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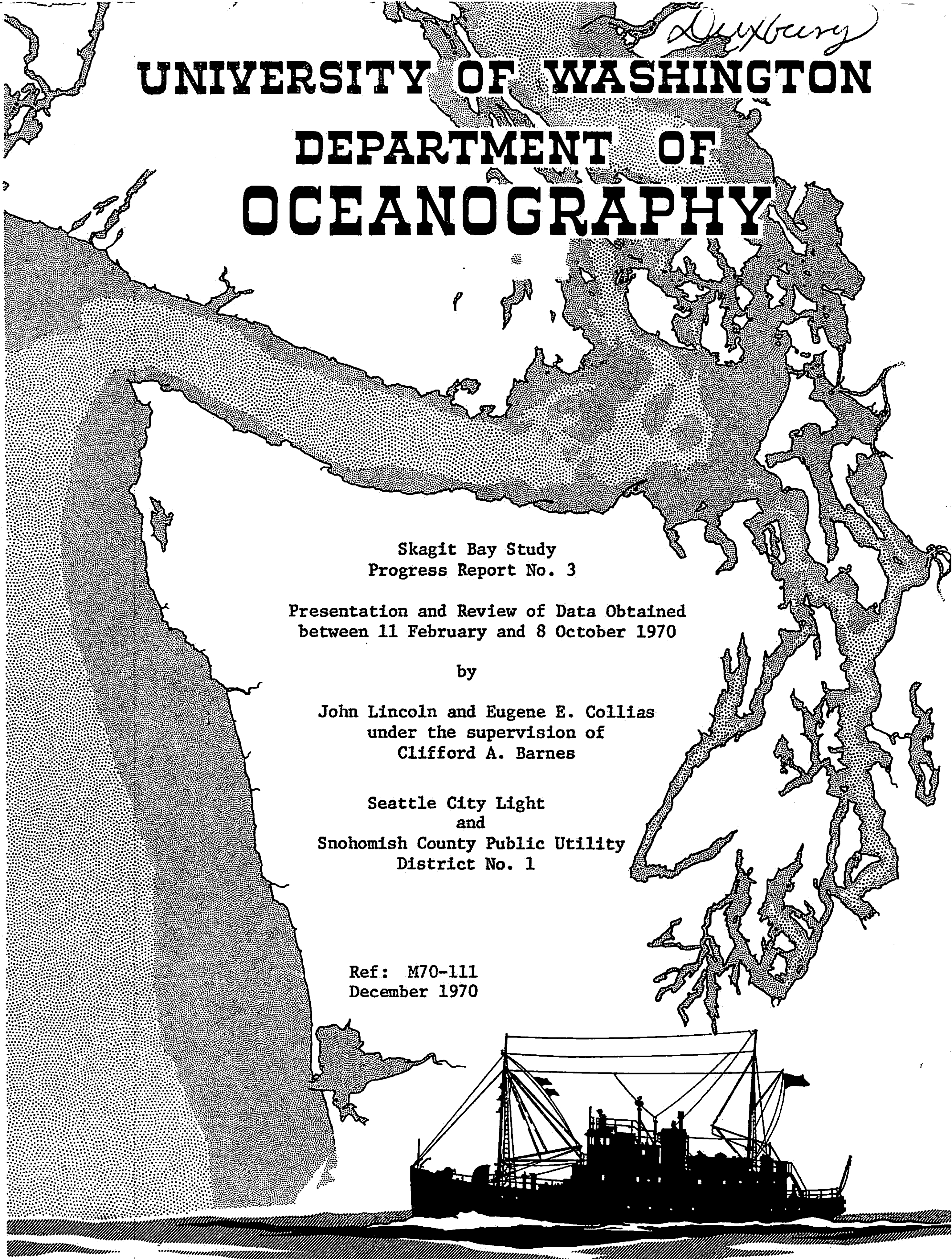

Skagit Bay Study
Progress Report No. 3

Presentation and Review of Data Obtained
between 11 February and 8 October 1970

by

John Lincoln and Eugene E. Collias
under the supervision of
Clifford A. Barnes

Seattle City Light
and
Snohomish County Public Utility
District No. 1

Ref: M70-111
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Clifford A. Barnes
Professor and Principal Investigator

George C. Anderson
Acting Assistant Chairman for Research

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ACKNOWLEDGMENTS

The fieldwork has been under the supervision of Mr. Gerald A. Sanger, using the R. V. Hoh and the R. V. Onar. The authors wish to express their gratitude to the 65 persons, students and members of the faculty and staff, who have participated in the field program, data analysis, and report preparation. Without their wholehearted willingness and cooperation, this project would not have been successful. A full list of all personnel will be included in the final report.

1.0 STUDY OBJECTIVES

1.1 *Introduction*

The present studies were initiated to define existing oceanographic characteristics of the area in the vicinity of Kiket Island and to provide a basis for assessing the distribution of waste heat through the discharge of cooling water from a proposed nuclear power plant.

The Skagit Bay system is influenced by processes and conditions operating or originating within its confines and by interaction with adjoining areas that provide the source seawater. These studies are aimed at developing knowledge of the water properties and dynamic processes within the Skagit Bay system and adjoining areas that is essential to establish their general characteristics and their seasonal and short-period variability. The data obtained should provide the base for evaluating the effects of introducing or altering a variable within the system under different ambient conditions. Moreover, the study should also provide information required for engineering designs, such as optimizing the location of intake and outfall, from the standpoint of minimum environmental impact, economics, and and feasibility.

The primary study area (Figures 1-1, 1-2, and 1-3) is part of a dynamic system in which water-mass characteristics are subject to continual change and therefore cannot be explicitly defined by single-value parameters. To a large extent, variability is periodic and characteristics can be described by a range of values, their period and rate of change, or the duration of a quasi-steady state. The studies will thus entail the determination of water characteristics existing in the Skagit Bay system and the dynamic processes that establish those characteristics and their variability. As properties characterizing the water mass in the local area of primary interest are affected by those of the larger system, the investigations must include the contiguous areas to some distance from the principal study area.

1.2 *Water properties*

Water properties studied include salinity, temperature, density, dissolved oxygen, and micronutrients (phosphate, nitrate, and silicate) and also their variability with location, depth, and time. Properties within the primary study area vary in response to changes in the source waters and to dynamic processes of local and regional extent such as tides, weather,

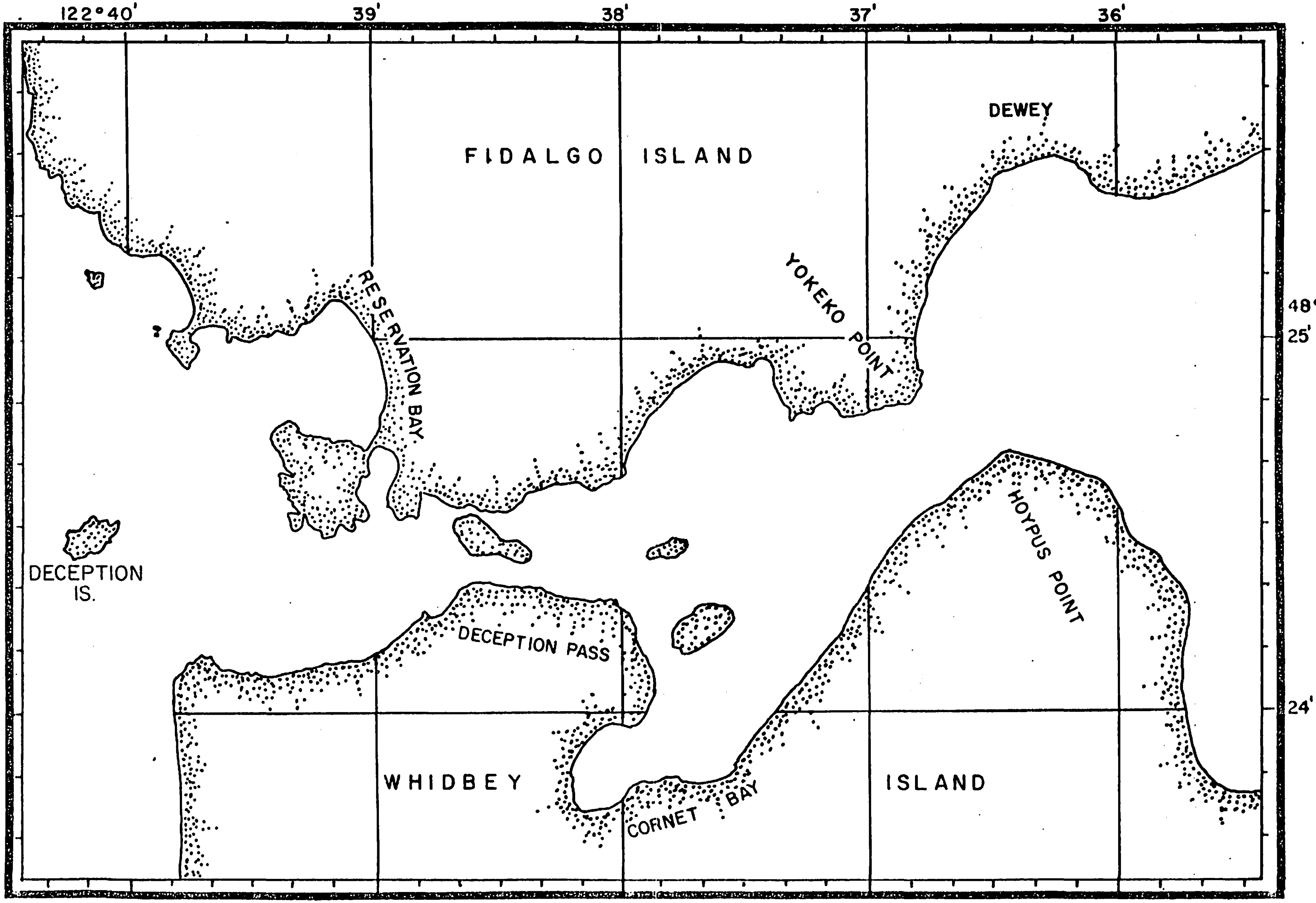

Figure 1-1 Location chart for the Deception Pass area

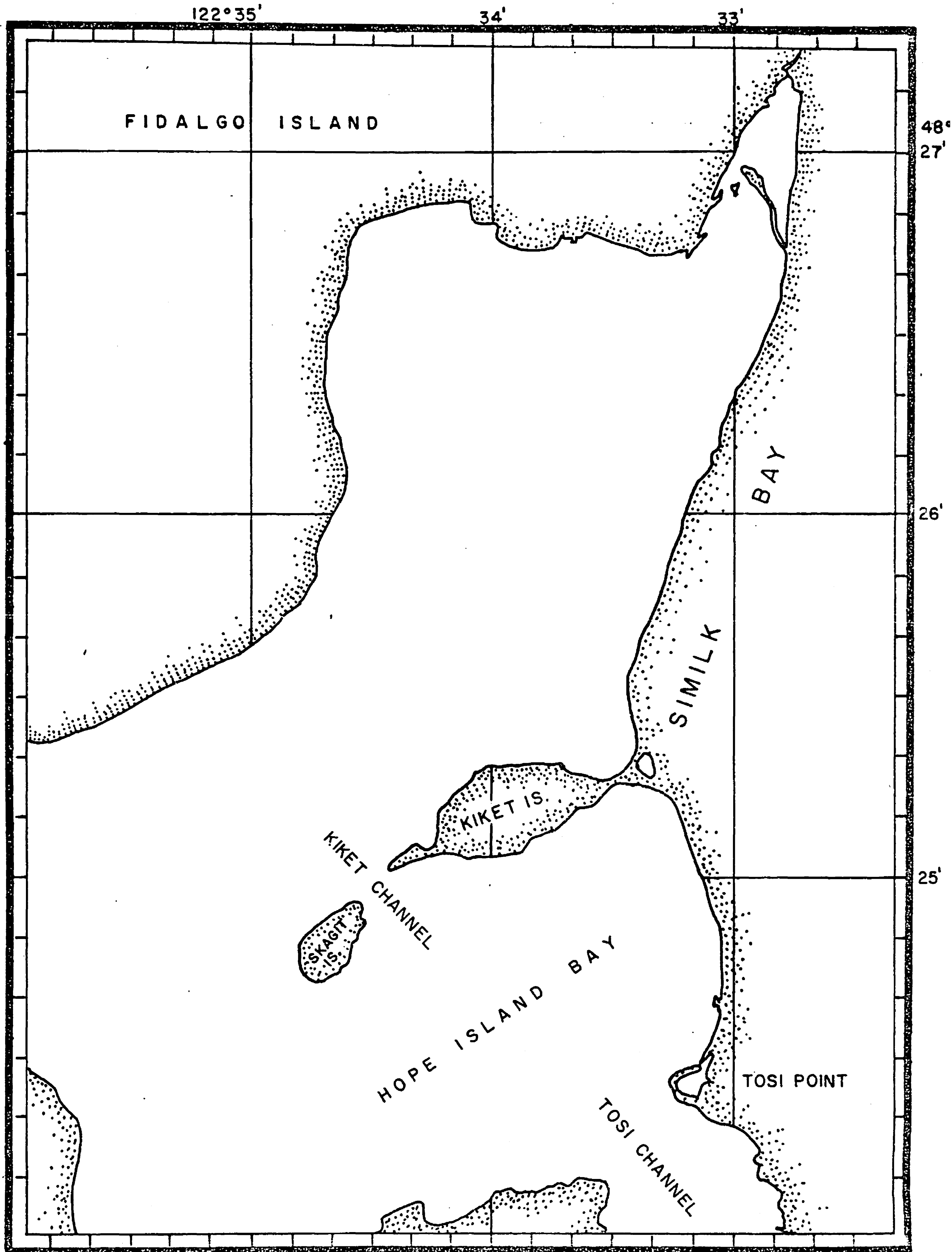

Figure 1-2 Location chart for the Similk Bay area

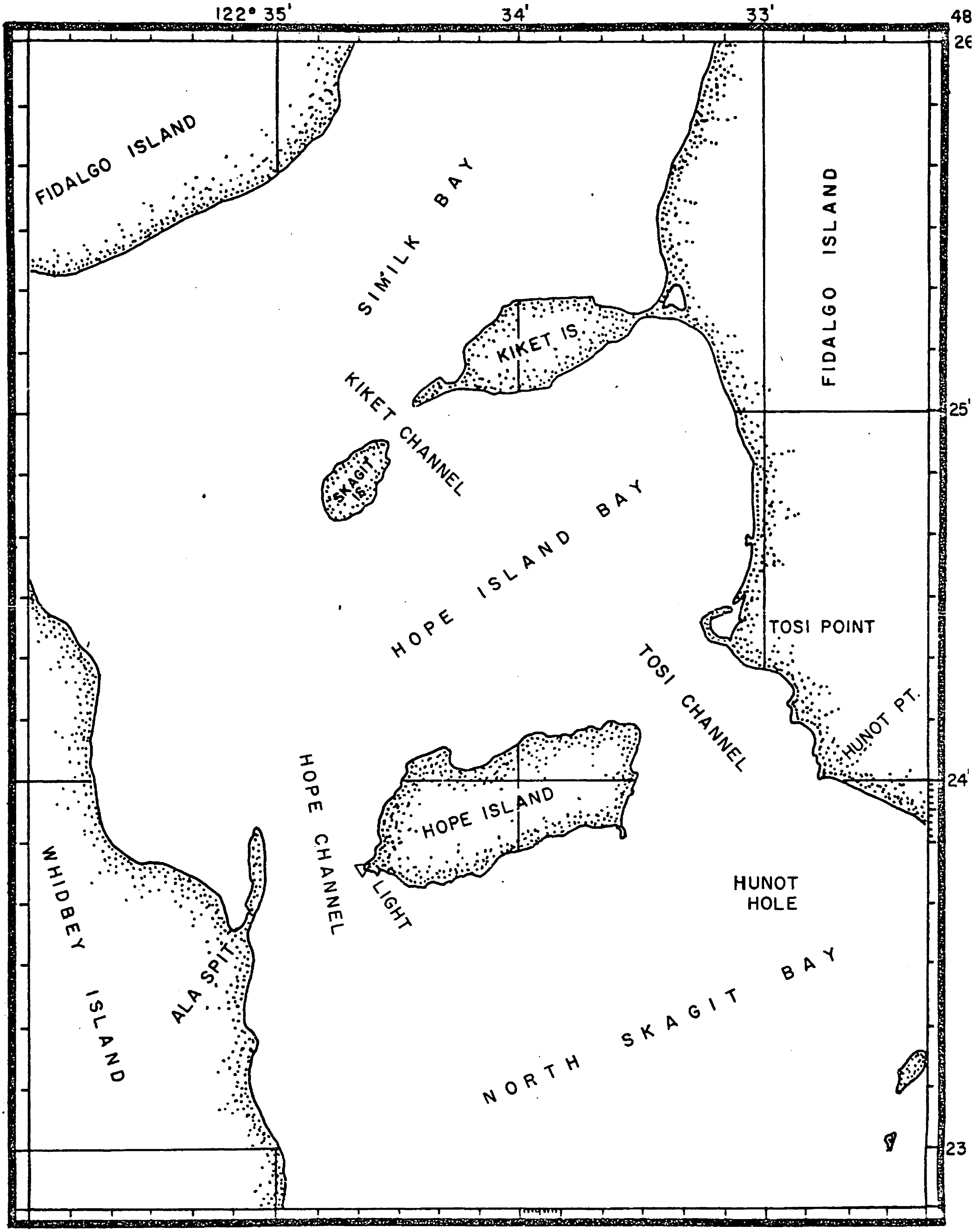

Figure I-3 Location chart for the Hope Island Bay area

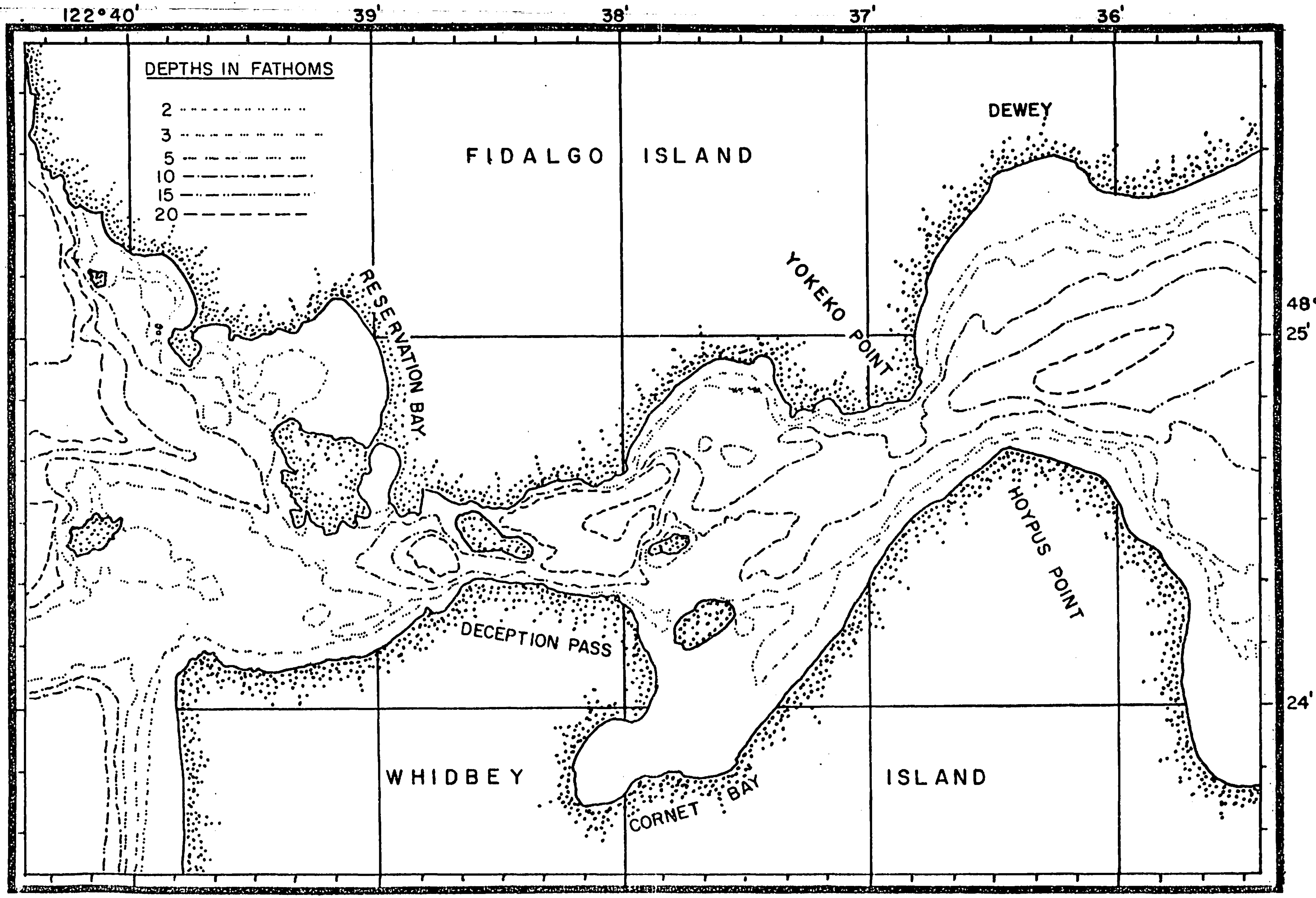

Figure I-4 Bathymetry of the Deception Pass area

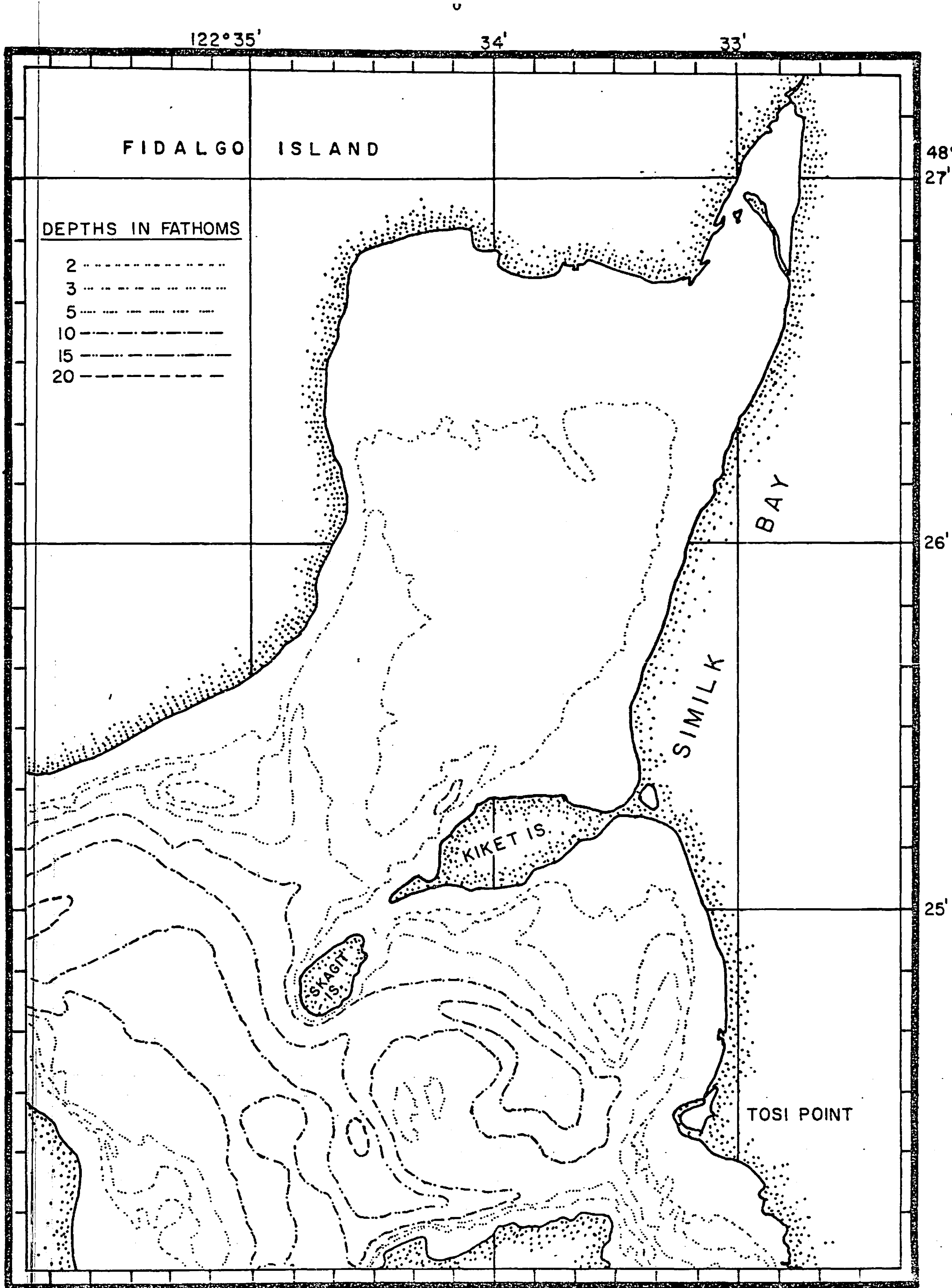

Figure I-5 Bathymetry of the Similk Bay area

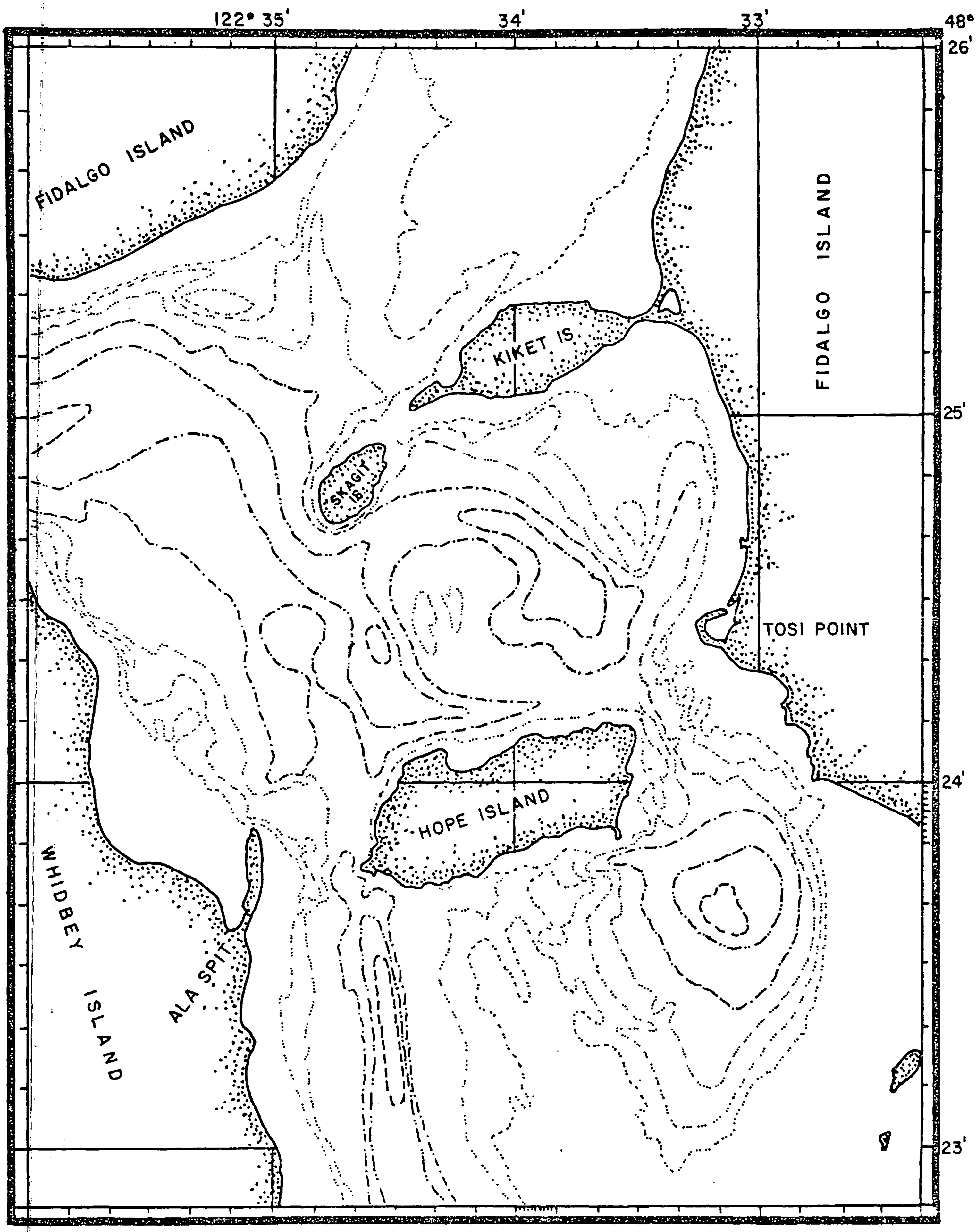

Figure 1-6 Bathymetry of the Hope Island Bay area

and river runoff that result in local water movement. The data obtained should define the normal properties and processes and serve as a base for evaluating the changes resulting from the addition of waste heat at a specified location.

1.3 *Water-mass dynamics*

Knowledge of the dynamics of water movement within the area is essential to understanding the natural variability of water properties and to evaluating the dispersion and dissipation of cooling water from different outfall locations. Each of the dynamic processes, their driving forces, and their interactions must be investigated and evaluated with respect both to their individual and combined effects on the water mass.

1.3.1 *Tides*

Astronomical tides are the principal driving force for oscillating water movement within the area as they produce a continuously varying volume of water within the system. The Skagit Bay system and contiguous areas consist of a number of basins with interconnecting channels in which water height differences result in variable hydraulic flow through the channels. Consequently tides in the adjoining areas of the Puget Sound system as well as in the primary study area are of direct concern to this study.

Tides over virtually the entire Puget Sound region are of the mixed type, having two highs and two lows each day. However, the tides become nearly diurnal each month near Port Townsend at the entrance to Admiralty Inlet, and almost completely diurnal at Victoria, B.C. A major characteristic of the Puget Sound mixed tides is the diurnal inequality, i.e., the difference in height of successive high and low waters, with the largest inequality being in the height of low water. Although the tides are astronomical in origin and are predictable, the actual height of water at a given time may differ from predicted height because of meteorological forces and to a lesser amount because of river runoff. This resulting difference can be significant with respect to currents and tidal exchange within a local system. Therefore water levels must be recorded at a number of locations both within the Skagit Bay system and in the adjoining basins. Of particular importance are simultaneous water-level measurements at both ends of Deception Pass because the associated hydraulic flow through this channel directly and to a major extent affects the oceanographic characteristics of the Skagit Bay system. The Skagit Bay system is connected at its southern end to the main Puget Sound basin through relatively wide Saratoga Passage and Possession Sound. Since the waters in both systems interact, observations are needed throughout in order to understand the dynamics of the Skagit Bay system.

1.3.2 *Circulation*

Circulation within the Skagit Bay system is of primary importance in transporting and dispersing any cooling water that may be introduced at a specified location. Circulation is driven by tidal forces, wind, hydraulic head, and density structure, and is complicated by the irregular topographic features of the several basins, the interconnecting channels between islands, and the large range of velocities that fluctuate rapidly in both speed and direction. These conditions necessitate that the system be studied both generally as a whole and each subsection in detail. Each part of the system (Skagit Bay, Hunot Hole, Hope Island Bay, Similk Bay, and the Deception Pass-Dewey section) has a unique but variable circulation with systems of eddies and gyres that may be unidirectional or alternately clockwise and counterclockwise during ebb and flood. Circulation in Hunot Hole and the area immediately south of Hope Island and in Hope Island is strongly affected by the channels at either end of Hope Island and Skagit Island and the outflow from the Skagit River. Similk Bay and Skagit Bay include relatively large areas of shallow water and tide flats that may be exposed at low tide. The area from Hoypus Point to Deception Pass has a circulation more typical of a large river except for its changing speed and direction. Because of this complexity and tidal variability, detailed study under different tide and weather conditions is required.

