A General Review of the Oceanography of the Queen Charlotte Sound-Hecate Strait-Dixon Entrance Region

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A GENERAL REVIEW OF THE OCEANOGRAPHY OF THE QUEEN CHARLOTTE SOUND-HECATE STRAIT-DIXON ENTRANCE REGION

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ABSTRACT

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Oceanographic cruises and sources of serial physical-chemical and tidal current data, primarily for the period 1934-71, and the results of past research for the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region are reviewed. The results of further analysis of these data, mainly of those for Queen Charlotte Sound and Hecate Strait, are presented. Other relevant information such as average wind conditions, monthly means of sea level (1944-73) and of zonal Ekman transport (1946-73), and annual and monthly means and anomalies of sea surface temperature and salinity (1934-73) for several lightstations located in the region, are also discussed.

Key words: Serial physical-chemical oceanographic data, temperature, salinity, density, dissolved oxygen content, tidal and residual currents, Queen Charlotte Sound, Hecate Strait, Dixon Entrance.

RÉSUMÉ

Dodimead, A. J. 1980. A general review of the oceanography of the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region. Can. MS Rep. Fish. Aquat. Sci. No. 1574: 248 p.

L'A. examine les résultats d'expéditions océanographiques et les sources de séries de données physico-chimiques et de données sur les courants de marée, principalement pour la période allant de 1934 à 1971, ainsi que les résultats de recherches ayant été menées sur la région du bassin Reine-Charlotte, du détroit d'Hécate et de l'entrée Dixon. Il présente les résultats d'analyses plus poussées, surtout des données sur le bassin et le détroit. Il discute aussi de'autres données intéressantes comme la vitesse moyenne du vent, la moyenne mensuelle du niveau de la mer (1944-1973) et du transport zonal selon Ekman (1946-1973) et des moyennes annuelles et mensuelles et des anomalies de la température et de la salinité à la surface de la mer (1934-1973) près de plusieurs phares de la région.

Mots-clés: Séries de données d'océanographie physico-chimique, témperature, salinité, densité, teneur en oxygène dissous, courants résiduels et courants dus à la marée, bassin Reine-Charlotte, détroit d'Hécate, entrée Dixon.

I. INTRODUCTION

Serial physical-chemical oceanographic observations in the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region (Fig. 1) were made initially in 1934, and have been continued aperiodically to the present. Most of the oceanographic data, including those on tidal currents, were collected during the period 1934-71 by personnel of the Pacific Oceanographic Group.[1] The data to 1963 have been published in data records, primarily those in the "Fisheries Research Board of Canada, Oceanographic and Limnological Series" (discontinued in 1967). All the serial data collected prior to 1972 are archived in the Marine Environmental Data Service (MEDS), Department of Fisheries and Oceans, Ottawa. While some oceanographic data have subsequently been obtained in this region, they are not yet as readily available as those collected prior to 1972. Some of the post-1971 data have been used to provide information on such major oceanographic features as the seasonal and spatial variability of water masses and the tidal and residual currents in the region[2]; however, this information is dispersed among several different publications. Also, a considerable amount of these data has not been analyzed, or has not been presented in a suitable and available format for researchers who have a continuing requirement for oceanographic and related information for this region. The purpose of this report is to present further analysis of the available serial physical-chemical and tidal current data, particularly of those for Queen Charlotte Sound and Hecate Strait. Other relevant information, such as average wind conditions, monthly means of sea level and of zonal Ekman transport, and annual and monthly means and anomalies of sea surface temperature and salinity at several lightstations located in the region, is also discussed. A documentation of oceanographic cruises and references for data sources primarily for the period 1934-71, as well as a general review of the results of past research, are also included.

It is hoped that the report will serve both as a complete source of available background oceanographic information, at least to 1972, for fisheries and other research studies, and as a means of identifying deficiencies in the data base. With respect to the latter, it is hoped that the report will serve as a catalyst for the design and implementation of oceanographic-biological time-series programs that will provide essential information for on-going and planned research studies, particularly those directly related to the management of the fishery resources in this region.

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[1]In October 1970, the Pacific Oceanographic Group of the Pacific Biological Station, Nanaimo, B.C. was disbanded; the physical oceanographers and their support staff were transferred to other Canadian west coast establishments.

[2]The term "region" throughout this report includes Queen Charlotte Sound, Hecate Strait, and Dixon Entrance.

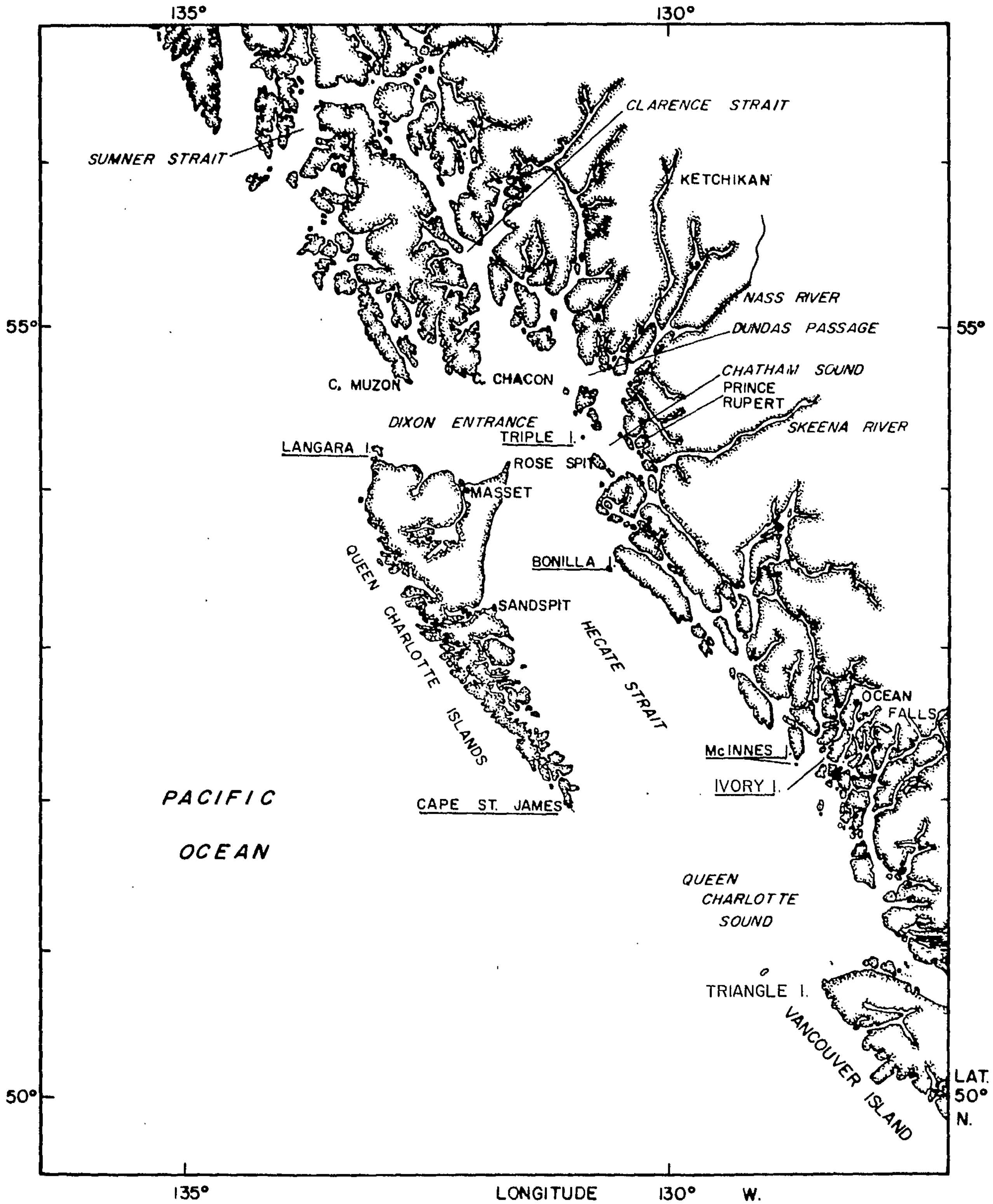

Fig. 1. Queen Charlotte Sound - Hecate Strait - Dixon Entrance Region.

II. OCEANOGRAPHIC CRUISES AND DATA SOURCES

A brief description of oceanographic projects and cruises, as well as charts showing station positions at which serial oceanographic and tidal current observations were made during the period 1934-71, are provided in this section. Other oceanographic data collected in this period and in subsequent years are briefly noted. Figures for this and subsequent major sections are found immediately following the text for each of the sections. Figures for this section start on page 9.

The first oceanographic cruise in the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region dates back to September 1934, at which time the late Dr. T. G. Thompson of the University of Washington, aboard MV CATALYST, made serial observations at three stations across the western entrance to Dixon Entrance (Fig. 2). This was followed by a second cruise in July 1937 (Fig. 2). The first Canadian cruise in the region was made in May-June 1938 under the leadership of Dr. J. P. Tully aboard MV AMLAC, and covered Dixon Entrance and northern Hecate Strait (Fig. 3). Along two of the north-south transects across Dixon Entrance (Sta. 104-1 to 104-4 and 105-1 to 105-4; Sta. 102-1 to 102-4 and 107-1 to 107-4) observations were made on opposite tidal phases. Over the remaining part of the area, only a general synoptic survey was made. In May 1951, serial observations were made in Dixon Entrance and, for the first time, in Queen Charlotte Sound and in southern and central Hecate Strait (Fig. 4) in conjunction with an oceanographic survey of the offshore region. This was followed by another survey in late July 1951 (Fig. 5). The data for all of these cruises were published in a single manuscript report (Pacific Oceanographic Group 1956).

Following these cruises, a major oceanographic study (Hecate Project) of the region was initiated in 1954 to define the water masses, their spatial and seasonal variability, and the tidal currents and circulation systems (Barber and Tabata 1954). The program included seven cruises - in May, June, July, August-September and November-December 1954, and in February, April and May-June 1955 (Fig. 6-12). Serial oceanographic measurements were made on a pre-planned grid of 75 stations, but for various reasons all stations were not occupied on each cruise. In July 1954, the cruise was interrupted on several occasions by adverse weather conditions. Again, in November-December 1954, the cruise suffered severely from unfavorable weather conditions, and was not completed because of storm damage to the research vessel, HMCS CEDARWOOD. In addition to the synoptic surveys, direct measurements of tidal currents at various depths from the surface to near-bottom were made at several stations, generally over a 50-hr period, in May, July and August-September 1954 and in June 1955 (Fig. 13). The data from these cruises were published by the Pacific Oceanographic Group (1955a,b,c).

In 1957, the Coastal Surveys were initiated. Four cruises covering primarily the areas off the west coast of Vancouver Island and of the Queen Charlotte Islands were made. On three of the cruises, those of April, September and November-December 1957, a few stations were occupied between the northern tip of Vancouver Island and the southern tip of the Queen Charlotte Islands (Pacific Oceanographic Group 1958). During the November-December cruise, a few stations were also occupied in Queen

Charlotte Sound and in Dixon Entrance (Fig. 14). Only the chart for the December cruise is presented, as the stations occupied across the western entrance to Queen Charlotte Sound in April and September are similar in position to those occupied in December.

In 1958, the Coastal-Seaways Project was undertaken to obtain data primarily to assess the changes in oceanographic conditions from the open ocean to the adjoining coastal seaways (Dixon Entrance, Queen Charlotte Sound, Juan de Fuca Strait). Cruises were made in November-December 1958, April, June and November-December 1959 (Fig. 15-18). These data were published by the Pacific Oceanographic Group (1959a,b c) and by Herlinveaux et al. (1960). The project was continued in October 1960 (Fig. 19) (Lane et al. 1960) and in February 1961 (Fig. 20) (Lane et al. 1961).

In 1961, the Monitor Project was initiated. It was essentially a consolidation of the several previous projects into a single one. The following surveys once again provided a reasonable spatial and temporal coverage of the region, particularly of Queen Charlotte Sound and Dixon Entrance, in July-August and September-October 1961 (Crean et al. 1962a), January and January-February 1962 (Crean et al. 1962b), March and March-April 1962 (Crean et al. 1962c) and September-October 1962 (Crean et al. 1963) (Fig. 21-27). With the completion of the project, resources were diverted to carry out programs in other areas, notably the Strait of Georgia.

It was not until 1967, with the initiation of the Oceanic-Coastal Program by the author, that observations were resumed in this region. This program was designed primarily to provide information on the continental shelf and offshore waters off the west coast of Vancouver Island northward to the Queen Charlotte Islands for 2 seasonal periods (early autumn and late winter). Several transects were made in the region under discussion - in September 1967, April and October 1968, April and October 1969, March 1970 and 1971 (Fig. 28-34). The data from these cruises were unique in that a Bissett-Berman (Plessey) 9006 STD system was used for the first time in this region; continuous profiles of temperature and salinity vs depth were obtained. Although these data have not been published, they have been processed and are on file with the Marine Environmental Data Service.

Other physical oceanographic data have been collected in the region during the period 1934-71, but these were primarily bathythermograms during fisheries research cruises conducted by the Pacific Biological Station. The bathythermograms have not been published, and are not discussed in this report. However, surface and bottom water temperatures for each cruise are provided in cruise and data reports (Westrheim 1967; Harling et al. 1967, 1968, 1969, 1970a,b and 1971; Butler and Smith 1968; Levings 1968; Westrheim et al. 1968, 1969a,b, 1970 and 1971; Davenport et al. 1971). Also, current and temperature observations were made from the drill rig, SEDCO-135, while operating in Queen Charlotte Sound and Hecate Strait in 1968-69. The analysis of these data has recently been completed, and the results will be published shortly (Herlinveaux, priv. comm).

Since 1971, physical-chemical oceanographic programs in the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region have been extremely limited in both spatial and temporal coverage. The collection of bathythermograms and some serial oceanographic data during fisheries research surveys has continued. In 1979, publication of the digitized bathythermograms from these cruises, as well as an assessment of temperature conditions, was initiated. The 1977 and 1978 data have been published (Dodimead et al. 1979a,b). In 1977, the Institute of Ocean Sciences, Patricia Bay, Sidney, B. C. collected salinity-temperature-depth (STD) data and obtained additional information on near-surface and bottom currents in Queen Charlotte Sound and Hecate Strait, but these data have not been published as yet.

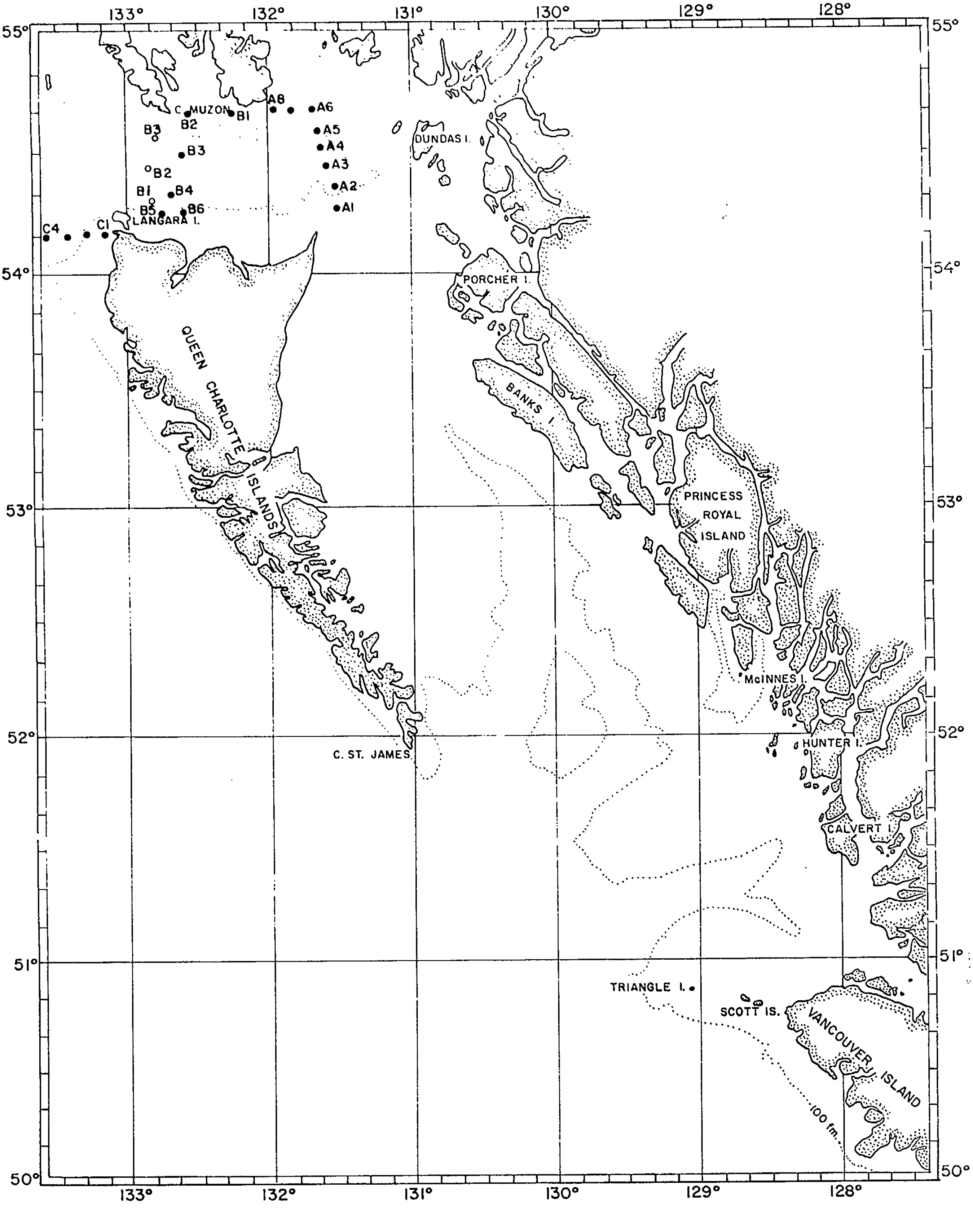

Fig. 2. Station positions, o -September 3, 1934 and ● -July 25-28, 1937 (Pacific Oceanographic Group 1956).

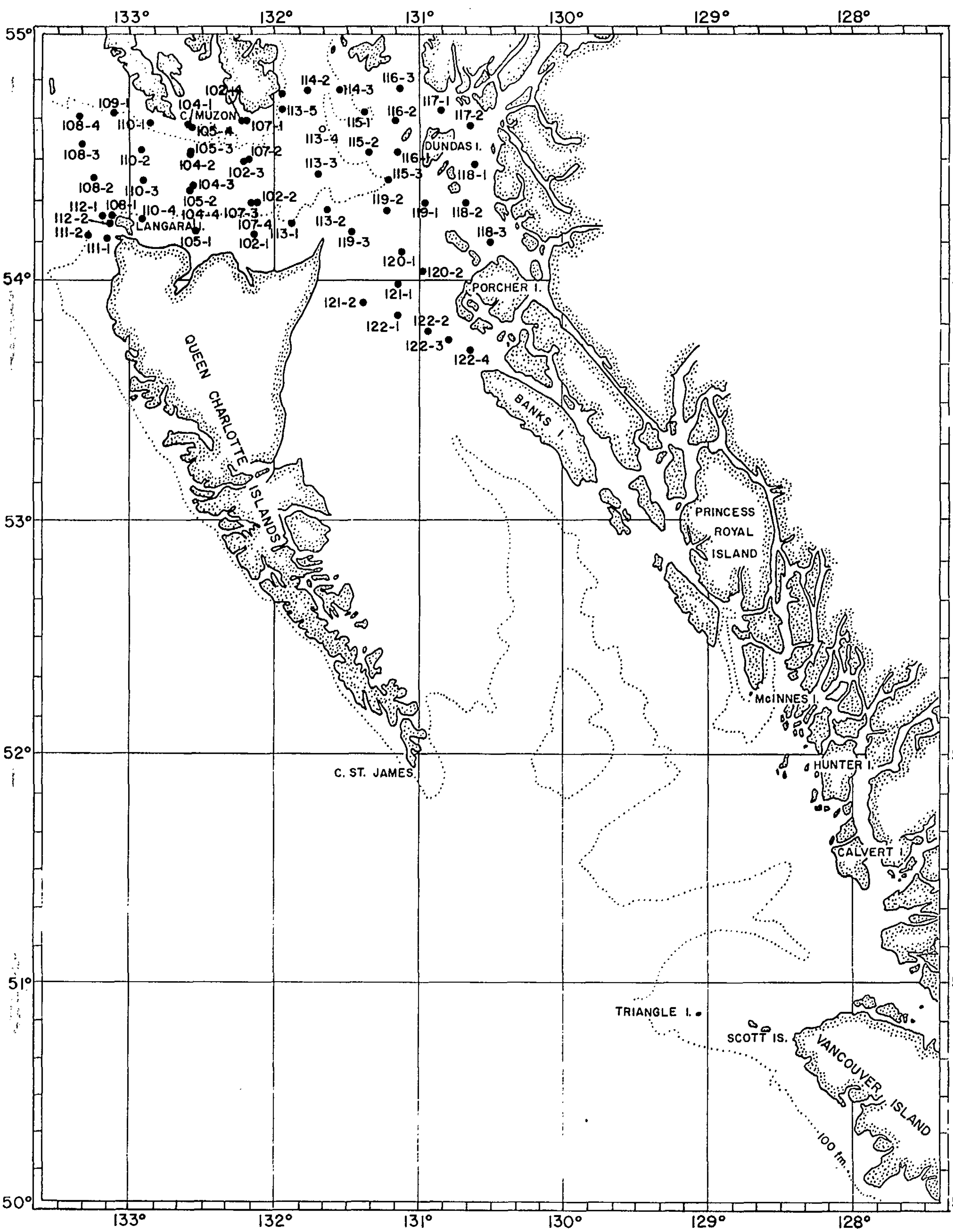

Fig. 3. Station positions, May 24-June 6, 1938 (Pacific Oceanographic Group 1956).

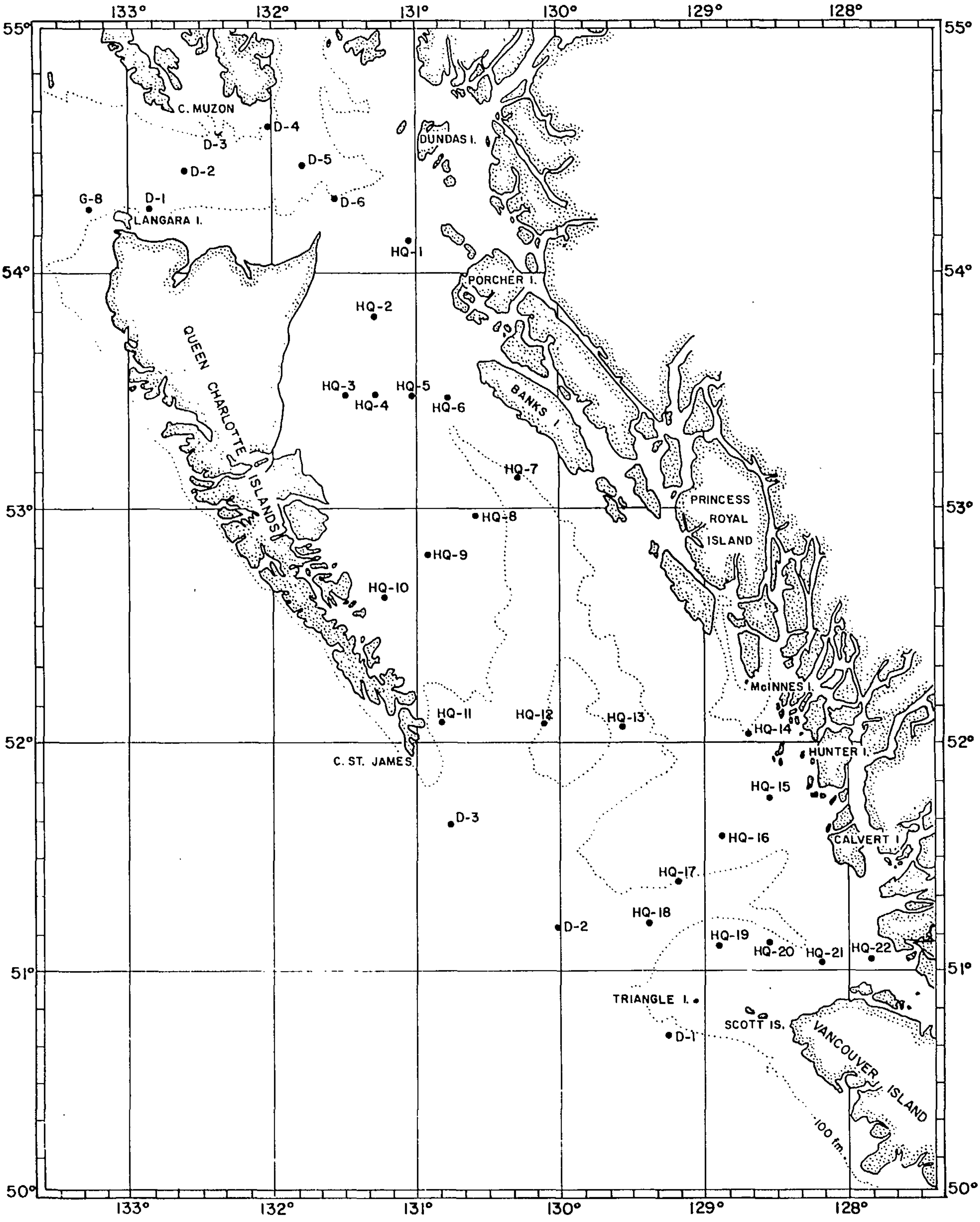

Fig. 4. Station positions, May 12-23, 1951 (Pacific Oceanographic Group 1956).

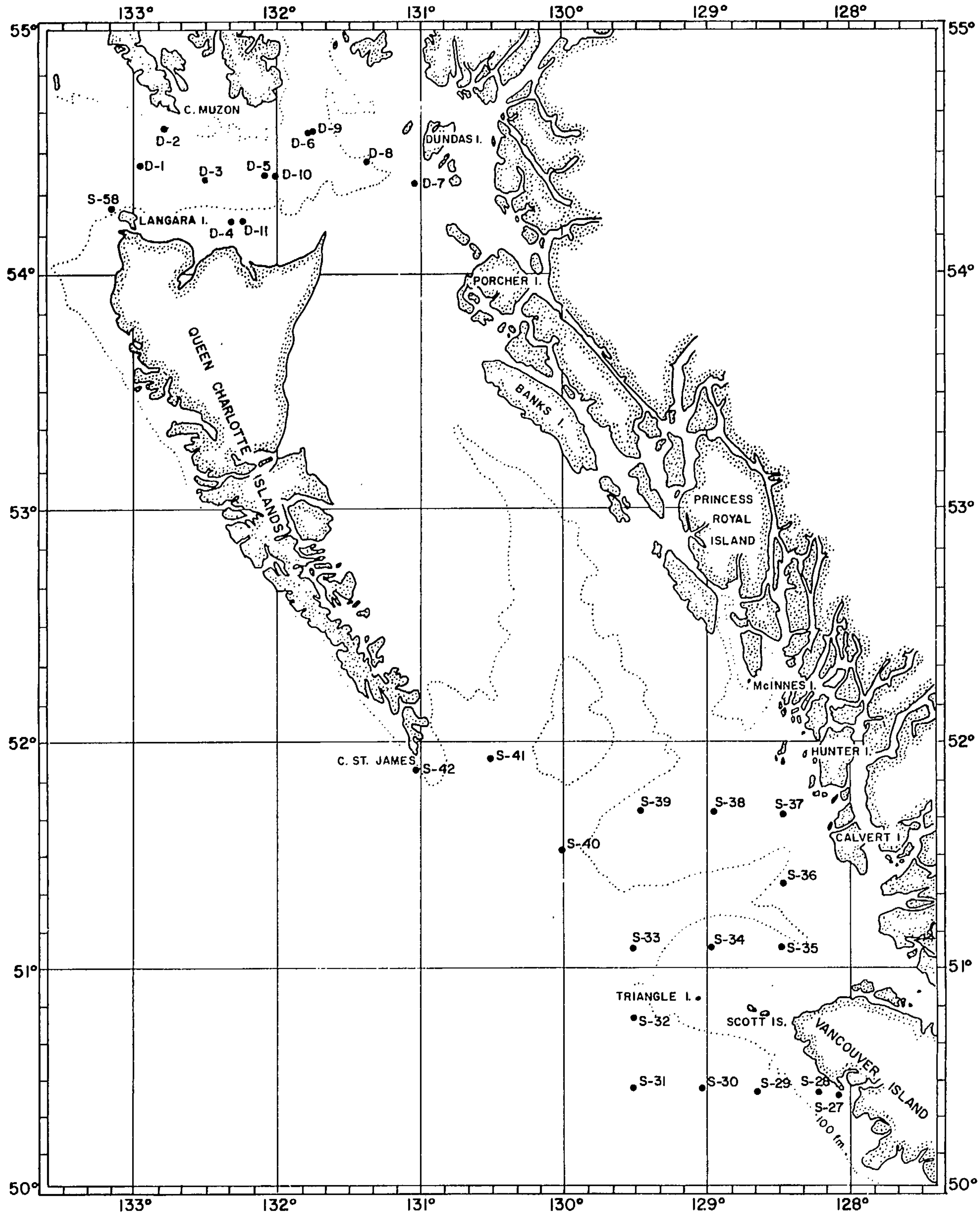

Fig. 5. Station positions, July 22-August 1, 1951 (Pacific Oceanographic Group 1956).

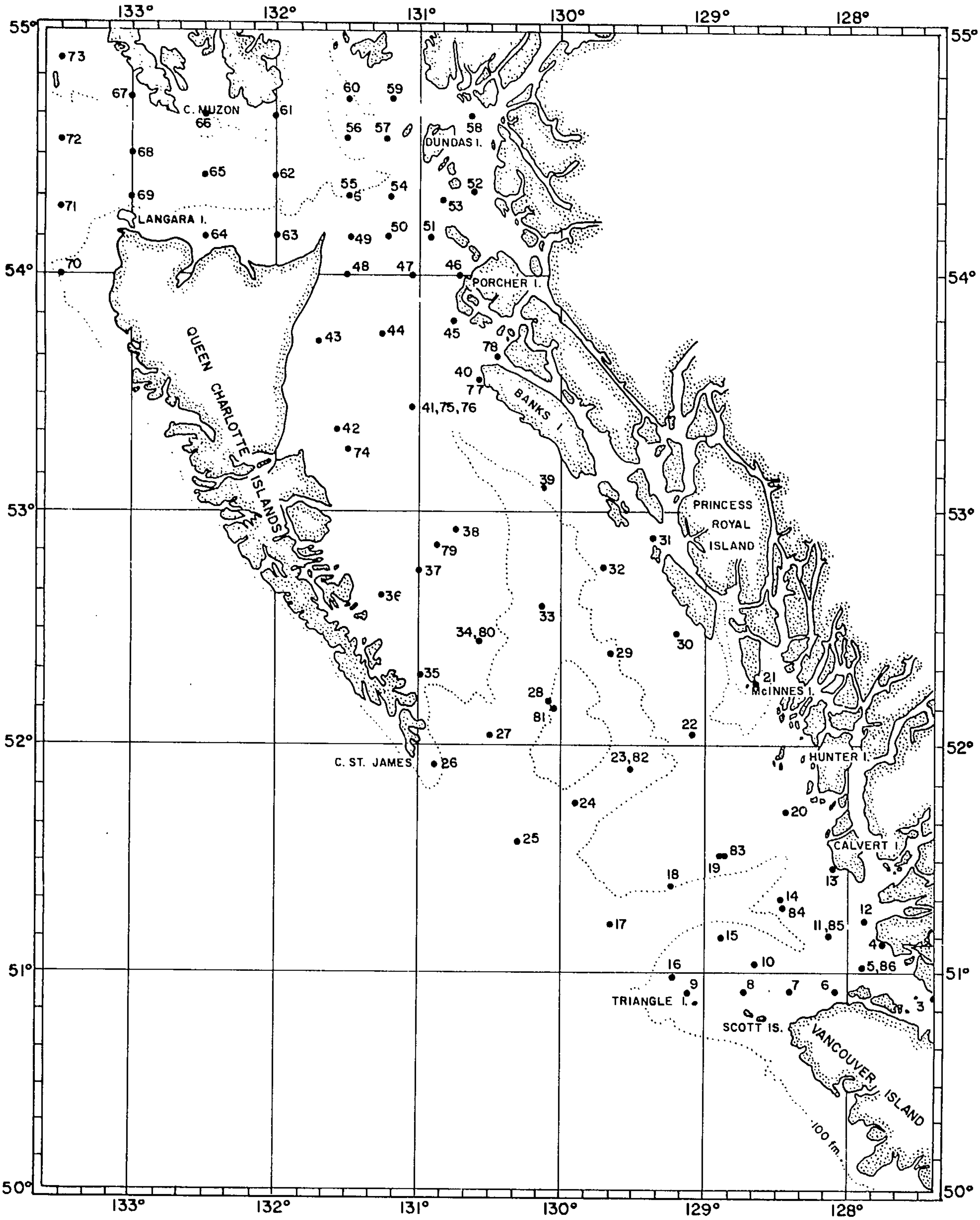

Fig. 6. Station positions, May 3-28, 1954 (Pacific Oceanographic Group 1955a).

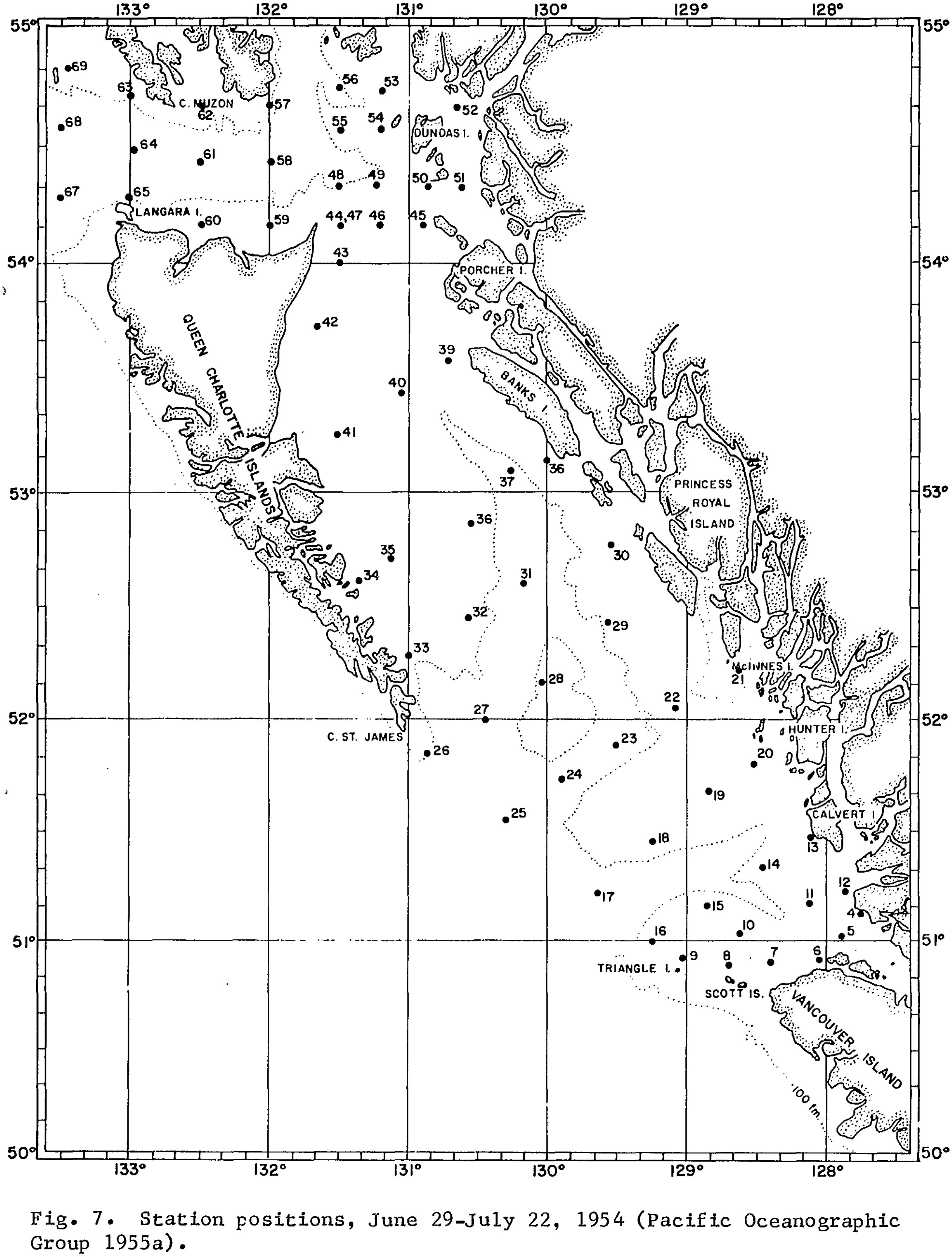

Fig. 7. Station positions, June 29-July 22, 1954 (Pacific Oceanographic Group 1955a).

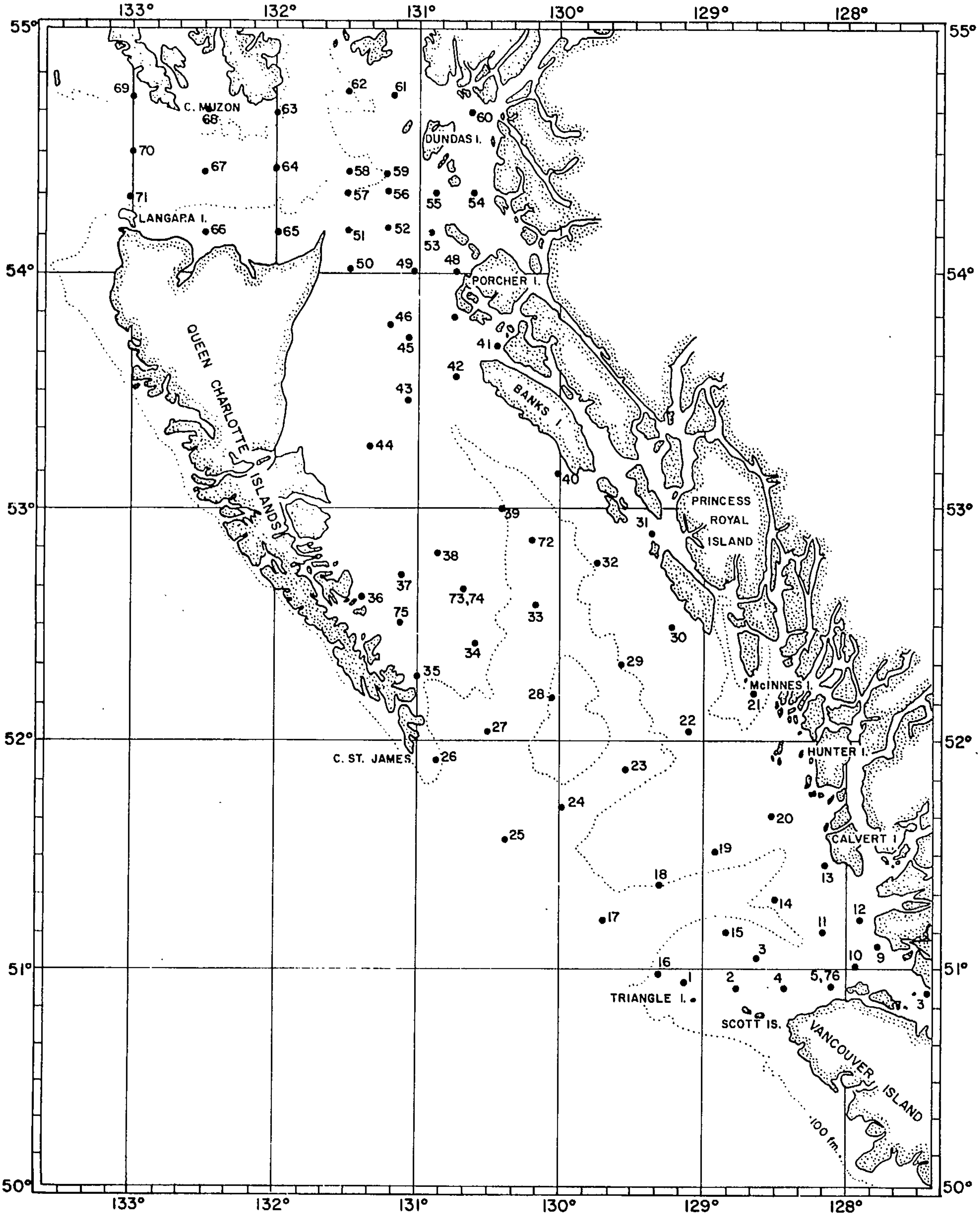

Fig. 8. Station positions, August 17-September 9, 1954 (Pacific Oceanographic Group 1955a).

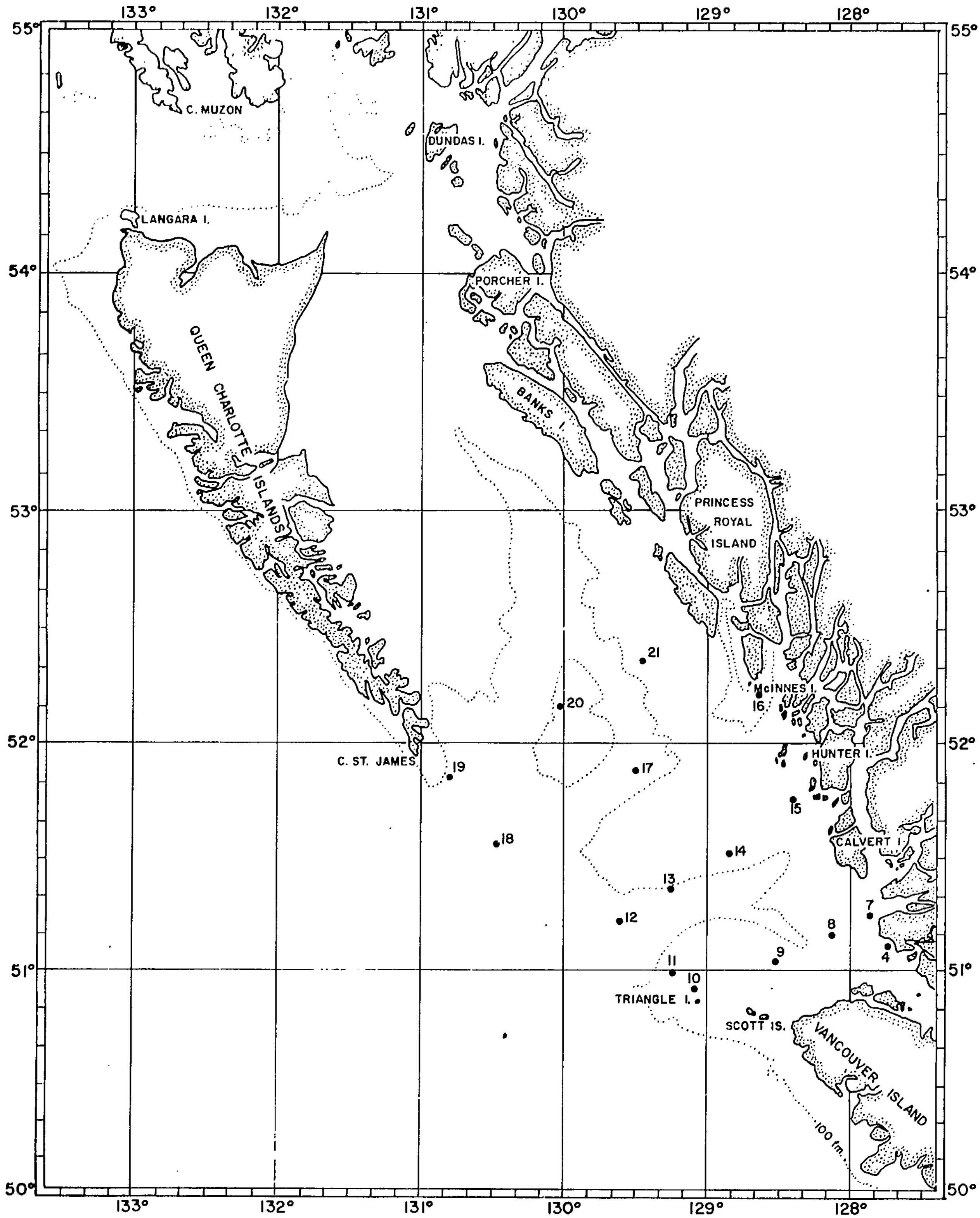

Fig. 9. Station positions, November 15-December 7, 1954 (Pacific Oceanographic Group 1955a).

