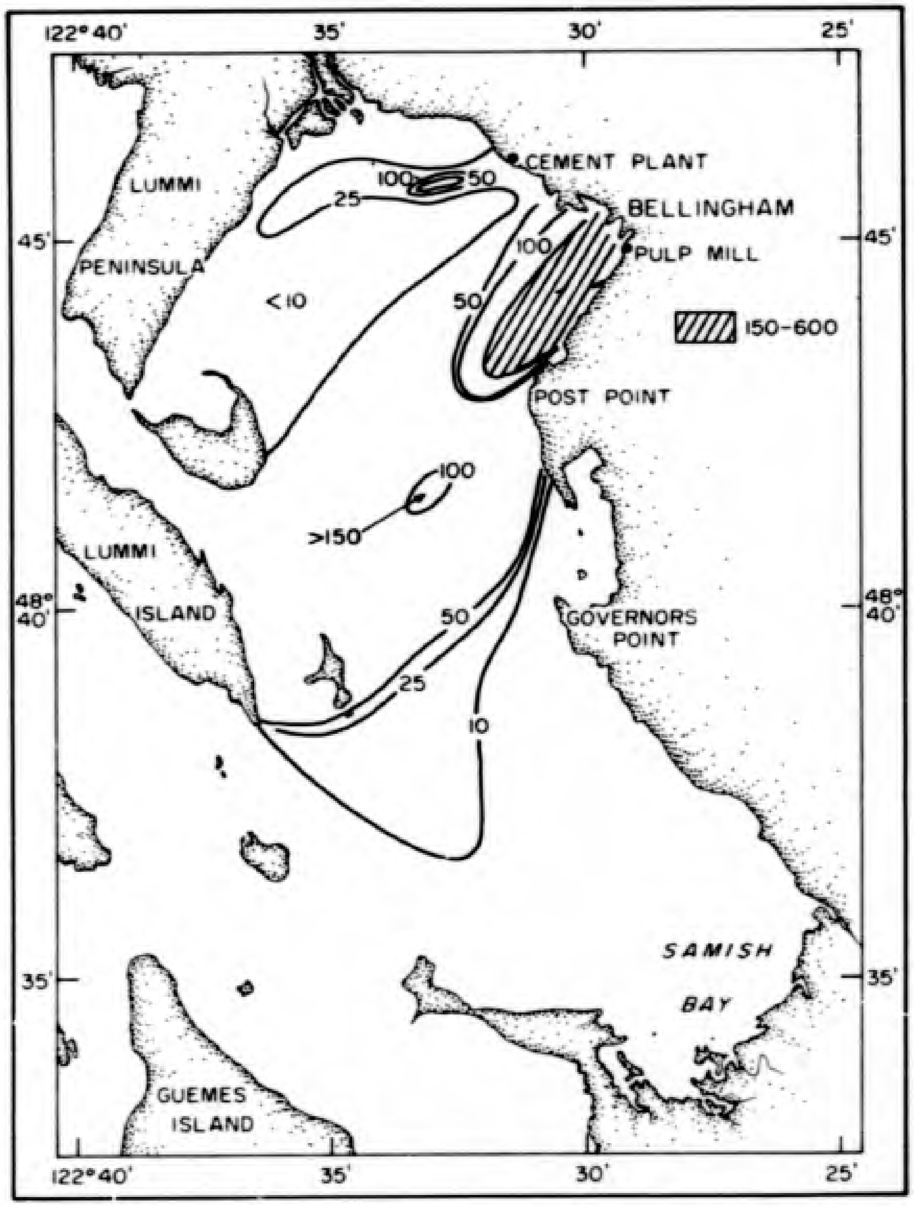

Fig. 2.56. Surface distribution of spent sulfite liquor for 21-22 June 1960.

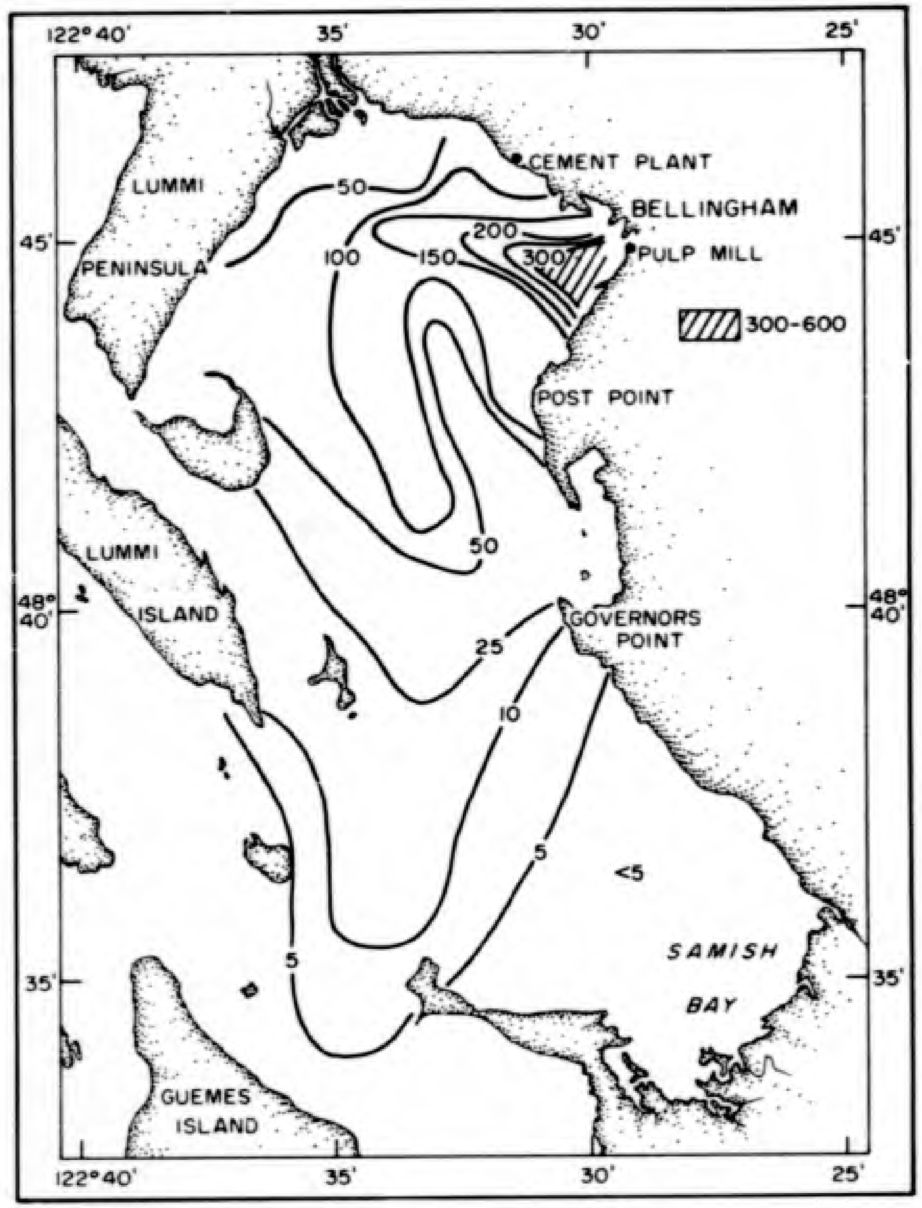

Fig. 2.57. Surface distribution of spent sulfite liquor for 18-19 July 1960.

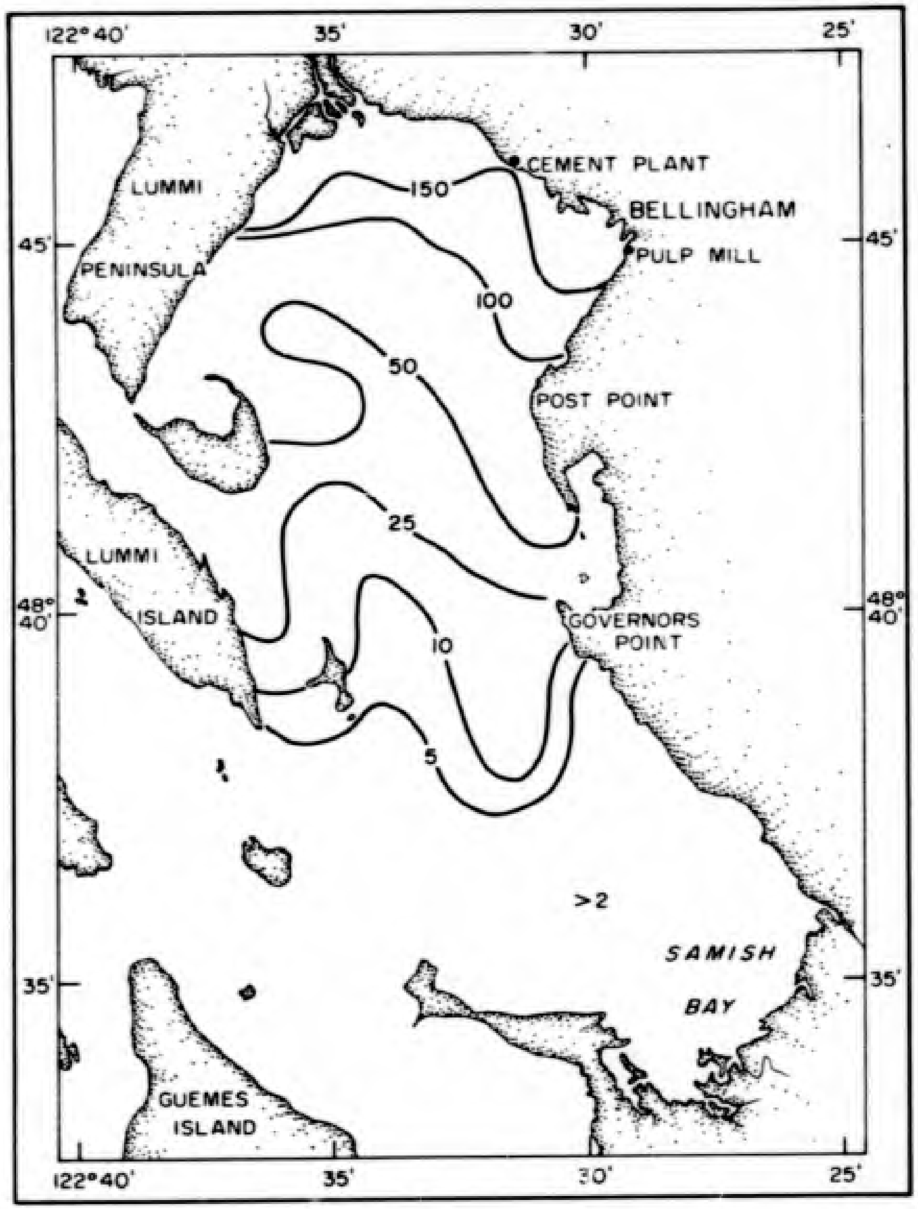

Fig. 2.58. Surface distribution of spent sulfite liquor for 23-24 August 1960.

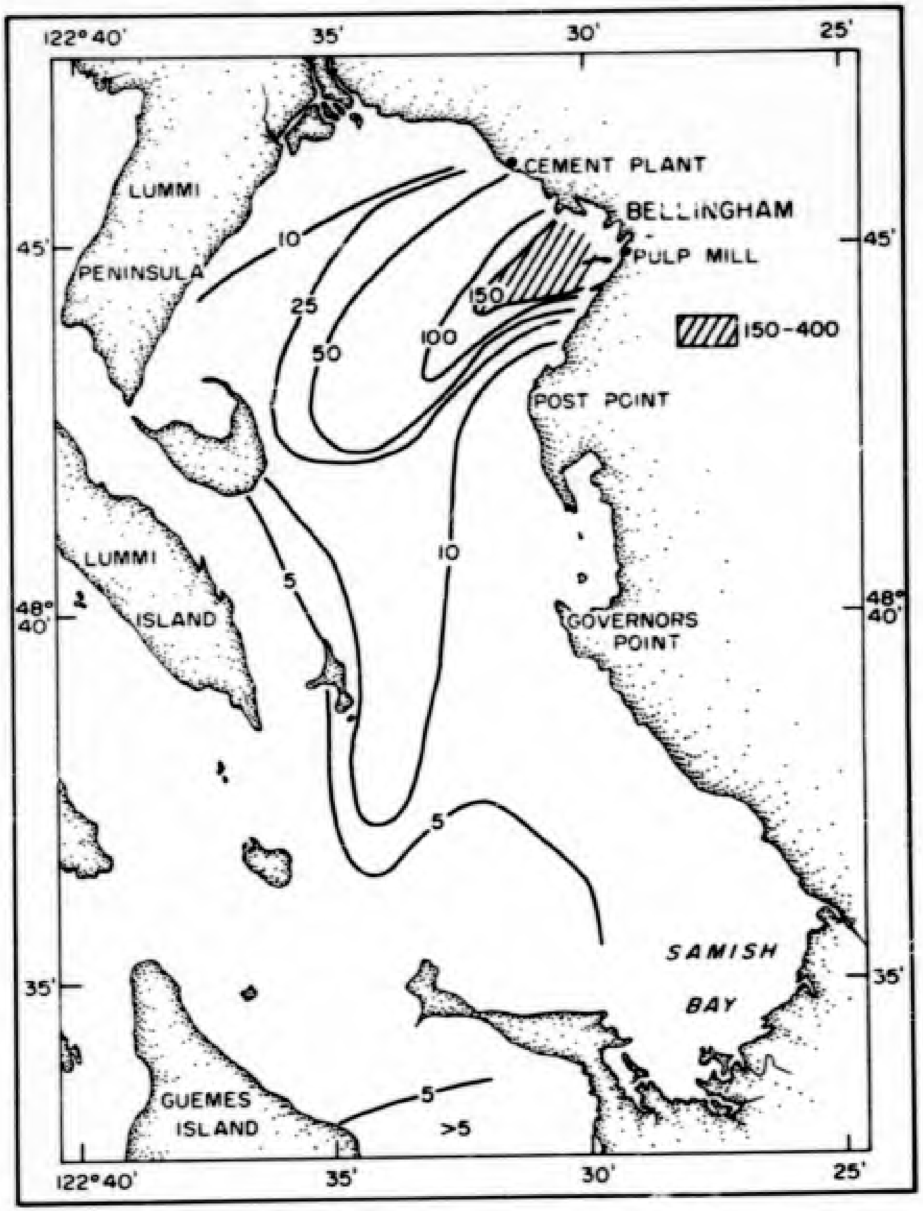

Fig. 2.59. Surface distribution of spent sulfite liquor for 28-29 September 1960.

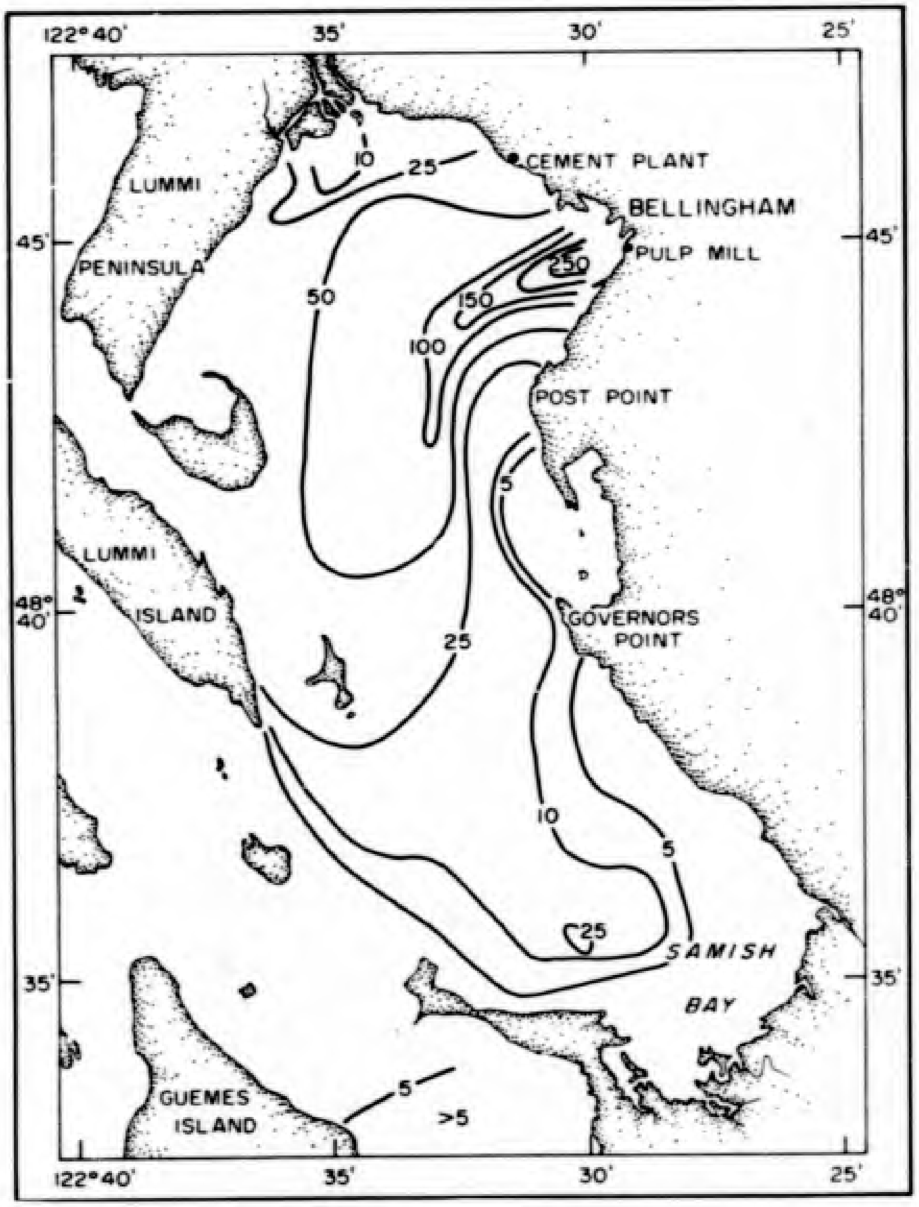

Fig. 2.60. Surface distribution of spent sulfite liquor for 3-4 November 1960.

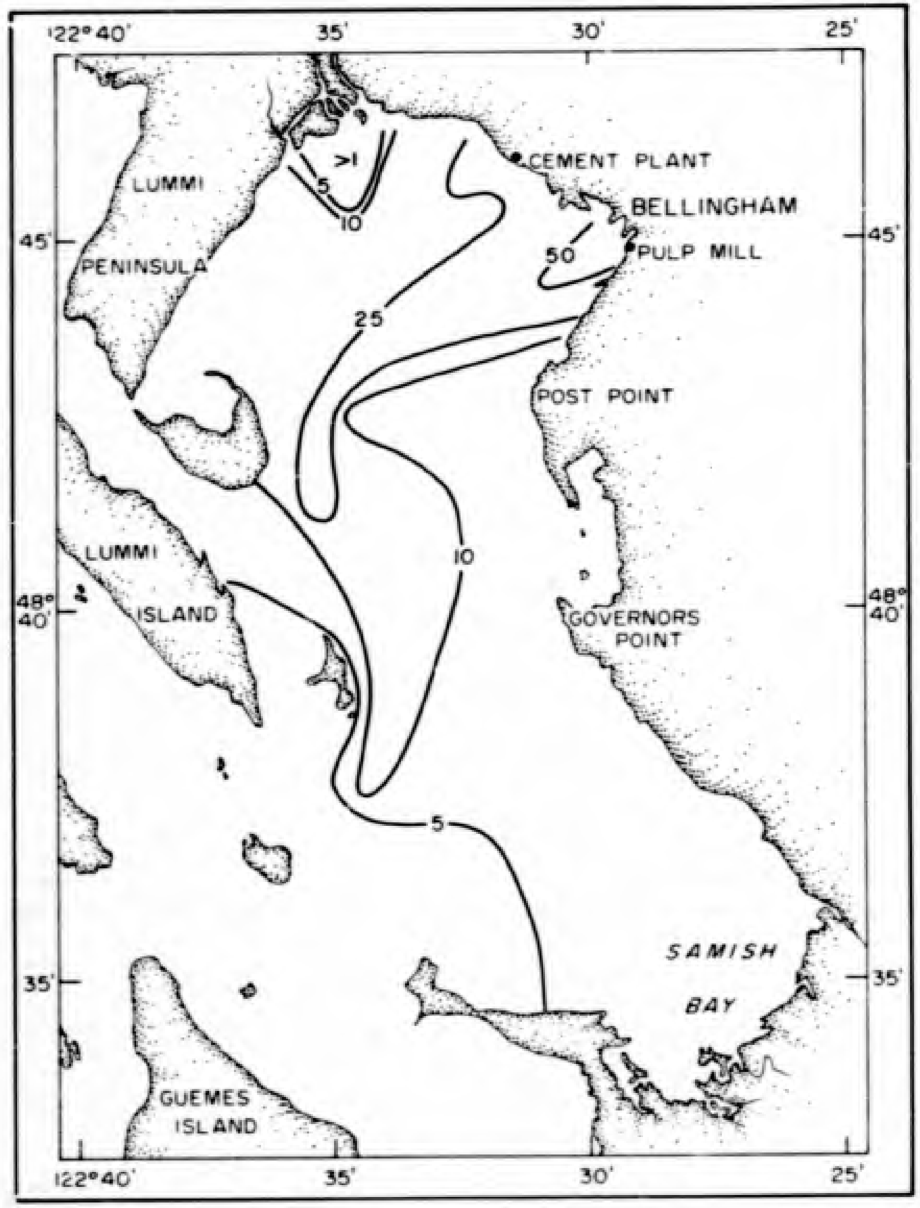

Fig. 2.61. Surface distribution of spent sulfite liquor for 16-17 December 1960.

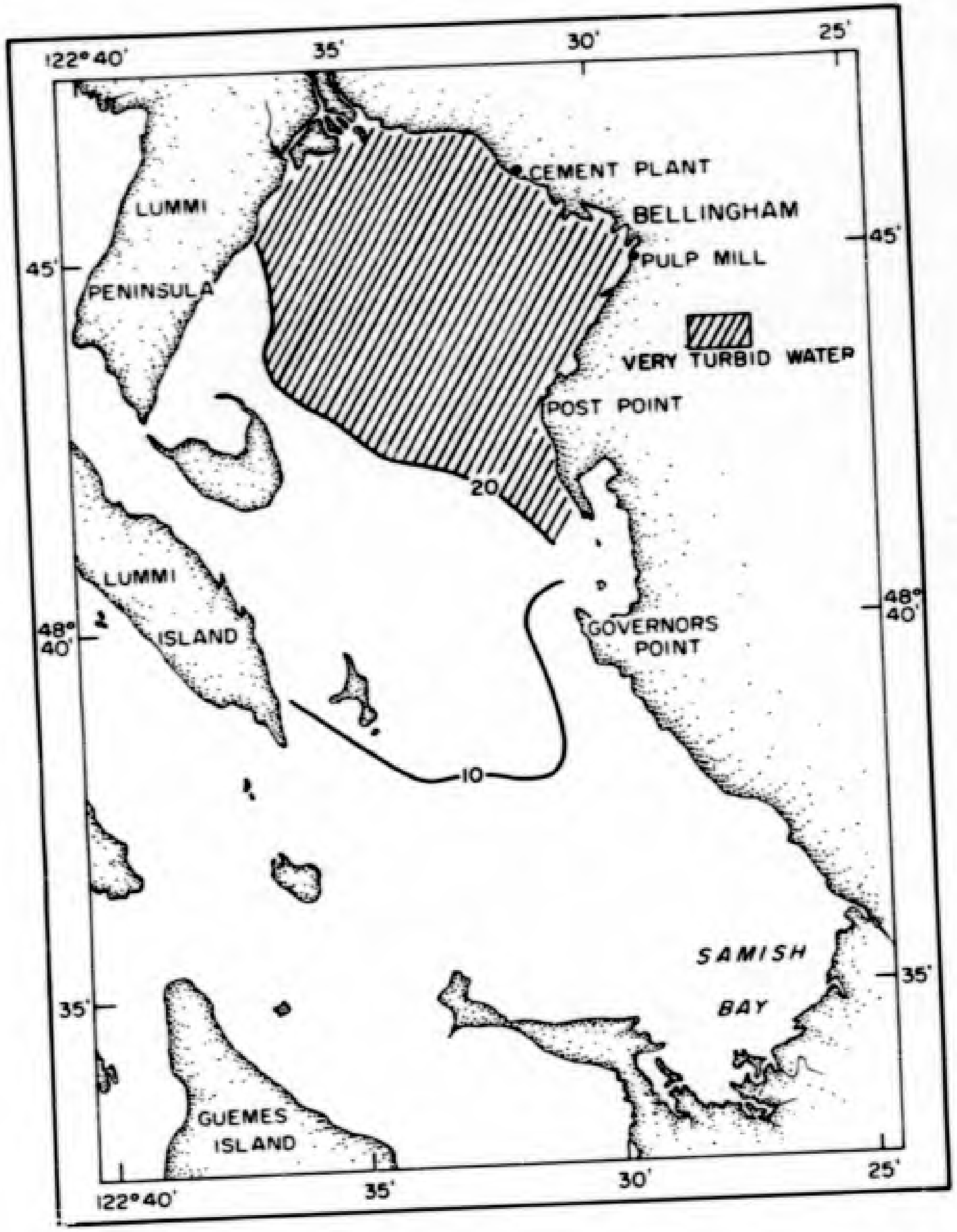

Fig. 2.62. Surface distribution of spent sulfite liquor for 6-7 February 1961.