Inflow of fresh water from the Skagit River produces a strong salinity gradient that can result in a different flow at the surface and at depth in some channels, particularly in the vicinity of Hope Island and to the south. Circulation is also affected by the connection between Skagit Bay and Saratoga Passage. Although tidal effects from Deception Pass and from Saratoga Passage appear to meet in the vicinity of Strawberry Point, this "nodal point" apparently shifts in location and depth and affects circulation within a large part of the local system.

Although the circulation is driven primarily by tidal forces and therefore is periodic and repetitive in general features, local wind stress and both wind and barometric pressure differences over the Puget Sound region may modify the circulation. Larger scale variations may significantly affect the flow in the deeper water, particularly within the interconnections coupling the local system to contiguous areas through both Saratoga Passage and in Deception Pass.

General features of the circulation within the local system are known, and additional characteristics can be inferred from the bathymetry (Figures 1-4, 1-5, and 1-6) and nature of bottom material. To provide data for investigating potential effects of the cooling water on the thermal environment of the local system, the circulation in this area must be determined in detail. Particular attention must be given to the circulation under conditions that result in minimum velocities for extended periods, such as during periods of small or standing tides or during winds that may tend to retain water locally in an area such as Similk Bay.

1.3.3 *Water exchange and flushing*

Water exchange and flushing are closely related to tidal exchange volume, fresh-water inflow, circulation, turbulent mixing, and to an unknown extent to seiches and internal waves in the main Puget Sound Basin to the south. Flushing of the various basins depends on both the net transport of water and the extent of mixing. Fresh water is introduced continuously in varying amounts from rivers, principally the Skagit; and after some mixing with the seawater, this fresh water contributes to the net outflow through Deception Pass. Water exchange within the basins must be investigated on the basis of water characteristics, transport through the connecting channels as determined by current measurements at multiple depths, and by tidal volume computations. Within the primary study area, the greatest exchange occurs through Deception Pass although an unknown contribution may occur from Saratoga Passage, most probably at depth, as a result of the shifting location of the Strawberry Point tidal flow node. This latter effect introduces an uncertainty in computing tidal prism volume of the Skagit Bay section south of Hope Island, and it stresses the need for measurements outside the principal study area.

Investigation of flushing and exchange is closely related to circulation because only part of the system volume is involved in each tide cycle. Thus, depending on the circulation pattern, residence time of a particular parcel of water will depend on its position within the basin, the varying range of each tide, the tidal prism, the low tide volume, and the amount of mixing that occurs. With partial mixing, as may occur in Similk Bay, in the large gyres, or in parts of Skagit Bay, introduced cooling water accumulation may have a varied distribution. Further, the residence time will be affected by existing winds, both local and regional.

1.4 *Engineering data*

This study must provide quantitative data pertinent to engineering studies that will enable reliable prediction and comparison of the consequences of removal of ambient water and discharge of heated water at various locations. These data should provide a means of evaluating the distribution and dispersion of heated water that may have an impact on the marine biota, and should facilitate selection of an intake and outfall location most suitable from the standpoint of environmental considerations, económics, and feasibility.

2.0 OBSERVATIONAL METHODS

2.1 *Currents*

Knowledge of current speeds and directions within the system is essential to an understanding of water movement, transport and mixing. Constraints on time, manpower, and instrumentation limit the detail to which currents within this complex system can be measured directly. Times, locations, and depths of measurement and the techniques used must be selected to obtain economically the necessary data that will permit reasonable interpretation of the system as a whole. The inevitable lack of direct measurements at all points and time will introduce some uncertainties in the interpretations but careful consideration in selection of the observational locations and time periods should minimize these uncertainties.

Planned and completed measurements employ both Eulerian and Lagrangian methods, which respectively measure the flow past a fixed position, and determining the trajectory of a parcel of water in space and time. The complementary use of these two basic methods provides a more reliable and detailed understanding of both the circulation pattern and water transport than either method alone would do.

2.1.1 *Current meters*

A limited number of current measurements have been made using recording meters at fixed locations and depths, primarily in the area of Hope Island Bay, the main channel between Hope Island and Ala Spit, and just north of Skagit Island. Current-meter arrays were designed to hold the meters either at a constant depth below the surface regardless of tide height, or at a constant height above bottom. In the first case, meters were suspended from floating buoys, with chain weights below the meters to hold them vertical. These arrays were anchored in position with a minimum scope to reduce buoy range with tide. Within the main channel, it was necessary to use submerged buoys to ensure that the arrays neither obstructed nor were imperiled by shipping, as there is considerable traffic, including log booms. These studies employed Braincon Type 381 histogram current meters that combine a savonious rotor speed sensor, a magnetic compass for recording direction, and a tilt indicator. Currents within the ranges of 0 to 2.5 kt or 0 to 5 kt are integrated over a 9.5-min period with 0.5 min taken for advancing the recording film. Speed is recorded with an accuracy of $\pm 3\%$ of full scale, direction to $\pm 1\%$, and tilt to $\pm 10^{\circ}$ in direction and $\pm 3\%$ in amplitude. During the preliminary investigations, measurements were taken at seven locations, as shown in Figure 3-1. Measurements were made at two depths at the station between Hope Island and Ala Spit, and at a single depth at the remaining stations.

2.1.2 *Drogues*

The drogues used in this study are essentially simple small parachutes used underwater. They were made using plastic sheet, seine twine, a small bag containing beach gravel for weight, and a block of polystyrene foam for a float. The drogues were attached to the weight suspended the desired distance below the surface float. The design of these inexpensive drogues is sketched in Figure 2-1.

In use, a number of the drogues are set adrift at selected locations and are followed by boat either for some specified time or until they are carried out of the area under investigation and then recovered. Positions are determined by measuring two horizontal angles between three targets or known location, the center target being common to both angles. A sextant is used to measure the angles to ± 1 minute of arc. As the drogues are carried by the currents, the tracking boat comes alongside each float in turn and the angles are measured. The positions are plotted either manually, using a three-arm protractor on a chart showing the target positions, or by computer. The plot of successive positions of each drogue shows the trajectory of the parcel of water with which it is identified. It is important that sightings of each drogue be as frequent as possible in areas of complex circulation and where speed and direction may be changing continuously, to avoid long straight-line representation of the trajectories where they may, in fact, be curved or possibly convoluted. It is apparent that using this method for detailed mapping of circulation in an area of complex flow or of appreciable size quickly becomes a difficult problem requiring a number of small boats, each with two or three persons (boat operator, recorder, and sextant operator).

Drogues may be suspended at a desired depth for measurements rather than being limited to surface flow. This feature is a distinct advantage where a layered system exists and where the currents within each layer may be different. It was found that the white polystyrene floats were plainly visible at considerable distance when the water was not rough. Some difficulty was experienced in locating the floats where there were numerous sea gulls sitting on the water, but this problem usually was resolved when the apparent float spread wings and took off. A similar difficulty may occur when measurements are attempted during windy periods that produce whitecaps on the water.

2.1.3 *Drift poles*

Drift poles are simple devices for measuring surface or near-surface water movement. Usually, they are sections of lumber (2 x 4 inches or 2 x 2 inches) weighted at one end to cause them to float on end and extend above the surface an amount adequate for visual sighting, but held to a minimum to reduce sailing in the wind. Their length is selected to measure the desired surface layer thickness. By their nature, they show movement integrated over their submerged length.

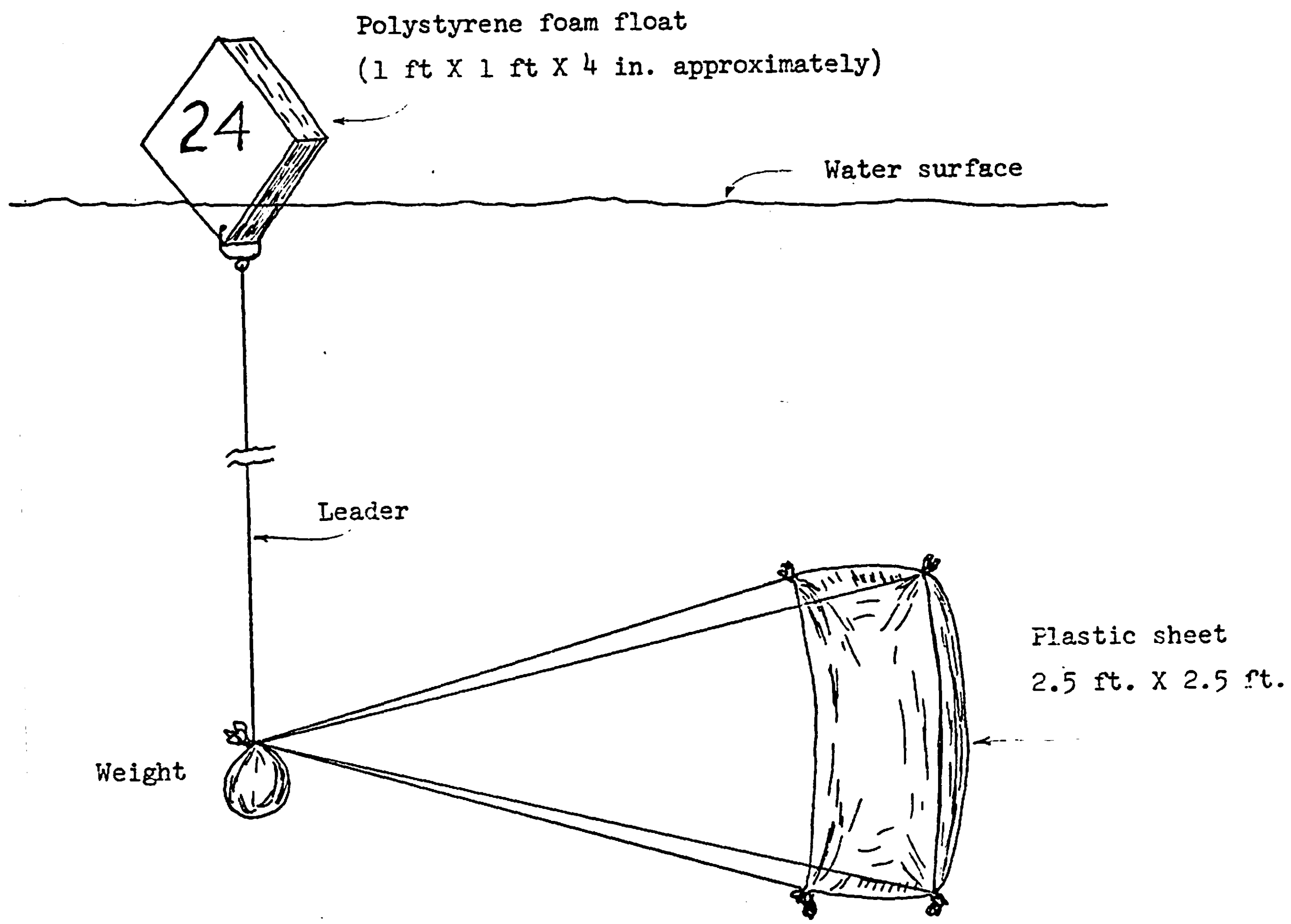

Figure 2-1 Sketch of small parachute drogue

The technique of using the drift poles is the same as that for the drogues. The principal difference between the two methods is that the information from the drift poles is limited to the surface layer of water, but the drogues may be placed at selected depth with a minimum of interference by flow above or below that depth.

2.1.4 *Dye*

A water parcel may initially be "tagged" by discharging a quantity of dye and mapping its progressive change in concentration and distribution. Usually a fluorescent dye such as Rhodamine-B is used and its concentration is determined quantitatively by a sensitive, continuous-flow fluorimeter aboard a small vessel cruising a grid track. As the vessel proceeds, a water sample from a known depth is continuously pumped through the instrument. Measured changes in dye concentration are then related to the vessel position and sample depth. This technique indicates the rate of mixing and dispersion within the water mass as well as the approximate Lagrangian current velocity.

A modification of this method, not as yet used in this study, involves the continuous metering of a known concentration of the dye into the water at a fixed location. Concentrations of the dye over the study area are monitored continuously or periodically. This technique is valuable in the investigation of the distribution, dispersion, and possible buildup of an effluent continuously discharged into the system. Ideally with this method, measurements over the study area should be continued until the dye concentration and distribution approach a steady-state condition. However, in this area the complex circulation, variable tides and winds would not permit a true steady-state to be reached. If appropriate time periods are selected, distribution representative of typical or extreme conditions can be approximated.

It should be noted that although Rhodamine-B is an intense brick-red color in high concentrations, fluorometric determination is sensitive to concentrations of a few tenths of a part per billion. Normally in such studies, dye concentration would be below that visible to the eye. Where a single quantity of dye is discharged in one location and tracked, the dye spot may be visible for a time until dispersion lowers the concentration below visual threshold.

Thus far in this study, only one attempt, a single slug dump, has been made to use the dye tracing technique, mainly because of the limited availability of suitable instrumentation.

2.2 *Water characteristics*

2.2.1 *Introduction*

Water characteristics of the study area and related sections of the Puget Sound system including the eastern part of the Strait of Juan de Fuca have been and will continue to be determined on a routine basis during scheduled triweekly surveys employing standard oceanographic techniques. Samples and measurements are taken at selected locations and depths to provide data on water characteristics in areas whose properties affect those within the study area and on the characteristics of the water within the study area in detail. Spatial variation of properties with both location and depth and their changes with time are of major concern. Locations of the stations that have been established as standard for the routine surveys are shown in Figure 2-2.

The triweekly interval was selected as being the maximum amount of time between cruises to show adequately the seasonal changes in water characteristics. Shorter term changes will not be observed without special cruises designed with this in mind. The first triweekly cruise was made 10-12 February 1970. The series will continue through 1971. A summary of the cruises to date is presented in Table 2-1.

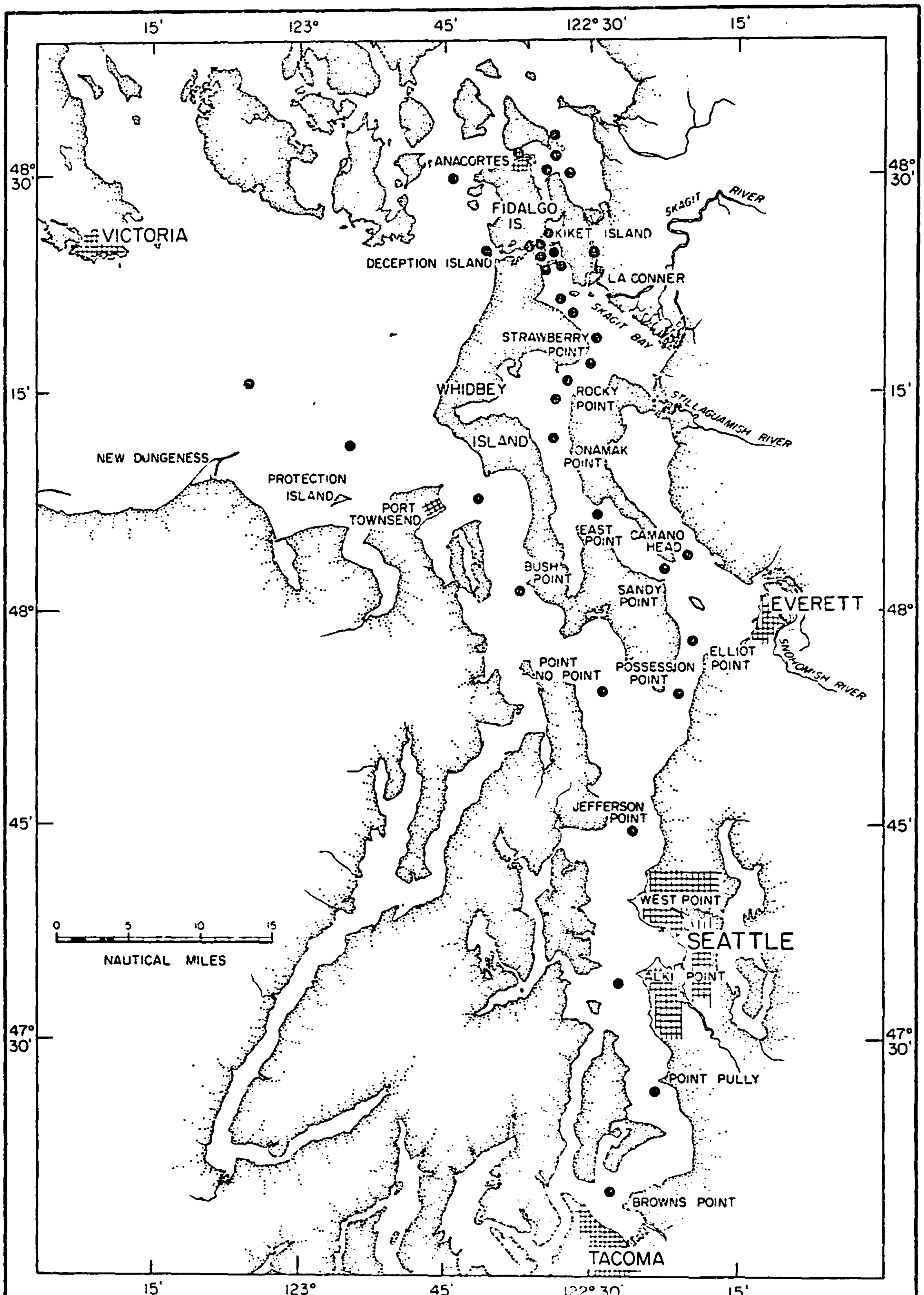

Figure 2-2 Station locations for triweekly cruises

TABLE 2-1

Triweekly cruises to Kiket Island and vicinity

KIK number	Ship	Cruise	Date	Stations
5	OA	299	10-12 Feb	28
7	OH	492	3- 5 Mar	29
10	OA	303	25-27 Mar	29
11	OH	497	14-16 Apr	36
14	OA	312	5- 8 May	35
15	OH	507	27-29 May	36
16	OH	510	16-19 June	61*
17	OH	515	7-10 July	41
18	OH	518	27-30 July	41
19	OH	522	14-16 Aug	41
20	OH	525	1- 3 Sept	44
22	OH	527	23-25 Sept	44
23	OH	530	6- 8 Oct	44
24	OH	536	27-29 Oct	45
26	OH	542	17-19 Nov	44

*Includes a special survey of Port Susan

2.2.2 *Chemical properties*

All water samples collected are analyzed for salinity and dissolved oxygen. The micronutrients are determined in samples taken at selected locations and depths. Salinity is determined by conductivity bridge measurements made under carefully controlled conditions that provide an accuracy of ± 0.005 parts per thousand (‰) (Paquette, 1959). Dissolved oxygen is determined by the Winkler method (Thompson, 1939). Samples taken for micronutrients are frozen immediately after collection for preservation and are returned to the laboratory for analysis. Colorometric methods are used for these analyses (Strickland and Parsons, 1968. Wood. et. al., 1967)

2.2.3 *Physical properties*

Water temperature is the principal physical property measured directly at each sampling depth. Standard oceanographic reversing thermometers are used, and temperatures are read to $\pm 0.01^{\circ}C$. Density is computed from salinity and temperature data (Knudsen, et al; 1901, and Cox, et al; 1970).

Water transparency is observed during daylight hours of the surveys, using a Secci disk 30 cm in diameter. The depth to which it is visible is a measure of transparency. This method does not distinguish between turbidity due to plankton and that due to suspended sediments originating in rivers or other sources. The measure is only semiquantitative as it is affected to some extent by the amount and size of surface waves and by the light level at the time of observation.

2.3 *Meteorology*

Local and regional weather conditions have a marked effect on the oceanographic characteristics of the primary study area. Winds are a driving force for surface transport and mixing, and as such they affect the local area directly and also more indirectly by their influence on Puget Sound, the Strait of Juan de Fuca, and the Rosario Strait-Strait of Georgia systems that act as the source of seawater for the study area through Deception Pass and Saratoga Passage. Barometric pressure differentials also affect water level and thereby influence tidal heights and flow. Regional meteorological conditions affect precipitation, a major controlling factor in the freshwater inflow from the Skagit River and other rivers, that in turn affects the salinity of the source water. Although regional weather parameters can be derived from the Weather Bureau data, those observations are inadequate for investigating the detailed effects of weather on the localized primary study area. It was necessary to establish a number of weather stations to monitor conditions within the study area and at supplementary locations in the contiguous areas. Locations of existing governmental weather stations and of supplementary stations established specifically for this study are listed in Table 2-2 and are shown in Figure 2-3.

The supplementary weather stations established for this study are Meteorological Research, Inc., Model 1071 and Model 1072. Model 1071 supplies wind speed and direction and air temperature. Model 1072 supplies rainfall data in addition to the above. Recorded data are retrieved, and the station is resupplied and serviced every four weeks.

2.4 *Water-level measurements*

Because of the major influence of regional water-level changes on the properties and behavior of the water within the Skagit Bay system, a number of observation stations were installed at selected locations. These stations are providing continuous data on actual water levels resulting from the combination of tidal forces and meteorological effects. The locations of the water-level recorders are listed in Table 2-3 and are shown in Figure 2-3.

Both digital and analog recorders are in use. These instruments measure the position of a float suspended in a 4-inch diameter pipe-well secured to a piling. The well is open to the seawater through an orifice, about 1 cm in diameter and 30 cm from the bottom end, that damps out oscillations of waves having a period of 10 sec or less. Rise and fall of the water level causes the float suspension wire to rotate a drum in the instrument. The recorders differ in the manner in which the drum position, i.e., the water level, is recorded. The digital recorders are Fisher and Porter Co., Model 1550 Punched Tape Level Recorder . These instruments employ mechanical means to convert angular position of the float-controlled rotating drum into a digital code that is punched in a paper tape at 6 min intervals. The tape is later run through an automatic reader that converts the code to digital values of time and water level and punches them on Hollerith cards in computer-compatible form.

The analog recorders are Stevens Type A-30 and A-35 Water-Level Recorder . In these instruments, a clock movement drives a strip chart at a predetermined

TABLE 2-2

Weather Stations

Location	Date Installed	Type	Height
Kiket Island	December 1968	M.R.I. 1072	< 30 ft.
Point No Point	1969	M.R.I. 1071	< 30 ft.
Point Robinson	1969	M.R.I. 1071	< 30 ft.
Strawberry Point	1969	M.R.I. 1071	< 30 ft.
Sandy Point	January 1970	M.R.I. 1071	< 30 ft.
West Point (Puget Sound Air Pollution Control Agency)			50 ft.
Ault Field, (Naval Air Station), Whidbey			

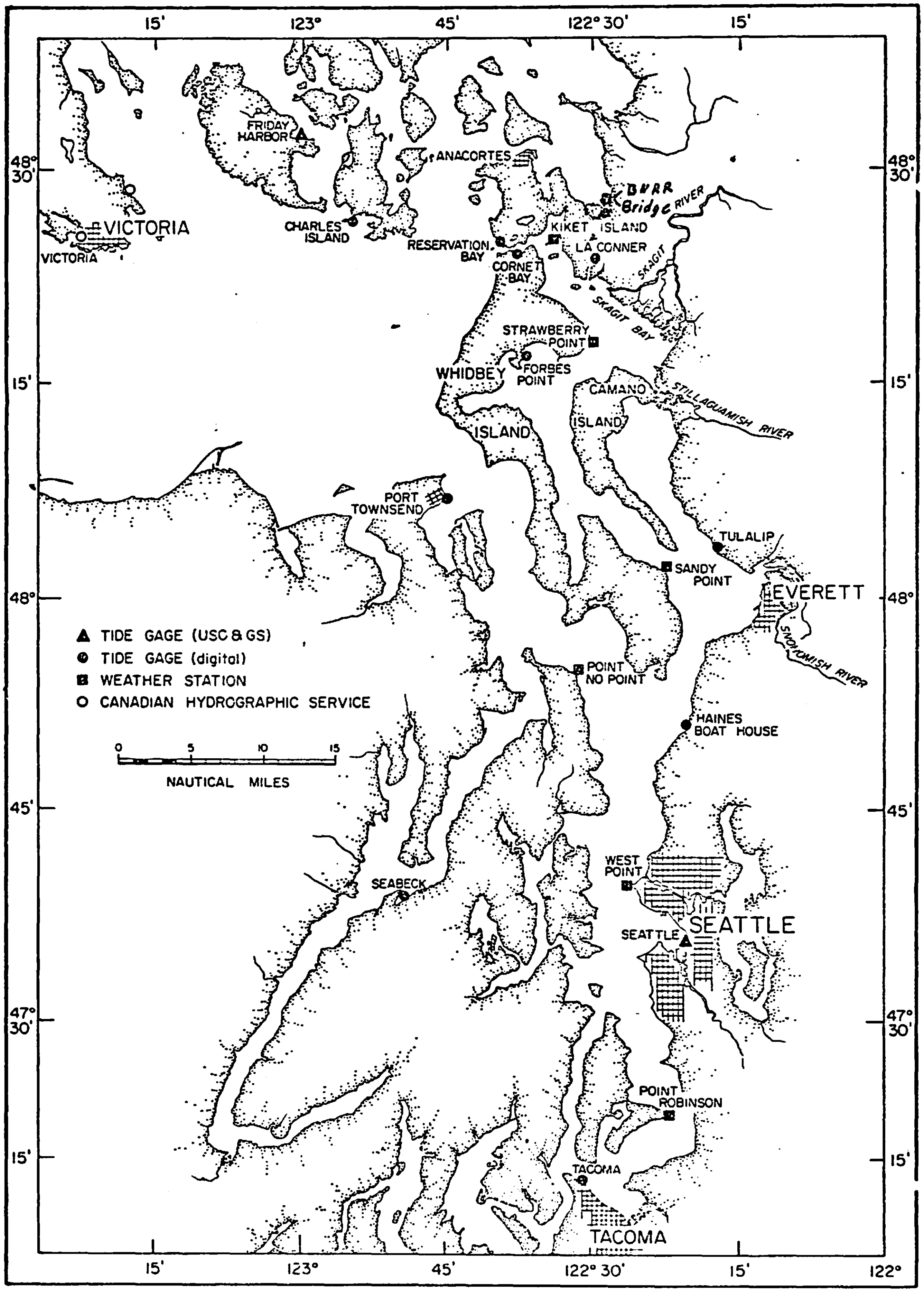

Figure 2-3 Location of weather stations and water-level measurement stations

TABLE 2-3

Water-level measurement stations[1]

Primary stations (U.S. Coast & Geodetic Survey)

Location	Type
Seattle	Digital
Friday Harbor, San Juan Island	Digital
Neah Bay, Strait of Juan de Fuca	Analog

Supplementary stations[2]

Location	Date Installed	Type
Cornet Bay	30 Dec 1968	Digital
Reservation Bay	30 Dec 1968	Digital
Port Townsend	20 Mar 1968	Analog replaced by Digital(1/70)
Charles Island	13 Apr 1968	Analog
Seabeck	21 June 1967	Digital replaced by Analog(7/70)
Tacoma	30 Dec 1969	Digital
Haines Boathouse	25 Sept 1969	Digital
Tulalip	18 Dec 1969	Digital
Forbes Point	26 Sept 1969	Digital
La Conner	25 Mar 1970	Digital
B. N. railroad bridge[3]	2 July 1970	Digital

[1]In addition to the stations listed, data were also obtained from the Canadian Hydrographic Service gauges at Victoria, Peddler Bay, Port San Juan, and at 20 additional locations in Georgia Strait.

[2]Stations installed by Department of Oceanography, University of Washington.

[3]Burlington Northern railroad bridge at the northern end of Swinomish Channel.

rate. A marking stylus controlled by the suspended float moves laterally across the chart in direct proportion to changes in the water level. Digital data are obtained by manually reading the chart record. The float and well are similar to those used with the digital recorders described above.

Basically, these instruments indicate only relative changes in water level. It is necessary to relate these measurements to a standard datum to enable direct comparisons among the various locations. This was accomplished by precise leveling based on U.S.C.& G.S. first-order level lines established in 1952. All stations except Tacoma have now been leveled and related to the Mean Sea Level (MSL) Datum of 1929, adjusted in 1947. It is necessary to relate these measurements to MSL rather than the usual tidal datum of Mean Lower Low Water (MLLW) since because this latter datum differs from geodetic level by various amounts at each station because of the change in tidal characteristics with location.

3.0 SUMMARY OF PRELIMINARY FINDINGS

The study results reported in this section are based on incomplete data and analyses and hence they must be considered as tentative and subject to revision. Major effort during the study thus far has been directed towards data collection to define significant long-period changes as well as selected shorter period fluctuations. Preliminary studies are being evaluated and as the study continues and more data are obtained, revision of some present interpretation can be expected.

3.1 *Water mass dynamics*

3.1.1 *Circulation*

Rosebrook and Hammond (1970) conducted an initial investigation of circulation in the primary study area. They measured currents directly with meters located at 7 selected positions in Hope Island Bay as shown in Figure 3-1. Meter locations and depths are listed in Table 3-1. These meters provided data on the principal flows in this area and delineated the general circulatory pattern. Currents here are primarily driven and controlled by tides, water-level differentials (principally through Deception Pass) that produce hydraulic flow, wind, and river runoff, and they are modified by

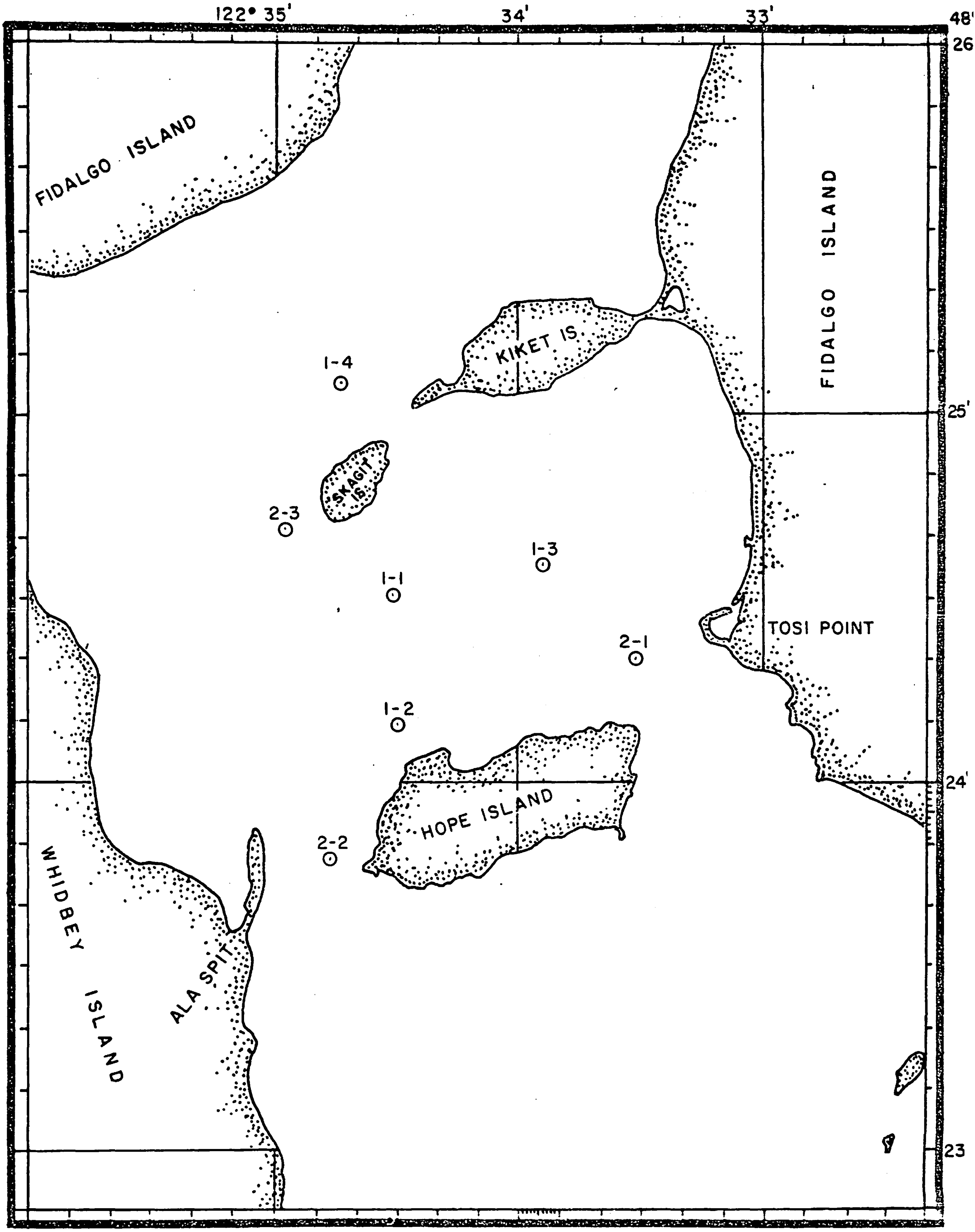

Figure 3-1 Locations of current meters of Rosebrook and Hammond

TABLE 3-1

Location of current meters by Rosebrook and Hammond

No.				
1-1	SE of Skagit Island	$48^{o}24.5'$ N	$122^{o}34.5'$ W	9.0 m below surface
1-2	N of Hope Island	$48^{o}24.2'$ N	$122^{o}34.6'$ W	9.0 m below surface
1-3	780 m S of Kiket Island	$48^{o}24.6'$ N	$122^{o}33.9'$ W	3.3 m below surface
1-4	N of Skagit Island	$48^{o}25.1'$ N	$122^{o}34.7'$ W	3.3 m below surface
2-1	W of Tosi Point	$48^{o}24.3'$ N	$122^{o}33.6'$ W	2.4 m below surface
2-2	W of Hope Island Light	$48^{o}23.8'$ N	$122^{o}34.8'$ W	9.0 m above bottom
2-3	W of Skagit Island	$48^{o}24.7'$ N	$122^{o}34.9'$ W	16.0 m above bottom 3.6 m above bottom

centrifigual force, inertia, and the bathymetry. Density gradients also affect the currents to some extent in maintaining the local salt budget. Circulation is dominated by flow through Deception Pass but is affected by the southern connection to Saratoga Passage and the Puget Sound system. Tidal effects from the south and those from Deception Pass appear to meet in the vicinity of Strawberry Point.