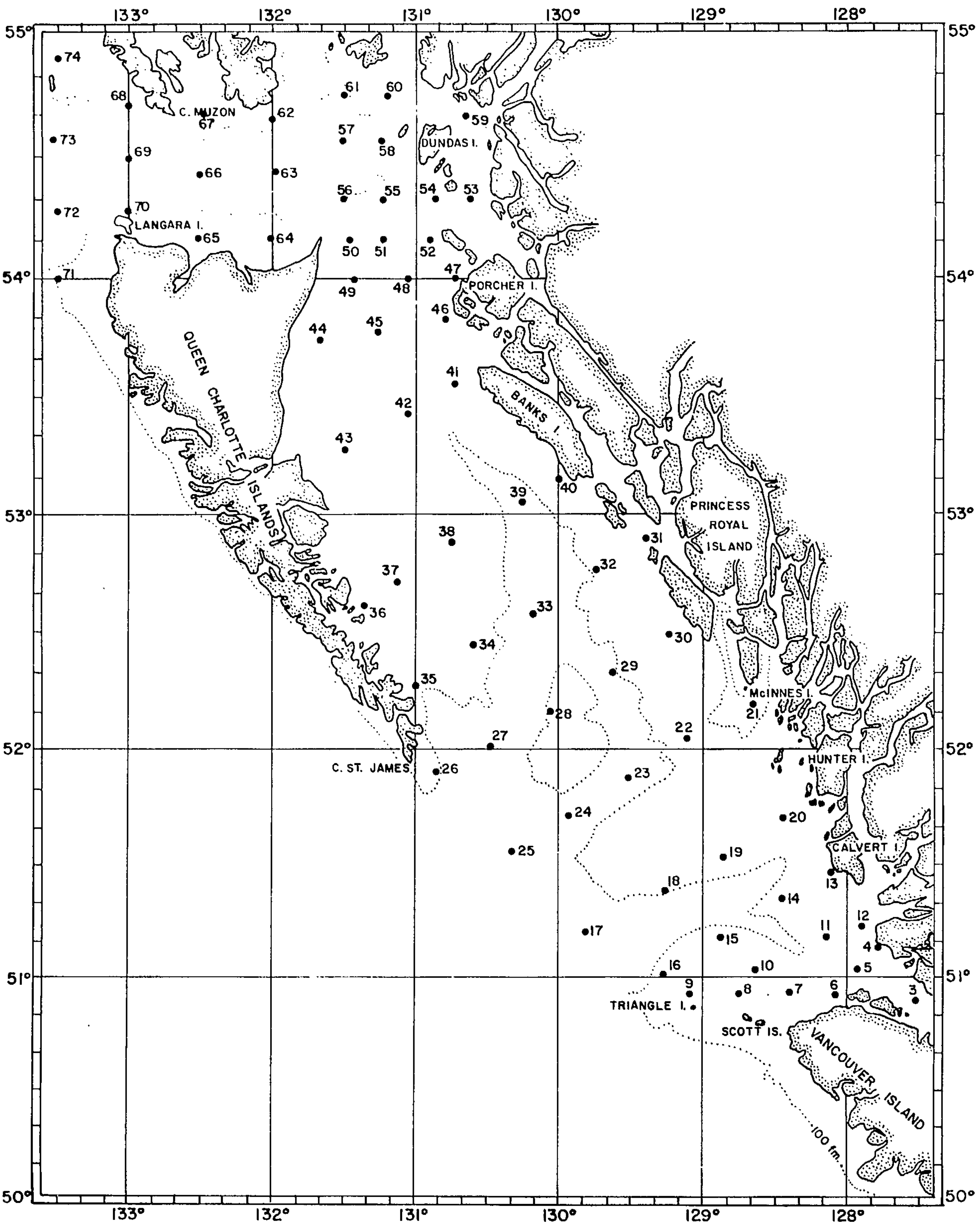

Fig. 10. Station positions, February 6-13, 1955 (Pacific Oceanographic Group 1955c).

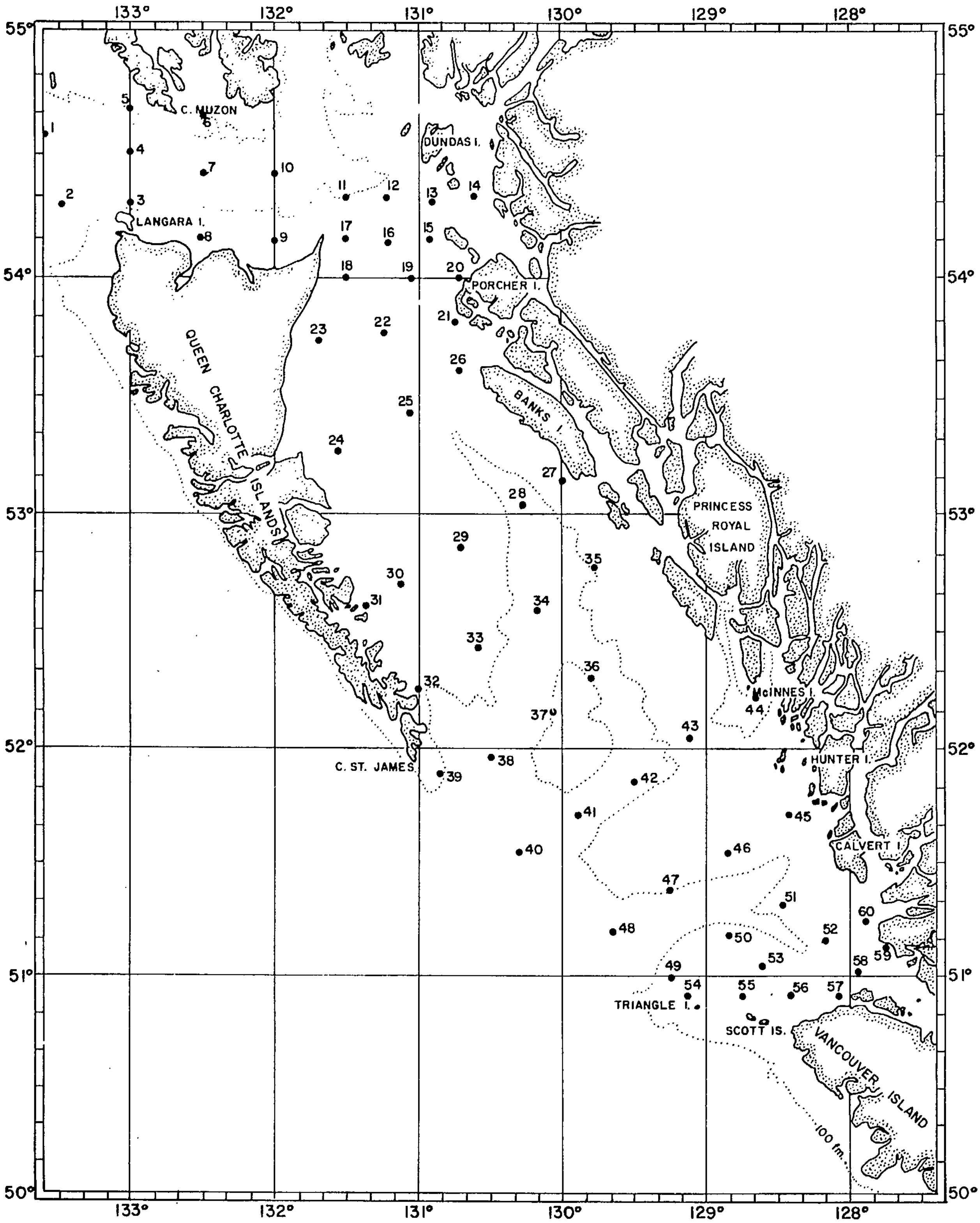

Fig. 11. Station positions, April 14-18, 1955 (Pacific Oceanographic Group 1955c).

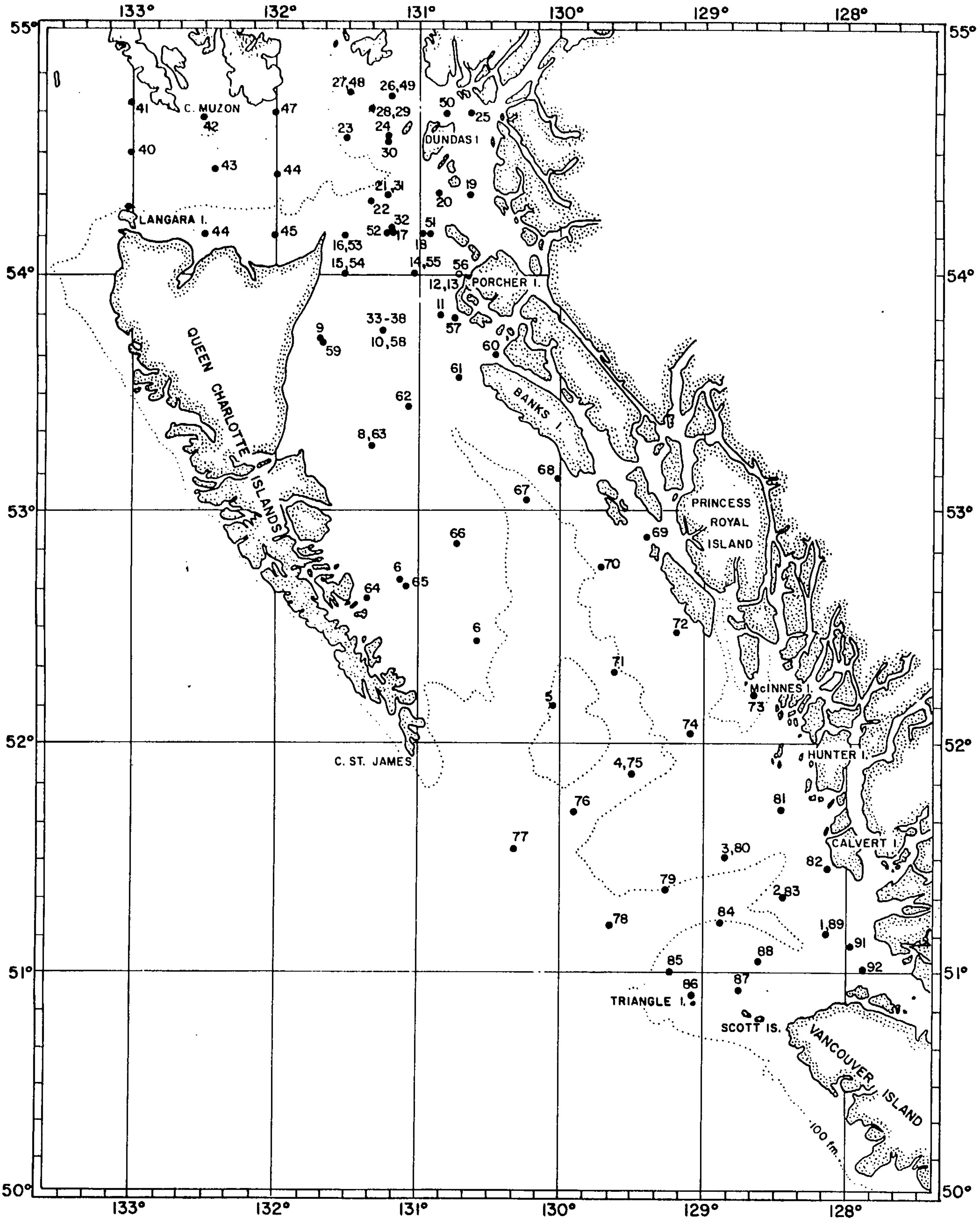

Fig. 12. Station positions, May 30-June 24, 1955 (Pacific Oceanographic Group 1955c).

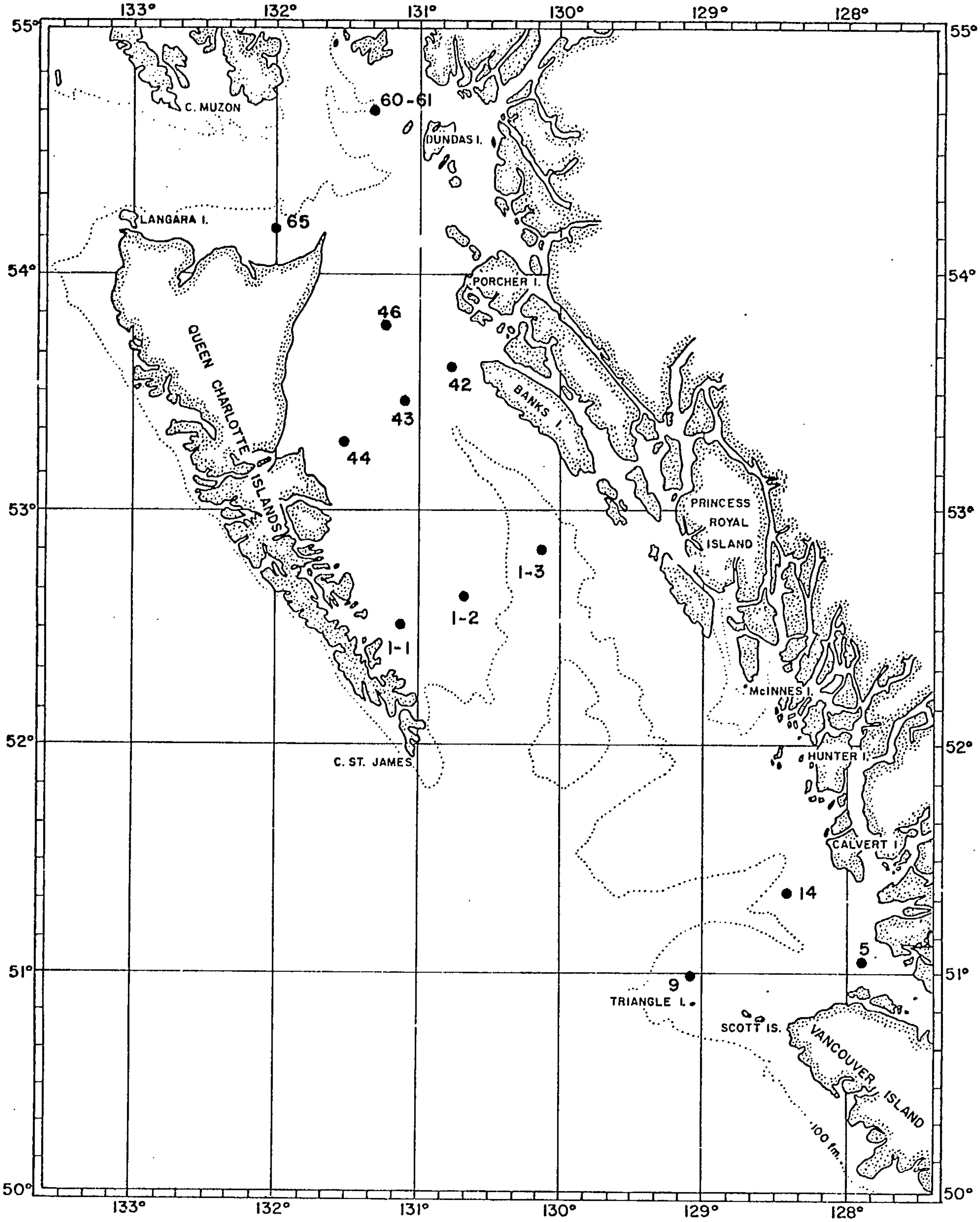

Fig. 13. Stations at which direct current observations were made in May, July and August-September, 1954 and in June, 1955 (Pacific Oceanographic Group 1955b, c).

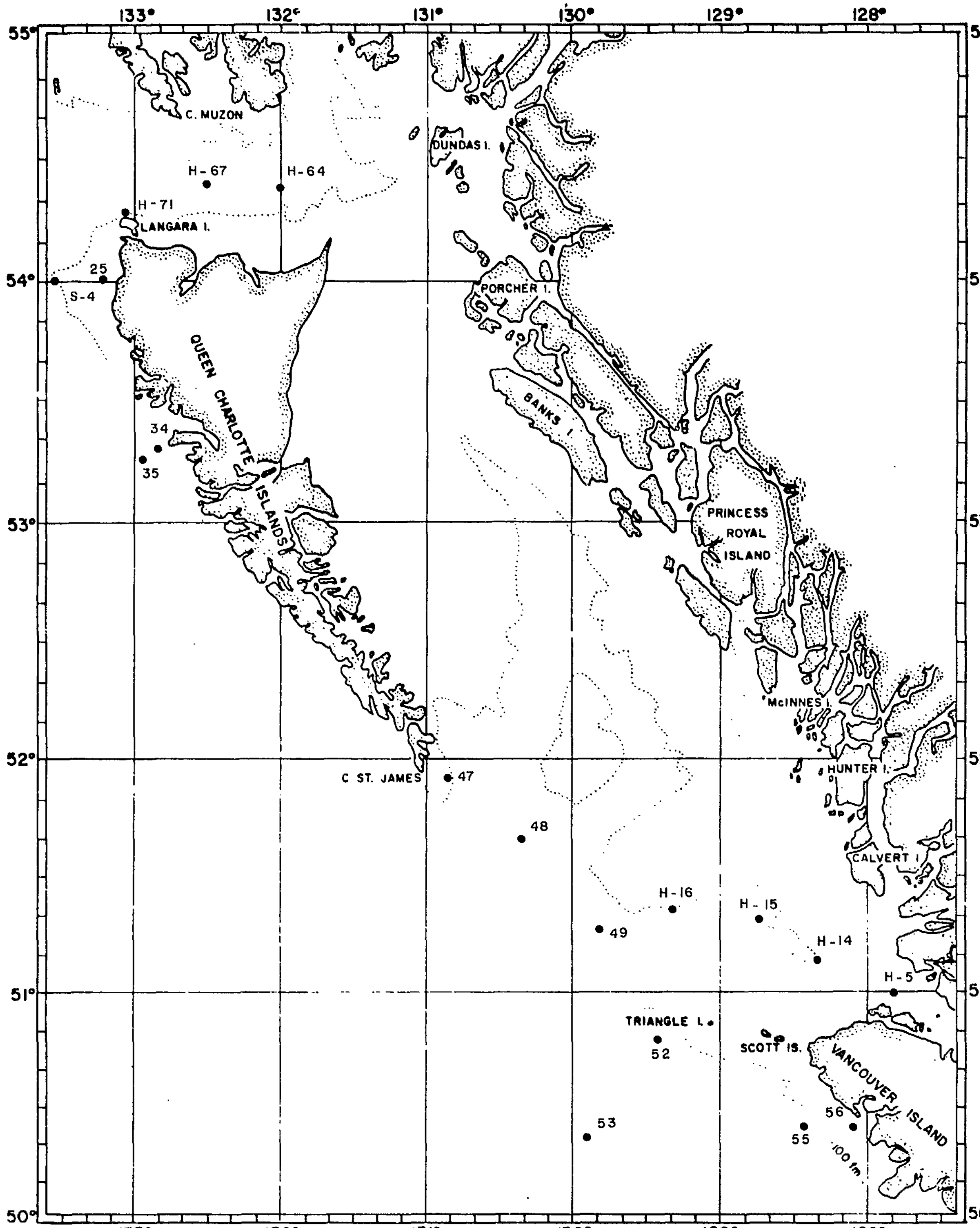

Fig. 14. Station positions, November 29-December 17, 1957 (Pacific Oceanographic Group 1958).

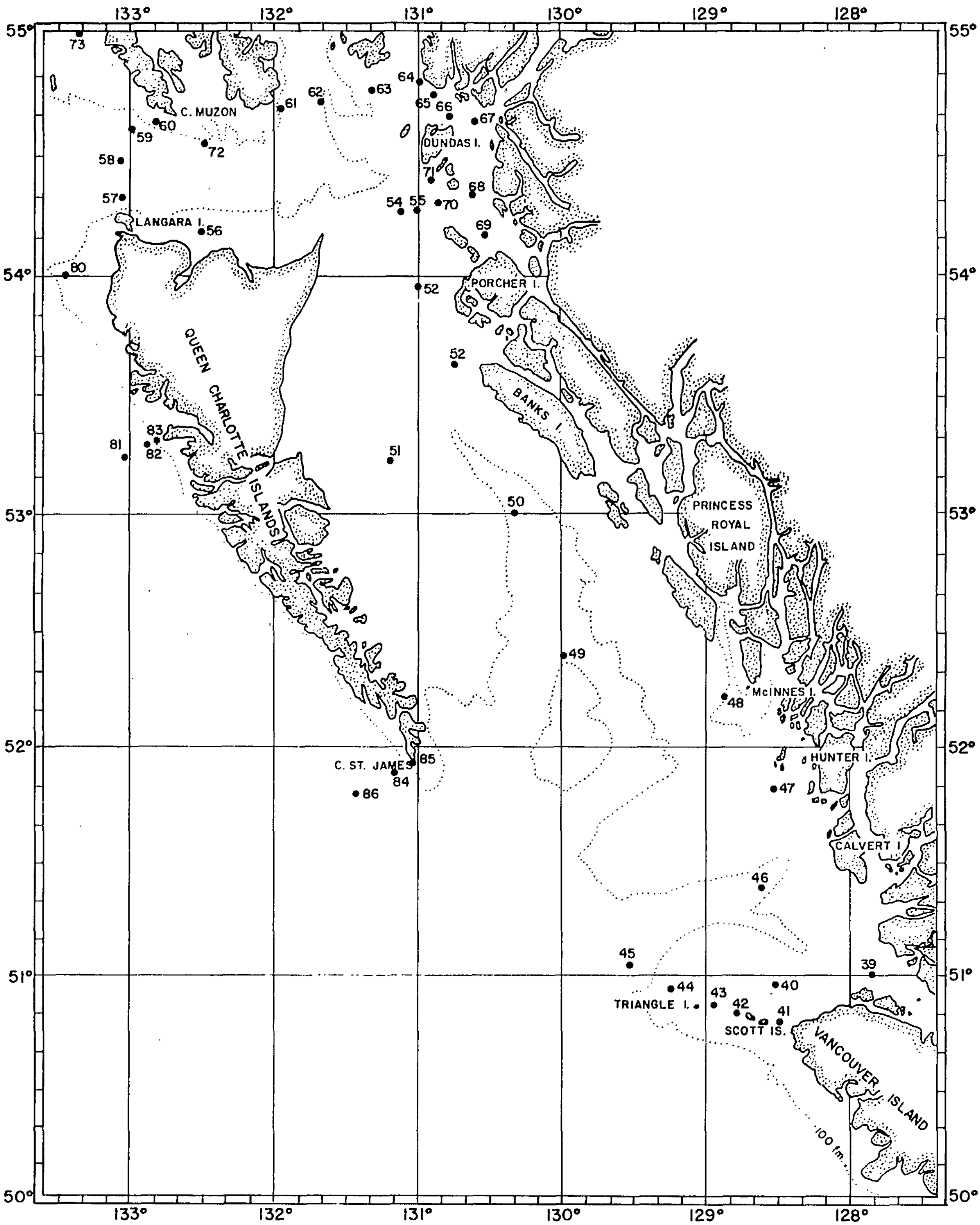

Fig. 15. Station positions, November 18-December 2, 1958 (Pacific Oceanographic Group 1959a).

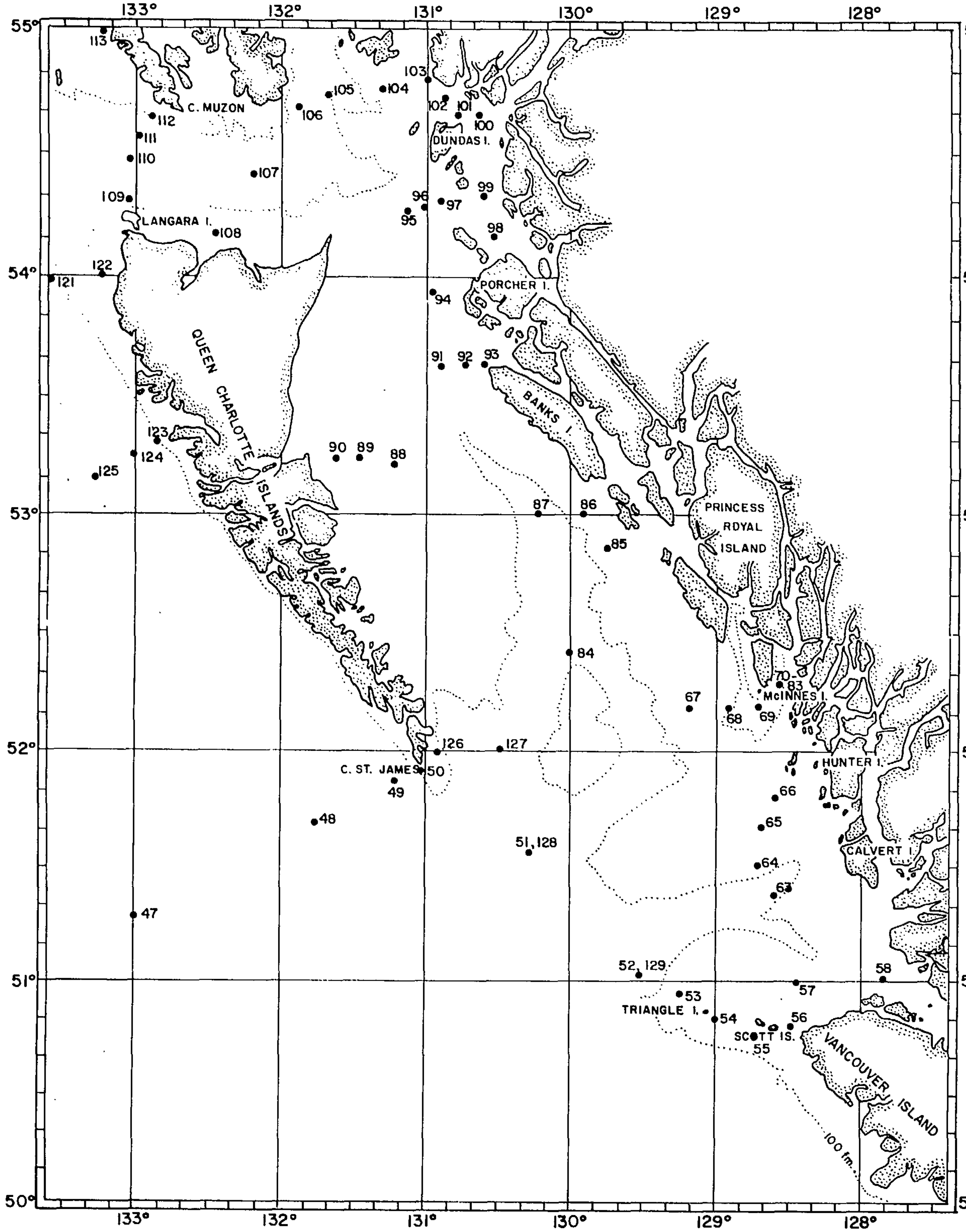

Fig. 16. Station positions, April 12-21, 1959 (Pacific Oceanographic Group 1959b).

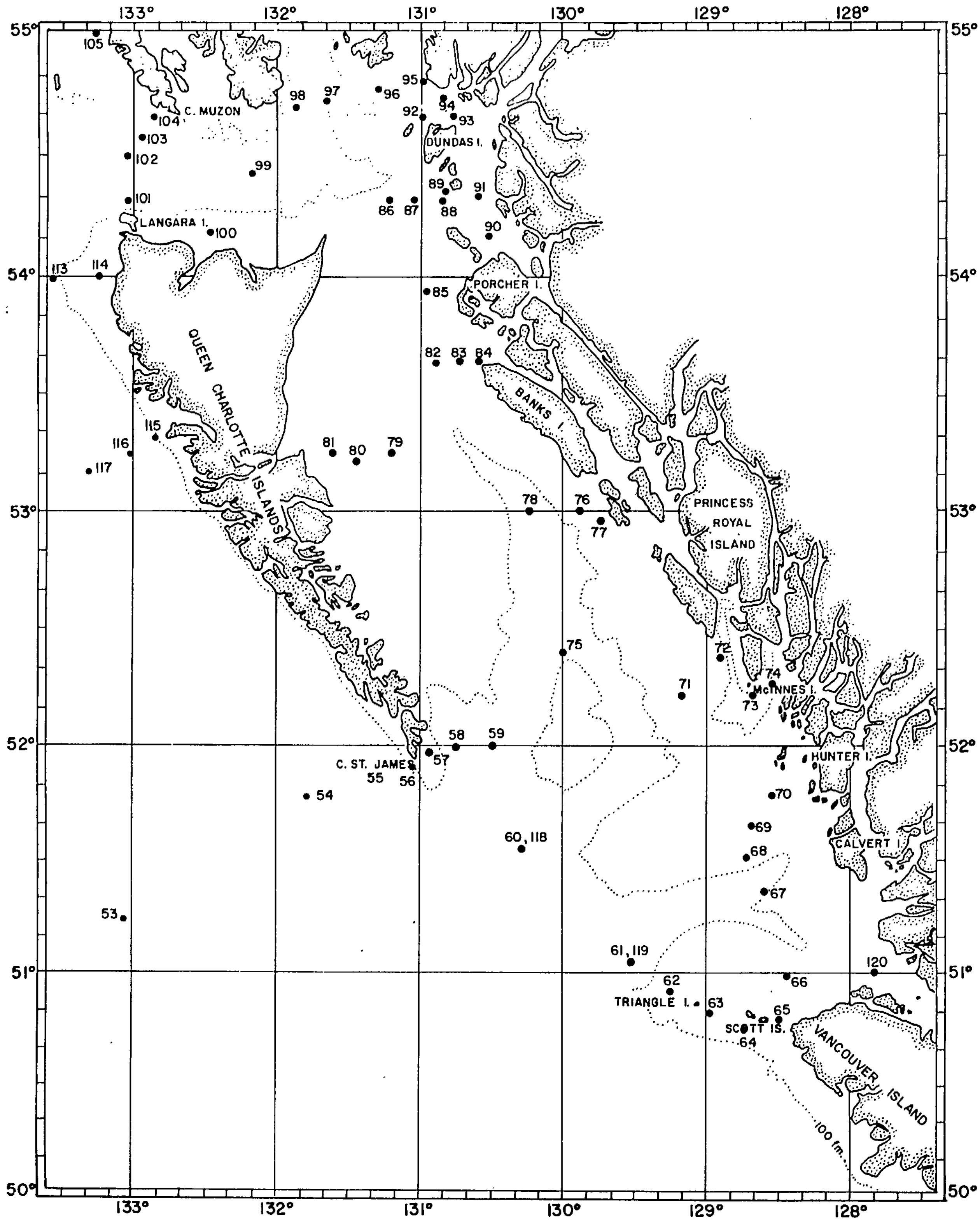

Fig. 17. Station positions, June 21-29, 1959 (Pacific Oceanographic Group 1959c).

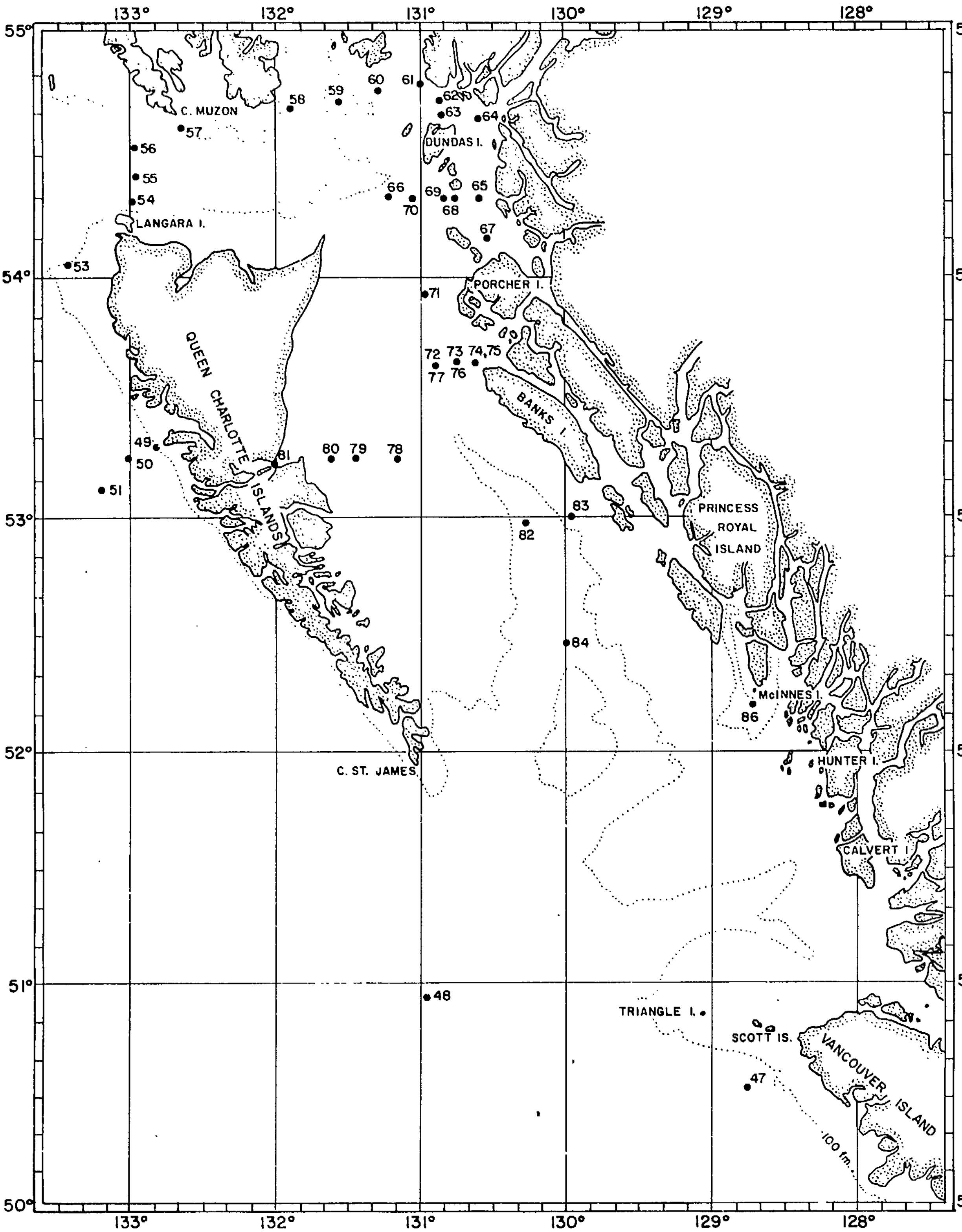

Fig. 18. Station positions, November 28-December 9, 1959 (Herlinveaux et al. 1960).

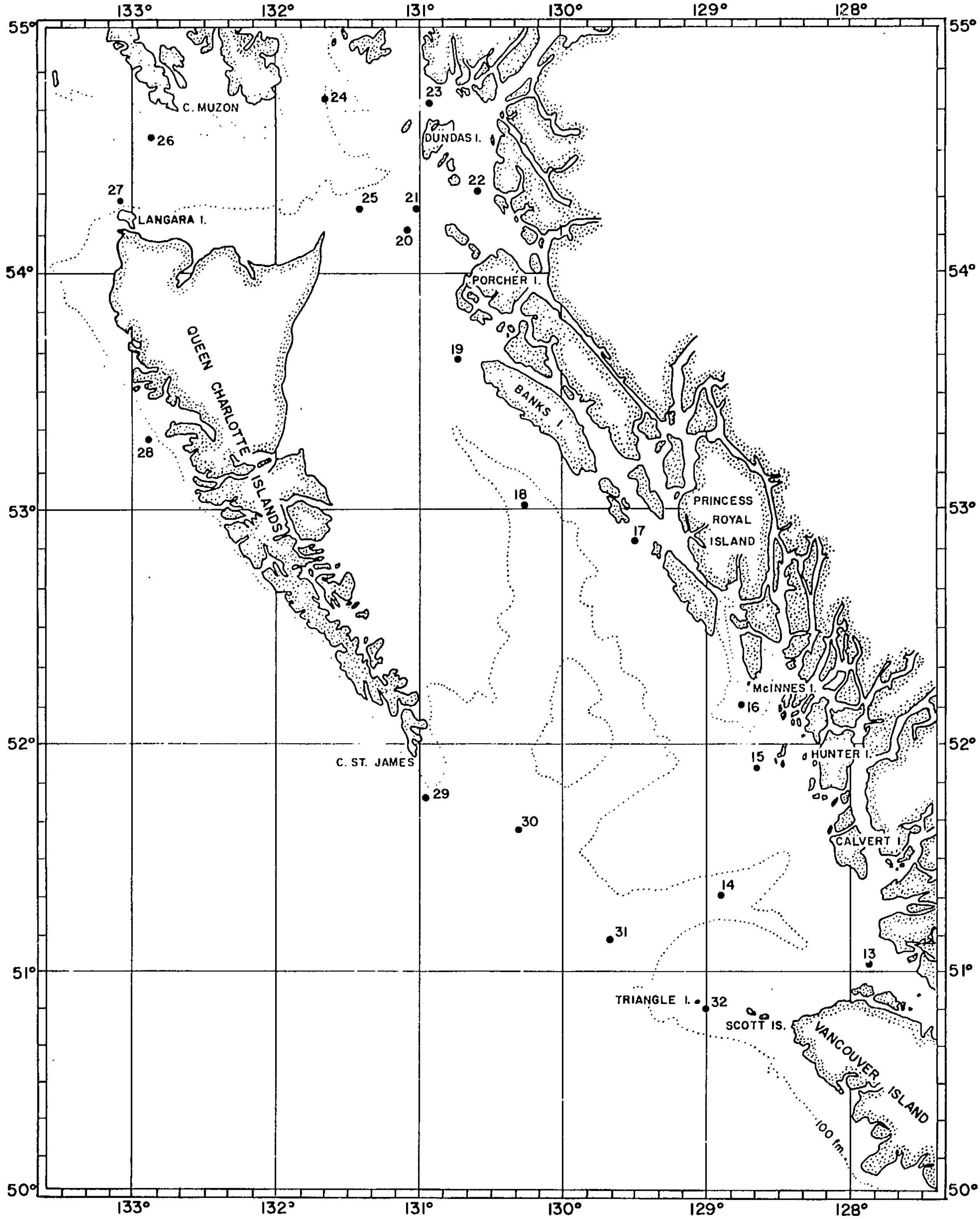

Fig. 19. Station positions, October 20-26, 1960 (Lane et al. 1960).

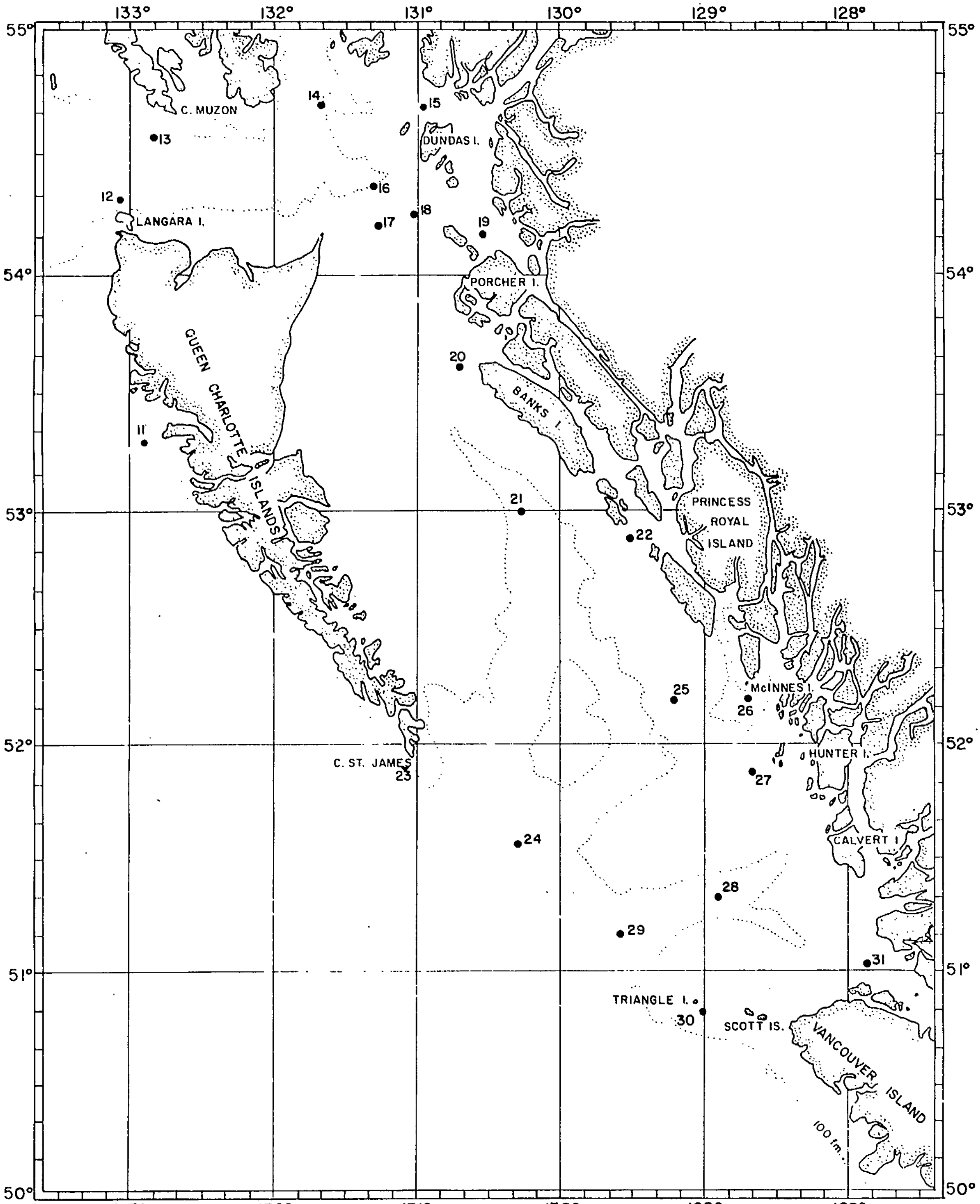

Fig. 20. Station positions, February 11-26, 1961 (Lane et al. 1961).