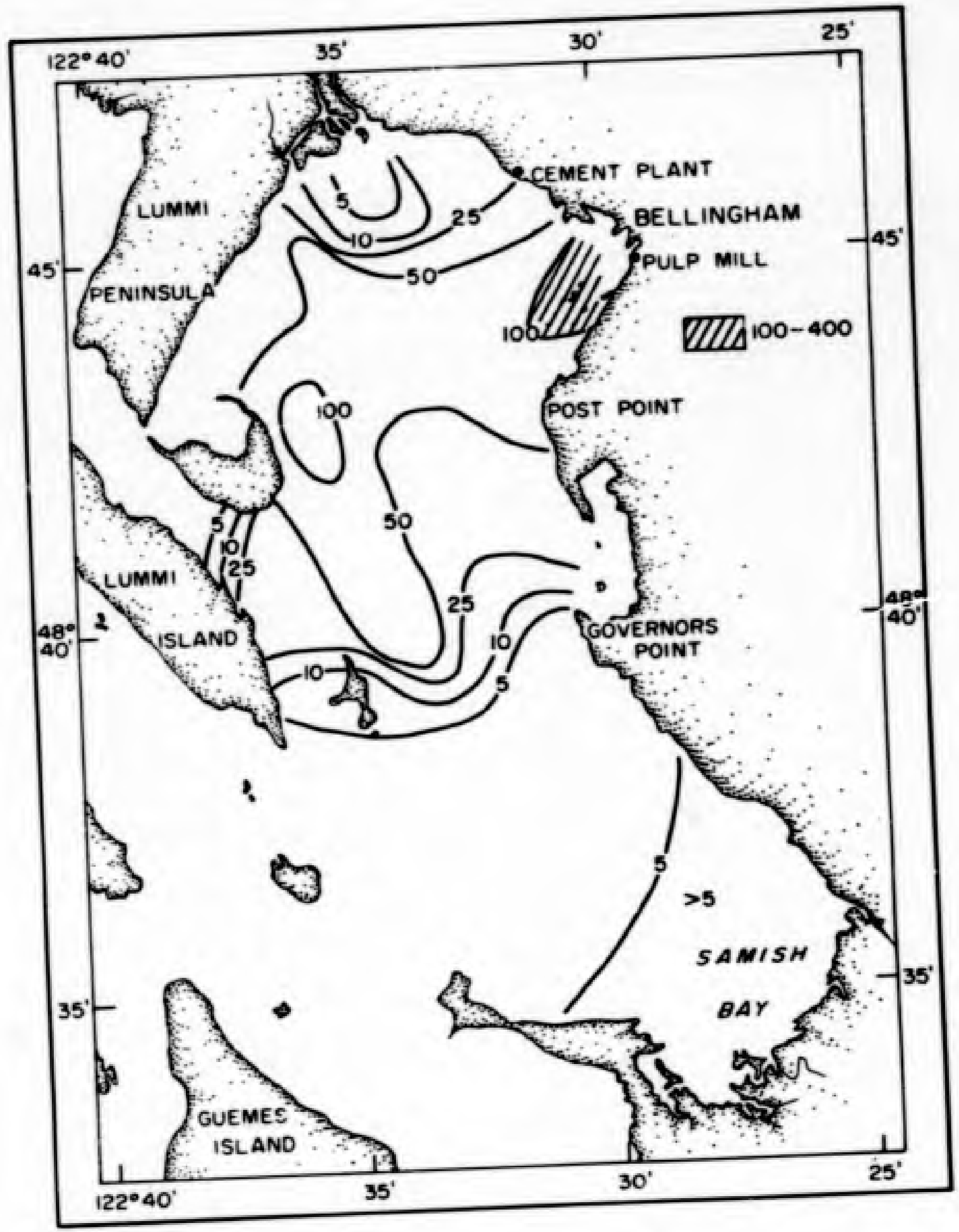

Fig. 2.63. Surface distribution of spent sulfite liquor for 20-22 March 1961.

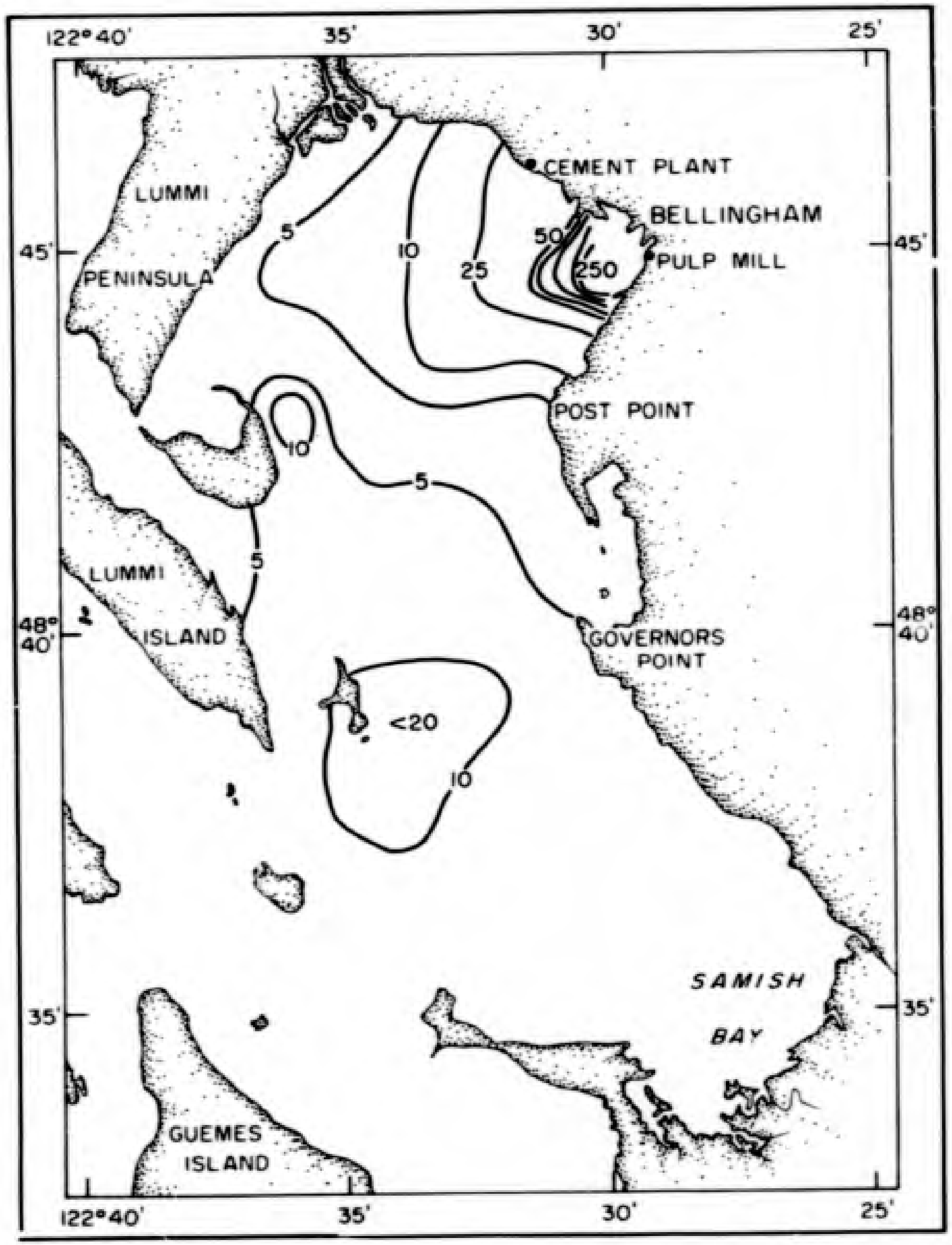

Fig. 2.64. Surface distribution of spent sulfite liquor for 10-11 July 1961.

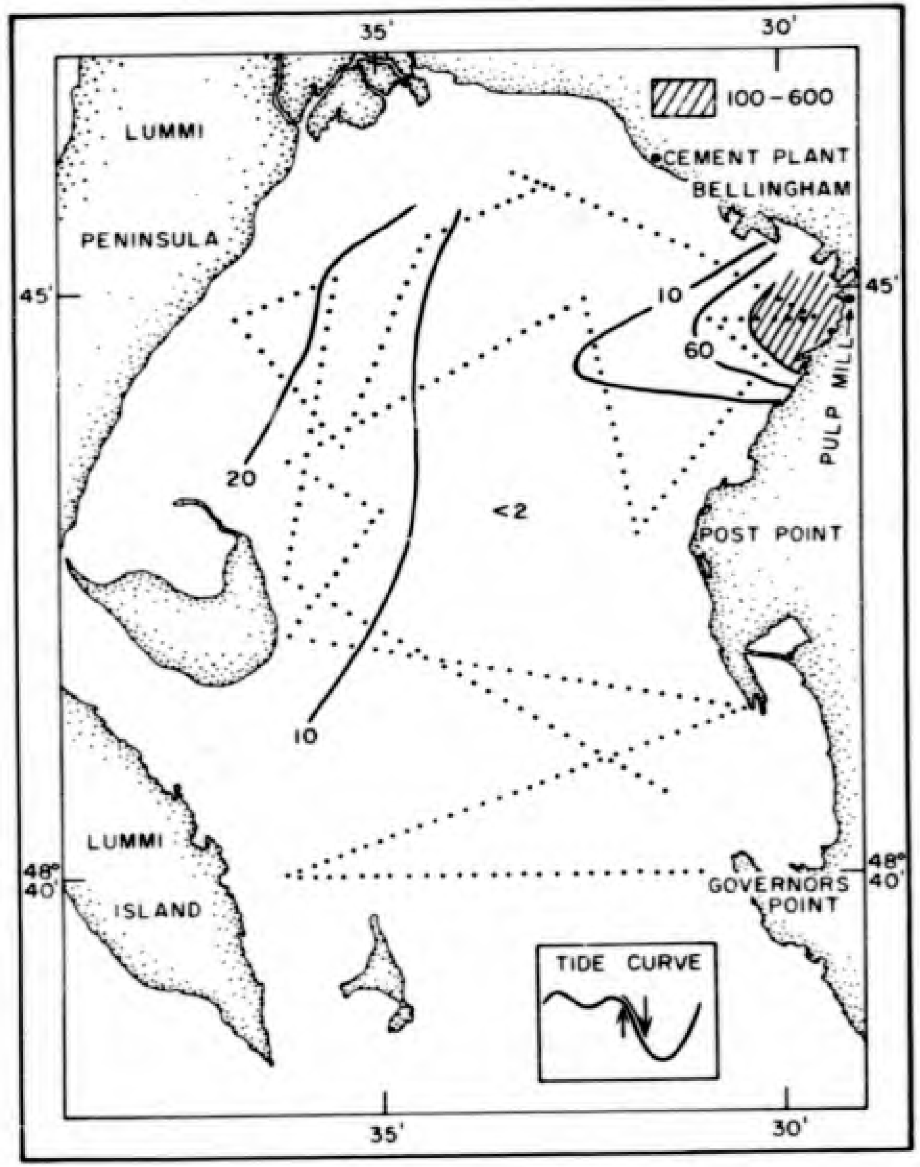

Fig. 2.65. Surface distribution of spent sulfite liquor in upper Bellingham Bay, 4 November 1959, 0744-1130.

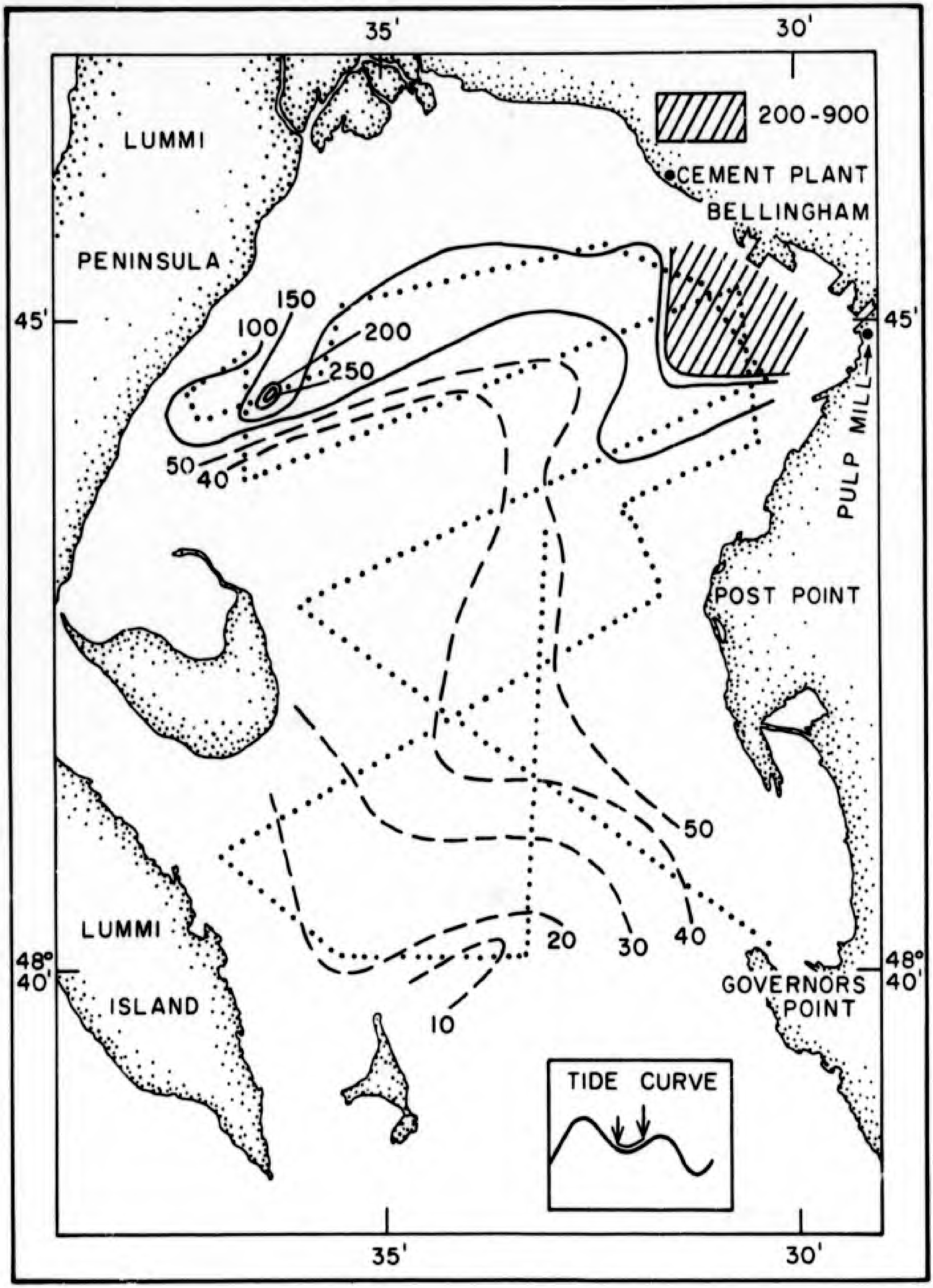

Fig. 2.66. Surface distribution of spent sulfite liquor in upper Bellingham Bay, 21 April 1960, 0845-1227.

3. MEASUREMENT OF WATER CURRENTS[7]

3.1. *Location of Current Stations*

Direct measurements of water movement in Bellingham Bay were made in two series of observations, one in July 1960 and another in July 1961. These current measurements were made at selected depths at 11 sites (Fig. 3.1) with the predominance of measurements made on flood tide. Observation periods were short, usually less than 10 hr.

3.2. *Methods of Measuring Water Currents*

Two basic methods were used to measure currents. The path or drift method (La Grangian method) was used to measure the actual trajectory of a water mass by tracking an object in the water. In this survey drift sticks and drift poles were used for measuring surface currents, while pilot-chute drogues, obtained from surplus parachutes, were used for subsurface currents. The drift sticks were made from wood 2 × 2 × 15 inches (5 × 5 × 38 cm), weighted on one end to float upright with 3 inches (7.6 cm) above the surface. The above-water portion was painted a distinctive color and numbered. The drift poles were 15 ft (4.6 m) long, made of wood 2 × 4 inches (5 × 10 cm), weighted to float with 3 ft (91 cm) out of the water, painted a color similar to the drift sticks, and numbered. Primarily, the drift sticks reflect the movement of the upper 12 inches (30 cm) of water whereas the drift poles integrate the water movement in the upper 12 ft (3.7 m). The pilot-chute drogue was 20 inches (51 cm) in diameter. It was suspended from a fine stainless steel stranded wire of 0.01 inch (0.3 mm) diameter, weighted on the lower end, and floated from the surface by a small can buoy. Water resistance on the can buoy and suspension wire being small, the movement of the can buoy at the surface was considered to be a rect measure of the movement of the drogue. The locations of

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[7]Current observations made after the survey period will be reported in another volume.

all drift devices were determined by the horizontal-angle method, using known landmarks and a sextant to measure the subtended angles.

The second method used for measuring currents, that of determining the flow past a fixed point (Eulerian method), was accomplished by suspending current meters from an anchored ship. The speed of the near-surface currents was measured using a Price current meter and the direction was determined by visual observation. At greater depths an Ekman current meter (Ekman, 1932) and the Ekman-Mertz modification of this meter were used. These current meters were of the propeller type, equipped with magnetic compasses to sense direction, and were messenger operated. They were raised to the surface at the end of each observation in order that the counters and compass might be read. With this type of meter it was possible to obtain readings at given depths only once every 10–15 min, depending upon the current velocity. Except during change of tide, the ship held its position well throughout all series of observations.

3.3. *Observations*

3.3.1. *18–20 July 1960:* During the period of 18–20 July 1960 measurements were made of currents across the entrance to Bellingham and Samish Bays from Eliza Island to William Point, and across the entrance of upper Bellingham Bay. On 18 July 1960, only drift devices were used, and the period of observation extended from 2 hr before to 2 hr after high water (Fig. 3.2). Drift poles released near station G-2 moved to the west while drift sticks moved to the southeast. Drift poles released about 0.5 mile (0.8 km) east of station G-3 drifted to the north. Winds during this period were from the south to west at speeds up to 12 knots (6 m/sec).

Drift devices released during the long flood of 19 July were tracked toward Hale Passage (Fig. 3.3). Drift poles released at 1151 hours near Point Frances were tracked into Hale Passage where they were lost. In the meantime, the drift sticks had traveled south-southwest to Lummi Island, and a pilot-chute drogue set at 10 m (33 ft) also drifted south-southwest but at a much slower rate. Drift poles released east of station D-2 (Fig. 3.4) moved west and northwest while drift poles released west of station D-2 moved south before turning to the west and north.

At station D-3 the drift pattern on the 19th (Fig. 3.5A, B, C) was different from that on the 20th (Fig. 3.5D, E, F). On the first day the drift was predominantly southerly, whereas on the latter day the drift was more to the north.

Currents at depth were measured from a ship anchored at station D-2 on 19 July and at station D-1 on 20 July (current-meter readings are presented in Appendix B). At D-2 the maximum current velocity observed was 1.1 knots (0.56 m/sec) at the 2-m (6-ft) level, while the maximum current in deeper water was 0.5 knot (0.26 m/sec) at 25 m (83 ft). In general, the direction was northwesterly near the surface and northerly at depth. At D-1 the maximum current observed was 1.2 knots (0.62 m/sec) at a depth of 2 m (6 ft), but no reliable measurements were obtained at greater depths during the peak currents. Generally the surface current direction was toward the northwest or the southwest.

3.3.2. *10–13 July 1961:* During the period 10–13 July efforts were concentrated on the B-line of stations. On the afternoon of 10 July one boat was anchored at station B-3 off the pulp mill to make current-meter observations while another boat released drift sticks and drogues at station B-3 and east of B-2 (Fig. 3.6). The surface currents at B-3 initially set toward the northeast but at change of tide from flood to ebb the flow changed to the southeast at a speed of about 0.2 knot (0.1 m/sec). Near B-2 the surface current initially set to the southeast but shifted to the north at change of tide.

On 11 July drift devices were released at stations B-1 and B-3 and tracked for 9 hr (Fig. 3.7). A boat was anchored at B-2 to measure currents at depth (Table B.4) and to release drift equipment. At station B-1 the drift was to the south near the end of the long ebb, but changed to the north-northwest during flood tide. At B-2 the drift was also south but changed to the north during flood tide, whereas a drogue set at 10 m (33 ft) drifted to the east. Drift sticks released at B-3 moved in the same direction as the poles but more rapidly. During the flood tide the overall drift was to the north and east.

On 12 July drift sticks were released northwest of Post Point simultaneously with Rhodamine B dye (see section 4) (Fig. 3.8). The drift sticks and dye patch moved together at about 0.4 knot (0.21 m/sec) toward the southeast and stopped along a tide rip.

On 13 July drift poles, drift sticks, and two drogues set at 20 and 30 m (66 and 99 ft) were released from station G-2 (Fig. 3.9). Initially, at the end of the ebb tide the water moved to the south, but shifted to the east at change of tide. Later in the flood all the drift devices began moving to the north.

3.4. *Results*

Although only a few observations on currents in the Bellingham-Samish Bay system were made, a probable surface current pattern can be inferred. During the flood tide (Fig. 3.10) surface water enters the system from Rosario Strait, travels in a circular path northward along Samish Bay, and is deflected toward Point Frances by Governors Point. In midbay the current splits, one part forms a large clockwise eddy in upper Bellingham Bay while the other part sets west toward Hale Passage. In Hale Passage the currents flood to the northwest. Off the city of Bellingham a counterclockwise eddy sometimes develops inshore near the pulp mill. In general the current speeds are less than 0.6 knot (0.3 m/sec) except in Bellingham Channel and Hale Passage.

There were fewer measurements of current on ebb than on flood. Indications are, however, that the circulation in upper Bellingham Bay reverses during the ebb with some water flowing into Bellingham Bay through Hale Passage and out of the bay via the deeper channels to the south. These inferred patterns may be expected to apply only in the absence of wind. Wind stress is very effective in moving the surface water. An example of wind effect was observed during the dye plant of 23 March 1961, when both dye and drift sticks moved northwest under the influence of the wind while a drift pole moved southwest across the wind.

Observations of suspended matter in the water often indicated that the upper 1 m (3 ft) or less was moving faster than the slightly deeper water. Thus industrial or domestic wastes introduced into the surface layer may at times move out of the bay at a rate faster than might be predicted from the usual circulation patterns.

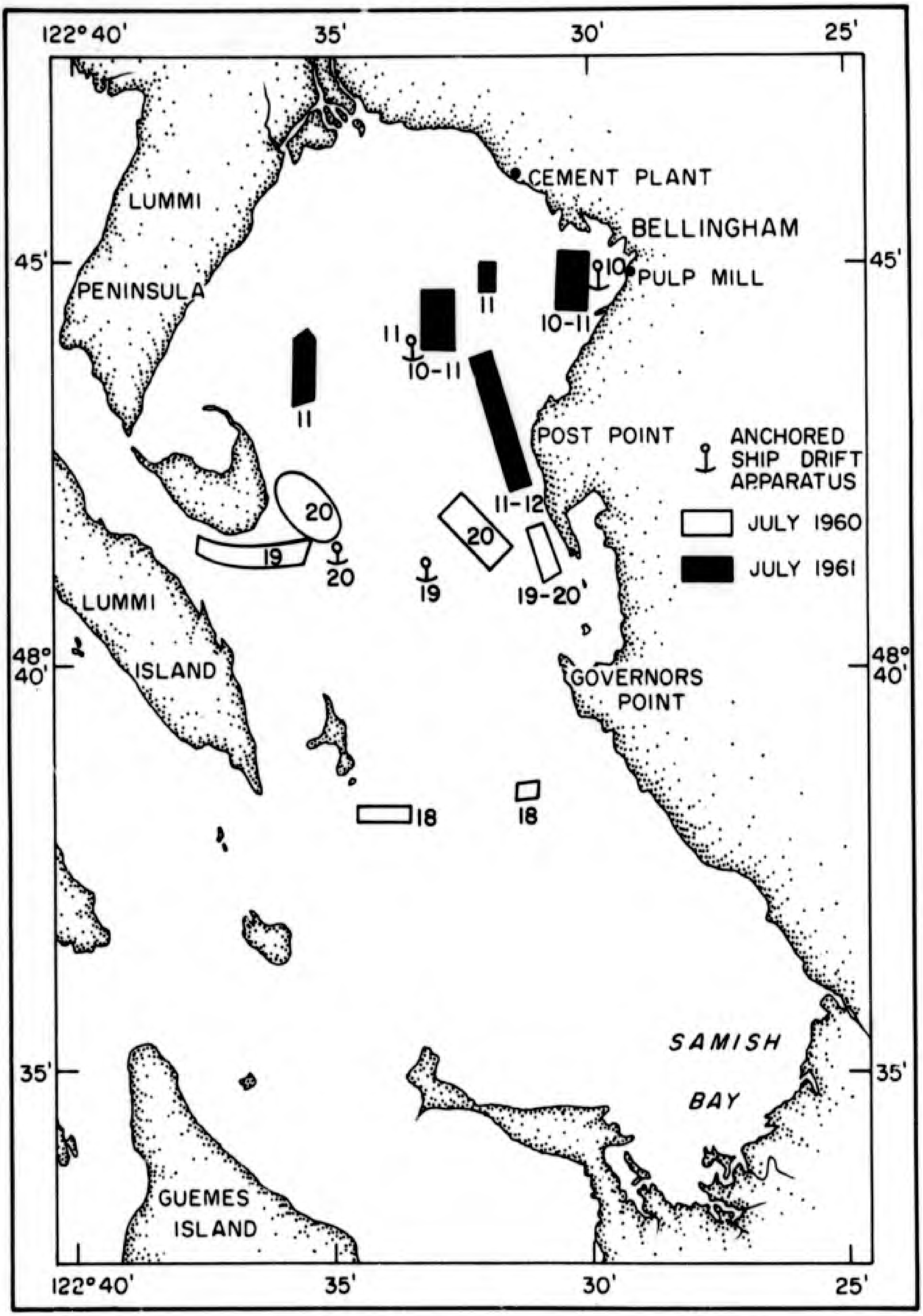

Fig. 3.1. Location of current observations in Bellingham Bay.

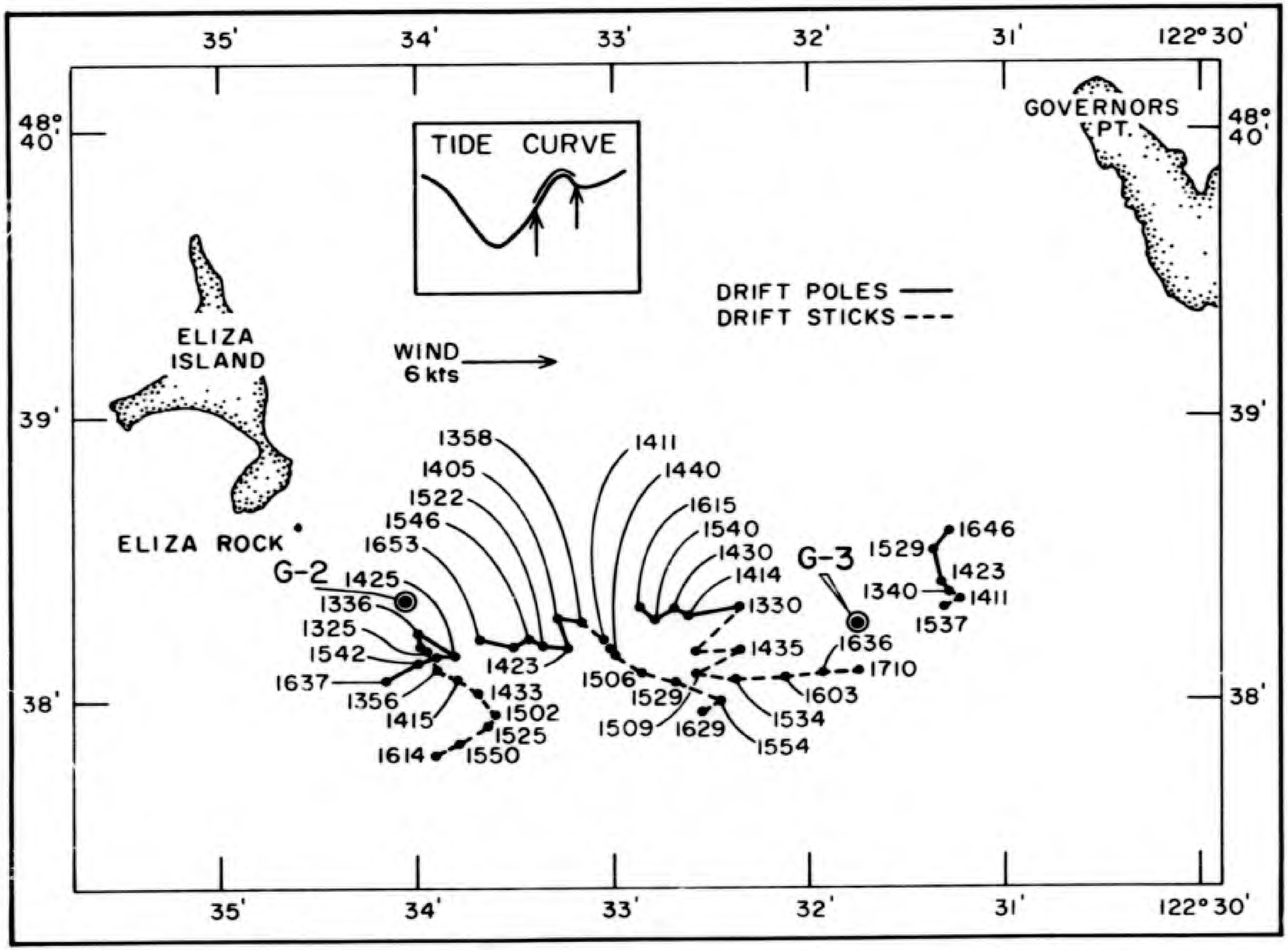

Fig. 3.2. Tracks of drift devices near stations G-2 and G-3, 18 July 1960.