Variations in current speeds in the northern part of the Skagit Bay system follow those through Deception Pass, with maxima occurring near high- or low-water stand rather than at the time of midtide as commonly occurring in the principal channels of Puget Sound. Therefore in the following discussion, flood currents are associated with flow from Rosario Strait, through Deception Pass into the Skagit Bay system, and ebb is associated with the reverse flow, rather than with a rise or fall of water level. At times, flood currents can occur while the water level is dropping, and ebb flow can occur for a time during a rising water level.

The description of general circulation in the area as derived from the initial study of Rosebrook and Hammond was limited to Hope Island Bay. A more detailed description of this bay and of Similk Bay had been obtained by a drogue study and will be reported later.

A generalized diagram of the flood circulation pattern in Hope Island Bay and vicinity, based on the initial observations, is shown in Figure 3-2. A more comprehensive and detailed description of the circulation and its changes during the tide cycle will be developed.

The major portion of water entering through Deception Pass swings south around Hoypus Point, passes through the principal channel west of Skagit Island, and continues south through Hope Channel to Skagit Bay. A portion enters Similk Bay, developing a northern flow in this area. During large tides, flood begins near low-water stand, and only a relatively small flow passes through the shallow Kiket channel. The restriction of Hope Channel causes an easterly diversion of flow along the north side of Hope Island that splits near Tosi Point. The major portion then flows south through Tosi Channel and the remainder enters a large counterclockwise gyre that develops between Hope and Kiket islands. This gyre receives added impetus from the strong southerly flow in the main channel. A southwesterly flow develops along the southeast side of Skagit Island resulting in a strong

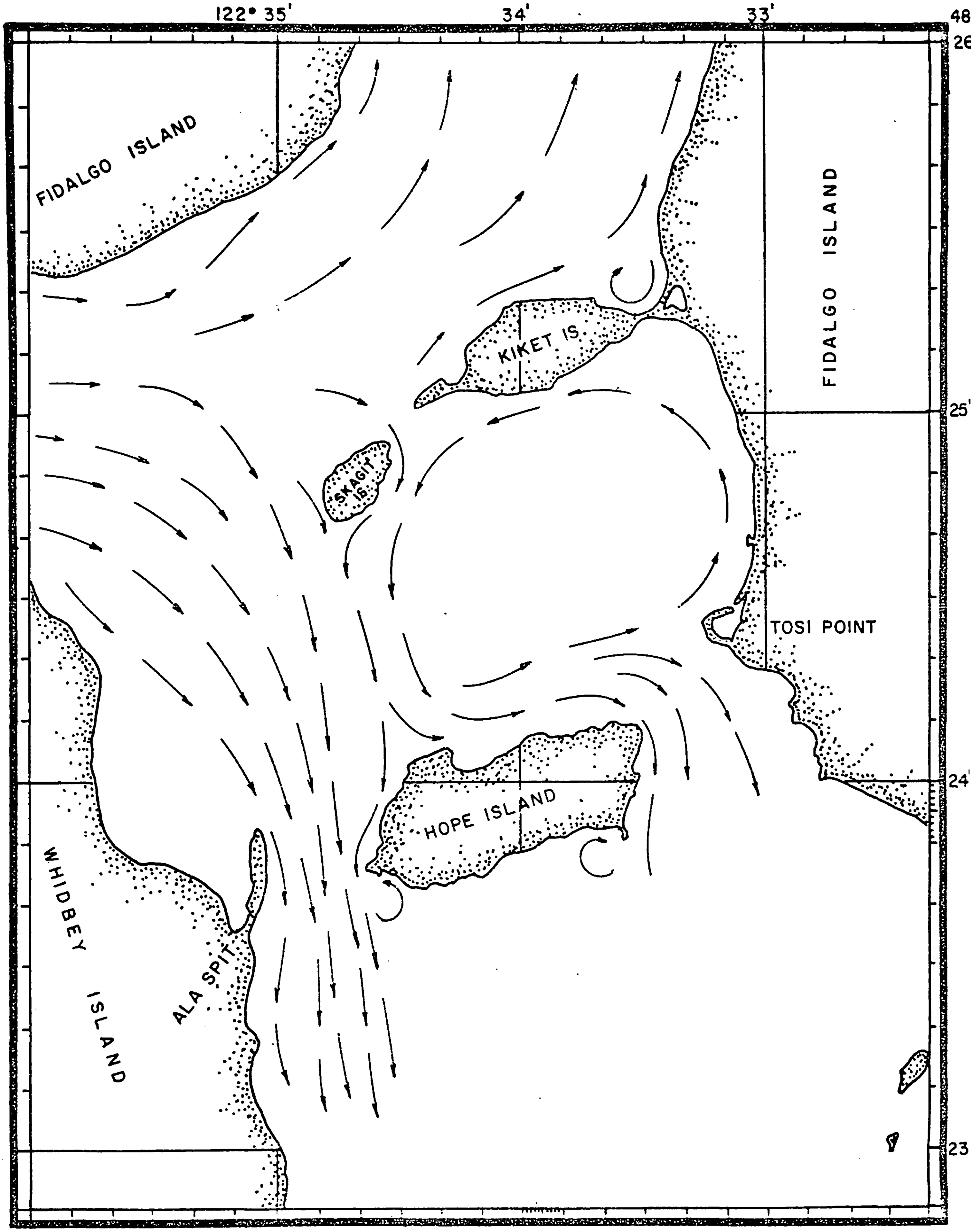

Figure 3-2 Generalized flood cirulation in the vicinity of Kiket Island

convergence near its southern point. As the water level rises, flow through Kiket Channel increases and joins the gyre.

Measurement and observation of circulation south of Hope Island have not been completed. Bottom characteristics and bathymetry, however, suggest that a strong, large-scale eddy exists south of Tosi Channel that has developed the basin referred to as Hunot Hole. The bottom of this basin appears to be well scoured and free of loose sediments. Similar evidence suggests that back-eddies form behind Hope Island at both the east and west ends. The main channel south of Hope Island lies near to and parallel with Whidbey Island to Strawberry Point. That this channel persists and appears to be scoured in spite of the influx of sediments from the Skagit River indicates the presence of relatively strong near-bottom currents. These currents, particularly to the south near Seal Rocks and toward Strawberry Point, may be more closely associated with inflow of more saline water from Saratoga Passage, and possibly seiches, than with the Deception Pass flow. Current measurements are now being made at Strawberry Point to investigate this possibility, but the data are not yet available.

When ebb begins, strong northerly current quickly develops in Hope Island Channel and continues north around Hoypus Point toward Deception Pass and northerly flow through Tosi Channel commences. As the water level is higher during the strength of ebb, flow through Kiket Channel is greater, and a "jet" flow across Hope Island Bay develops between Tosi Channel and Kiket Channel. Part of this flow is deflected toward the west by Skagit Island. The jet again produces the counterclockwise gyre south of Kiket Island that appears to be stronger than during flood although smaller in size as it is confined between the jet and the main channel. At the western side of the gyre, flow is counter to the ebb direction in the main channel and a sharp shear occurs that frequently is very apparent by visual observation. A second clockwise gyre develops east of the jet as water is diverted toward the east by Kiket Island and then south toward Tosi Point. Flow through Kiket Channel swings west, joining the outward flow from Similk Bay toward Deception Pass. Observations of the ebb flow south of Hope Island have not been completed.

A tentative generalized diagram of the ebb flow circulation pattern in Hope Island Bay and vicinity, based on initial observations, is shown in Figure 3-3.

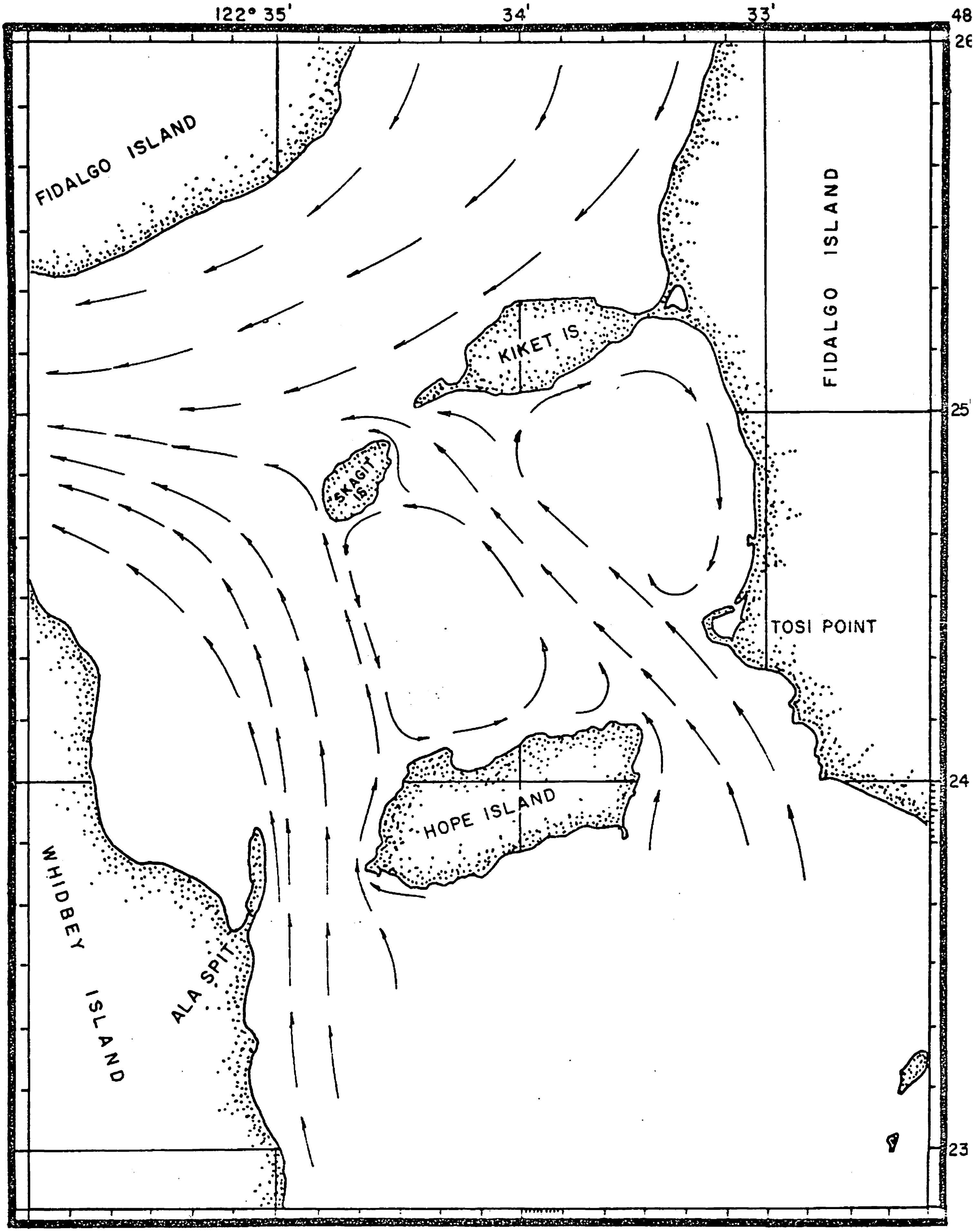

Figure 3-3 Generalized ebb circulation in the vicinity of Kiket Island

3.1.2 *Direct current measurements*

Measurements obtained in the main Hope Channel were obtained in mid-channel at a depth of 9.0 m (29.5 ft,) above bottom where the depth of water is about 15 m below MLLW. This meter was in operation for 124 hr. During this time, flood current set between 177° and 195° for 44% of the time and ebb set between 342° and 003° for 42% of the time. Speeds ranged from zero to 149 cm/sec (2.9 kt), with most values between 56 and 93 cm/sec (1.1 and 1.8 kt). Speeds in excess of 100 cm/sec (1.9 kt) occurred about 19% of the time. Change in current direction between ebb and flood was rapid and speeds increased rapidly. About 10 min was required for direction change and only between 10 to 15 min for speeds to exceed 100 cm/sec. Maximum speeds occurred during flood near low-water stand and were 15-30 cm/sec stronger than at ebb.

Although no measurements were obtained near the surface, appreciably different speeds can be presumed because of the presence of a low-salinity surface layer, from the Skagit River flow, particularly during ebb. The differential between ebb and flood speeds also can be explained at least partially on the basis of the difference in cross-section between high and low water. Flood occurs near low water when the cross-section is lower and therefore speeds would be greater for a given transport volume. During ebb, surface speeds can be expected to be higher under the influence of the accumulated fresh water from river runoff.

Adequate direct current measurements in this channel are difficult to obtain because of the considerable traffic, including frequent tows of log booms and commercial fishing. To make measurements over an extended time period necessary to evaluate tidal effects, the meters must be maintained at a depth below that which would constitute a hazard to shipping. Even then, if measurements are attempted during open fishing periods, the meters are likely to be carried away by nets (as learned from sad experience). Because of these problems, no measurements at or near the surface have been obtained in this location.

The current meters placed in Hope Island Bay by Rosebrook and Hammond (Figure 3-1) demonstrated the existence of the counterclockwise gyre near the center of the bay, and the flow through both Tosi Channel and Kiket Channel. Station 1-2, north of western Hope Island was within but near the western side of the gyre where currents were predominantly southerly (72% of the 325 hours of observation). During a relatively short period near the end of flood and start of ebb, a weak northerly set developed but then the southerly set resumed even during a strong ebb. It is likely that the brief northerly set may be the result of a meander of the main channel flow that temporarily displaced the gyre to the east. During strong floods this station location was also influenced by the easterly diversion of some flow along the north side of Hope Island.

Flow through the Tosi Channel strongly influences circulation in Hope Island Bay. Currents at Station 2-1, west of Tosi Point, showed a set between 111° and 135° (flood) 41% of the time and between 318° and 336° for 47% of the time. Speed ranged from zero to 140 cm/sec (2.7 kt) with most values between 63 and 113 cm/sec (1.2 and 2.2 kt). Following a change from flood to ebb, an hour was required for speeds to exceed 100 cm/sec (1.9 kt). Both flood and ebb decrease slowly following their maximum but increase more rapidly. Ebb flows were stronger and lasted about 14% longer than floods.

At Station 1-3, near the center of the bay, relatively strong currents were observed during ebb under the influence of the flow from the Tosi Channel towards Kiket Channel. However, currents during flood were weak and variable. This location is strongly influenced by the counterclockwise gyre. It appears that the gyre may move towards the north during flood so that this location is closer to the center of the bay where the flow is weaker. Flow setting between 213° and 324° persisted for 85% of the time and was restricted to between 285° and 315° for 43% of the time. Maximum speed observed was 104 cm/sec (2.02 kt), with most values ranging between 0 and 20 cm/sec (0-0.39 kt).

Currents at Station 1-1 were predominantly toward the west to southwest under the influence of the gyre. A set between 213° and 288° occurred about 76% of the time with values usually less than 28 cm/sec (0.54 kt). A maximum speed of 67 cm/sec (1.30 kt) was measured. During flood, currents were generally weak and variable, because of smaller eddies developing near the southern tip of Skagit Island. A southwesterly surface flow close and parallel to the steep rocky shore of the island has been observed there during this phase of tidal flow.

The station north of Skagit Island, Station 1-4, is influenced both by flow associated with Similk Bay and by that passing through Kiket Channel.

During the early part of the flood, when water level is low, the direction is more toward Similk Bay, but near the end of the flood the direction swings toward the small channel. At the start of ebb, when the water level is higher, the direction swings to the northwest as ebb flow through Kiket Channel commences. The speed increases as the "jet" from Tosi Channel extends across Hope Island Bay. Current then swings toward the southwest parallel to Skagit Island where the flow joins the main current to Deception Pass.

3.1.3 *Water-level measurements*

A few of the water-level measurements obtained have been studied at this time primarily as a means of assessing an analytical method. The data considered were measurements from a one-week period, 15-21 July 1969, at Reservation Bay and at Cornet Bay. Data from these stations were taken for the preliminary study because of the major influence of flow through Deception Pass on the water characteristics and processes within the principal study area.

Flow through Deception Pass is primarily hydraulic, as a result of water-level differential between the Rosario Strait area and that within the Skagit Bay system near Cornet Bay produced by the tidal phase and amplitude differences at these two locations. However, there does not appear to be a simple, direct correlation between height differences and predicted current speed, indicating that other factors have some influence on the flow. These factors include wind, river runoff, regional barometric pressure differences, and the inertia of the moving water mass.

Winds will affect water level by surface transport, causing a higher or lower water level, depending on wind direction and duration. Thus a southerly wind will tend to pile up water to the north within Skagit Bay and the northern part of the system and cause an increase in flow through Deception Pass during ebb. Southerly winds may be expected to shift the Strawberry Point tidal node toward the north and thereby increase the effect of the southern connection to Saratoga Passage during a rising water level. Winds over Puget Sound and the Strait of Juan de Fuca also will affect water level at the outer end of Deception Pass. As the wind dies out or changes direction, the relaxation will temporarily reverse the direction of the effect.

River runoff, principally that of the Skagit River, will affect flow and water exchange. The additional volume accumulated during flood tide must be discharged during ebb, thereby increasing this flow. Second, the river water will be mixed with seawater as it flows toward and through Deception Pass, and therefore inflow will increase to maintain the local salt budget. This mechanism produces differences in current with depth as an increase in net outflow near the surface and a net inflow at depth.

Regional differences in barometric pressure can affect the general water level, causing anomalous high water during local low pressure. This effect, however, would be less significant to height differences across Deception Pass, but again, a change in pressure would have some effect as the volume of water readjusts. It is expected that this effect will be minor with respect to water exchange within the study area.

Inertial effects will occur with each change of tide and will vary with the current speed. Inertia will tend to reduce flow and delay onset of current at the beginning of a flood or ebb and to cause currents to persist for some time after water levels are equal at both ends of Deception Pass. Slack water, as a result, may not occur precisely at the time of equal water levels. That is, water level at Cornet Bay must be somewhat higher than at Reservation Bay before an ebb will begin. Ebb will continue until water level is somewhat lower in Cornet Bay than in Reservation Bay. For a short time the flow will, in a sense, be running uphill. This effect will be more evident at times of strong currents and less evident when small tides and lower currents occur.

From visual observation, it is evident that flow through Deception Pass is very turbulent. It follows that because of this, the currents and therefore transport of water not bear a simple linear relationship to the hydraulic head or height differential (ΔH) between the two ends of the Pass. Flow, or mean current velocity, at any time follows an exponential function of ΔH. An exponential increase in ΔH is required per unit increase in transport because of the increased energy dissipated in the formation of turbulence. Therefore water exchange through Deception Pass cannot be approximated on the basis of simple average ΔH and duration of flood or ebb.

Tide heights in the Puget Sound region normally are referenced to the Mean Lower Low Water datum (MLLW). To determine the values of ΔH properly

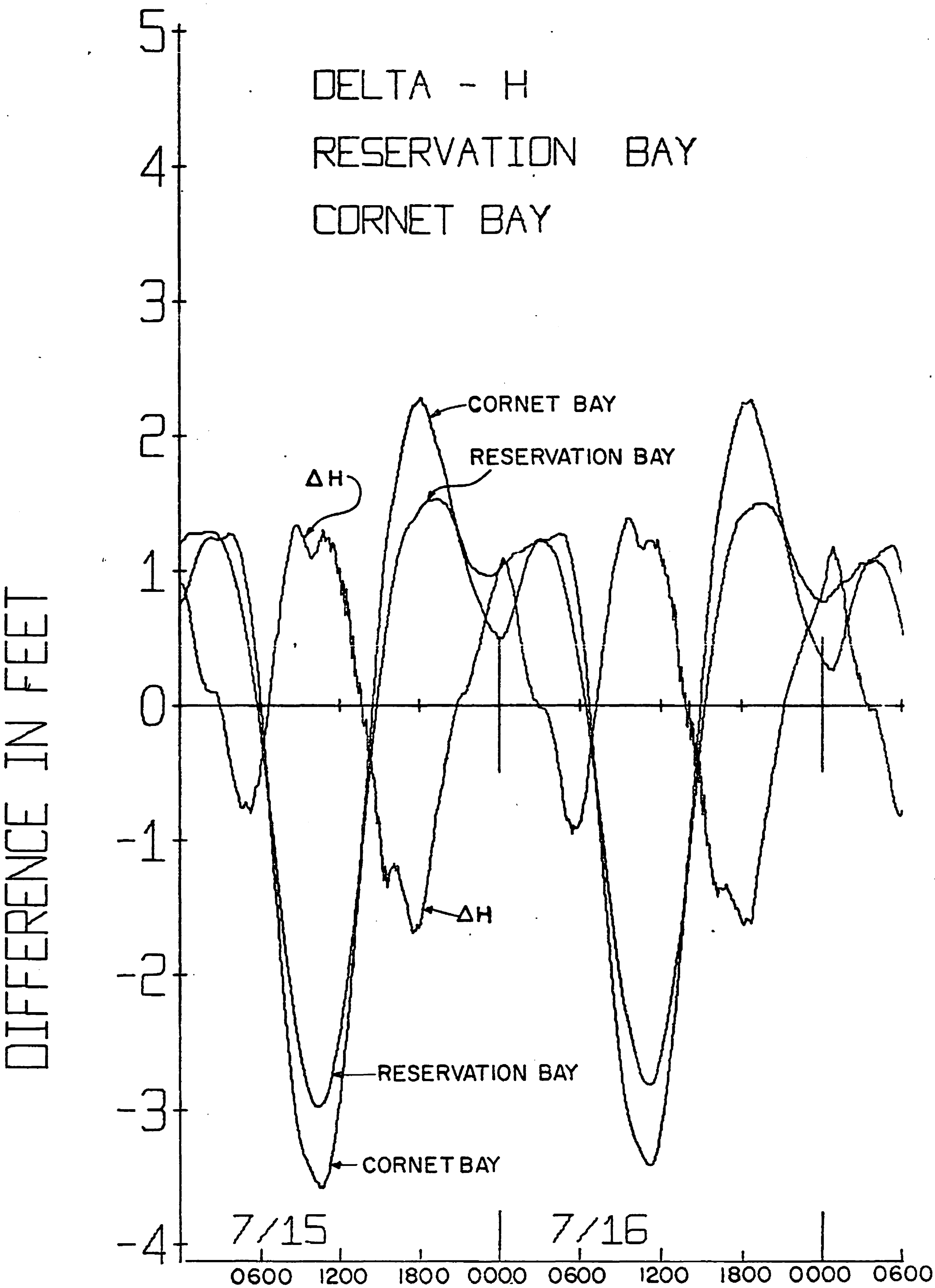

Figure 3-4 Water-level measurements at Reservation Bay and Coronet Bay, and computed ΔH.

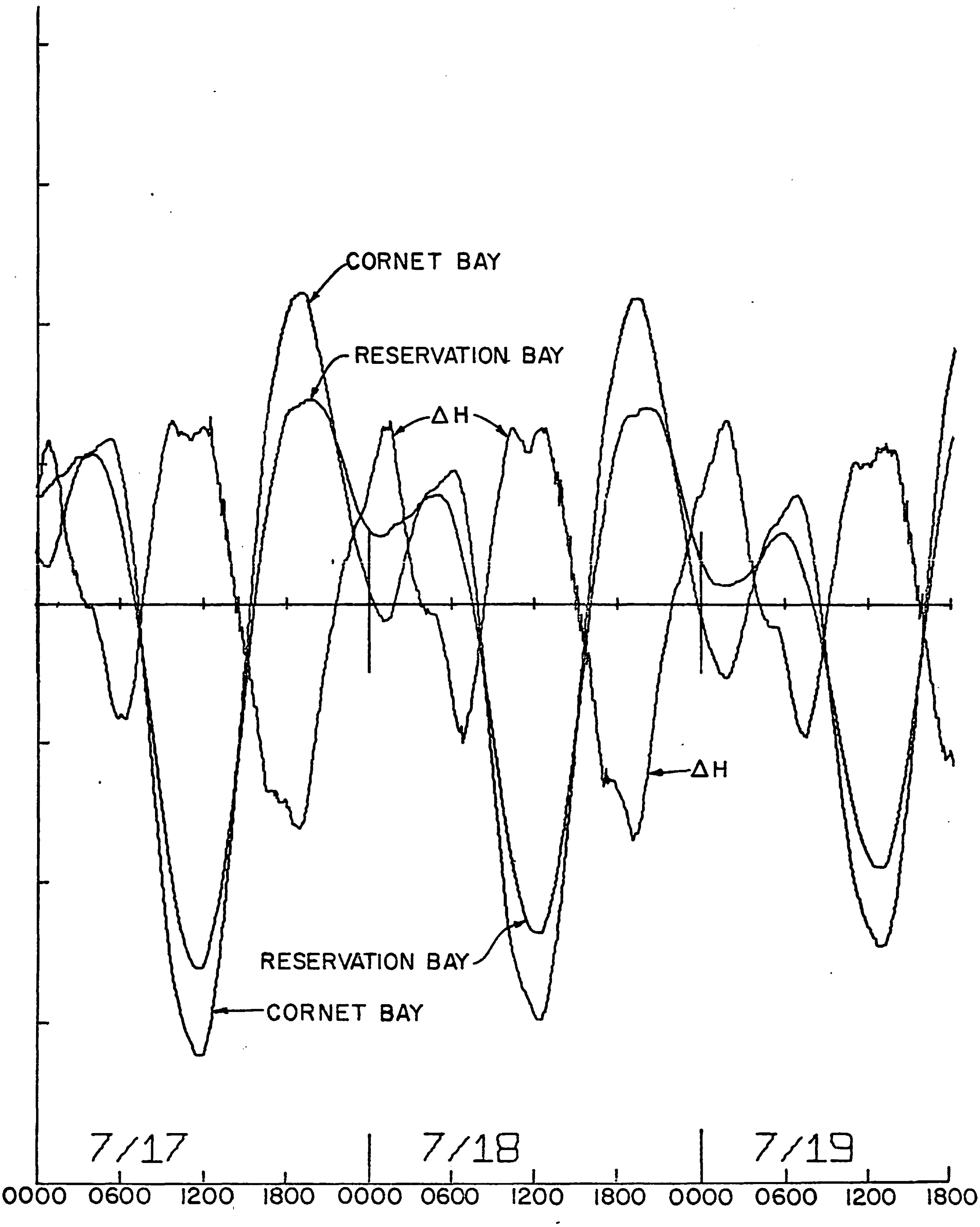

Figure 3-4 (continued)

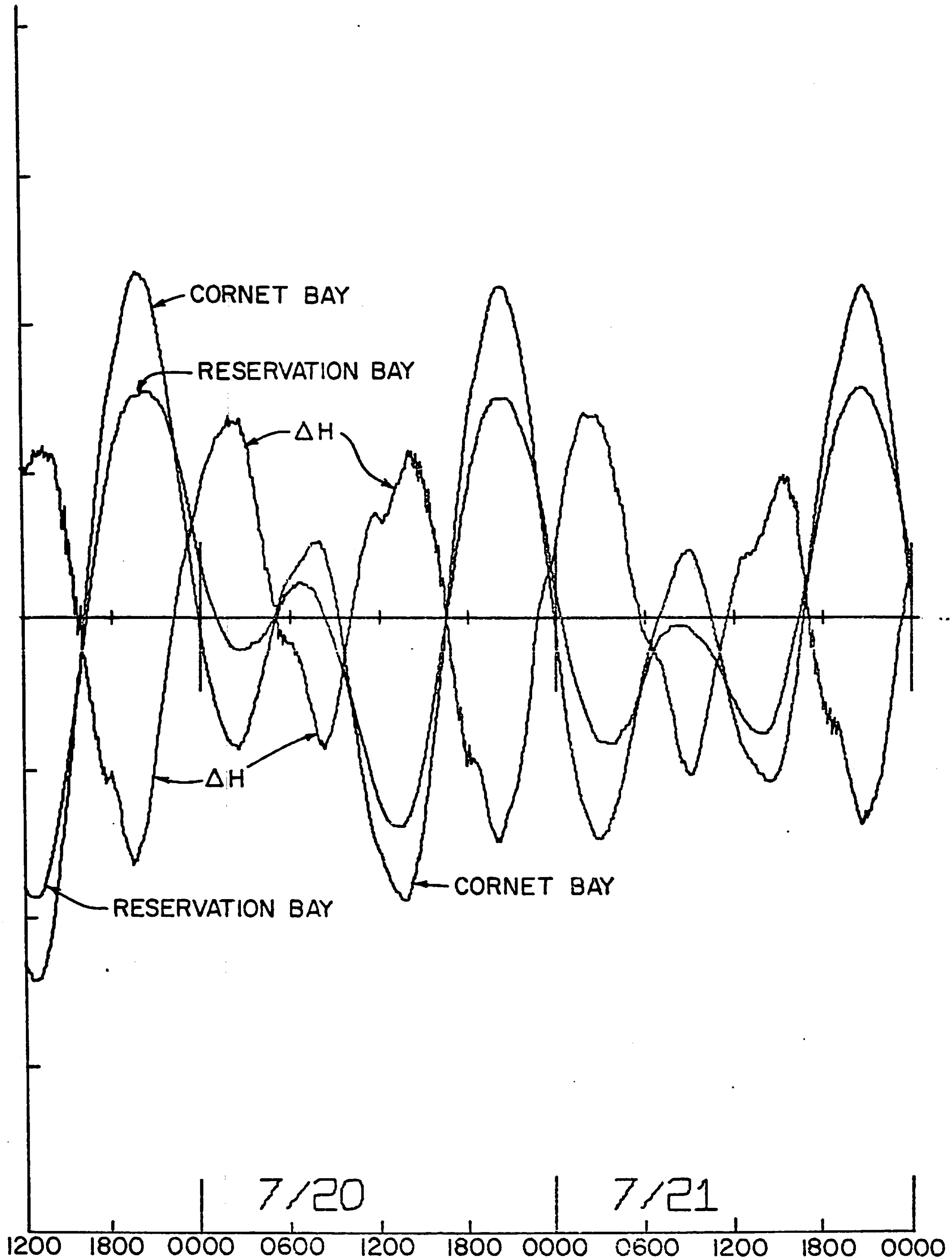

Figure 3-4 (concluded)