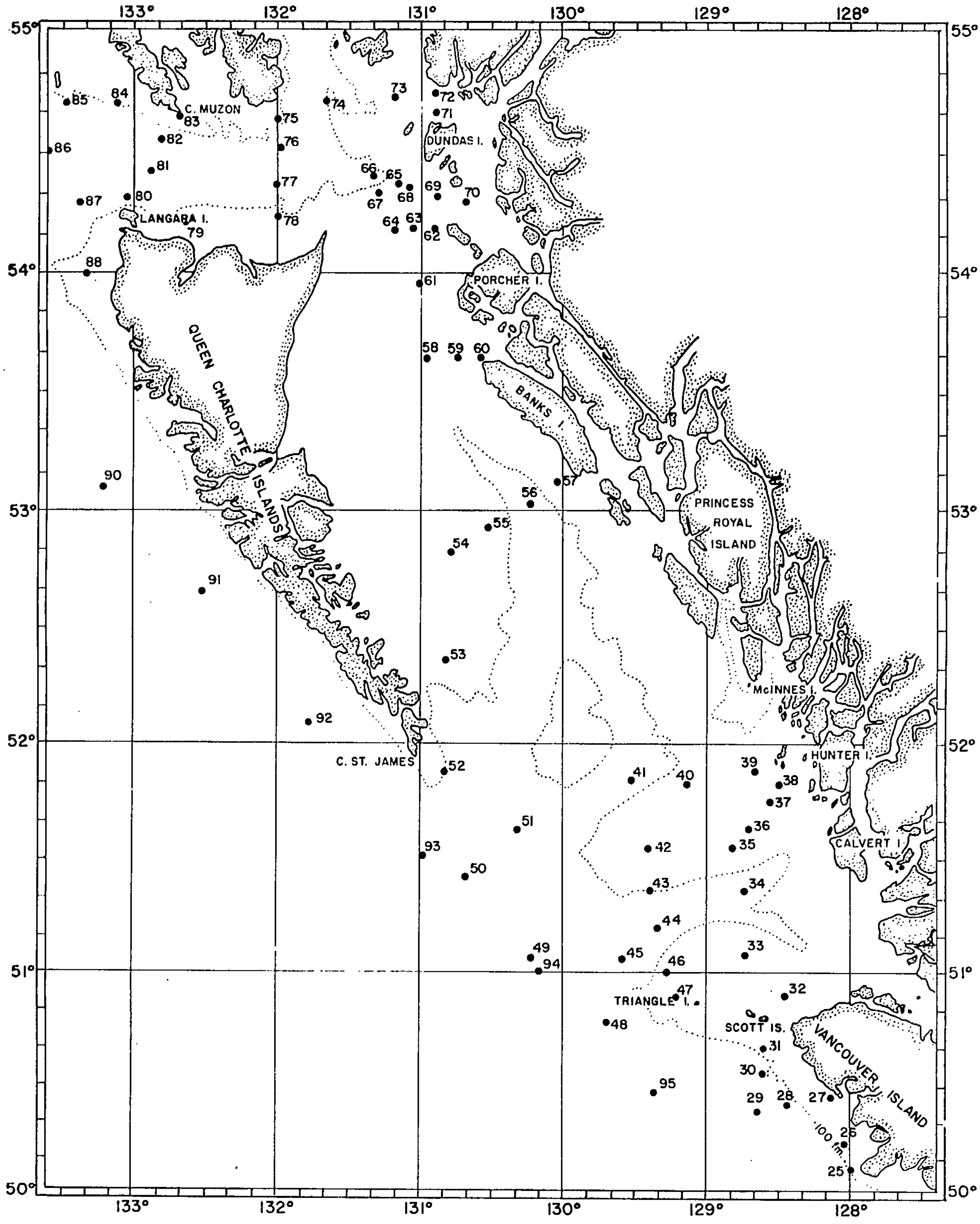

Fig. 21. Station positions, July 27-August 5, 1961 (Crean et al. 1962a).

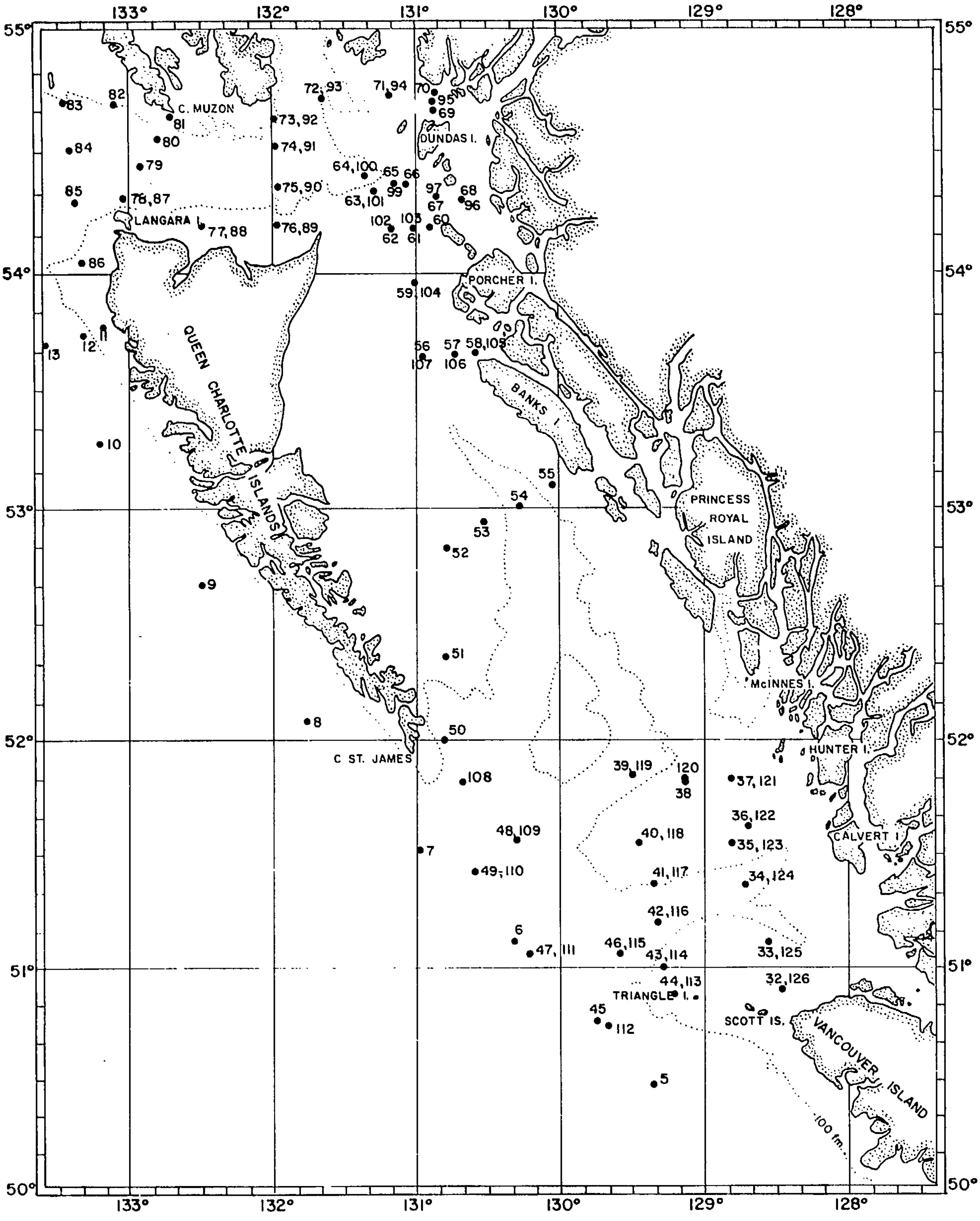

Fig. 22. Station positions, September 22-October 17, 1961 (Crean et al. 1962a).

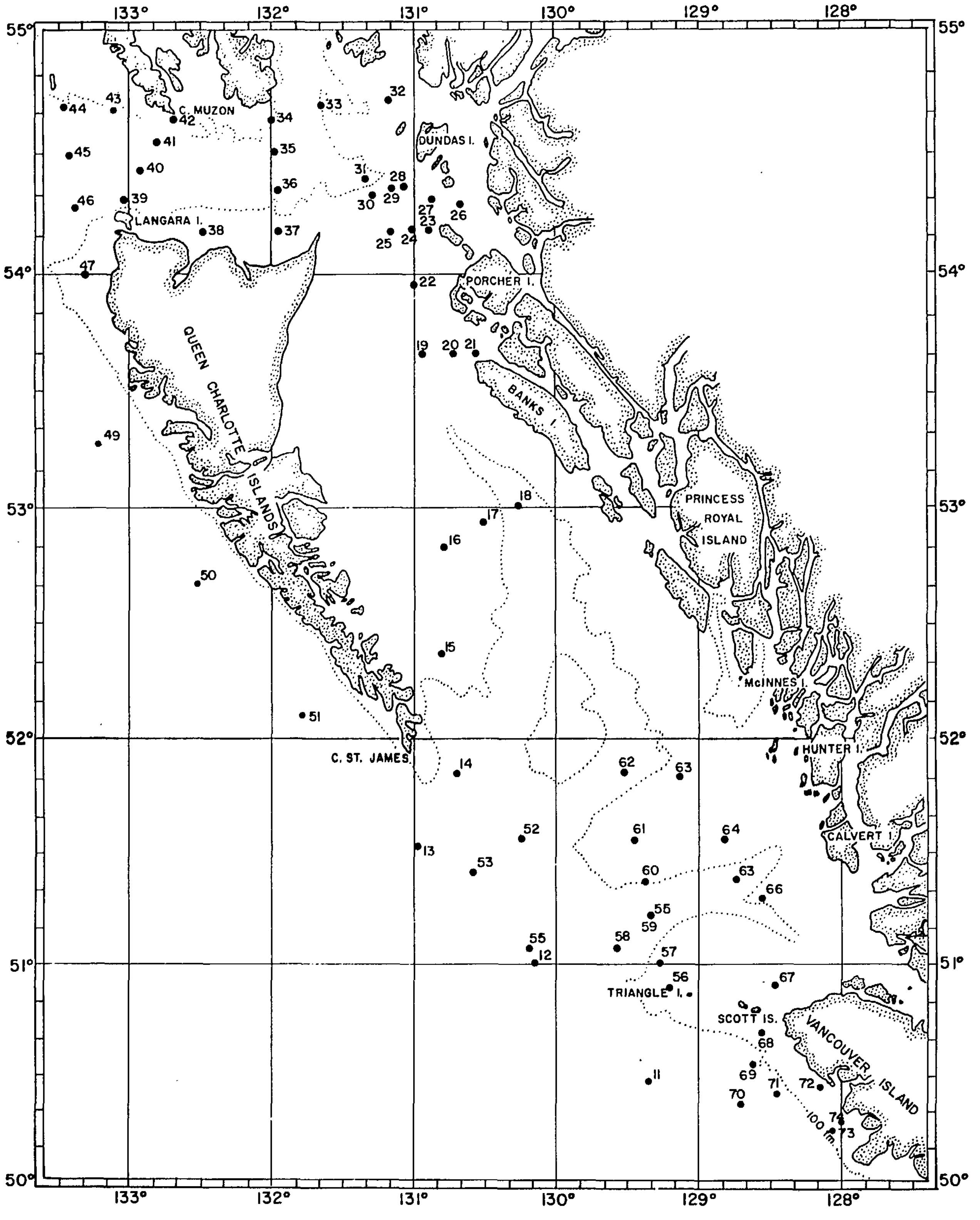

Fig. 23. Station positions, January 17-24, 1962 (Crean et al. 1962b).

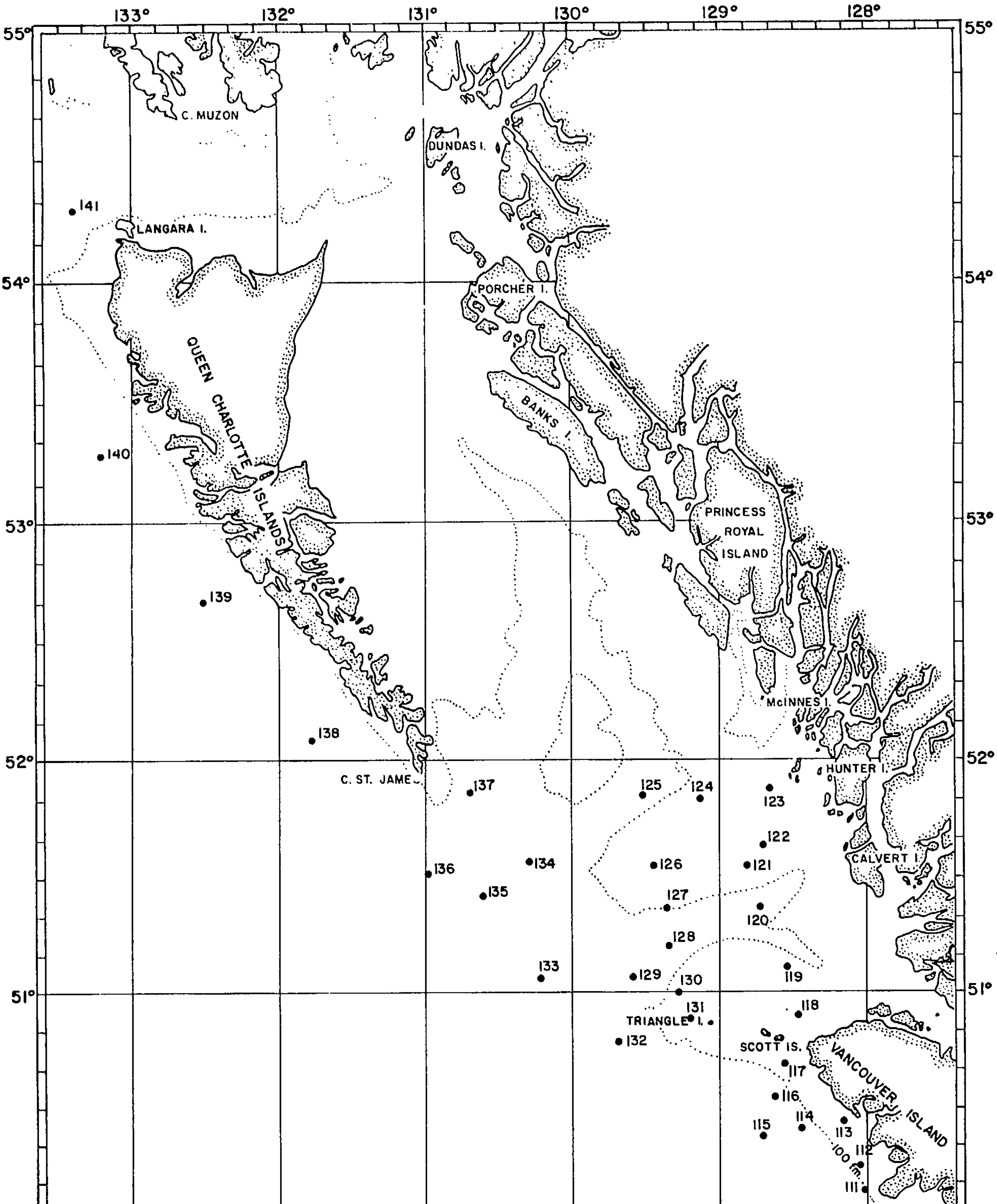

Fig. 24. Station positions, January 31-February 4, 1962 (Crean et al. 1962b).

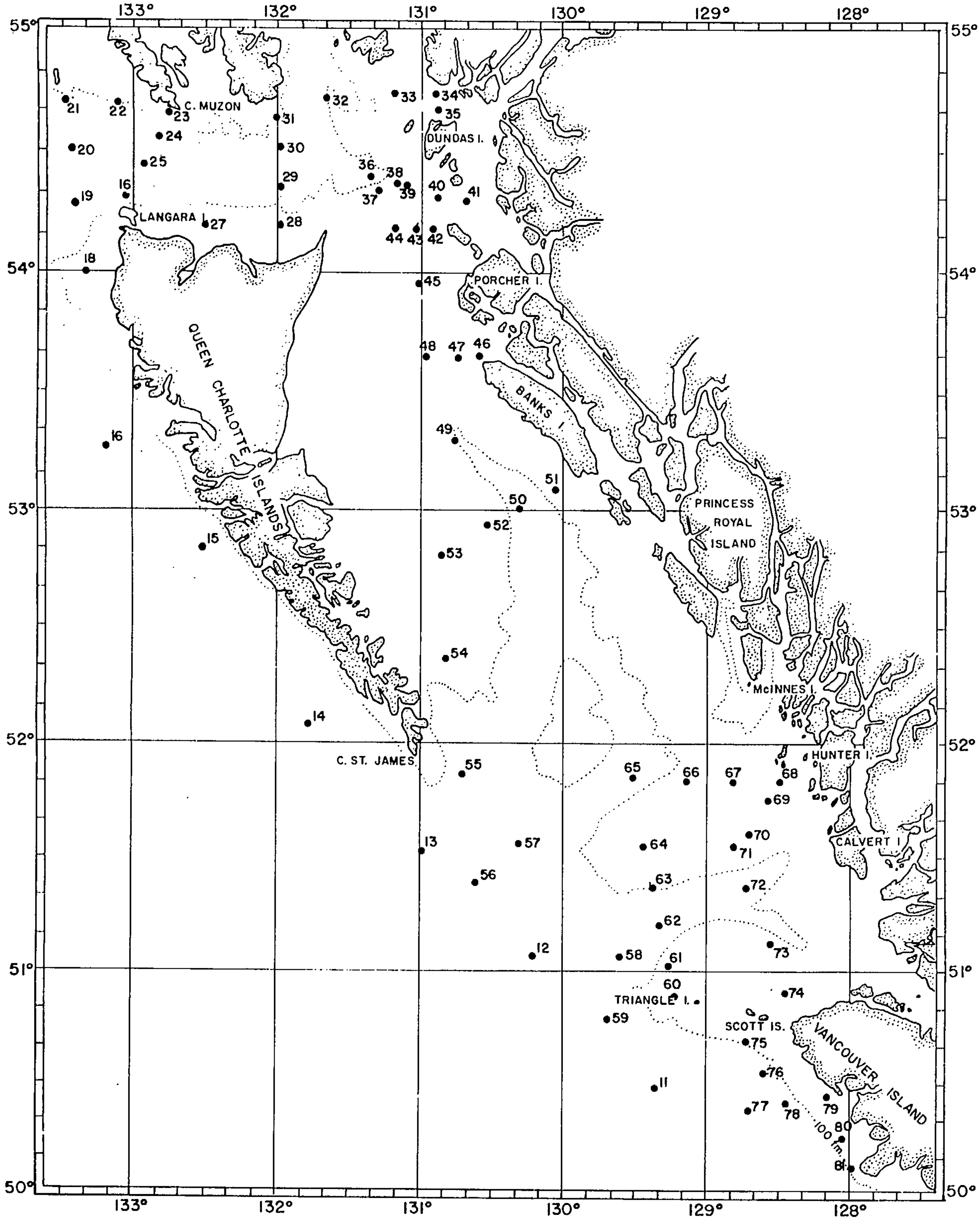

Fig. 25. Station positions, March 13-20, 1962 (Crean et al. 1962c).

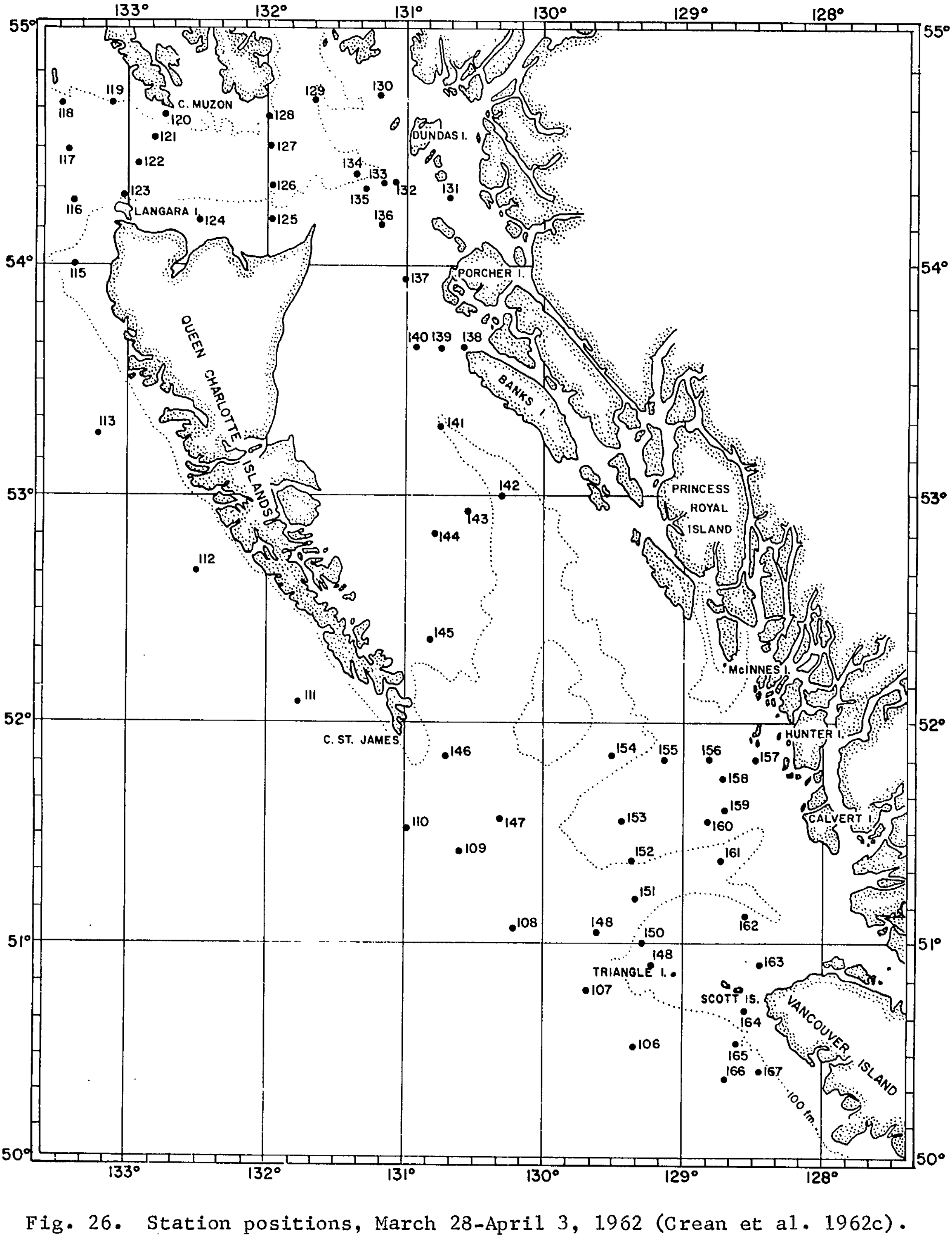

Fig. 26. Station positions, March 28-April 3, 1962 (Crean et al. 1962c).

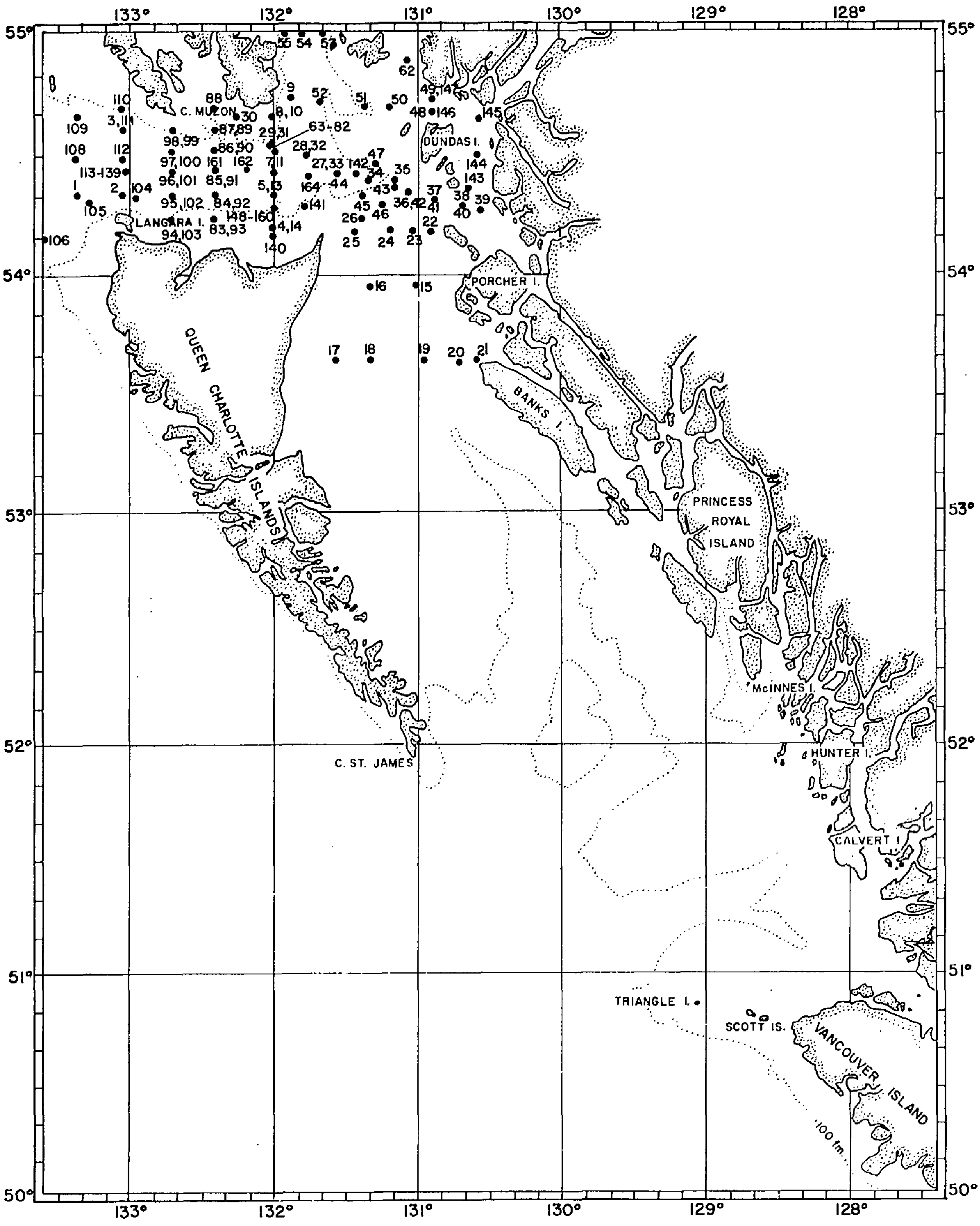

Fig. 27. Station positions, September 19-October 9, 1962 (Crean et al. 1963).

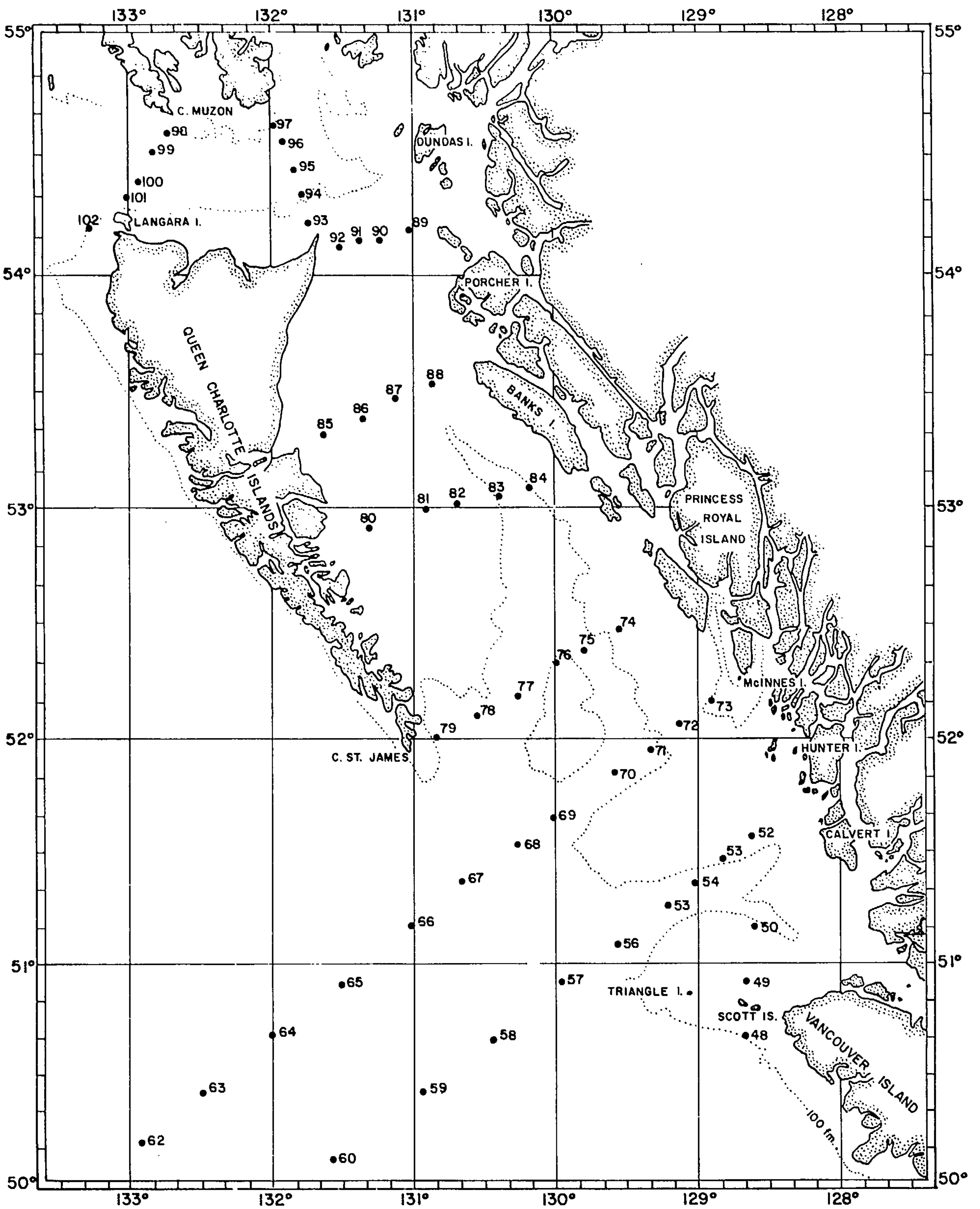

Fig. 28. Station positions, September 18-25, 1967.

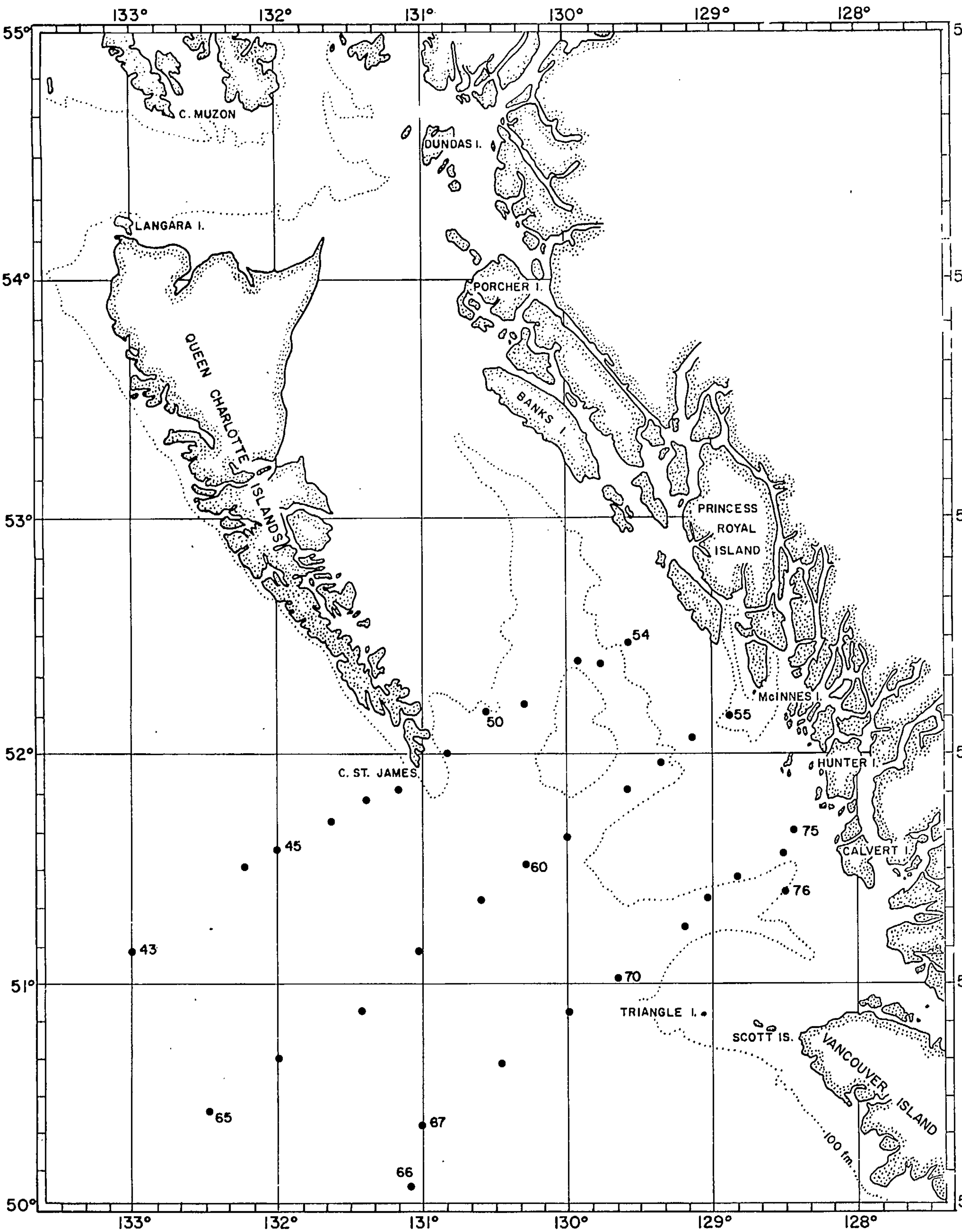

Fig. 29. Station positions, April 24-28, 1968.

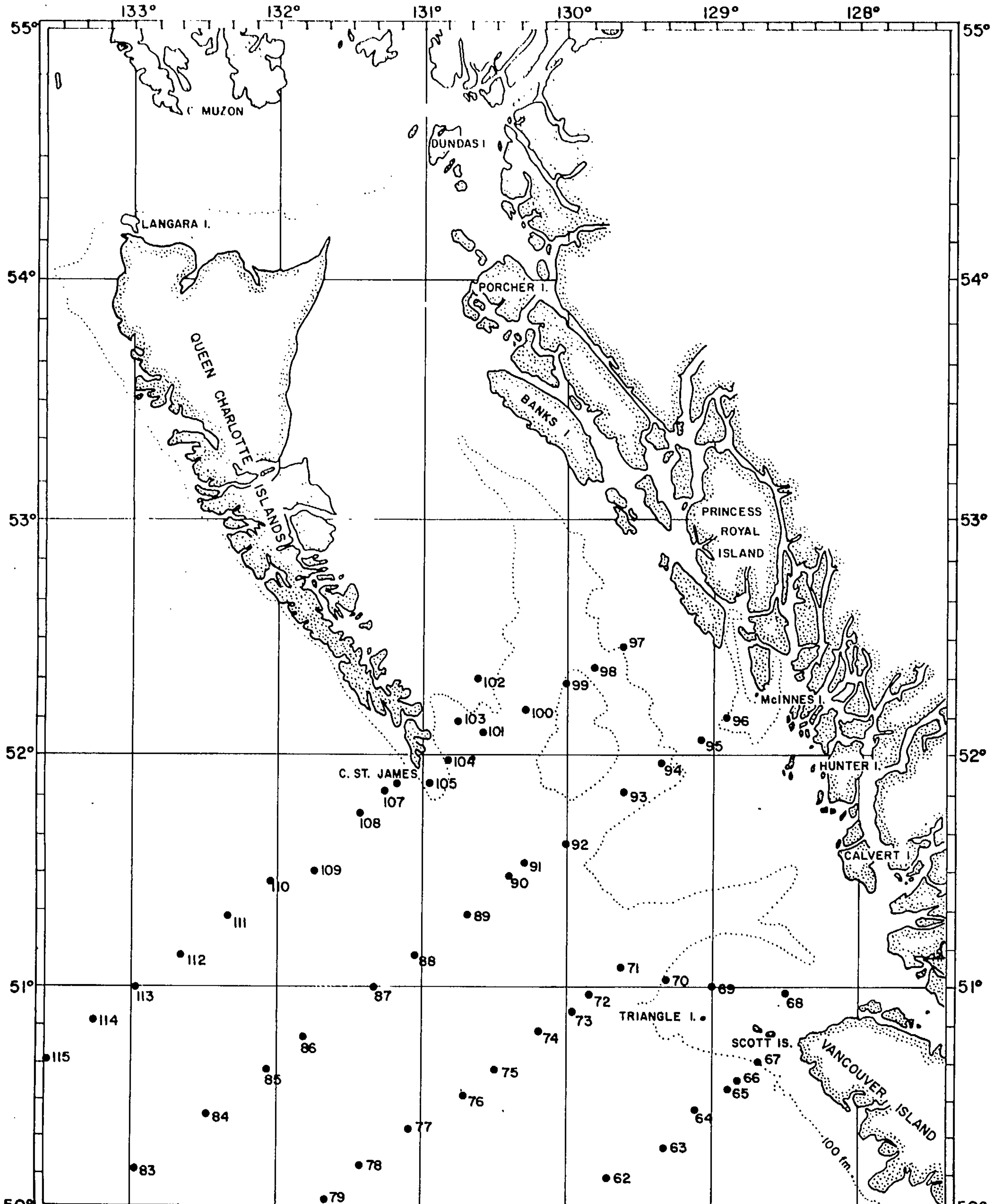

Fig. 30. Station positions, October 3-13, 1968.

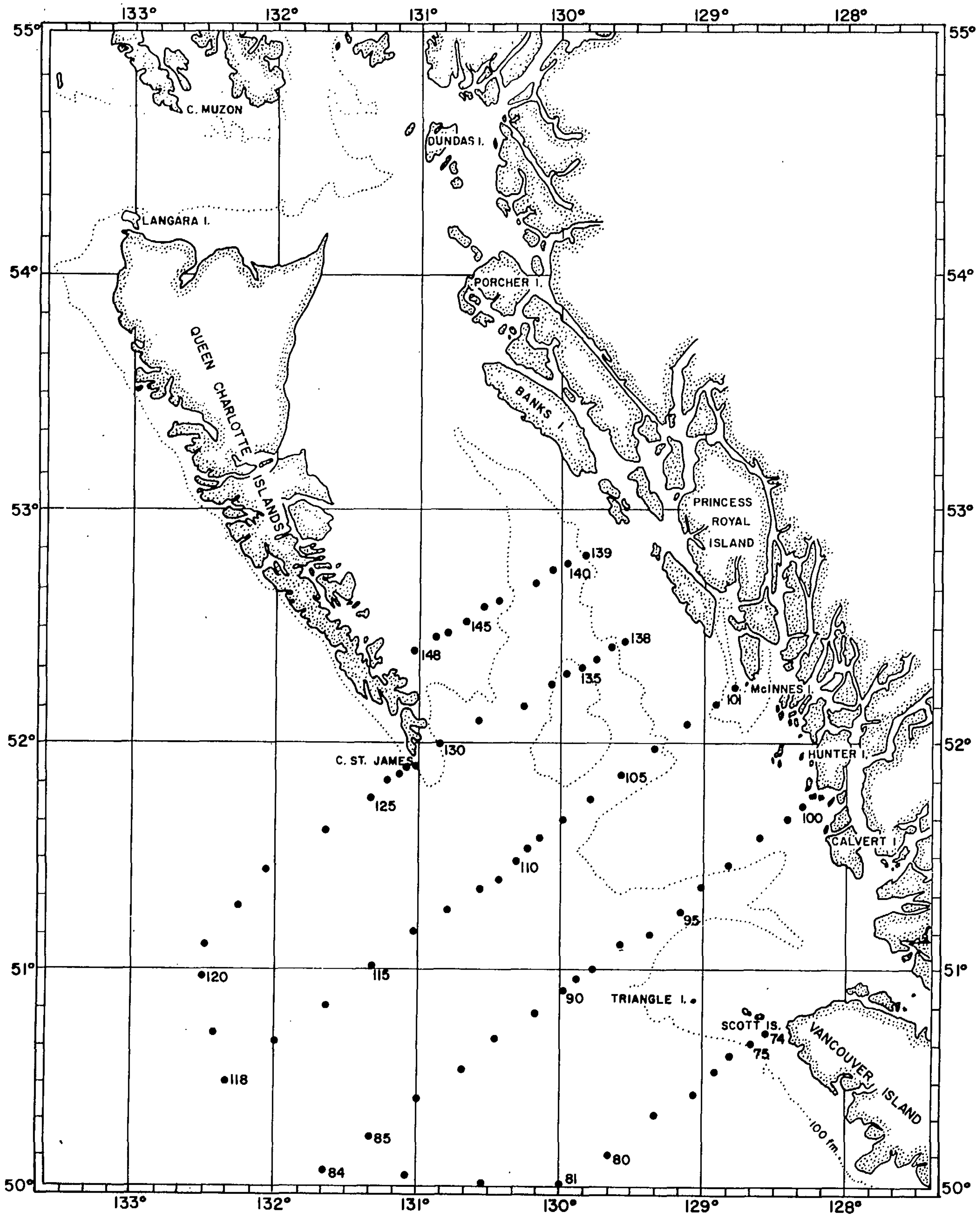

Fig. 31. Station positions, April 25-30, 1969.

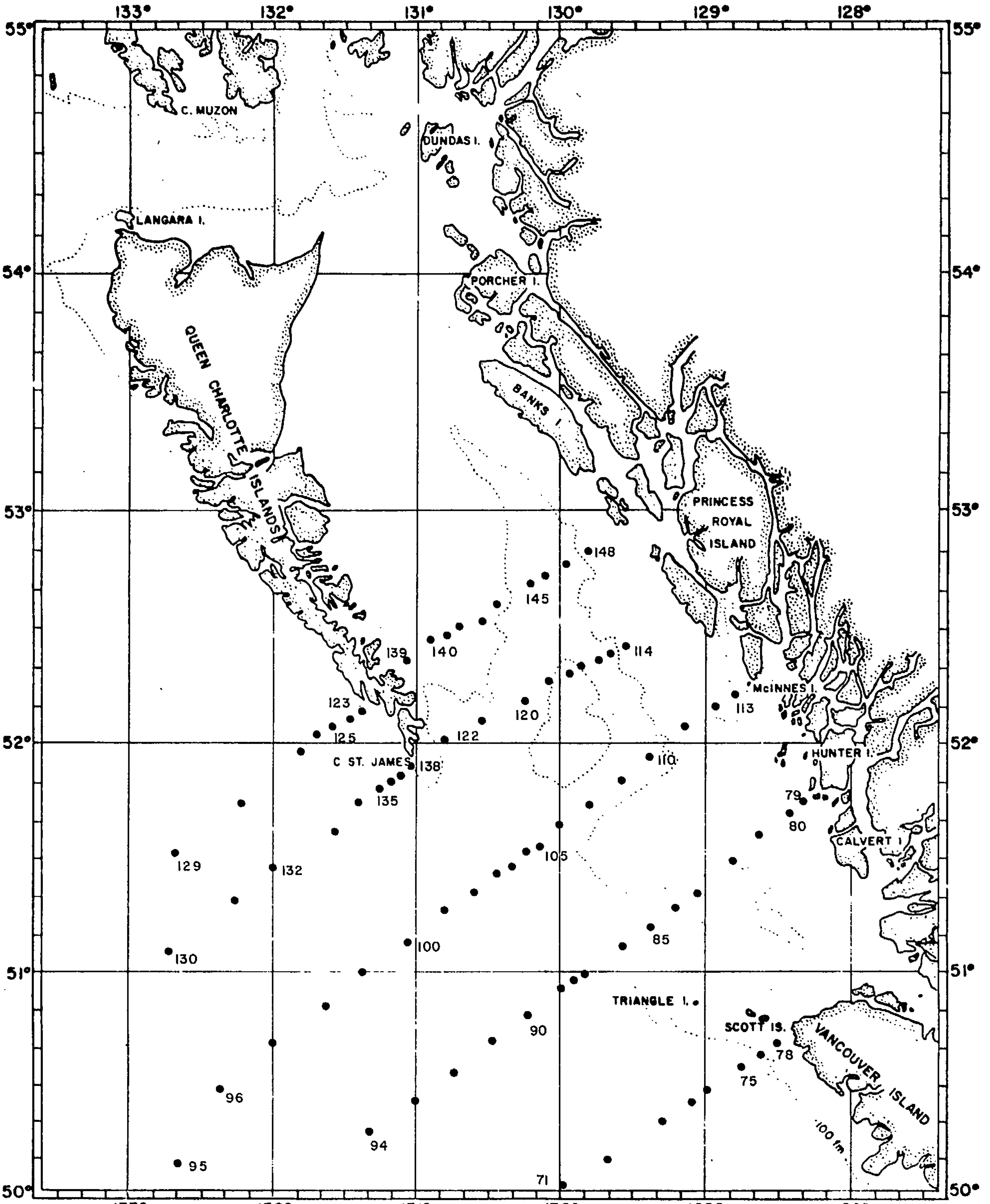

Fig. 32. Station positions, October 8-16, 1969.