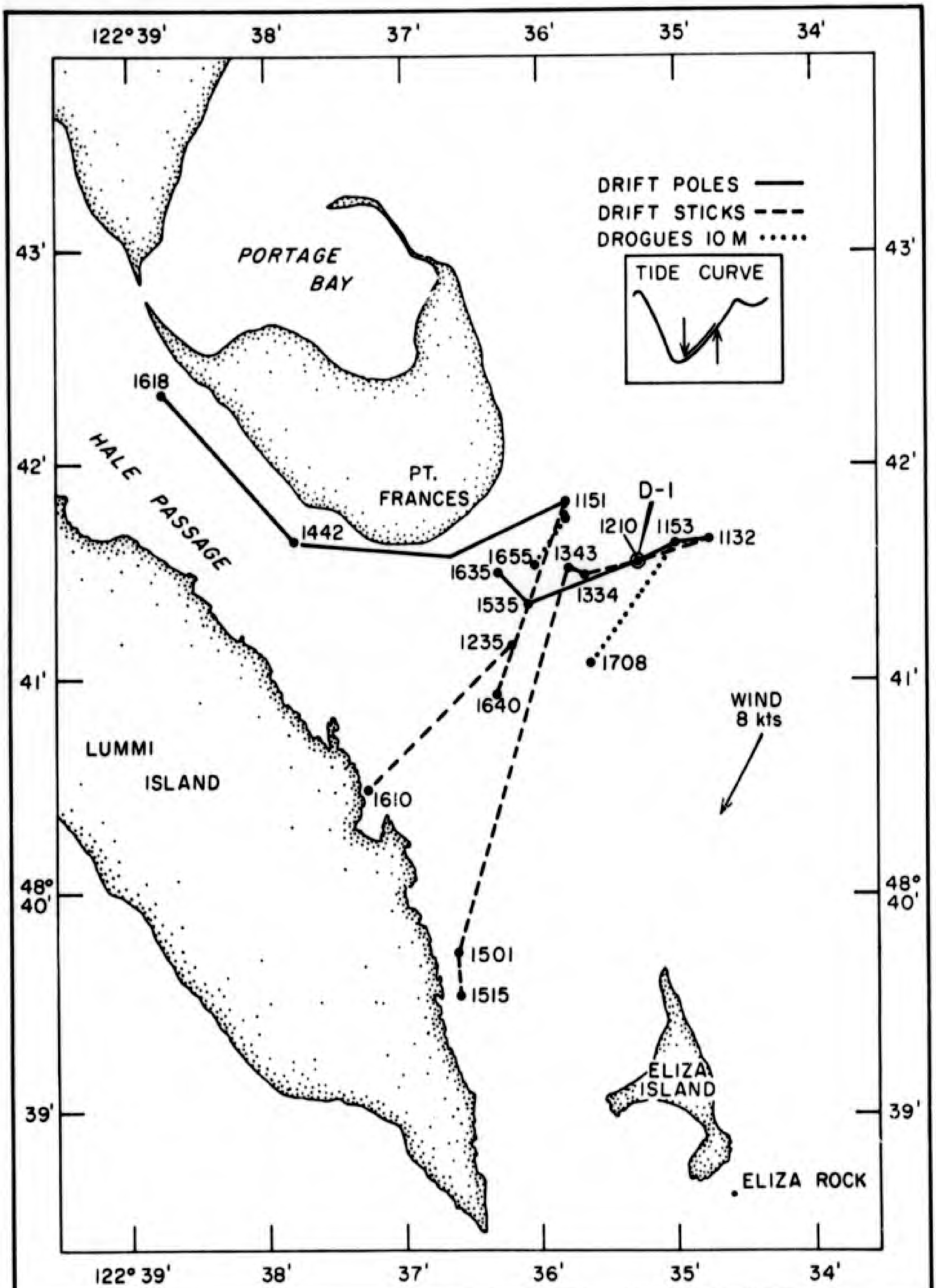

Fig. 3.3. Tracks of drift devices near stations D-1, 19 July 1960.

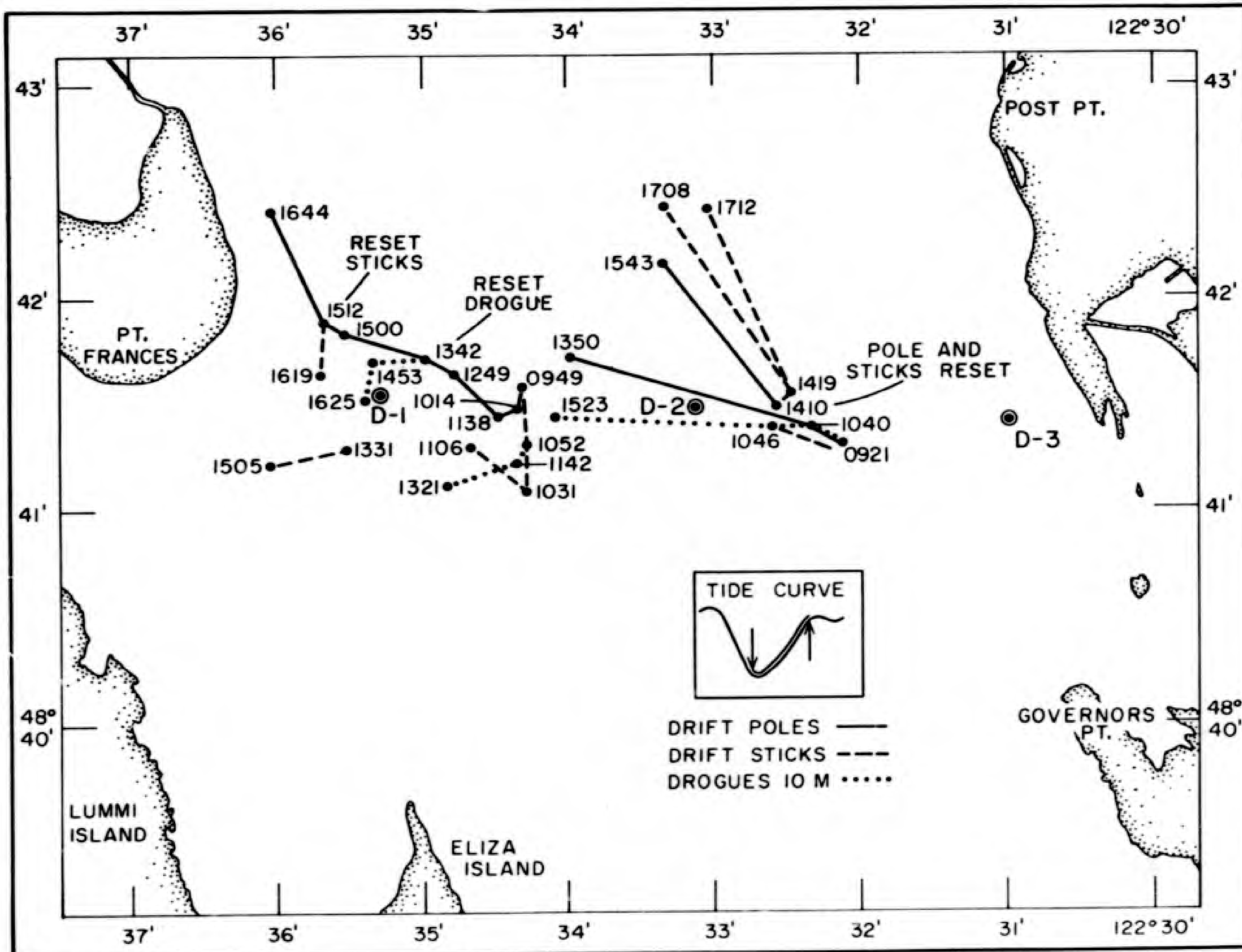

Fig. 3.4. Tracks of drift devices near stations D-2, 19 July 1960.

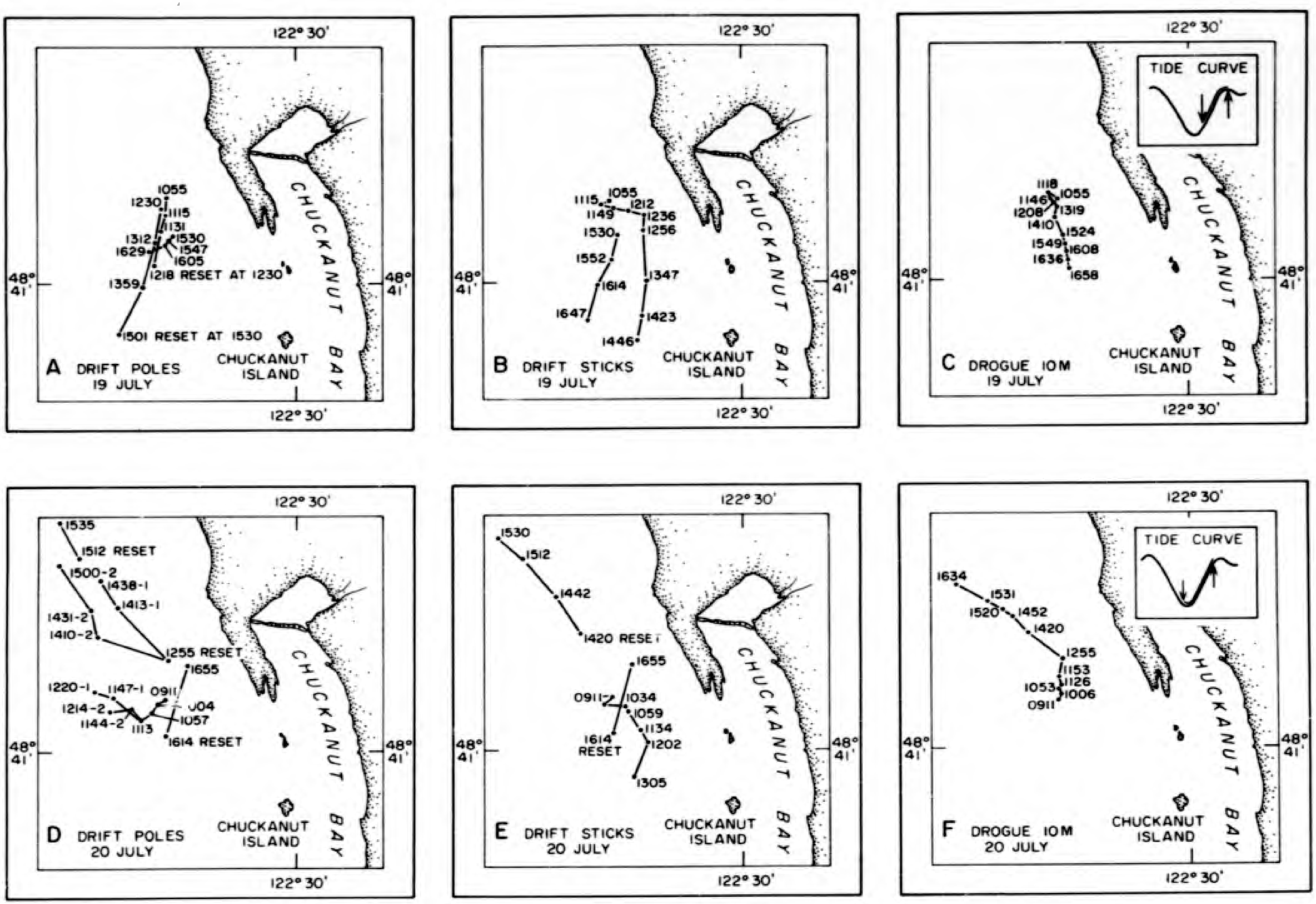

Fig. 3.5. Tracks of drift devices near station D-3, 19-20 July 1960.

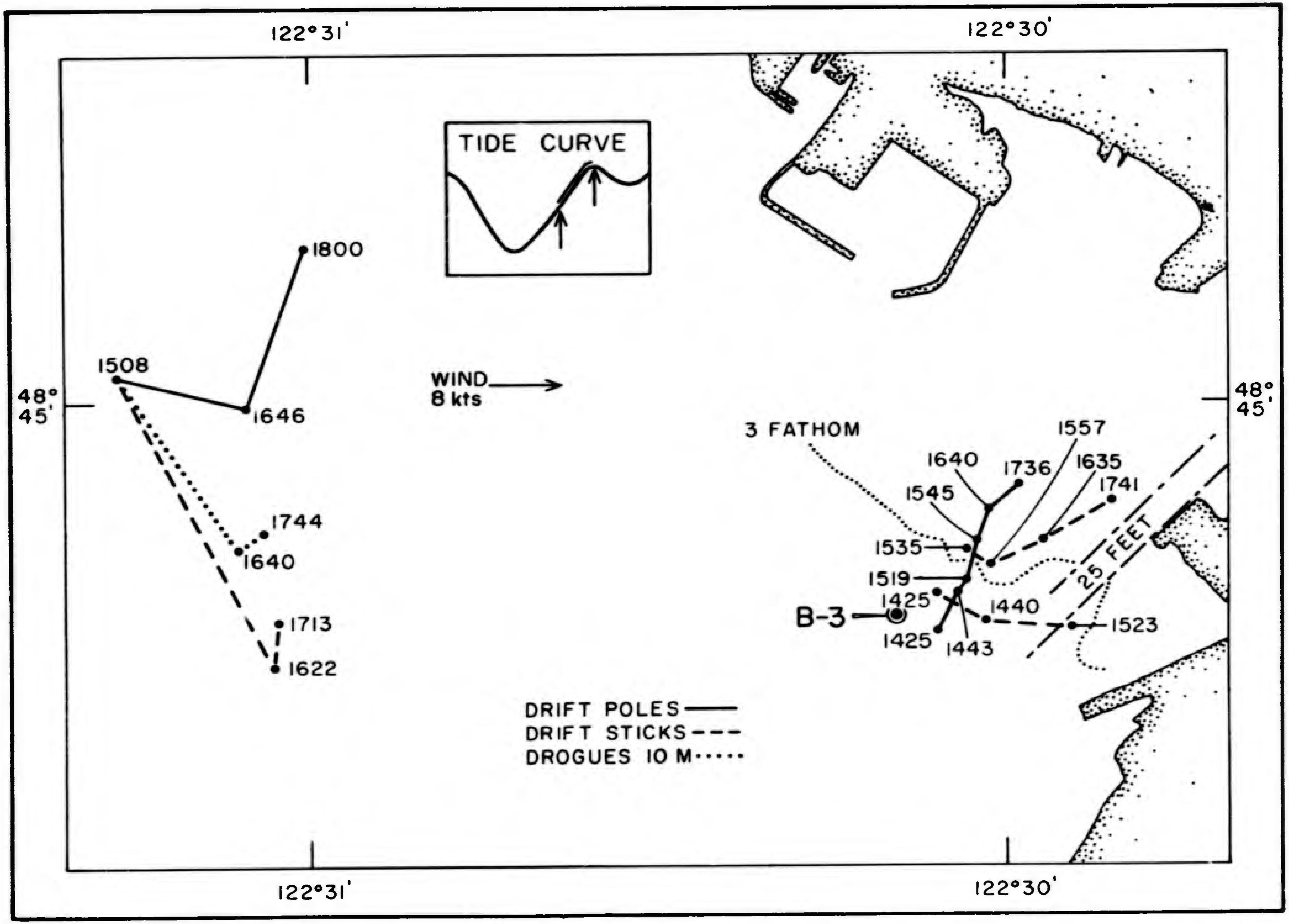

Fig. 3.6. Tracks of drift devices near station B-3, 10 July 1961.

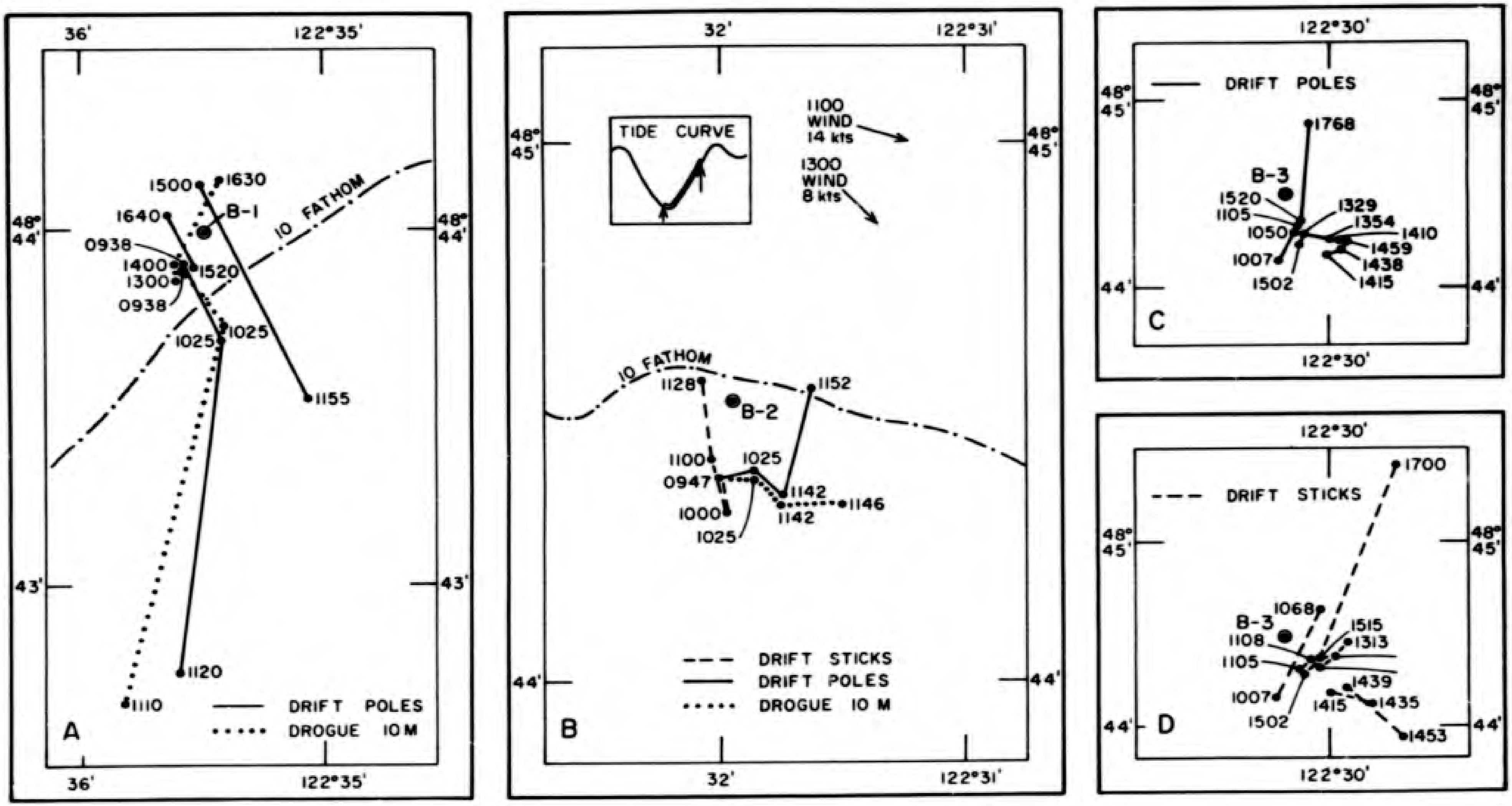

Fig. 3.7. Tracks of drift devices near station B-1, B-2, and B-3, 11 July 1961.

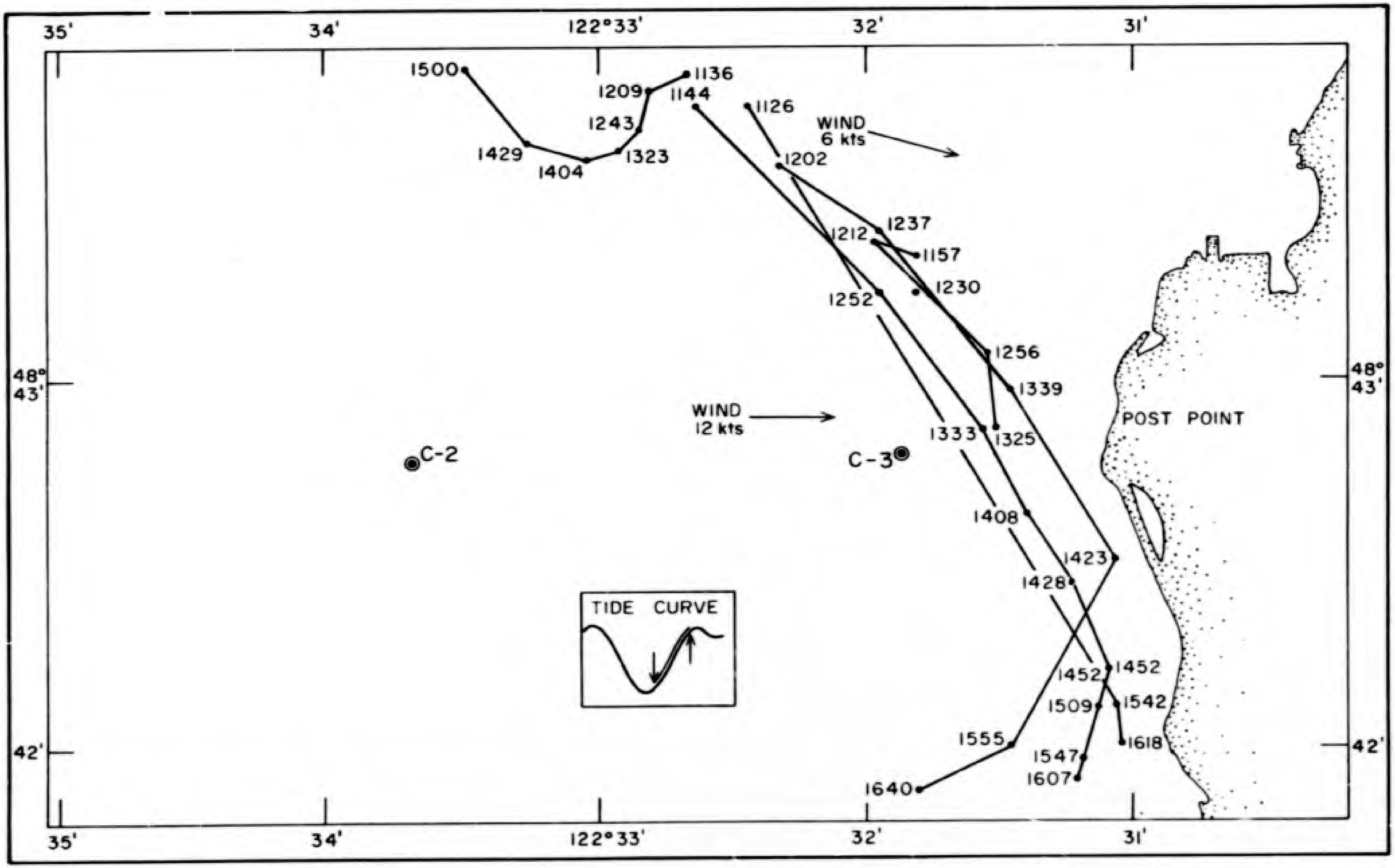

Fig. 3.8. Tracks of drift devices near Post Point, 12 July 1961.

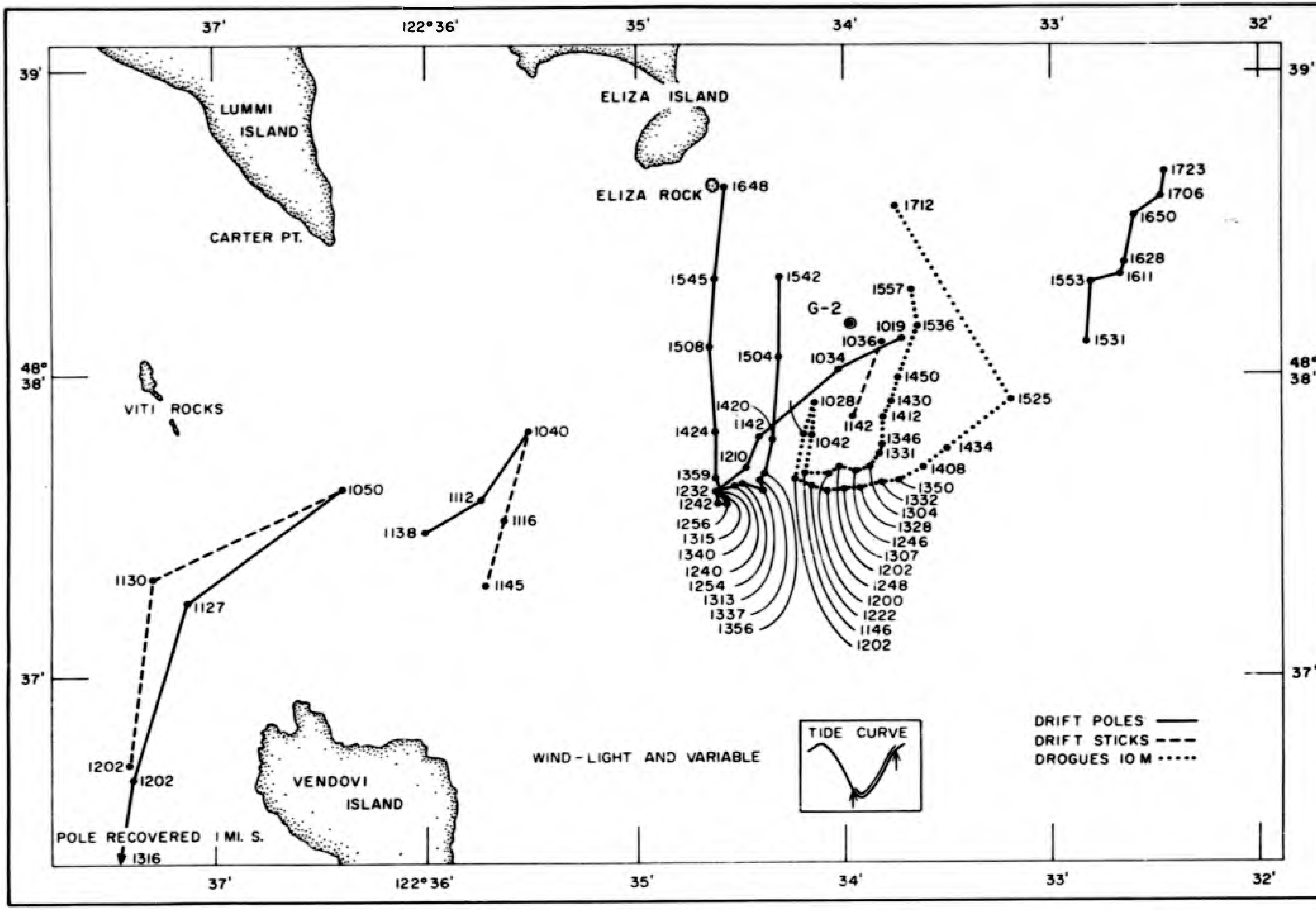

Fig. 3.9. Tracks of drift devices near station G-2, 13 July 1961.