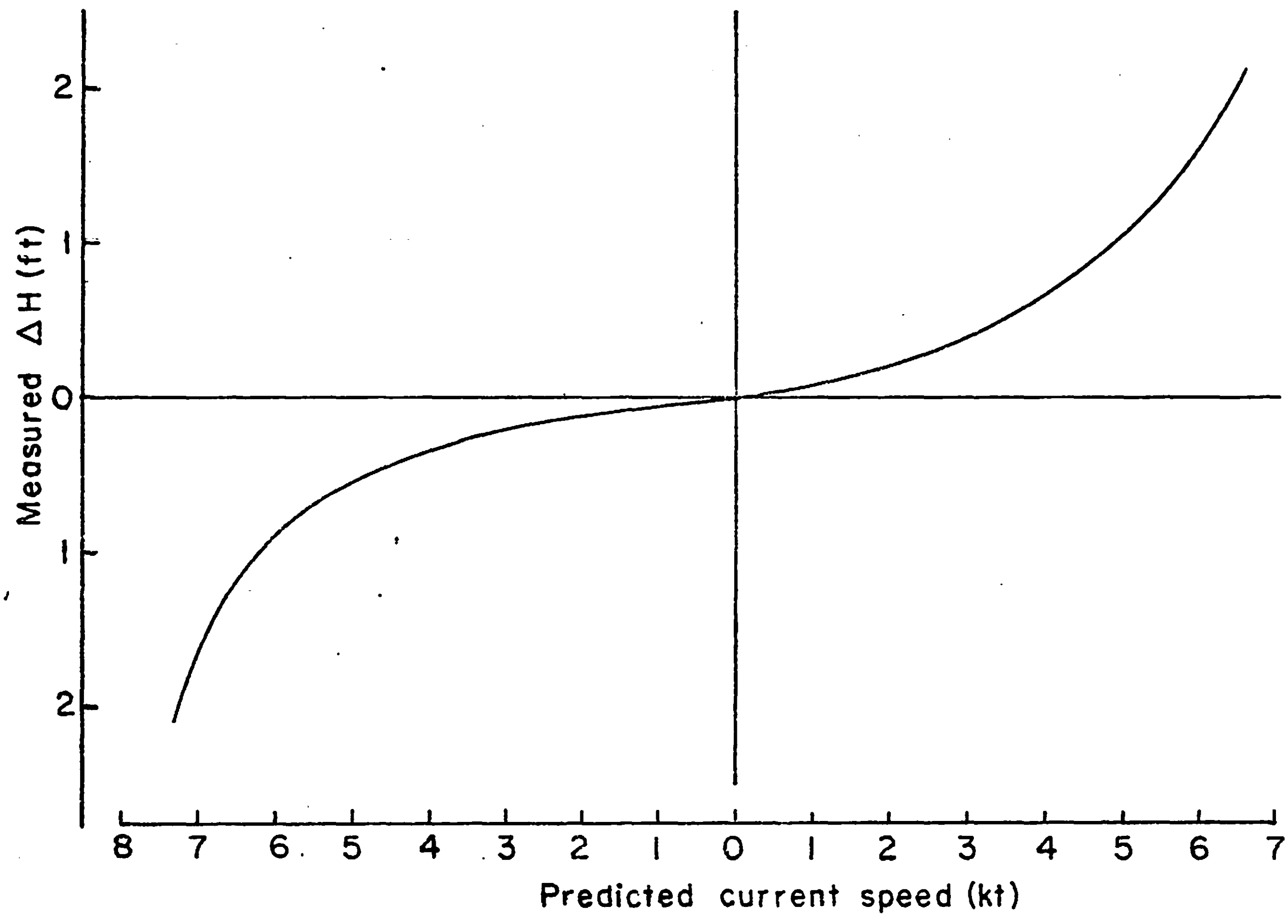

Figure 3-5 Observed ΔH vs Deception Pass currents

between two stations, heights must be referenced to a common geodetic level rather than MLLW. Mean Sea Level provides the common standard level datum. When the water-level gauges were established, precise leveling was done to permit direct determination of true water-level differences between the stations. Leveling at Reservation Bay and at Cornet Bay was based on a first-order level-line referenced to Mean Sea Level established by the U.S.C. & G.S. in 1952. Using known bench marks established for segments of the line, a second-order level was run to each gauge, with closing error of $\pm$ 0.02 ft. Mean Sea Level at Reservation Bay is 4.57 ft above MLLW and 5.68 ft above MLLW at Cornet Bay.

An example of the observed water-level measurements at Reservation Bay and Cornet Bay and the computed ΔH (Reservation Bay minus Cornet Bay) is shown in Figure 3-4 for the period of 15-21 July 1969.

In the case of the larger tides, the ΔH curve shows two peaks or a broad irregular peak. During this period, the ΔH curve also shows irregularity occurring from near the maximum flood to maximum ebb that may be interpreted as short-period (15 to 20 min) oscillations apparently originating as a resonance effect. These oscillations do not appear during the period from maximum ebb to maximum flood; that is, they occur during a rising water level but not during a fall.

If the Deception Pass currents are principally hydraulic, the currents and water-level differential between Cornet Bay and Reservation Bay should show a correlation. It should then be possible to derive an estimate of flow from these differentials and, knowing the cross-sectional area of the Pass, compute the transport volume. This has been done for four days of those shown in Figure 3-4 to investigate this approach.

Some assumptions and approximations were necessary for this study. Actual measured currents in the Pass were not available. Therefore a plot (Figure 3-5) of measured height differences (ΔH) vs. predicted currents (V) was prepared from the one-week period. The predictions give only maximum currents; thus only a limited number of points were available and these were clumped near ebb speeds of about 6 to 7 kt and flood speeds of 4 to 6.5 kt. Since low peak speeds did not occur during this period (15-21 July 1969), it was necessary to approximate the ΔH vs. V curve for the low velocity portion, which introduces uncertainty in the results.

The measured ΔH vs. time curves for ebb and flood for four tidal days were numerically integrated at 0.1 ft ΔH intervals and, using ΔH vs. V curve, the equivalent flow in knot-hours* was computed. These values are tabulated in Table 3-2. For the 4-day period, including eight floods and eight ebbs, the total flood was 96.2 kt-hr and the ebb 102.8 kt-hr or a net ebb of 6.6 kt-hr. This is readily converted to transport volume or net flow on the basis of the cross-section area of Deception Pass (3540 m^2).

$$1 \text{ nautical mile} = 1852 \text{ m}$$

$$1852 \times 3540 = 6.56 \times 10^6 \text{ m}^3 \text{ kt-hr}^{-1}$$

or

$$\frac{1852 \times 3540}{3600} = 182 \text{ m}^3 \text{ sec}^{-1} \text{ kt-hr}^{-1}$$

through Deception Pass. The mean net flow is therefore 1200 m^3 sec^{-1} net ebb. Considering the approximations and the "guesstimation" of the ΔH vs. V curve, this value agrees, within reason, with the value of 566 m^3/sec derived by Rosebrook and Hammond for the net northerly flow through Hope Channel on the basis of their current measurements and approximation of tidal volumes within the system. It appears that the estimation of tidal exchange based on the Deception Pass ΔH is valid, provided that the ΔH vs. V curve is developed with greater reliability. This method also shows promise of providing a means of deriving a correlation between the water exchange and other significant factors such as the Skagit River runoff and meteorological effects.

3.1.4 *Controlling factors*

A number of factors control the dynamic processes occurring in the primary study area. While tides, winds, and river runoff provide the principal driving forces, the manner in which the water moves-- the circulation or flow characteristics-- is affected to a large extent by the magnitude and duration of those forces, the location or area over which they act, and the physical characteristics of the system of basins and connecting channels. The complexity of those forces and their interaction impose considerable difficulty in assessing their individual contribution to the dynamic processes. It is possible, however, to obtain some insight by analogy with other systems and by observation of the consequences of those processes.

*The flow equivalent to a current of one knot for a period of one hour.

TABLE 3-2

Deception Pass transport computed from ΔH
(for selected dates in July 1969)

FLOOD			EBB		
Date	Time	kt-hr	Date	Time	kt-hr
7/15	0633-1330	16.2	7/15	1330-2042	18.1
15-16	2042-0300	7.8	16	0300-0718	7.5
16	0718-1348	14.2	16	1348-2106	18.7
16-17	2106-0324	7.8	17	0324-0742	6.8
17	0742-1424	15.8	17	1424-2130	19.6
17-18	2130-0348	9.4	18	0348-0824	7.0
18	0824-1506	14.6	18	1506-2154	17.7
18-19	2154-0406	10.4	19	0406-0906	7.4
Total		96.2			102.8

Flow through a system will be affected by bathymetry and geographic characteristics, and the nature and distribution of bottom sediments will reveal much regarding relative velocities of the deeper or near-bottom currents. This has been alluded to in the description of circulation within Hope Island Bay. The existence of subsurface valleys with little fine sediment indicates the presence of strong or relatively strong currents, while the location and orientation of such valleys suggest direction, or directions where reversal of direction occurs. Such inference cannot replace direct observation but it can be of importance in interpreting those observations and provide reasonable extension into limited areas that may not have been covered by direct observations in the desired detail. This technique is of value in predicting the formation of small eddies that promote mixing, probable locations of upwelling, convergences, and possible shear zones.

Geography and bathymetry largely determine the pattern of circulation and relative velocities by directing and channeling flow or retarding it. By inducing turbulence, mixing processes are enhanced. By impeding or diverting flow, bathymetry may retard mixing or increase residence time in certain areas while increasing mixing or shortening residence time in others. Although wind is a driving force, it may result in the temporary entrapment of surface waters in embayments or drive the surface waters out of embayments and tend to produce upwelling at their head. This is particularly true in closed areas such as Similk Bay where a southerly wind may tend to hold or collect surface water while a northerly wind will assist flushing. In either case, wind will play a significant part in establishing circulation in this area of shallow water and currents that are weak in comparison to those of most of the northern Skagit Bay system.

Although few direct substantiating measurements are as yet available, there is evidence that dynamic processes within the main Puget Sound basin play a significant part in the water exchange and flushing of the primary study area, through changes in the characteristics and depth of the pycnocline there and on through Saratoga Passage. If and when the pycnocline rises in Saratoga Passage, as a result of seasonal variation or as a result of oscillations within the main Puget Sound basin, intrusion of a greater volume of deeper, more saline water past Strawberry Point may occur. This process would then contribute to the net discharge through Deception Pass and thus enhance the exchange and flushing of the northern part of the Skagit Bay system. Current meters are now emplaced at Strawberry Point to obtain direct measurements for investigation of this effect. These direct observations, together with the periodic oceanographic observations within Puget Sound, will provide the quantitative data necessary to evaluate the frequency and magnitude of this effect.

3.2 *Water properties*

3.2.1 *Introduction*

The waters in the vicinity of Kiket Island have been divided into seven oceanographic subregions as shown in Figure 3-6. These subregions are: (1) southern Rosario Strait, which serves as the source water for Deception Pass; (2) from Deception Pass to Dewey; (3) Similk Bay; (4) Hope Island Bay; (5) the passages at the west and east ends of Hope Island; (6) Skagit Bay; and (7) the region south of Strawberry Point including Saratoga Passage and Possession Sound, which serves as the source water for the southern part of the Skagit Bay system. The source waters at both ends of this system originate in the Strait of Juan de Fuca. As oceanic water moves landward at depth, it is modified by mixing with fresher water from precipitation and runoff. Water entering Rosario Strait is less modified than is the water feeding Possession Sound. This latter water is influenced by mixing in Admiralty Inlet and the main basin of Puget Sound and by runoff from the Puget Sound drainage basin.

3.2.2 *Strait of Juan de Fuca*

Water properties in the Strait of Juan de Fuca are determined to a large extent by properties of the oceanic water off Cape Flattery. Inflowing Pacific Ocean water forms a deep layer below about 100 m throughout the year. A shallower surface layer is formed by runoff and mixing. The characteristics of the deeper water vary in response to seasonal changes in offshore winds. During the summer months, winds from the north predominate along the Washington Coast, causing deeper oceanic water to be brought closer to the surface by upwelling. This upwelled water is relatively cool, highly saline, nutrient-rich, and low in dissolved oxygen. In late July and August, flow is landward at depth throughout the entire length of the Strait of Juan de Fuca,

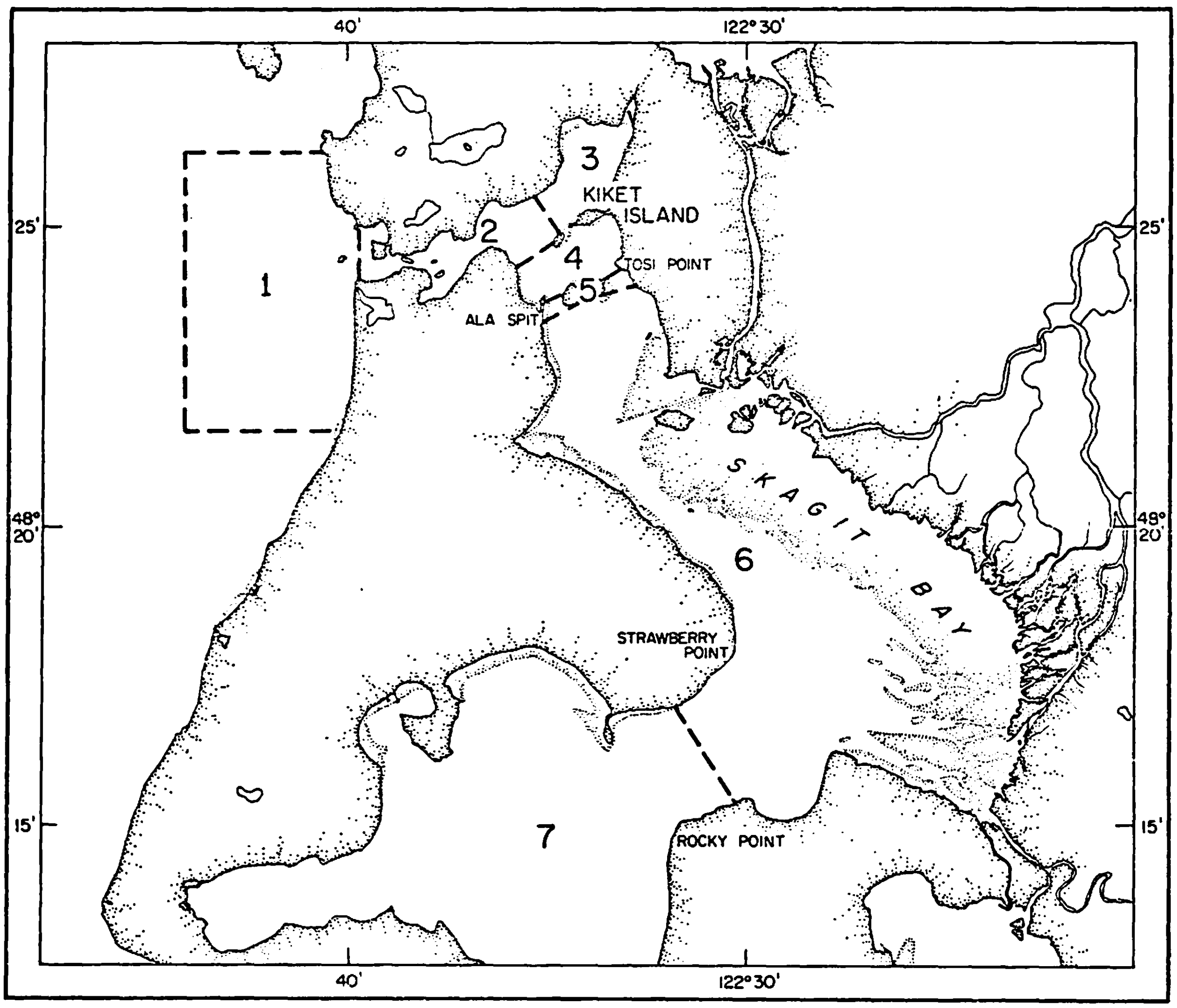

Figure 3-6 Oceanographic subregions in the vicinity of Kiket Islands

and oceanic type water can penetrate into Puget Sound and Rosario Strait. Also during the summer months, river runoff diminishes to its annual minimum flow following the early summer peaks caused by snow melting in the mountains. By late autumn, after 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. Concurrently, the surface becomes less saline because of increased runoff and lower in temperature because of seasonal cooling. Hence a seasonal cycle of water characteristics is developed in response to the meteorological cycle. To illustrate the changes in water properties observed in the Strait of Juan de Fuca, semi-monthly averages of temperature, salinity, dissolved oxygen, and density[1] at selected depths for a station off Pillar Point[2] are presented in Figure 3-7.

For the present study, the most seaward station occupied on the tri-weekly cruises is northeast of New Dungeness (see Figure 2-2). Water properties observed at this station are presented in Figure 3-8. Conditions here are very similar to those observed at Pillar Point, with the maximum intrusion of oceanic water being observed during August.

3.2.3 *Puget Sound Main Basin*

As seawater moves inward from the Strait of Juan de Fuca, it is mixed with fresher and often warmer water leaving both Puget Sound and Georgia Strait. The primary mixing zone for water entering and leaving the main Puget Sound basin is Admiralty Inlet. A portion of this mixed water moves into Puget Sound at depth and forms the deeper source water for Possession Sound.

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[1]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:

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

[2]This station is located at 48°18.2'N and 124°02.1'W, about 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 the late Dr. Thomas G. Thompson.

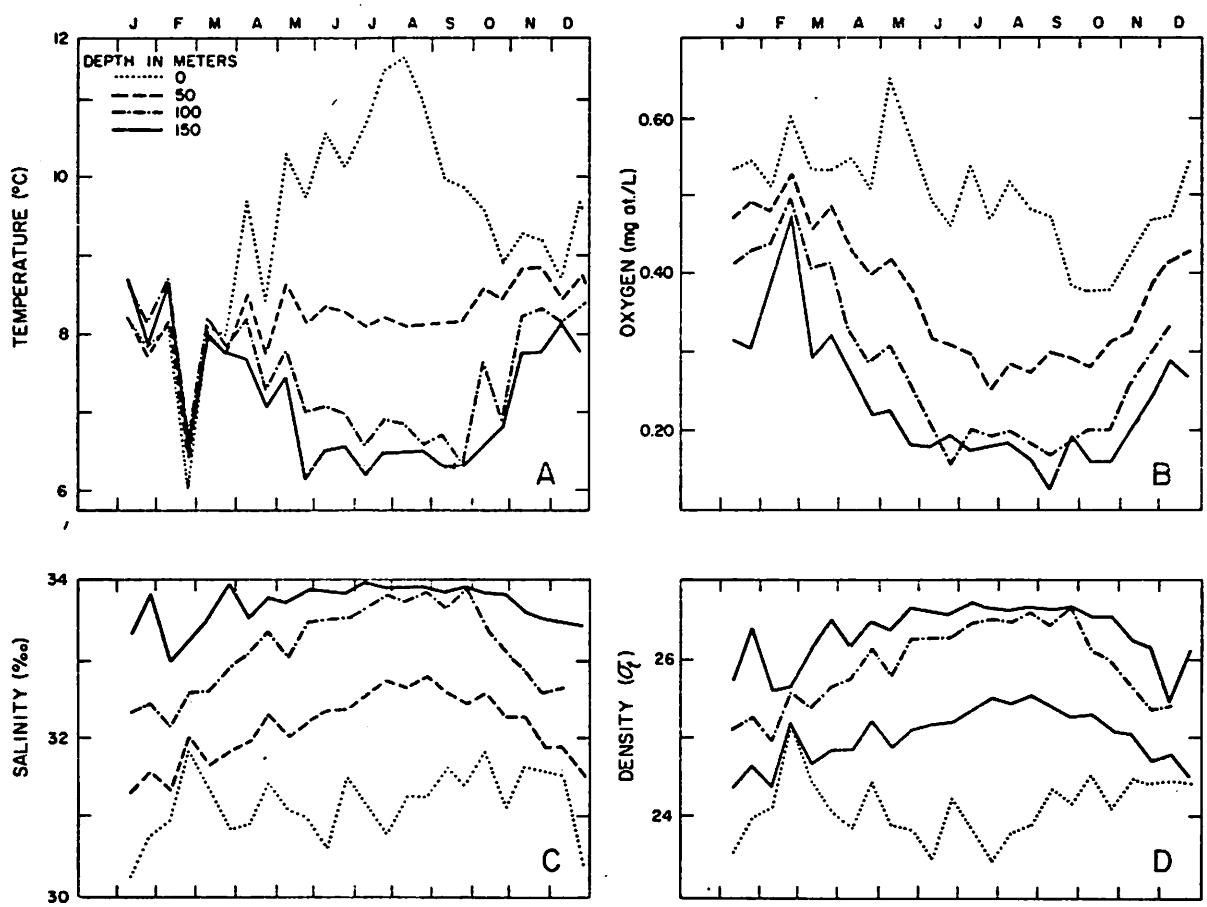


Figure 3-7 Water properties at Pillar Point

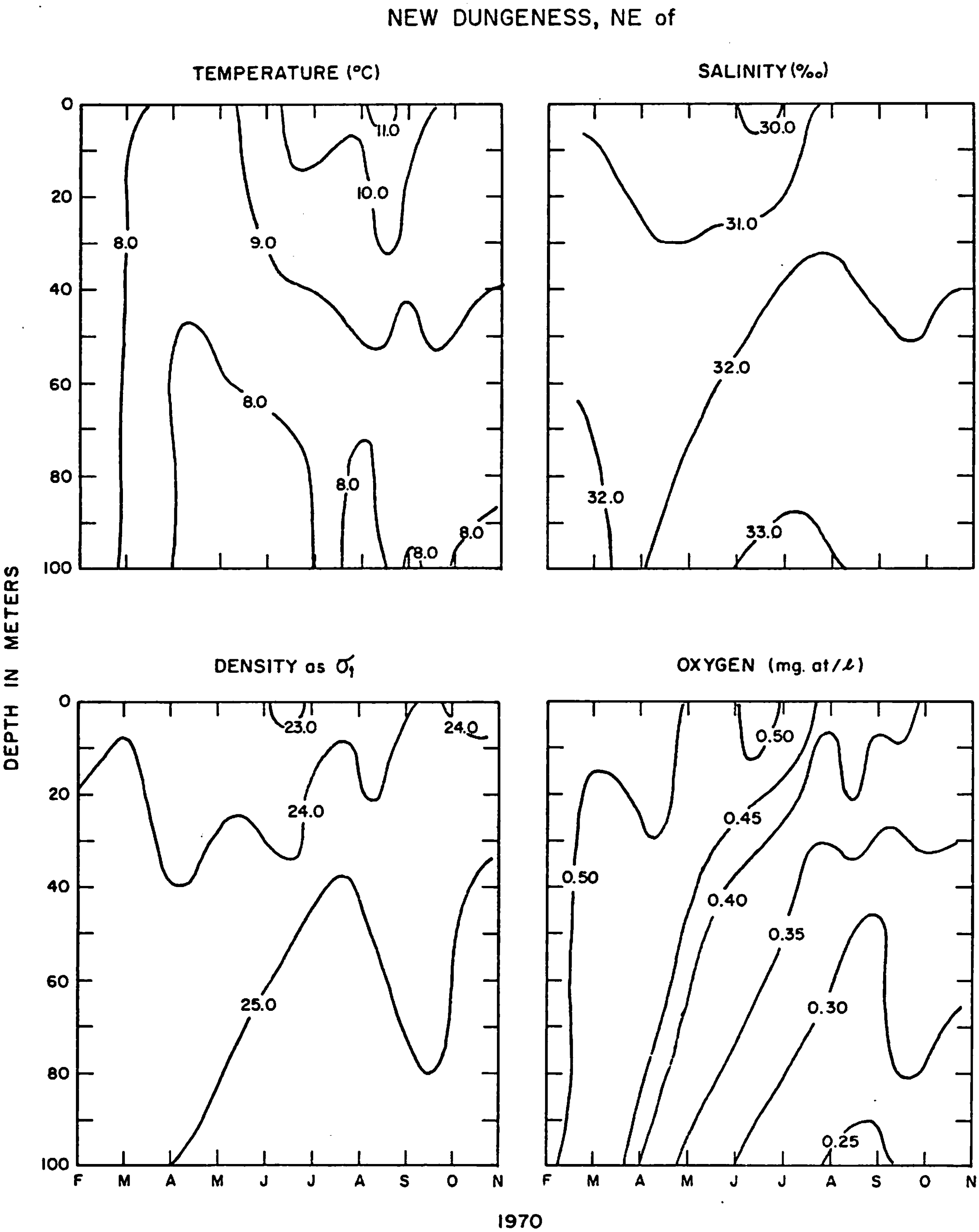


Figure 3-8 Water properties at New Dungeness: February-October 1970

Vertical profiles of temperature, salinity, density, and dissolved oxygen at 9-week intervals are presented in Figures 3-9 through 3-13 for a line from New Dungeness, continuing through the main basin, to just north of Tacoma. During the winter, (Figure 3-9) water temperatures over this entire region were nearly isothermal and varied only from 7.6° to 8.5°C. By April, (Figure 3-10) the average temperature had increased slightly and the first evidence of a near-surface thermocline was noted. During late spring and summer, (Figures 3-11,-12) a significant thermocline developed with a maximum surface temperature of 13.5°C being observed off Seattle. By October (Figure 3-13) seasonal cooling had commenced and the waters were again becoming isothermal.

Significant salinity stratification was present in the upper 50 m throughout most of this period. Minimum gradients were observed in August. Intrusion of oceanic type water entering the Strait of Juan de Fuca in summer influenced all parts of Puget Sound as a marked increase of salinity at depth. The timing and magnitude of this change varied with distance from Cape Flattery and local conditions.

Densities were observed to be minimum in winter and maximum in late summer. Density stratification was most dependent upon salinity structure. The oxygen content of the water below 20 m was highest in winter and lowest in late summer. The highest surface oxygen was noted in June (Figure 3-11) when the effect of the spring phytoplankton bloom was at a maximum.