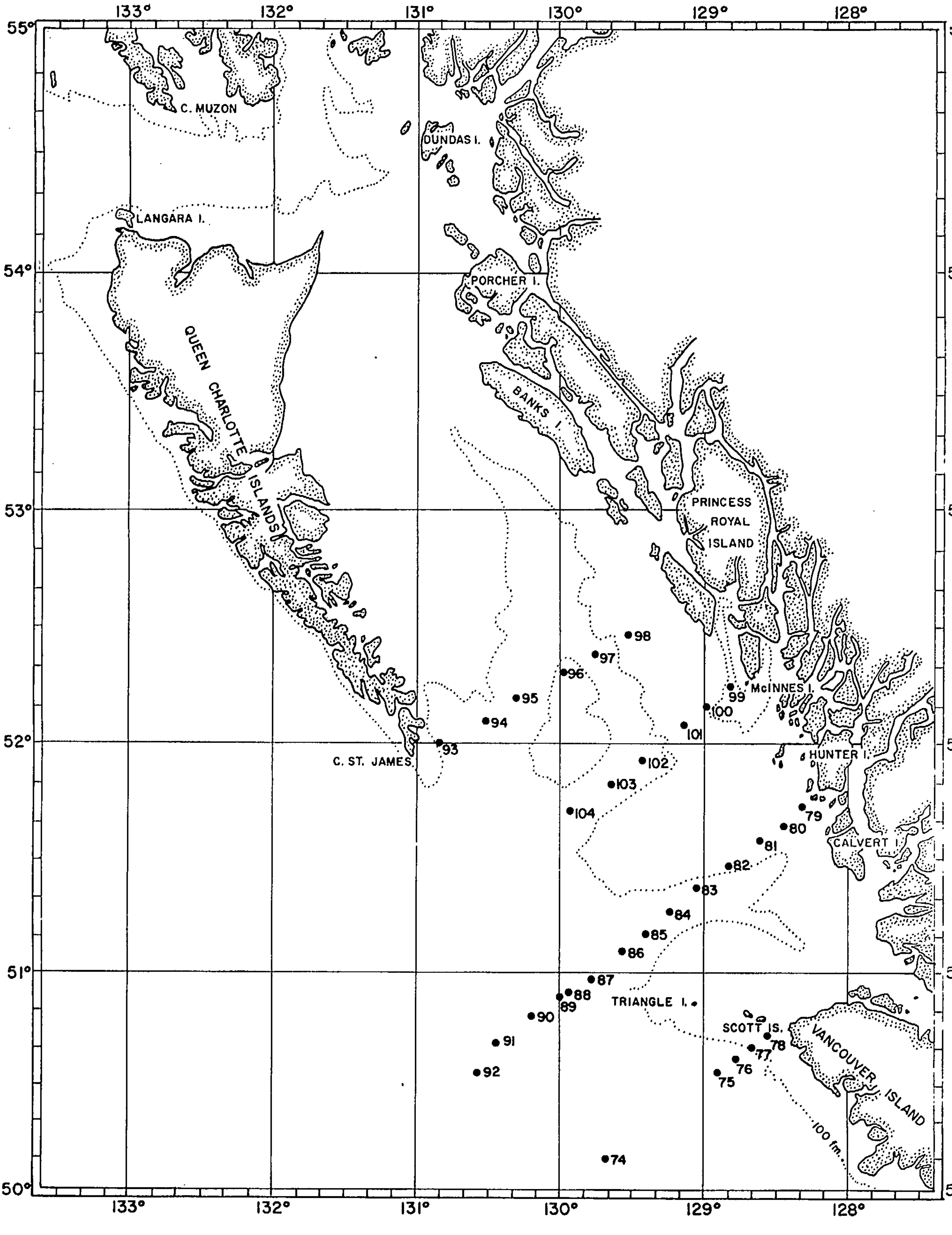

Fig. 33. Station positions, March 13-19, 1970.

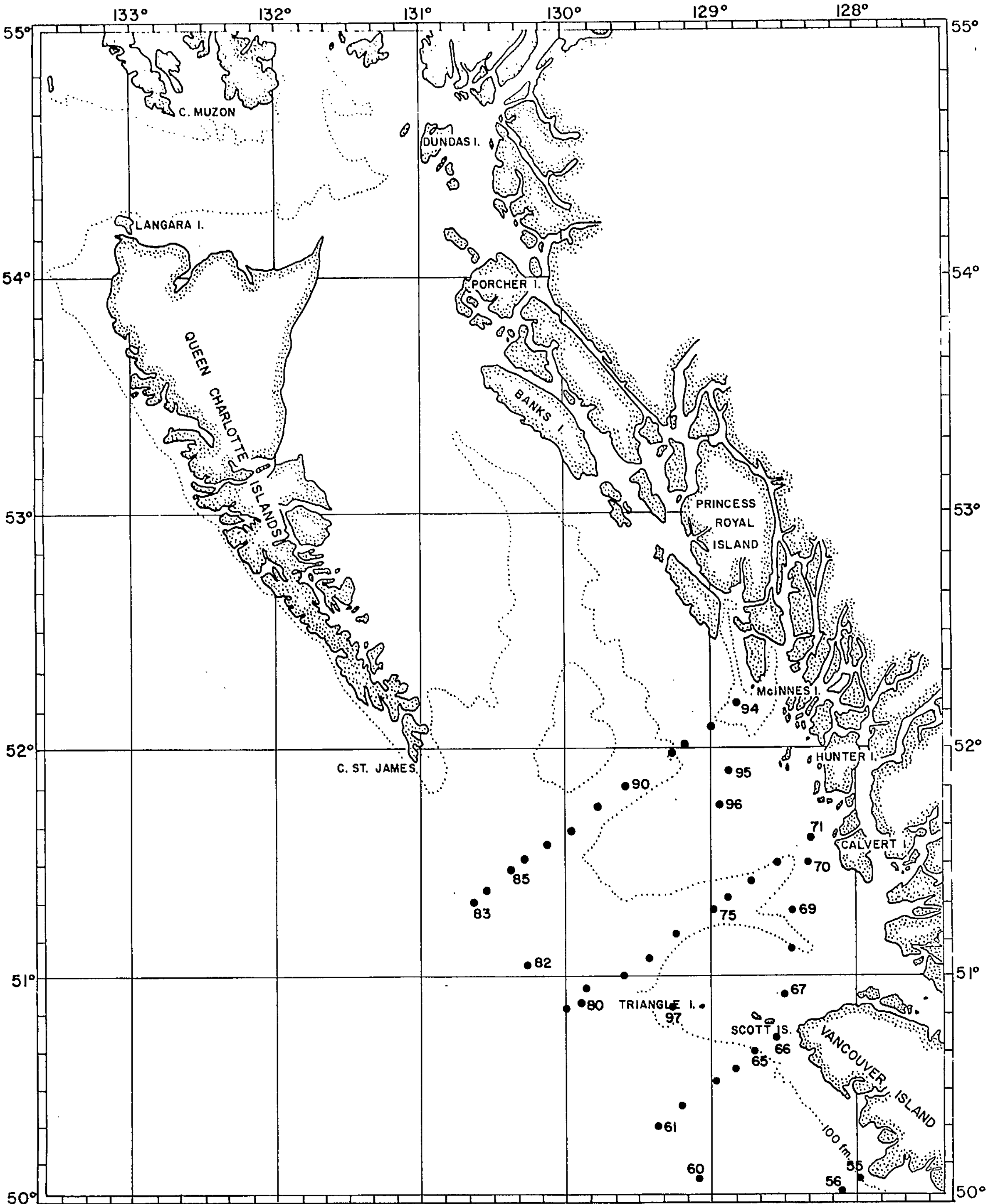

Fig. 34. Station positions, March 17-20, 1971.

III. SUMMARY OF PREVIOUS RESEARCH RESULTS

The earlier studies on the physical-chemical and tidal current features of the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region are reported in several different publications. Also, some of the reports are based on a preliminary analysis of the data. Most of the reports are summarized here in terms of areas - Queen Charlotte Sound-Hecate Strait, and Dixon Entrance. The others are included in the discussions in Section IV. Figures for this section start on page 53.

A. Queen Charlotte Sound-Hecate Strait

Oceanographic information for Queen Charlotte Sound and Hecate Strait results primarily from the analysis of data from the Hecate Project (1954-55). Barber and Tabata (1954) and Barber (1957b, 1958a,b) have utilized some of these data to describe the general features of the surface temperature and salinity distributions (including those for Dixon Entrance) as well as the seasonal variability of temperature, salinity, and dissolved oxygen content of the deep water masses and the mechanisms involved. Some information on the tidal and residual currents in Queen Charlotte Sound and in Hecate Strait has been provided by MacKay (1954), Barber and Groll (1955), Barber (1957a, 1958b) and Wickett (1973). Information on the heat budget of the waters in the vicinity of Triple Island in eastern Dixon Entrance has been provided by Tabata (1958). Other relevant studies include those by Ketchen (1956a,b) who reported on long-term trends in air and sea surface temperatures at coastal stations in Hecate Strait and Dixon Entrance, and on correlations between winter sea surface temperatures and year-class strengths of several groundfish species. A comparison of air circulation indices in Hecate Strait with sea surface temperatures at Triple Island was made by Eber (1957). Although the authors of the latter four reports used data primarily from Triple Island - located in eastern Dixon Entrance - their results reflect processes in Hecate Strait generally, and are therefore included in this sub-section. All the reports noted above are reviewed in some detail in the following sections; most are relatively short, but provide pertinent information on the oceanographic and meteorological conditions for these two areas.

1. Surface temperature and salinity

Barber and Tabata (1954) reported that sea surface temperatures in May 1954 were about 46°F (8°C), with a small decrease in temperature toward the north, particularly in Dixon Entrance. In July 1954, surface temperatures were generally from 51 to 54°F (10 to 12°C) and varied irregularly over the region; however, the water on the mainland shore was warmer than that to seaward. During this period clouds of relatively warm water occurred in Dixon Entrance - near Chatham Sound - and north of the Queen Charlotte Islands. By August, surface temperatures over the region ranged from 52 to 57°F (11 to 14°C). Barber (1957b) noted that the surface temperature ranged from 14°C in August 1954 to 6°C in April 1955. Also, the surface waters of Queen Charlotte Sound and Hecate Strait were generally warmer than those in Dixon Entrance.

In May 1954, before the freshets of the major rivers (Skeena, Nass, Bella Coola and Dean) influencing these areas developed, surface salinities were about 31.5‰ along the mainland coast and increased to 32‰ along the east coast of the Queen Charlotte Islands (Barbara and Tabata 1954). In July, surface salinities along any line parallel to the axis of Hecate Strait were nearly constant; however, at any latitude the waters were somewhat fresher on the mainland side than on the seaward (Queen Charlotte Islands) side. The presence of fresh water was clearly evident in the southern part of Queen Charlotte Sound, in Dixon Entrance near Chatham Sound, and in the passages leading to southeast Alaska. In August, the picture intensified over that observed in July; the waters in the low-salinity areas became fresher and the distribution of this less-saline water was more extensive. The dilution was most apparent in Dixon Entrance, where surface salinities were 2-3‰ lower in August than in July. In general, surface salinities were relatively low (30-32‰) throughout the region during all seasons (Barber 1957b). In Queen Charlotte Sound and Hecate Strait surface salinities were found to be generally greater than those in Dixon Entrance (although numerical values were not reported).

Additional information on the spatial distribution and temporal variability of surface temperature and salinity for the region (together with several examples which show the features described above) is presented in a later section (p. 69).

2. Subsurface temperature, salinity and dissolved oxygen content

Barber (1957b) has reported that, in the subsurface waters of Queen Charlotte Sound, there is an annual cyclic alteration of water masses. In winter, the subsurface waters are warmer and less saline than in summer; the range in this variation was found to be greatest along the mainland coast, and became less evident to seaward. The variation was attributed principally to strong southeast winds in winter, and to a relaxation of these winds in summer. During southeast winds, surface waters are transported shoreward in Queen Charlotte Sound, resulting in an accumulation of surface waters along the coast and a compensating offshore displacement of deeper waters. In spring, when the intensity of the southeast winds decreases, a relaxation of the onshore transport occurs; surface waters move offshore, and there is a compensating inshore movement of deeper waters. Barber suggested that this seasonal variability in water masses is responsible for a large part of the seasonal sea-level oscillation observed at Prince Rupert, B.C. He also noted that the combination of wind and sea-level data suggests that variations in transport during winter may occur. In January 1950, little southeast wind occurred, and mean sea level was about 24 cm lower than normal. He noted that, under these conditions, the warmer less saline water at depth would not be observed. He suggested that the observations of mean sea level would provide an index to the major changes in subsurface water characteristics.

In a subsequent paper, Barber (1958b) reported that the seasonal variation in the deep water in Queen Charlotte Sound resulted from two features: the depression of the oceanic halocline in winter, during the period of maximum southerly winds; and the rise of this halocline along the coast during light southerly or northwest winds and maximum runoff, which occur most frequently during summer. He suggested that sufficient surface outflow occurs to allow the entrainment process, and hence the deep flow, to persist during all seasons in Queen Charlotte Sound. The variation in the depth of the halocline, together with the persistent deep-water inflow, would lead to marked changes of salinity - which in turn would result in changes in the salinity of the deep waters in the entire system. Also, a complete renewal of deep water in Queen Charlotte Sound could occur in a period as short as 2 weeks.

Barber (1958a) also reported on the seasonal sequence of dissolved oxygen content at a selected station in Queen Charlotte Sound, noting that the least oxygen content in the deep water occurs during the summer months, at which time temperatures are low and salinities high. In July 1954 and June 1955, the dissolved oxygen content was less than 2 mg/L (2.8 ml/L) at depths below 250 m. However, in December 1954, values less than 2 mg/L were not observed above 400 m. He noted that the seasonal variation of dissolved oxygen content was similar to that observed at other positions in the region. He suggested that this variation could influence the seasonal depth migration of bottom fishes.

3. Tidal and residual currents

Barber (1957a) reported on the results of analysis of direct current observations made in June 1955 at Station 9, located north of Triangle Island in the southwestern part of Queen Charlotte Sound (Fig. 13). He noted that at all depths the currents were rotary, changing direction continually in a clockwise manner with a semi-diurnal or tidal period. At a depth of 20 m, the current was directed east at high water, and west at low water. The principal direction of the flood was northeast, and that of the ebb southwest. The maximum speed, slightly over 50 cm/sec (1 kn), occurred during the flood - between 3 and 4 hr after low water. A comparison of observed velocities at 20 m and 75 m indicated that the deep currents were generally "ahead" in their rotation with respect to those at 20 m; at low water, currents at 75 m were directed north (west at 20 m), and at high water were directed south (east at 20 m). The calculated residual (net) movements were small, 2.5-5 mi/day (5-11 cm/sec) and the predominant direction was easterly into Queen Charlotte Sound; these results are summarized in Table 1.

Table 1. Calculated residual (net) movements at Sta. 9 located in southwestern Queen Charlotte Sound, June 1-3, 1955 (Barber 1957a).

Depth (m)	Speed (mi/day)	Speed (cm/sec)	Direction (°T)
0	4	9	070
10	3	6	135
20	2.5	5	110
30	2.5	5	095
45	5	11	070
75	4	9	030

Analyses of current data obtained during the period June 6-8, 1955 at Station 5 - located near the mainland coast in Queen Charlotte Sound (Fig. 13) - showed that at 10 m a net seaward movement of about 20 km (11 mi) occurred during a (tidal) day (Barber 1958b). At 50 m there was little net movement. At 125 m, a large net movement again occurred, however, it was directed shoreward at about 15 km/day (8 mi/day). The vertical distribution showed that above 50 m a net seaward movement occurred, having a maximum speed of nearly 25 cm/sec (0.5 kn) and decreasing steadily to zero at 50 m (Fig. 35). Below 50 m, a net movement into the seaway occurred, averaging about 15 cm/sec (0.3 kn) between depths of 75 and 125 m. Based on the results from these two stations (Sta. 5 and 9), Barber concluded that the deep flow was continuous from seaward well into the inner part of southern Queen Charlotte Sound. Also, the contrary directions of the surface and deep water indicated the existence of considerable shear with consequent mixing occurring at all depths.

MacKay (1954) published the results of five short series of surface and bottom (41 fm, 75 m) current observations made in northern Hecate Strait, at approximately 54°10'N, 131°00'W, in July 1952. He concluded that, at this position, tidal currents were rotary with the dominant directions and velocities parallel to the coastline. The surface currents rotated clockwise semi-diurnally with a maximum speed of 1-1.5 kn (50-75 cm/sec) southward, and the minimum of less than 0.1 kn (5 cm/sec) northward. The net progress of water was to the south at about 0.4 kn (20 cm/sec). There was no evidence that the component of steady southward flow was associated with either wind or land drainage. The bottom tidal currents varied irregularly from 0.2 to 0.6 kn (10 to 30 cm/sec), and were notable in that their rotation was counter-clockwise, opposite to that of the surface currents. The speed of the steady current near the bottom was less than 0.1 kn (5 cm/sec).

Wickett (1973) reported on an unusually strong surface current that was observed from a drill rig operating in Hecate Strait on September 25, 1968. The current occurred on a falling spring tide and was reported to be southerly with an estimated velocity of about 2.5-3 kn (125-150 cm/sec), at a time when winds and seas were calm. However, this current occurred about 8 to 10 hours after about a 24-hour period of very strong southerly and westerly winds.

4. Heat budget

Tabata (1958) analyzed meteorological and oceanographic data from 1945 to 1955 and determined the magnitudes of the terms in the heat budget equation for the sea in the vicinity of Triple Island. Grand monthly means (1947-54) and their standard deviations are presented in Fig. 36 and a summary of his observations follows. The annual cycle of radiation absorbed by the sea (Q_s) is in phase with the total incident solar radiation under cloudless sky conditions (Q_o) and with total incident solar radiation under mean cloud cover (Q_i), and attain a minimum (35 g-cal/cm^2/day) in December and a maximum (350 g-cal/cm^2/day) in June. The annual amplitude of the effective back radiation (Q_b) is small compared to that of solar radiation and the extreme was seldom greater than 25% of the annual mean. The heat loss from the sea surface by this process varies from a maximum of 130 g-cal/cm^2/day in winter, more than twice the magnitude of the absorbed solar energy, to a minimum of 85 g-cal/cm^2/day in summer, less than one-third of the absorbed solar energy. The annual cycle of heat loss associated with evaporation (Q_e) possesses a maximum (175 g-cal/cm^2/ day) during winter and a minimum (25 g-cal/cm^2/day) in summer. The annual amplitude is approximately one-half that of the absorbed solar radiation. The monthly transfer of sensible heat (Q_h) is from sea to atmosphere in winter and is relatively large, reaching its maximum value (145 g-cal/cm^2/ day) in January. During late summer the exchange is directed from atmosphere to sea at a rate of less than 15 g-cal/cm^2/day. During winter the combined influence of evaporation (Q_e) and conduction (Q_h) is much larger than that of solar radiation. Tabata concluded that, during the cold months, these cooling processes play a dominant role in changing the sea surface temperature.

Tabata (1958) reported that the principle feature of the annual cycle of total heat transfer across the air-sea boundary is that the greatest loss from the sea (about 350 g-cal/cm^2/day) occurs in December and January, and the greatest gain (more than 200 g-cal/cm^2/day) occurs from May to September (Fig. 37). Periods of no net transfer occur during the latter part of March and of September. The monthly means of the total heat transfer of individual years follow the general cyclic trend of grand monthly means. However, there were appreciable differences in the year-to-year deviation of monthly means (Fig. 37). Because of these year-to-year fluctuations, the times of no net tranfer vary. In spring it may occur at any time during the five weeks between early March and early April, but in autumn it occurs in the shorter period from late September to early October.

The annual cycle of the total heat transfer across the air-sea boundary and the annual cycle of sea surface temperature at Triple Island are not in phase (Fig. 37). Tabata considered two likely possibilities for the discrepancy: vertical transfer of heat from deeper water, and lateral transport of water. He indicated that in winter it is probably due to transfer of warmer water from depth to the surface, or transport of warmer water into the region, or a combination of both. In summer, it is attributed to the exchange of heat with colder water at depth, and/or to an intrusion of cold water into the region.

Tabata (1958) also made a comparison of total heat transfer at the air-sea boundary at Triple Island and the change of heat content of the water column throughout Dixon Entrance for the period May 1954 to June 1955. Between May and July 1954, an increase in heat content twice than that to be expected from heat gain through the boundary was found to have occurred; this was attributed to transport of warmer water from the south through Hecate Strait, from the ocean by way of Dixon Entrance, or from both. A "decrease" in heat content between July and August 1954 was attributed to inshore transport of cold upwelled oceanic water from seaward of Dixon Entrance. Between August 1954 and February 1955, the decrease in heat content was much smaller than would be expected from the loss occurring at the sea surface. This condition was believed due to warmer oceanic water entering the area from the south through Hecate Strait and from offshore. During February and April 1955, the decrease of heat in the column was more than twice as much as that determined as being lost from the sea surface, and was attributed to intrusion of cold water from the north or northwest.

The influence of advection on the heat budget of the water was small during the period April to June 1955. Tabata concluded that, advective as well as surface energy transfer processes play an important role in affecting coastal sea temperatures in these areas.

5. Other studies

Other relevant studies include those by Ketchen (1956a,b) and by Eber (1957). Ketchen (1956a) examined long-term trends in the annual mean air and sea surface temperatures at several coastal station located in the region. He noted that at Masset, B.C. the annual mean air temperature declined by nearly 4°F (2°C) between 1906 and 1922. Thereafter, the mean rose fairly steadily, by more than 4°F (2°C), to a peak around 1941. A sharp decline occurred from 1941 to 1950. During the latter period annual mean sea surface temperatures at Triple Island also declined. Ketchen (1957b) examined winter sea surface temperatures and abundance of several groundfish species and obtained reasonable correlations. High negative correlations were obtained with year-class strength of English (lemon) sole and mean winter sea surface temperatures at Triple Island. He postulated that, when such temperatures are low, the larvae are carried for a longer period by the northward current through Hecate Strait, and as a result, greater numbers are deposited on the rearing grounds located in the shallow areas of northern Hecate Strait. He suggested that the observed relationship between water temperatures and brood strength might be dependent upon the wind-induced current.

Considering the above hypotheses and the fact that, during winter and spring, currents in the vicinity of Triple Island are generally northward and the mean isotherms are roughly perpendicular to the coastline, Eber (1957) postulated that the sea surface temperature in this area should be related to the northward component of geostrophic air flow. He obtained a positive correlation between sea surface temperatures at Triple Island and northward geostrophic wind components for January data for the period 1938-56. Advection associated with wind-induced water movements appeared to provide a plausible mechanism for this relationship. In summary, he suggested that high average sea surface temperatures in January may result from advection caused by winds with strong northward components. Low January average surface temperatures may occur if winds are weak, since cooling due to net radiational heat loss then becomes the dominant factor. Anomalies created in January tend to persist until spring. An increase in surface temperature from January to February, at which time the net heat exchange is negative and the southerly wind component is strong, indicates that significant advective processes do occur.

B. Dixon Entrance

Crean (1967) has provided a relatively comprehensive report on the oceanography of Dixon Entrance. He has described the characteristics of the seasonal cycles associated with precipitation, runoff, winds, Ekman transport, sea level, heat transfer and sea surface temperatures and salinities using long-term monthly means of data obtained in Dixon Entrance and vicinity. Seasonal distributions and vertical structures of temperature, salinity and density for four seasonal periods - spring

(April and May), summer (June through August), autumn (September and October), and winter (November through March), based upon data collected on the Hecate Project (Fig. 6-12) and an autumn cruise in 1962 (Fig. 29), were presented and discussed. The seasonal circulation patterns and causative factors were also discussed. Some of his results are briefly noted here; a few of his figures are also presented. For additional information the original report should be consulted. In addition, Barber and Groll (1955) have briefly discussed bottom currents at one location in Dixon Entrance.

1. Surface temperature and salinity

The seasonal sequence of sea surface temperature, for Dixon Entrance and northern Hecate Strait, described by Crean (1967) is shown in Fig. 38. In spring, the differences in surface temperature in Dixon Entrance are relatively small. The warmest water during this period is located in northern Hecate Strait. In summer, high surface temperatures are associated with the area of low-salinity water found along the northern shores of Dixon Entrance and in the southern reaches of Clarence Strait (Fig. 39). In autumn, surface temperatures throughout Dixon Entrance are generally lower than those to seaward or in northern Hecate Strait; in winter, surface temperature differences throughout these areas are small.

Crean noted three persistent features in the surface salinity distributions (Fig. 39): (1) an area of low-salinity water associated with Chatham Sound, Clarence Strait, and the northern shores and west central part of Dixon Entrance; (2) a horizontal gradient of salinity at the mouth of Dixon Entrance, with surface salinities in Dixon Entrance being less than those in the adjacent ocean; and (3) an irregular area of water, associated with the northern part of Hecate Strait, and displaying salinities (>30.5‰ in summer, >31.5 during the remaining seasons) higher than those in the remainder of Dixon Entrance. In summer, a marked reduction in salinity over the whole area occurs as a consequence of dilution due to the spring freshet of the Skeena and Nass rivers and to drainage provided by local streams.

2. Water structure and deep water masses

Crean (1967) also reported that the most distinctive feature of the water structure in summer and autumn is a strong thermocline ($\Delta t \sim 6°C$), which is coincident with a strong permanent halocline ($\Delta s \sim 3‰$). In winter, the thermocline is absent, and there is evidence of a weak temperature inversion at depth. In spring, a thin surface layer of warm water is apparent, while below this the changes of temperature with depth are small. There is a marked variation in the depth of the halocline with time of year; the depth is a minimum in summer and increases throughout the autumn to a maximum in winter, and becomes shallower again in the spring. The variation in depth is consistent with that reported by Barber (1957b) for Queen Charlotte Sound (p. 44). Below the halocline, temperatures are lower and salinities are greater in summer and autumn than in winter and spring; in winter, temperatures are higher and salinities are lower than those in any other seasons.

3. Tidal and residual currents

Barber and Groll (1955) reported on the analysis of hourly current observations made near the bottom in Dixon Entrance just north of Graham Island at Station 65 in July 1954 (Fig. 13). They noted that the general directions of flood and ebb streams were parallel to that of the nearest coastline. The times of minimum current corresponded to the times of high and low water, and the times of maximum flood and ebb occurred close to mid-range of the tidal rise and fall. Over a tidal cycle a net movement of about 1.1 mi (2 km) to the southeastward was observed, equivalent to a steady current of about 0.1 kn (5 cm/sec). This movement was observed from the surface to within 3 fm (5.5 m) of the bottom.

Crean (1967) utilized density sections and dynamic topography, as well as the results from a hydraulic model experiment (Bell and Boston 1962; 1963 and Bell 1963) and from direct current observations, to define the basic circulation in Dixon Entrance. The hydraulic model experiments showed a strong net cyclonic vortex in central Dixon Entrance (Fig. 40), attributed to the meeting of the Queen Charlotte Sound and Dixon Entrance tides in northern Hecate Strait. Density sections across this vortex showed a well-developed doming of the isopcynal surfaces during the flood tide; the dome partially collapsed during the ebb. The results of the direct current observations made at three locations across the vortex indicated that the net components, to the south and west at Sta. A, to the north and west at Sta. B, and to the north and east at Sta. C (Fig. 41), were clearly consonant with the vortex circulation shown in the hydraulic model experiments. Also, a comparison of the net flow directions at Sta. A and C with the distribution of dynamic height from 0 to 125 m (Fig. 42) showed reasonable agreement with respect to this general rotation. There was a net inflow along the southern side of Dixon Entrance; this flow may be enhanced by westerly winds.

In his summary, Crean defined a seasonal model of oceanographic behaviour for Dixon Entrance. By spring (April-May) the strong southeast winds characteristic of the preceding winter months have moderated considerably. The discharge of fresh water into Dixon Entrance increases rapidly. The net northward flow through Hecate Strait is reduced. Most of what flow occurs continues northward through Clarence Strait. The general onshore convergence of surface waters in the adjacent ocean begins to relax. In Dixon Entrance a basically conservative system is dominated by the net cyclonic circulation induced by the meeting of the tides in northern Hecate Strait.

In summer (June-August) the influence of southeast winds is minimal. In early summer, a strong discharge of fresh water from the Nass and Skeena rivers moves seaward through Dixon Entrance. The net northward flow through Hecate Strait becomes negligible. The strong freshwater discharge seaward, acting in concert with a densimetric flow occasioned by the final relaxation of the onshore convergence, engenders a major flushing of brackish water from the region, and a strong intrusion of cold, saline water at depth. Throughout the remainder of the summer, the seaward flow of fresh water decreases and is largely confined to Clarence Strait and the northern shores and west-central part of Dixon Entrance. The net cyclonic circulation includes in its extent the seaward approaches.

In autumn (September-October) there is a marked increase in southeast winds. The freshwater discharge associated with large precipitation in the coast drainage area increases to a secondary maximum in October. This discharge is confined largely to Clarence Strait. The northward flow through Hecate Strait increases and a general onshore convergence of surface waters in the adjacent ocean begins. The net tidal cyclonic circulation dominates the central part of Dixon Entrance and the seaward flushing of brackish water through Dixon Entrance is weak.

In winter (November-March) two régimes of behavior are distinguished. In early winter, when southeast winds are maximal, the discharge of fresh water is relatively small since most of the precipitation is retained on the bordering mountains as snow. There is a marked onshore movement of oceanic surface water; associated with this movement is a well-developed northward flow through Hecate and Clarence straits. In particular, in its passage through Hecate Strait, this flow is enhanced by the direct action of wind channelled northward through the Strait. In consequence a marked movement of water seaward through Dixon Entrance occurs. The water comprising the northward flow through Hecate Strait is relatively warm, due to the mitigation of local cooling by the rapidity of this northward motion. In late winter, the southeast winds gradually decrease. The freshwater discharge remains small. The flow through Hecate Strait is reduced, most of it continuing northward through Clarence Strait. The onshore movement of oceanic surface water continues, but with diminished intensity. In Dixon Entrance a basically conservative situation obtains, dominated by the net cyclonic circulation. The seaward flushing of brackish water is weak.

Crean notes that this general model of behavior undoubtedly represents a major simplification of the actual processes involved. However, further understanding of the problem would involve the continuous recording of variables at strategic locations throughout the region (an extremely costly procedure), and the relating of these variables to the primary causal factors.

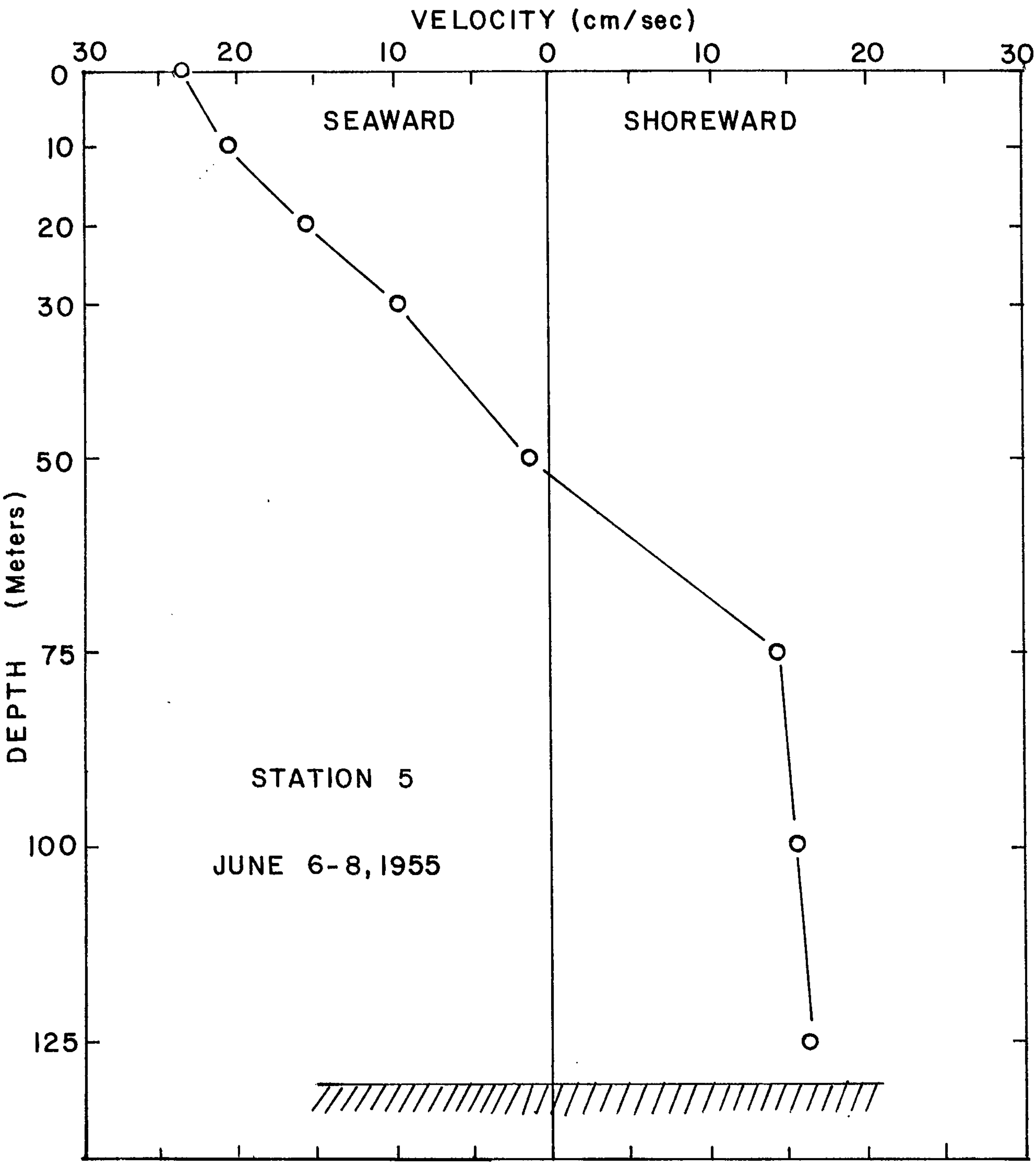

Fig. 35. Vertical profile of net movement at Station 5 located in southeastern Queen Charlotte Sound, June 6-8, 1955 (Barber 1958b).

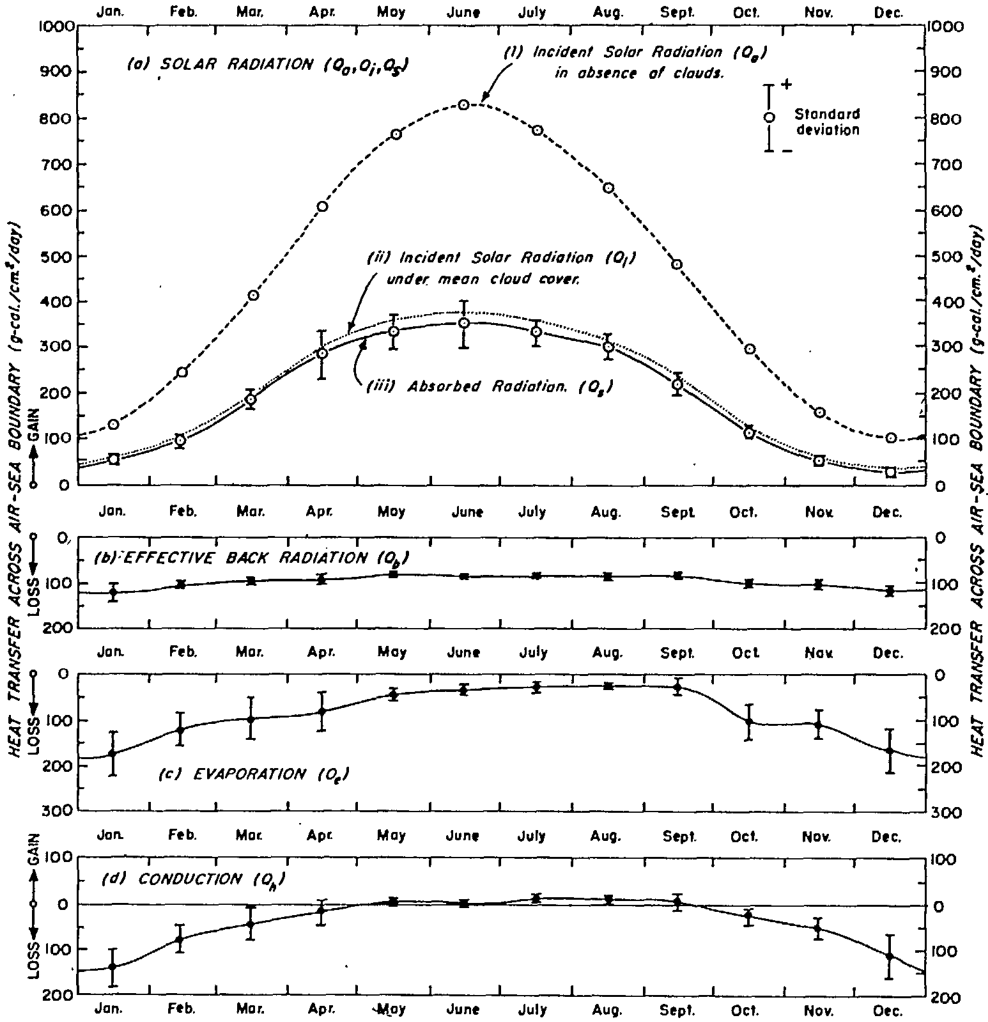

FIG. 36. Grand monthly means (1947–1954) with standard deviations of
(a) Solar radiation (Q_o, Q_i, Q_s),
(b) Effective back radiation (Q_b),
(c) Evaporation (Q_e), and
(d) Conduction of sensible heat (Q_h) at Triple Island.
(Tabata 1958)

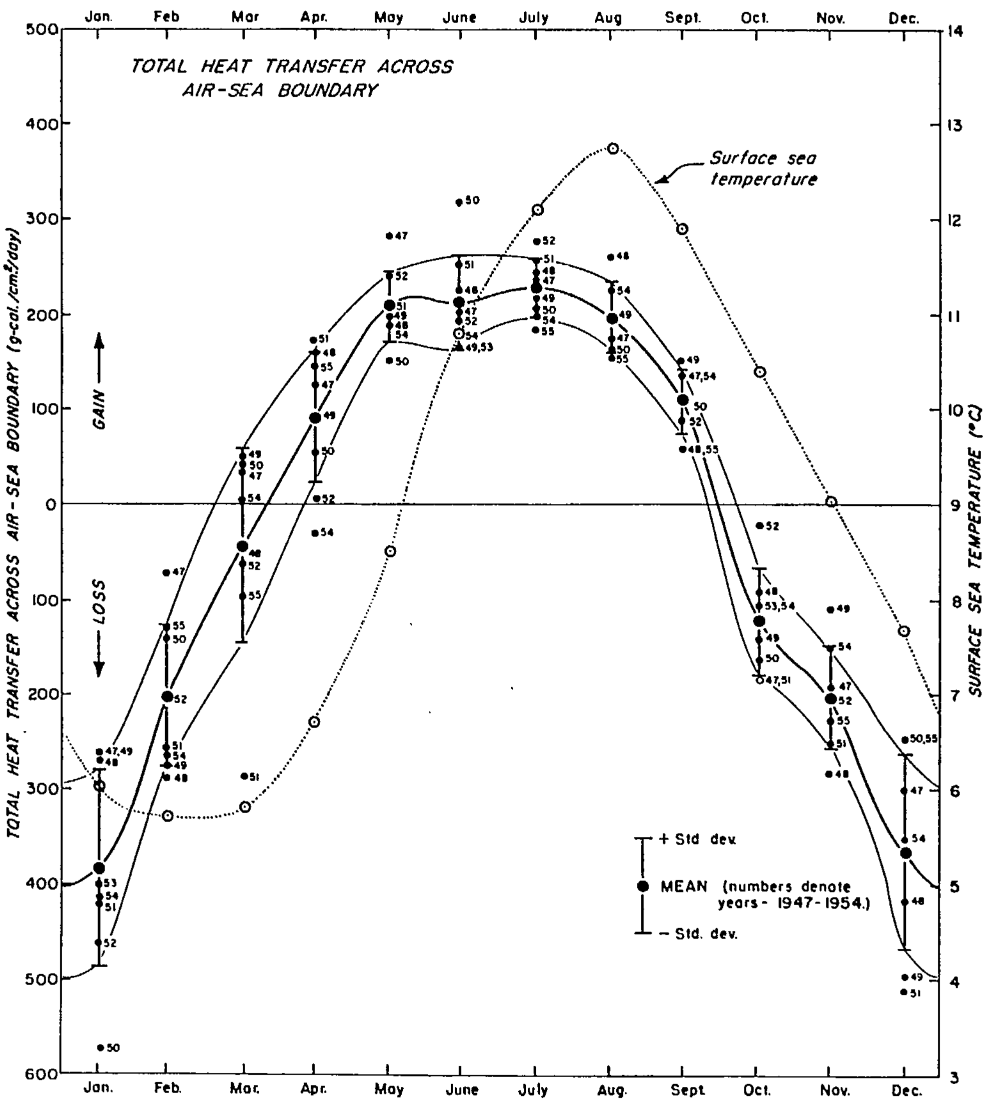

FIG. 37. Grand monthly means (1947–1954) with standard deviations of total heat transfer across air–sea boundary at Triple Island. Grand monthly means of surface sea temperature at Triple Island during same period are also shown. (Tabata 1958)

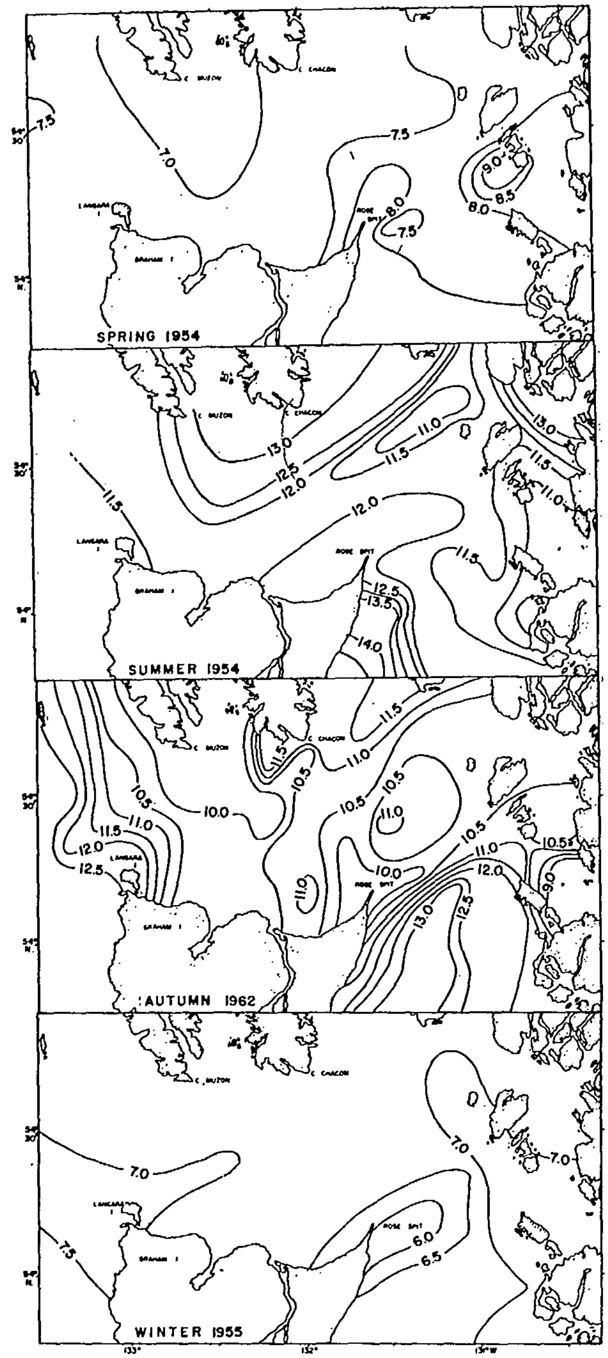

FIG. 38. Seasonal surface temperatures (*C*) in spring (May 1954), summer (August 1954), autumn (September-October 1962), winter (February 1955).
(Crean 1967)