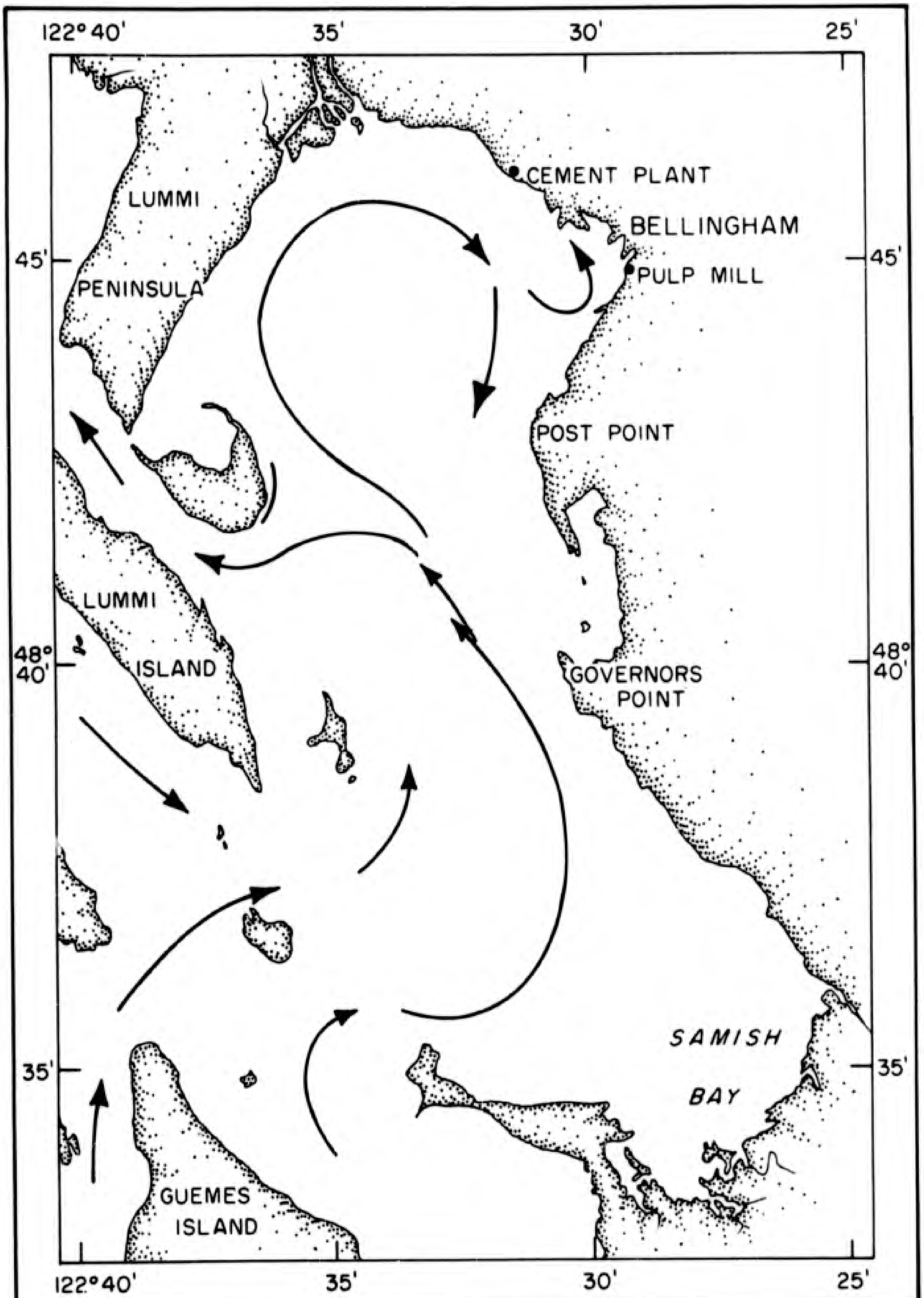

Fig. 3.10. Inferred flood-current pattern.

4. DYE-TRACER STUDIES

4.1. *Introduction*

In order to measure the movement and diffusion of individual water masses in upper Bellingham Bay, Rhodamine B dye was injected into the water at several locations and times (Fig. 4.1). Rhodamine B dye is highly fluorescent when excited by the green line of a mercury vapor lamp (5460 A), and can be detected by a fluorometer in concentrations as low as 0.05 part per billion.

Before Rhodamine B dye was introduced into the water, a known weight of concentrated dye solution was diluted with seawater obtained from the depth of the planned observation. Then sufficient methanol was added to adjust the density of the mixture to that of the original seawater and 5 ml of General Electric Antifoam-60 were added to prevent excessive foaming. If the dye was to be released at the surface, the mixture was made less dense than the surface water. Finally, the dye was pumped into the water at the desired depth.

Dye concentrations were measured by pumping seawater from depth by means of a submersible deep-well pump attached to 1-inch (2.5-cm) steam hose. A portion of this water was diverted to a self-balancing fluorometer, Turner Model 111, equipped with a continuous-flow door and strip-chart recorder. Two sampling techniques were used. For vertical profiles, the ship was hove to at the desired position and the pump was lowered in a stepwise fashion with sufficient time at each step to permit flushing of the hose. In the second method the pump was towed to measure the dye concentration at a given depth along a selected course. Horizontal sextant angles were used for determining the position of the ship. A combination of these methods made it possible to determine both the lateral and vertical spread of the dye patch. The results of this dye study have been discussed by Driggers (1964), and are reproduced in part below.

4.2. *Description of the Dye Injections*

4.2.1. *8 February 1961:* The first dye injection was made on 8 February 1961 from the RV *Brown Bear* anchored in the vicinity of station D-3. The wind was from the south-southeast at 18–25 knots (9–13 m/sec) and the tide was ebbing. A solution containing 10 kg (22 lb) of Rhodamine B dye was injected at the surface. The extremities of the dye patch were tracked visually from a small boat while vertical profiles of dye concentration were made from the *Brown Bear*. For the first 2 hr the dye patch moved west-northwest but veered to the northwest or nearly downwind as the tide slackened (Fig. 4.2). During the observation period the dye patch increased continuously in area (Table 4.1) and the dye concentration at its center decreased (Fig. 4.3). The water in this vicinity was practically homogeneous in the upper 12 m (40 ft), with an increase in density below that depth. This permitted quick vertical mixing of the dye to 12 m (Fig. 4.4).

4.2.2. *22 March 1961:* The second dye injection was made from the *Astor* near station B-3 as a surface release, using 6.4 kg (14 lb) of dye in solution. The initial spreading of the dye patch was observed but equipment failure prevented adequate delineation of the dispersion pattern. By the time repairs were made the dye patch had disappeared from the surface but was observed below the brackish layer from the Nooksack River.

4.2.3. *23 March 1961:* The third dye injection was made on 23 March 1961 at station B-3 from the *Astor* after a careful search of the area was made to ascertain that dye from the previous day was no longer present. Winds were from the south at 4–10 knots (2–5 m/sec) and the tide was ebbing. Ten kilograms (22 lb) of dye in solution were released at the surface at 1025. The patch was followed both visually and by instruments until 1320, when the dye was again covered by the Nooksack River water. Although the dye patch was fully covered by the freshwater layer, it was possible to detect the dye by towing the pump at 3 m (10 ft) depth. The dye patch was also visible in the ship's wake. The dye was found below 0.3 m (1 ft), the approximate depth of the surface layer. A drift pole planted in the center of the dye patch drifted to the

TABLE 4.1

Area of dye patches at various times

Time	Area of patch (km^2)
8 February 1961	
1240	Dye released
1330	0.028
1400	0.036
1430	0.069
1500	0.075
1600	0.092
1630	0.105
23 March 1961	
1025	Dye released
1100	0.064
1130	0.108
1200	0.116
1230	0.261
1320	Covered by river water

west and south, while the dye patch moved to the northwest at 45° to the left of the wind. Figure 4.5 shows the movement of the dye patch and drift pole during this observation period and Fig. 4.3 shows the change of concentration with time. The change in area of the dye patch is given in Table 4.1.

4.2.4. *12 July 1961:* The fourth dye injection was made on 12 July 1961 from the *Astor* by releasing 2.8 kg (6 lb) of dye in solution at the surface near station B-2. Winds were from the west at 6–12 knots (3–6 m/sec). Simultaneously, drift poles and drift sticks were released and tracked with the dye. The dye patch and sticks drifted together to the southeast past Post Point but the poles moved more slowly. By 1700 both the dye and the drift sticks collected in a tide line developed during the change from ebb to flood tide. After about 30 min the dye was almost completely dissipated. Figure 4.6 shows the spread of the dye patch and Fig. 3.8 shows the movement of the drift sticks.

4.3. *Results*

From these data Driggers (1964) computed the vertical diffusion coefficient for the first three dye injections to be 4 cm^2/sec. Data from studies by Pritchard and Carpenter (1960) indicate that the maximum concentration C of a dye after time t was given by the equation

$$C = kt^{-m} \tag{4.1}$$

where k is a constant. The results shown in Fig. 4.3 indicate an average value for the exponent m of 2.4 for upper Bellingham Bay. Driggers also calculated m for Lake Union as 2.2. Hela and Voipio (1960) obtained a value of 2.4 for the Gulf of Bothnia. Thus results for Bellingham Bay agree well with other available data.

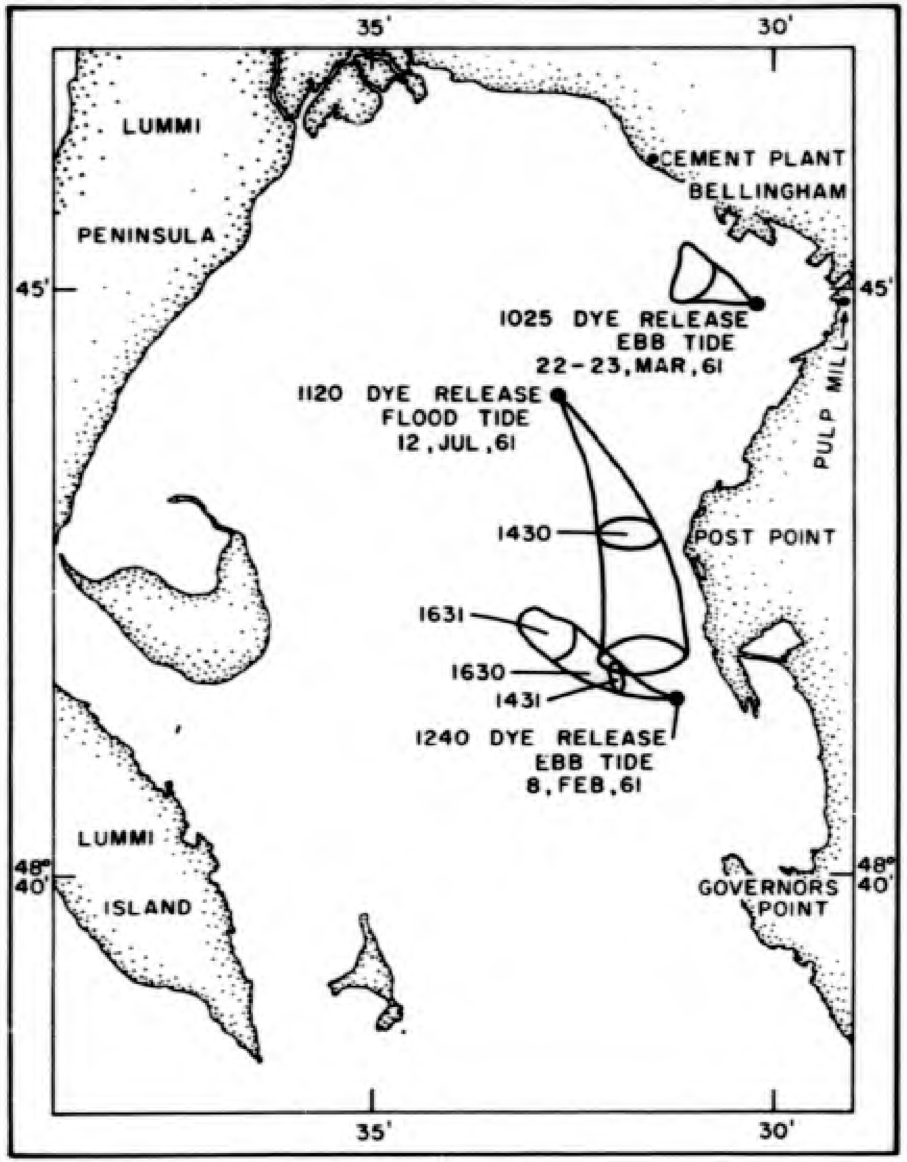

Fig. 4.1. Location of dye injections in Bellingham Bay.

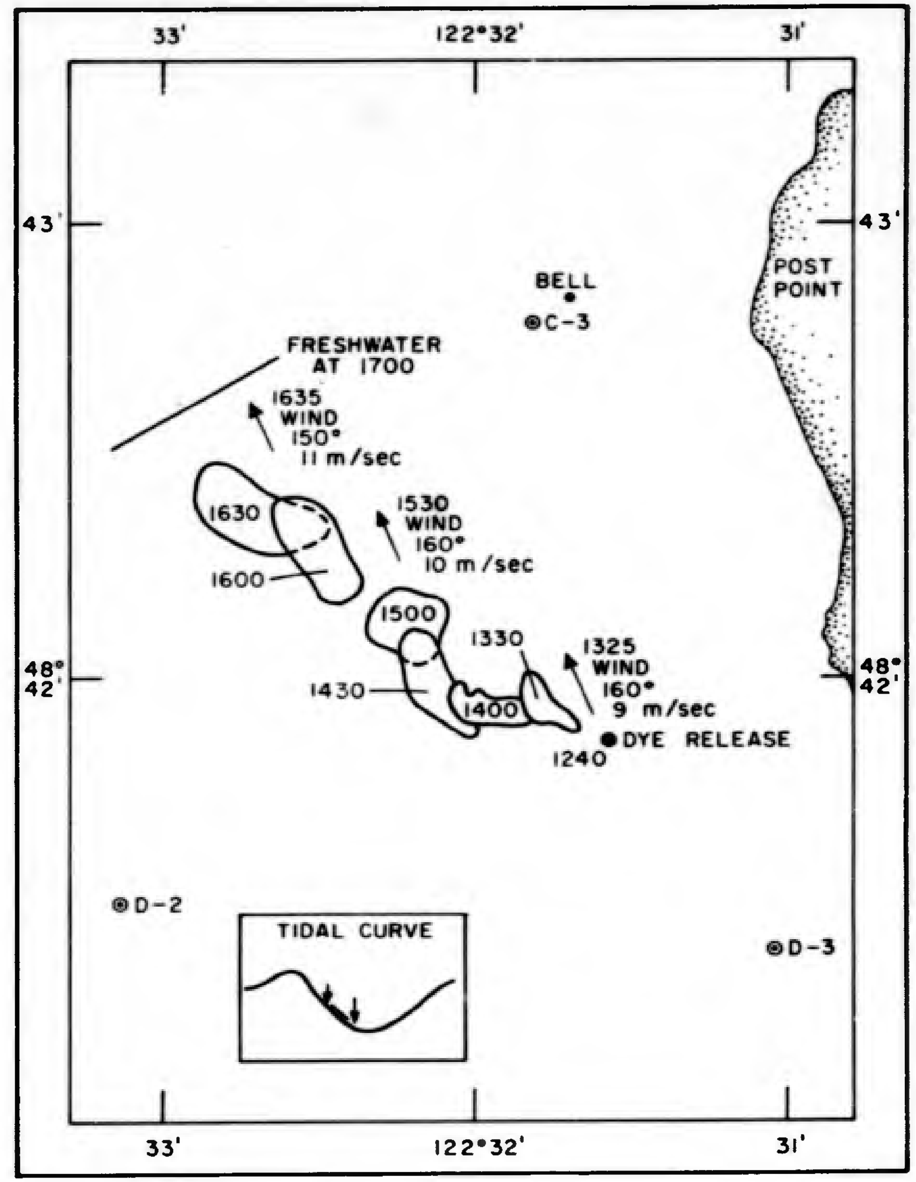

Fig. 4.2. Spread of surface dye injection, 8 February 1961.

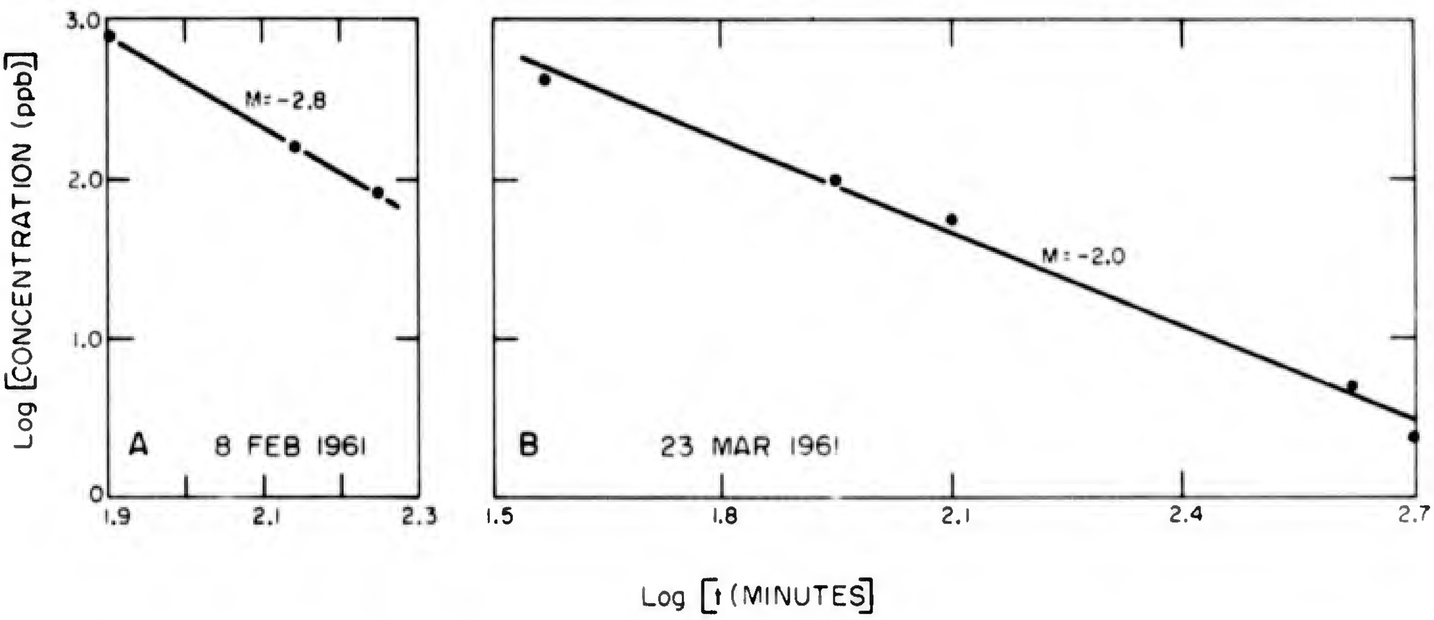

Fig. 4.3. Change of maximum concentration of dye with time, 8 February and 23 March 1961.

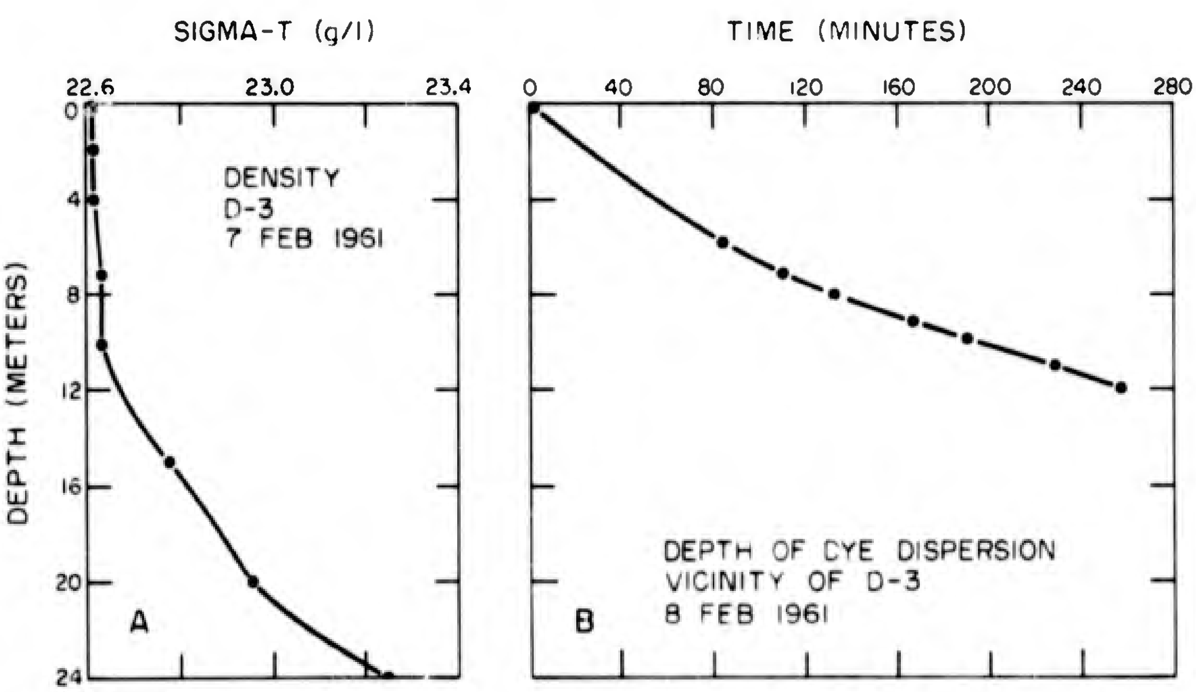

Fig. 4.4. Density distribution and depth of dye dispersion, 7-8 February 1961.

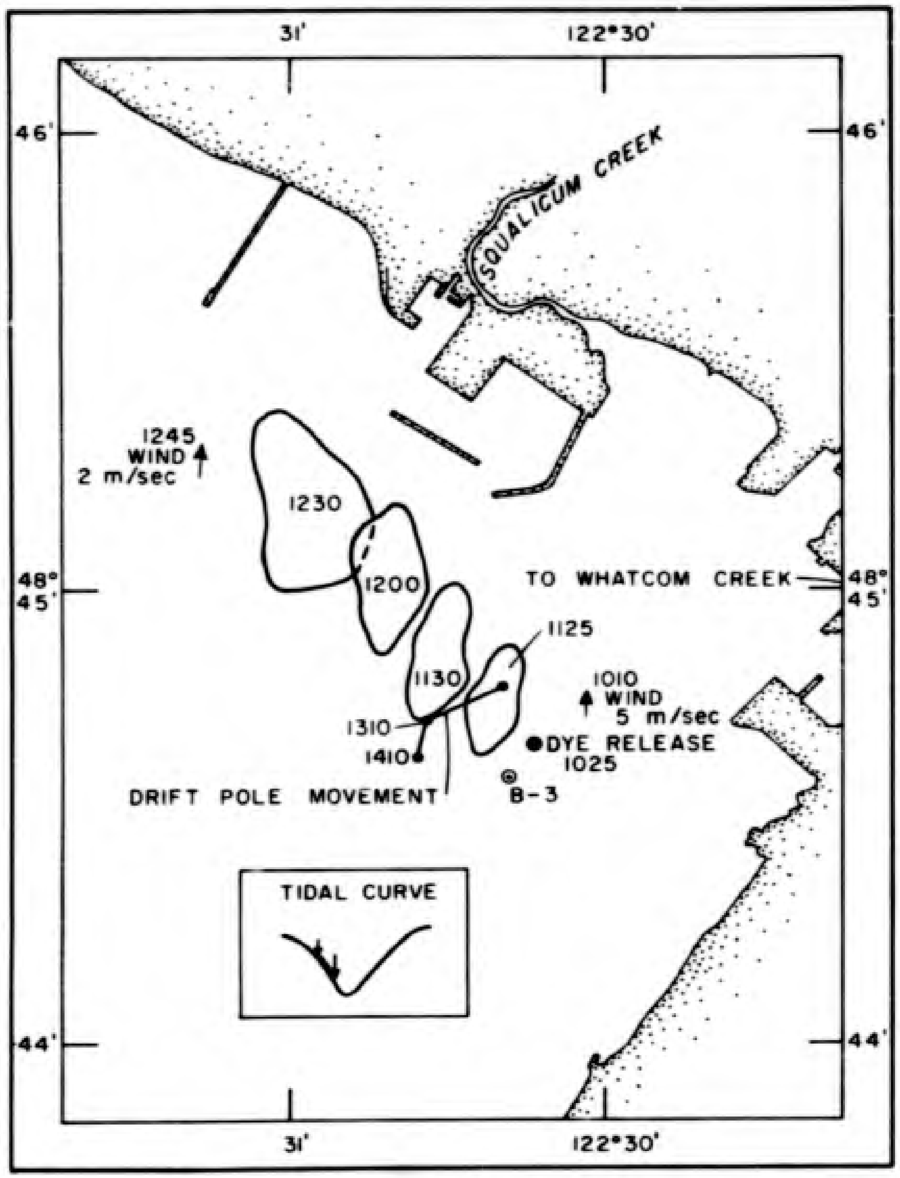

Fig. 4.5. Spread of surface dye injection, 23 March 1961.