3.2.4 *Possession Sound-Saratoga Passage*

The waters of Possession Sound and Saratoga Passage are strongly influenced by runoff from the Skagit, Stillaguamish, and Snohomish Rivers. On an annual basis, these three rivers collectively contribute over 75% of all fresh water entering the Puget Sound system. The Skagit River contributes 50% of this total and exhibits two peaks in runoff. The winter peak occurs as the result of land drainage when rainfall is greatest. But the highest peak occurs in June when the snow melts in the mountains. Since this river is regulated by a series of dams, the peaks are often broader than would be the case if they were unregulated. The Stillaguamish River is predominantly rain-fed and has a major peak in winter with only a minor spring snowmelt peak. The Snohomish River also exhibits two peaks in runoff in a manner similar to the Skagit, but this river is unregulated. As a

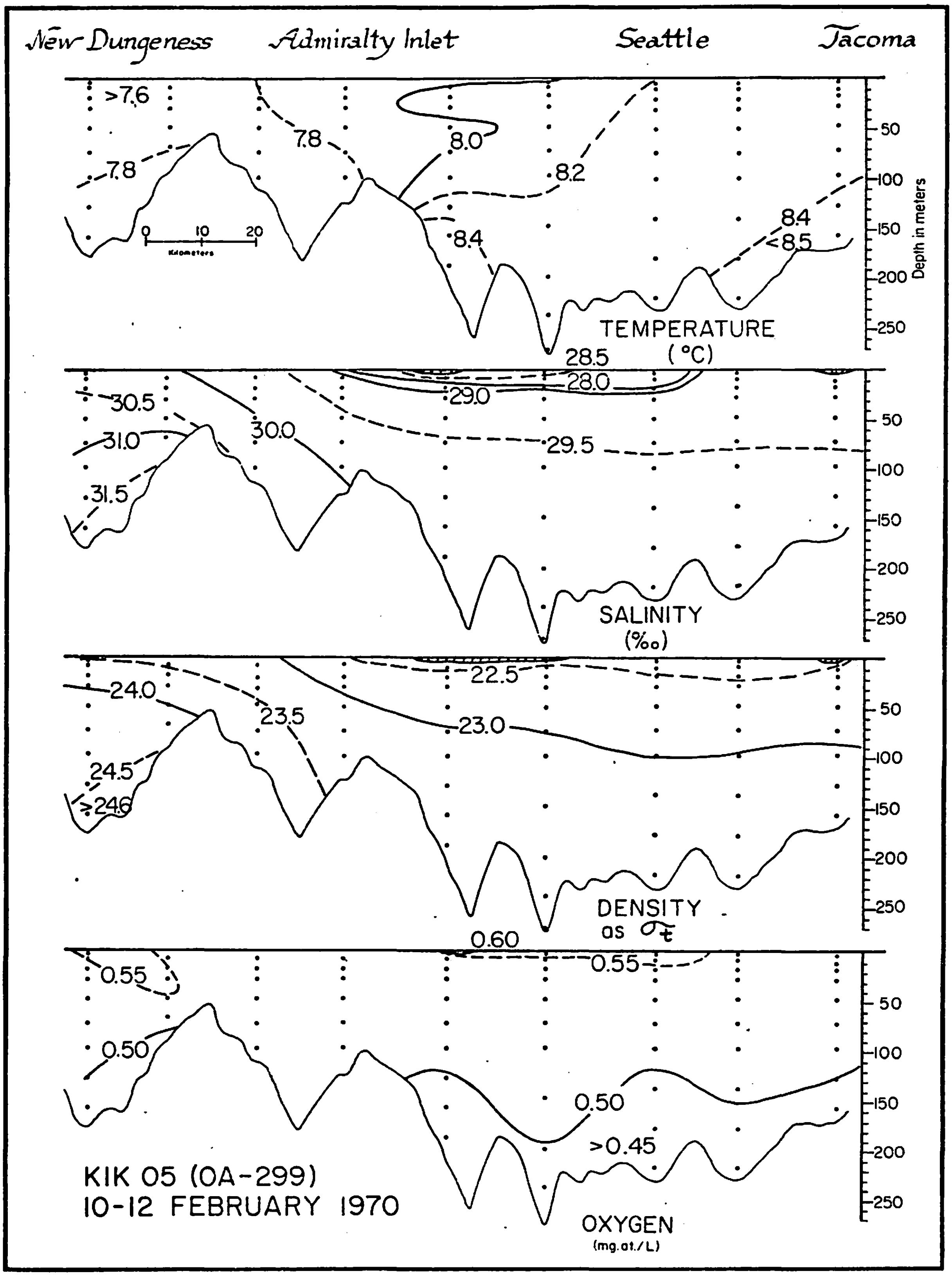


Figure 3-9 Water properties in Puget Sound Main basin, 10-12 February 1970

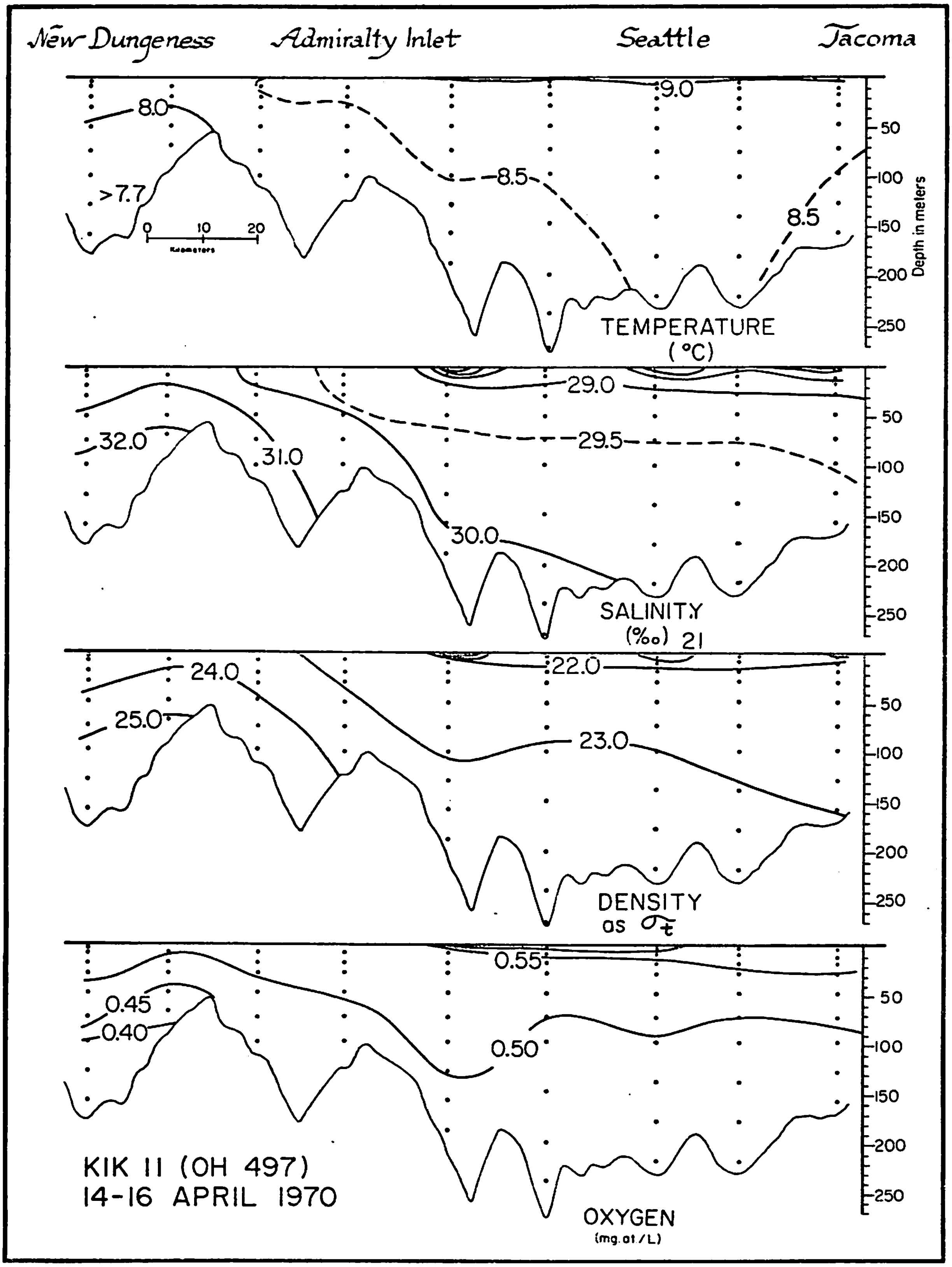


Figure 3-10 Water properties in Puget Sound main basin, 14-16 April 1970

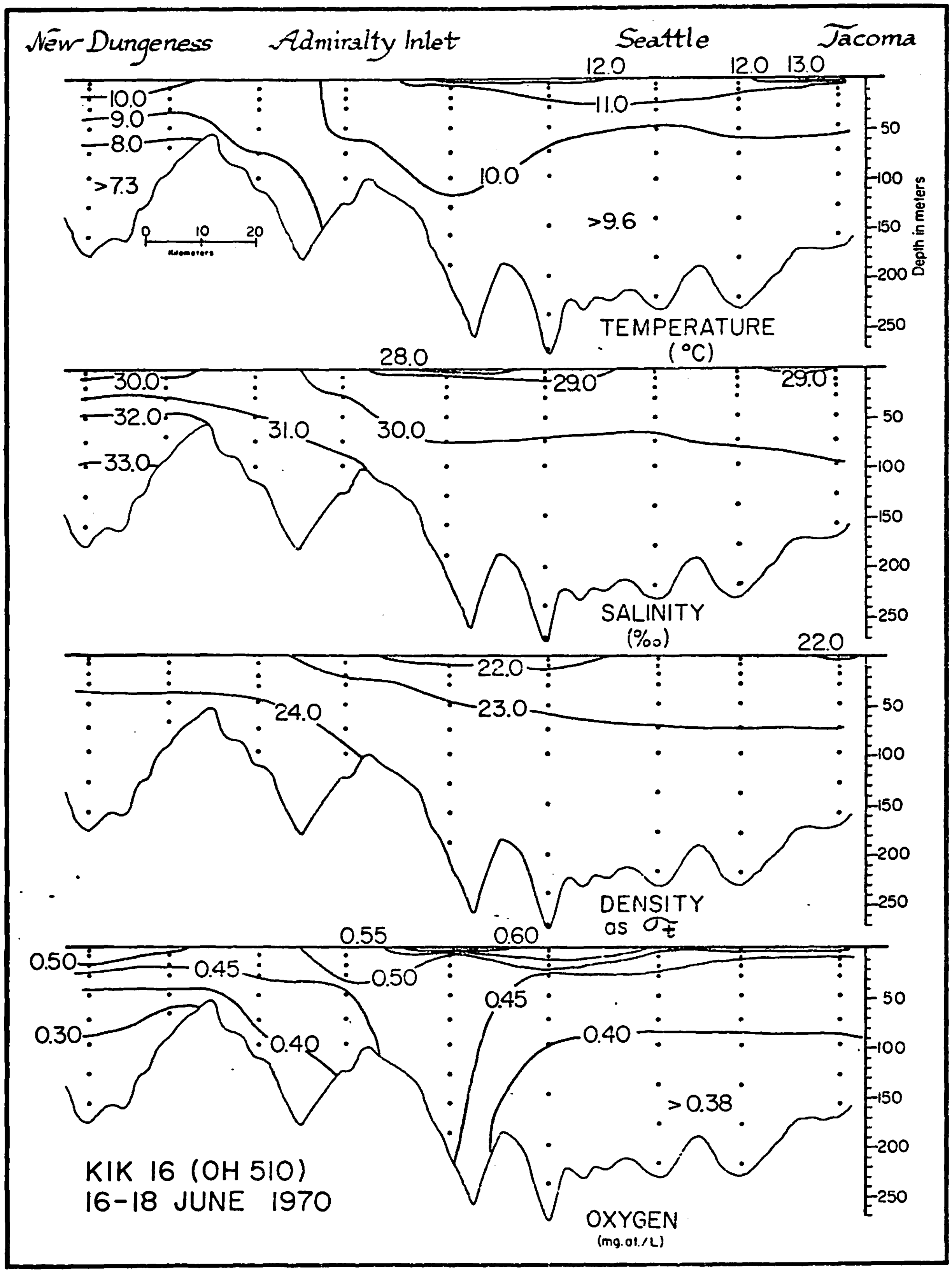


Figure 3-11 Water properties in Puget Sound main basin, 16-18 June 1970

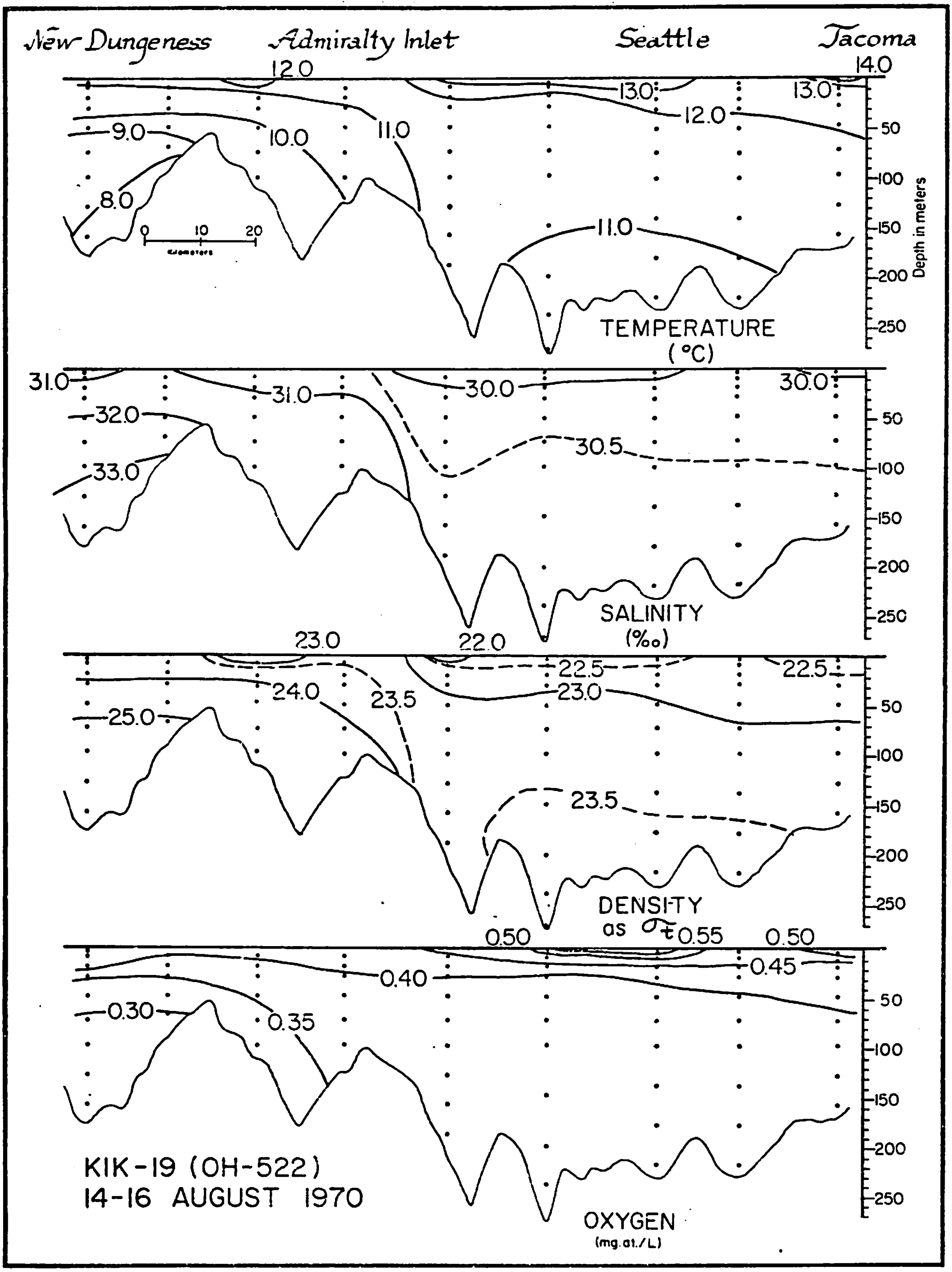


Figure 3-12 Water properties in Puget Sound main basin, 14-16 August 1970

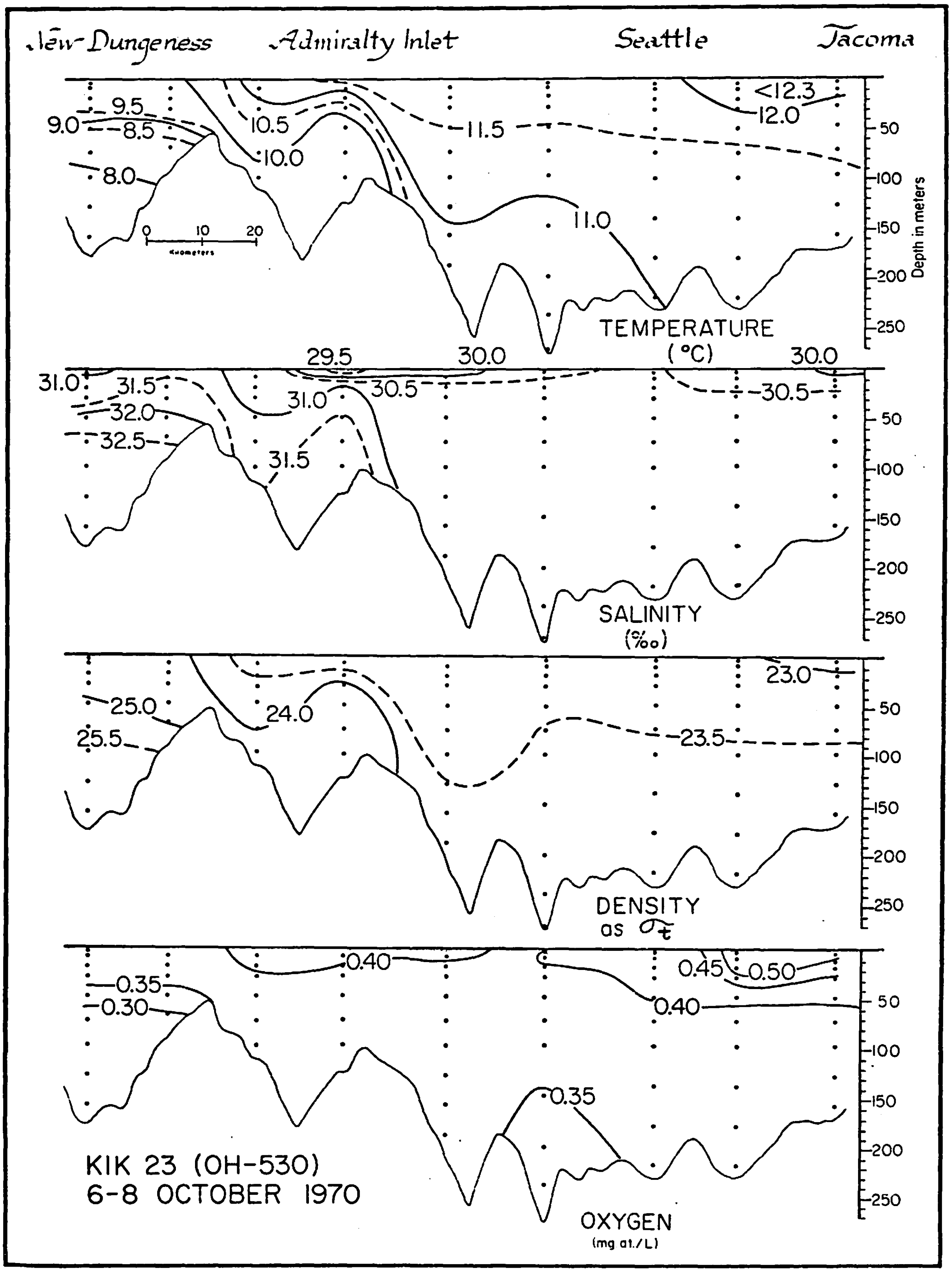


Figure 3-13 Water properties in Puget Sound main basin, 6-8 October 1970

result, a nearly continuous source of fresh water enters this subregion and the Skagit Bay subregion for about ten months of the year. A relatively thick (3-10 m) surface layer is thereby developed with its salinity and depth being partly controlled by the total amount of accumulated river discharge at any given time.

Changes in water characteristics at the Possession Point station are presented in Figure 3-14 for the period between February and October 1970. The intrusion of water of increasing salinity progressed from May to September during which period the salinity at depth increased to nearly 31‰ and the oxygen decreased to about 0.35 mg atoms/liter. The warmest surface water (slightly over 15°C) occurred in early July and the minimum temperatures were observed in March with a low of 7.6°C.

The properties of the waters in the Possession Sound - Saratoga Passage subregion are shown at 3-week intervals along vertical profiles in Figures 3-15 through 3-27. These profiles are sections from Seattle to Deception Island and pass through the Kiket Island subregion. The effect of the large amount of fresh water being discharged in this region is prominent in all the profiles as indicated by the fresher and less dense surface layer.

The most significant change in distribution of variables along these profiles was dissolved oxygen. In February 1970 (Figure 3-15) oxygen concentration below the surface layer from Possession Point to the south end of Skagit Bay was relatively high and decreased with depth. By April (Figure 3-18) a pronounced oxygen minimum began to develop at about 30 m. The oxygen content in the deeper layers of Saratoga Passage continued to decrease through early October (Figure 3-27). Because data from later cruises were not available at the time of writing, the trend is not yet established. This low oxygen at depth is the result of limited circulation in Saratoga Passage coupled with oxygen depletion by decay of organic matter produced in the surface layer where high production of phytoplankton occurs in spring. Zooplankton then feed on the phytoplankton and as the plants and animals die, the remains begin to settle. In the deeper more quiet waters, the oxygen demand becomes high and dissolved oxygen is utilized in the decay processes. This low-oxygen-content water was also characterized by lower temperatures, indicating that it is relatively old in comparison with other water in the system.

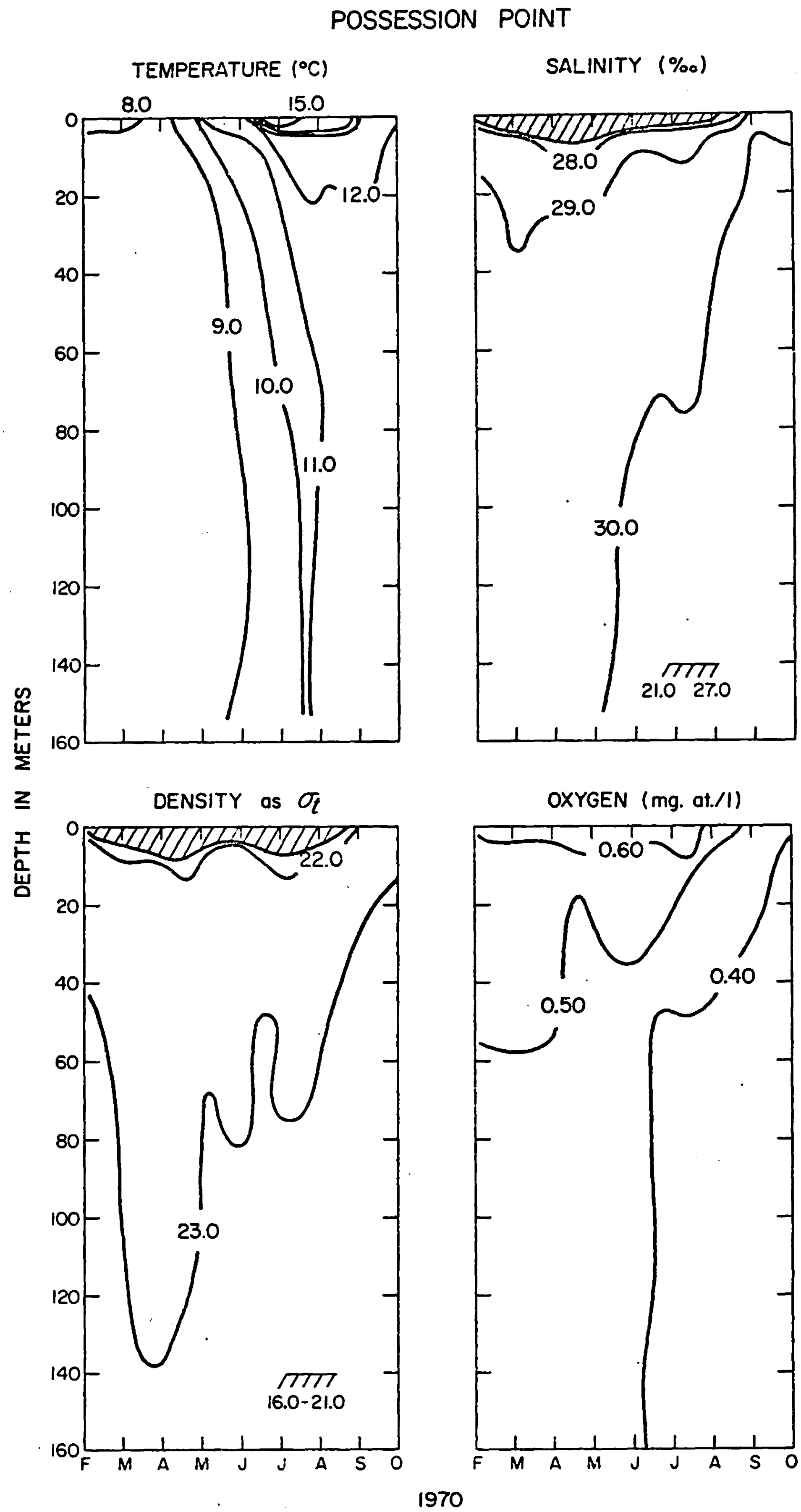


Figure 3-14 Water properties at Possession Point: February-October 1970

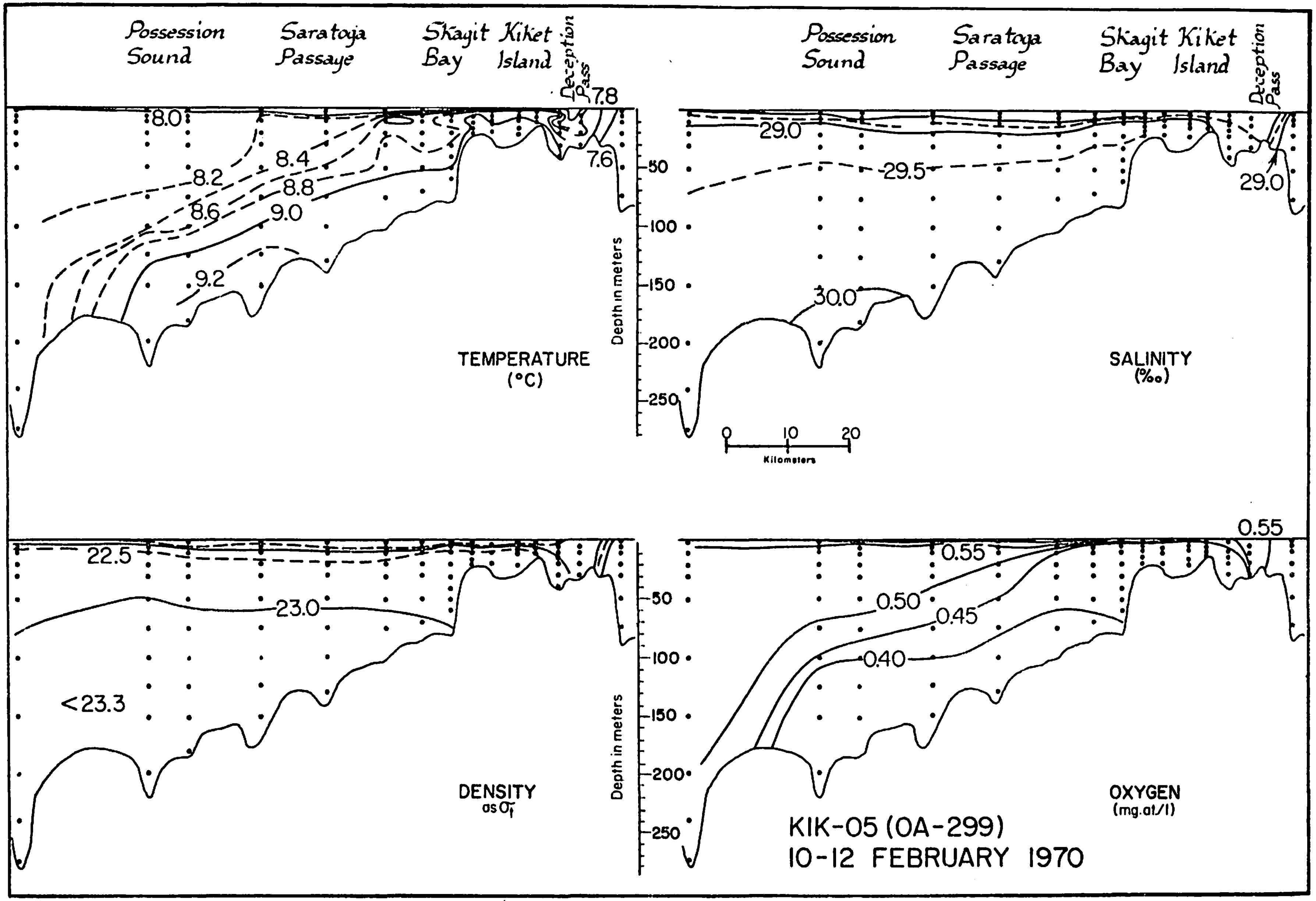
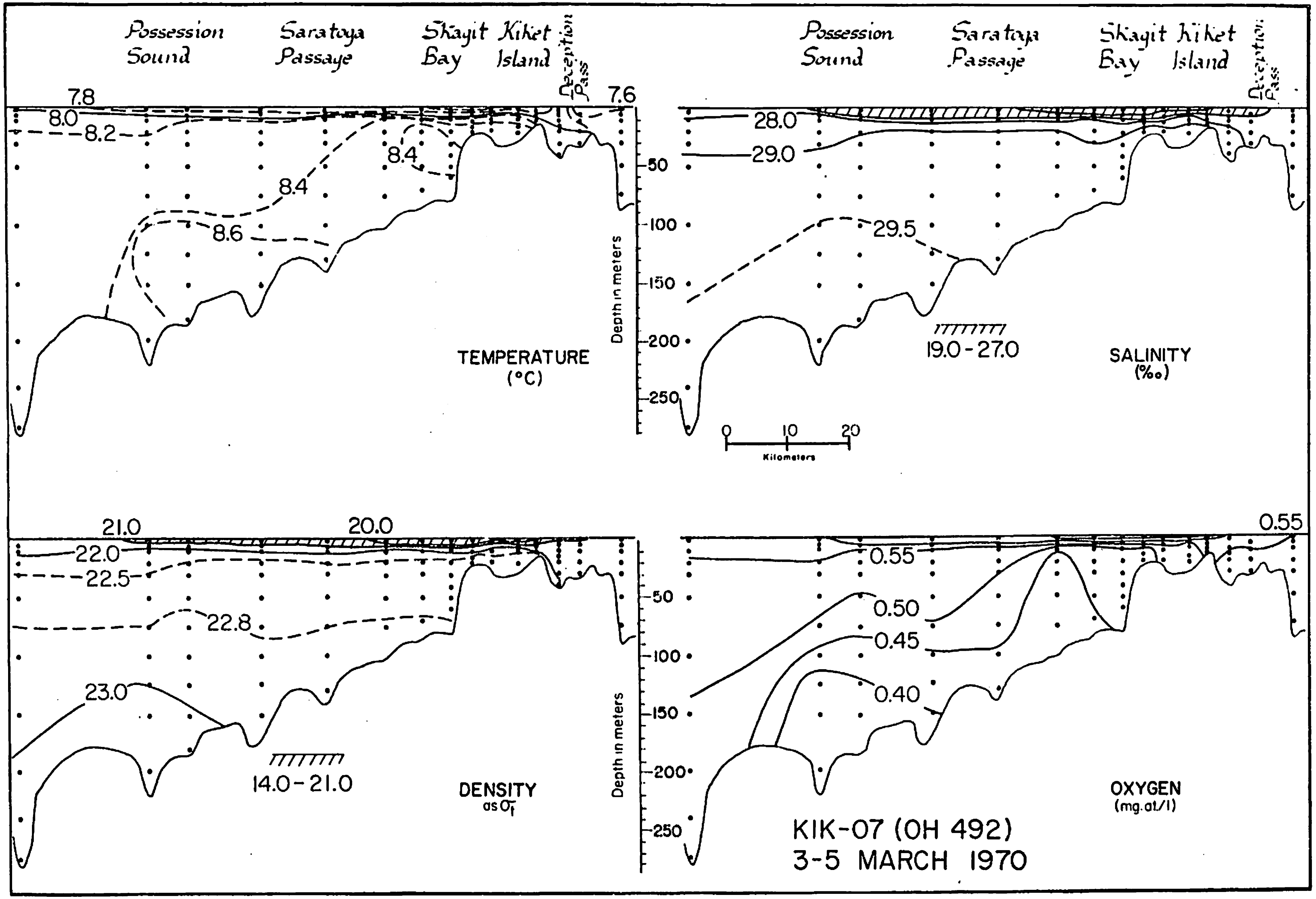