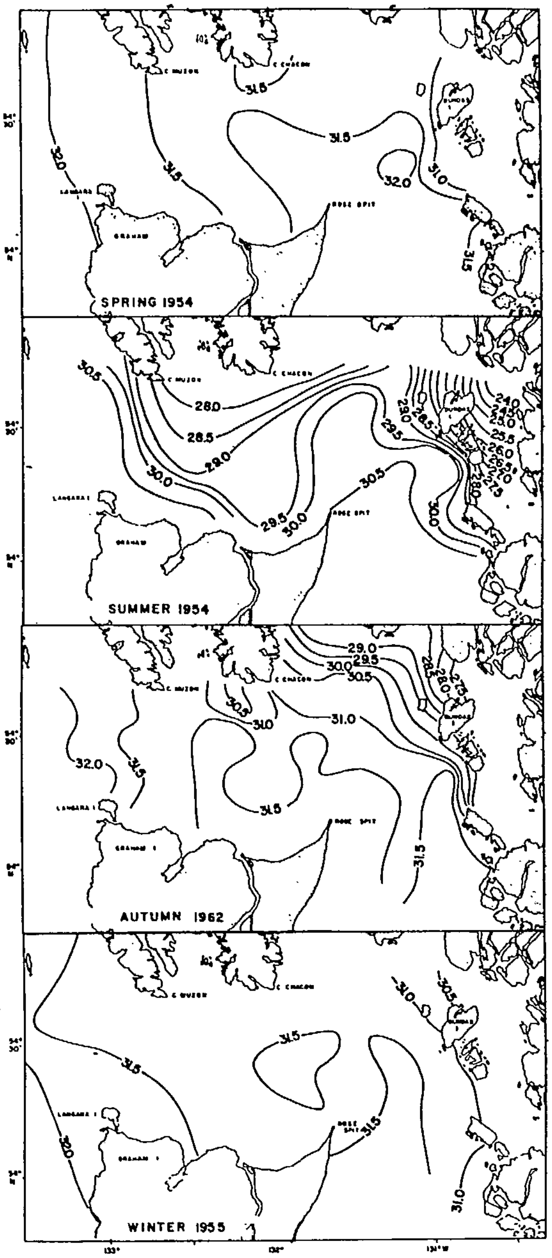

FIG. 39. Seasonal surface salinities (‰) in spring (May 1954), summer (August 1954), autumn (September–October 1962), winter (February 1955).(Crean 1967)

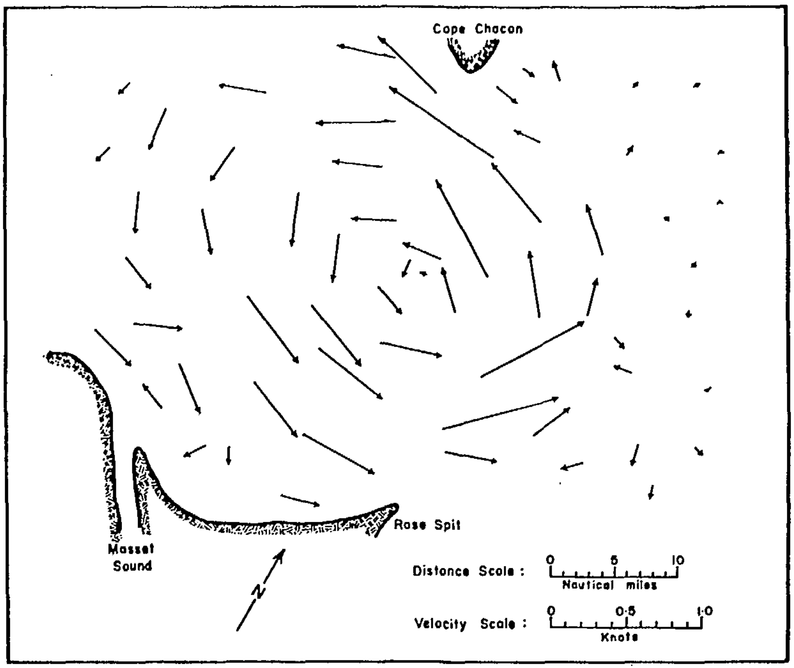

FIG. 40. Resultant current vectors over one M2 tidal cycle, using the method of Lagrange, in the hydraulic model of Dixon Entrance. (Crean 1967)

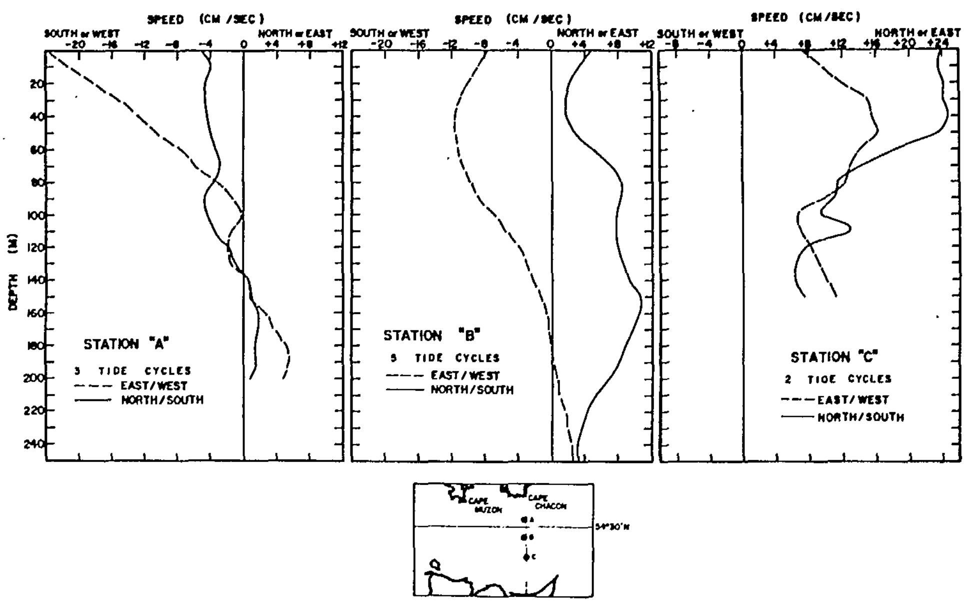

FIG. 41. Average current components at three locations across the vortex, September–October 1962. (Crean 1967)

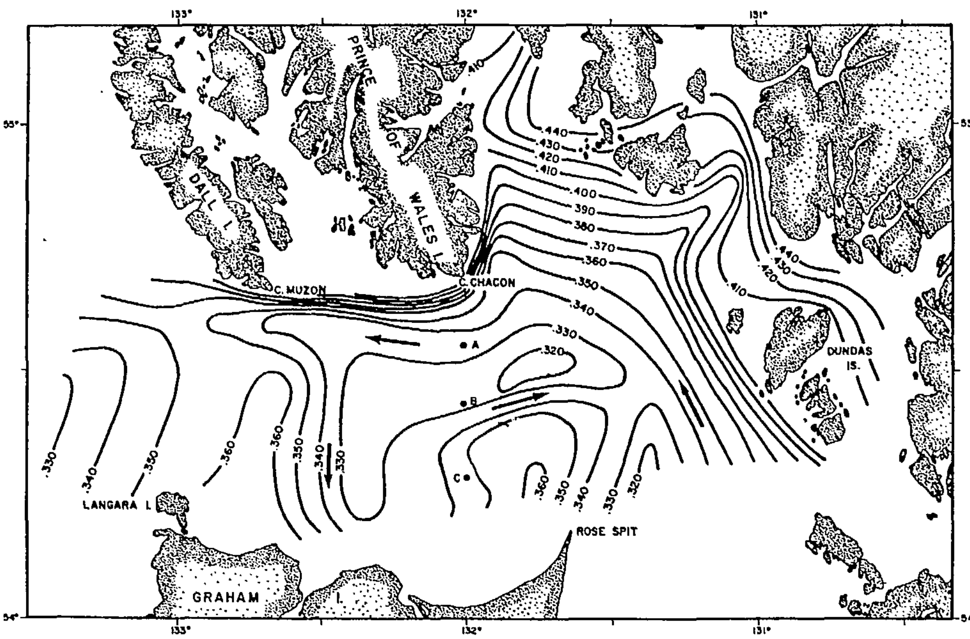

FIG. 42. Distribution of dynamic height anomaly (ΔD), 0/125 m September-October 1962. (Crean 1967)

IV. RECENT RESEARCH RESULTS

In this section, the seasonal features of coastal winds, sea level and zonal Ekman transport, based on monthly means, are reviewed. Yearly and monthly means and anomalies of sea surface temperature and salinity for several lightstations located in the region are discussed. Surface distributions of temperature and salinity for the region are also presented. The principal features of structure of temperature, salinity, density (as given by sigma-t) and dissolved oxygen content, and their spatial and temporal variability for Queen Charlotte Sound and Hecate Strait are described. Finally, additional information on the general features of the tidal and net flows in Hecate Strait and Dixon Entrance is provided. Figures for this section start on page 95.

A. Coastal Winds

Crean (1967) has provided a description of the dominant features of the annual cycle of winds in Dixon Entrance, Hecate Strait and Queen Charlotte Sound, based on wind data from four instrumented observing stations in the region - Prince Rupert, Sandspit, Cape St. James and McInnes Island (Fig. 1). He noted that the dominant winds are parallel to the coastal mountain barriers, which tend generally southeast-northwest. His observations, which are based on 8-10 yr averages of monthly total miles of winds resolved along these directions, are briefly discussed below. Also included is a description of the location of the weather stations and of the features of the surrounding areas, as reported by Environment Canada (1975).

At Prince Rupert, the station reported here is located at the airport. The surrounding area is hilly and wooded. There are mountains to the north, east and south, with the Pacific Ocean to the west. There is a small hill 1/2 mile to the southeast which affects winds from that direction to some extent. At this station, considered a somewhat sheltered location, the southeast component is dominant throughout the year, but shows a marked annual cycle (Fig. 43) (Crean 1967). The wind mileage increases rapidly from September and attains an annual maximum in October, November and December. From January on, there occurs a gradual decrease to a minimum in July.

At Sandspit, the anemometer is located at the airport which is situated on a flat spit projecting northward into Hecate Strait from the northeast corner of Moresby Island. There are hills to the southwest and west with mountains beyond. A dense belt of trees, about 80 ft high, to the south and west affects winds from the south and west quadrants. Although Sandspit is a more exposed station than Prince Rupert, the total wind mileages are considerably less than those at Prince Rupert (Fig. 43). The southeast component is still dominant throughout the year. The monthly mean mileages show an annual cycle similar to that at Prince Rupert, though the increase from September to October is more gradual than that at the latter location.

At Cape St. James, the station is located on a small plateau [(approximately 60' (18 m) by 200' (61 m)] on a cone-shaped hill [300' (91 m) above mean sea level] on St. James Island (southern extremity of the Queen Charlotte Island). Turbulence is created by local topography. At this station the annual cycle of winds is dominated by a strong northwest component in summer, and thus differs markedly from those at the other locations (Fig. 43). This dominance is attributed to the effect of the mountain barrier, which will tend to deflect winds into the direction parallel to its own northwest-southeast axis, and thereby increase the portion of winds from this direction. A contributory factor to the relatively large mileages may be the relatively high location of the anemometer, as noted above.

McInnes Island is considered to be the best source of data on the prevailing winds in Queen Charlotte Sound and Hecate Strait. At this station there is open sea from northwest through west to south-southeast, with islands in the remaining directions. Winds from west-northwest through north to east-southeast are affected locally by higher ground and by trees on the island. At this station the southeast component clearly dominates, except in July,at which time a weak northwest component is apparent (Fig. 43). The amplitude of the annual cycle is greater than that at either Prince Rupert or Sandspit.

Long-term monthly means of wind speeds and of percentage frequencies along 8 points of the compass at McInnes Island are presented in Fig. 44. From October through April, the largest mean speeds, about 20-29 mi/hr (9-13 m/sec), characterize the southeast and south components. From June through August, mean speeds along these directions are about one-half the winter values, but are greater than the mean northerly speeds, which are about 3-8 mi/hr (1.3-3.6 m/sec). Northerly speeds are relatively constant throughout the year. The percentage frequency of winds reflects their seasonal variability, relatively large values (about 20 to 30%) for the east and southeast components from October to April and for the northwest component from May to October.

B. Sea Level and Zonal Ekman Transport

Sea level and calculated wind-driven transport are of considerable significance in identifying variability in flow and in water structure and properties. As examples, Favorite (1974) has shown that in the Gulf of Alaska there is a near-linear relationship between monthly-mean increases in sea level (corrected for atmospheric pressure, seasonal steric effects and precipitation) and wind-driven transport, except during summer. As noted earlier in this report, Barber (1957b) has suggested that the annual alteration in water masses in Queen Charlotte Sound is responsible for a large part of the seasonal sea level oscillation observed at Prince Rupert. He also reported that below-average sea level in winter (January) indicates the absence of warm subsurface waters in Queen Charlotte Sound. Wickett and Thomson (1973) reported that there is good coherence between Ekman transport normal to the coast at lat. 50°N, long. 130°W and sea level at Prince Rupert; high sea level is associated with large onshore Ekman transport, whereas very low sea level is associated with relatively large offshore transport.

Monthly means of sea level (uncorrected for atmospheric pressure) for Prince Rupert, and of zonal Ekman transport at 50°N, 130°W for the period 1944-1973 are presented in Fig. 45. Sea level values greater than 12.75 and less than 12.25 ft and transport values greater than 500 tons/km/sec and negative values (offshore transport) are shaded to clearly show the seasonal and annual variability in the monthly means. An annual cycle is clearly evident. Abrupt increases in sea level and in transport normally occur in October-November, coincident with the onset of the strong southerly winds, and the values generally remain relatively high in January and February. Lowest annual values of sea level and negative values of transport generally occur from May through September.

In autumn, winter and early spring, zonal Ekman transport is generally directed onshore (Fig. 45), reflecting a convergent condition associated with the strong southerly winds that generally prevail during these periods. With a relaxation of these winds and an increase in the frequency of northerly winds in late spring and summer (May to October), transports are generally directed offshore (negative values); they are relatively small, reflecting a weak divergent condition.

The general coherence between sea level at Prince Rupert and Ekman transport normal to the coast at 50°N, 130°W (Wickett and Thomson 1973) is apparent in these data, particularly during autumn-winter, with high (low) monthly means of sea level generally associated with large (small) monthly means of Zonal Ekman transport (Fig. 45).

Marked yearly variations both in sea level and in zonal Ekman transport are also evident (Fig. 45). The persistence of relatively low and high monthly-mean values during both the winter (December through March) and the summer (June through August) periods are noted here. During the December-March period, sea levels were generally relatively low in 1946-47, 1948-49, 1949-50, 1955-56, 1956-57, 1961-62, 1964-65, 1970-71 and 1971-72. Zonal Ekman transports for this period were relatively small in 1946-47, 1948-49, 1949-1950 (except in February), 1955-56 (except in January), 1956-57, 1961-62, 1964-65, 1968-69, 1970-71 and 1971-72, and, except for 1968-69, corresponded to winter periods of relatively low sea level. Winter periods of high sea levels and large zonal Ekman transports are less obvious because of the marked fluctuations in the monthly-mean values during this period. Sea levels were generally high in the winters of 1952-53, 1957-58, 1960-61, 1965-66, 1967-68, 1969-70 and 1972-73. Ekman transports during this period were generally large in 1952-53, 1957-58, 1958-59, 1960-61, 1963-64 and 1969-70, in most cases, corresponding to the high sea levels of those winters. The significance of these anomalies in relation to winter sea surface temperature anomalies at the lightstations is discussed in a later section (p. 67).

During the June-August period, the yearly variations in sea level and zonal Ekman transport were small in comparison to those in winter; thus the anomalies are not easily identified. Sea levels appear to have been relatively low in 1944, 1945, 1951, 1958 (July) and 1962. Offshore transport (negative values) during this period were relatively large in 1948, 1949, 1951, 1952, 1958 (June and July) and 1963. Sea levels were relatively high in 1954, 1957, 1964, 1968, 1969, 1971, 1972 and 1973. Relatively small offshore or onshore transport generally occurred in 1957, 1964, 1968, 1969 (August), 1971, 1972 and 1973 (June and July), and, except for one year (1954), corresponded to summer periods of high sea level. Generally, the coherence between sea level and zonal Ekman transport appears to be less in summer than in winter.

C. Surface Conditions at Coastal Lightstations

Long-term records of daily observations of sea surface temperature and salinity are available at several lightstations located in the region. Some of these records date back to 1934 and have been used by numerous researchers to provide information on the seasonal cycles and long- and short-term variations in surface temperature and salinity. Long-term monthly means and standard deviations, and annual and monthly means and their deviations from the long-term monthly means are discussed. The data, presented here in graphical form, have been published in tabular form to 1971 by Hollister and Sandness (1972). Subsequent data (1971-76) are available in Pacific Marine Science Report 72-14 (Hollister 1972); 74-1 (Hollister 1974); 74-11 (Giovando and Hollister 1974); 78-2, 78-8 and 78-12 (Giovando 1978a,b,c). In the figures, temperatures have been plotted usually in °F, the same units used in the above reports, but values in the text are cited in both °F and °C. Figures for this sub-section start on page 100.

1. Annual surface temperature and salinity cycles

Long-term monthly means and standard deviations of temperature and salinity for Langara (1940-70), Cape St. James (1934-70), Triple Island (1940-70) (observations discontinued in 1971), Bonilla Island (1960-70), McInnes Island (1954-70) and Ivory Island (1937-55) (observations discontinued in 1956) are presented. The locations of these stations are shown in Fig. 1.

(a) Temperature

The annual temperature cycles are similar at each of the stations (Fig. 46) and are characteristic of the sea surface temperature régime for these latitudes, namely, a temperature maximum in August, and a minimum in February-March. The annual range varies from about 10 to 15°F (5.5 to 8.3°C), and is less at the "outside" stations (Cape St. James and Langara Island) than at the "inside" stations (Triple, Bonilla, McInnes and Ivory Island). The annual ranges are: at Langara, 42.9-52.8°F (6.1-11.6°C); Cape St. James, 44.4-54.7°F (6.9-12.6°C); Triple Island, 43.5-54.8°F (6.4-12.7°C); Bonilla Island, 43.2-54.0°F (6.2-12.2°C); McInnes Island, 43.6-56.2°F (6.4-13.4°C); and Ivory Island, 43.2-58.1°F (6.2-14.5°C). At the outside stations, the summer maximum and winter minimum temperatures decrease from south to north. However, at the inside stations, the long-term-average minimum temperatures are very similar (43.2-43.6°F, 6.2-6.4°C), but the corresponding maximum temperatures range from 54.0 to 58.8°F (12.2 to 14.9°C), a difference of 4.8°F (2.7°C). The relatively large differences in the maxima may be attributed to "local" variability in the stability of the near-surface water column. This variability can result from several factors acting singularly or in combination - fresh water input, tidal mixing, advection, and local differences in air-sea energy exchange. The small differences in the long-term minima between the southern and the northern inside stations indicate that advection is generally the dominant process during winter.

(b) Salinity

Pickard and McLeod (1953) have classified the daily seawater observation stations according to three climatological regions, based on the annual near-surface salinity cycle. The first includes areas far removed from the influence of river runoff. In such areas open-oceanic conditions prevail and there is little annual variation in surface salinity. The second includes those areas where surface salinity is dominated by runoff draining the regions of snow storage; here salinities are at a minimum in early summer. The third includes those areas characterized by a salinity minimum in winter associated with local runoff resulting from heavy winter precipitation. Each of these climatological regions occurs within the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region. Langara Island and Cape St. James are areas dominated by oceanic conditions, with a relatively small annual range, about 0.25‰ (Fig. 47). At Langara, two minima occur each year, in summer (July) and in late autumn (November), while at Cape St. James only a summer (August) minimum occurs. The second classification is reflected at Triple Island and Ivory Island, which are featured by a marked salinity minimum in summer. At Triple Island, the minimum occurs in June-July and is related to the peak discharges of the Skeena and Nass rivers, which occur in June. The salinity minimum at Ivory Island occurs later, July-August and is attributed to the peak discharges of the Dean and Bella Coola rivers. The difference in time of the minima is considered to be due to the difference in distance the waters of these rivers must travel before reaching the region - the waters of the Dean and Bella Coola moving further than those of the Skeena and Nass. On the other hand, McInnes Island shows a salinity minimum in November, and is typical of the third classification, whose stations are dominated by heavy local precipitation and runoff - which are a maximum at this time of the year. Bonilla Island shows a fairly marked minimum in November, and also a slight minimum in July-August, showing the effects of both local late-autumn runoff and early-summer river discharge. A slight minimum also occurs in February. This may be due to some "relaxation" of the early-winter onshore transport allowing the low-salinity waters from the mainland pasages to spread into the region.

Deviations of yearly averages from the long-term annual means of sea surface temperature and salinity for Langara Island, Cape St. James and Triple Island for the period 1940-75 are presented in Fig. 48. A marked cooling trend is evident during the period 1940-50, followed by a warming one from 1950 to 1963, and a cooling one from 1963 to 1972 (Fig. 48a). The deviations are very similar at each of the stations. Warm years occurred in 1940-42, 1953, 1958, 1963, and cold years in 1950, 1955-56 and 1971-72. A 5-6 yr periodicity in negative and positive anomalies of sea surface temperature of the North Pacific Ocean reported by Favorite and McLain (1973) is also indicated in these data.

The yearly deviations suggest a general decrease in surface salinity during the period 1940-75 at each of the stations (Fig. 48b). The rate of decrease is similar at each station, and is similar to that recently reported by Webster and Farmer (1977) for the 1935-1970 period - about 0.4‰ /35 yr at Langara Island and at two lightstations (Amphitrite Pt. and Kains Is.) located on the west coast of Vancouver Island. Yearly deviations in salinity show some coherence between stations, but less than that for temperature. Also, there appears to be little coherence between temperature and salinity fluctuations - a feature also noted by Webster and Farmer (1977) for other lightstations along the B.C. coast.

2. Monthly means of surface temperature and salinity

Monthly means of sea surface temperature and salinity for Cape St. James (1934-73), Ivory Island (1937-53), McInnes Island (1954-73) (replacing Ivory Island in 1954) Langara Island (1937-73) and Triple Island (1940-70) are presented in Fig. 49-52. Differences from the long-term monthly means are indicated by the vertical bars (light and heavy lines). Differences greater than one standard deviation are shown by the heavy vertical bars and are considered to identify significantly anomalous conditions.

(a) Monthly means of surface temperature and anomalies

In general, all stations reflect similar temperature trends, although differences from the long-term monthly means may vary from station to station (Fig. 49 and 50). From 1934 to early 1945, there was a dominance of anomalously warm surface conditions at all stations, particularly during the winter months (December through March). Warm winter conditions generally prevailed in 1937-38, for three consecutive years in 1939-40, 1940-41 and 1941-42 (no data for Cape St. James) and again in 1943-44 and 1944-45. These conditions usually persisted until mid-summer, but the anomalies were generally somewhat less than those in winter. These winters were followed by a lengthy period (1946-57) in which there was a dominance of cold surface conditions in winter - 1946-47, 1948-49, 1949-50, 1955-56 and 1956-57. During this 11-yr period, there was only one summer period in which temperatures were relatively high, namely 1957. Although temperature conditions were variable during the period 1958 to early 1964, the trend was toward warm conditions - winter to mid-summer 1958, winter 1962-63, generally throughout 1963 and in winter 1963-64. Cold conditions generally prevailed during the first half of 1962. From 1964 through 1973 anomalous conditions occurred in late summer (August through September) 1967 (warm), in mid-winter(January-February) 1969 (cold), in winter 1969-70 (warm) and in winters 1970-71 and 1971-72 (both cold).

(b) Monthly means of surface salinity and anomalies

In contrast to the marked similarity in surface temperature trends at each of the lightstations, there is considerably less coherence in the surface salinity trends (Fig. 51 and 52), reflecting the highly regional variability in freshwater discharge and mixing processes. At the outside stations, large anomalies tended to persist for several months, whereas at the inside stations, the persistence of very large anomalies was of shorter duration. The general trends at each of the stations are briefly noted.

At Cape St. James, there was a predominance of very low-salinity water in 1934, 1935, 1954, 1955 and in 1967 (Fig. 51). Relatively high-salinity water was present in 1937, in the latter part of 1942 and generally throughout 1944 and 1945. From 1938 to mid-1942 and from 1957 to 1967, anomalies were relatively small, generally less than one standard deviation.

At Langara Island, above-average salinity conditions generally prevailed from mid-1942 to 1947 (Fig. 52), generally coinciding with periods of above-average conditions at Cape St. James. Below-average salinity conditions occurred in the latter part of 1953, in 1961, in the first half of 1963 and of 1964 and in the latter half of 1967.

At Triple Island, high-salinity water was present in the first half of 1945 and of 1950, with low-salinity water dominant in 1954 and 1955 (Fig. 52). From 1956 through 1969, average salinity conditions generally prevailed, except for the large anomalies that are evident in June and July in some years.

At Ivory Island (1937-53), salinity conditions were generally below average in 1939, and above average in the latter part of 1951. At McInnes Island (1954-69), salinities were anomalously low in 1967 and 1968 and high in late 1955, in early 1956 and in summer 1965.

(c) Winter (December through March) anomalies of surface temperature, sea level and zonal Ekman transport

Monthly mean sea surface temperatures for various periods have been tested as an index of changes in year-class strengths of several groundfish stocks in Hecate Strait (Ketchen 1956a,b). A general assessment of temperature conditions that prevailed at the lightstations during the winter period (December through March) for the years 1939 through 1973 is provided in Table 4. The anomalies in temperature are compared to those of sea level and zonal Ekman transport, where data are available. The cold conditions in the winter of 1946-47, 1948-49, 1949-50, 1955-56, 1956-57, 1961-62, 1964-65, 1968-69, 1970-71 and 1971-72 (Table 4) were associated with low sea level (except in 1968-69) and small Ekman transport (see p. 63 and Fig.45). The warm winter conditions in 1957-58, 1960-61 and 1969-70 were associated with high sea level and large Ekman transport. However, the warm conditions in winter 1962-63 were associated with slightly above-average sea levels and average transports. Also, in 1963-64, only transports were moderately large. However, sea level and Ekman transport were above average in October and/or November for both of these winter periods. Other discrepancies in these relationships are obvious. In winter 1944-45, temperature conditions were anomalously warm, but sea levels were low (no transport data). The relatively high sea levels and large Ekman transports in 1952-53 were associated with average temperature conditions. In 1968-69, cold conditions generally prevailed, but sea levels were relatively high. However, Ekman transports were relatively small during this winter period. Apart from these few discrepancies, it appears that both anomalies in sea level at Prince Rupert and zonal Ekman transport at 50°N, 130°W are associated with anomalous winter surface temperature conditions in the region.

Table 4. Summary of sea surface temperature conditions, December through March, at coastal light stations in the Queen Charlotte Sound-Hecate Strait-Dixon Entrance region, 1939-1973.

	Stations			
Year	Langara	Triple Island	C. St. James	Ivory Island McInnes Island (to 1954)
1939-40	-	V.W.	-	V.W.
1940-41	V.W.	V.W.	-	V.W. - W
1941-42	V.W.	V.W. - W	-	V.W. - Av.
1942-43	Av.	Av.	Av.	Av.
1943-44	V.W. - W	V.W. - W	V.W.	W
1944-45	V.W. - W	V.W. - W	V.W.	W - V.W.
1945-46	Av.	Av.	Av.	Av. - C
1946-47	V.C.	V.C. - C	C	V.C. - C
1947-48	Av.	Av.	Av.	Av.
1948-49	V.C. - C	V.C.	V.C. - C	V.C. - C
1949-50	V.C.	V.C.	V.C. - C	V.C.
1950-51	Av. - C	Av. - C	Av. - C	Av. - C
1951-52	C	C	C	C
1952-53	Av.	Av.	Av.	Av.
1953-54	Av.	Av.	-	-
1954-55	W - Av.	Av.	W - Av.	W - Av.
1955-56	C - V.C.	C - V.C.	V.C.	V.C.
1956-57	C - Av.	V.C. - Av.	V.C.	V.C. - Av.
1957-58	Av. - V.W.	V.W.	Av.	W - Av.
1958-59	Av. - W	Av.	Av.	Av.
1959-60	Av.	Av.	Av.	Av.
1960-61	W - Av.	W - Av.	W	W - Av.
1961-62	Av.	C	Av. - C	C
1962-63	W - V.W.	W	V.W. - W	V.W. - W
1963-64	W	W	V.W.	V.W. - W
1964-65	C - Av.	C - Av.	C - Av.	C - Av.
1965-66	Av.	Av.	Av. - W	Av.
1966-67	Av.	Av.	Av.	Av.
1967-68	Av.	Av. - C	Av.	Av.
1968-69	V.C. - C	C	C - Av.	V.C. - Av.
1969-70	W - Av.	W - Av.	W - V.W.	W - Av.
1970-71	C - Av.	-	Av.	C - V.C.
1971-72	V.C.	-	V.C.	V.C.
1972-73	Av.	-	Av.	Av. - C

C - cold
V.C. - very cold
Av. - average
W - warm
V.W. - very warm

D. Surface distributions of temperature and salinity

Distributions of surface (3 and 5 m) temperature and salinity for various periods in 1954-55, 1959 and 1961-62 are presented. These two depths are those used by Crean (1963) and are considered to eliminate short-term surface effects such as those due to diurnal variations in temperature and to local runoff. The distributions reflect the principal seasonal and spatial features and some of the year to year variations that can be expected in the near-surface waters. Also, some information on the surface circulation can be inferred from the configuration of the isolines, in particular the isohalines. The inferred flows that appear to show some consistency in time and/or space are indicated in the figures by arrows. Figures for this sub-section start on page 119.

1. Surface temperature

In May 1954, the sea surface temperature distribution was generally irregular, but surface (3 m) temperatures were relatively uniform over the region, about 8°C in Queen Charlotte Sound and Hecate Strait and 7-7.5°C in Dixon Entrance (Fig. 53). A tongue of relatively low-temperature water appears to have formed in southern Queen Charlotte Sound. Based on temperature conditions at the lightstations, this distribution reflects slightly below-average temperature conditions for May.

By July 1954, the effects of seasonal heating are clearly evident in Fig. 54. Temperatures throughout the region were 3-4°C higher than those observed in May. A relatively marked gradient had developed in southern Queen Charlotte Sound, and is attributed to the relatively cold mixed waters inflowing from Queen Charlotte Strait. A slight gradient had also developed off the southeast coast of the Queen Charlotte Islands, possibly associated with a local upwelling condition. Over the remainder of the region the distribution was irregular, with tongues and cells of warm and cold water the dominant features; these are attributed to weak and irregular flow patterns. This distribution is also considered to represent slightly below-average conditions for this time of the year.

In August-September 1954, marked gradients, tongues and cells were the dominant features (Fig. 55). The temperature gradient in southern Queen Charlotte Sound had increased from that observed in July, but the gradient that was present off the southeast coast of the Queen Charlotte Islands in July had dissipated. However a relatively marked gradient, with temperatures increasing to seaward, had formed along the eastern (mainland) side of Hecate Strait, and was continuous across the northern part of the Strait. This gradient is attributed to upwelling along the mainland side. Temperatures ranged from 9°C in southern Queen Charlotte Sound to 14.5°C in the central part of the Sound, from about 10 to 14°C in Hecate Strait, and from about 11.5 to 13°C in Dixon Entrance. Maximum temperatures in Dixon Entrance were about 1 to 1.5°C lower than those observed in Hecate Strait and in Queen Charlotte Sound. This distribution is considered to reflect average conditions for this period.

In February 1955, relatively uniform conditions again prevailed throughout most of the region (Fig. 56). Surface temperatures were highest (~8°C) in southwestern Queen Charlotte Sound, while the lowest temperatures occurred within a small cell off Rose Spit (~6°C) and in the mainland approaches to the region (~7°C). In Dixon Entrance, temperatures ranged between 6.5 and 7°C, about 1-1.5°C lower than those observed in Queen Charlotte Sound and in southern Hecate Strait. This distribution is indicative of near-average conditions.

In mid-April 1955 also, temperatures decreased from south to north, with a range of about 1.5°C (Fig. 57) - similar to that observed in other periods. In Hecate Strait and central Queen Charlotte Sound the isotherms were oriented perpendicular to the coasts. Temperatures were about 1°C lower than those observed in February throughout the region and are indicative of below-average conditions.

The temperature distribution for June 1955 shows features considered typical for the summer period, namely a marked gradient in southern Queen Charlotte Sound, cells of relatively warm and cold water in Queen Charlotte Sound and Hecate Strait, and temperatures increasing seaward from the mainland side of Hecate Strait (Fig. 58). This distribution also reflects below-average conditions.

The temperature distributions for subsequent periods show seasonal features similar to those already noted, and also reflect the annual variability that can occur. In April 1959 the general south-to-north decrease (1.5°C) is again evident (Fig. 59). Throughout the region temperatures were about 1-1.5°C higher than those observed in April 1955, and are indicative of average conditions.

In late June 1959, the dominant features were the tongues of relatively warm water along the mainland side of Queen Charlotte Sound, Hecate Strait and Dixon Entrance, and the gradients in southern Queen Charlotte Sound and at the seaward entrance to Dixon Entrance (Fig. 60). In central Dixon Entrance temperatures were relatively uniform, 11-11.5°C.

Distributions for early October 1961, January and March 1962 were generally typical of those for autumn and late-winter periods, with temperatures decreasing northward and the absence of any appreciable gradients (Fig. 61-63). In mid-March 1962, temperatures ranged from 6.5°C in Queen Charlotte Sound to less than 5°C in Dixon Entrance (Fig. 63). Below-average temperature conditions prevailed throughout the region during this period.

2. Surface salinity

Surface (3-5 m) salinity distributions are presented for essentially the same periods as are those for temperature. In May 1954, surface salinities ranged from about 31 to 32‰ over most of the region, with lowest salinities (<31‰) at the eastern approaches, and highest salinities (32‰) at the western approaches to Queen Charlotte Sound and Dixon Entrance (Fig. 64). There is evidence of the development of a tongue of relatively low-salinity water in southern Queen Charlotte Sound, as indicated by the configuration of the 31.5‰ isohaline. The development of this tongue is also evident in the surface temperature distribution for this period (Fig. 53). The relatively high salinity water (>31.8‰) in western Hecate Strait is considered a remnant of a northward intrusion of oceanic water that normally occurs during the winter months. The terminus of this intrusion is indicated by a small cell of relatively high salinity (32‰) in southeastern Dixon Entrance. From central Dixon Entrance salinities increased slightly to seaward, and decreased slightly to the mainland coast.

In July 1954, low-salinity water and marked horizontal gradients along the mainland side of Queen Charlotte Sound and in eastern and northeastern Dixon Entrance were the dominant features (Fig. 65). The gradients are attributed to the peak discharges in June of the large snow-melt fed mainland rivers. A gradient was also present at the western entrance to Dixon Entrance, marking the boundary between the oceanic and coastal waters. Over the remainder of the region, salinities were relatively uniform, 31 to 32‰. In central Dixon Entrance, surface salinities were about 0.5‰ lower than those observed in May, but little change had occurred in Hecate Strait. The tongue of low-salinity water in southern Queen Charlotte Sound was now a well-developed feature, with a predominantly westward flow indicated.

By August-September 1954, the low-salinity water, which in July was confined to the eastern and northern boundaries of the region, had spread seaward, and as a result, salinities in Dixon Entrance were about 1‰ lower, and in Hecate Strait from 0.5 to 1.5‰ lower (Fig. 66), than those in July. In general, surface salinities were also lower in Queen Charlotte Sound, except in the low-salinity tongue, and as a result the gradient associated with the tongue was less marked than that in July. However, the tongue had progressed further seaward, but not to the extent noted in some other years - e.g. in August 1958 (Favorite 1961) and in June-August 1966 (Dodimead 1968). There was a significant change in the configuration of the isohalines in Hecate Strait, with a general east-west orientation indicated - in contrast to the predominantly north-south orientation that normally occurs in winter, spring and early summer. This implies that there was little north-south flow during this period in Hecate Strait. A westward flow of surface water is indicated in northern Dixon Entrance.

During late November 1954, salinities in Queen Charlotte Sound (Fig. 67) were, in general, higher than those for August. This condition is attributed to the retention of local runoff at the eastern shores by the southerly winds which are usually dominant at this time of year - as is evident by the marked gradient in the vicinity of McInnes Island. Also, vertical mixing of surface waters with the subsurface waters occurs, resulting in an increase in salinity in the surface layer. A remnant of the low-salinity tongue in southwestern Queen Charlotte Sound is evident.

By February 1955, surface salinities were again relatively low throughout the region, generally ranging between 30.5 and 31.5‰ (Fig. 68). This is attributed to an early "relaxation" of the winter onshore transport, resulting in a westward spread of the low-salinity waters which had been confined along the mainland coast. In addition, a general northward flow is indicated in Queen Charlotte Sound and in Hecate Strait, as shown by the general north-south orientation of the isohalines. In Dixon Entrance, the surface flow appears to have been weak and irregular, with a seaward surface flow in northern Dixon Entrance and a relatively weak inflow near Langara Island.

In April 1955, surface salinities were relatively high and uniform throughout most of the region (Fig. 69), being about 0.5% higher than those observed in February. These conditions reflect the extremes of late winter conditions, associated with low surface temperatures, minimum stability in the water column, and the lack of substantial local and snow-melt runoff. A definitive flow pattern is not evident in this period. During this period, the low salinity water in eastern Dixon Entrance had intruded southward into northern Hecate Strait, displacing or overriding the high-salinity water normally encountered in this part of the region. In central Dixon Entrance, Hecate Strait and northern Queen Charlotte Sound, salinities were generally similar to those in May 1954.

Near surface (5 m) distributions of salinity for April and June 1959, July-August and October 1961, and January, March and March-April 1962 show major features and seasonal variations similar to those just described (Fig. 71-77). However, as with temperature, some year to year differences are apparent in the figures. In April 1959, salinities were about 1% lower over most of the region, and the north-south configuration of the isolines was more definite, than was the case in April 1955 (Fig. 69 and 71).

In June 1959, the salinity distribution (Fig. 72) was essentially the same as that for June-July 1954(Fig. 54), with marked gradients and very low-salinity water in eastern Dixon Entrance, relatively low-salinity water and a gradient at the western entrance to Dixon Entrance, a tongue of low-salinity water in southern Queen Charlotte Sound, and relatively uniform salinities (31 to 32%) over the remainder of the region.

During July-August 1961, the surface salinity over most of Queen Charlotte Sound was relatively uniform, and low (Fig. 73) compared to that observed in August 1954. The tongue of low-salinity water, previously identified by the 31.5% isohaline, appears to have had a much greater westward and northward extent than in other summer periods for which data have been presented.

From October 1961 to mid-January 1962, surface salinities increased by about 0.5% throughout Queen Charlotte Sound, Hecate Strait and southern Dixon Entrance (Fig. 74-75). The increase occurred during a period of very low sea level and small Ekman transport (Fig. 45), indicating little northward flow during this period. Thus, the increase does not appear to be associated with a marked northward intrusion of relatively high-salinity water through Queen Charlotte Sound. It may be due to mixing and evaporation, coupled with small freshwater runoff during this period.

By mid-March and in early April 1962, surface salinities were slightly lower than those observed in January, and were relatively uniform, about 31.5 to 32%, over most of the region (Fig. 76-77). These figures indicate that changes in surface salinities, over a period of about 2 weeks are relatively small during this period.

E. Annual Cycle of Subsurface Temperature, Salinity, Density and Dissolved Oxygen Content in Queen Charlotte Sound and Hecate Strait

The occurrence of an annual cycle in the subsurface waters (considered to be those waters at depths of 125 m and greater) of Queen Charlotte Sound (Barber 1957 b, 1958 a,b) and of Dixon Entrance (Crean 1967) has been noted. Examples to demonstrate this annual cycle in the vertical structure of temperature, salinity, density (as given by sigma-t) and dissolved oxygen content are presented for 5 separate areas in Queen Charlotte Sound and Hecate Strait shown in Fig. 78. The stations representing each area are either coincident or closely spaced. The 1954-55 and 1960-62 data sets provide the best temporal coverage to indicate this cycle. However, the data are not of sufficient density with respect to time and depth to define precisely when and to what depths the extremes of the seasonal subsurface conditions occurred in these periods. Figures for this sub-section commence on page 145.

The annual cycle is similar in each of the areas (here and in subsequent discussions and in the figures, these are referred to as stations) (Fig. 79-85). In mid-summer (July - August), the dominant features of the vertical structures are the thin mixed or near-mixed surface layer, and underlying this layer, the relatively marked gradients associated with the thermocline, halocline, pycnocline and oxycline. During this period these gradients are at their minimum depth. Below them the waters are of relatively low temperature and dissolved oxygen content, and of high salinity and density. These features and conditions occur most frequently in mid-summer and are defined as "summer" conditions.

Coincident with the development of the generally strong and persistent southerly winds of autumn and early winter (October-December), marked changes occur throughout the water column. The surface layer thickens; the thermocline, halocline, pycnocline and oxycline are displaced downward (e.g. Fig. 80), and are considered to reach their maximum depth by late December. By this time the subsurface waters have been replaced by waters of relatively high temperature and dissolved oxygen content and of low salinity and density. Also, during this period, erosion of the summer thermocline continues because of surface cooling and convective and wind-induced mixing. These surface processes continue until late March - early April. During late winter the thermocline disappears and temperatures decrease, and near-isothermal conditions may extend to depths of 150-200 m (e.g. Fig. 81). However, the vertical gradients of salinity, density and dissolved oxygen remain, but are considerably deeper than those observed in mid-summer. In the shallower areas, marked vertical gradients are indicated in the near-bottom waters (e.g. Fig. 84 - dissolved oxygen). Temperature inversions are common features during late winter. These features and conditions are defined as "winter" conditions.

With the relaxation of southerly winds in spring, the surface waters which have accumulated along the mainland coast move seaward, and there is a compensating movement of subsurface oceanic water shoreward. As a result, the subsurface waters are replaced by waters of relatively low temperature and dissolved oxygen content and of relatively high salinity and density. There is also an upward displacement of the vertical gradients of salinity, density and dissolved oxygen, marking the return to "summer" conditions.