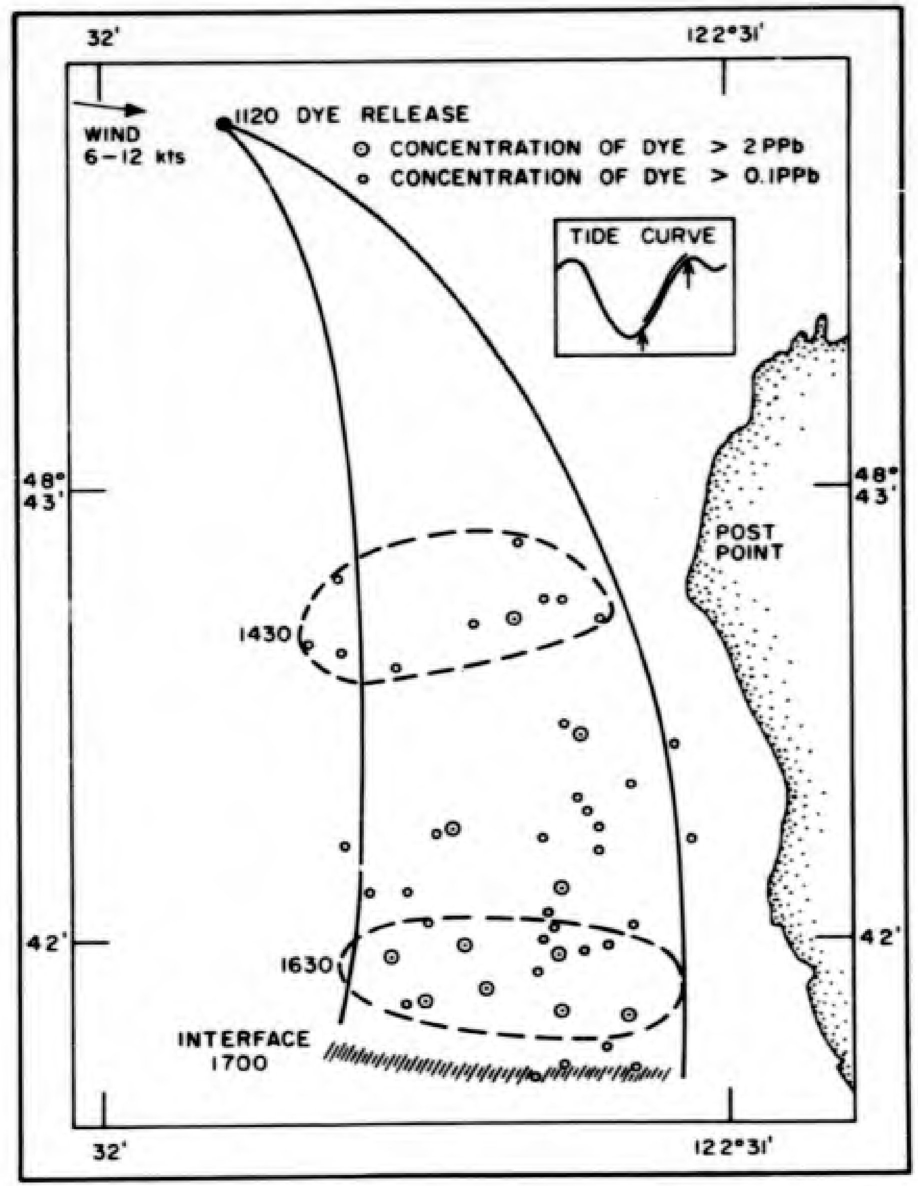

Fig. 4.6. Spread of surface dye injection, 12 July 1961.

5. FRESHWATER ACCUMULATION AND FLUSHING

5.1. *Introduction*

The method used to calculate the freshwater accumulation in Bellingham Bay was based on work by Tully (1949). In Tully's study, an estuary was considered to be a long, narrow body of water, with a river entering at the head the only freshwater source and the ocean at the mouth the only seawater source. It was also assumed that tidal action resulted in mixing of the river- and seawater so that the estuarine water contained a measurable amount of salt (Ketchum, 1951).

The investigation by Tully was applied to Alberni Inlet in British Columbia, a long and narrow fjord-type estuary with steep sides and a sill at its mouth. The mixing processes in this inlet were such that lateral gradients were very slight except close to the river mouth. A two-layer system was established in which an upper layer of low salinity water was separated from the deeper, more saline layer by a sharp boundary. The transport of mixed water and seawater was considered to be confined to the upper and lower layers, respectively. Strong winds blowing up or down the estuary caused small changes in the normal distribution pattern of freshwater, whereas changes in river runoff had a much greater effect.

The oceanographic and geographic conditions found in the Bellingham-Samish Bay system differ considerably from Alberni Inlet and waters first considered by Ketchum. For example, the large ratio of lateral to longitudinal dimensions in Bellingham Bay permits significant lateral gradients of water characteristics to develop. An estuarine analogy was applied by Ketchum, Redfield, and Ayers (1951) to the open coastal waters of the New York Bight, and by Ketchum and Keen (1955) to the open shelf waters between Cape Cod and Chesapeake Bay. Because Bellingham Bay is neither a "true" estuary nor open water, the mathematical approaches must be modified for application to this system.

From the presentation of the salinity distribution (see section 2.3) it is evident that the strongest salinity gradients in Bellingham Bay were found above 20 m (66 ft) regardless of external conditions. The maximum salinity at 20 m varied from 20.8 to 30.5‰ during the survey period, and within any given cruise the salinity range at this depth was less than 0.5‰ throughout Bellingham and Samish Bays. For the evaluation of freshwater accumulation, it was assumed that all the freshwater was confined to the upper 20 m and application of the estuarine analogy was made accordingly. This is equivalent to putting a false bottom at all stations where the water depth is greater than 20 m. A similar adaptation was suggested by Ketchum (1951).

In this chapter, the lateral profiles through stations A-1, A-2, and A-3; B-1, B-2, and B-3; . . . will be referred to as A, B, ... Longitudinal profiles through the stations suffixed 1, 2, and 3 will be referred to as 1, 2, and 3, respectively. Also, large inclusive areas beginning at the head of Bellingham Bay off the mouth of the Nooksack River and extending to the seaward limit of the last lateral profile considered will be designated as 0-A, 0-B, . . . (Fig. 5.1).

5.2. *Computations*

5.2.1. *Upper-Layer Depth:* The method devised by Tully (1949) was used to compute the upper-layer depth (H), the depth above which 90% of the freshwater was contained at any given station, for each station within Bellingham Bay on each cruise. The upper-layer depth was computed by first determining the proportion of freshwater (F_i) in the water column for each depth at the station from the equation

$$F_i = 1 - \frac{S_z}{S_r} \tag{5.1}$$

where S_z is the salinity at the depth z and S_r is the salinity at the reference depth z_r, taken as 20 m (66 ft) or the bottom if shallower than 20 m. Then the equivalent thickness of freshwater layers (ΔC_i) between successive depths was computed as

$$\Delta C_i = (0.5)(F_{i+1} + F_i)(\Delta Z) \tag{5.2}$$

where i indicates the shallower level, $i + 1$ is the next deeper level, and ΔZ is the distance between the two depths. The results from equation (5.2) were summed beginning with zero at the surface and continuing to the deepest sample in order to obtain the accumulated equivalent thickness of the freshwater layer (ΔC_z) as

$$\Delta C_z = \sum_{i=0}^{i=j} \Delta C_i \tag{5.3}$$

The fractional accumulation of freshwater to any depth (F_z) was computed as

$$F_z = \Delta C_z / \Delta C_r \tag{5.4}$$

where ΔC_r is the value of ΔC_z at the reference depth as obtained from equation (5.3). Finally, the upper-layer depth (H) was computed by linear interpolation to the depth at which the 90% value occurred in the data calculated from equation (5.4).

5.2.2. *Mean Salinity of the Upper Layer:* The mean salinity of the upper layer (S_u) was calculated from

$$S_u = S_r \, (1 - C_u) \tag{5.5}$$

where C_u is the mean concentration of freshwater in the upper layer as given by

$$C_u = (0.9)(\Delta C_r)/H \tag{5.6}$$

Because the mean salinity as computed from equation (5.6) was relative to the reference salinity S_r, which varied with station location and time, it was necessary to establish a common basis for further computations, hence a base salinity (S_b) was determined for each cruise and the remaining calculations were referred to this value.

5.2.3. *Base Salinity:* A base salinity of the source seawater was determined for each cruise by inspection of the salinity structure at stations G-1, G-2, G-3, and K-1. Usually the variations in salinity gradient at these stations were small, especially below 15 m (50 ft), so that a representative salinity for the deeper water at each station could be determined. These values were compared with the maximum salinity found at 20 m (66 ft) in Bellingham and Samish Bays, and the highest value was selected as the base salinity for that cruise. Table 5.1 presents the base salinities used for each cruise.

5.2.4. *Mean Concentration of Freshwater:* The mean concentration of freshwater (F_u) was computed for each station from the base salinity and the mean salinity in the upper layer by the equation

$$F_u = (S_b - S_u)/S_b \tag{5.7}$$

Hence irregularities in the reference salinity used for each individual station resulting from the many variables affecting the salinity of the source waters were reduced and seasonal variations were incorporated, giving a more realistic description of the freshwater in the bay.

5.2.5. *Freshwater Volumes:* Estimation of the volume of freshwater accumulated within Bellingham Bay must take into account the fact that the depths of samples used in the previous calculations were referred to the water surface and that the actual volume of water contained in the bay at any given time was dependent upon tide level. That is, calculations of the freshwater volume must be made in such a manner as to account for variations of tide height.

To estimate the volume of freshwater it was necessary to determine the volume of water contained within a small region surrounding each station. This was done by dividing the bays into small regions based upon the established stations and determining the volume of water at selected depth intervals.[8] It was assumed that the water characteristics observed at each station were representative of the region surrounding that station.

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[8]Details and results of the volume analysis of Bellingham and Samish Bays are presented in Appendix A.

TABLE 5.1

Base salinities used for computations in Bellingham Bay

Cruise[a]	Month and year	Base salinity (‰)
BB-243 (BLL-01)	November 1959	30.00
BB-257 (BLL-02)	April 1960	30.08
BB-262 (BLL-03)	May 1960	30.00
BLL-04	June 1960	29.95
BLL-05	July 1960	29.84
BLL-06	August 1960	30.00
BLL-07	September 1960	29.98
BLL-08	November 1960	30.54
BB-272 (BLL-09)	December 1960	30.00
BB-276 (BLL-10)	February 1961	29.97
BLL-11	March 1961	29.57
BLL-12	May 1961	29.81
BLL-13	July 1961	29.29
BLL-14	November 1961	30.48

[a]See Table 1.8.

For each station, the total volume of water in the upper layer (V_u), contained between the actual water surface, as determined from the tide height at the time of observation, and the bottom of the upper layer, was computed from the appropriate hypsographic curve.[9] The volume of freshwater in the upper layer (V_f) was then computed as

$$V_f = F_u \times V_u \tag{5.8}$$

For each lateral profile of three stations (A, B, · · ·) the volume of freshwater in the upper layer (P_f), and the volume of the upper layer (P_u) were summed as follows:

$$P_f = \sum_{i=1}^{i=3} V_{f_i} \tag{5.9}$$

and

$$P_u = \sum_{i=1}^{i=3} V_{u_i} \tag{5.10}$$

From these values a new mean concentration of freshwater ($\overline{C}_u$) in the profile was calculated as

$$\overline{C}_u = P_f/P_u \tag{5.11}$$

To determine the depth of the upper layer ($\overline{H}$) in the total profile, it was necessary to compute a hyposographic curve for each profile using the average tide height over the period of observations for the surface level. From this curve the depth corresponding to the volume of freshwater computed for that profile from equation (5.9) was determined and labeled ($\overline{H}$).

Finally, for each inclusive area (0-A, 0-B, · · ·), the volumes of freshwater and the upper layer were determined by summing the values

[9]A hypsographic curve is a plot of the accumulated volume of water contained within a body versus depth. The data in Appendix A were used to prepare these curves.

determined from equations (5.9) and (5.10) from the head of Bellingham Bay to the seaward limit of each profile. Then the concentration of freshwater in each inclusive area (C'_u) was determined from an equation analogous to (5.11), and the depth of the upper layer (H') for the inclusive area was determined in a manner similar to that for ($\overline{H}$).

Thus, by use of hypsographic curves, the bathymetry and tidal heights are accounted for; and by obtaining the mean concentration of seawater and the effective upper-layer depth for each profile and the entire bay as a weighted mean by volume, the resulting picture is more realistic than if simple arithmetic means of the various parameters had been used. Results of these calculations for the inclusive area O-C are presented in Table 5.2.

5.2.6. *Flushing Time:* The "flushing time" (t) of an estuary, as defined by Pritchard (1952), is the ratio of the total volume of freshwater contained within the system to the volume of river flow (R) per day (or in this case per tidal day[10]) so that

$$t = P_f/R \tag{5.12}$$

The flushing time for upper Bellingham Bay (inclusive area O-C) was calculated from the combined discharges of Nooksack River and Fishtrap Creek averaged for the seven days preceding each cruise. The results are listed in Table 5.2.

5.2.7. *Transport:* Ketchum, Redfield, and Ayers (1951) applied the estuarine analogy to the New York Bight and evaluated the amount of transport of fresh- and seawater across a section. They assumed that the amount of freshwater moving through any section of the upper layer was a function of the river flow and that the total volume of mixed water (V_m) moving seaward over a complete tidal day (T) is given as

$$V_m = R/C'_u \tag{5.13}$$

[10]A tidal day was taken to be the average period between two successive higher high waters, or 24 hr 52 min.

TABLE 5.2

Results of calculations of various parameters in Bellingham Bay for the inclusive area O–C

Cruise	Date	Upper layer depth (H') (m)	Volumes (10^6 m^3) Fresh-water	Upper layer	River runoff[a]	Flushing times[b] (hr)	Transports (10^6 m^3) Mixed	Counter	Nontidal drift (cm/sec)	Horizontal diff. coef. (10^6 cm^2/sec)
BB 243	Nov. 1959	10.8	35.4	420.2	9.40	94	111.6	102.2	1.80	2.59
BB 257	Apr. 1960	9.1	43.7	430.6	8.74	124	86.1	77.4	1.60	3.31
BB 262	May 1960	6.7	43.7	337.8	12.21	89	94.4	82.2	2.42	1.05
BLL 04	June 1960	5.4	31.2	308.3	12.54	62	124.0	111.5	3.91	c
BLL 05	July 1960	7.2	56.6	369.0	8.38	168	54.6	46.2	1.29	1.21
BLL 06	Aug. 1960	9.1	48.2	402.4	4.69	256	39.1	34.5	0.72	0.81
BLL 07	Sep. 1960	7.5	11.4	426.1	3.99	71	148.3	144.3	3.40	c
BLL 08	Nov. 1960	7.0	20.9	380.9	13.83	38	252.4	238.5	6.23	9.17
BB 272	Dec. 1960	9.7	11.0	518.8	11.37	24	536.3	525.0	9.42	13.33
BB 276	Feb. 1961	6.4	64.1	335.1	18.11	88	94.7	76.6	2.52	1.37
BLL 11	Mar. 1961	6.8	39.2	358.5	14.25	68	130.5	116.2	5.87	3.72
BLL 12	May 1961	7.4	23.5	424.2	9.08	64	163.6	154.5	3.81	4.60
BLL 13	July 1961	9.9	32.1	464.6	7.59	105	109.7	102.1	1.90	c

[a] River discharge rates are in 10^6 m^3 per tidal day averaged for the seven days preceding the cruise.

[b] Flushing times have been converted from tidal days to hours.

[c] When the distribution of freshwater concentration is nearly uniform over the entire bay or if wind and other causes have moved freshwater out of upper Bellingham Bay, it is possible to obtain a negative A_h. The values were not reported.

To balance this seaward transport of mixed water, the net counter-transport (V_s) of seawater through the section was the difference between the volume of mixed water and the river flow or

$$V_s = V_m - R \tag{5.14}$$

The net nontidal drift (*NTD*) of mixed water was

$$NTD = V_m/(TS_{u,n}) \tag{5.15}$$

where $S_{u,n}$ is the area of the section from the actual surface to depth of upper layer (H'). These calculations were made for upper Bellingham Bay to the seaward end of inclusive area 0-C. The results are presented in Table 5.2.

5.2.8. *Horizontal Diffusivity:* For a vertically homogeneous estuary, Stommel (1953) has shown that the net seaward flux of material across any section can be expressed as

$$F_x = Rc - SA\frac{dc}{dx} \tag{5.16}$$

where c is the concentration of material, S the area of the section being considered, A the eddy diffusivity, and x the distance along the axis of the estuary taken positive in the seaward direction. If freshwater is considered to be the conservative property then

$$F_x = R \tag{5.17}$$

and if the estuary is divided into equally spaced segments of length a, equation (5.16) can be expressed in a finite difference form to give for the nth segment

$$A_h = \frac{R2a(1 - C_n)}{S_n(C_{n+1} - C_{n-1})} \tag{5.18}$$

Since, in the case of Bellingham Bay, the segments were not equally spaced, the expression for eddy diffusivity becomes

$$A_h = \frac{2RL_-L_+(1 - C_n)}{[(C_- - C_n)L_+ + (C_n - C_+)L_-]S_{u,n}} \tag{5.19}$$

where C_n is the concentration of freshwater in the upper layer at segment n; L_- and L_+ are the distances between the preceding and following profiles; C_- and C_+ are the concentrations of freshwater in the upper layer at the preceding and following segments. This approach has been applied to stratified as well as vertically homogeneous systems. Then A_h expresses in terms of a single parameter the complex processes of diffusion and advection in maintaining the longitudinal salt balance in the estuary rather than solely horizontal diffusion as postulated by Stommel (1953). The mean horizontal coefficients of eddy diffusivity along the axis of Bellingham Bay to the seaward end of profile C are presented in Table 5.2.

5.3. *Freshwater Distribution*

Freshwater entering Bellingham Bay from rivers or other sources must eventually leave the bay through the upper layer as a mixture with seawater. The seawater is supplied by a counterflow of deeper, more saline water toward the head of the bay. In addition to the factors affecting the surface salinity distribution as discussed in chapter 2, the Coriolis effect[11] must be considered. In a narrow estuary Coriolis effect is negligible and lateral variations of properties are likely to be small. The nontidal flow is seaward in the upper layer and landward in the deeper layer. Also, the up- or down-estuary component of the wind may retard or accelerate the net flow of water and thus influence the distribution of freshwater. When the estuary is wide in comparison to length, as is the case with Bellingham Bay, the Coriolis effect may cause a lateral variation in the depth of the upper layer or even produce a circular motion in the water currents as opposed to

[11]Coriolis effect is the apparent change of direction in the path of any object in motion on the earth's surface due to the rotation of the earth. Coriolis effect is perpendicular to and directed to the right of the object's motion in the northern hemisphere. The magnitude is dependent upon the velocity of the object and the sine of the latitude, being most effective at the poles and zero at the equator.

a linear motion in narrow estuaries. Because the freshwater is confined to the upper layer, its distribution can be affected by the wind stress in two dimensions as well as by the Coriolis effect. The freshwater distribution and flow then become much more complicated than in a narrow estuary.

The computed mean distribution of freshwater F_u for each cruise, as determined by equation (5.7), are presented in Fig. 5.2 through 5.14. The amount of freshwater present in the water column at any given location varied from less than 1% to over 50% depending upon river flow and wind conditions. Usually most of the freshwater was observed along the north shore of Bellingham Bay with a marked decrease south of Post Point. When the winds were low (December 1960, March and May 1961) most of the freshwater was found along the west shore as would be expected from consideration of Coriolis effect. During periods of southerly and westerly winds the freshwater concentration increased in the northeast part of the bay. Frequently station B-3 exhibited anomalous values and appeared to be isolated from the remainder of the bay.

5.4. *Steady-State Dispersion Characteristics of the Inner Bay*

An analysis of the steady-state dispersion characteristics of inner Bellingham Bay[12] was made as a guide to the behavior of materials discharged into Bellingham harbor. Spent sulfite liquor (SSL) discharged into the northeast corner of Bellingham Bay is mixed into a layer 3–5 m (10–16 ft) deep and moved laterally from the head of the harbor by wind and tidal currents. Although there may be large transient variations of concentration, data gathered by the Survey Division of the Washington Pollution Control Commission during six weekly surveys during the summer of 1957 (Wagner, Ziebell, and Livingston, 1957) indicate that the mean concentration field is approximately radially symmetric about the point of discharge.

[12]Inner Bellingham Bay is considered to be those waters within 2 nautical miles (3.7 km) of the pulp mill.

The vertical scatter of points in Fig. 5.15 is an index to the departure of the concentration field from radial symmetry. The open circles on this figure represent data from stations in the northern half of the inner bay and the closed circles represent data from those in the southern half. Five of the six surveys contributing to the average values were made during flood tide. The distribution of tidal current on the flood tide described in section 3.4 accounts qualitatively for much of the scatter, and it is believed, therefore, that the actual mean concentration field is even more nearly radially symmetric than indicated in Fig. 5.15. The behavior of the field of mean concentration of SSL is therefore considered to be governed by isotropic horizontal diffusion of SSL outward in a cylindrical quadrant from a vertical line source of strength Q/D, where Q is the SSL discharge rate and D is the uniform depth of mixing.

Lindsay, Westley, and Woelke (1960) found the chemical half-life of SSL in seawater to be on the order of one week in an enclosed lagoon and several weeks in glass bottles. If SSL is dispersed rapidly relative to its rate of chemical decomposition, as it seemingly must be to avoid degradation of the marine environment when released in large amounts, then the mean concentration field can be assumed to satisfy the equation

$$\frac{d}{dr}\left[rK_h \frac{dP}{dr}\right] = 0 \tag{5.20}$$

where P denotes the Pearl-Benson index for SSL concentration, r is radial distance from the point of discharge, and K_h is a gross diffusion coefficient which, like that considered in section 5.2.8, coalesces all processes effecting the redistribution of the diffused material into a single parameter. The magnitude and spatial variation of such coefficients are known only in very general terms. It has been found that the magnitude of K_h increases with the size of the phenomenon observed. The literature on marine disposal contains many inferences to diffusion "laws" based on hypothesis, dimensional argument, or correlation of single values of K_h with size of phenomenon. These laws often have the form:

$$K_h \propto L^{\beta} \qquad (5.21)$$

where L is a length characteristic of the diffusion phenomenon and β is a constant between 1 and 4/3. This type of variation can be adapted to the present problem by writing

$$K_h = \alpha r^{\beta} \qquad (5.22)$$

where α is a constant. The general solution of equation (5.20) subject to the condition that P approach zero at great distance from the source is

$$P = \text{const } r^{-\beta} \qquad (5.23)$$

The concentration field of P observed in Bellingham Bay does not define β with any confidence. In fact, equation (5.22) does not adequately describe the field for any value of β. The observed mean concentration field between 0.5 and 3.5 km (0.27 and 1.9 nautical miles) from the source is reasonably described by the function

$$P = P_o \exp \frac{-r}{r_o} \qquad (5.24)$$

where r is measured in kilometers, r_o is 1.25 km (0.7 mile), and P_o is 685 ppm. A somewhat different approach will therefore be taken to interpret the data.

Integration of equation (5.20) and differentiation of equation (5.24) yields

$$\frac{dP}{dr} = \frac{C_1}{rK_h} = -\frac{P_o}{r_o} \exp \frac{-r}{r_o} \qquad (5.25)$$

where C_1 is an unspecified constant. It is required therefore that K_h must be of the form

$$K_h = \alpha \frac{r_o}{r} \exp \frac{r}{r_o} \qquad (5.26)$$

where α is a constant. The inferred form of K_h has a minimum value at $r = r_o$ and diverges at $r = 0$, probably becoming invalid at distances less than 1 km (0.53 nautical mile) from the SSL source. It is descriptive of what may be called the "far field" of P. The magnitude of K_h can be determined from the requirement that in steady state the flux of SSL across any cylindrical shell must equal the rate of SSL discharge into the harbor

$$Q = -\int_0^{\pi/2} D\rho P r K_h \frac{dP}{dr}\, d\Theta = \frac{\pi D\rho P_o \alpha}{2r_o} \tag{5.27}$$

where ρ denotes the density of seawater and

$$\alpha = \frac{2r_o Q}{\pi\rho P_o D} = 10\ \mathrm{m^2/sec} \tag{5.28}$$

The horizontal diffusivity computed from equation (5.26) therefore increases from about $3 \times 10^5\ \mathrm{cm^2\ sec^{-1}}$, becoming approximately equal to those computed for the section 0-C (Table 5.2) for the summer season at a distance of about 4 km (2.1 miles) from the SSL source.

There are inadequate data to model the "near field" closer than 1 km (0.53 mile) from the source. Concentrations of SSL in the near field probably depend strongly upon the mechanics of the discharge system and the density of the effluent; those in the far field should be determined primarily by natural mixing conditions in the bay and total SSL input.

The accumulation of SSL between distances r_1 and r_2 is easily calculated as

$$\sum \mathrm{SSL} = \int_0^{\pi/2} \int_{r_1}^{r_2} \rho P r\, dr\, d\Theta$$

$$= \frac{\pi}{2} D\rho P_o r_o^2 \left[\left(1 + \frac{r_1}{r_o}\right)\exp\frac{-r_1}{r_o} - \left(1 + \frac{r_2}{r_o}\right)\exp\frac{-r_2}{r_o}\right] \tag{5.29}$$

Figure 5.16 shows the accumulation in discharge days as a function of distance from the discharge point computed from equation (5.29). Extrapolation of the results from equation (5.24) all the way to the point of discharge is questionable, but the possible error arising therefrom can hardly exceed one-half discharge day. It is apparent that, on the average, SSL spends less than two days in the inner bay, which may be taken as justification for the omission of a decomposition term in equation (5.20).

It must be kept in mind that these computations are based on time- and vertically averaged concentrations. Vertical variations associated with the distribution of density and transient effects of surface winds may cause local variation of an order of magnitude or more from the average condition. The dashed line in Fig. 5.15, for example, shows the range of maximum concentration found at the surface during the six surveys providing the basis for this analysis.

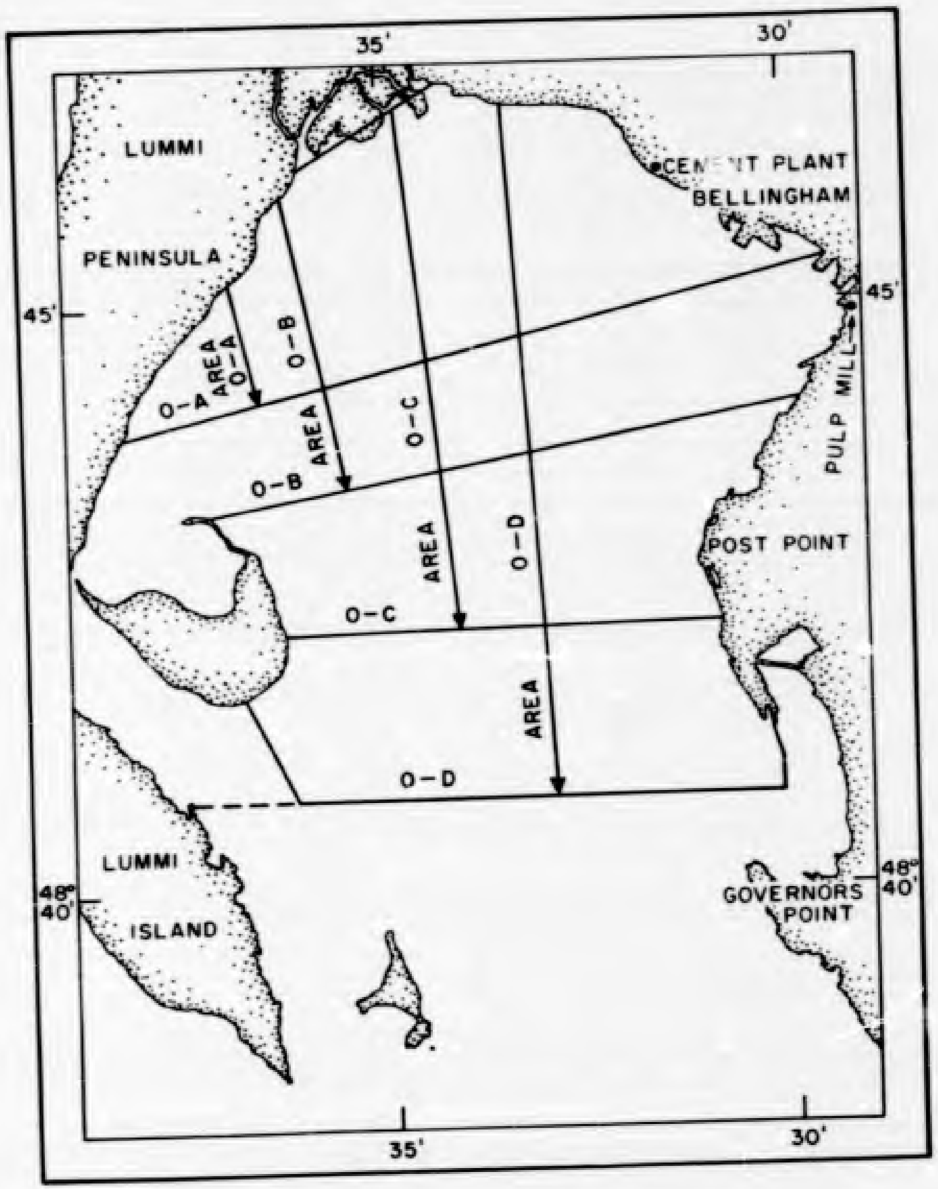

Fig. 5.1. Location of inclusive areas in Bellingham Bay.