Figure 3-15 Water properties; Seattle to Deception Pass: 10-12 February 1970

Figure 3-16 Water properties; Seattle to Deception Pass: 3-5 March 1970



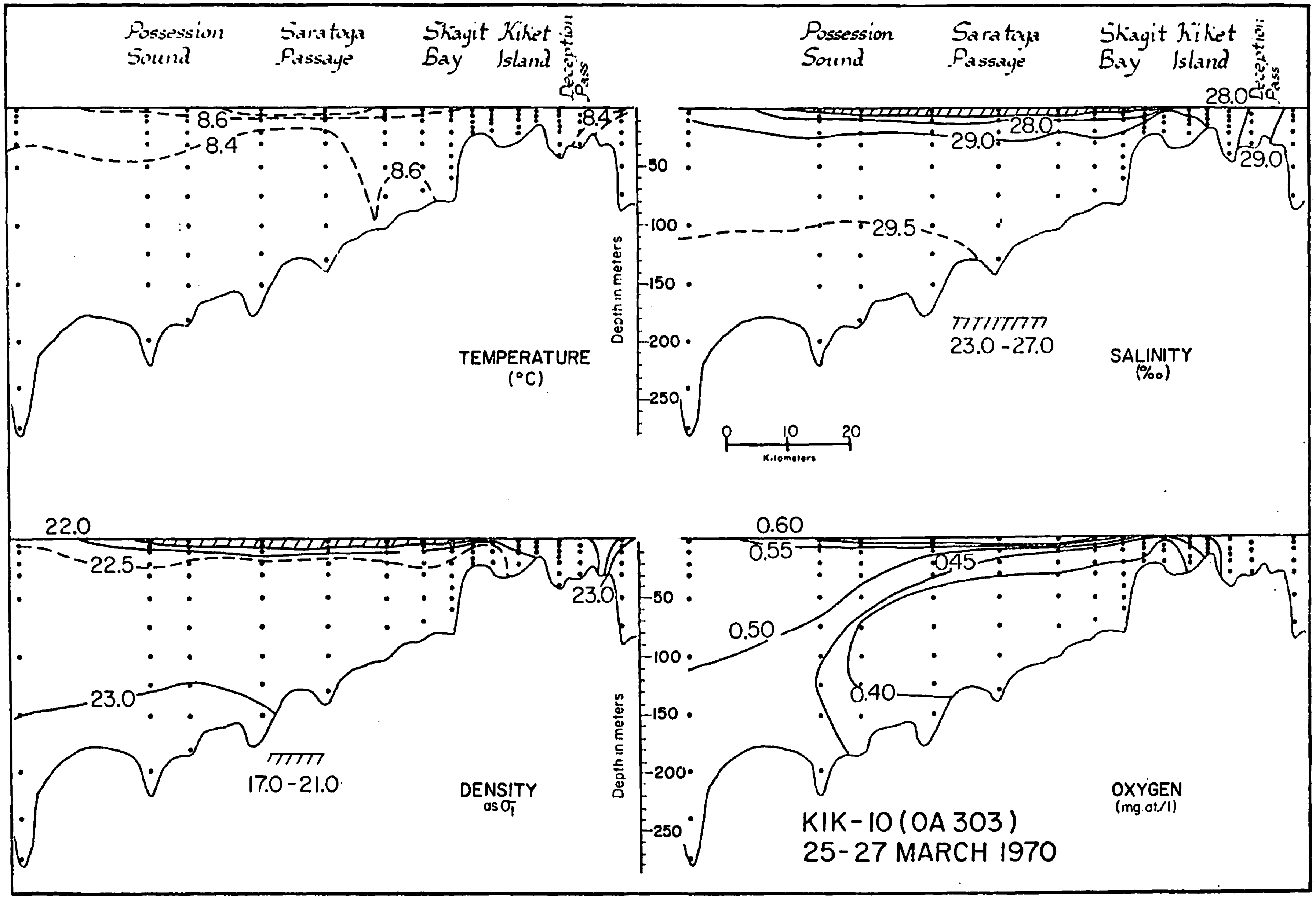


Figure 3-17 Water properties; Seattle to Deception Pass:
25-27 March 1970

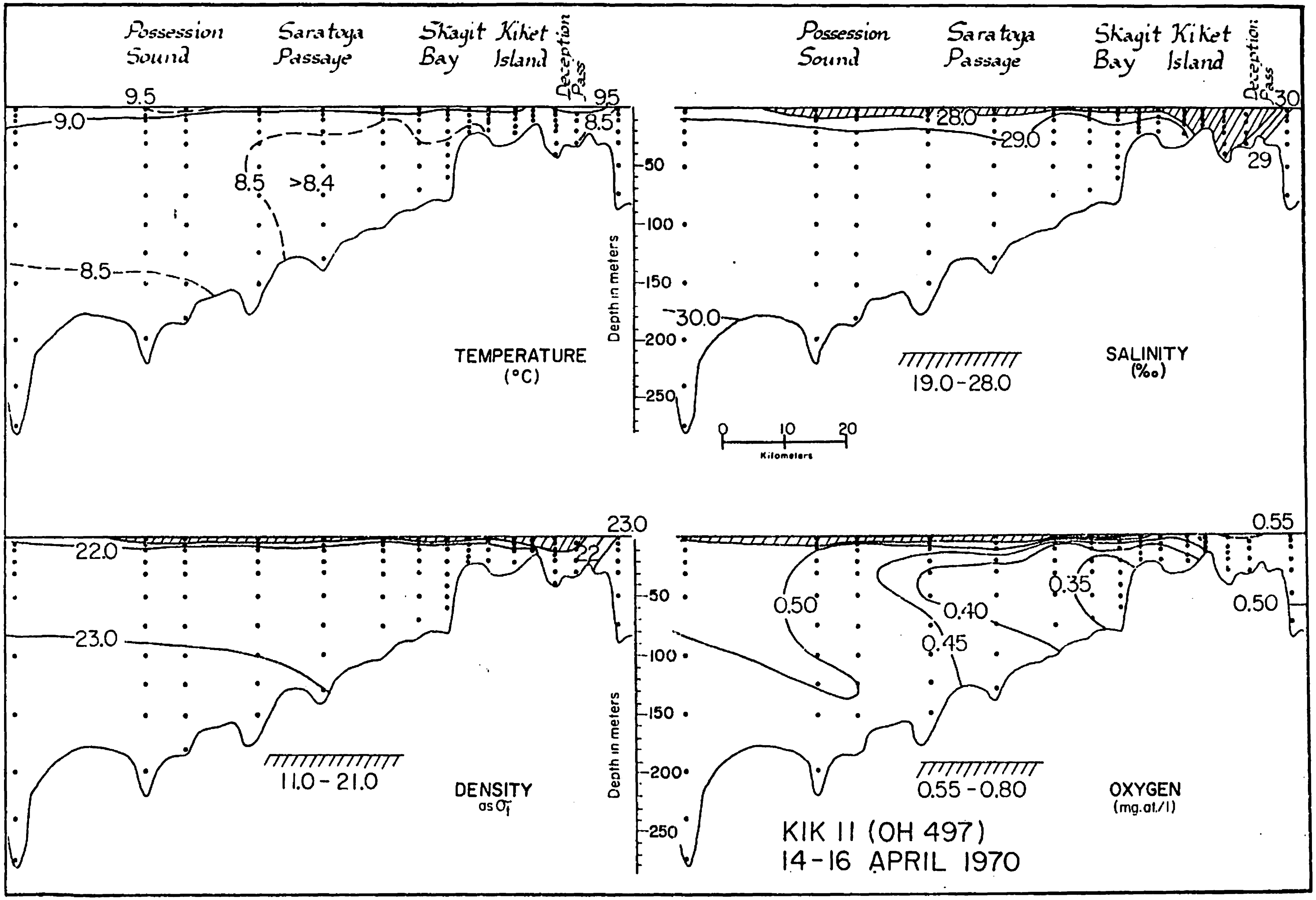


Figure 3-18 Water properties; Seattle to Deception Pass: 14-16 April 1970

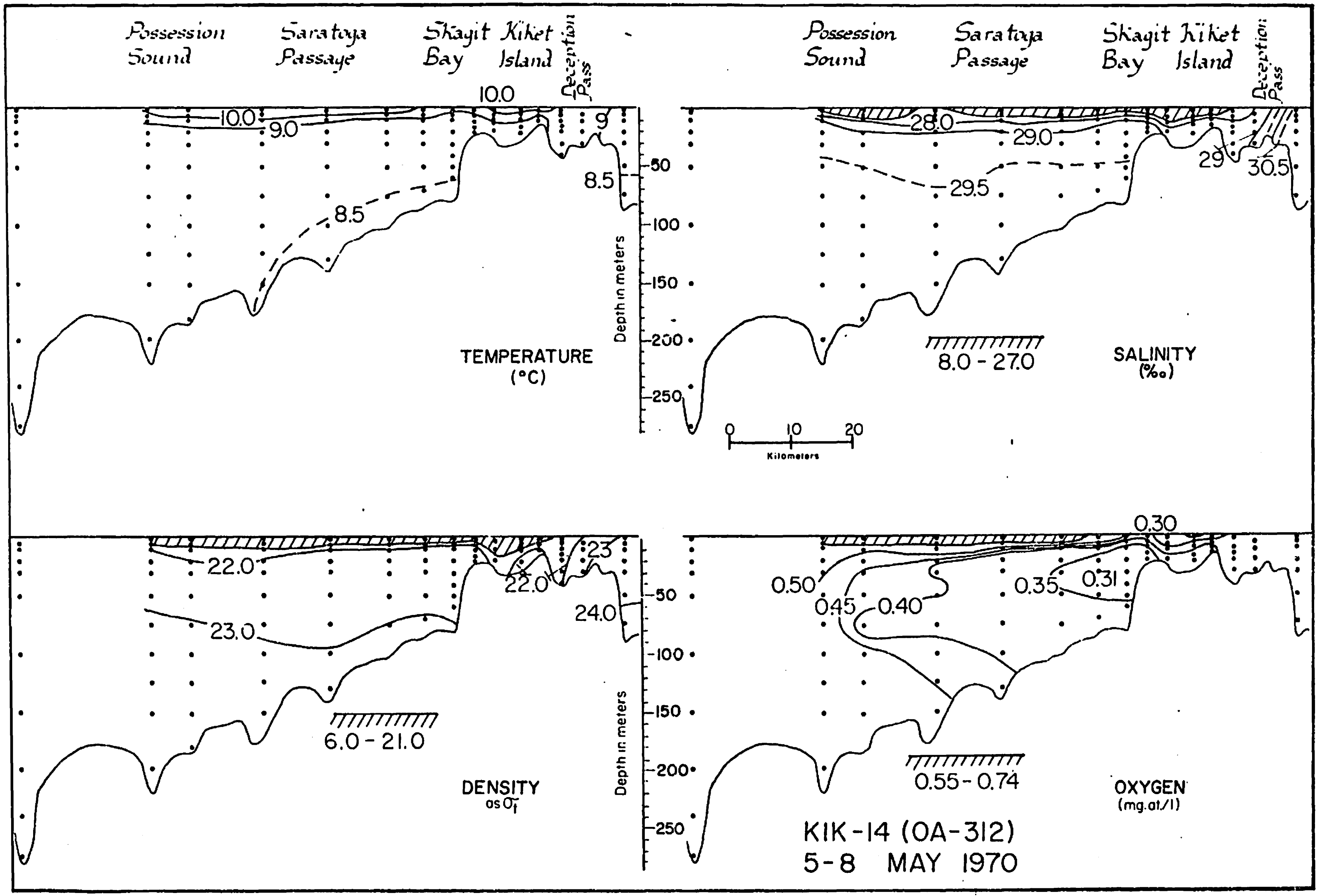


Figure 3-19 Water properties; Seattle to Deception Pass: 5-8 May 1970

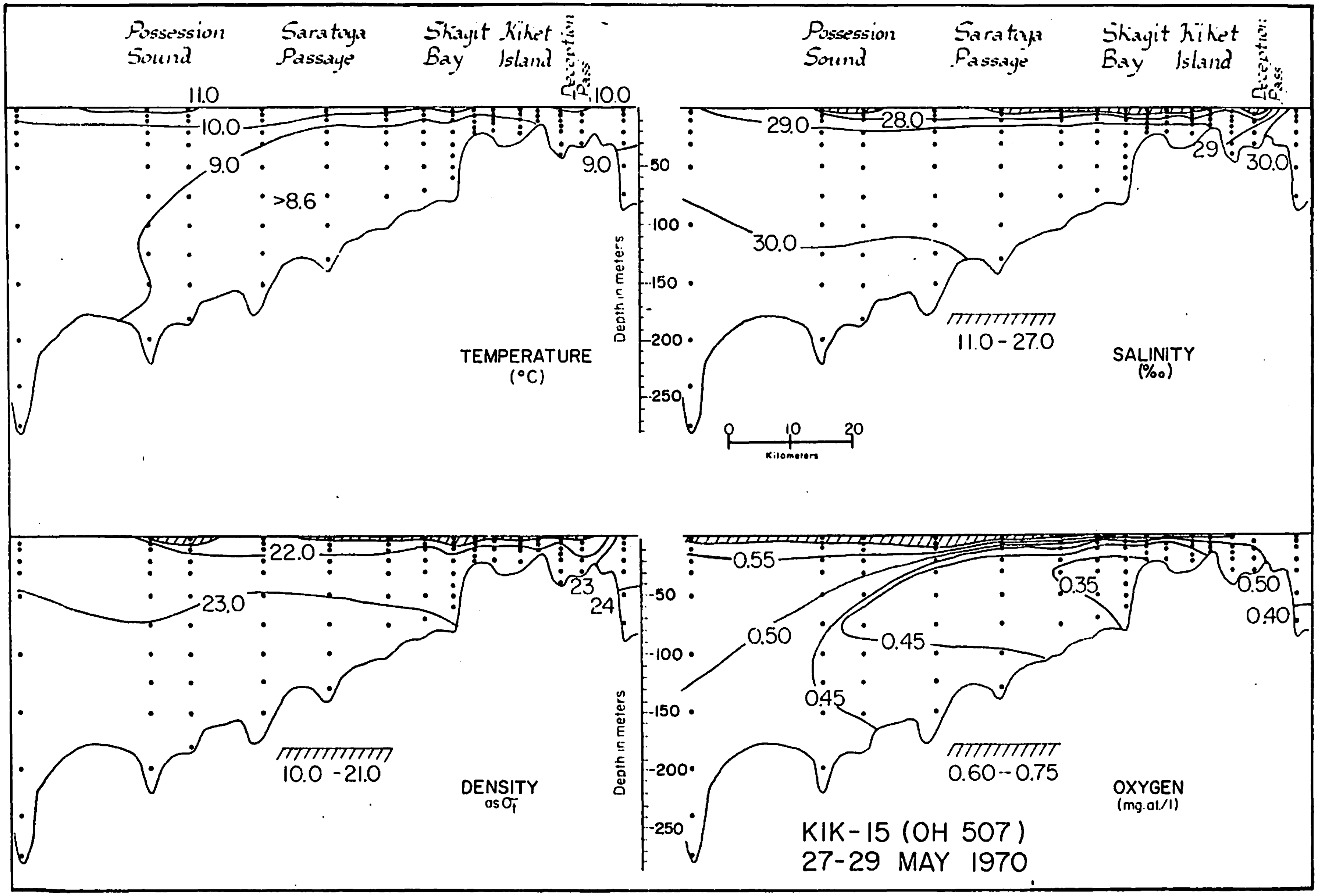


Figure 3-20 Water properties; Seattle to Deception Pass: 27-29 May 1970

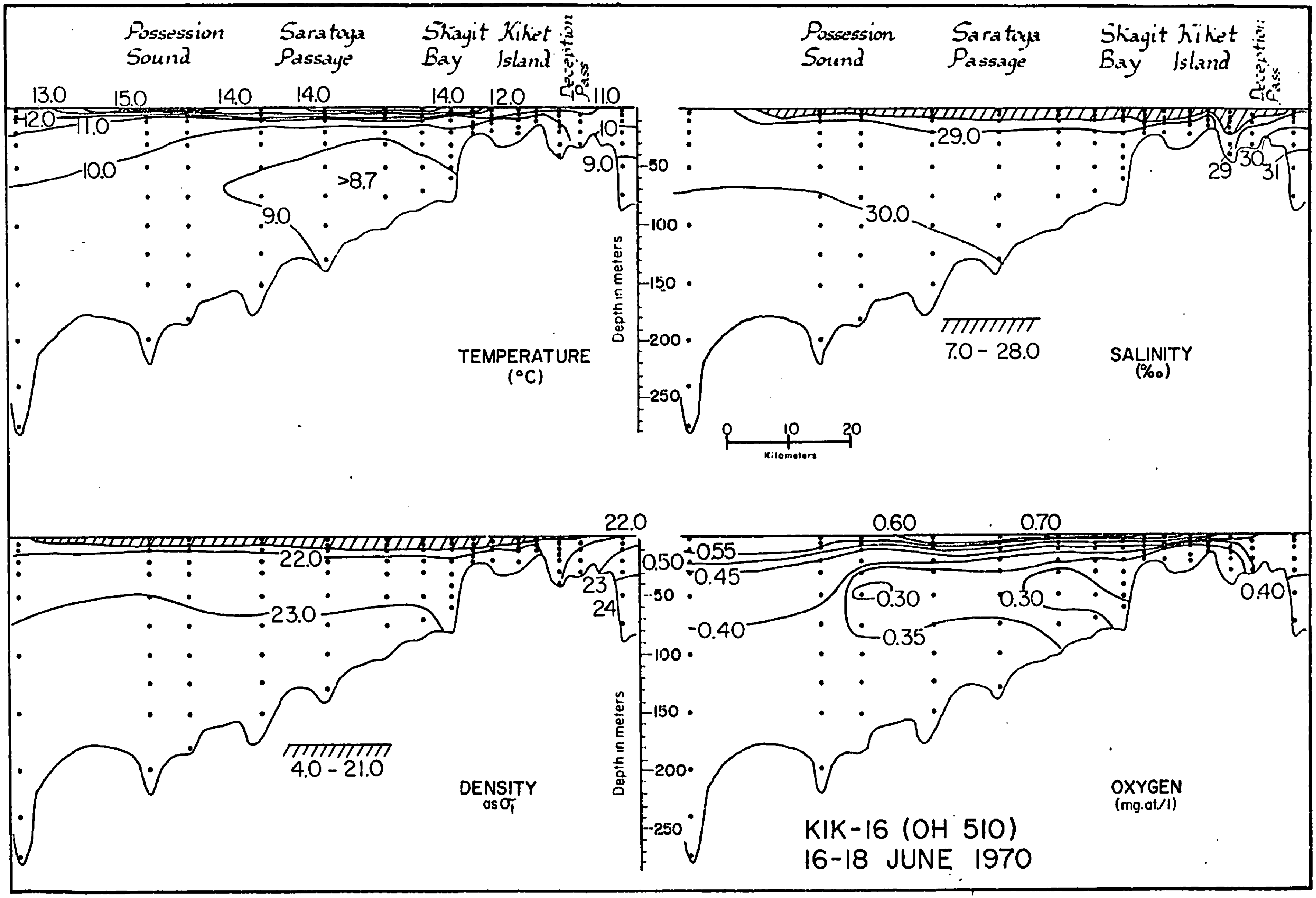


Figure 3-21 Water properties; Seattle to Deception Pass:
16-18 June 1970

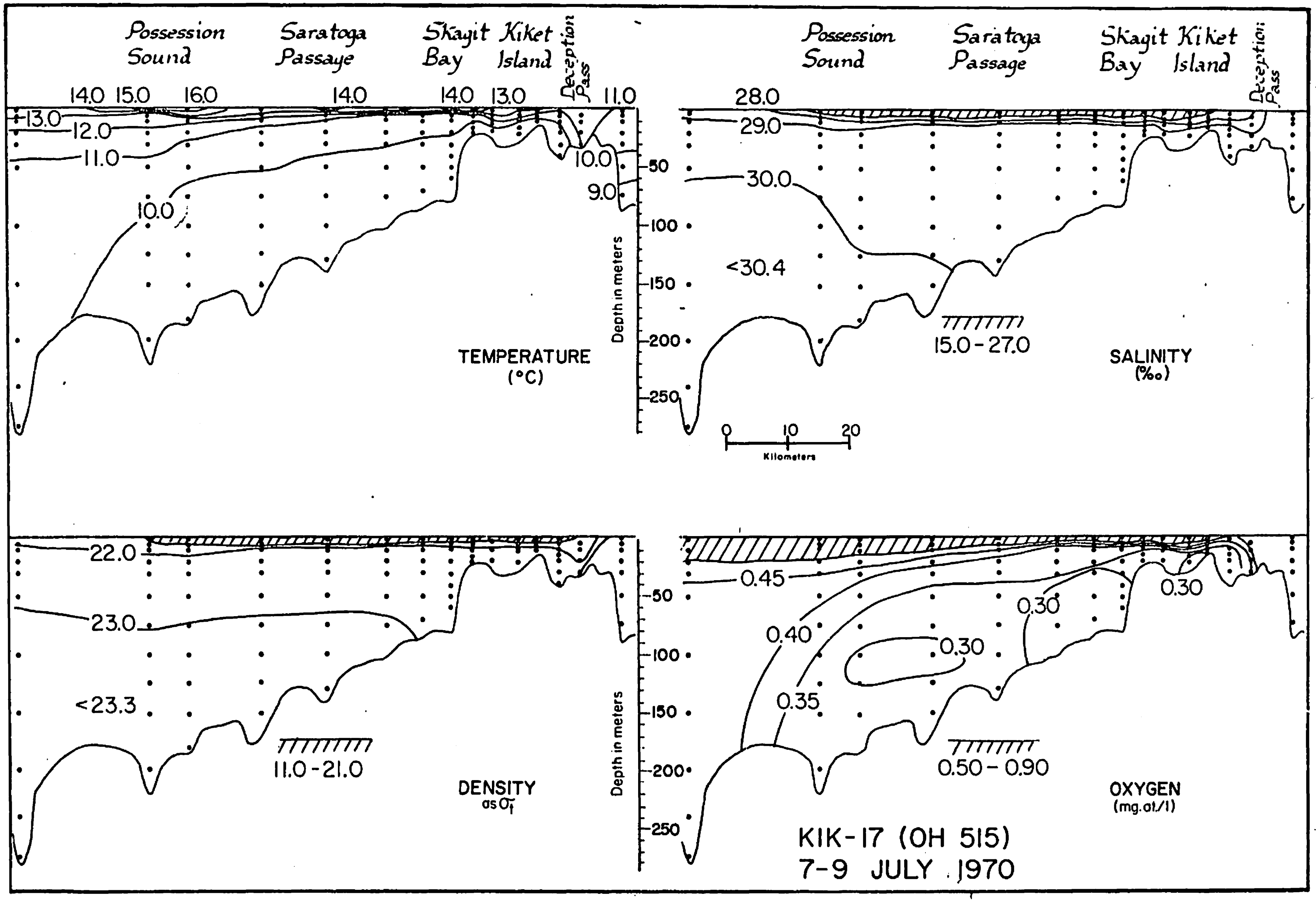


Figure 3-22 Water properties; Seattle to Deception Pass:
7-9 July 1970

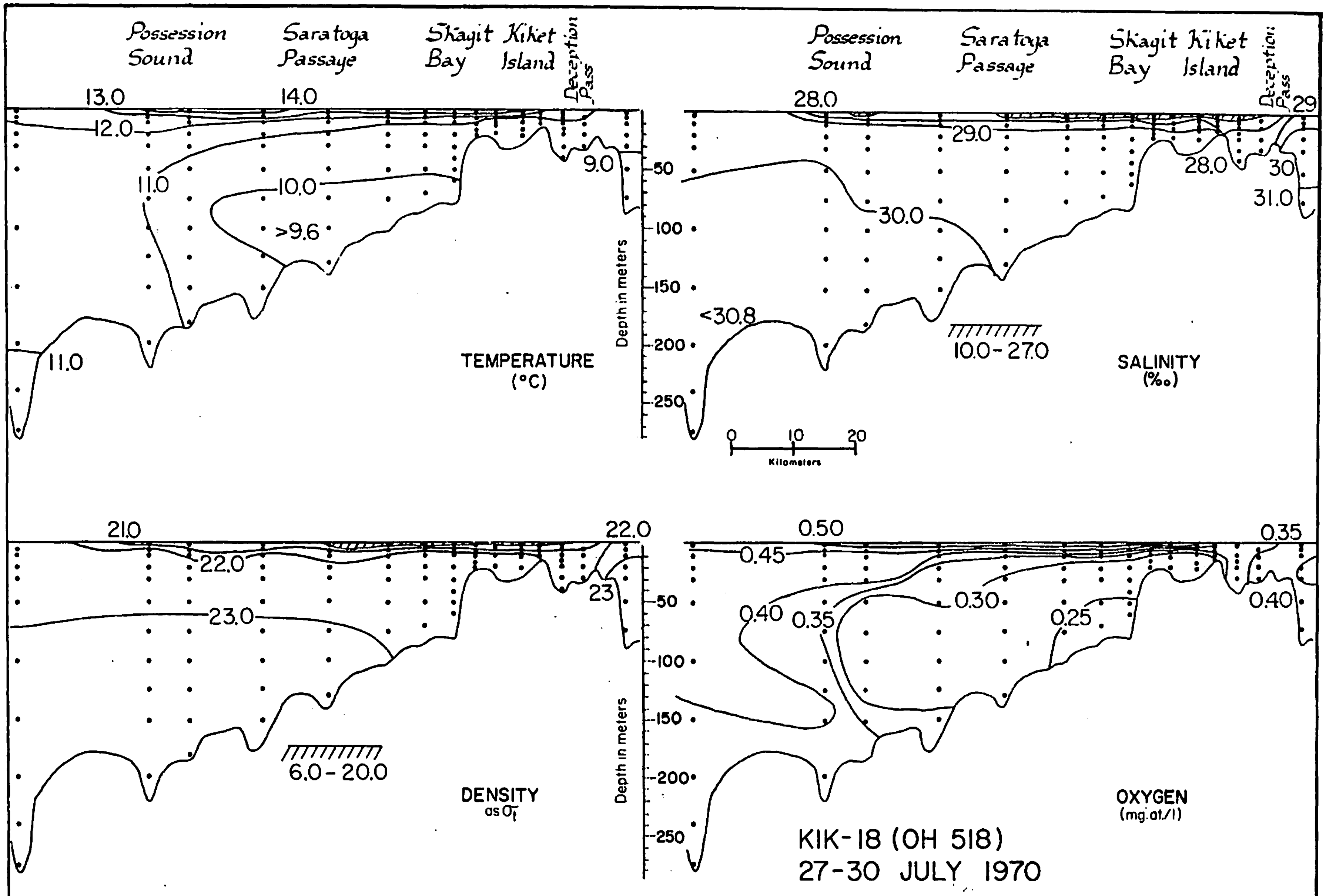
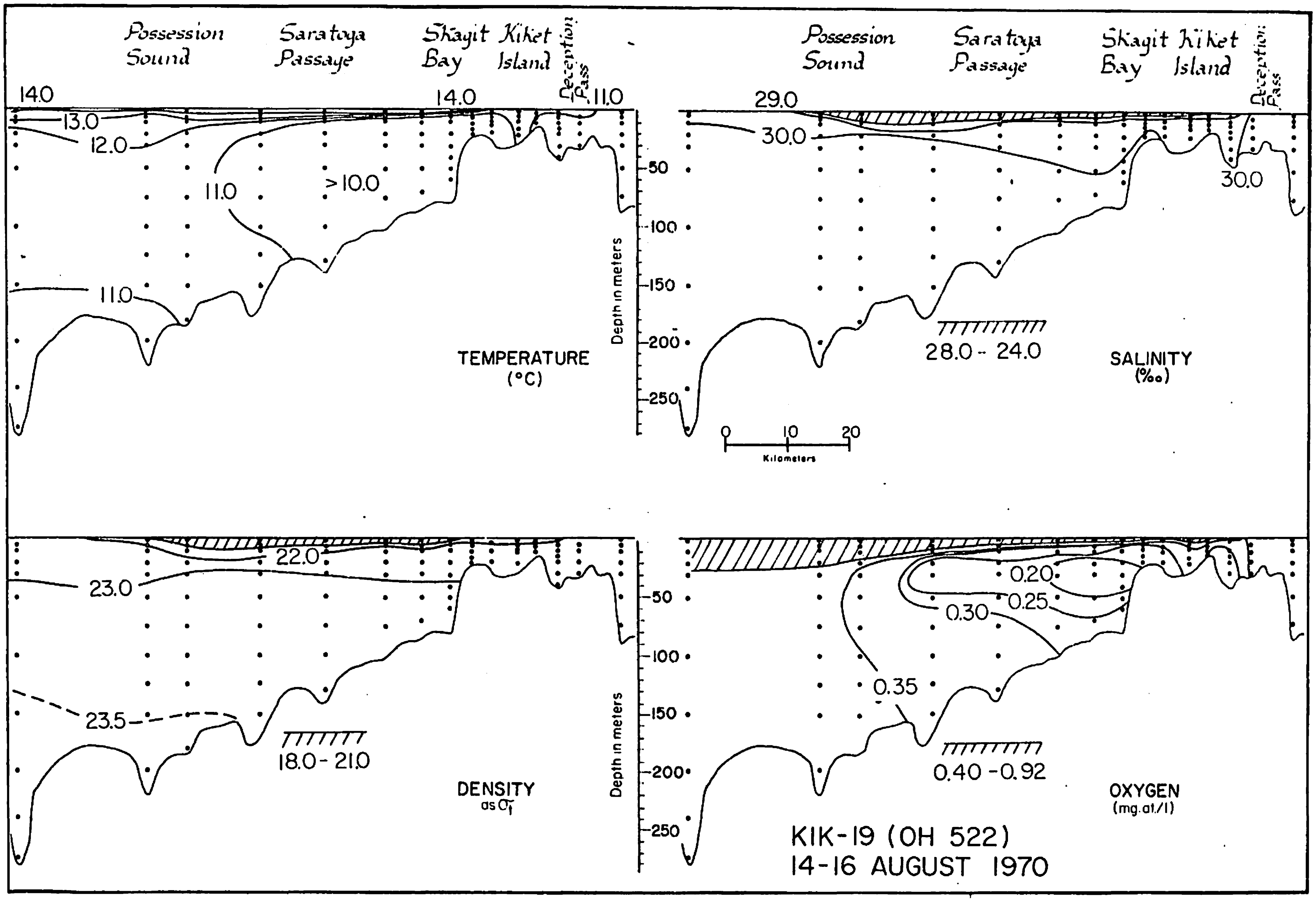