In these figures the isolines have been drawn to indicate relatively gradual changes between the extremes of "summer" and "winter" conditions. However, because of the marked variability in the onset, strength and duration of the seasonal winds, considered to be the prime factor related to the occurrence of these conditions, it is reasonable to assume that variations in the onset and duration of the change probably occur. Strong southerly winds usually commence about mid-October, and remain relatively strong through December. Therefore the change to "winter" conditions will generally occur during this period. However, the relaxation of these winds is extremely variable, and may occur at any time from late winter to late spring; also, the relaxation process may be gradual or relatively abrupt within this time frame. Therefore, it follows that the subsurface conditions could change accordingly; the return to "summer" conditions may be abrupt or gradual and may occur at any time from late winter through late spring. The data for 1954 indicate a relatively late and abrupt change to "summer" conditions, between May and early July 1954.

Another feature evident in these data is the variability that can occur in "winter" conditions. The deepening of the isolines appears to have been less in winter 1961-62 than in winter 1960-61 (Fig. 80, 81, and 84). Also, by late winter (January-February), temperatures throughout the water column were lower in the winter of 1962 (January) than that of 1961 (February). Several factors were associated with the relatively cold conditions in winter 1961-62; monthly means of sea level and zonal Ekman were relatively low, as has been noted previously, and monthly means of air temperature at McInnes Island were between 0.8 and 2.5°C lower in the winter of 1961-62 than in that of 1960-61.

F. Vertical Temperature and Salinity Structures in Queen Charlotte Sound and Hecate Strait.

To show clearly the characteristic features of the temperature and salinity structures, as well as the ranges in temperature and salinity for the waters of Queen Charlotte Sound and Hecate Strait, all available data (excluding bathythermograph data) for 3 stations (Sta. A, C, E; Fig. 78) are presented. Sta. A is considered representative of waters in the western approach to Queen Charlotte Sound and Sta. C and E representative of waters of the deeper areas of central Queen Charlotte Sound and Hecate Strait, respectively. The data have been grouped arbitrarily into four 3-month periods, July-September, October-December, January-March and April-June. Although the data are relatively sparse in most of these periods, they do provide an indication of the seasonal and yearly variability that can be expected in these properties. Figures for this sub-section start on page 152.

In July-September, the distinctive features of the temperature and salinity structures are the thin mixed or near-mixed surface layer and the marked thermocline and halocline (Fig. 86-88). In the absence of surface mixing, the thermocline and halocline will extend to the surface. The thermocline extends from near-surface to about 75-100 m depth at Sta. A and to about 100-125 m at Sta. C and E. The magnitude of the thermocline is dependent upon the degree of surface heating and mixing and is about 6 to 8°C. The halocline extends from near-surface to depths of 125-150 m at

Sta. A and C, and to about 150 m at Sta. E. The upper portions of the thermocline and halocline are generally coincident in depth, but the lower limit of the halocline appears to be deeper than that of the thermocline. The magnitude of the halocline is dependent upon the freshwater input, and therefore varies with location, but is about 2 to 3‰. During this period, the thermocline and halocline are at their minimum depth. Below these gradients temperature decreases, and salinity increases, slightly with depth; temperatures are low and salinities high throughout most of the water column. In the subsurface waters (125 m to bottom), the ranges in temperature and salinity in these data are about 1.0°C and 0.5‰, respectively, at 125 m depth, decreasing to about 0.7°C and 0.15‰ at 200 m depth. These values are considered representative of the variability generally occurring in this period.

In October-December the dominant processes and their sequence are considered to be: surface cooling (primarily through conduction and evaporation), wind-induced and convective mixing, onshore transport of the surface layer accompanied by an accumulation and downward displacement of these waters along the mainland side, and offshore transport at depth resulting in a displacement of subsurface waters to seaward. These processes are reflected by changes in the structures. The initial changes are the thickening of the surface mixed layer and the downward displacement of the thermocline and halocline in late October (Fig. 89-91). These result in large changes in temperature and salinity at intermediate depths (75-100 m). By late-December, the subsurface waters have been replaced and are now relatively warm and of low salinity. The range of temperature for October-December for these data is about 2.5°C at 125 m, decreasing to about 1.9°C at 200 m, while the corresponding salinity values at the two depths are about 1.1 and 0.7‰.

During late winter (January-March) the cooling, mixing and advective processes continue. The main features are the near-isothermal conditions to depths of 150-200 m and the relatively large temperature inversions common at depth, particularly at Sta. C and E (Fig. 92-94). The variability in temperature and salinity in the subsurface waters is generally similar to that of the previous period.

In April-June, mixing and surface cooling are replaced by surface heating and dilution. Also, there is a relaxation in southerly winds; this is accompanied by an offshore movement of surface waters, and a compensating onshore flow of subsurface waters. These processes result in the development of the summer thermocline, an increase in the magnitude of the halocline, a decrease in the depth of the halocline and a reentry of relatively cold and saline subsurface waters (Fig. 95-97), marking the return to "summer" conditions. The range in temperature is about 1.5°C between 125 and 250 m, while the salinity range is about 1‰ at 125 m, decreasing to about 0.1‰ at 250 m depth, again indicative of the seasonal and yearly variability that can be expected in these areas during this period.

During April-June, both "summer" and "winter" conditions may occur. Conditions in April 1955 and 1968 were generally characteristic of "summer" (Fig. 95, 96), whereas during April 1969, conditions were generally typical of those for "winter" (Fig. 97).

The near-isothermal feature of the temperature structure in late winter is of considerable significance, as surface conditions in this period generally reflect the subsurface conditions to depths of 150-200 m (p.113). Thus, the anomalies in the long-term records of sea surface temperature at the lightstations are considered to reflect corresponding anomalies in the subsurface waters to at least these depths (150-200 m), in these areas, during late winter. It follows that, since there is good coherence between sea level at Prince Rupert, zonal Ekman transport at 50°N, 130°W and sea surface temperature anomalies, any or all of these can be used in Queen Charlotte Sound and Hecate Strait as indices of subsurface temperature conditions during late winter. As noted earlier Barber (1957a) suggested sea level at Prince Rupert as an index of subsurface temperature conditions.

A schematic diagram indicating the approximate overall annual range and the range of "summer" and "winter" conditions for the subsurface waters (those below 125 m) is presented in Fig. 98. The overall range in temperature is about 3.5°C at 125 m, decreasing to about 1.3°C at 300 m depth. Similarly, the salinity range decreases from about 1.8‰ at 125 m to 0.3‰ at 300 m depth. Incidently, the figure also shows the large variability in temperature and salinity characteristic of depths between the surface and 125 m.

G. Vertical Sections of Temperature, Salinity, Density and Dissolved Oxygen Content in Queen Charlotte Sound and Hecate Strait.

Vertical sections of temperature, salinity, density (as given by sigma-t) and dissolved oxygen content along six sections transecting Queen Sound and Hecate Strait reflect the seasonal sequence of events as well as the spatial and yearly variability of these properties and of flow in these areas. Two sections transect Queen Charlotte Sound and four transect Hecate Strait (Fig. 99). Most of the data presented are those for 1954-55. The remainder are those for 1961-62 (section 4) and for 1967-70 (sections 1 and 2). Figures for this sub-section start on page 166.

1. Section 1 - Queen Charlotte Sound (Fig. 100-110).

In early May 1954, vertical and horizontal gradients of properties were small throughout this section (Fig. 100). In the western part of the section, there is evidence of a deepening of the isolines shoreward, at least in the upper layer to about 75 m depth. Near the mainland coast, temperatures and dissolved oxygen content were relatively high, and salinities and densities were relatively low, in the near-bottom waters at 100-150 m depth. Temperatures and salinities appear to fall within the range of typical "winter" conditions (Fig. 98).

By early July 1954, temperatures in the upper 75 m of the water column had increased as the summer thermocline developed (Fig. 101). However, salinities in this layer were very similar to those observed in May, except for the formation of a thin surface layer of low-salinity water near the coast. As noted previously, this indicates the effect of the early summer discharges from the large snow-melt-fed rivers. Below 100 m depth, temperatures and dissolved oxygen decreased, and salinities and densities increased from May to July. The greatest change occurred between the depths of 100 to 150 m near the shore; there the decrease in temperature and dissolved oxygen was about 1.0°C and 3 ml/l, respectively, and the increase in salinity about 0.5‰, indicating a relatively late and abrupt return to "summer" conditions (Fig. 98).

In the latter part of August, temperatures in the surface layer increased as the summer thermocline developed, with the warmest waters occurring to seaward (Fig. 102). In the western part of the section, temperatures and dissolved oxygen at depths below 100 m were slightly higher, and salinities and densities were slightly lower, than those in July. The apparent net increase in heat content of these waters is opposite to that reported for the waters of Dixon Entrance during this period (Tabata 1958). However, near the coast, conditions in the deeper waters remained almost unchanged between the beginning of July and late August. The deepening of the isolines (except those of dissolved oxygen) shoreward to depths of at least 125 m is again evident in the western part of the section.

In early December 1954, surface cooling and mixing as well as advective processes dominated, resulting in a marked thickening of the surface mixed layer and a downward displacement of the vertical gradients associated with the thermocline, halocline, pycnocline and oxycline (Fig. 103). With respect to conditions in mid-August, marked increases in temperature and dissolved oxygen and decreases in salinity and density, occurred to depths of at least 300 m. At 150 m depth, the changes in temperature, salinity and dissolved oxygen were relatively large, about 2°C, 1‰ and 1.5 ml/l, respectively, from August to December. These conditions are indicative of the extremes of "winter" conditions. The downward slope of the isolines in the upper portion of the water column, observed in the western part of the section in May-August, was absent.

In February 1955, sampling depths were limited to those above 100 m, but the data show a typical decrease in temperature of about 2.5°C (Fig. 104) from that observed at corresponding depths in December.

In mid-April 1955, temperatures were relatively uniform to about 150 m depth (Fig. 105), and were about 1°C lower than observed in February. Below 125 m depth, conditions were in general similar to those observed in early May 1954.

By late June 1955, the distributions of properties were very similar to those observed in early July 1954, particularly in the subsurface waters (Fig. 106). The downward slope of the isolines shoreward to depths at least 150 m is clearly evident in the western part of the section. This appears to be a spring and summer feature of the structure along this section.

During the period 1967-70, continuous profiles of temperature and salinity were obtained along approximately the same track as in 1954-55 (Fig. 99). The 1967-70 observations extended further to seaward, but covered only two seasonal periods, March-April and September-October. The distributions of temperature and salinity obtained (no dissolved oxygen data available) provide additional information on the seasonal and yearly variations - especially at depth - in these properties (Fig. 107-110).

In mid-September 1967, the isolines at depths below 250 m deepened toward the continental slope (Fig. 107), whereas in April 1968 the corresponding isolines rose toward the shelf area (Fig. 108). As a result, the continental slope waters at these depths were colder and more saline in the latter period.

Temperature and salinity conditions at depths between 150 and 300 m depth were generally similar in April 1969 and March 1970 in the western part of the section (Fig. 109 and 110), but were considerably warmer and less saline than those in April 1968 (Fig. 108). Also, near the coast temperatures were higher and salinities were lower at depths between 100 and 150 m in April 1969 and March 1970 than in April 1968. Further, temperatures and salinities of these waters were generally similar in April 1968, July 1954 and June 1955. This indicates a relatively early intrusion of the cold saline oceanic waters, marking an early return to "summer" conditions, in April 1968.

Temperature inversions are characteristic of the temperature structure in late winter and early spring. These data show that inversions occurred to depths of about 175 m.

2. Section 2 - Queen Charlotte Sound (Fig. 111-121).

Vertical sections are presented for the same seasonal periods in 1954-55 as for Section 1, except that data are not available for December 1954. Distributions of temperature and salinity for September 1967, April and October 1968, and April and October 1969 are also shown.

In general, the seasonal sequence of events was similar to that noted for Section 1. An intrusion of relatively cold, saline, dense and low dissolved oxygen content water occurred along the continental slope and shelf between early May and early July 1954 (Fig. 111 and 112).

By the latter part of August temperature and dissolved oxygen content were slightly higher, and salinity and density slightly lower (Fig. 113) than those observed in July in the shelf and slope waters; similar conditions were noted in Section 1.

In February 1955, the dominant feature was the deepening of the isolines shoreward near the mainland side of the section (Fig. 114). This indicates an onshore movement of surface waters resulting in a relatively strong northward flow. This is considered a characteristic feature of the winter circulation.

The downward slope of the isolines in mid-April (Fig. 115) also indicates northward flow; it appears to be weaker but to extend further seaward than in February. Conditions in the subsurface waters in mid-April approached those observed in early May 1954.

By late June 1955, conditions in these waters (Fig. 116) were similar to those in early July 1954 (Fig. 112).

The continental slope waters at depths below 250 m were of higher temperature in September 1967 than in April 1968 (Fig. 117 and 118), as noted for Section 1. However, the salinity of these waters was generally similar for these periods. Also, in April 1968, temperatures of the waters of the continental shelf and slope, between 150 and 300 m depth, were up to 1°C lower than those in October 1968 (Fig. 119), April 1969 (Fig. 120) and October 1969 (Fig. 121), except near the mainland coast. Here, near-bottom water temperatures were similar (~7°C) in April 1968 and April 1969, and similar (~6.5°C) in October 1968 and October 1969.

3. Section 3 - Hecate Strait (Fig. 122-126).

A significant feature of this section is the difference between the properties of the waters in Hecate Strait and those to the east of the sill on the mainland side of the Strait. In all periods for which there are data, waters below 50 m depth in the latter area were of higher temperature and dissolved oxygen and of lower salinity and density than those in the former (Fig. 122, 124, 125).

In July and August 1954 (Fig. 123 and 124), the subsurface waters were of lower temperature and dissolved oxygen content and of higher salinity and density than those in May 1954, with the extreme of "summer" conditions again occurring in July, as noted for sections 1 and 2. Another significant feature is the difference in the slope of the isolines in July and August. In July the isolines sloped slightly downward toward the eastern shore between depths of 50 and 150 m, while in August they appeared to slope upward. This indicates an upwelling or divergent condition along the eastern shoreline in August, which would be accompanied by a southward flow in this area of Hecate Strait. This is opposite to the convergent condition and northward flow inferred from the slight downward slope of the isolines in July. This change may account for the change in properties from May to August in the waters east of the sill, where, below the sill depth, there was a slight decrease in temperature and dissolved oxygen and a slight increase in salinity and density.

The deepening of the isolines near the mainland coast in February and April 1955 (Fig. 125-126), as occurred in Section 2 to the south, reflects continuity in the northward flow between sections 2 and 3. Conditions in the subsurface waters in April 1955 were similar to those in May 1954.

4. Section 4 - Hecate Strait (Fig. 127-134).

Data obtained along Section 4 in 1954-55 and 1961-62 are presented. In July 1954, the main features were the general downward slope of the isolines throughout much of the water column and the retention of a relatively thick surface layer of low salinity at the eastern shore, indicating a convergent situation (Fig. 127).

By August 1954, the slope of the isolines in the upper 100 m of the water column was reversed - the isolines sloped upward in the eastern part of the section (Fig. 128). As in Section 3, this implies an upwelling condition, resulting in relatively low temperatures from 0 to 100 m depth, and an offshore and southward flow of surface waters along the mainland side of the Strait. In the deeper waters (below 100 m depth), temperature and dissolved oxygen appear to be slightly lower, and salinity and density slightly higher, in August than in July, opposite to the change in conditions that occurred in Queen Charlotte Sound and in southern Hecate Strait during these two months.

In February 1955, temperatures were relatively uniform throughout the water column (Fig. 129), with the bottom water temperatures at 150 m being about 2°C higher, and salinities about 0.8‰ lower, than those observed in August. The downward slope of the isohalines and isopycnals indicates an extension of the northward flow that was noted to the south of this section.

The northward flow was still evident in April 1955 (Fig. 130), but temperatures throughout the water column had decreased about 1°C from those observed in February.

By late June 1955, conditions in the subsurface waters (Fig. 131) had returned essentially to those observed in early July 1954, except that dissolved oxygen was slightly lower in June 1955 than in July 1954.

In the latter part of July 1961, conditions were in general similar to those observed in late August 1954, and are considered to be typical of mid-summer conditions (Fig. 132). By early October 1961, temperatures and dissolved oxygen had decreased, and salinities and densities had increased, in the surface layer. However, changes in the bottom waters at 150 to 200 m depth were very small and, except for dissolved oxygen, opposite to those in the surface layer, i.e. temperature increased and salinity and density decreased slightly (Fig. 133).

The mid-March 1962 distribution shows relatively cold and high-salinity conditions above 100 m depth. A southward flow between the surface and 100 m depth is indicated, opposite to that noted in February and April 1955. The southward flow is reflected in the low sea levels at Prince Rupert for this period.

5. <u>Section 5 - Hecate Strait (Fig. 135-140).</u>

This section extends across Hecate Strait past the northern tip of Banks Island (Fig. 99). In May 1954, the depths of the isolines remained relatively constant across the Strait (Fig. 135). The difference in the vertical distribution of properties west and east of Banks Island is evident - below 50 m depth temperature and dissolved oxygen were higher, and salinity and density lower, to the east of Banks Island than to the west.

In early July 1954, a marked downward slope of the isolines (toward the eastern shore) in the upper layer is indicated (Fig. 136). In the deeper waters, temperature, salinity and density increased, and dissolved oxygen decreased, with respect to conditions in May.

In late August, a reversal in the slope of the isoline from that observed in July is indicated to occur to at least a depth of 50 m (Fig. 137), again reflecting an upwelling condition and a change from northerly to southerly flow. As a result, the near-surface waters on the western side of the Strait were considerably warmer than those adjacent to the eastern shore.

In February 1955, the waters were virtually homogeneous throughout the water column (to at least 100 m), with temperature decreasing slightly (~0.2°C), and salinity increasing (~0.4‰), from east to west (Fig. 138).

In April 1955 (Fig. 139), temperatures were lower (1°C) and salinities were higher (~0.2‰) than those observed in February.

By June 1955, the vertical structures associated with summer conditions are apparent (Fig. 140). Also, conditions were generally similar to those in early July 1954.

A dominant feature in this section was the absence of any appreciable vertical gradients in the relatively shallow waters on the western side of the Strait throughout the year.

6. Section 6 - Hecate Strait (Fig. 141).

Vertical distributions of properties across northern Hecate Strait are displayed in Fig. 141. The dominant features were: the high temperature and dissolved oxygen contents and low salinities and densities of the bottom waters in July, as compared to those for the other periods shown; and the absence of any appreciable vertical gradients in the shallow waters on the western side of the Strait throughout the year, also noted in Section 5. From mid-July 1954 to late August, temperature and dissolved oxygen decreased, and salinity and density increased, at depths below 50 m.

In winter (February 1955), the waters on the western side of the Strait were slightly colder than those on the mainland side. The distributions for June 14 and 19 show the marked changes that can occur in the surface layer over a relatively short period (5 days).

H. Tidal and Residual Currents in Hecate Strait and Dixon Entrance.

Most of the available information on tidal and residual currents at depth resulted from the direct current observations made during the Hecate Project (1954-55). Observations were made at various levels from the surface to near-bottom at several locations in Queen Charlotte Sound, Hecate Strait and Dixon Entrance (Fig. 13) (Pacific Oceanographic Group 1955b,c). Observations at the surface were made with a current drag and at depth with an Ekman current meter. The current drag consisted of crossed metal vanes buoyed up with 4-inch glass balls. The dimensions of one face of the vane was 1 1/2 ft square (0.14 m^2). Observations were made hourly or half-hourly from an anchored vessel, generally over a 50-hour period. Some of the results for Queen Charlotte Sound and Dixon Entrance have been reviewed in an earlier section (p. 45,50). Included here is a very gross analysis of the data from 6 stations in Hecate Strait (Sta. 42-44; Sta. I-1 - I-3) and one station in Dixon Entrance (Sta. 65)(Fig. 13), at which observations were made over a 50-hour period. The data are presented as progressive vector diagrams to show the general features of the tidal and net flows. Representative wind vectors for wind speeds greater than 5 m/sec (10 kn) are included in the surface (0 m) and/or 10 m plots. Times of high and low water are also indicated, and are those predicted for Prince Rupert (Department of Mines and Technical Surveys 1954). Net speeds and directions for each depth are summarized in tabular form. Some of these results and diagrams originate from earlier analysis of these data by F. G. Barber and his associates.

Before discussing the tidal and current data, the results of experiments to determine the effect of the ship's roll upon the behavior of the Ekman current meter (Tabata and Groll 1956) are reviewed, since some of the measurements were made in "roll" conditions with such meters. Tests were made employing a pair of meters in the following experiments: (1) simultaneous measurements from a steady ship in a calm seaway; (2) simultaneous measurements from a rolling ship in a rough seaway; and (3) simultaneous measurements during an artificial ship's roll in which one instrument was given an oscillation simulating a motion caused by a ship's roll while the other was kept stationary. Direct underwater observations of the behavior of the instruments were made during the third experiment.

For a steady ship in a calm seaway, the current speeds recorded by the two instruments agreed to within 5% and the directions to within 4 degrees when the current speeds ranged from 5 to 45 cm/sec. In weaker currents (<5 cm/sec) the disagreement in directions was about twice as large.

During experiment (2), sea/swell conditions varied from 0/0 to 2/3 on the Beaufort scale, creating a ship's roll of up to 20°. During sea/swell less than 1/1 (Beaufort scale of 1 is equivalent to sea/swell heights of 0.25 to 0.75 m), the ship's roll was small; differences in recorded speeds were the same as those measured from a steady ship, whereas differences in direction were about twice as great, 10° compared to 4°. However, when a sea/swell of 1/2 or 2/1 (2 is equivalent to heights of 0.75 to 1.25 m) was reached, accompanied by an increase in the ship's roll, the disagreements in speed doubled from 5 to 10%, while those in direction remained unchanged. Tabata and Groll considered that recorded speeds were trustworthy only when sea/swell conditions are $\leq$1/1, and too high when they are >1/1. Directions appear reliable (within $\overline{10}$°) to sea/swell as large as 2/3 (3 is equivalent to heights of 1.25 to 1.75 m).

The third test was conducted to determine the effect of a 10 to 15° artificial roll of the ship on the meter readings. When the current speeds ranged from 20 to 30 cm/sec (recorded by the stationary instrument), the oscillating instrument recorded speeds that were greater than 1.5 times those of the stationary one. However, the mean difference in direction only amounted to 4°. When currents were less than 10cm/sec, the recorded speed of the oscillating instrument was again much larger, and there was a wide variation in direction. The authors note that "the method used here in creating the motion caused by an artificial roll may not be an accurate reproduction of the ship's roll in the sea where irregular rolling occurs, but it is assumed that it can be used to first approximation."

With due consideration of the conclusions from these experiments with respect to the wind and sea/swell conditions prevailing at the time of the observations and also of runoff conditions, results from the Hecate Project are considered to reflect the general characteristics of the tidal and net flows, in particular those in the deeper waters below 10 m depth, in these areas.

1. Tidal and Residual Currents in Hecate Strait.

Direct current observations were made at Sta. 42-44 across central Hecate Strait during May 19-25, 1954 and at Sta. I-1 - I-3 across southern Hecate Strait during August 30-September 6,1954. The "finer structure" of the currents is described first, followed by a short discussion of the net motions involved. The data for each section are presented in numerical sequence of stations (i.e., 42, 43, and 44; I-1, I-2, and I-3). However, it should be noted that this is the reverse of the chronological order in which the stations were occupied.

At Sta. 42 (depth 182 m, 100 fm), located on the mainland side of Hecate Strait, observations were made hourly at 0 and 10 m by current drag, and at 20, 30, 50, 100 and 150 m depth by Ekman current meter during May 23-25, 1954. During the period of these observations, winds were southerly, generally varying in strength from light airs to 3 m/sec (6 kn) - except for a brief period during the latter part of the experiment, at which time wind speeds of 6 m/sec (12 kn) were recorded. Progressive vector diagrams for the currents at 10, 20, 30, 50, 100 and 150 m depth are presented in Fig. 142-147. The currents at 0 are not presented as they were similar in both direction and speed to those at 10 m. Wind vectors are indicated by the dashed lines and arrows in Fig. 142.

The currents tended to rotate with a semi-diurnal tidal period (Fig. 142-147). The rotation was most marked at 20 and 30 m. At 100 m, the changes in direction of the currents were such that a "saw-toothed" configuration was the significant feature. At the shallower depths, 0-50 m, the rotation if present was generally clockwise, but at 100 and 150 m, it was predominantly counter-clockwise. These results are consistent with those of MacKay (1954), who also reported a counter-clockwise rotation at 100 m depth, opposite to that at shallower depths, as previously noted for northern Hecate Strait (p. 46).

Speeds were generally a maximum during the mid-tide stage and a minimum during the turn of the tide (reference station, Prince Rupert). Maximum speeds of 40 to 50 cm/sec (0.8 to 1 kn) were recorded at all depths except 10 m, but the observations were few - only 1 to 3 at each depth. An analysis of the percentage frequency of observations within 10 cm/sec increments (0-9, 10-19 cm/sec, etc.) showed that, at all depths sampled the dominant speeds were 10-29 cm/sec (0.2-0.6 kn) - for about 60 to 70% of the observations (reported here to the nearest multiple of 5%).

At Sta. 43 (depth 60 m, 33 fm), located in mid-strait, observations were also made approximately hourly at 0 and 10 m (current drag), and half-hourly at 10, 20, 30 and 50 m depth (Ekman current meter) during May 21-23, 1954. At the time of these observations, relatively strong southeast winds prevailed, varying in strength between 5 and 11 m/sec

(10 and 22 kn). During the latter part of the observational period, the state of the sea caused the vessel to roll quite heavily. Progressive vector diagrams are presented for all depths (Fig. 148-152).

At each depth the currents exhibited a very marked clockwise rotation with a semi-diurnal tidal period (Fig. 149-152). Speeds were generally at a maximum (40-60 cm/sec) (0.8-1.2 kn) during the mid-tide stage, and at a minimum during the turn of the tide. Generally, the stronger tidal currents occurred more frequently during the ebb than during the flood tide. For example, at 20 m the percentage frequency of currents between 45 and 60 cm/sec was about 25% during the ebb tides, but only about 15% during the flood tides (approximately 50 observations at 1/2 hourly intervals on the flood and on the ebb stages. At 30 m, the frequency of currents of these magnitudes was 25% for the ebb and 5% for the flood. The dominant speeds - those characterizing between 50 and 70% of the observations - were found to be between 20 and 39 cm/sec (0.4 and 0.8 kn).

At Sta. 44 (depth 33 m, 11 fm), located on the western side of the Strait, observations were also made half-hourly at 10 and 17 m with an Ekman current meter (observations made at 0, 5 and 10 m with a current drag are not presented as generally they were not taken regularly. Relatively strong winds prevailed during the first 8 hours of the observations (May 19-21, 1954). Thereafter, winds were relatively weak - generally less than 4.6 m/sec (9 kn) - with occasional periods of light airs.

Tidal currents at 10 and 17 m were very similar (Fig. 153-154). The rotary nature of the currents noted at the other stations was entirely absent at all depths sampled. Instead, the currents parallelled the coast, reversing direction with each change of the tide. Maximum tidal currents were again observed during mid-tide, and were generally between 40 and 60 cm/sec (0.8 and 1.2 kn). The dominant speeds were between 20 and 49 cm/sec (0.4 and 1 kn) - 60 and 70% of the observations at 10 and 17 m, respectively.

A summary of net speeds and directions over the 50-hr period of observations at the 3 stations is presented in Table 5. At Sta. 42, net speeds were similar, 3-5 cm/sec (0.08-0.1 kn), at all depths except at 50 m, at which the net velocity was about 3-5 times as large as those at the other depths. These are equivalent respectively, to net excursions of 2.7 to 4.5 km and 12.6 km over a tidal day. From 0 to 50 m net flows were southerly, but at 100 and 150 m were westerly and northwesterly, respectively.

At Sta. 43, net flows were northerly at 0 and 10 m, but the net speed at 0 m was twice that at 10 m. This difference may be attributed to wind, enhancing the flow at the surface to a greater degree than that at 10 m depth. At 20, 30 and 50 m, the net flows were southerly, 4-5 cm/sec (0.08-0.1 kn), equivalent to daily net excursions of about 3.5-4.5 km.

At Sta. 44, net flows at 10 and 17 m were southerly, but the speeds were relatively small (<1 to 2 cm/sec) (<0.02 to 0.04 kn), resulting in small net excursions over a tidal day.

Table 5. Summary of net speeds and directions of currents in Hecate Strait, May 19-25, 1954.

	Station 42		Station 43		Station 44	
Depth (m)	Speed cm/sec	Dir. (°T)	Speed cm/sec	Dir. (°T)	Speed cm/sec	Dir. (°T)
0	4	150	8	345	-	-
10	4	150	4	030	2	105
17	-	-	-	-	<1	220
20	5	190	4	225	-	-
30	5	175	4	205	-	-
50	14	180	5	195	-	-
100	5	270	-	-	-	-
150	3	325	-	-	-	-

(Speeds are reported to nearest whole number of cm/sec and directions to nearest multiple of 5°.)

At Sta. I-1 (depth 88 m, 48 fm), located on the southwest side of Hecate Strait, observations were made hourly at 10, 20, 30, 50 and 75 m (Ekman current meter) and half-hourly at 0 m (current drag) during September 4-6, 1954. Light airs prevailed for the first 9 hours of these observations. Thereafter, relatively strong southerly winds prevailed, ranging from 7 to 13 m/sec (14 to 24 kn). Progressive vector diagrams are presented for all depths (Fig. 155-160).

The tidal currents showed some rotation at all depths (Fig. 155-160). However, no rotation was observed at 0 and 10 m subsequent to the development of strong southerly winds (Fig. 155-156). The rotation was generally clockwise at depths of 0 to 50 m. At 75 m, the rotation was counter-clockwise. Maximum speeds were generally between 30 and 50 cm/sec (0.6 and 1 kn) at depths of 0 to 30 m. However, during the period of strong southerly winds, current speeds of 70 to 100 cm/sec (1.4 to 2 kn) were observed at 0 m. At depths of 50 and 75 m, maximum speeds were 30-40 cm/sec (0.6-0.8 kn). The dominant speeds were 10-39 cm/sec (0.2-0.8 kn) at 10, 20 and 30 cm - for about 80% of the observations - and 10-29 cm/sec (0.2-0.6 kn) at 50 and 75 m - for about 75% of the observations.

At Sta. I-2 (depth 137 m, 75 fm), located in mid-strait, observations were made hourly at 10, 20, 30 (period of observations was only 32 hours) 50, and 100 m (Ekman current meter) and half-hourly at 0 m (current drag) during September 2-4, 1954. Winds were northerly, but generally less than 6 m/sec (12 kn), except for a 12-hour interval during the mid-period of the observations, at which time they varied between 7 and 9 m/sec (14 and 19 kn). Progressive vector diagrams are presented for 0, 10, 20, 50 and 100 m (Fig. 161-165).

Currents were similar at 0, 10 and 20 m (Fig. 161-163). There was little rotation at these depths, in sharp contrast to the marked rotation observed at these depths at Sta. 43 (Fig. 148-150), also located in mid-strait. At 50 m, currents rotated (clockwise) to some degree (Fig. 164). At 100 m, the rotation was predominantly counter-clockwise (Fig. 165). From 0 to 20 m depth, maximum speeds of about 40-60 cm/sec (0.8-1.2 kn) were observed. Generally speeds decreased with depth, with maximum speeds between 30 and 50 cm/sec (0.6 and 1.0 kn) at 50 m, and generally between 20 and 30 cm/sec (0.4 and 0.6 kn) at 100 m depth. The dominant speeds at 0 and 10 m were 10-39 cm/sec (0.2-0.8 kn) - (60 and 75%, respectively), 10-29 cm/sec (0.2-0.6 kn) at 20 m (50%), 20-29 cm/sec (0.4-0.6 kn) at 50 m (50%) and 10-19 cm/sec (0.2-0.4 kn) at 100 m depth (for 65% of the observations).

At Sta. I-3 (depth 234 m, 128 fm), located on the eastern side of the Strait, observations were made hourly at 10, 20, 50, 100 and 200 m (Ekman current meter) and half-hourly at 0 m (current drag) during August 30-September 1, 1954. Winds were southeasterly for the greater part of the experiment, changing from light airs to northwesterly during the latter part of the period. However, the winds at all times were relatively weak, less than 5 m/sec (10 kn). Progressive vector diagrams are shown for all depths (Fig. 166-171).

Similar characteristics to those noted at the other stations were generally observed. There is evidence of intervals counter-clockwise rotation at 100 m depth, in contrast to the slight clockwise rotation indicated at the other depths. Maximum velocities were relatively large, at 0 and 10 m, 50-70 cm/sec (1.0-1.4 kn); at 20 m, 40-60 cm/sec (0.8-1.2 kn); and at 50-200 m depth, 30-40 cm/sec (0.6-0.8 kn). However, the dominant velocities were 20-49 cm/sec (0.4-1 kn) at 0 m (65%), 20-39 cm/sec (0.4-0.8 kn) at 10 m (65%), 20-39 cm/sec (0.2-0.8 kn) at 20 m (55%); and 10-29 cm/sec (0.2-0.6 kn) at 50, 100 and 200 m depth (for about 80% of the observations).

The net speeds and directions are summarized in Table 6. At Sta. I-1, the net flows were northerly, with speeds generally decreasing with depth. Net excursions over a tidal day ranged from 27 km at 0 m to about 6.5 km at 75 m depth.

At Sta. I-2, the net flows were southeasterly from 0 to 50 m, opposite in direction to those at Sta. I-1, and westerly at 100 m depth. Net excursions over a tidal day were relatively great at depths of 0 to 30 m, averaging about 20 km. At 50 and 100 m, the net daily excursion was only about 8 km.

At Sta. I-3, the net flows were northeasterly and relatively strong at 0 and 20 m. At 100 and 200 m, net flows were considerably less than those at 0 to 20 m, and were southeasterly. Net excursions were generally similar to those at other stations at corresponding depths.

Table 6. Summary of net speeds and directions of currents in Hecate Strait, August 31 - September 3, 1954.

	Sta. I-1		Sta. I-2		Sta. I-3	
Depth (m)	Speed cm/sec	Dir. (°T)	Speed cm/sec	Dir. (°T)	Speed cm/sec	Dir. (°T)
0	30	350	24	150	27	040
10	20	020	23	140	31	045
20	12	000	24	135	22	050
30	9	000	22	145	-	-
50	10	030	8	155	10	060
75	7	315	-	-	-	-
100	-	-	9	260	9	135
200	-	-	-	-	6	120

(Speeds are reported to the nearest whole number of cm/sec and directions to the nearest multiple of 5 degrees.)

2. Tidal and residual currents in Dixon Entrance.

Current observations were made hourly in south central Dixon Entrance - Sta. 65 (depth 84 m, 44 fm) at 0 m (current drag) and at 10, 30, 50, and 75 m (Ekman current meter) during July 17-19, 1954. During this period, southerly winds prevailed, varying in strength from light airs to speeds of about 5 to 8 m/sec (10 to 15 kn). Progressive vector diagrams for each of the depths are presented in Fig. 172-177.

The rotation of the currents was most marked at depths of 20 to 75 m. At depths of 0 to 20 m it was either clockwise or counter-clockwise (Fig. 172-174), but at depths of 30 to 75 m predominantly clockwise (Fig. 175-177), with a semi-diurnal tidal period. At and near mid-tide stage, the prevailing direction of flow was generally east-west, parallelling the northern coast of Graham Island; notable exceptions were the northerly ebb flows at 0 and 10 m depth during a period when strong southerly winds prevailed. Apparently the wind-induced northerly flow was sufficiently strong to suppress the tidally-induced flow. However, the southerly winds appeared to have little effect on the direction of the flood flow at these depths. Also, at depths below 10 m, the winds appeared to have little or no effect on the directions of either the flood or ebb tidal currents. Maximum speeds ranged from about 50 to 65 m/sec (0.8 to 1.3 kn) at all depths, and they generally occurred during the mid-range of the flood and the ebb tides. The dominant speeds were 10-29 cm/sec (0.2-0.6 kn) at 0 (70%) 10 (65%), 20 (65%) and 30 m (55%); 20-39 cm/sec (0.4-0.8 kn) at 50 m (80%) and 30-49 cm/sec (0.6-1 kn) at 75 m depth (for 60% of the observations).

Net speeds varied from 4 to 12 cm/sec, while directions varied from northeasterly (0 m), to easterly (10 m), to southeasterly (20-75 m) (Table 7). At the surface and 10 m, net flows averaged 11 cm/sec. Between 20 and 75 m, they averaged about 6 cm/sec (0.12 kn), equivalent to a net excursion of about 5.5 km over a tidal day.

Table 7. Summary of net speeds and directions at Sta. 65 in Dixon Entrance, July 17-19, 1954.

Depth (m)	Net speeds (cm/sec)	Direction (°T)
0	10	045
10	12	090
20	6	105
30	8	145
50	4	135
75	6	135

(Speeds are reported to nearest whole number of cm/sec and directions to nearest multiple of 5°.)

3. Summary of tidal and residual currents

Based upon the above-discussed results, as well as some obtained earlier, general statements on the tidal and residual currents in the region can be made. The currents tended to be rotary with a semi-diurnal tidal period. There were differences in the degree of rotation, with the most distinct rotation generally occurring at stations furthest from shore. At stations nearest to shore, little or no rotation was found; the dominant directions were parallel to the coast. The rotation was clockwise from the surface to 75 m depth, except at Sta. I-1, where the rotation was predominantly anti-clockwise at 75 m depth. At depths of 100 and 150 m, the rotation was predominantly anti-clockwise, while at 200 m the rotation was again clockwise.

Maximum tidal currents varied with position, but were of the order of 40-60 cm/sec (0.8-1.2 kn), generally decreasing with depth. Maximum flows generally occurred during the mid-range of the tide, and minimal flows occurred close to, or at, the times of high and low water. There appeared to be a variation in current speed and direction associated with the diurnal inequality of the tidal amplitudes. The greater current and more evident rotation occurred between higher high water and lower low water.

Calculated net movements indicate net flows of about 5 to 25 cm/sec (0.1 to 0.5 kn). The largest such motions were generally observed in the surface waters, although at some positions they were greatest at intermediate and near-bottom depths. The near-surface net flows appear to be related both to wind and to the discharge of fresh water from runoff, and thus it is to be expected that they would vary seasonally.

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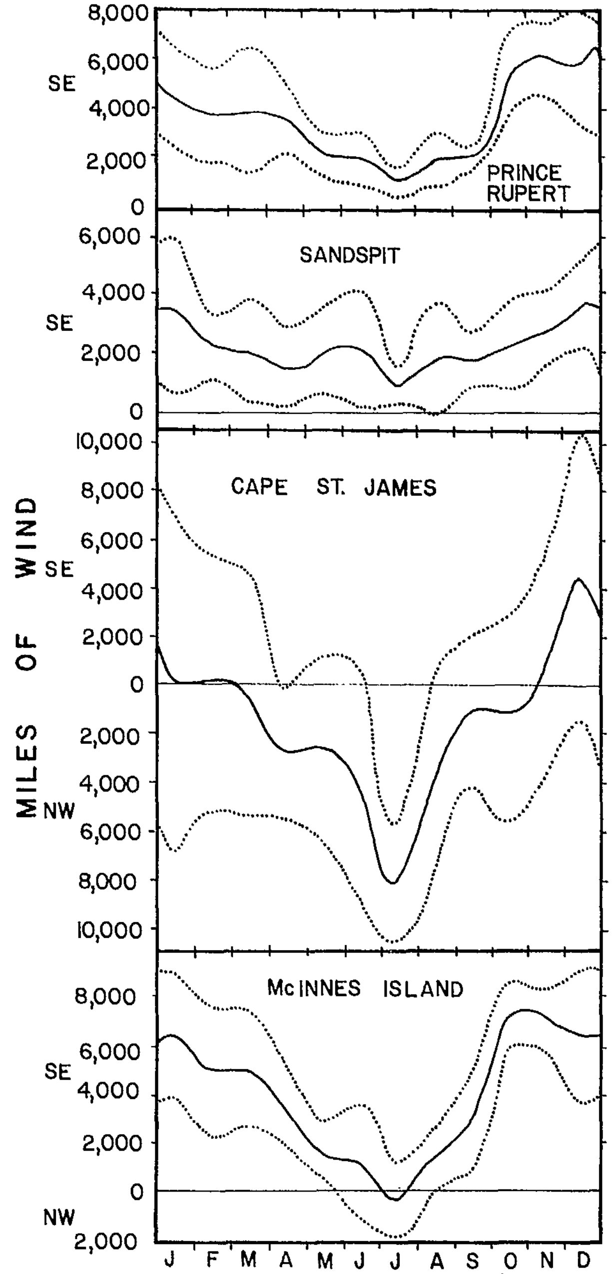


FIG. 43. Grand means and standard deviations of monthly total miles of wind resolved along the southeast axis at Prince Rupert, 1954 through 1962, Sandspit, 1955 through 1964, McInnes Island, 1955 through 1963, and Cape St. James, 1955 through 1963. (Crean 1967)

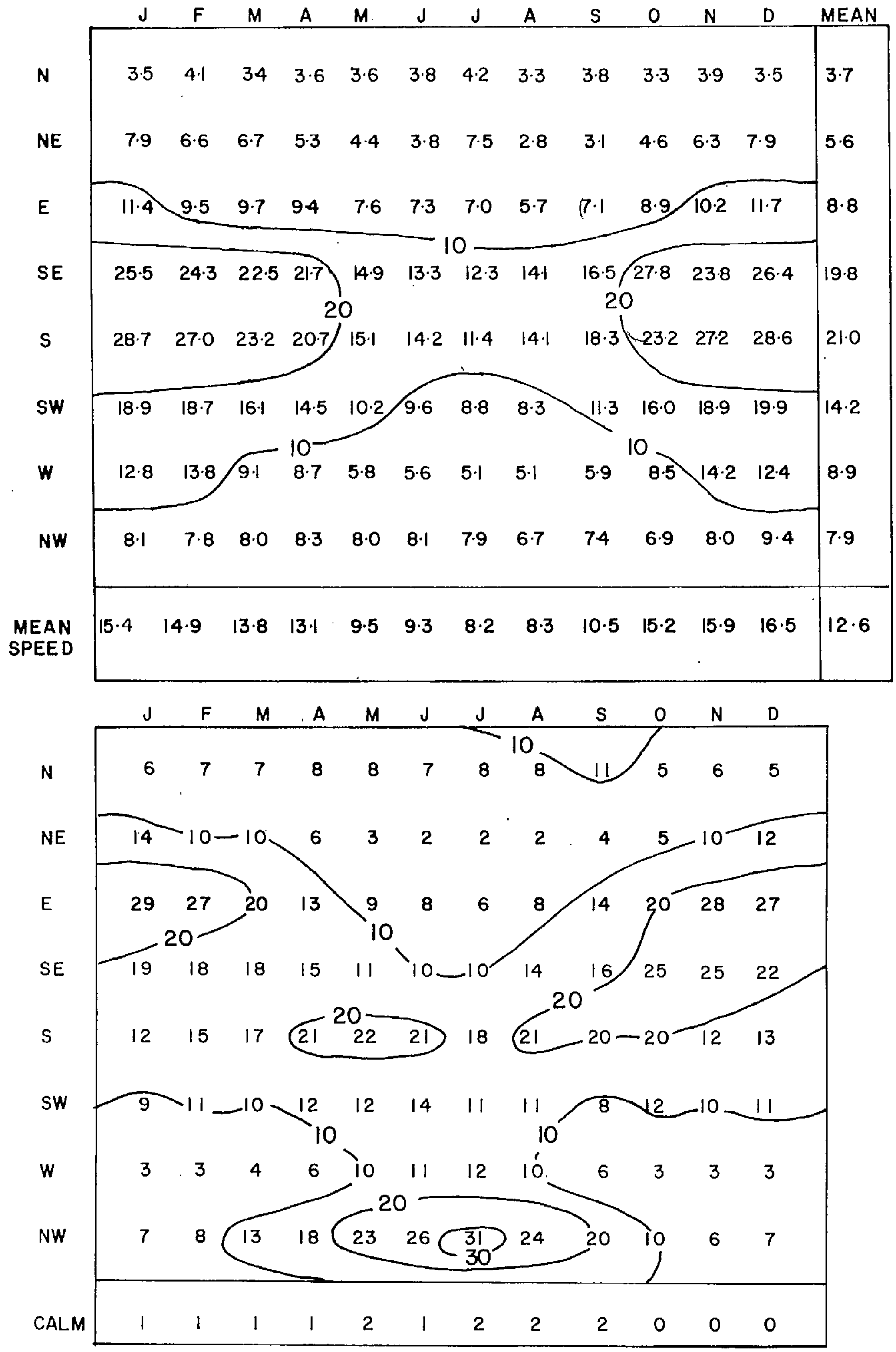


Fig. 44. Long-term monthly means (1955-72) of wind speed (mi/hr) (upper plate) and of percentage frequency (lower plate) along 8 points of the compass, McInnes Island.