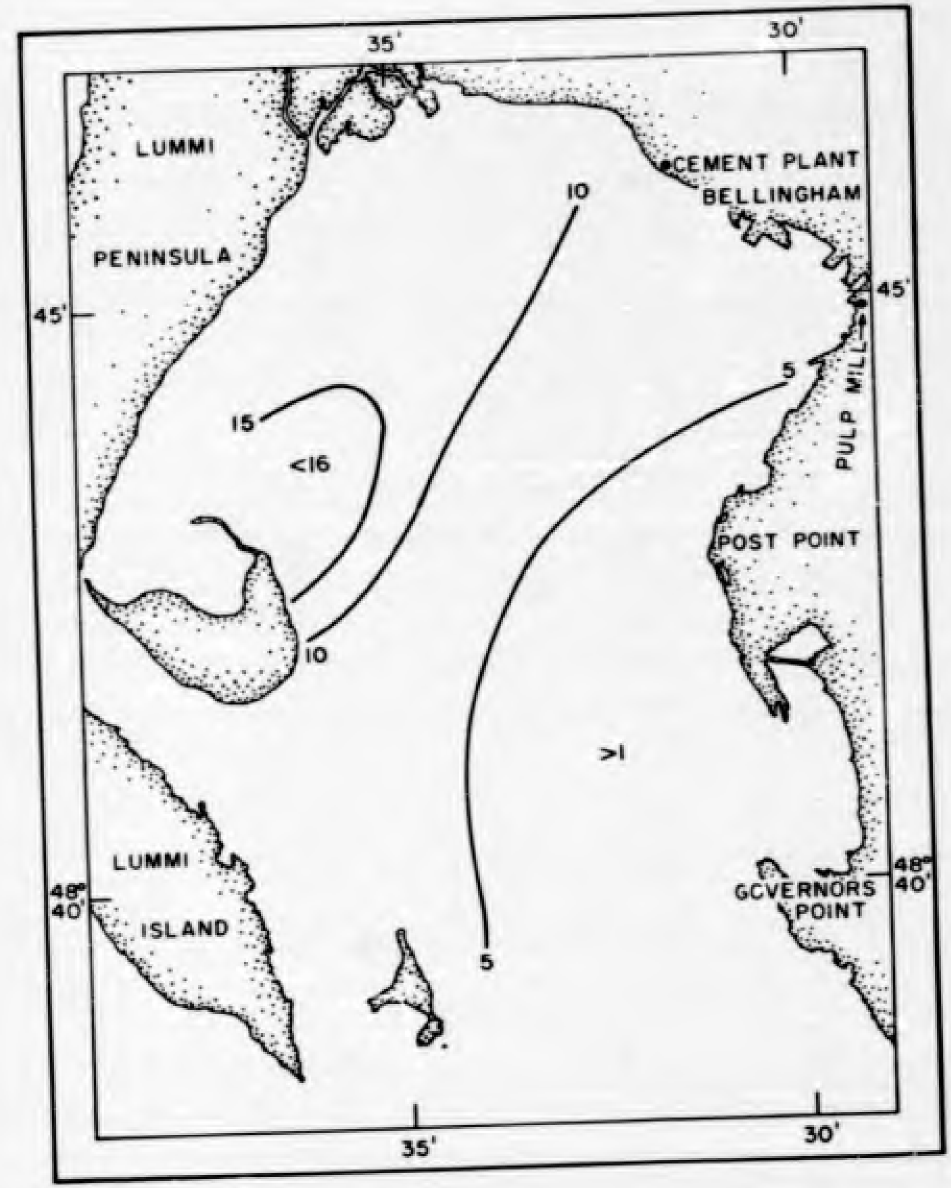

Fig. 5.2. Mean concentration of freshwater (as F_u, in percent), 2-4 November, 1959.

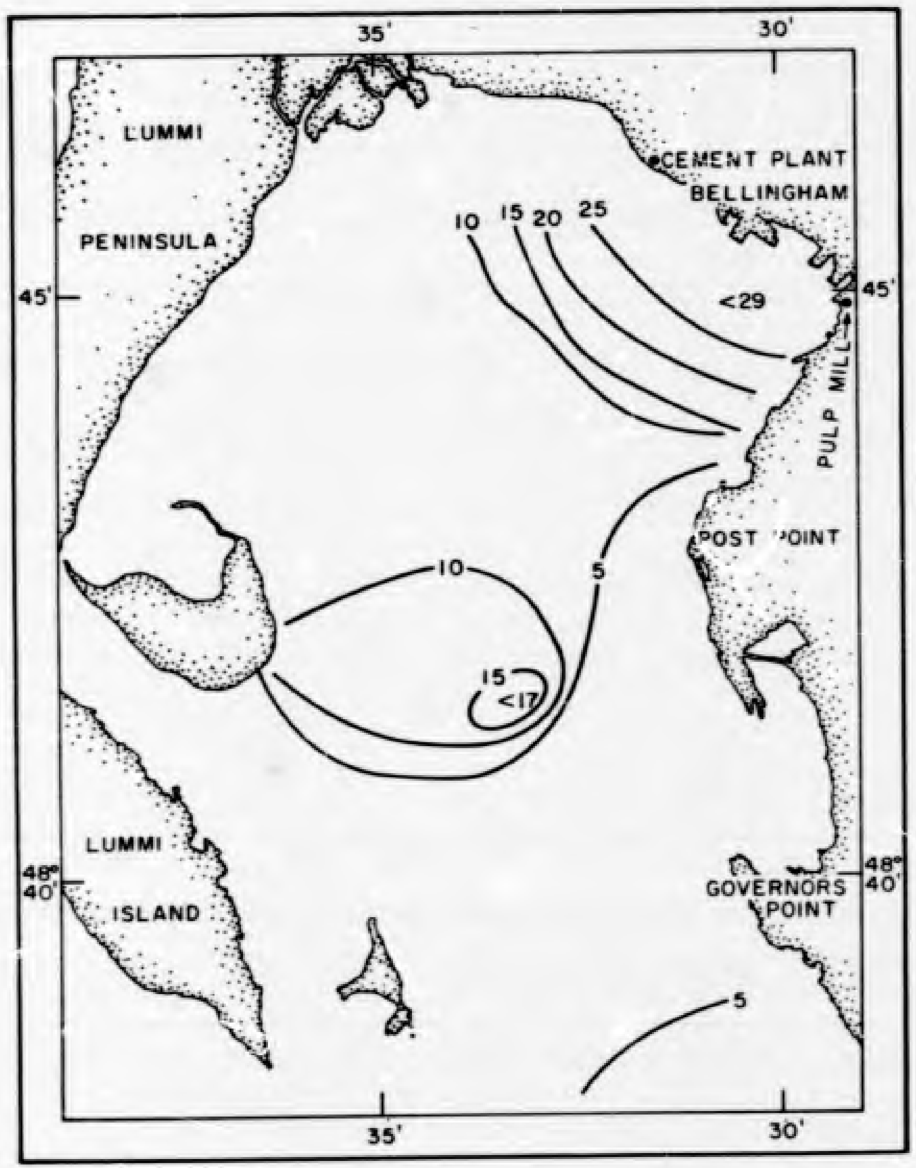

Fig. 5.3. Mean concentration of freshwater (as F_u, in percent), 19-21 April 1960.

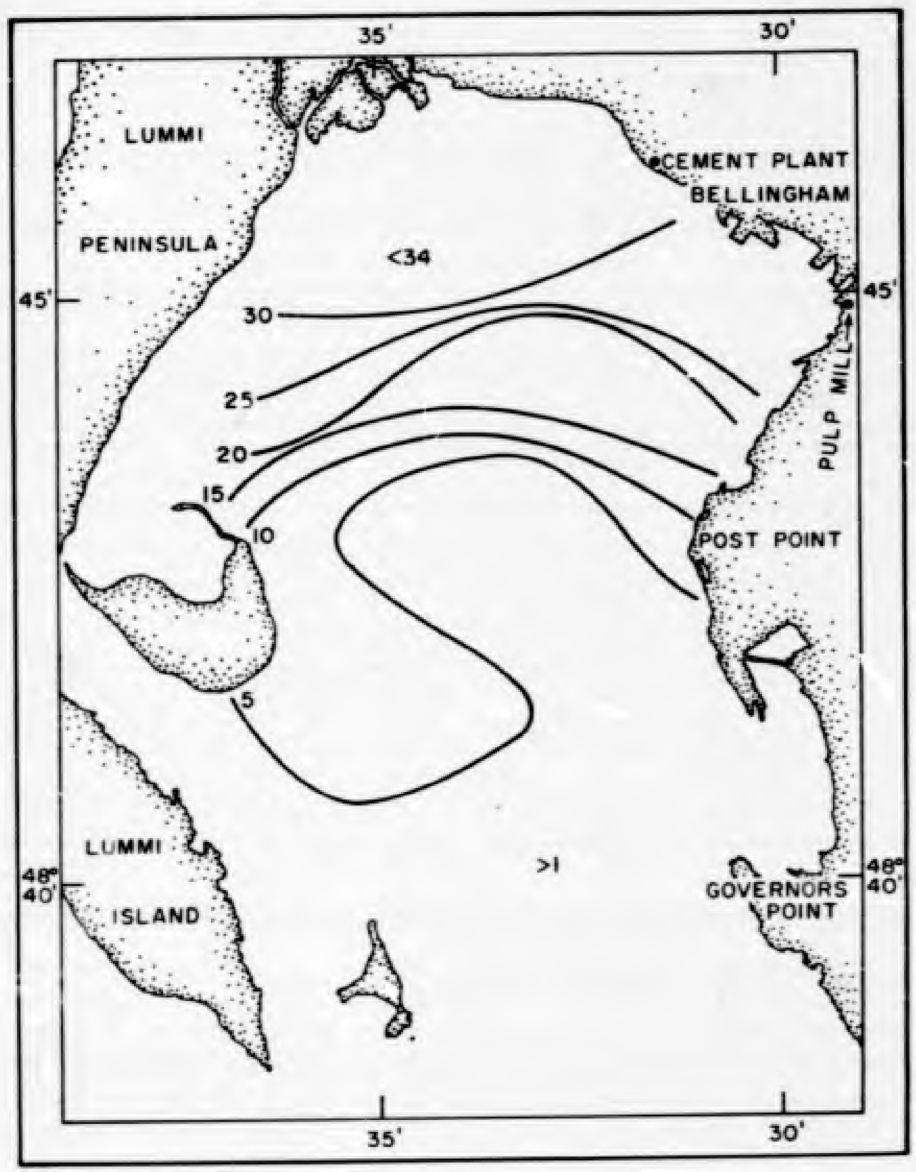

Fig. 5.4. Mean concentration of freshwater (as F_u, in percent), 20-22 May 1960.

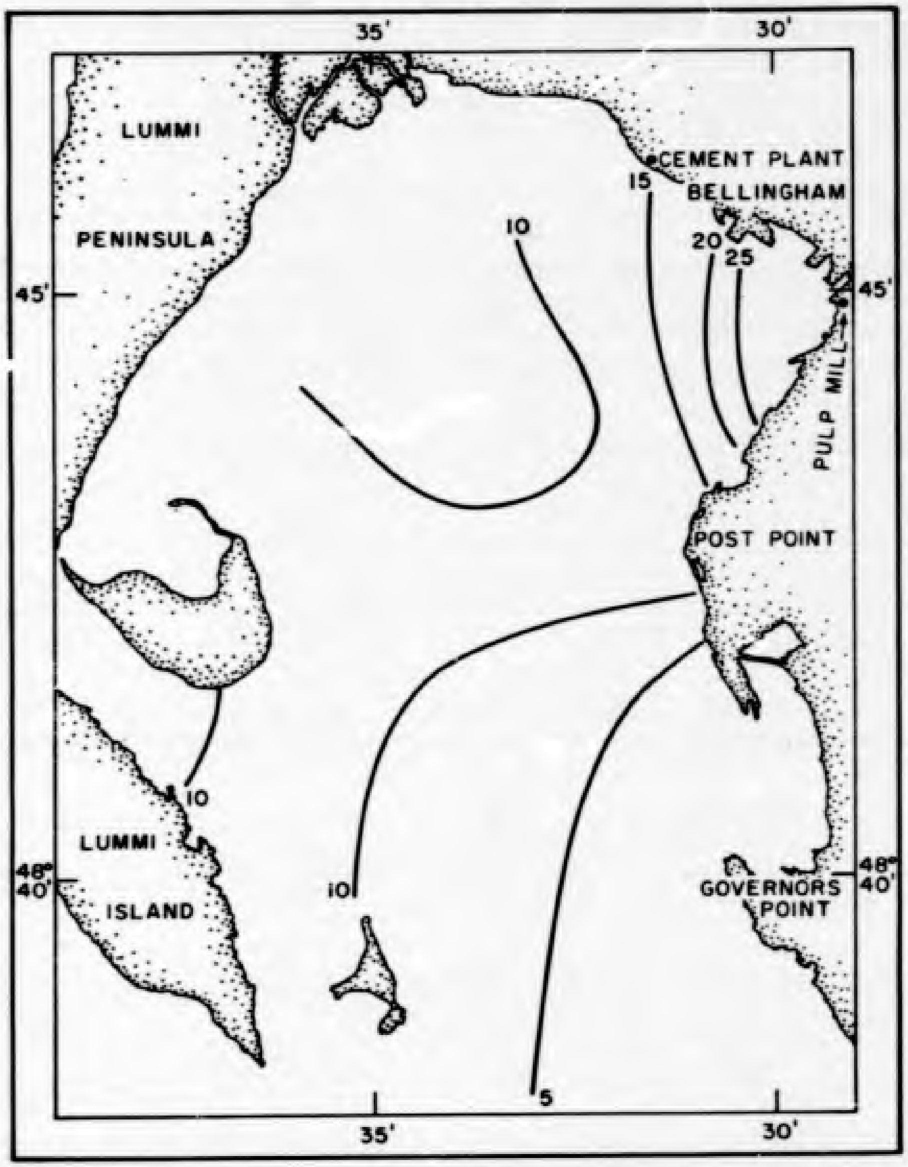

Fig. 5.5. Mean concentration of freshwater (as F_u, in percent), 21-22 June 1960.

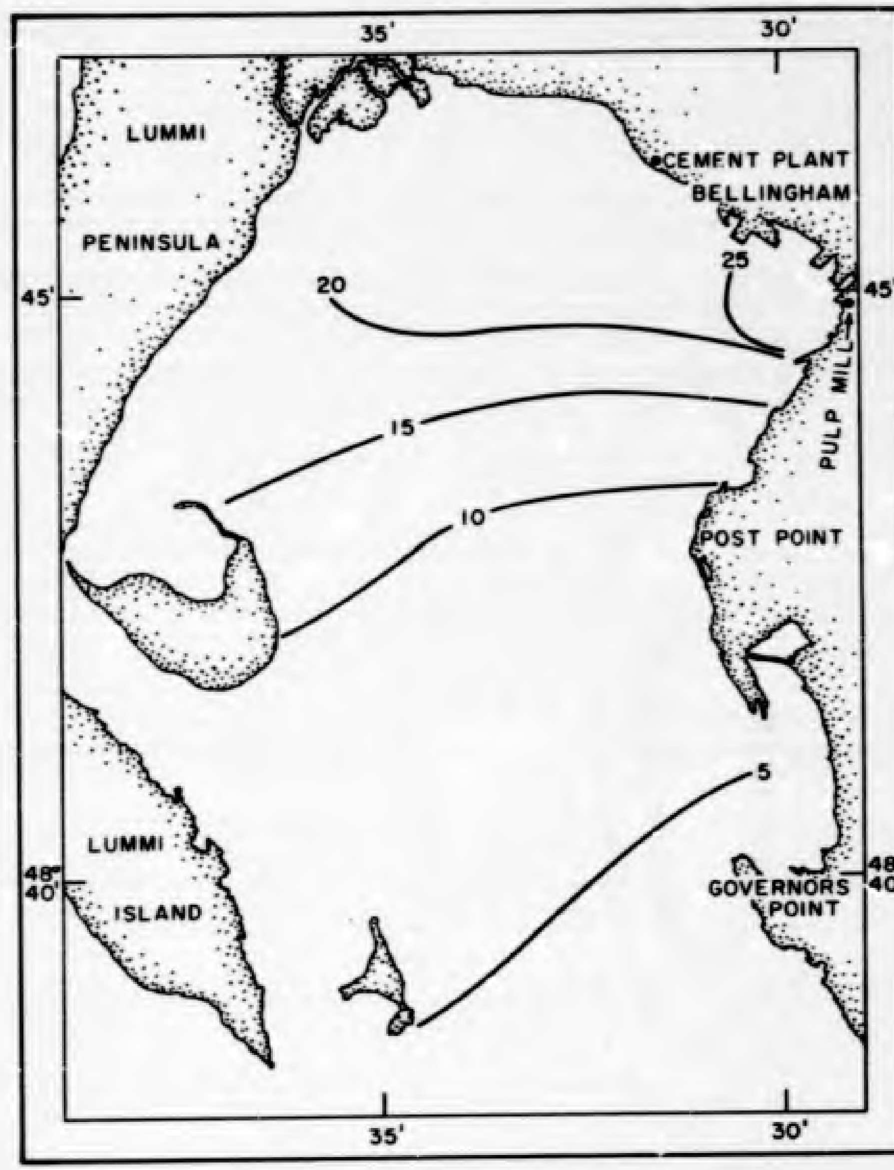

Fig. 5.6. Mean concentration of freshwater (as F_u, in percent), 18-19 July 1960.

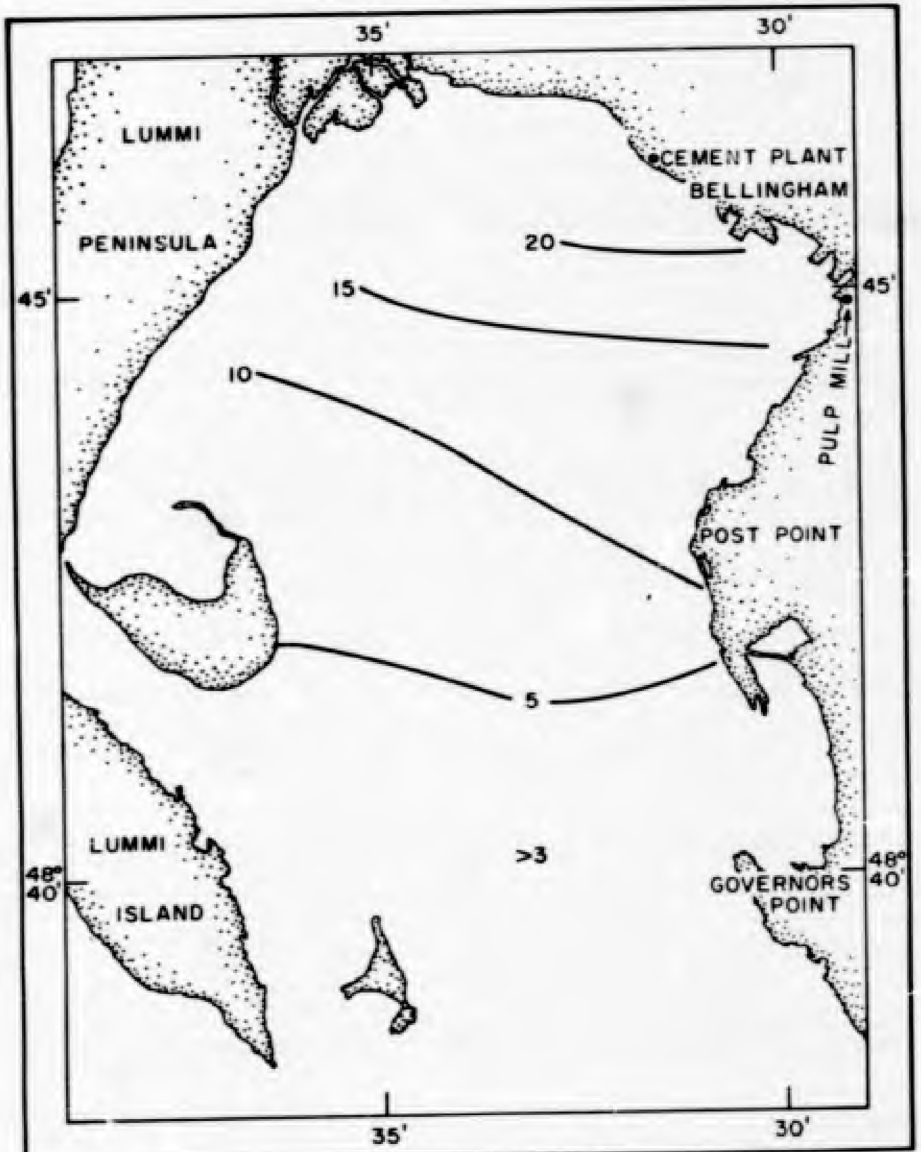

Fig. 5.7. Mean concentration of freshwater (as F_u, in percent), 23-24 August 1960.

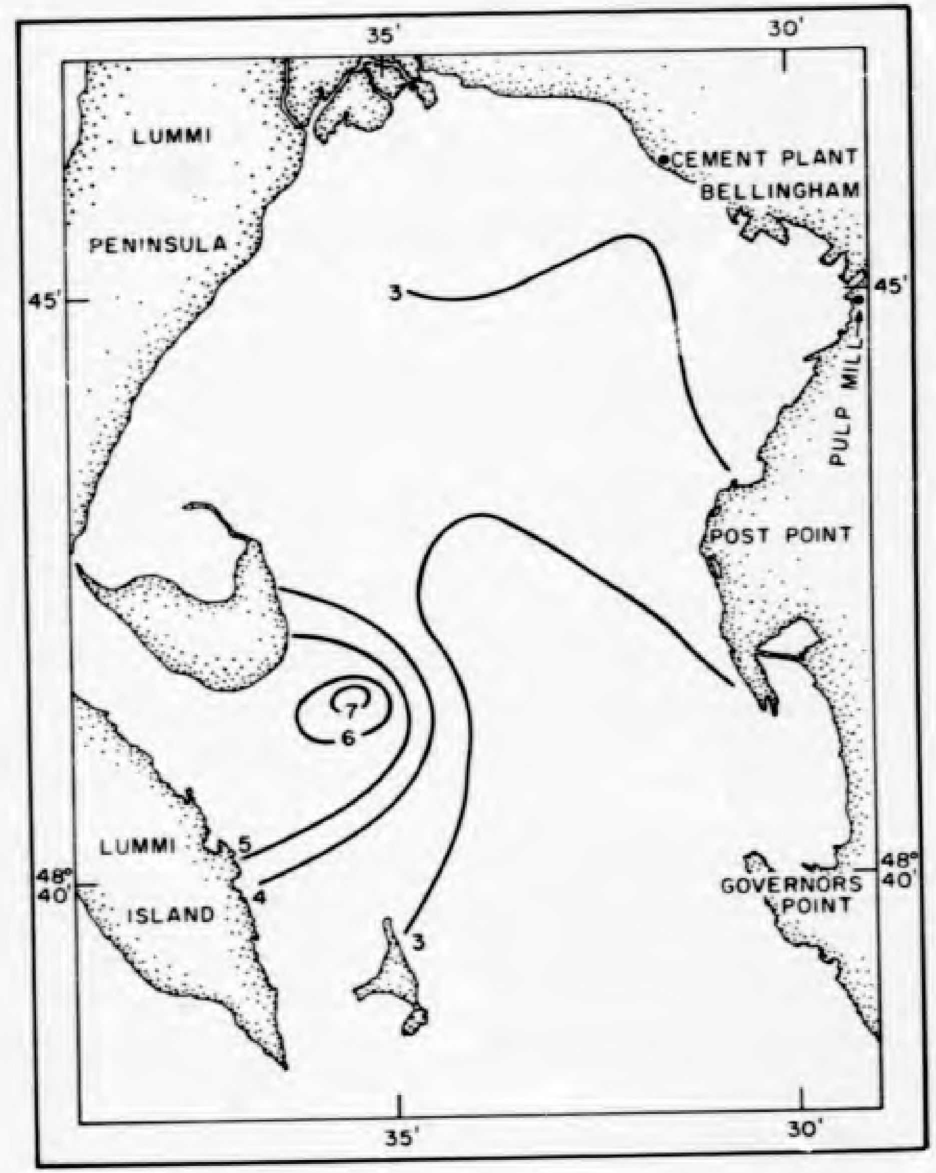

Fig. 5.8. Mean concentration of freshwater (as F_u, in percent), 28-29 September 1960.

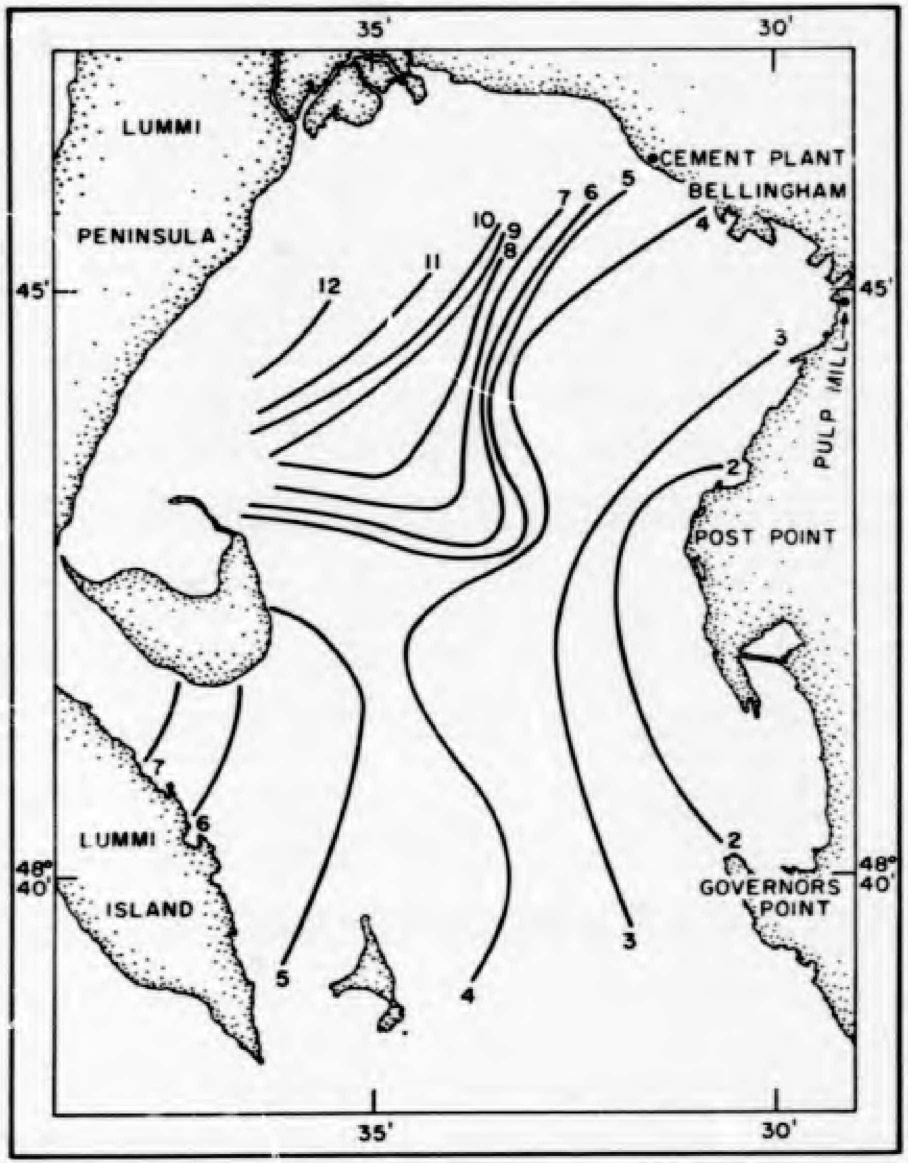

Fig. 5.9. Mean concentration of freshwater (as F_u, in percent), 3-4 November 1960.