Figure 3-23 Water properties; Seattle to Deception Pass: 27-30 July 1970

Figure 3-24 Water properties; Seattle to Deception Pass:
14-16 August 1970



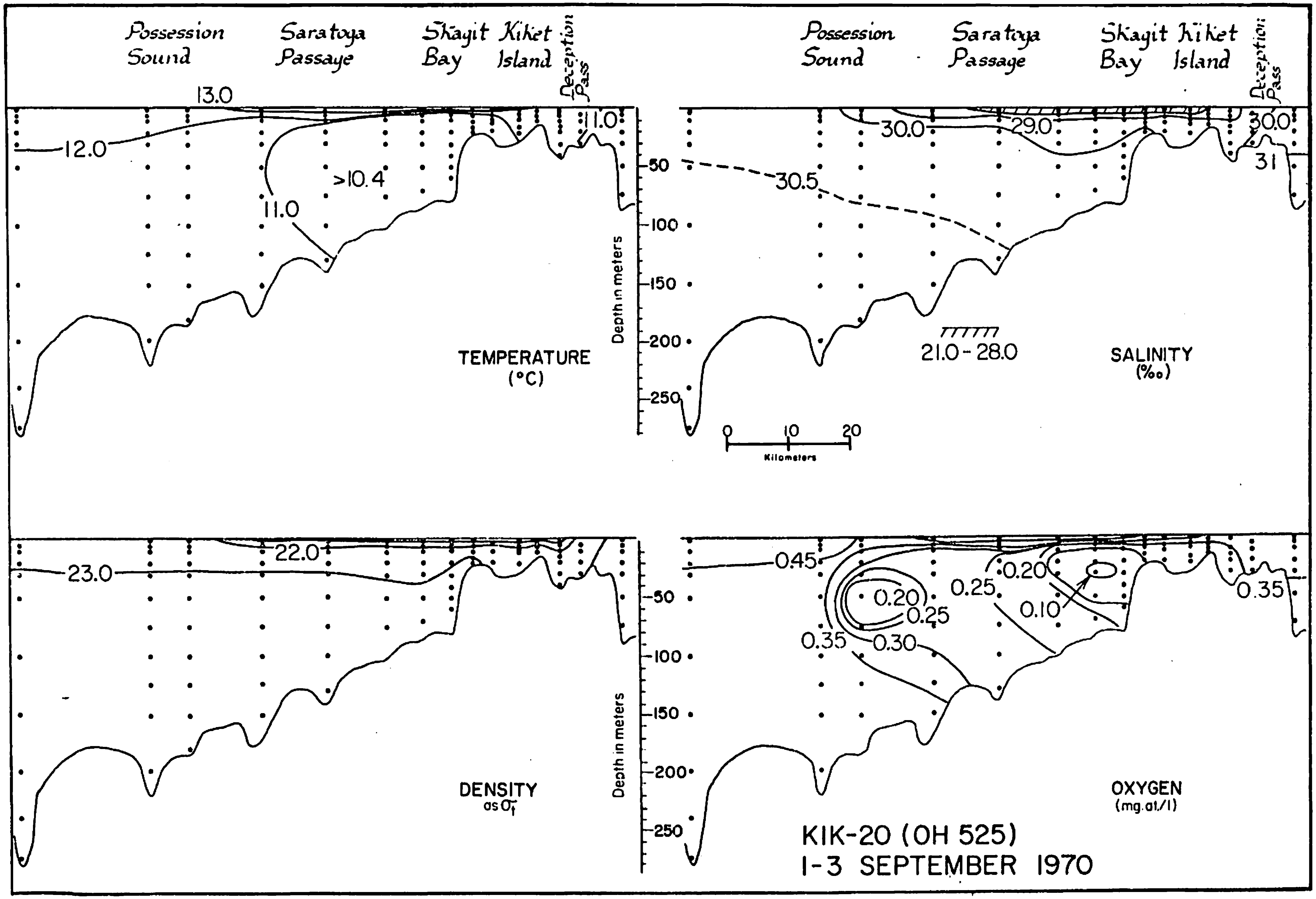


Figure 3-25 Water properties; Seattle to Deception Pass: 1-3 September 1970

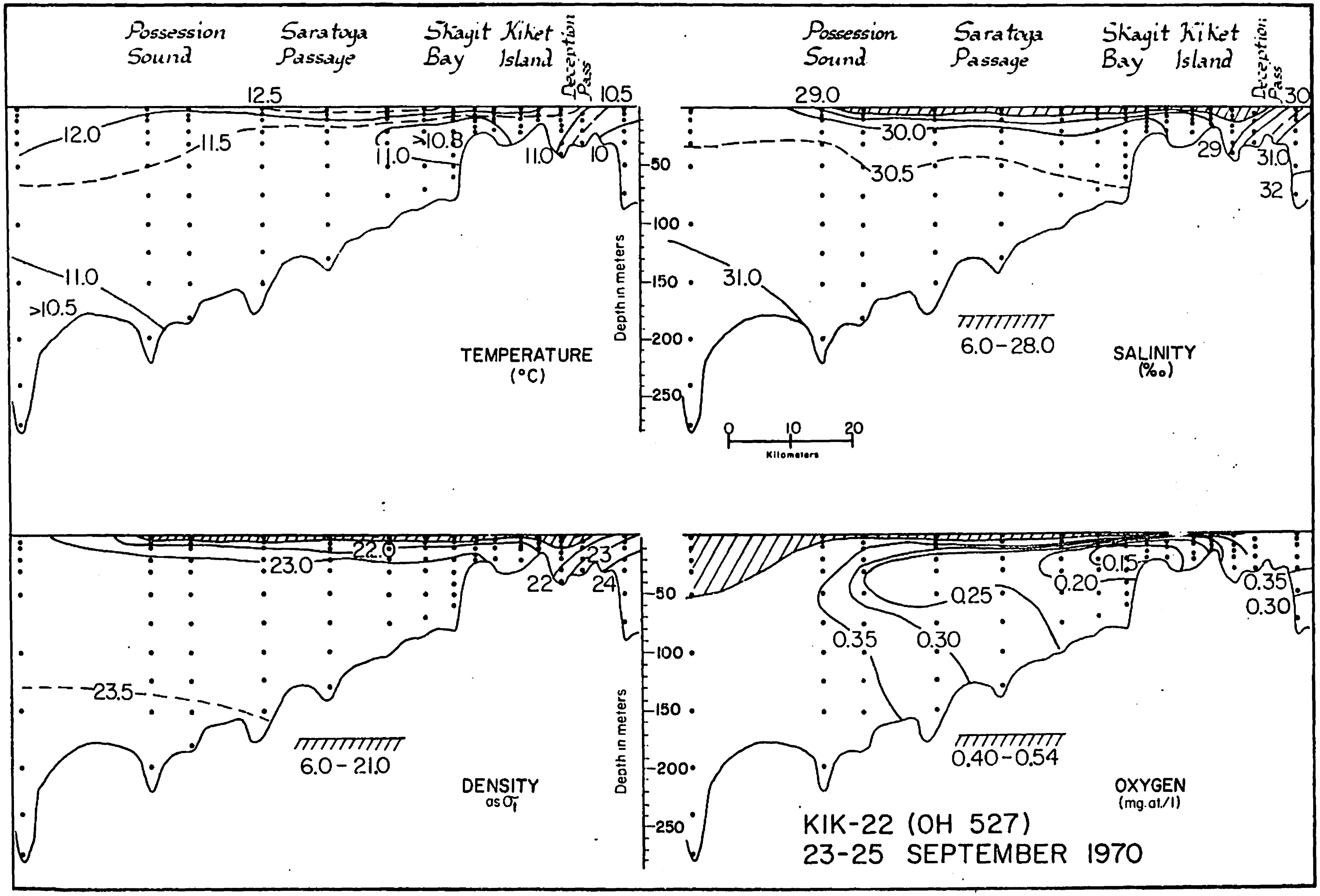


Figure 3-26 Water properties; Seattle to Deception Pass: 23-25 September 1970

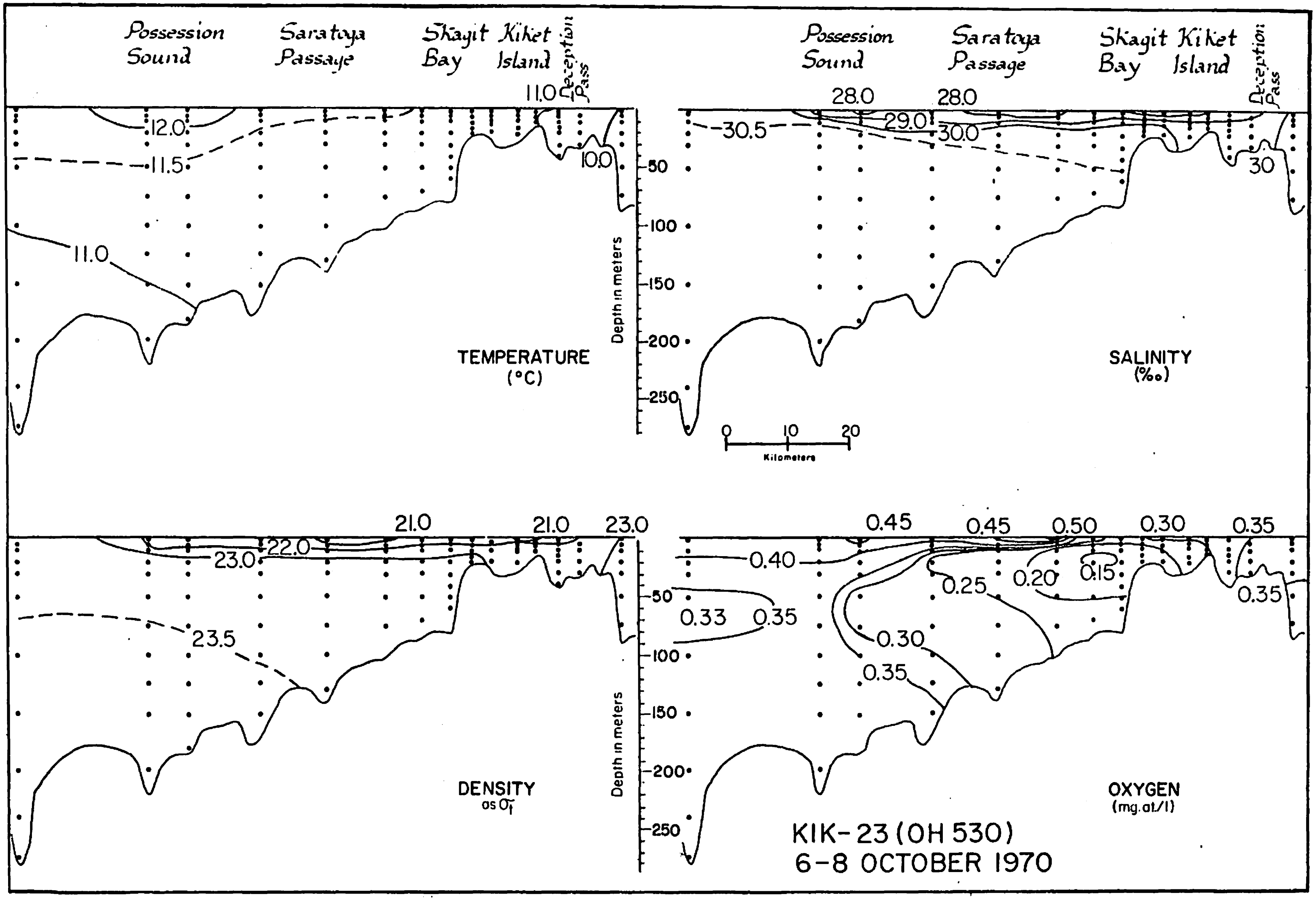


Figure 3-27 Water properties; Seattle to Deception Pass:
6-8 October 1970

3.2.5 *South Skagit Bay*

Water characteristics in Skagit Bay are influenced by properties of water entering from three sources. Near its southern end, water at depth comes from Saratoga Passage and is more closely associated with the properties of the main Puget Sound basin that are somewhat modified within Possession Sound and Saratoga Passage. Properties in the northern part of the bay are more closely related to flow through Deception Pass. The major influence on the properties and structure of the water in the area, however, is the discharge from the Skagit River, which enters the bay through two deltaic forks. The relative flow through the two forks, which separate south of Mt. Vernon, is not known but must vary with river stage, tide height, and changes in the river bed near the fork. The South Fork discharges north of Camano Island and has the greater influence in the southern part of Skagit Bay as it flows toward Strawberry Point. The North Fork discharges near Goat Island and has a strong influence not only in this part of the bay but also in the northern part of the local system. Because of the influence of the source waters, Skagit Bay can be considered as two rather distinct areas. South Skagit Bay is taken as extending south from the vicinity of Goat Island to south of Strawberry Point, where it connects with Saratoga Passage. North Skagit Bay extends from the vicinity of Goat Island to Hope Island.

The tidal currents from the north and from the south meet near Strawberry Point, and on a flood the incoming water from the north and south again meets at about the same place. This behavior produces a nodal point where the tidal currents are weak and variable and water movement is essentially vertical. The location of the nodal point is not stationary but appears to move to the north or south depending on variations in tide, weather, river runoff, oscillation of the pycnocline in Saratoga Passage and the Puget Sound main basin, and possibly other factors as yet unknown. These changes increase oscillating flow through the area, and as a result, the channel along Whidbey Island is kept open to a depth of at least 16 m (9 fm) in spite of the sediment load carried by the Skagit River.

Water properties at the Strawberry Point station in South Skagit Bay, as observed during the present investigation, are shown in Figure 3-28. During the first part of April 1970, a freshet occurred that increased the Skagit

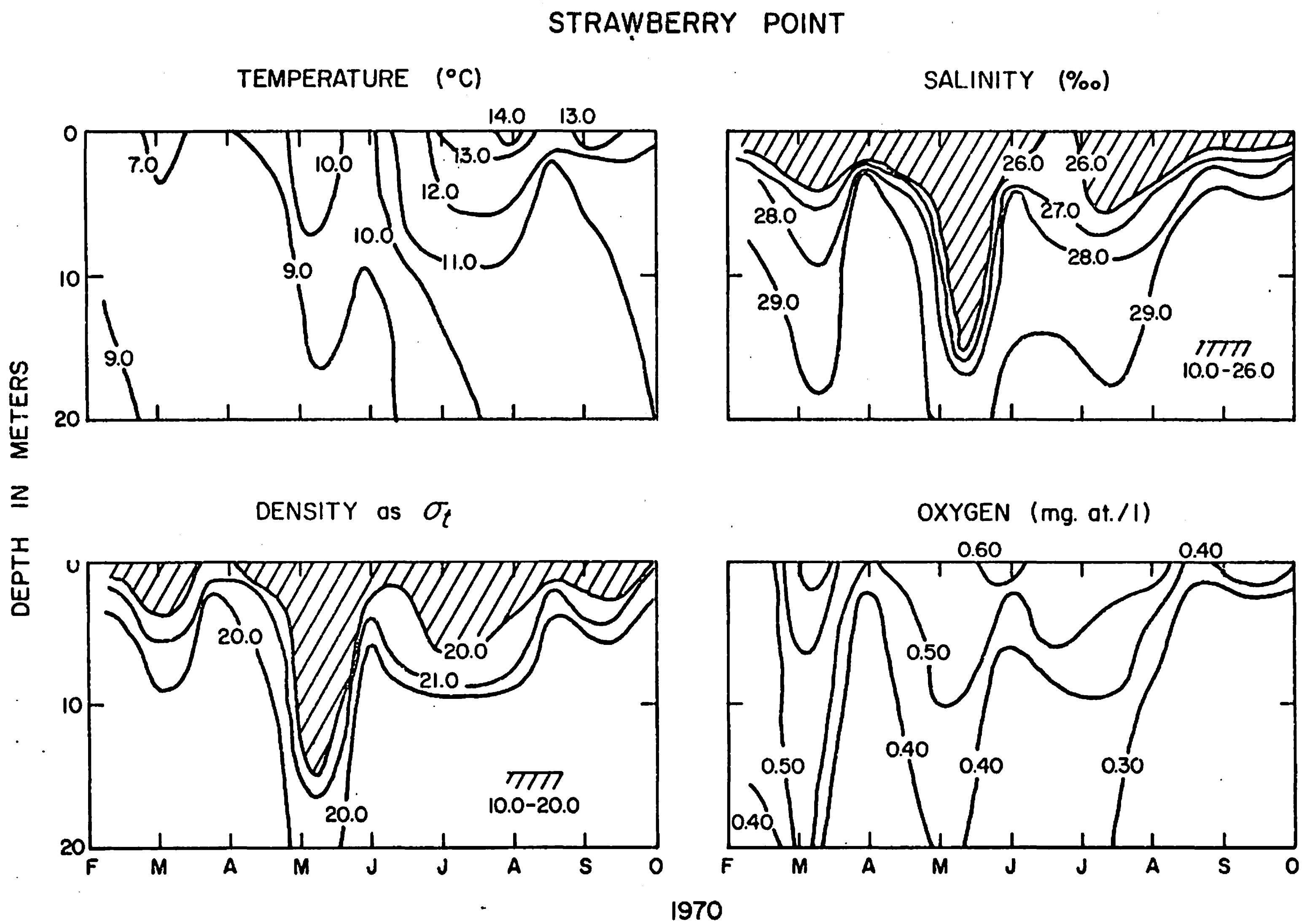


Figure 3-28 Water properties at Strawberry Point; February-October 1970

River flow at Concrete from 261 m^3/sec (9,230 cfs) on 5 April to 719 m^3/sec (25,400 cfs) on 10 April. The flow slowly decreased to 240 m^3/sec (8,470 cfs) by 17 April and remained quite low until 17 May. The snow melt peak was observed to reach a maximum of 861 m^3/sec (30,400 cfs) on 4 June. Flow slowly decreased until 30 June to the low summer rate. These large discharge rates are reflected in the salinity and density of the waters in Skagit Bay (see Figures 3-18 and 3-21). Only a portion of this water goes toward the north. The majority of it flows south in the surface layer and eventually is discharged into Puget Sound off Possession Point.

3.2.6 *Rosario Strait*

Rosario Strait supplies the water that enters Deception Pass on a flood tide and receives water from the northern subregions during ebb current. Variations in water properties in the southern end of Rosario Strait were determined by taking water samples at a station about 0.5 mile west of Deception Island. These results are presented in Figure 3-29. In comparison with the water off New Dungeness (see Figure 3-8), the water near Deception Island is fresher and slightly cooler, and its oxygen content is somewhat higher. Seasonal changes occur at about the same time at both stations. The fresher water is in part from the Fraser River in Canada, which contributes a very large amount of fresh water to Georgia Strait. As this water moves seaward, it dilutes the waters in Rosario Strait and the eastern end of the Strait of Juan de Fuca. Current velocities near Deception Island are rather high so that most water discharged into Rosario Strait on the ebb current is carried to the west and well mixed. This reduces the amount of water returned through Deception Pass on the succeeding flood tide.

3.2.7 *Deception Pass*

Deception Pass is characterized by strong currents and turbulance on both flood and ebb, with predicted speeds frequently in excess of 8 kt. As a result, the waters are usually thoroughly mixed from top to bottom and are quite uniform from the Pass to the east past Dewey. This uniformity is most evident on a flood current (see Figures 3-17, 3-24, and 3-25), whereas the waters on ebb are more stratified (Figure 3-27) as the less saline surface water from Skagit Bay moves northward through Hope and Tosi channels. Thus, considerable changes in water properties occur rapidly over short distances.

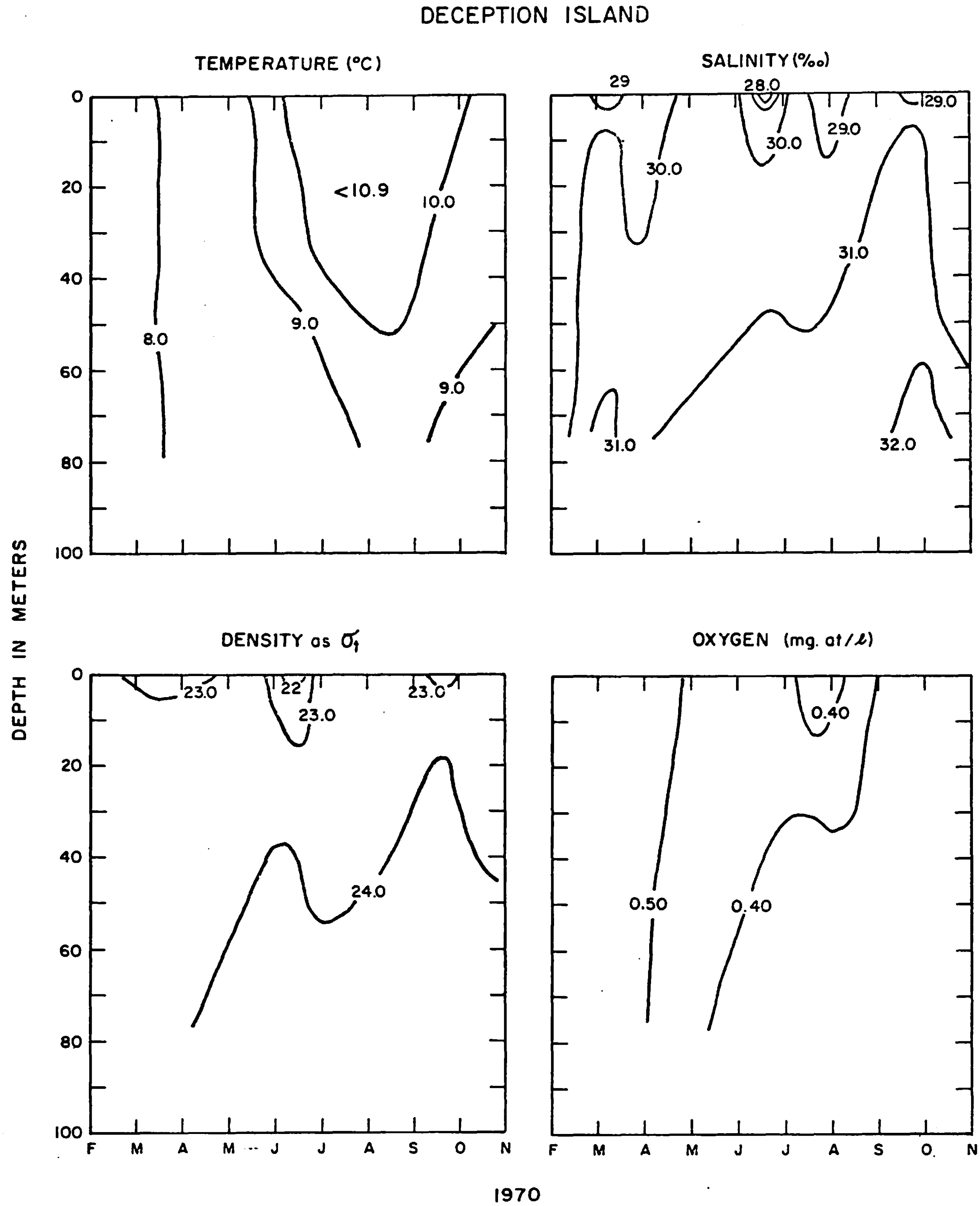


Figure 3-29 Water properties near Deception Island; February-October 1970

The minimum observed temperature in this subregion was 7.8°C in winter and the maximum was 11.5°C in late summer.

Data obtained at the Dewey station from February to October 1970 are presented in Figure 3-30. The waters at Dewey were less saline and warmer than those found off Deception Island and the oxygen content was generally higher. In late summer, the oxygen concentration decreased as low-oxygen -content water from south of Goat Island penetrated into this subregion (see Figure 3-26).

The waters at Dewey exhibit significant diurnal variations associated with tidal action, as shown in Figures 3-31 and 3-32. Large changes occur near high-water stand or near low-water stand, which in turn are directly related to maximum ebb current and maximum flood current in Deception Pass. Care must be taken to relate the data at stations in this subregion to the tide or more particularly to the Deception Pass current stage at the time of observation.

3.2.8 *Similk Bay*

Because of the interaction of oceanographic and meteorological processes and the physical characteristics of Similk Bay, it appears that this subregion and the Hope Island Bay subregion are of major importance in the problem of limiting the environmental effects of the proposed cooling water effluent. Similk Bay, being a semi-enclosed shallow area, has less net tidal exchange than occurs in other basins of the Skagit Bay system. Therefore, any flow is more restricted. Tidal currents in Similk bay are relatively weak and tend to be toward the head of the bay during the flood and towards the mouth during ebb. The low current speed associated with tidal currents increases the relative importance of surface transport by wind, beyond that prevailing in other subregions where tidal currents are dominant.

Since the water tends to remain in Similk Bay longer and is shallower in depth, insolation during the summer produces significant warming. These summer water temperatures frequently are about 2.5°C above those found at Dewey. Water characteristics for a station on the west side of Similk Bay for the period of February to October 1970 are shown in Figure 3-33. When northerly winds predominate, wind stress on the surface will tend to assist in removal of the warmed surface water in summer and promote flushing, although some thermal stratification does develop. In winter, the water is

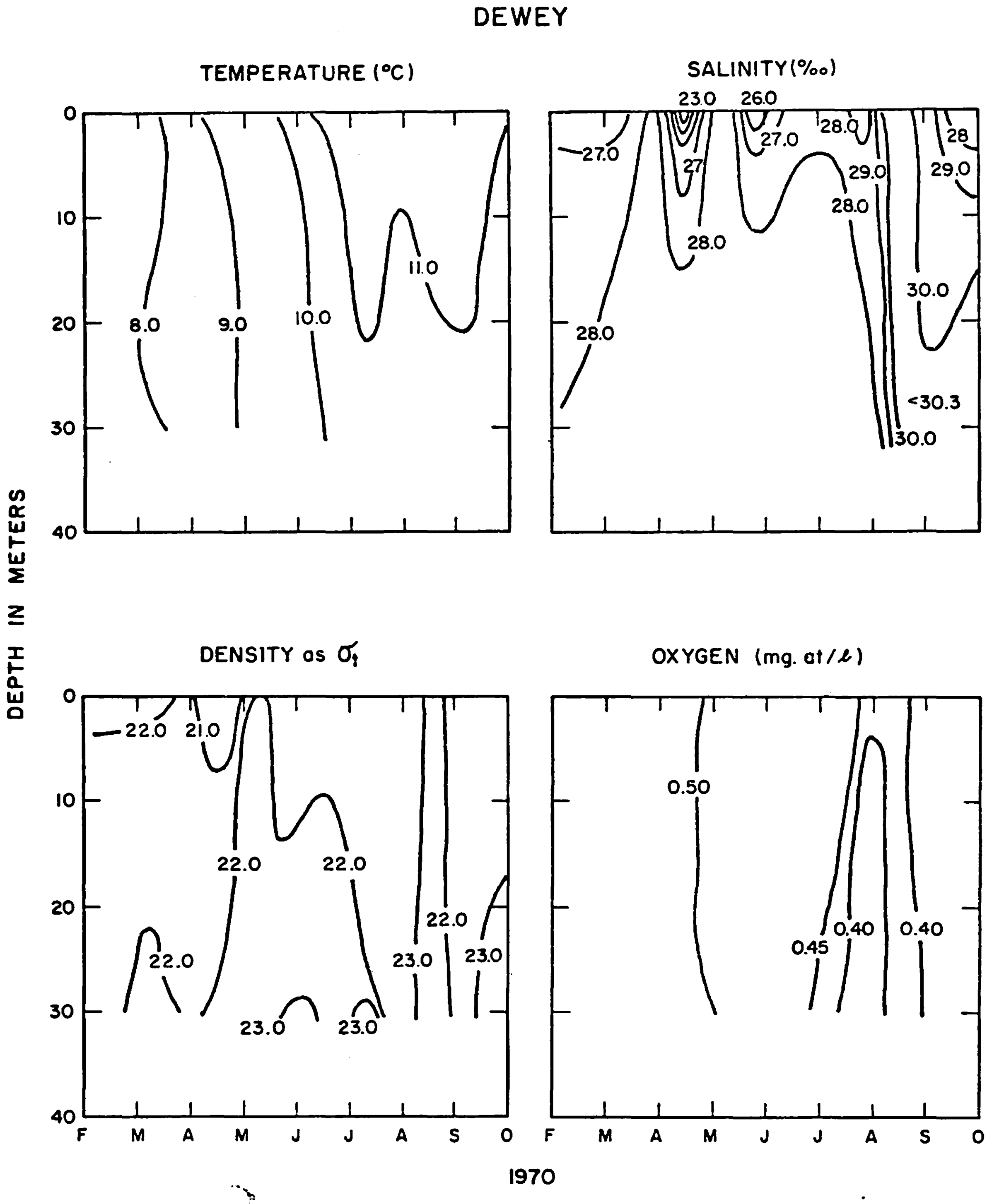


Figure 3-30 Water properties at Dewey; February-October 1970

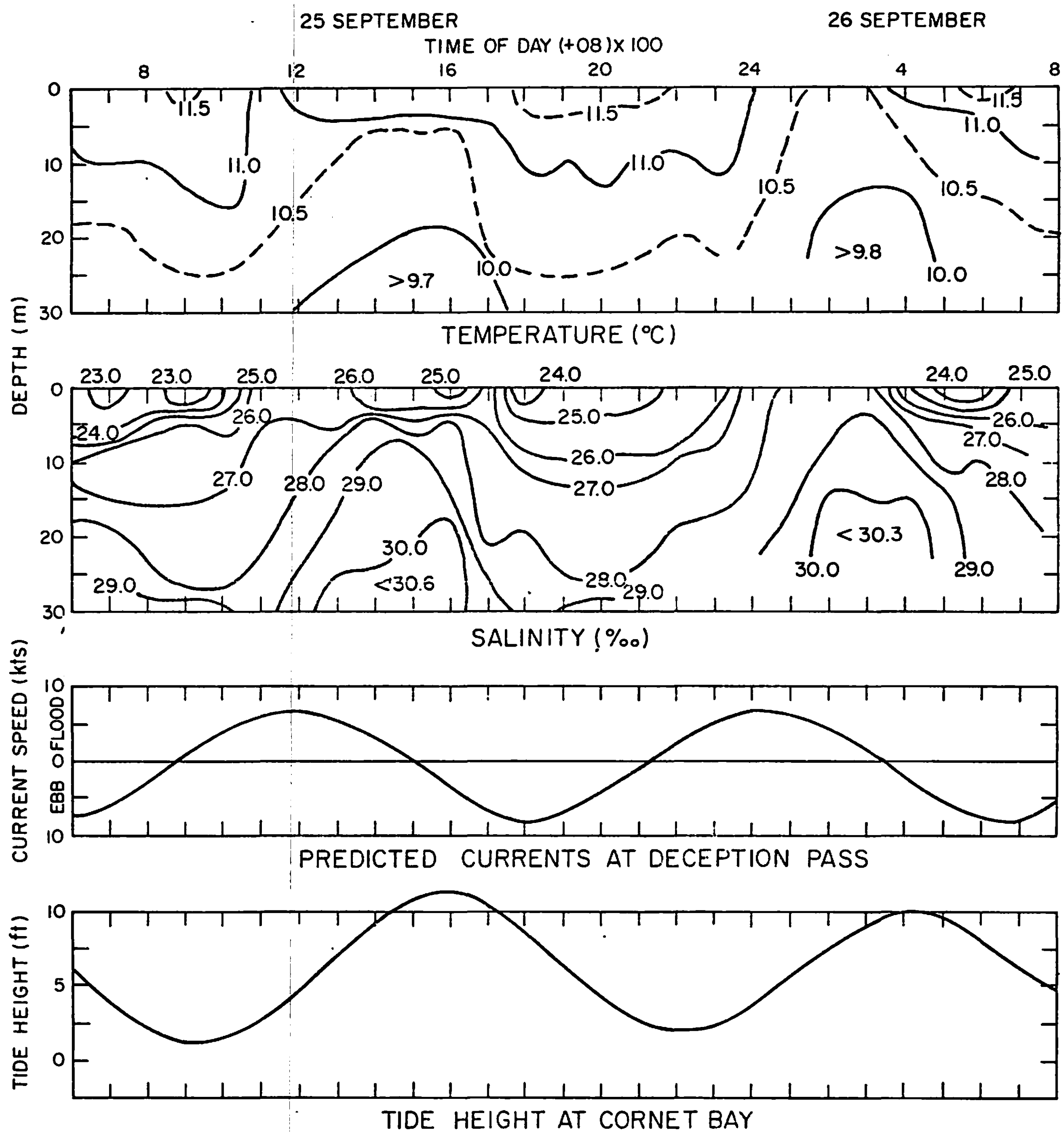


Figure 3-31 Tidal effects on the distribution of variables at Dewey, 25-26 September 1969

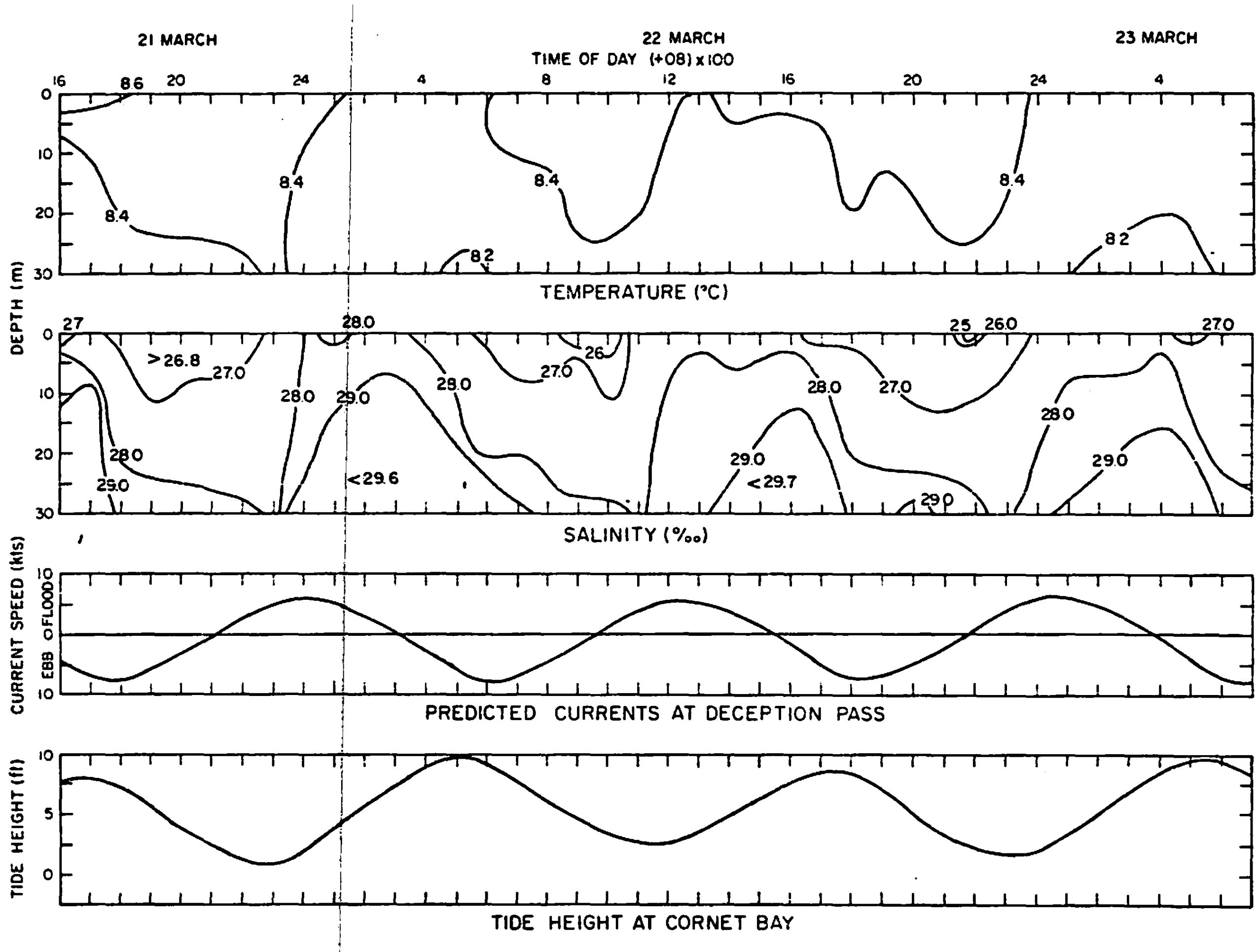


Figure 3-32 Tidal effects on the distribution of variables at Dewey, 21-23 March 1970