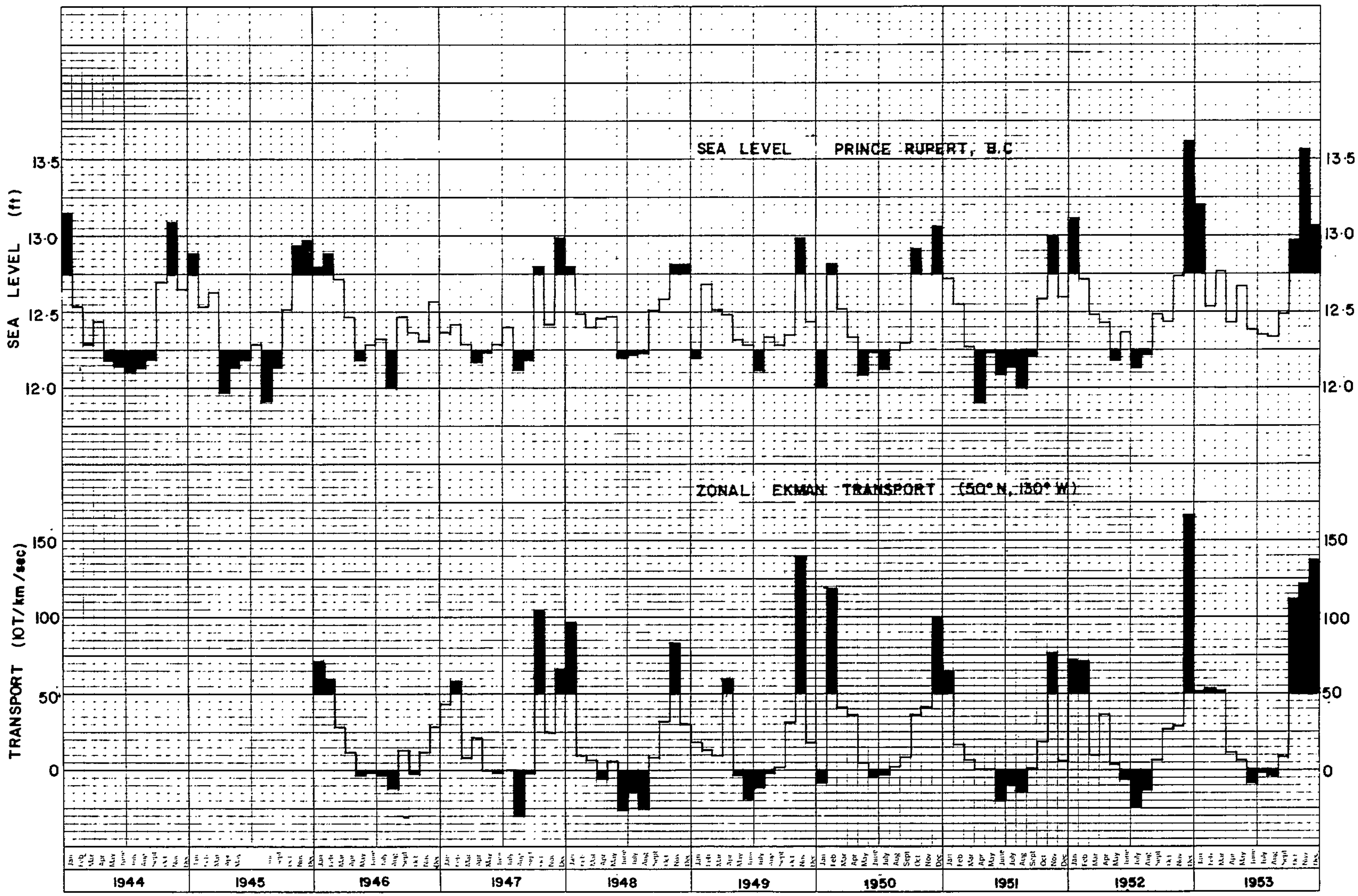


Fig. 45. Monthly mean sea level at Prince Rupert, B.C., 1944-73 and monthly mean zonal Ekman transport at 50°N, 130°W, 1946-73.

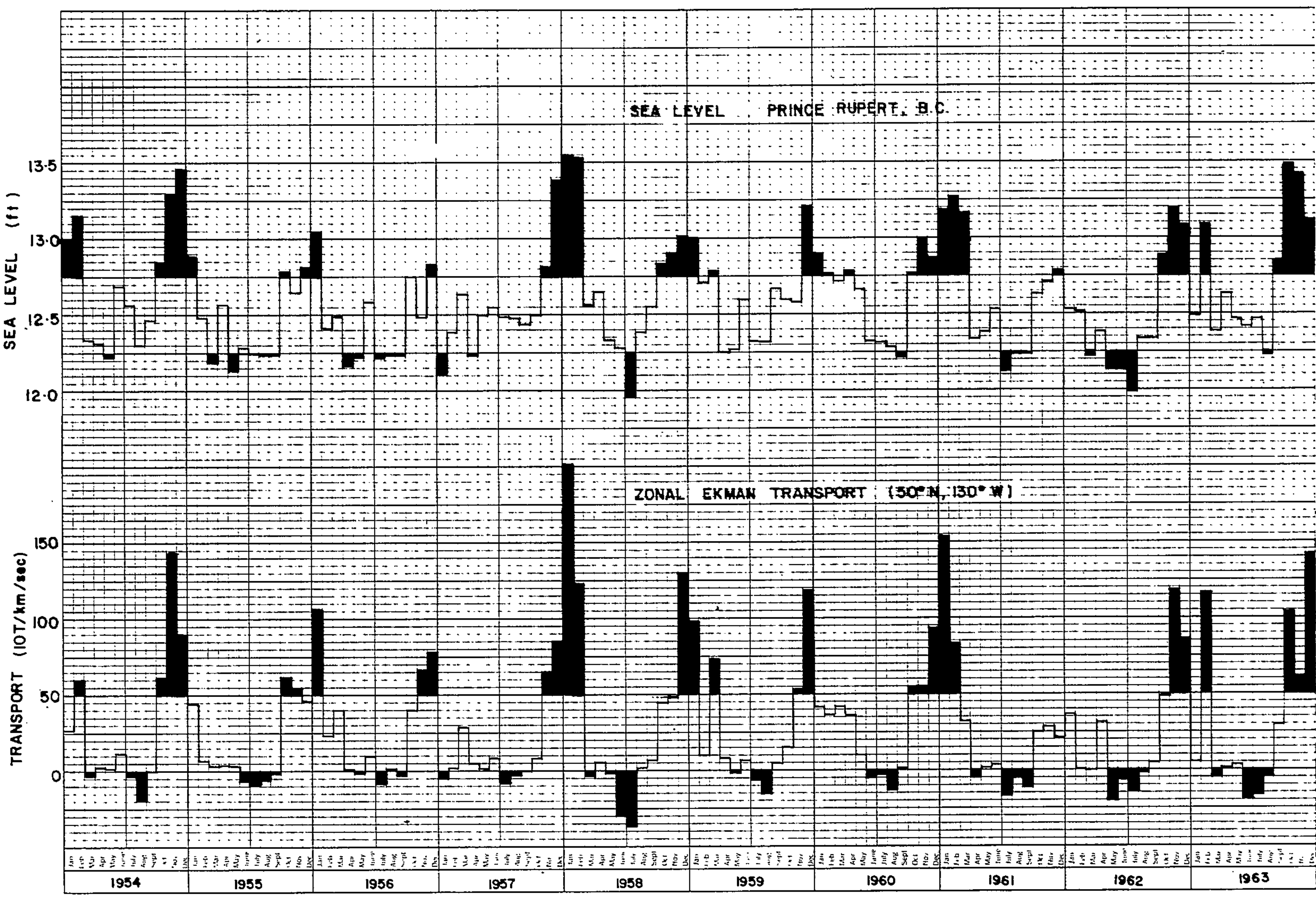
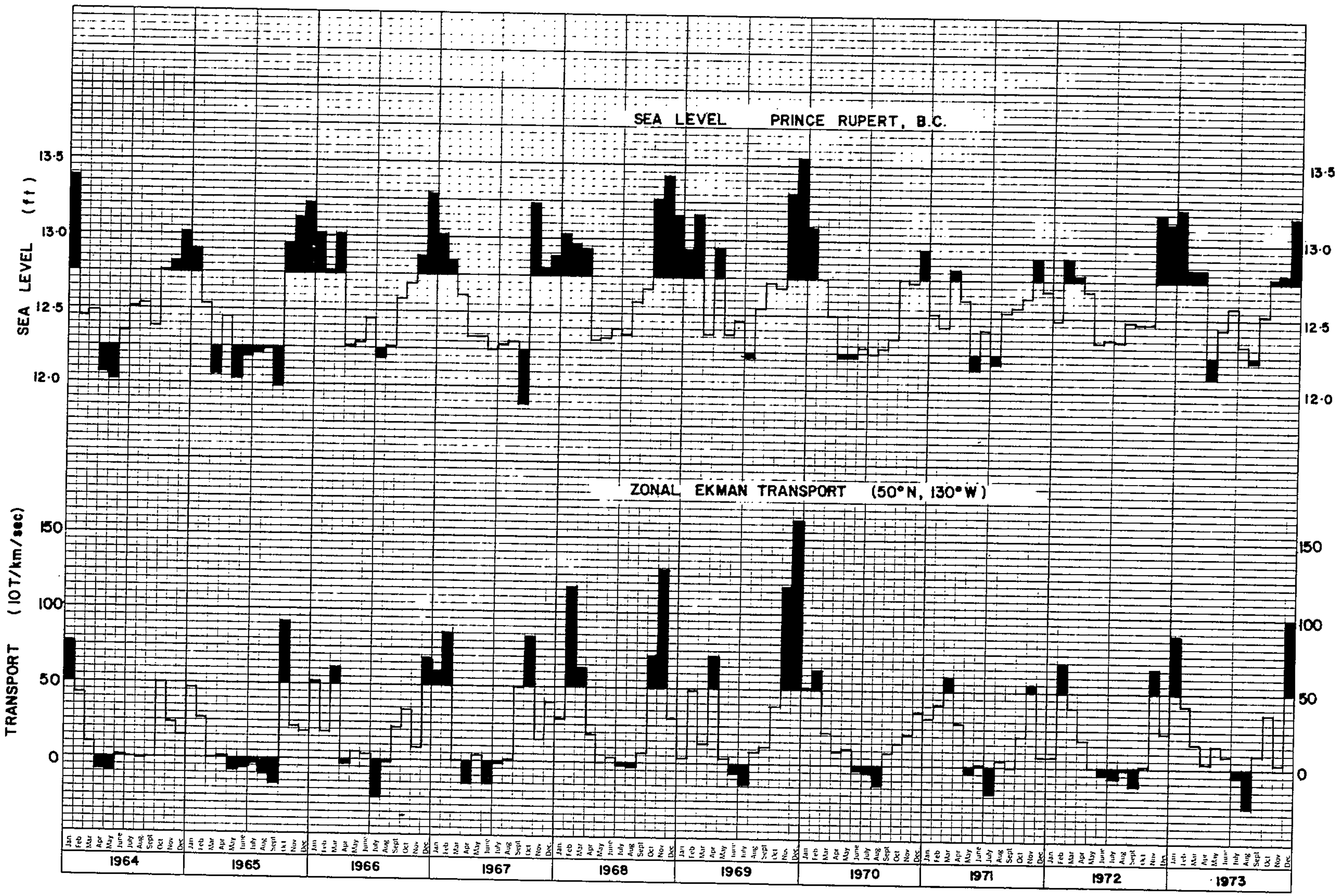

SEA LEVEL PRINCE RUPERT, B.C.
SEA LEVEL (ft)
13·5
13·0
12·5
12·0
ZONAL EKMAN TRANSPORT (50°N, 130°W)
TRANSPORT (10T/km/sec)
150
100
50
0
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963

Fig. 45 (cont'd).



SEA LEVEL PRINCE RUPERT, B.C.
SEA LEVEL (ft)
13·5
13·0
12·5
12·0
ZONAL EKMAN TRANSPORT (50°N, 130°W)
TRANSPORT (10T/km/sec)
150
100
50
0
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973

Fig. 45 (cont'd).

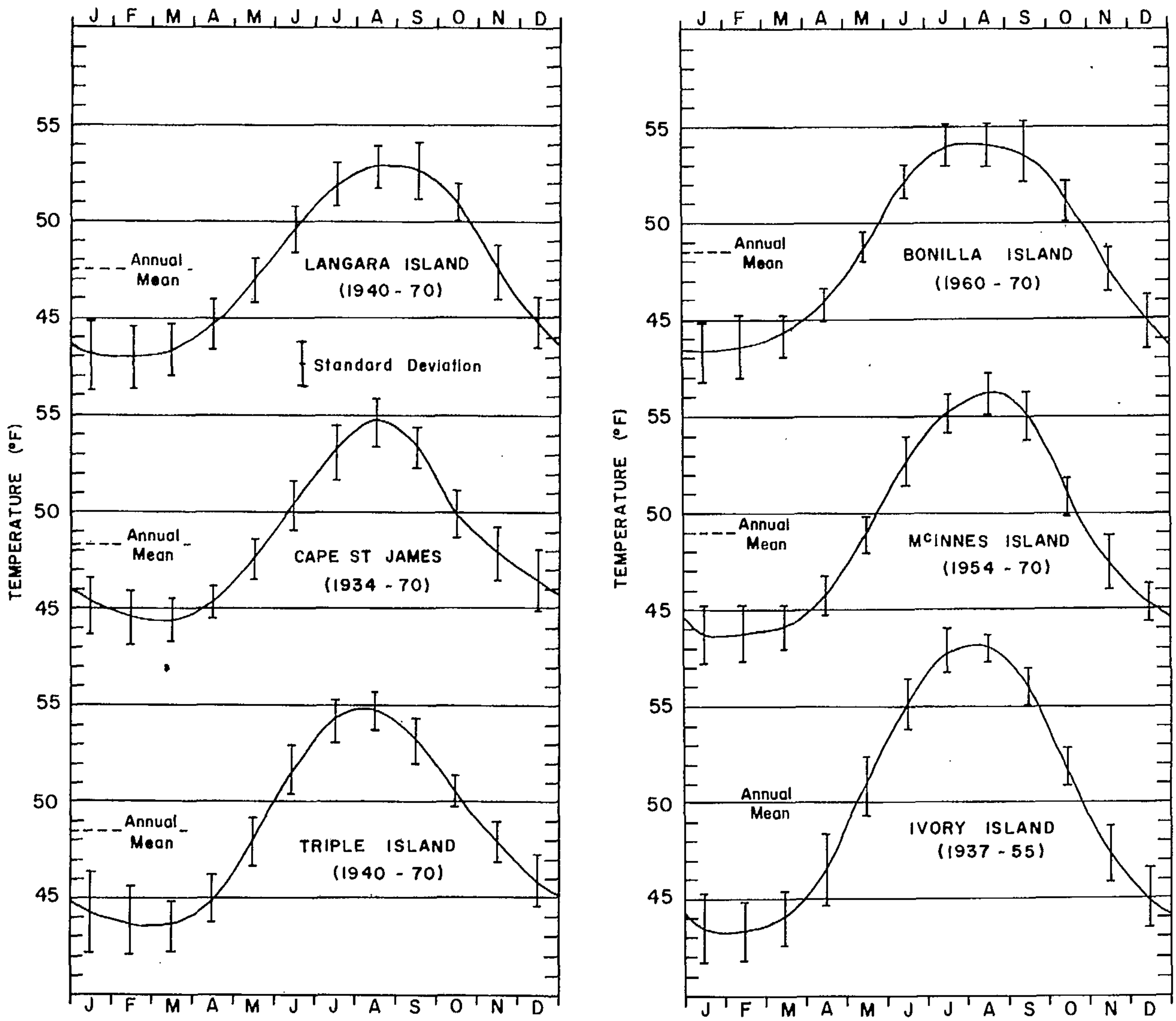


Fig. 46. Long-term monthly means and standard deviations of sea surface temperature at 6 lightstations located in the Queen Charlotte Sound - Hecate Strait - Dixon Entrance region.

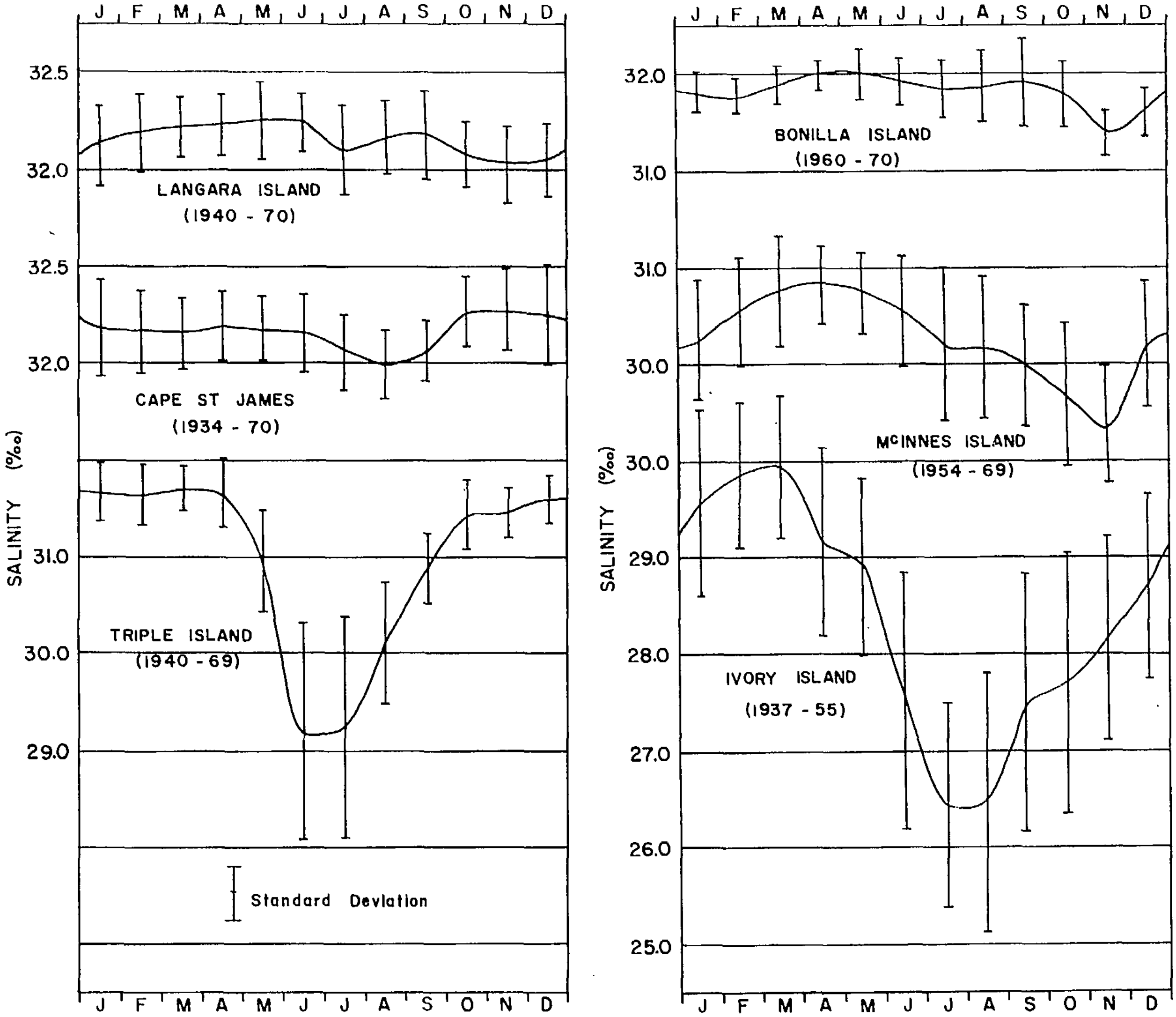


Fig. 47. Long-term monthly means and standard deviations of surface salinity at 6 lightstations located in the Queen Charlotte Sound - Hecate Strait - Dixon Entrance region.

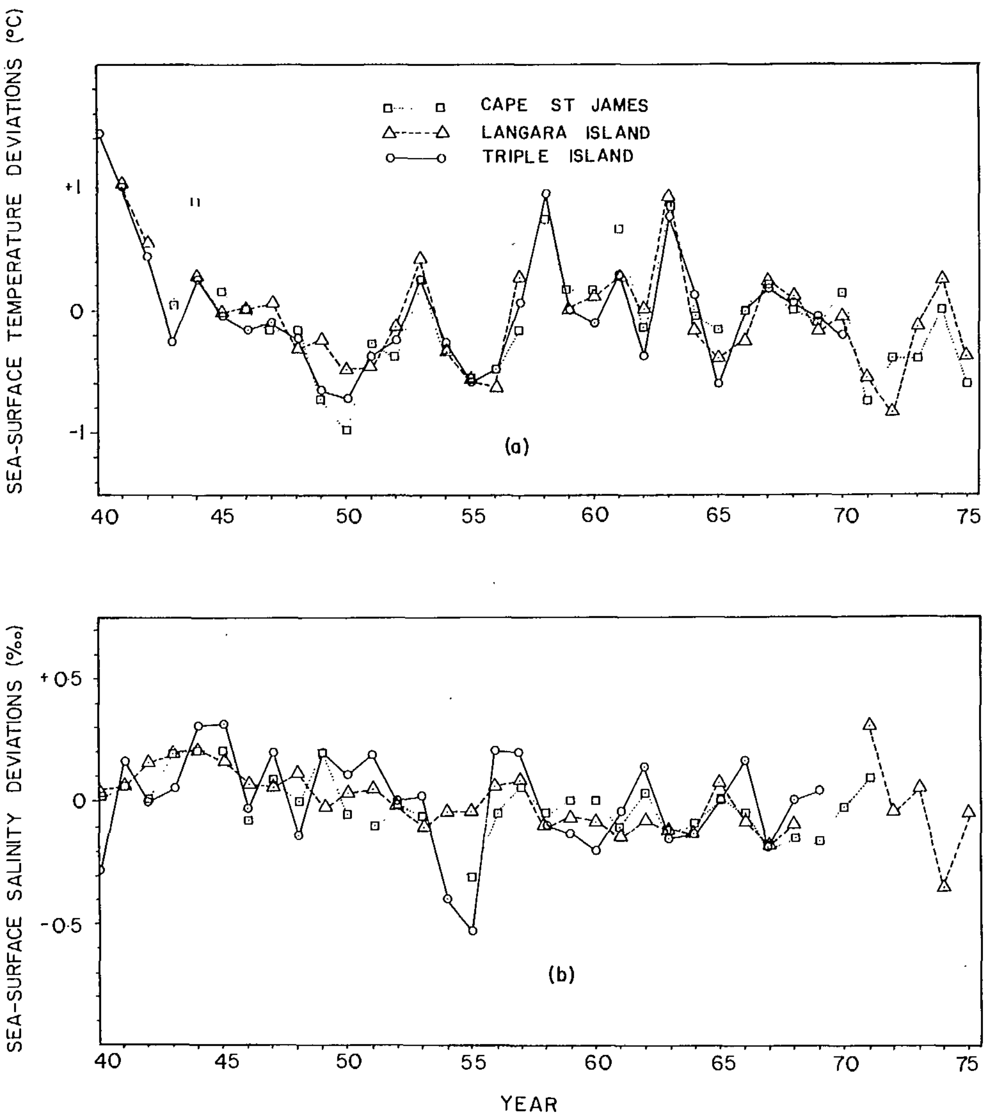


Fig. 48. Deviations of annual means from long-term annual means of (a) sea surface temperature, and (b) surface salinity at C. St. James, Langara Is. and Triple Is., 1946-75.

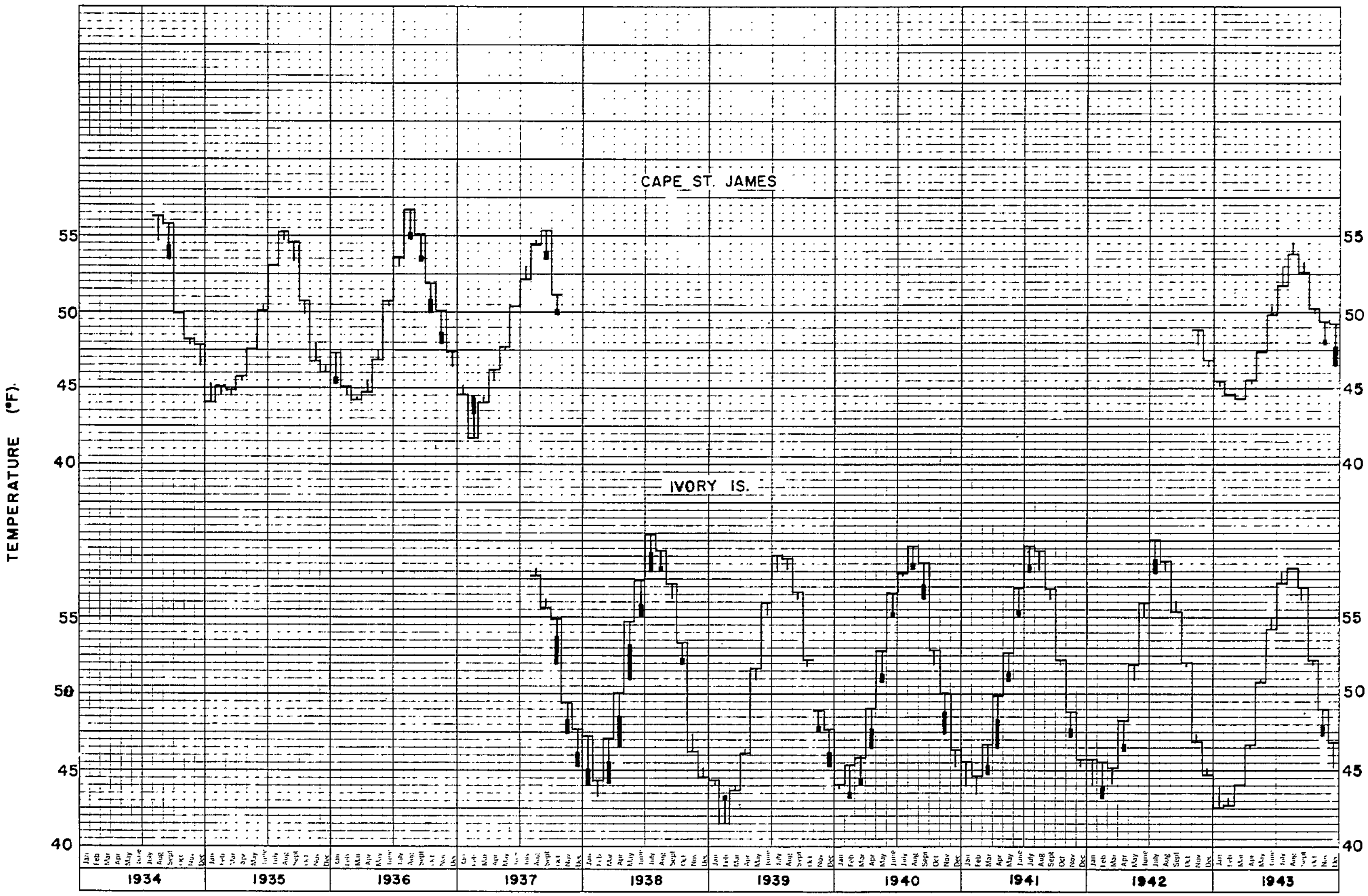


Fig. 49. Monthly mean sea surface temperature and difference from long-term monthly mean at Cape St. James and Ivory Is., 1934-73 (heavy bar indicates a difference greater than one standard deviation).

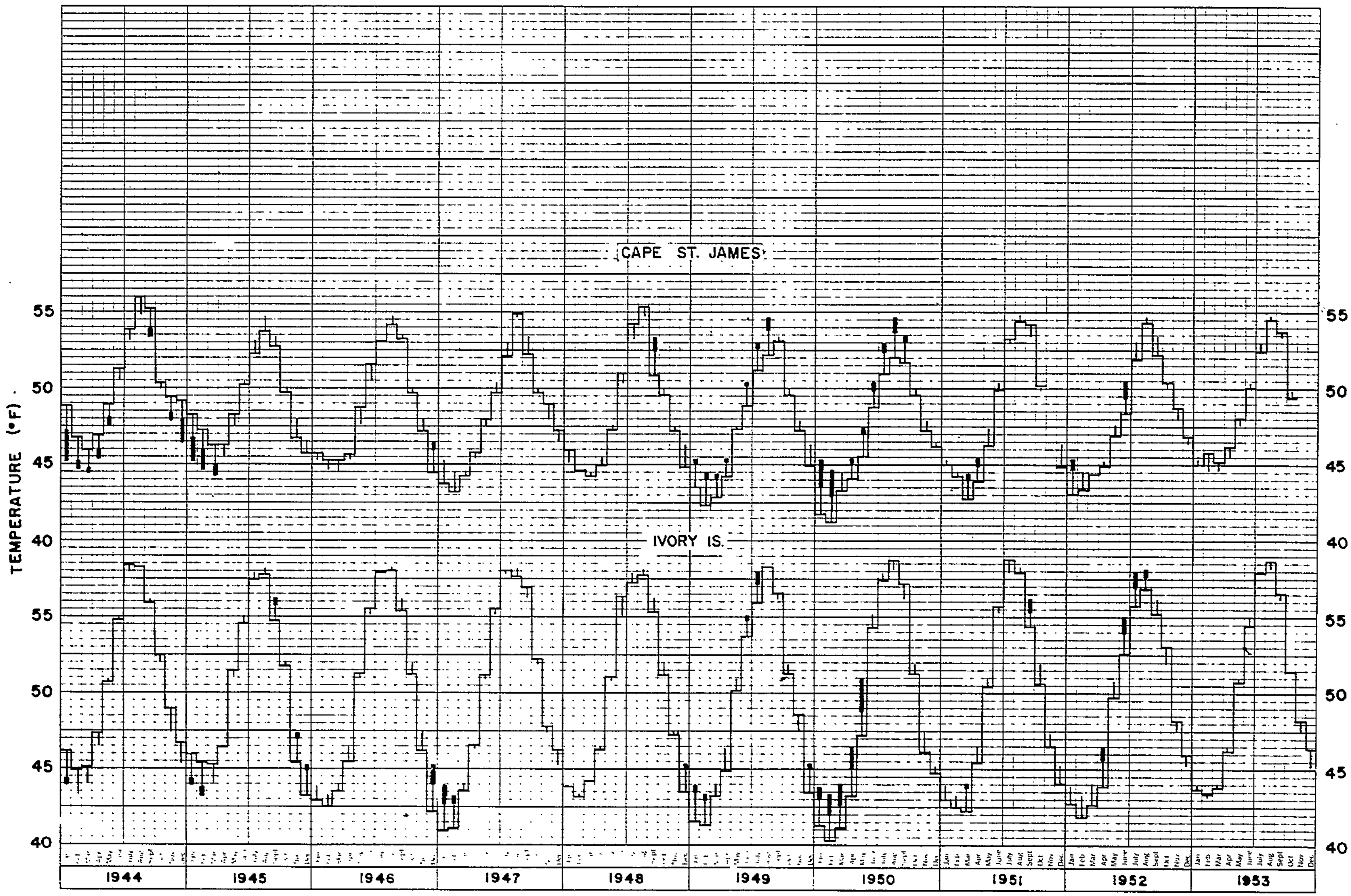

CAPE ST. JAMES
IVORY IS.
TEMPERATURE (°F)
55
50
45
40
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953

Fig. 49 (cont'd).

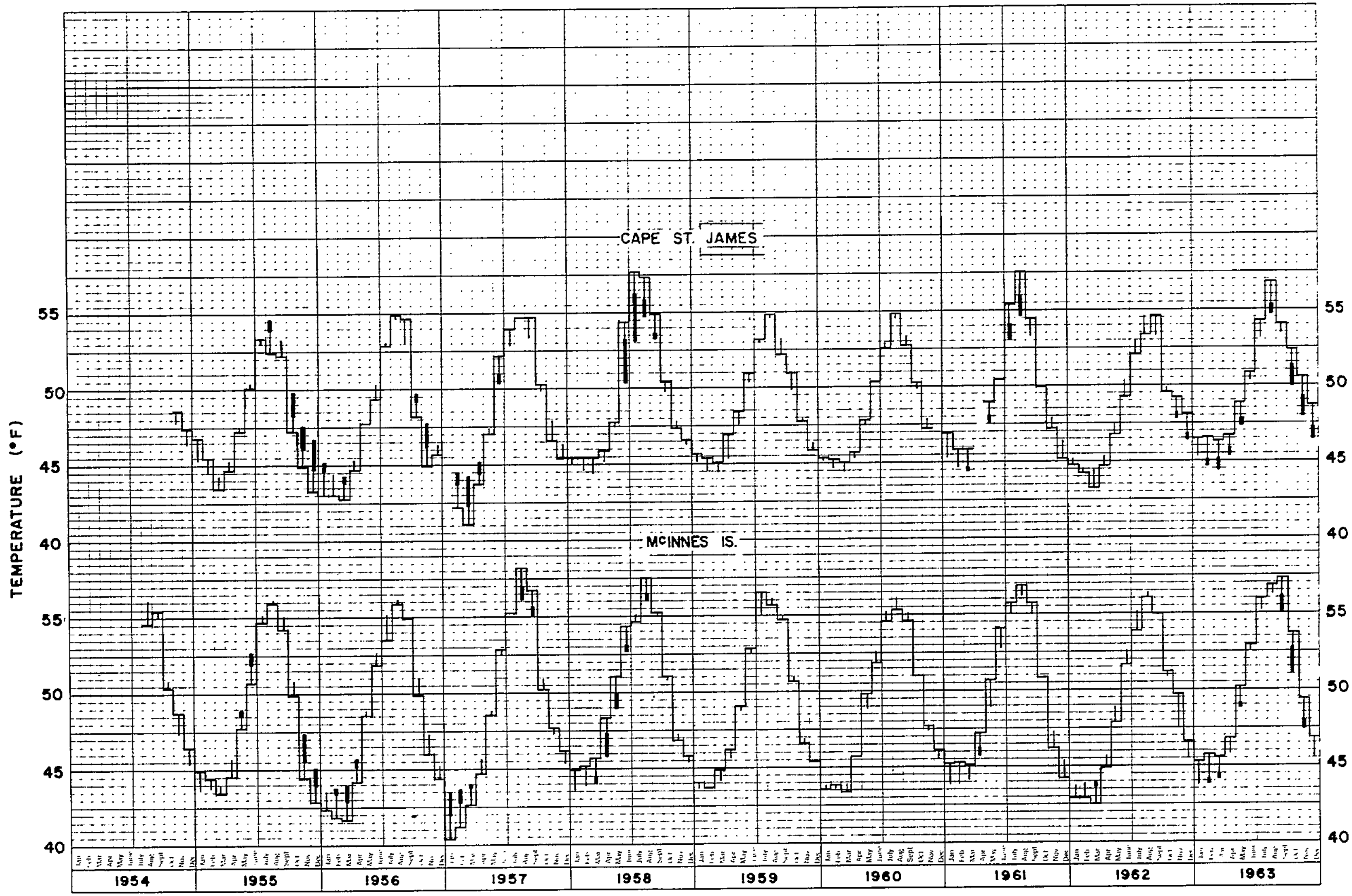


Fig. 49 (cont'd) (McInnes Is. replacing Ivory Is.).

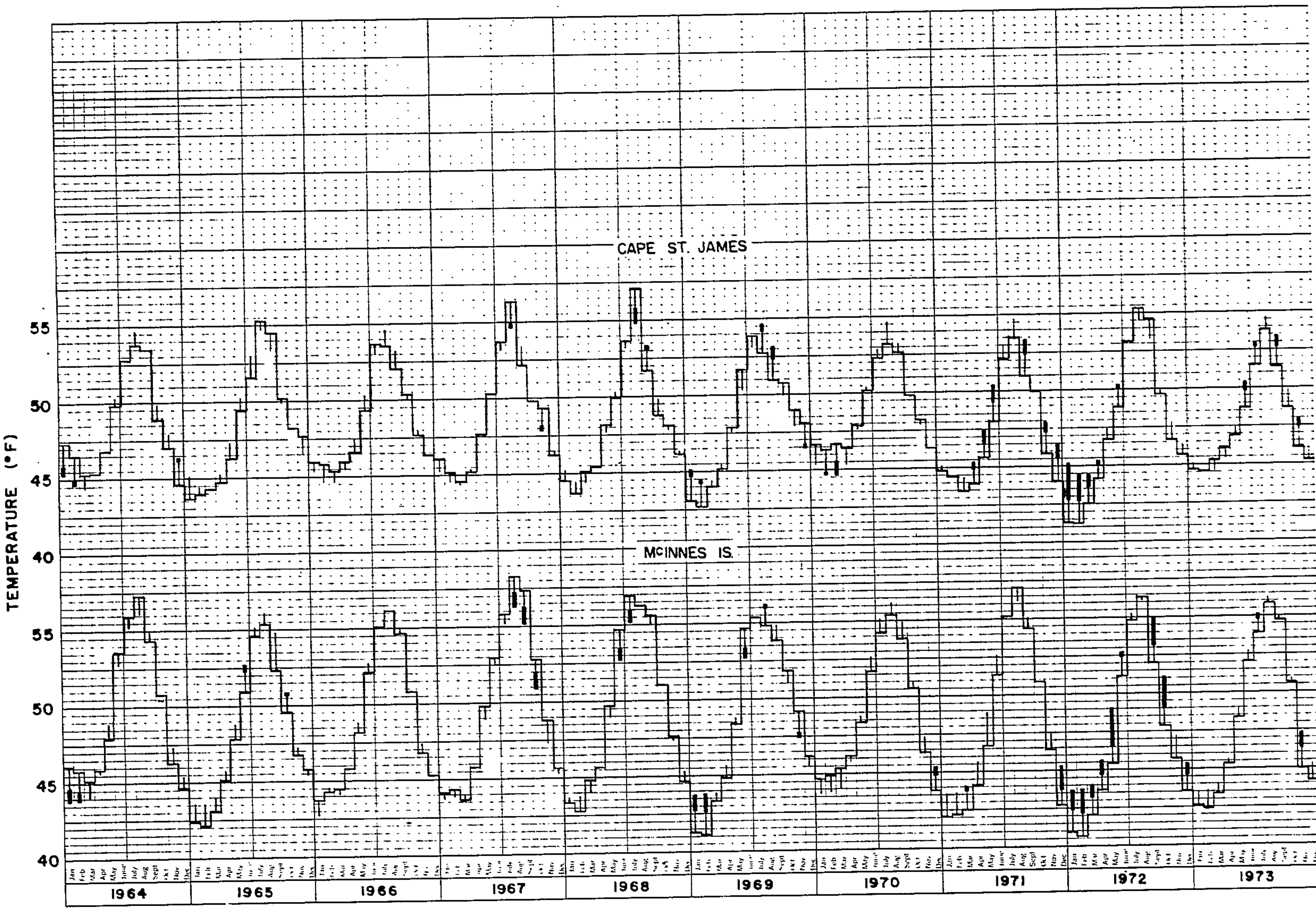

CAPE ST. JAMES
McINNES IS.
TEMPERATURE (°F)
55
50
45
40
55
50
45
40
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973

Fig. 49 (cont'd).

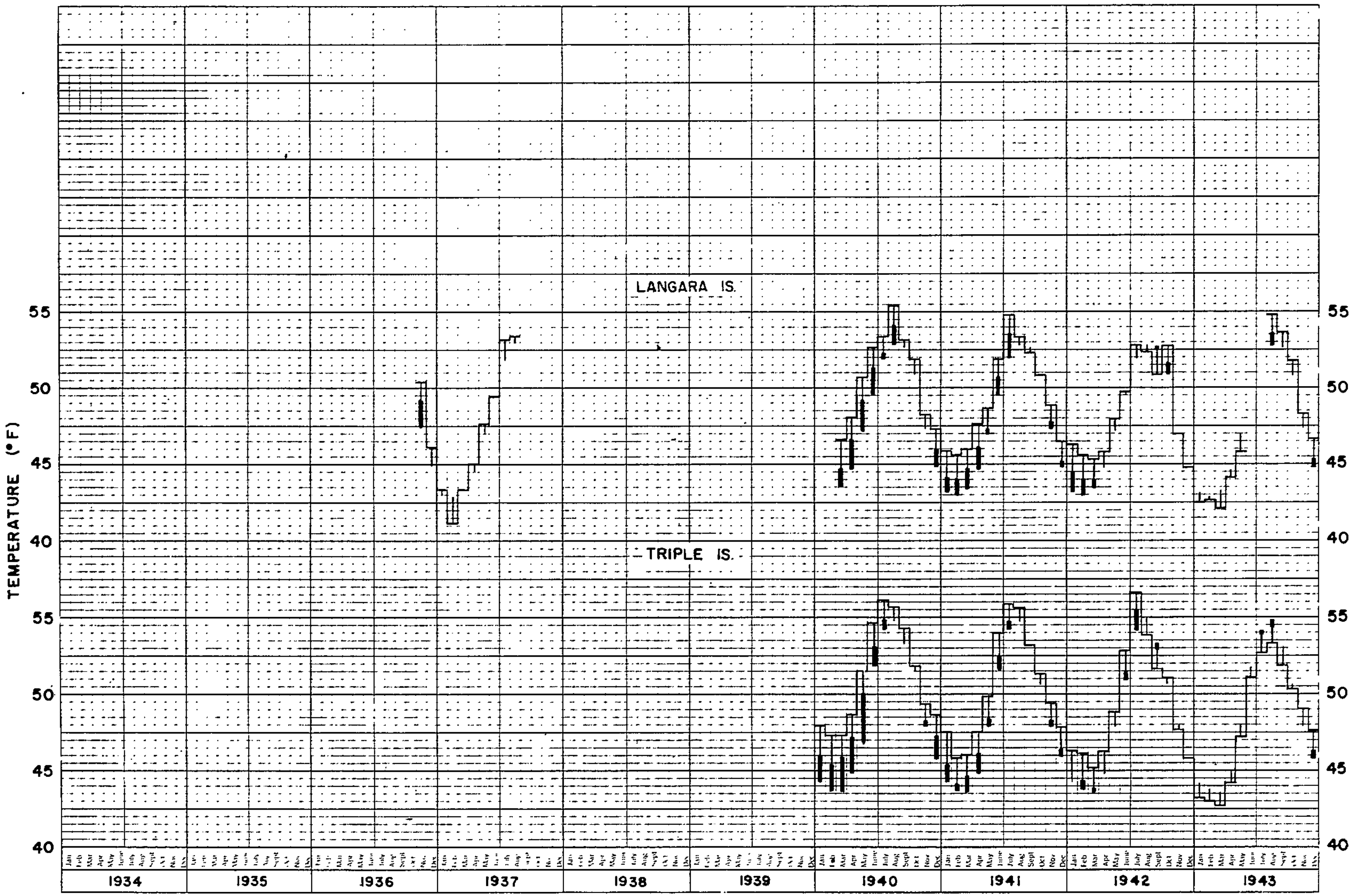


Fig. 50. Monthly mean sea surface temperature and difference from long-term monthly mean at Langara Is. and Triple Is., 1936-73 (heavy vertical bar indicates a difference greater than one standard deviation).