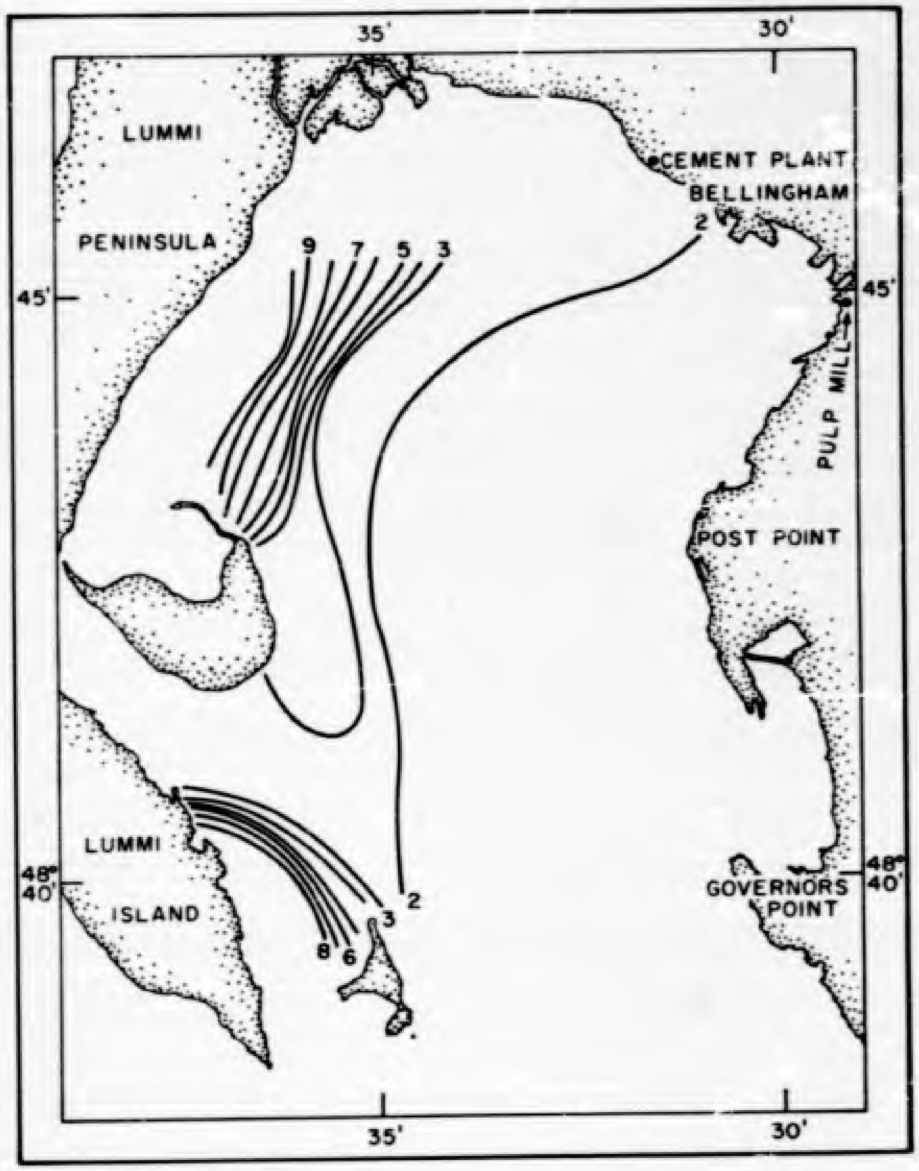

Fig. 5.10. Mean concentration of freshwater (as F_u, in percent), 16-17 December 1960.

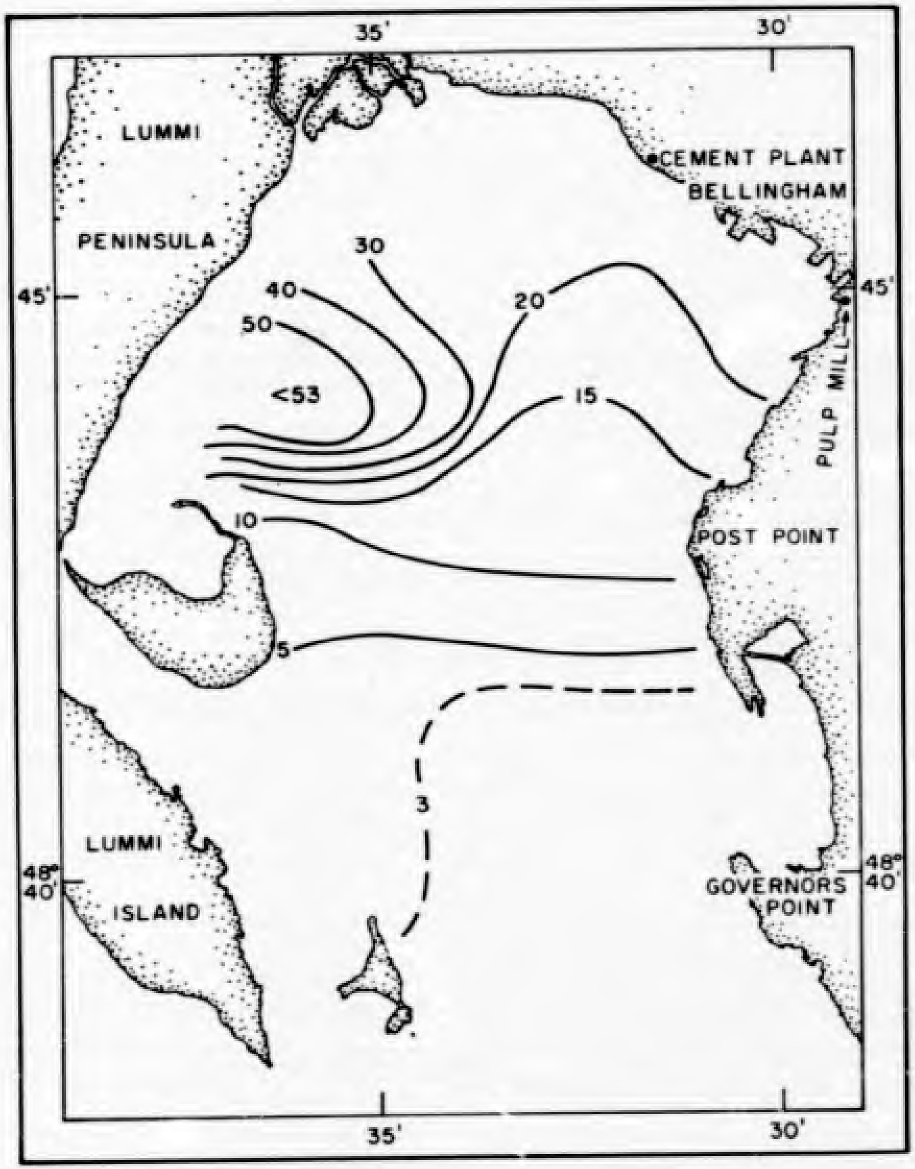

Fig. 5.11. Mean concentration of freshwater (as F_u, in percent), 6-7 February 1961.

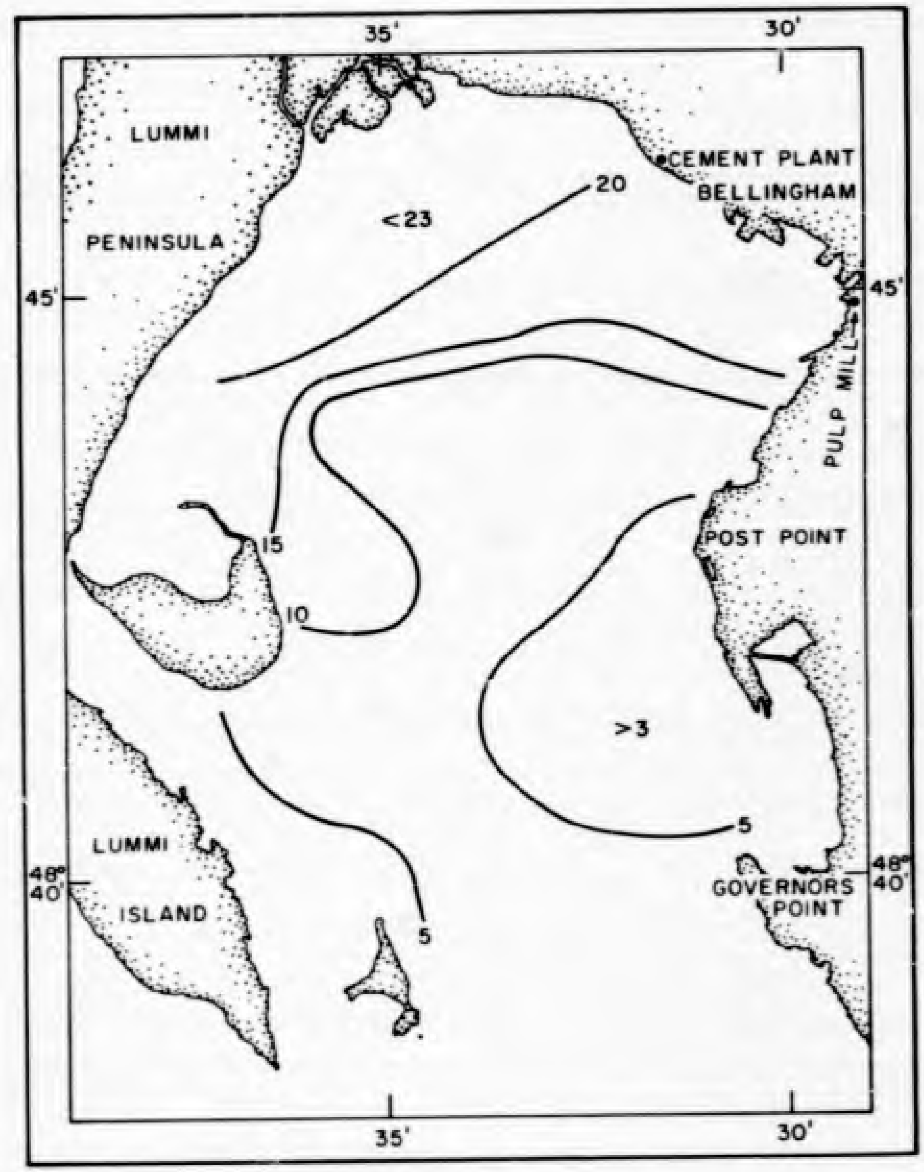

Fig. 5.12. Mean concentration of freshwater (as F_u, in percent), 20-22 March 1961.

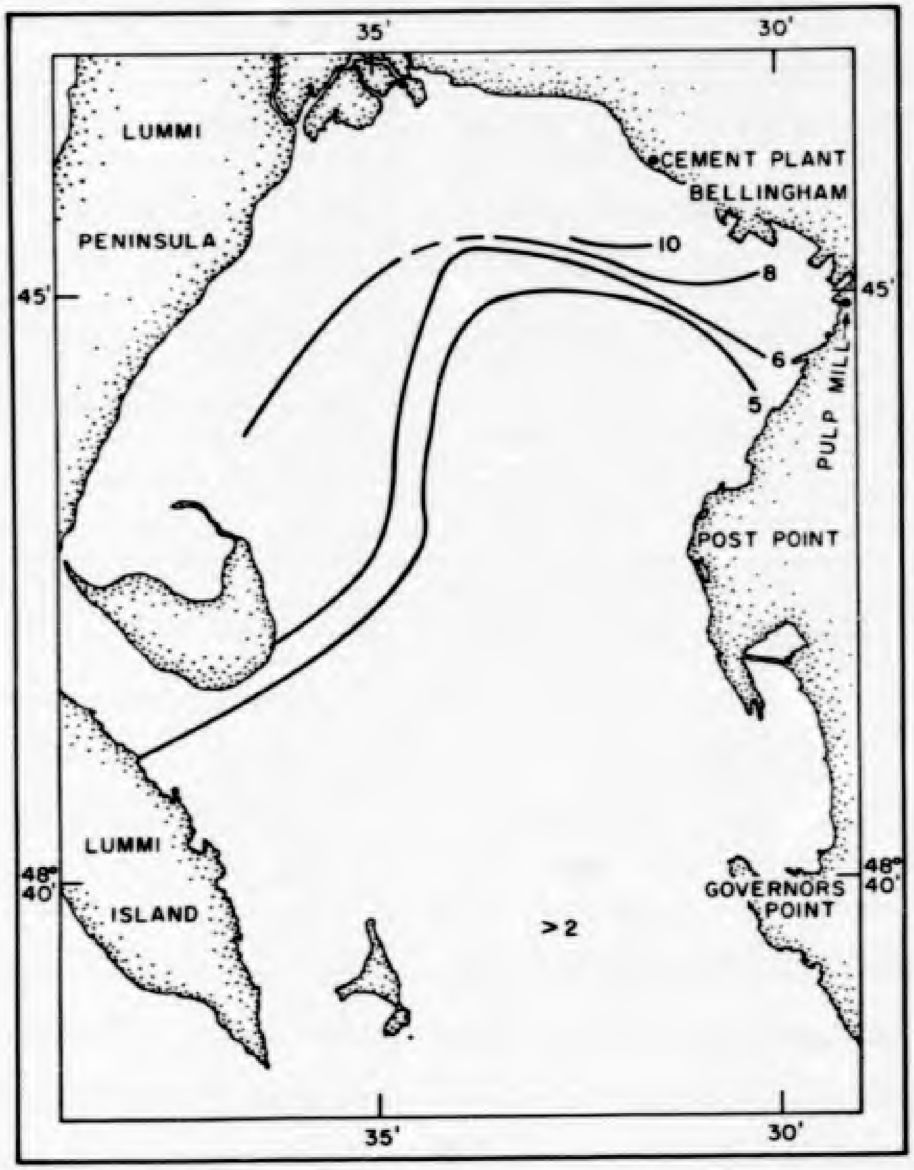

Fig. 5.13. Mean concentration of freshwater (as F_u, in percent), 15-16 May 1961.

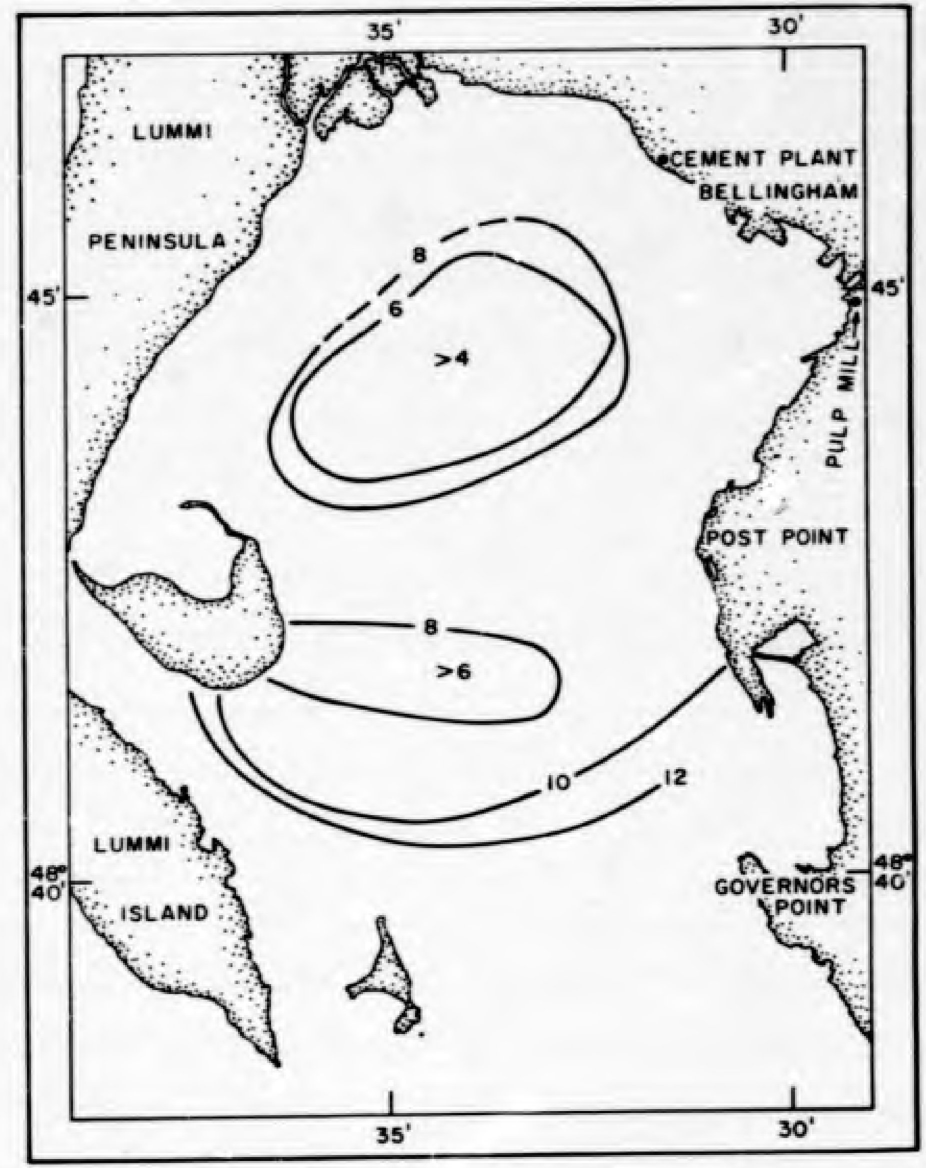

Fig. 5.14. Mean concentration of freshwater (as F_u, in percent), 10-11 July 1961.

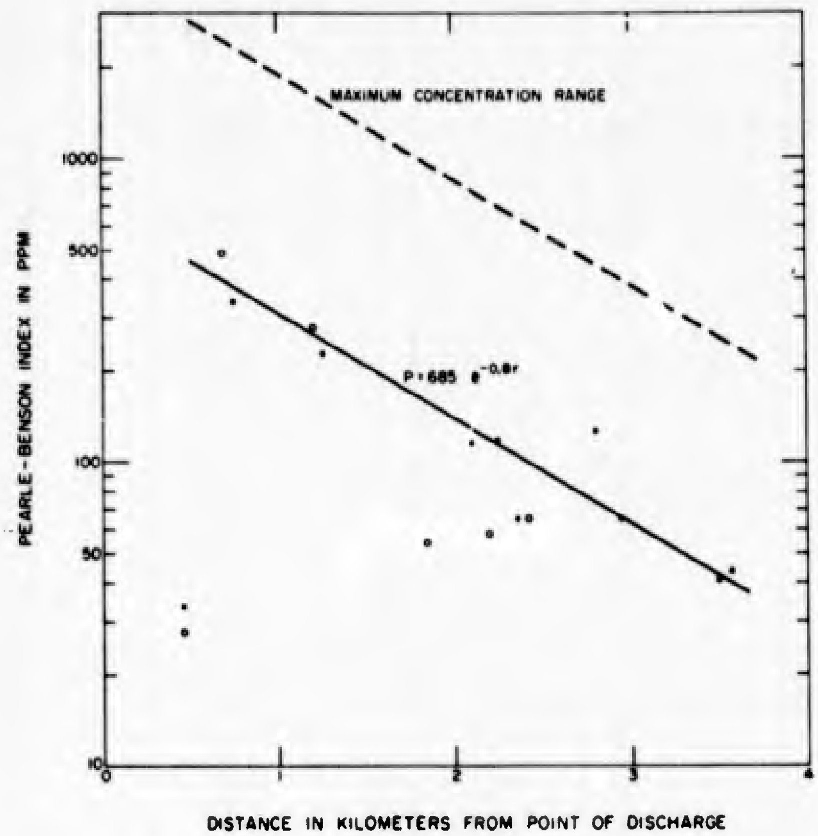

Fig. 5.15. Pearl-Benson index for SSL observed in inner Bellingham Bay during summer, 1957.

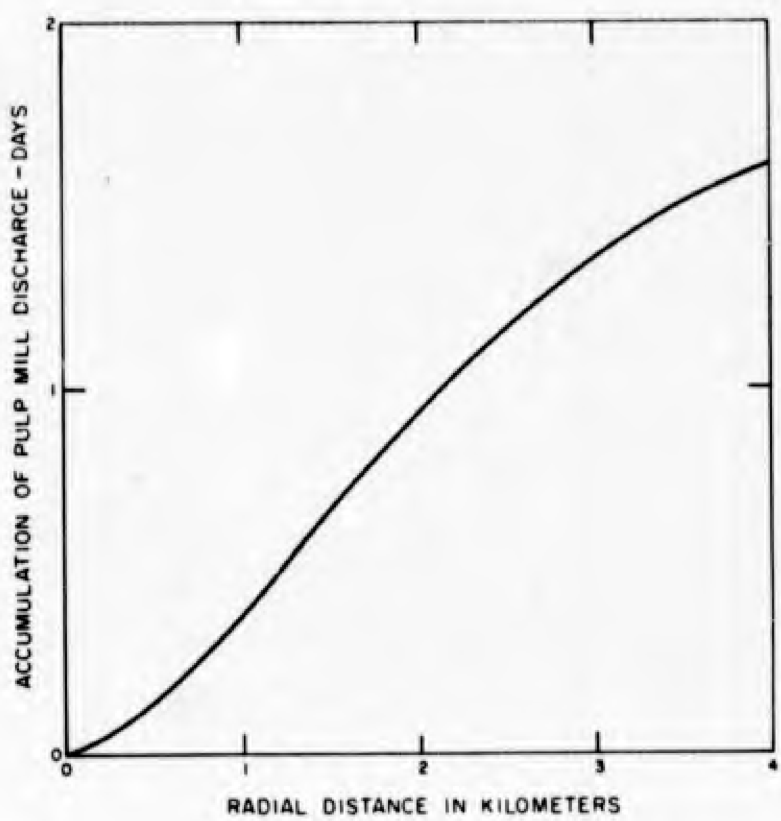

Fig. 5.16. Mean concentration of SSL as a function of radial distance from source.

6. GENERAL DISCUSSION AND CONCLUSIONS

6.1. *Salinity Distribution*

6.1.1. *Effect of River Discharge:* The Nooksack River is the dominant influence in controlling the surface salinity of the entire Bellingham-Samish Bay system, and is most influential in upper Bellingham Bay. The Samish River, being much smaller, dilutes the surface water locally in Samish Bay but has little effect elsewhere. The rate and duration of river discharge determine the depth of the fresher surface layer produced by each river. High discharge rates of the Nooksack River produce a thin, low salinity layer covering a considerable portion of upper Bellingham Bay. When the combined Nooksack River and Fishtrap Creek flows approached the average annual discharge rate, the resulting surface layer reached its maximum extent both horizontally and vertically. As the river flow decreased, the density difference between surface and deeper water decreased and the water column offered less resistance to vertical mixing. This produced a deep surface layer containing a considerable amount of freshwater. When the Nooksack and Samish River flows decreased to a minimum in late summer, the surface layer practically disappeared and the salinity observed throughout the entire bay approached that of Rosario Strait.

6.1.2. *Effect of Wind:* The effect of wind upon the waters of Bellingham and Samish Bays varies with direction, speed, and duration. As the wind moves the surface water away from one part of the system, a deep compensating counterflow is established. This counterflow is often cooler and more saline than the original water and may appear at unexpected locations within the system. Strong winds blowing from the southwest move the surface layer toward the head of the bay and deepen it near shore. When the winds subside, the deepened surface layer flows seaward at an accelerated rate until the system returns to equilibrium. On the other hand, northerly winds move the surface layer from the head of Bellingham Bay and may cause pockets of fresher water to form in the center of the bay. These statements also apply to Samish Bay if the wind direction differs by about 130° to the right. Thus a southeast wind may push the surface layer out of Samish Bay, while deepening the Nooksack River water and localizing it in the northwest portion of upper Bellingham Bay.

6.1.3. *Effect of Tide:* The tide stage and range influence the current velocities found in and near the system and also affect the location of the fresh- and seawater fronts or tide rips. Tidal currents generate turbulence which speeds the mixing of fresh- and seawater. They also primarily determine the short-term trajectories of waterborne substances. Although the number of data on tidal currents were minimal, a pattern for the flood current was inferred and presented in Fig. 3.10.

6.1.4. *Effect of Seawater Source:* The immediate source of seawater feeding Bellingham and Samish Bays is Rosario Strait, which in turn is influenced by the Strait of Juan de Fuca to the south and Georgia Strait to the north. The southern end of Georgia Strait usually exhibits a salinity maximum in October or November, and a surface salinity minimum in early summer during the peak runoff of the Fraser River. This runoff produces a surface layer in Georgia Strait that may at times enter Rosario Strait. Factors influencing the waters of the Strait of Juan de Fuca have been discussed in chapter 2 and will not be repeated here. Although Rosario Strait has two types of source waters, the relatively high currents and shallow depths cause the water to be mixed fairly uniformly from top to bottom, and as a result water characteristics may vary along its length. The value of any property at any location in Rosario Strait is intermediate between those at either end.

The salinity structures at a station off Lawrence Point in Rosario Strait and station G-1 off Viti Rocks indicate that the latter is usually about 0.1‰ fresher than Rosario Strait, but that the trend in salinity throughout the year is the same. As the salinity increases in Rosario Strait, the increase is reflected at depth in Bellingham and Samish Bays.

6.2. *Oceanographic Regions*

The concept of an oceanographic region is often useful in describing smaller elements of a larger system. All regions possess similar properties and are closely related. The boundaries may be either geographic in nature or due to circulation patterns, both tending to isolate portions of the system from each other. In Bellingham Bay, findings from the previous chapters indicate that five oceanographic regions may be established as follows (Fig. 6.1):

Region I, upper Bellingham Bay, north of lat 48°43' N
Region II, extending south of region I to lat 48°39' N, but excluding Hale Passage
Region III, the seawater supply region
Region IV, Samish Bay
Region V, Hale Passage

Each of these regions has distinguishing characteristics setting it apart from its neighbor; but it must be realized that the boundaries are not sharp, and they move depending upon external conditions. Region I is strongly influenced by the Nooksack River, receives the largest load of industrial and domestic wastes, and has the lowest current velocities observed within the system. It is possible to subdivide region I into two parts with the inner harbor (region IA) being somewhat different from the rest of this region. Region II is a transition zone between the supply region and waters of upper Bellingham Bay. Region III serves as a buffer between Bellingham Bay (region I) and Samish Bay. Water enters the system from Rosario Strait at this point and mixing of various waters occurs in this region. Region IV consists of the waters covering the extensive Samish tidal flats and the seaward edge of the bay. Hale Passage (region V) is considered separately because the sill extending from Point Frances to the northern tip of Eliza Island (see Fig. 1.3) isolates the water in this passage lying below 8 m (26 ft) from the deeper waters of region II, so that only the surface waters have free interchange across the sill.