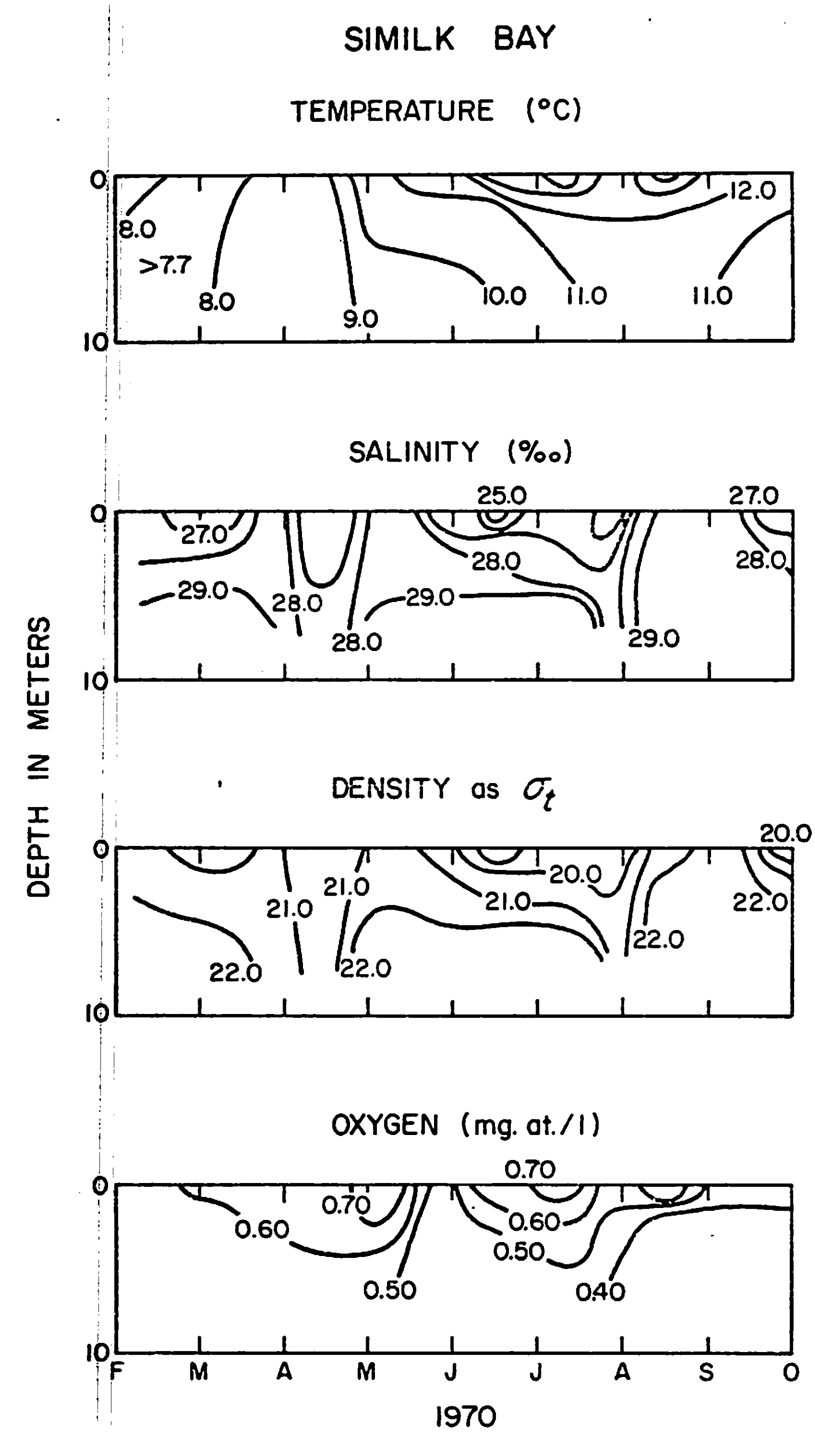


Figure 3-33 Water properties in Similk Bay; February-October 1970

virtually isothermal at about 7° to 8°C. Warming begins in April, and by May a thermocline is evident. The highest observed temperature, 14.1°C, occurred in early July. At the same time, the maximum temperature at depth was near 11°C. Because of the 3-week interval between observations, it is possible that somewhat higher temperatures may have been missed.

A halocline develops during the periods when flow from the Skagit River is high. This water is partly mixed as it transits through Hope, Tosi, and Kiket channels. Preliminary observations indicated that an important source of this surface water is from a jet on ebb that develops in Hope Island Bay from Tosi Channel to Kiket Channel. Some water flowing through Kiket Channel near the end of the ebb would tend to be carried into Similk Bay at the beginning of the following flood. Visual observations of this phenomenon have been made. As mixing is not marked in Similk Bay, the surface layer tends to persist. During the periods of low Skagit River flow, prior to and following the major snowmelt peak, the water in Similk Bay becomes more nearly isohaline, although a late summer thermocline is present.

3.2.9 *Hope Island Bay*

Active circulation in Hope Island Bay occurs on all tides so that the water characteristics are dependent upon the currents and the properties in the adjacent basins. As a result of the circulation, the water in this bay is quite uniform in the lateral extent. On a flood current, cooler and more saline water from Deception Pass penetrates into this subregion (Figure 3-22). Upon change of the current to ebb, the waters become somewhat stratified, less saline, and more similar to those found in the northern Skagit Bay. Observations made at a station northwest of Tosi Point are presented in Figure 3-34. The maximum temperature observed at this station was 12.1°C in early July 1970 and the coolest was 7.7°C in March. The temperatures at this station were usually about 0.5°C warmer than those observed off Dewey at the same time.

Considerable diurnal changes occur in this bay. In March 1970 (see Figures 3-35) changes in temperature of 0.6°C at the surface and 0.2°C at 20 m were observed at the Tosi Point station. Corresponding changes in salinity were 1‰ and 0.7‰, respectively. Because of these rather large variations, it will be necessary to install continuously recording monitors at selected locations in Hope Island Bay to define adequately the conditions near Kiket Island.

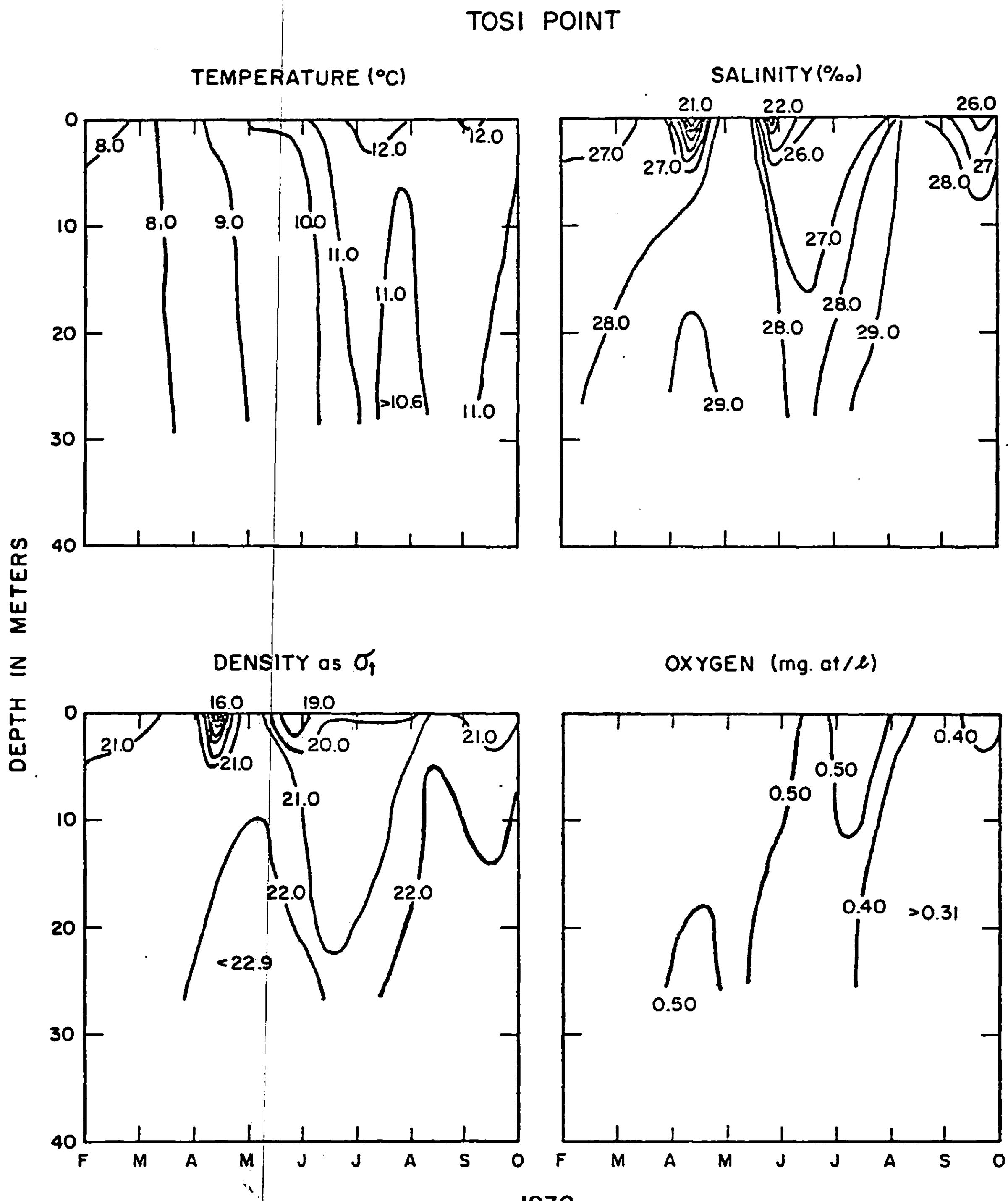


Figure 3-34 Water properties northwest of Tosi Point; February-October 1970

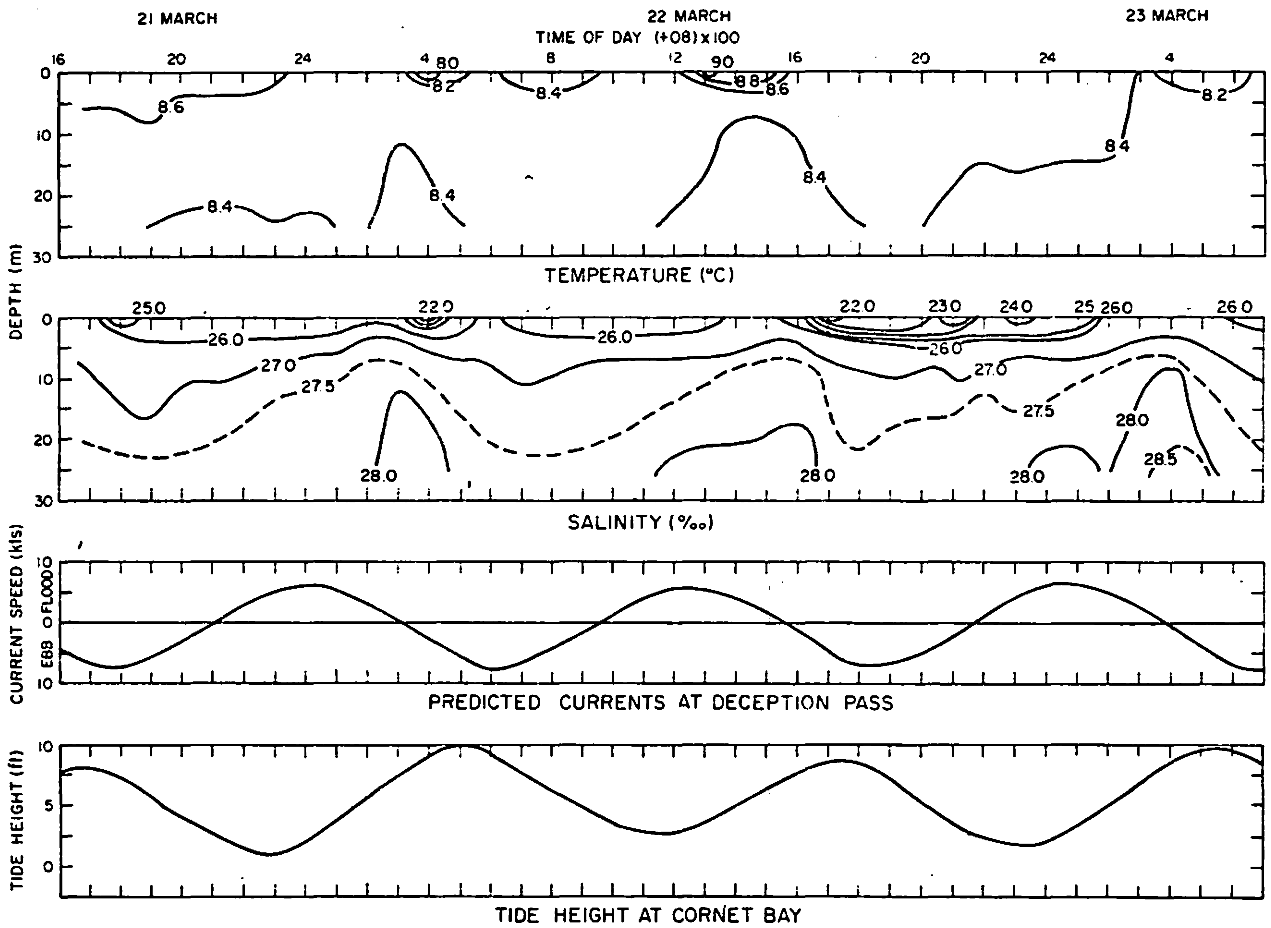


Figure 3-35 Tidal effects on the distribution of variables near Tosi Point; 21-23 March 1970

3.2.10 *Hope and Tosi Channels*

During the stronger tidal currents, the passages on each end of Hope Island are effective in mixing the waters flowing between northern Skagit Bay and Hope Island Bay. Water properties observed in each passage are governed by the currents and conditions in the adjoining basins. During an ebb current, the water may be somewhat stratified, and clouds of fresher Skagit River water will move north through Hope Channel. On the flood, Deception Pass type water will move south especially through Hope Channel. The water flowing south through Tosi Channel on the flood reflects conditions in Hope Island Bay. A station occupied in Hunot Hole for a 12 hr period on 8 November 1969 (Figure 3-36) shows variations in water properties as they change with tide and current stage.

3.2.11 *North Skagit Bay*

Water characteristics in north Skagit Bay are strongly influenced by the Skagit River. Accumulations of fresh water between Strawberry Point and Goat Island reflects the effect of river runoff. Observations at the Goat Island station are presented in Figure 3-37. As water from Goat Island moves to the north, mixing increases and the salinity increases. This increase is shown in the salinity at the Hope Island Light station (Figure 3-38). The maximum observed surface temperature in this subregion was 12.3°C in August and the minimum 7.6°C in early March. Low-oxygen-content water from Saratoga Passage was observed to the north in September, but by October the oxygen content of the water was higher (Figures 3-24, 3-25, 3-26, and 3-27).

4. OBSERVATIONS AND STUDIES PLANNED FOR 1971

4.1 *Routine observations*

4.1.1 *Triweekly cruises*

The triweekly cruises for obtaining oceanographic data that were started in February 1970 will be continued through December 1971, to provide nearly two years of data on the water properties of the study area and the related basins of Puget Sound, Rosario Strait, and the Strait of Juan de Fuca. Modification of station locations and sampling depths may be made to delineate

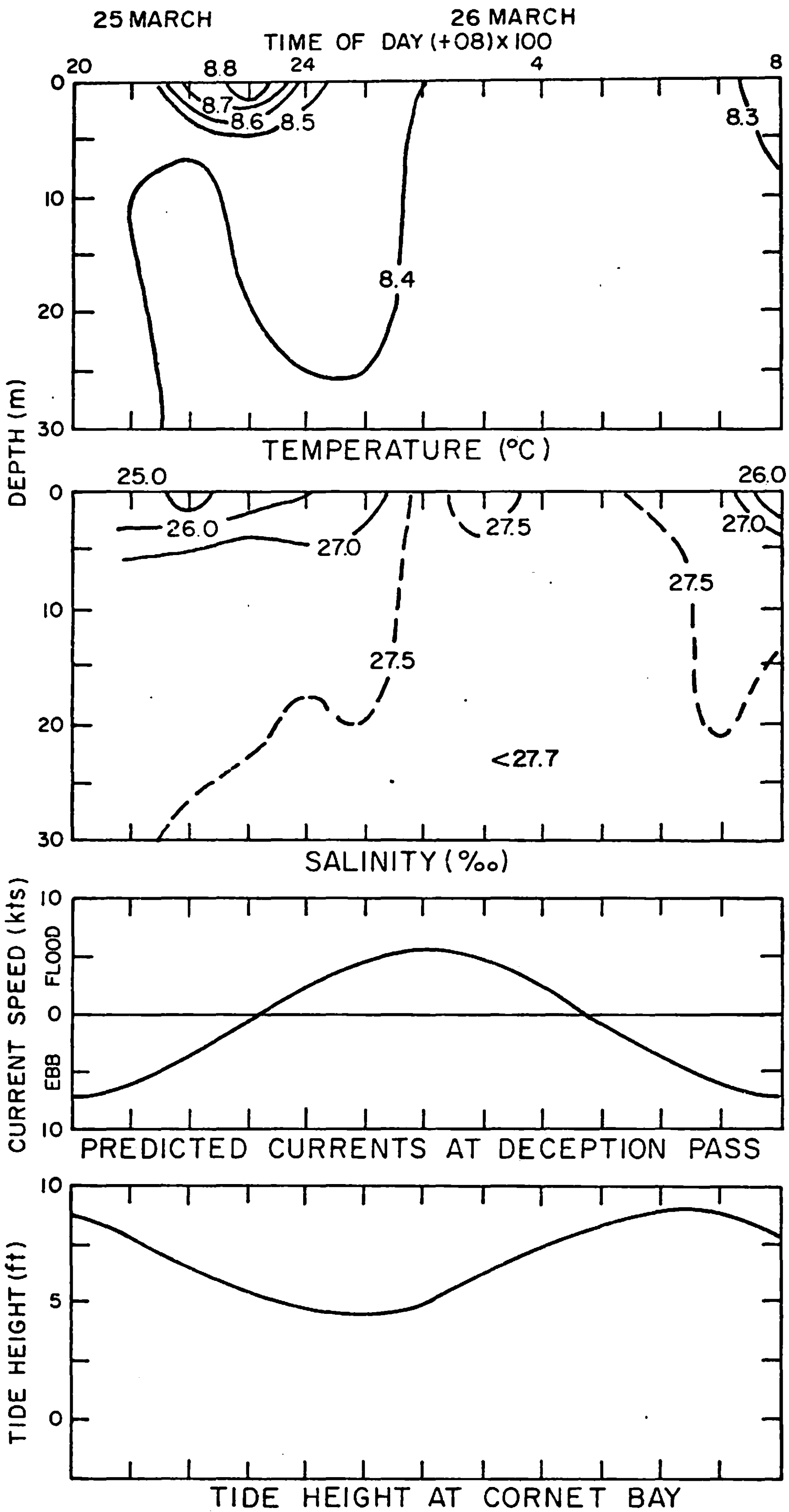


Figure 3-36 Tidal effects on the distribution of variables at Hunot Hole; 25-26 March 1970

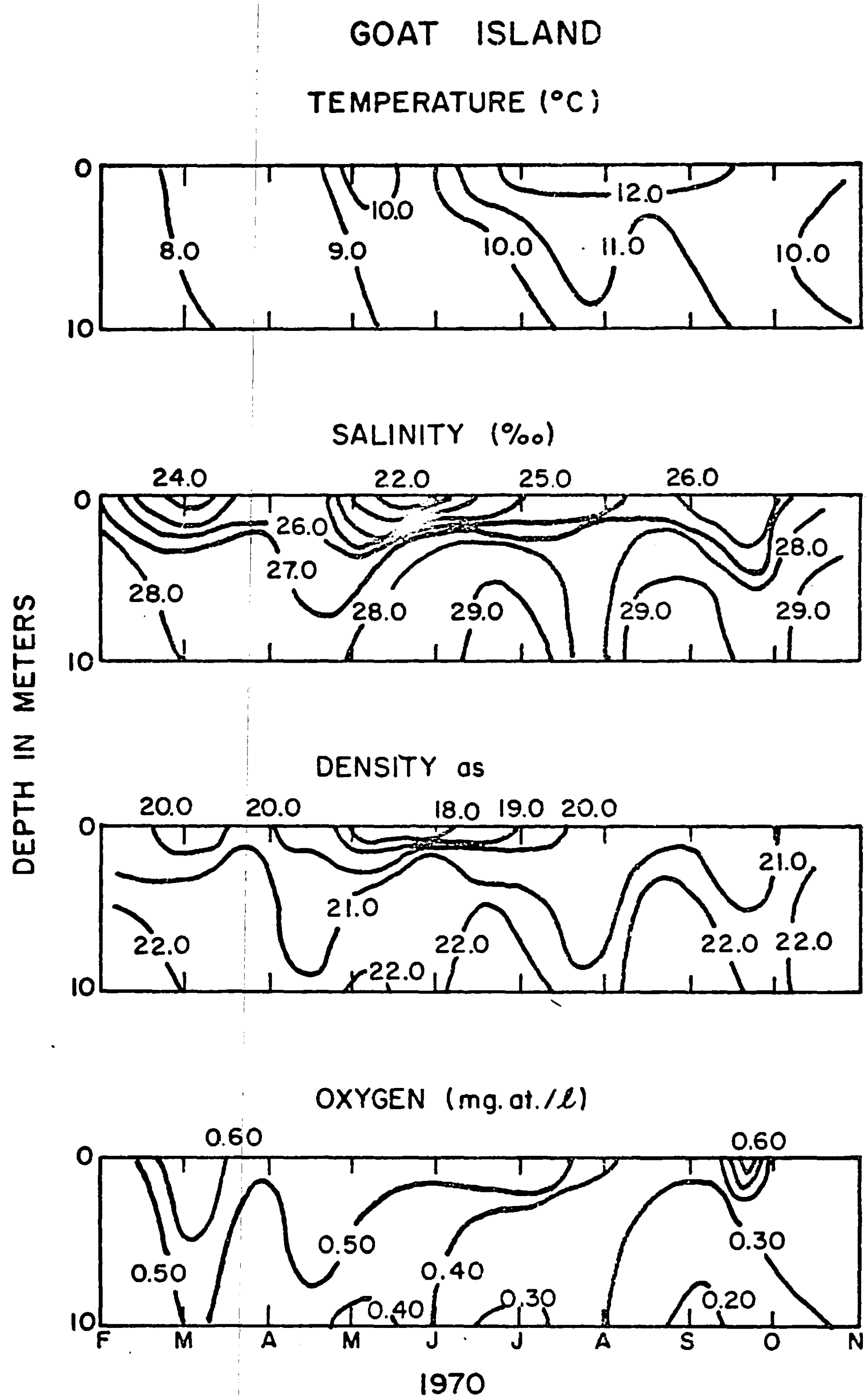


Figure 3-37 Water properties near Goat Island; February-October 1970

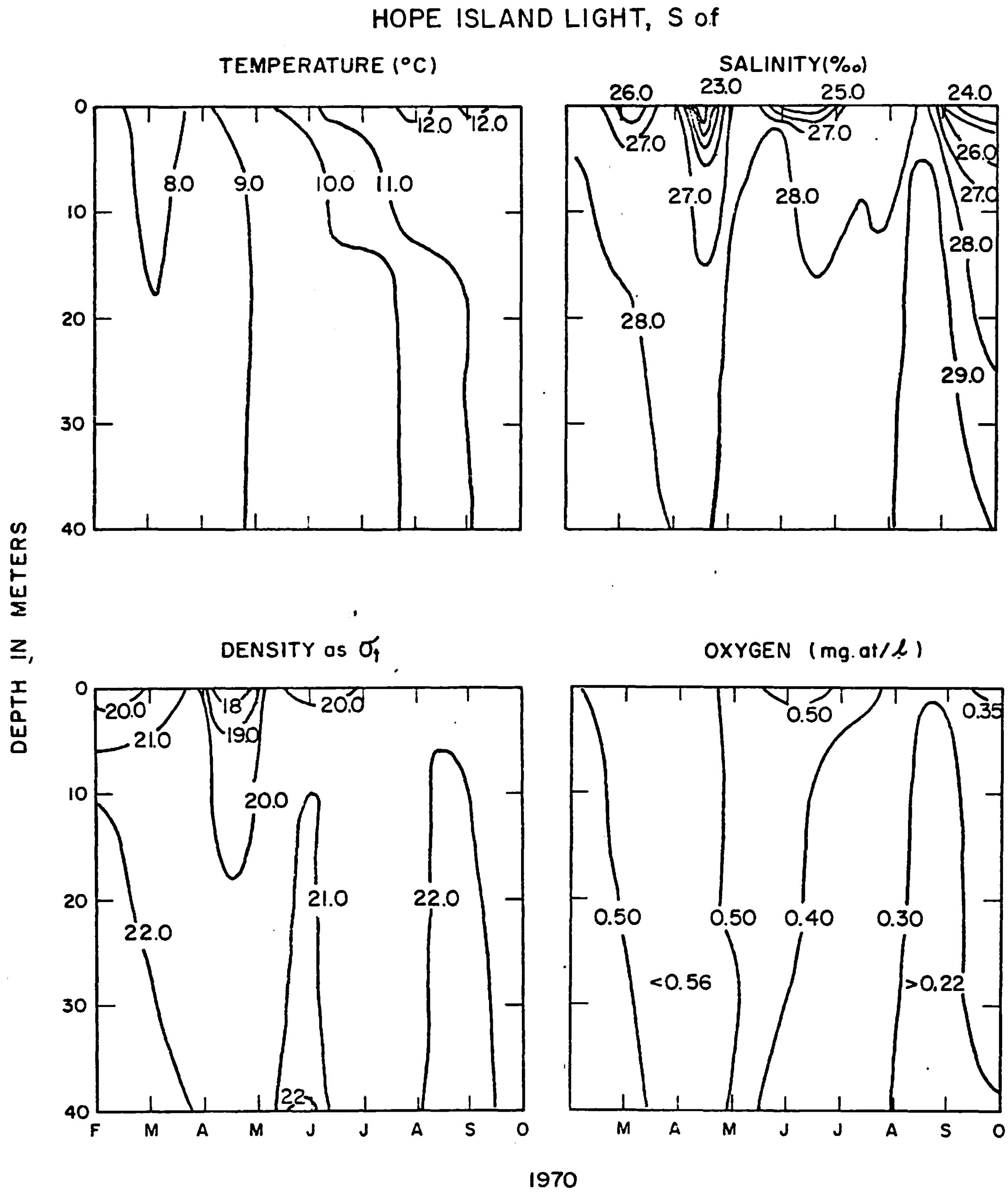


Figure 3-38 Water properties west of Hope Island Light; February-October 1970

better the distribution and variability of properties as indicated by analysis of the acquired data.

4.1.2 *Water-level measurements*

The tide stations that have been established will be maintained. The recorder at Tacoma will be accurately referenced to the standard datum of Mean Sea Level by leveling referenced to the U.S.C. & G.S. level-line. Leveling at all other stations will be verified.

Water-level measurements at the various stations will be correlated with meteorological effects. Particular attention will be given to correlating water-level differences through Deception Pass with water exchange, conditions within the Skagit Bay system, and observations at Strawberry Point.

4.1.3 *Weather observations*

The established weather stations will be maintained. The weather station at Kiket Island will be replaced with an MRI Model 1073 that measures insolation in addition to wind speed and direction, precipitation, and air temperature.

4.1.4 *Current measurements*

Current meters will be maintained in the channel at Strawberry Point through October or until fishing season begins.

4.2 *Special studies*

4.2.1 Similk Bay

4.2.1.1 Drogue studies

Drogue studies to establish the circulation patterns will be made at four different times to provide information on the circulation under different conditions of tide and wind. Attempt will be made to schedule the observations to obtain data representative of "worst-case" conditions with reference to the effects of cooling water effluent--that is, a period of minimum tide change together with southerly wind. Scheduling for the desired tide conditions is possible, but the combination with the desired wind will probably be more fortuitous.

4.2.1.2 Dye studies

It is hoped that dye-tracer studies using the technique of continuous injection of dye from a fixed location can be made. Although these studies are considered to be of great importance, they are contingent on obtaining suitable instrumentation and equipment.

4.2.1.3 *Water properties*

Detailed observations of the temperature structure will be made during spring and summer months. These measurements will be made using either an electronic bathythermograph or an STD to enable the most rapid coverage of both vertical and horizontal distribution.

Diurnal changes in water characteristics will be measured at selected locations during different conditions of tide, river runoff, and wind.

4.2.2 *Hope Island Bay and North Skagit Bay*

The same studies outlined for Similk Bay will for the most part be made in Hope Island Bay and Skagit Bay south near Seal Rock. Drogue studies in this area will be made as nearly concurrent with those in Similk Bay as possible within the limitations of available manpower and equipment. Dye studies will also be made in this area, with the dye injection made at sites near the proposed outfall location. Water properties will be determined at close temporal and spatial intervals to investigate diurnal changes and changes related to river runoff. An STD will be used for these measurements.

4.2.3 *Swinomish Channel*

An M.R.I. Model 1071 weather station will be established north of the Burlington Northern railroad bridge at the northern end of Swinomish Channel.

Water-level measurements will be made at several locations along the channel. These measurements will be correlated with winds, currents, and other influences.

Water characteristics will be determined at close temporal and spatial intervals. If possible, continuous monitoring of properties over a tide cycle will be made. The rather large amount of detritus in the water makes this difficult as it tends to clog the instruments.

4.2.4 *Deception Pass area*

Currents in this channel will be determined across a section either at Deception Pass or between Yokeko Point and Hoypus Point. These measurements will be made using either current meters or electromagnetic methods to determine actual water transport through Deception Pass. Current-meter measurements will most likely be made between Yokeko Point and Hoypus Point because of the extreme difficulty in maintaining meters in the strong currents of the Pass. These data will be correlated with the observed water-level differences between Cornet Bay and Reservation Bay to establish the relationship between the height difference and current speed. This will enable determination of transport over the period of the entire study from the continuous water-level measurements.

4.2.5 *Internal seiches*

Internal seiches in Puget Sound-Saratoga Passage believed to be significant in affecting water properties and behavior in the Skagit Bay system will be explored. Computations of the internal seiches will be made by the method of De Fant starting at the Tacoma Narrows and continuing to Kiket Island or Deception Pass.

4.2.6 *Pycnocline variation*

The pycnocline depth in the main basin of Puget Sound, as obtained from existing data, will be closely examined to determine the variations in depth, amplitude, and frequency with time. If indicated by this information, the spacing of the stations of the triweekly cruises will be adjusted to give adequate definition of the various nodal points in the system. Observations of the pycnocline in Saratoga Passage and Skagit Bay will be made in a close space-time network and correlated with observed currents in the channel off Strawberry Point.

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