6.3. *Spent Sulfite Liquor*

When the pulp mill effluent enters Whatcom Creek waterway, it mixes with salt water from the bay. The amount of mixing depends upon prevailing meteorological conditions, river flow, tide conditions, and other factors affecting surface salinity. Some SSL was observed throughout both Bellingham and Samish Bays on each cruise with the maximum amount always at or near station B-3 and the minimum concentrations at stations G-1, K-1, and J-1. Values greater than 10 ppm were rarely observed below 10 m (33 ft) depth, with most of the SSL being confined to the upper 5 m (16 ft). Of the 2200 SSL analyses made during this survey, 78% were 10 ppm or less, 20% were from 11 to 100 ppm, and only 2% were greater than 100 ppm. In water of salinity greater than 28‰ the SSL concentration was less than 10 ppm, except in 77 of the 1506 cases. Most of the higher SSL values were confined to the upper layer in the inner harbor (region IA) near the pulp mill and were associated with relatively low salinity water. Occasionally the SSL was discharged into higher salinity water. As this water moved into the central portion of upper Bellingham Bay it flowed beneath fresher water of lower SSL content (see Fig. 2.33 and 2.34).

6.4. *Oxygen Distribution*

The oxygen distribution in the bays is affected by the oxygen content of the source waters and by biochemical reactions. Below 10 m (33 ft) the dissolved oxygen concentration varied from 0.33 to 0.60 mg-atom/liter (5.2 to 9.6 ppm). High oxygen values in the surface layer during spring and summer reflect increased photosynthetic processes by phytoplankton. Near the pulp mill, low oxygen values were frequently the result of depletion because of the high chemical oxygen demand of the SSL, but this was a local situation. Normally the oxygen content of the entire area was greater than the 5 ppm minimum generally considered adequate for support of fish life.

6.5. *Disposition of Freshwater*

6.5.1. *Flushing Times:* An overall indication of the rate of mixing within an estuary is given by the flushing times determined from equation (5.12). The values obtained for upper Bellingham Bay (region I) varied from one to ten days with an average of four days. This determination gives an "average" time a particle of freshwater will remain in the upper layer before being removed from the system, but provides little insight as to the exact mechanism of mixing or transport of individual water particles. For example, the flushing time so computed may be in error when the surface layer is very thin and hence difficult to detect with conventional water-sampling techniques. In this case, the actual flushing time may be much less than the calculated value. A flushing time of about two days was computed for the inner harbor (region IA) using the SSL distribution during the summer months.

6.5.2. *Transports:* The volume of water transported in the upper layer depends upon the intensity of vertical turbulent mixing which in turn is dependent upon tidal currents and wind action. The salinity of the waters in upper Bellingham Bay increases from head to mouth establishing a pressure field that produces a nontidal flow toward the mouth of the bay in the upper layer and a counterflow at depth. The volume of water involved in the upper-layer transport (see section 5.2.7 and Table 5.2) is about ten times that of the river discharge entering upper Bellingham Bay during "normal" periods of runoff. Periods of high river discharge show a lowering in the ratio of transport in the upper layer to river flow to about five. This is because the freshwater spreads out into a much thinner layer and the increased vertical density gradients reduce vertical mixing. When the river discharge is low, vertical mixing is greater and the volume of seaward transport may be as much as 40 times that of the river flow for that particular period.

The resulting nontidal drift varied in strength from 0.03 to 0.18 knot (1.6 to 9.4 cm/sec) or less than one-tenth the tidal current. This is an average value for the entire upper layer at a section from Post Point to Point Frances and does not account for the fact that frequently the upper layer shows a marked tendency to favor one side of the bay and varies in depth across the section.

6.5.3. *Diffusivity:* The computed horizontal diffusion coefficients (see Table 5.2) combine the effects of all processes affecting the distribution of freshwater, including advection as well as turbulent mixing on all size scales. The values, therefore, are applicable for estimation of the dispersion of other substances that have distributions like that of freshwater.

The magnitudes of the diffusion coefficients for upper Bellingham Bay are comparable or somewhat larger than those computed for the James

River estuary, the Delaware River estuary, and other east coast estuaries (Kent, 1958), but are only one-fifth to one-tenth of that found for the Columbia River estuary (Hansen and Rattray, 1965). In the inner harbor of Bellingham bay substantially smaller values of horizontal diffusion were found, reflecting the smaller scale of processes effecting the redistribution of material in this more confined area.

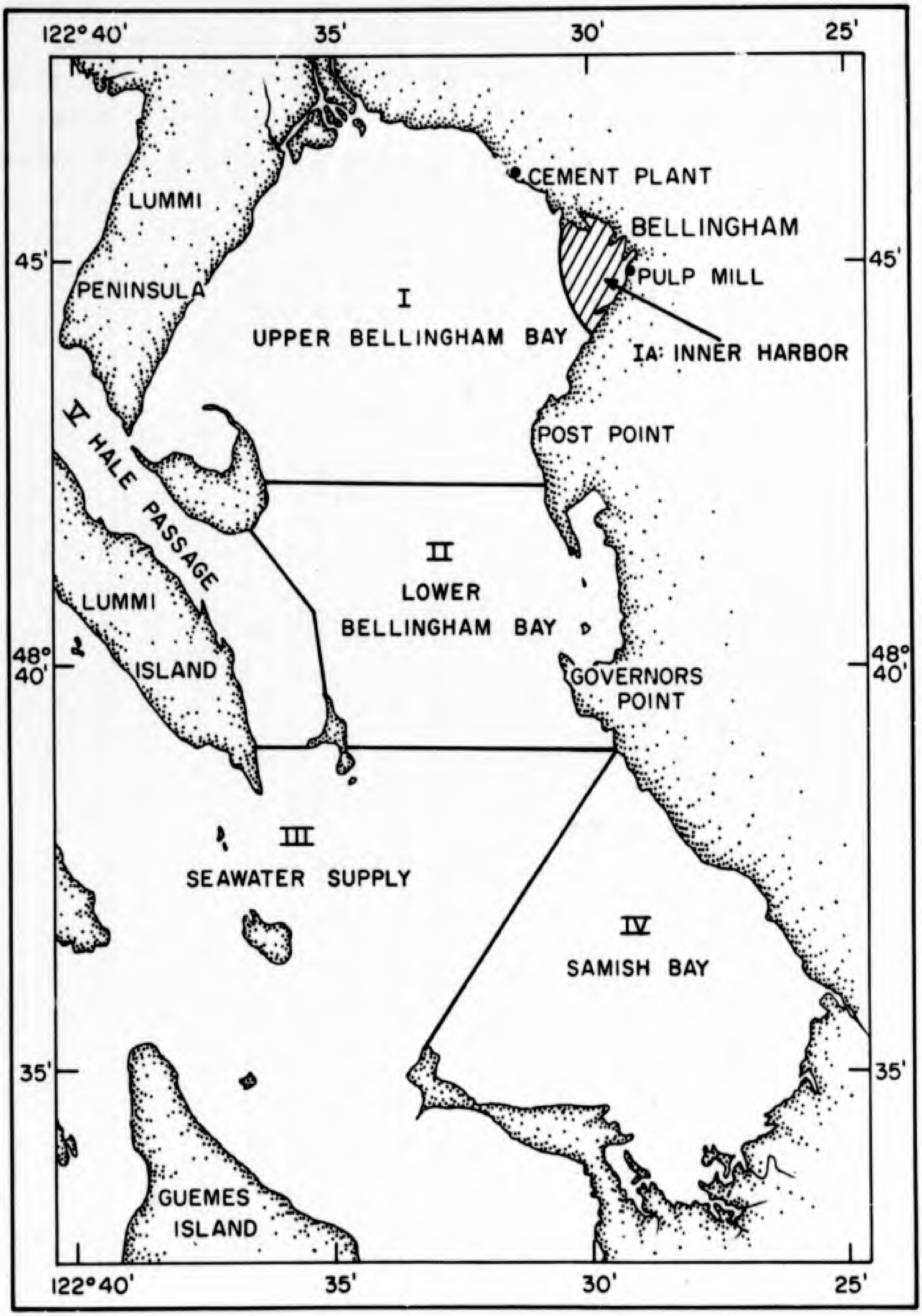

Fig. 6.1. Oceanographic regions in the Bellingham-Samish Bay system.

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APPENDIX A

AREA AND VOLUME ANALYSES OF BELLINGHAM AND SAMISH BAYS

The area analysis of Bellingham and Samish Bays was accomplished by first contouring a copy of USC&GS chart no. 6378 at depths of 5, 7, 13, 15, 20, 30, 40, 50, and 60 fathoms (9, 13, 24, 27, 37, 55, 73, 91, and 110 m). Contour lines at mean higher high water (MHHW), mean lower low water (MLLW), 3 fathoms (5 m), and 10 fathoms (18 m) were printed on the chart. Several squares, equivalent of exactly 2 nautical miles (3.7 km) on a side, were drawn at several locations on the chart. Then the water portion was divided into 26 subdivisions based upon the location of the oceanographic stations commonly occupied in the system (Fig. A.1). Next the area enclosed by a given contour within each subdivision was measured using a compensating polar planimeter; at least four readings were made along each contour. The "2-mile squares" were measured several times each day to check for changes in the dimensions of the chart due to change in weather. By following this procedure, the probable error in measuring the individual areas was reduced to about 1%. The actual water area enclosed within any given contour, however, was large because of the small scale of the chart (i.e., 1:40,000). Closely spaced soundings were not printed on the chart so the exact position of each contour line was estimated. The overall error in calculating the actual water area was less than 5%.

The volume of water contained within each subdivision was determined by plotting the area within each contour against the depth of that contour. The resulting curve was smoothed, and the area confined by that curve was equivalent to the water volume in that particular subdivision. Because the spacing between contour intervals was kept small in the upper 20 fathoms (37 m), it was possible to use an analytical method of obtaining the water volume, rather than the graphical method. The IBM 650 and IBM 709 computers were programmed to do the necessary computations.

A brief summary of the calculations is presented in Table A.1 and a listing of the volumes in the subdivisions at selected depths is presented in Table A.2.

TABLE A.1

Summary of area and volume analyses of the Bellingham-Samish Bay system

Area at MHW	225 km^2
Area at MLLW	179 km^2
Volume at MHW	4063×10^6 m^3
Volume at MLLW	3535×10^6 m^3
Tidal prism	528×10^6 m^3
Mean tide range	2.82 m
Average depth at MHW	18 m

TABLE A.2

Volume of water in each subdivision from listed depth to bottom

Subdivision	Values in 10^6 m^3									Maximum depth (m)
	MHW	MLLW	2 m	5 m	10 m	15 m	20 m	25 m	30 m	
A-1	40.55	22.75	14.04	3.87	0.24					12
A-2	53.62	34.00	25.96	15.03	4.32					15
A-3	50.59	31.72	21.83	9.54	1.42					13
B-1	108.5	81.79	68.43	48.38	27.55	12.39	3.11			24
B-2	129.9	113.6	101.1	82.47	51.38	23.74	5.81			24
B-3	61.56	46.45	36.89	22.53	7.27	1.58				18
C-1	106.7	94.19	85.42	72.26	52.20	32.34	14.39	2.41		27
C-2	235.0	214.1	198.1	174.2	134.2	94.33	54.41	17.23		29
C-3	160.3	141.7	127.8	107.0	75.11	47.61	23.35	7.10		29
D-1	164.0	147.8	135.8	117.9	90.03	64.53	39.80	17.60	4.47	33
D-2	201.7	183.1	168.9	147.6	112.1	76.61	41.12	11.80		29
D-3	124.6	111.6	101.8	87.09	63.23	39.44	16.26	2.86		28
E-1	274.6	235.6	208.2	167.1	110.8	68.32	33.81	14.57	3.77	44
F-1	132.6	114.9	102.0	82.7	54.36	31.39	12.58	3.82	2.22	44
F-2	307.2	277.5	255.3	222.0	168.6	120.8	78.20	48.62	33.19	84
F-3	133.1	116.8	104.6	86.3	56.75	30.19	8.75			24
G-1	1536.	1452.	1391.	1299.	1153.	1012.	878.1	751.6	639.7	108
G-2	840.7	789.6	751.2	693.5	598.9	507.7	423.6	350.1	295.7	115
G-3	152.0	128.7	110.8	84.03	39.40	10.00	0.12			22
G-4	160.7	141.8	127.4	105.8	69.73	34.17	10.35	0.69		29
G-5	211.9	194.6	181.5	161.9	129.9	99.02	70.55	46.49	29.89	59
G-6	595.4	524.5	478.5	410.2	303.6	208.5	129.5	73.64	47.11	70
H	81.11	25.63	11.77							5
H-1	70.91	54.82	44.29	29.87	11.99	1.67				17
H-2	104.5	86.10	72.22	52.02	23.08	3.45				17
H-3	113.1	92.00	78.13	58.74	31.53	10.85				20
CHK	43.54	34.73	28.93	20.24	8.29	2.13	0.10			24

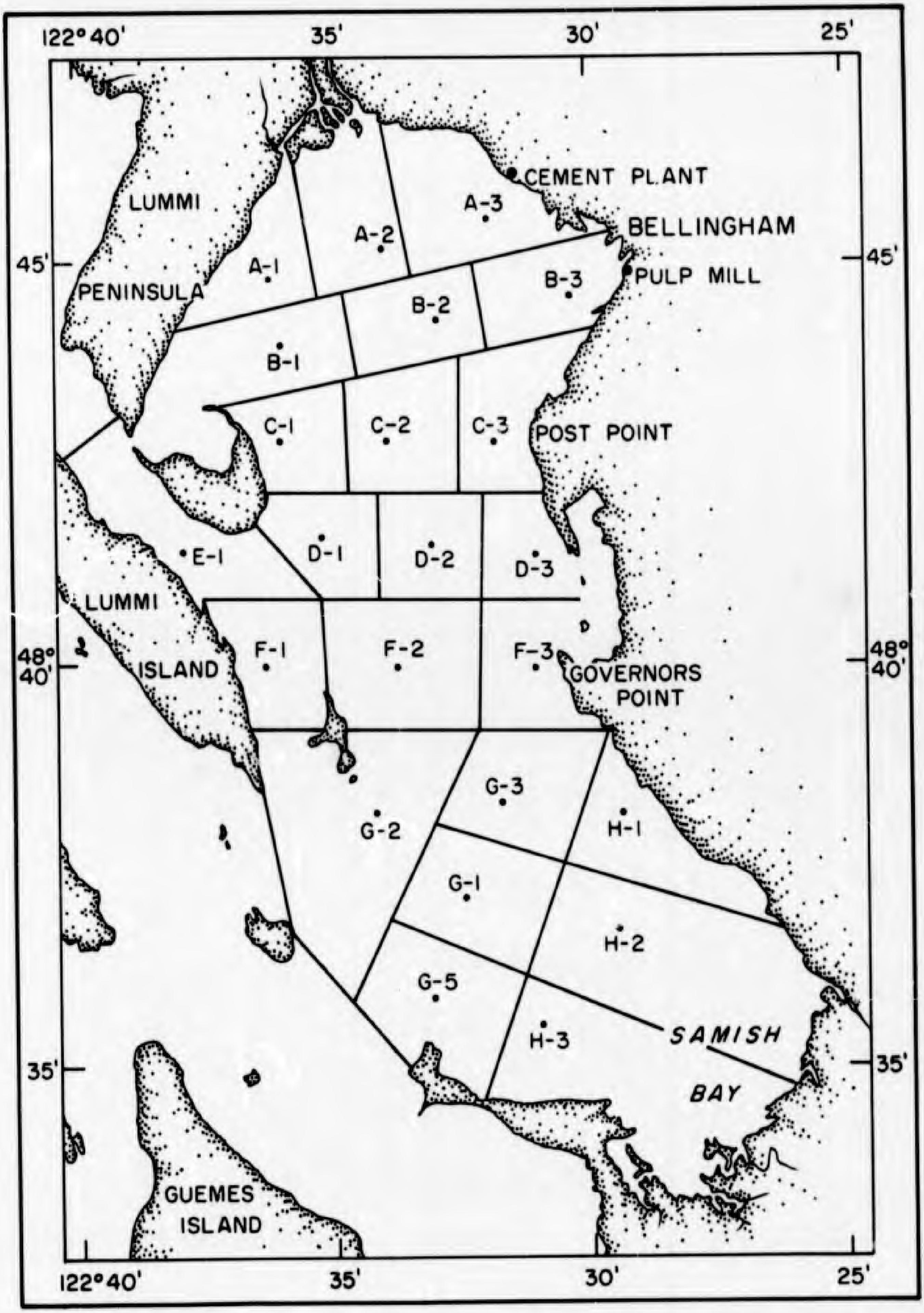

Fig. A.1. Subdivisions used for volume analysis of Bellingham and Samish Bays.

APPENDIX B

RESULTS OF CURRENT MEASUREMENTS IN BELLINGHAM BAY

Appendix B presents the results of the actual readings of the various current meters used at selected stations, times, and depths in Bellingham Bay. The times are all based upon Pacific Standard time (+8). Asterisks (*) in the direction field indicate that the value was omitted because of malfunction of the current meter or that the current speed was too low to give a satisfactory direction with the particular type of meter. Speed is given in knots; depth is in meters. The stations referred to are the same as those shown in Fig. 1.5.

TABLE B.1

Currents near station D-2, 19 July 1960

(48°41.5' N, 122°33.1' W)

Price meter at 6 ft (1.8 m)			Ekman-Merz meter			
Time (+8)	Speed (knots)	Direction (°T)	Time (+8)	Depth (m)	Speed (knots)	Direction (°T)
1050	0.32	323	1101	2	0.16	315
1101	0.33	293	1159	2	0.08	303
1111	0.29	*	1212	10	0.16	308
1118	0.23	*	1228	20	0.44	023
1131	0.26	233	1245	25	0.48	023
1155	0.22	238	1308	5	0.38	324
1159	0.16	238	1318	10	0.35	342
1204	0.22	248	1339	15	0.24	063
1212	0.25	313	1405	5	0.18	270
1228	0.34	293	1437	20	0.33	065
1245	0.44	293	1449	5	0.19	286
1308	0.62	*	1519	15	0.19	082
1318	1.13	001	1528	20	0.14	*
1330	0.88	*	1545	8	0.09	283
1339	0.38	326	1605	12	0.01	*
1349	0.44	301	1624	2	0.14	225
1405	0.38	301	1630	4	0.19	*
1412	0.48	301				
1422	0.41	301				
1437	0.40	301				
1449	0.38	301				
1456	0.39	301				
1510	0.26	301				
1528	0.28	301				
1538	0.29	301				
1545	0.18	301				
1556	0.36	301				
1605	0.26	301				
1614	0.25	297				
1624	0.29	301				
1630	0.28	301				

TABLE B.2

Currents near station D-1, 20 July 1960

(48°41.6' N, 122°35.3' W)

Price meter at 6 ft (1.8 m)			Ekman-type meters			
Time (+8)	Speed (knots)	Direction (°T)	Time (+8)	Depth (m)	Speed (knots)	Direction (°T)
0938	0.36	193	0954	15	0.09	*
0954	0.40	201	1017	5	0.12	323
1008	0.44	201	1034	2	0.38	263
1017	0.70	201	1111	5	0.08	073
1026	0.51	221	1135	5	0.37	271
1034	0.44	223	1141	6	0.22	156
1053	0.40	203	1147	20	0.12	323
1103	0.55	203	1223	5	0.14	213
1111	0.35	236	1246	6	0.14	163
1122	0.40	236	1257	2	0.60	128
1135	0.44	*	1307	6	0.24	193
1147	0.40	*	1320	2	0.39	128
1158	0.51	213	1334	6	0.18	241
1223	0.55	213	1346	10	0.15	233
1235	0.88	213	1347	2	0.49	121
1257	0.81	263	1355	6	0.20	181
1307	0.64	243	1405	2	0.59	113
1320	0.84	278	1418	4	0.33	280
1334	0.67	306	1441	2	0.77	105
1346	0.77	315	1454	20	0.24	168
1355	0.75	320	1455	4	0.17	178
1405	0.95	318	1506	15	0.16	178
1418	1.06	313	1507	6	0.18	175
1431	1.20	316	1517	10	0.16	316
1441	1.19	316	1527	8	0.23	236
1454	1.14	340	1550	10	0.14	244
1506	0.84	346	1606	4	0.16	*
1517	0.90	344	1613	2	0.43	*
1527	0.73	346				
1540	0.64	011				
1550	0.90	046				
1559	0.89	066				
1606	0.53	076				
1613	0.41	089				

TABLE B.3

Currents at station B-3, 10 July 1961

(48°44.6' N, 122°30.3' W)

Price meter		
Time (+8)	Speed (knots)	Direction (°T)
Depth—2 m		
1251	0.30	060
1258	0.27	060
1312	0.30	080
1321	0.27	250
1329	0.27	195
1337	0.21	060
1344	0.21	080
1351	0.24	050
1357	0.27	060
1405	0.21	050
1413	0.18	050
1418	0.18	050
1424	0.22	050
1431	0.21	050
1439	0.21	040
1447	0.24	030
1458	0.21	340
1510	0.21	330
1525	0.18	330
1537	0.30	330
1550	0.24	340
1558	0.21	320
1611	0.35	130
1633	0.30	130
1650	0.40	130
Depth—3 m		
1453	0.18	065
1503	0.12	350
1512	0.06	*
1529	0.06	035
1542	0.03	*
1553	0.03	330
1602	0.09	220
1627	0.18	040
1659	0.12	*

Ekman-Merz meter		
Time (+8)	Speed (knots)	Direction (°T)
Depth—1 m		
1458	0.12	293
1538	0.12	341
1627	0.13	003
Depth—2 m		
1322	0.15	*
1334	0.36	335
1417	0.33	359
1449	0.23	357
1545	0.17	003
1635	0.22	056
Depth—3 m		
1308	0.15	033
1507	0.08	323
1632	0.12	*
1642	0.05	123
Depth—4 m		
1400	0.00	
1513	0.31	103
1558	0.09	193
1649	0.08	153
Depth—6 m		
1315	0.02	*
1353	0.00	
1524	0.09	153
1608	0.18	216
Depth—8 m		
1344	0.00	
1532	0.17	166
1618	0.16	183

TABLE B.4

Currents at station B-2, 11 July 1961

(48°44.3' N, 122°32.9' W)

Price meter

Time (+8)	Speed (knots)	Direction (°T)
Depth—2 m		
1100	0.30	055
1120	0.35	055
1140	0.30	085
1200	0.24	325
1230	0.30	310
1245	0.80	020
1300	0.18	335
1315	0.28	310
1330	0.21	340
1345	0.24	335
1400	0.18	335
1430	0.27	300
1445	0.27	330
1500	0.27	320
1515	0.24	340
Depth—4 m		
0902	0.24	310
0907	0.27	310
0915	0.35	250
0923	0.32	260
0931	0.32	260
0942	0.44	210
0952	0.47	210
1004	0.65	330
1024	0.18	330
1036	0.38	330

Ekman-Mertz meter

Time (+8)	Speed (knots)	Direction (°T)
Depth—1 m		
0841	0.23	291
0941	0.60	281
1050	0.18	075[a]
1141	0.20	093
1254	0.18	*
1339	0.06	063
1420	0.10	*
1601	0.15	348
Depth—2 m		
0849	0.28	337
0951	0.54	278
1057	0.23	293
1201	0.25	058
1310	0.31	359
1346	0.27	328
1427	0.39	349
Depth—6 m		
0859	0.18	303
1009	0.71	286
1109	0.10	333
1227	0.33	337
1316	0.37	330
1352	0.39	330
1535	0.41	345

See footnote at end of table.

TABLE B.4 (continued)

Price meter			Ekman-Mertz meter		
Time (+8)	Speed (knots)	Direction (°T)	Time (+8)	Speed (knots)	Direction (°T)
Depth—5 m			*Depth—10 m*		
0923	0.41	080	0907	0.24	263
0931	0.50	210	1023	0.22	253
0942	0.65	210	1116	0.15	255[a]
0952	0.80	210	1234	0.42	283
1004	0.89	330	1323	0.15	208
1024	0.27	330	1400	0.25	220
1036	0.35	330	1443	0.17	*
1100	0.35	115	*Depth—15 m*		
1120	0.41	115	0921	0.15	246
1140	0.38	085	1032	0.22	103[a]
1200	0.15	325	1057	0.16	150
1230	0.56	300	*Depth—20 m*		
1245	0.44	340	0931	0.43	245
1300	0.44	340	1041	0.19	075[a]
1315	0.56	340	1125	0.25	328
1330	0.62	310	1246	0.20	320
1345	0.80	340	1431	0.13	335
1400	0.62	005	1509	0.07	023
1430	0.32	310			
1445	0.30	110			
1500	0.30	130			
1615	0.35	130			

[a]Direction variable during measurement; value listed is an average.

APPENDIX C

Table of equivalents

(English system to metric system)

Distance		
1 inch	=	2.54 cm (exact)
1 ft	=	0.348 m
1 fathom	=	1.829 m
1 statute mile	=	1.609 km
1 nautical mile	=	1.853 km
Area		
1 sq statute mile	=	2.589 km^2
1 sq nautical mile	=	3.434 km^2
Volume		
1 gallon	=	0.003785 m^3
1 acre-ft	=	1233 m^3
1 cu nautical mile	=	6.362 km^3
1 cfs	=	0.02832 m^3/sec
Speed		
1 mph	=	0.4470 m/sec
1 knot	=	0.5148 m/sec
Temperature		
(°F - 32)5/9	=	1°C

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13. ABSTRACT An oceanographic survey of the Bellingham-Samish Bay tidewater system in northwestern Washington was conducted from November 1959 through November 1961. Characteristics of temperature, salinity, dissolved oxygen, dissolved inorganic phosphate, and spent sulfite liquor are described for selected locations and depths. Exploratory measurements and dye diffusion experiments were conducted. The net circulation consists of a surface inflow of riverwater entering the north end and flowing south, and a bottom inflow of saline water entering the south end and flowing north. Water in the main body of the system is a variable mixture of these two source waters. The surface water responds primarily to changes in Nooksack River discharge. The salinity increases from head to mouth and from surface to bottom in both winter and summer. The temperature does likewise in winter but decreases from head to mouth and from surface to bottom in summer. Surface exchange of water, oxygen, and heat, affectsthe properties of the layer above a depth of 10 m. Below that depth dissolved oxygen decreases and soluble phosphate increases. The Samish River, entering Samish Bay near the mouth of Bellingham Bay, is much smaller than the Nooksack, and has little effect on the overall circulation or water properties. Samish Bay shows little dilution that can be attributed to water from the Nooksack River and upper Bellingham Bay. The dispersion of industrial and municipal wastes discharged into the northeastern corner of upper Bellingham Bay was estimated using spent sulfite liquor (SSL) as a tracer. The average concentration of SSL at a distance of 9 km from the outfall was about 1% of that near the outfall. In general, the SSL tended to remain in the upper few meters and appeared to have little effect on the physical and chemical regimes of the open bay.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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