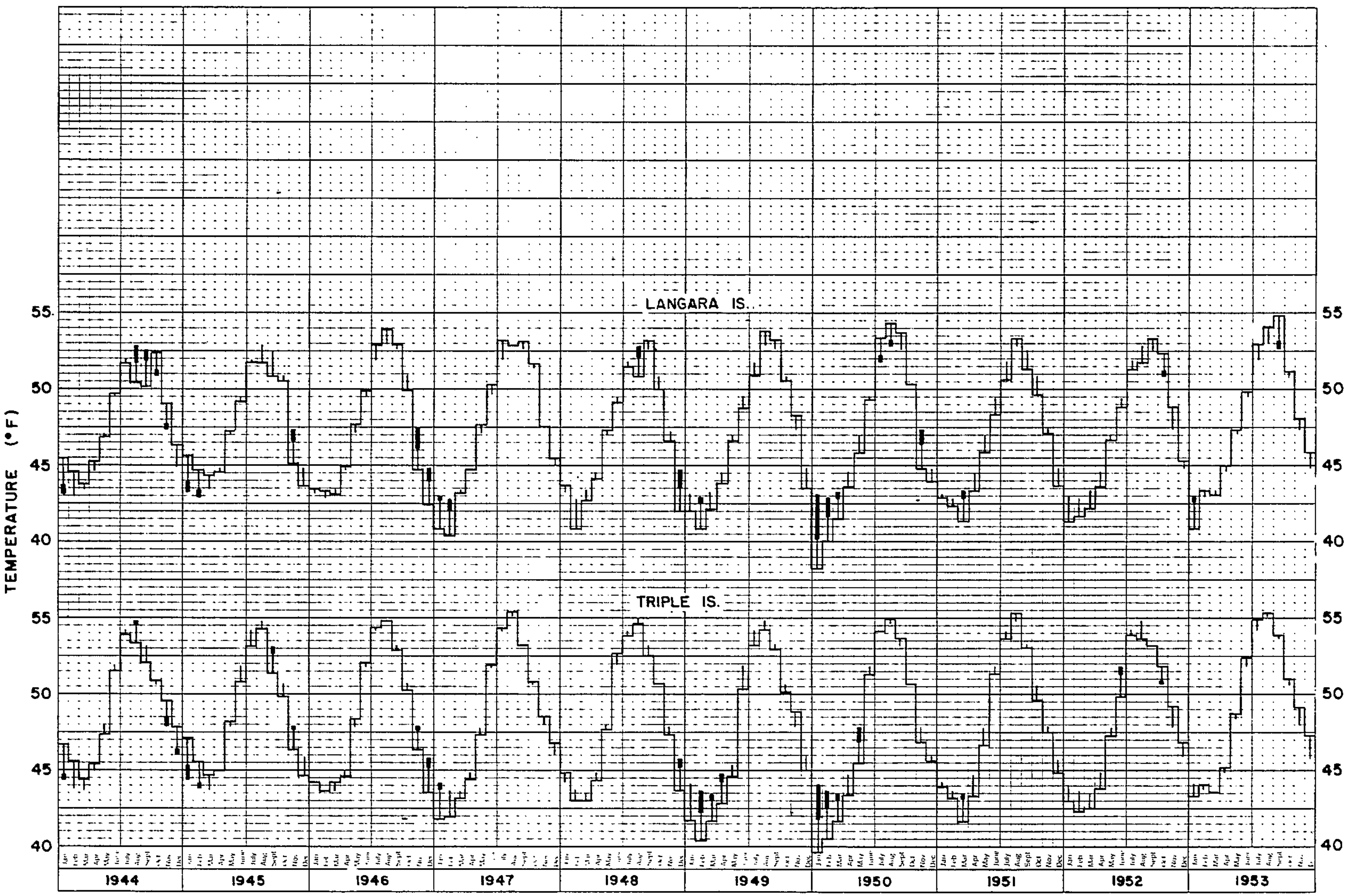

LANGARA IS.
TRIPLE IS.
TEMPERATURE (°F)
55
50
45
40
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953

Fig. 50 (cont'd).

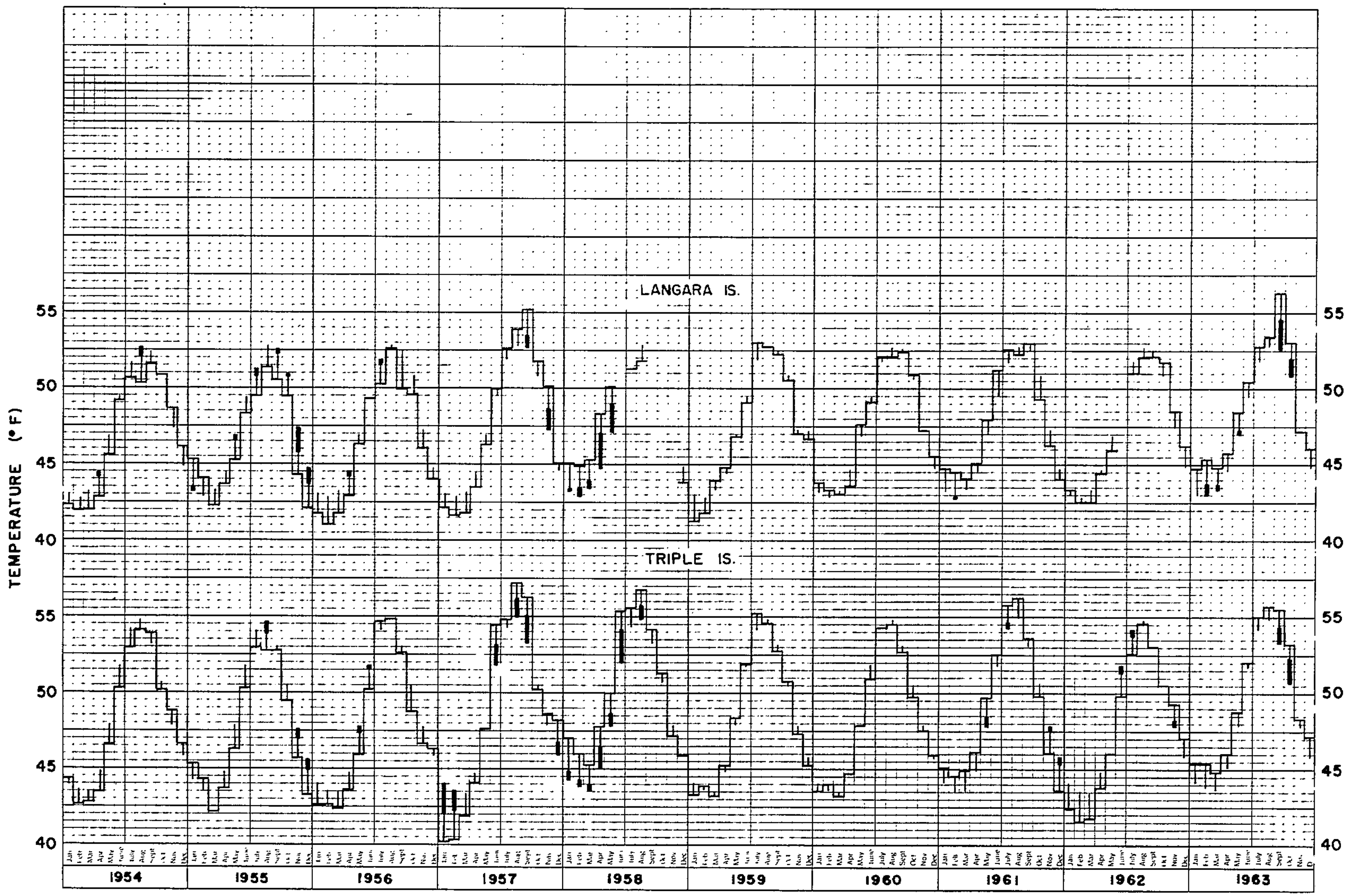

LANGARA IS.
TRIPLE IS.
TEMPERATURE (°F)
55
50
45
40
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963

Fig. 50 (cont'd).

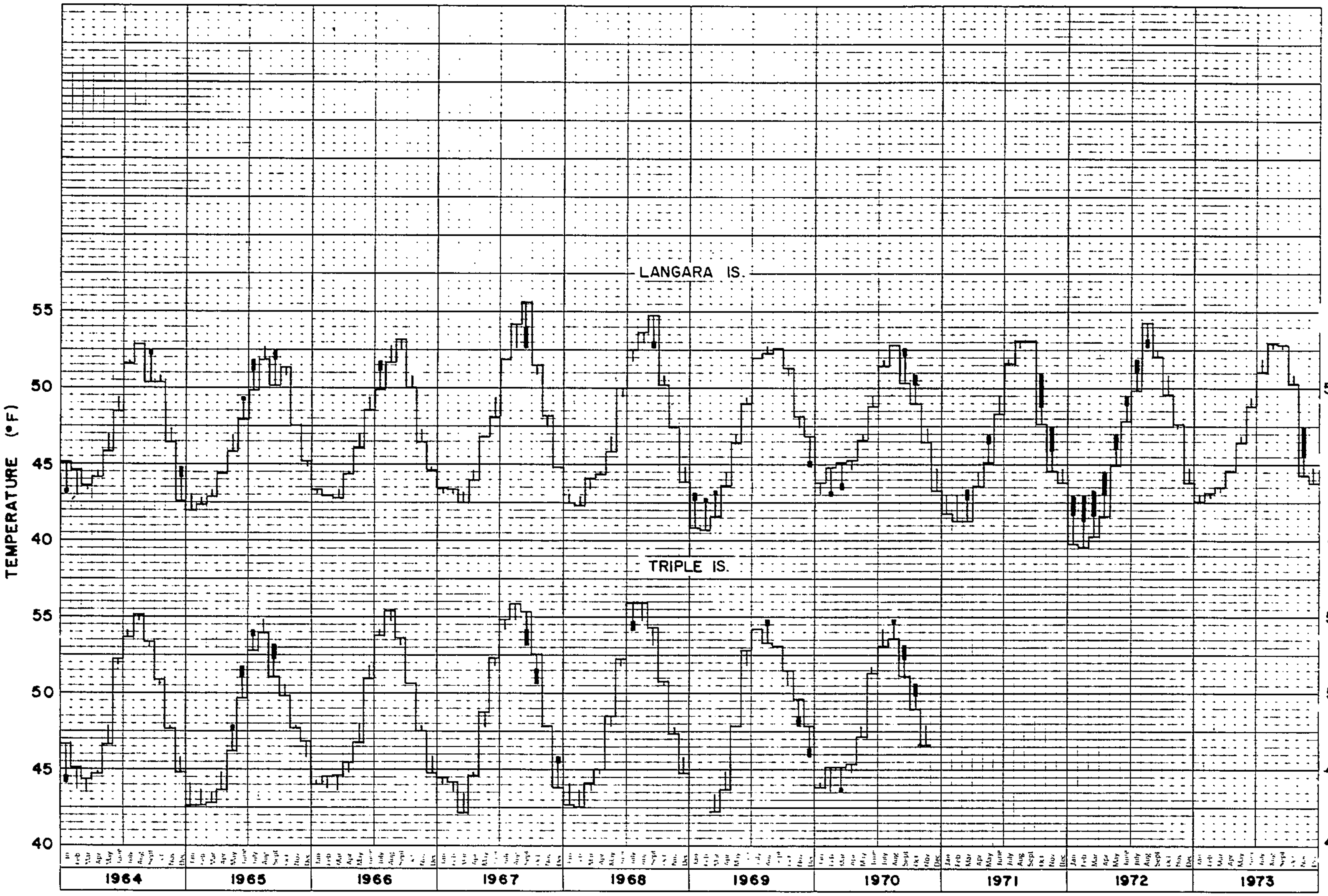

LANGARA IS.
TRIPLE IS.
TEMPERATURE (°F)
55
50
45
40
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973

Fig. 50 (cont'd).

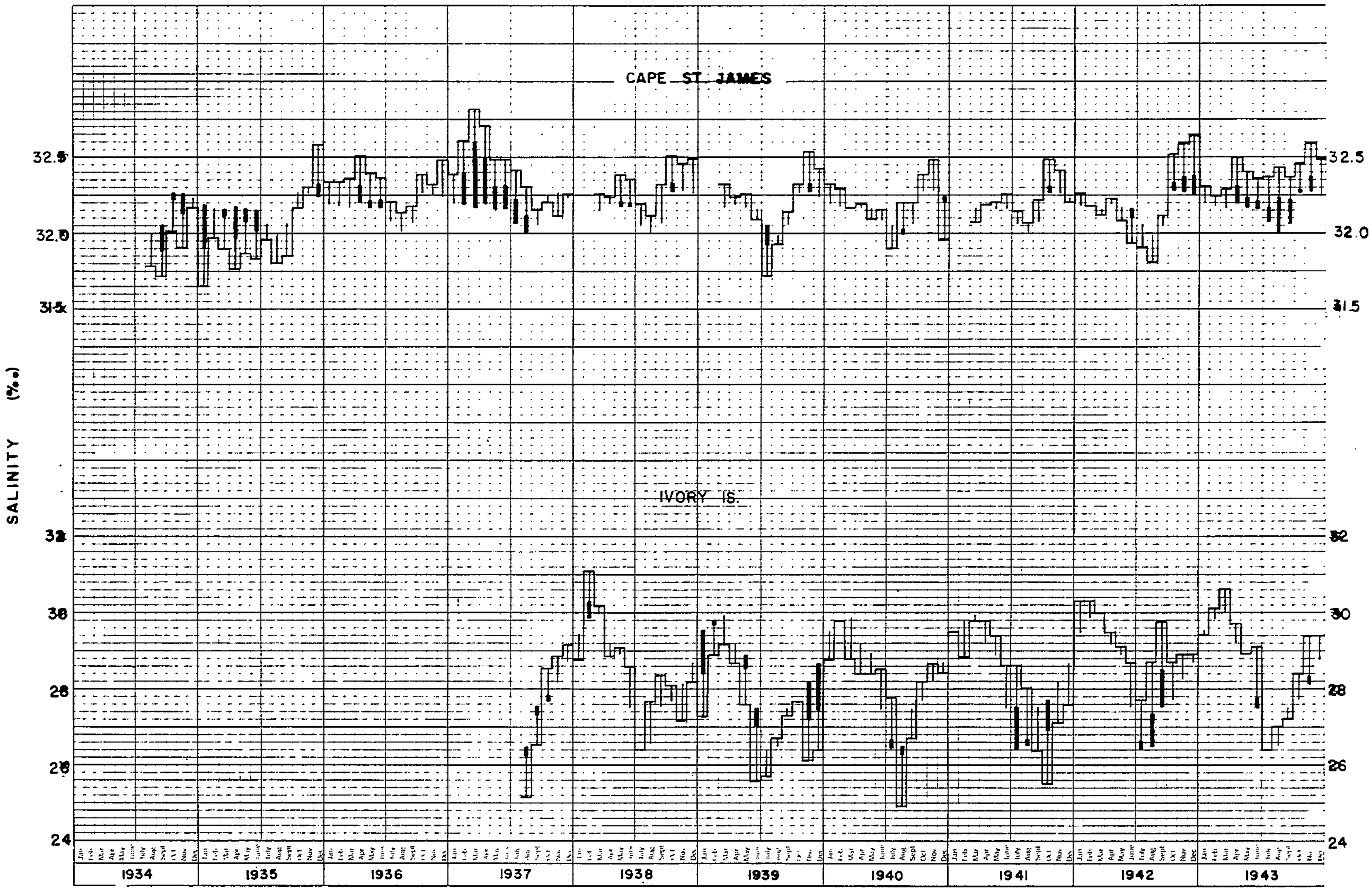


Fig. 51. Monthly mean surface salinity and difference from the long-term monthly mean at Cape St. James and Ivory Is., 1934-70 (heavy bar indicates a difference greater than one standard deviation).

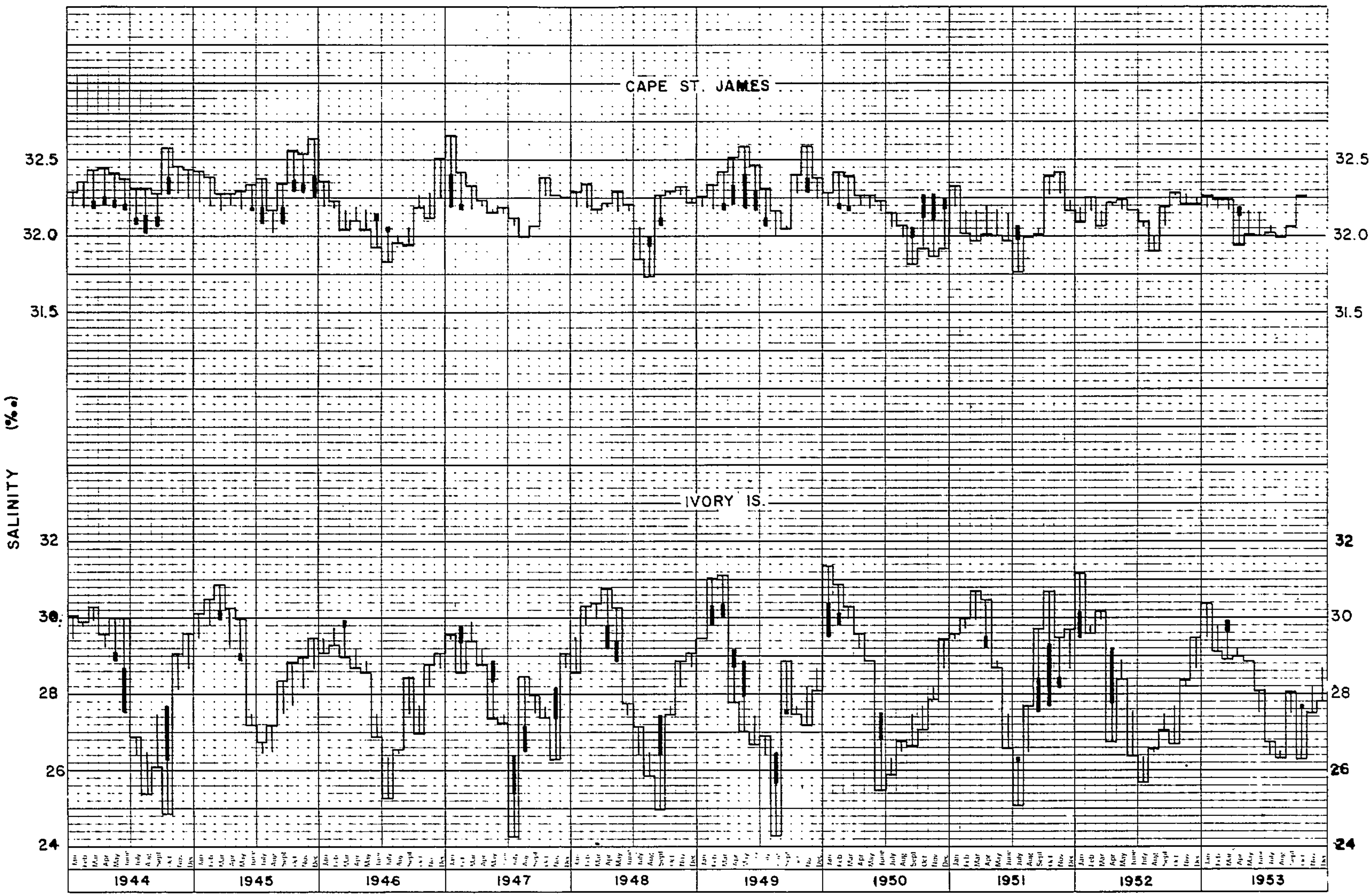

CAPE ST. JAMES
IVORY IS.
SALINITY (‰)
32.5
32.0
31.5
32
30
28
26
24
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953

Fig. 51 (cont'd).

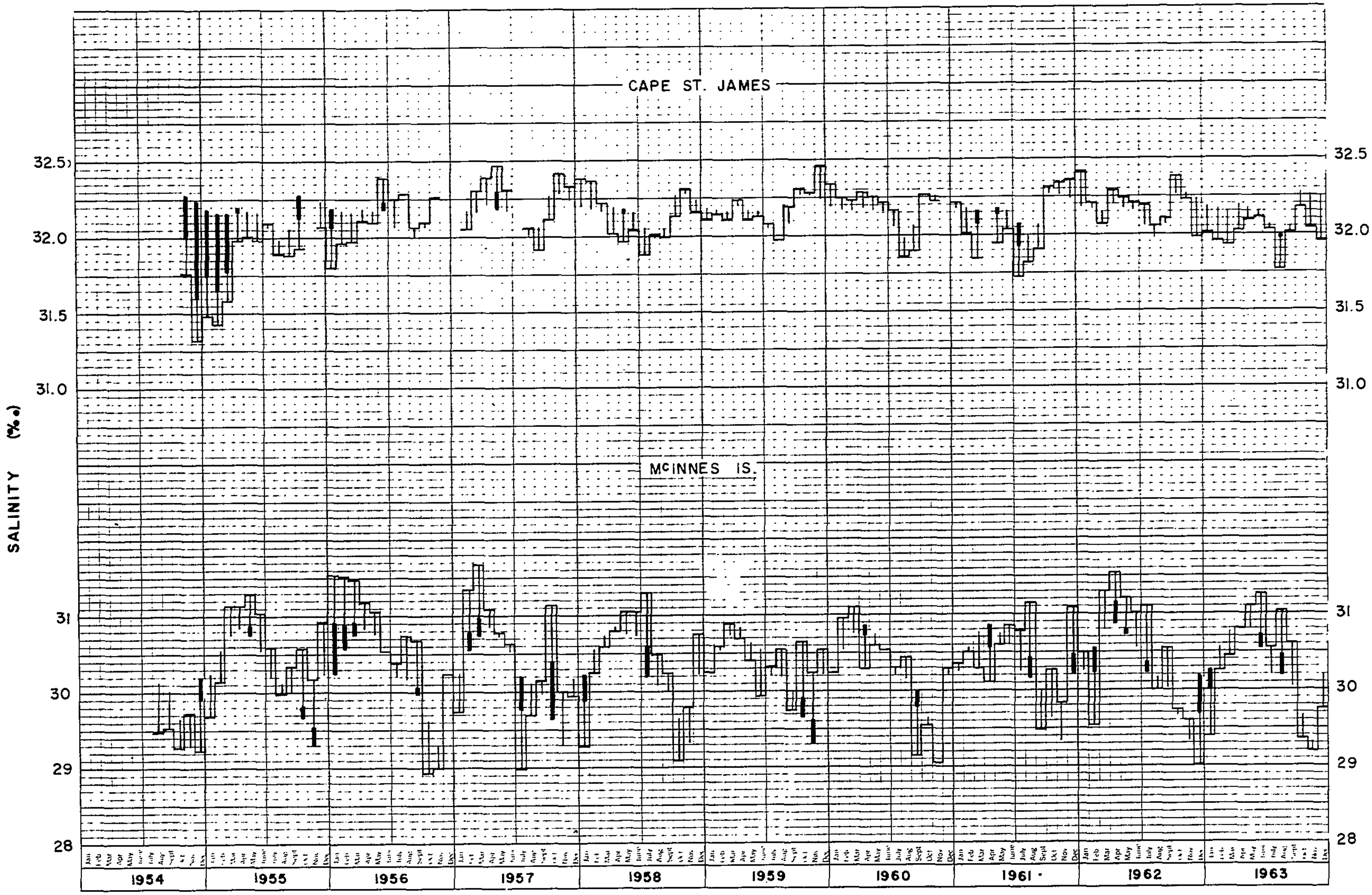
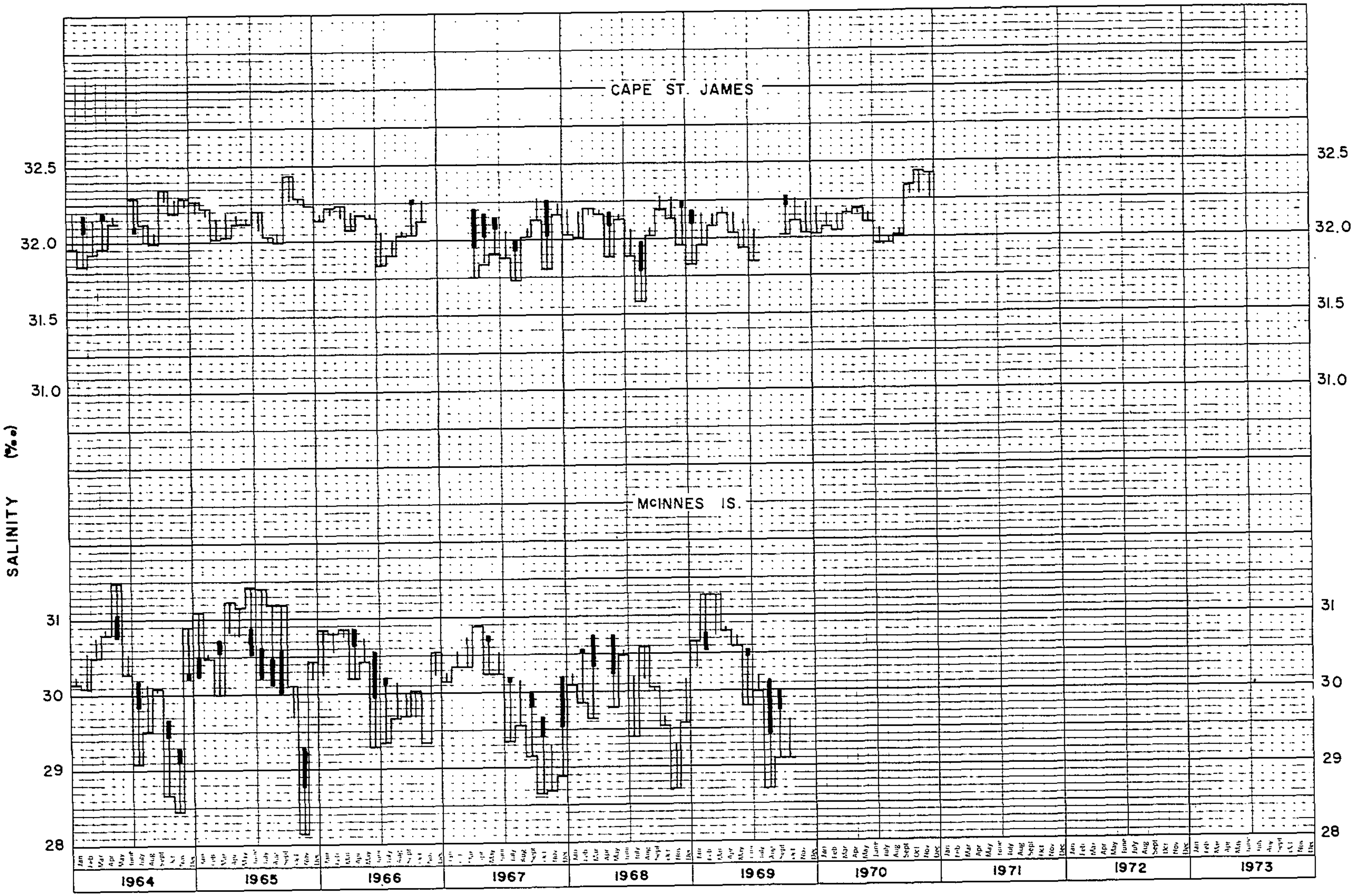


Fig. 51 (cont'd) (McInnes Is. replacing Ivory Is.).



CAPE ST. JAMES
McINNES IS.
SALINITY (‰)
32.5
32.0
31.5
31.0
31
30
29
28
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973

Fig. 51 (cont'd).

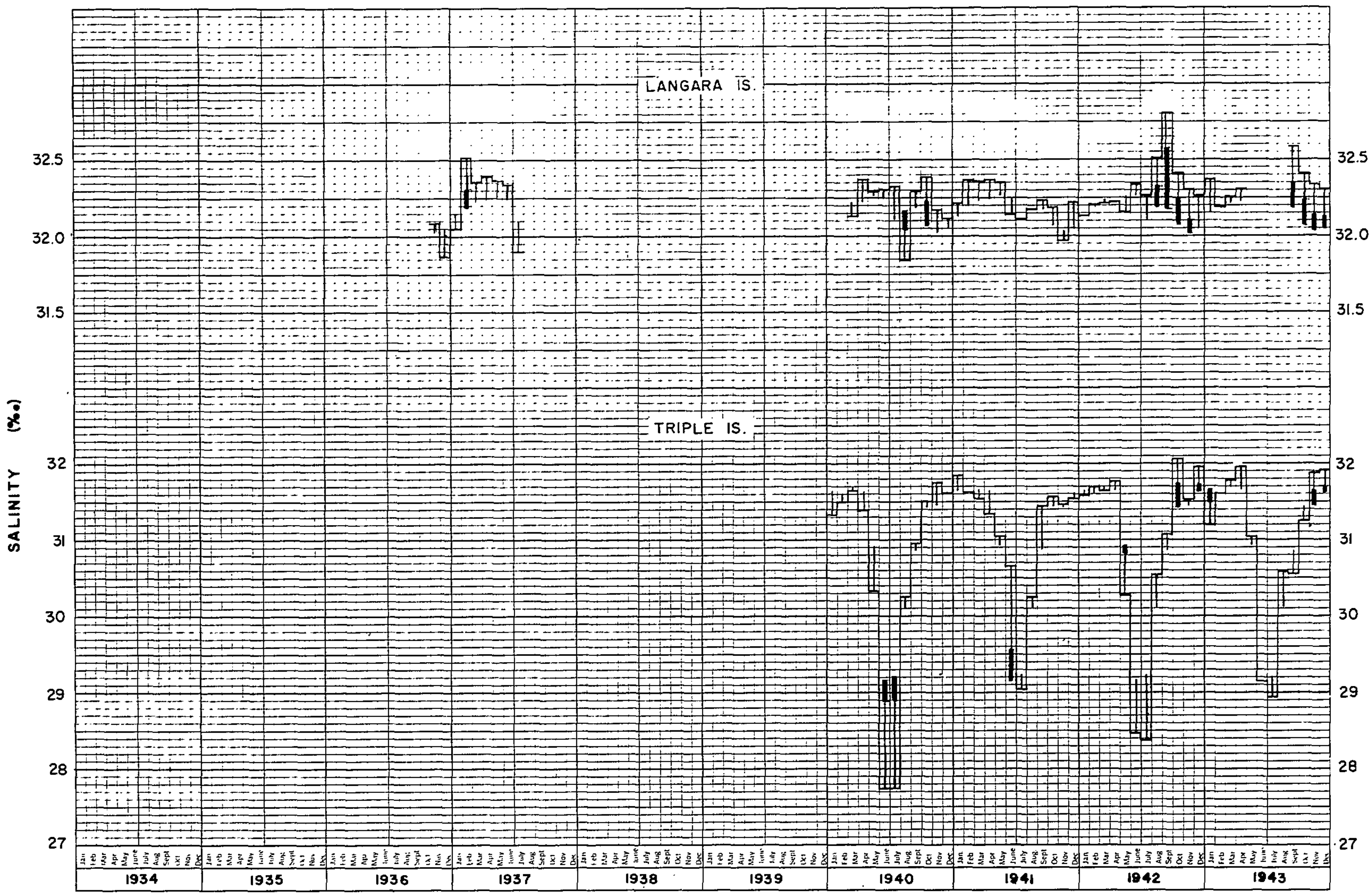


Fig. 52. Monthly mean surface salinity and difference from long-term monthly mean at Langara Is. and Triple Is., 1937-69 (heavy bar indicates a difference greater than one standard deviation).

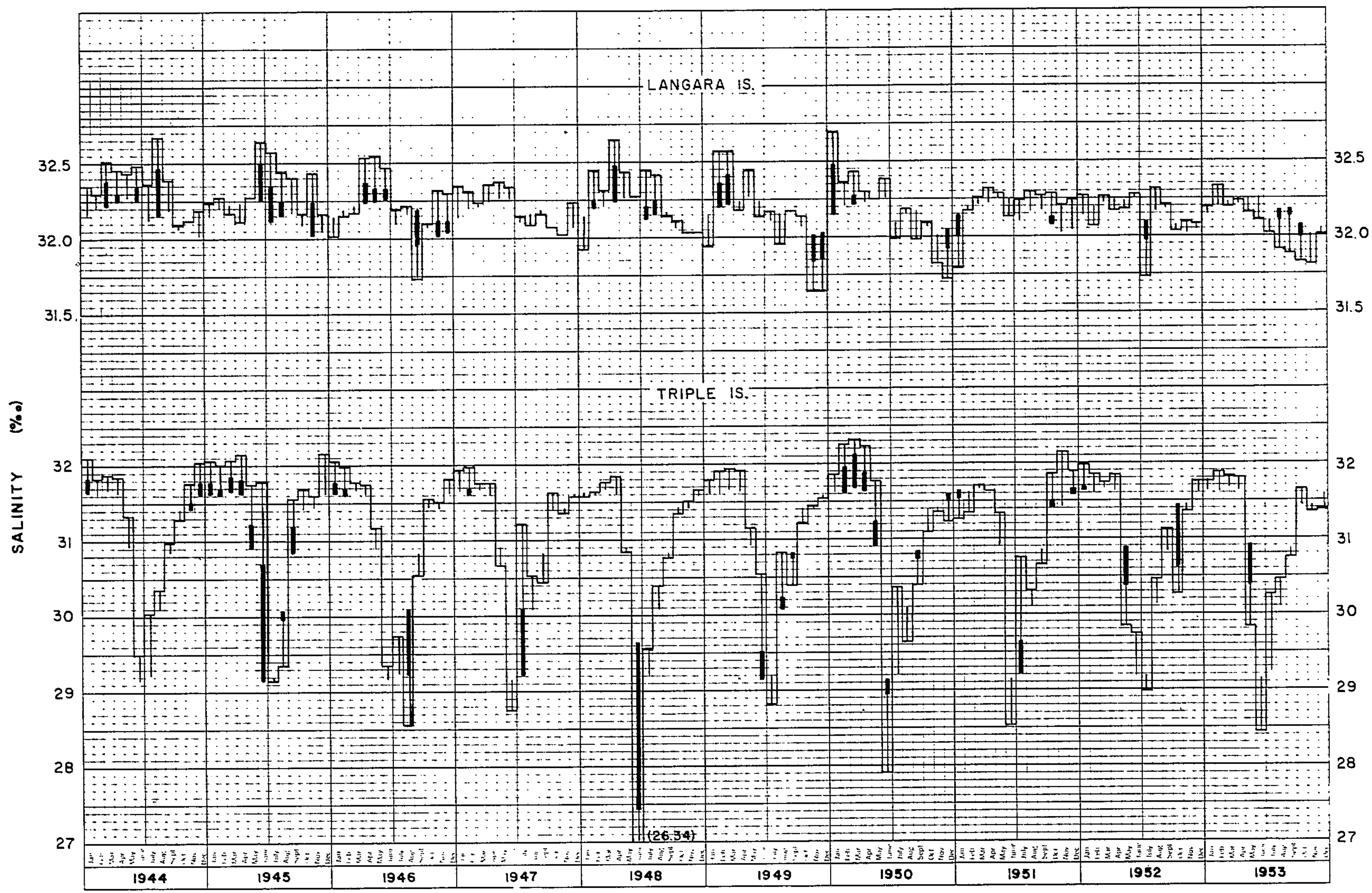

LANGARA IS.
TRIPLE IS.
SALINITY (‰)
32.5
32.0
31.5
32
31
30
29
28
27
(26.34)
1944
1945
1946
1947
1948
1949
1950
1951
1952
1953

Fig. 52 (cont'd).

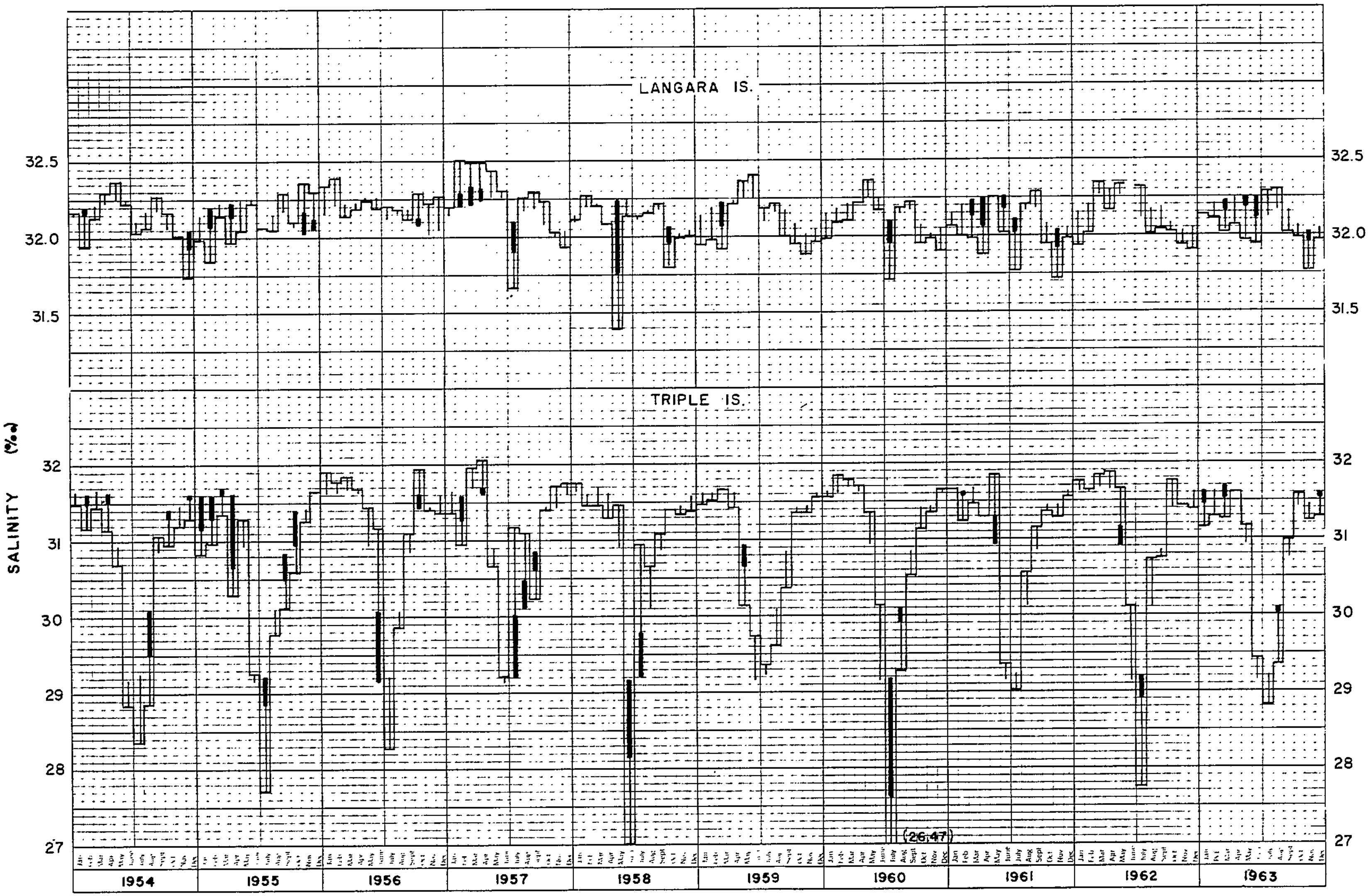

LANGARA IS.
TRIPLE IS.
SALINITY (‰)
32.5
32.0
31.5
32
31
30
29
28
27
(26.47)
1954
1955
1956
1957
1958
1959
1960
1961
1962
1963

Fig. 52 (cont'd).

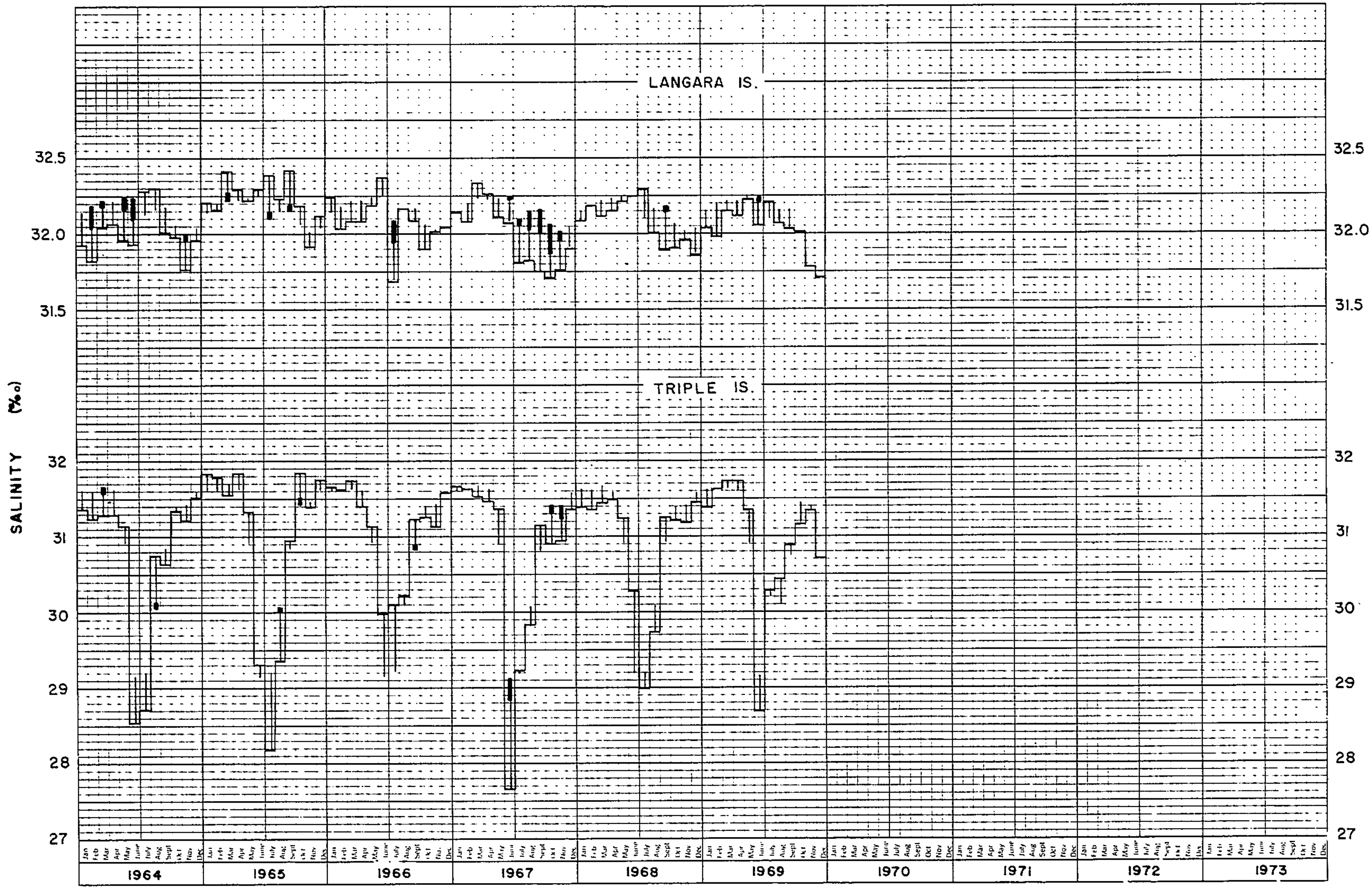

LANGARA IS.
TRIPLE IS.
SALINITY (‰)
32.5
32.0
31.5
32
31
30
29
28
27
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec
1964
1965
1966
1967
1968
1969
1970
1971
1972
1973

Fig. 52 (cont'd).

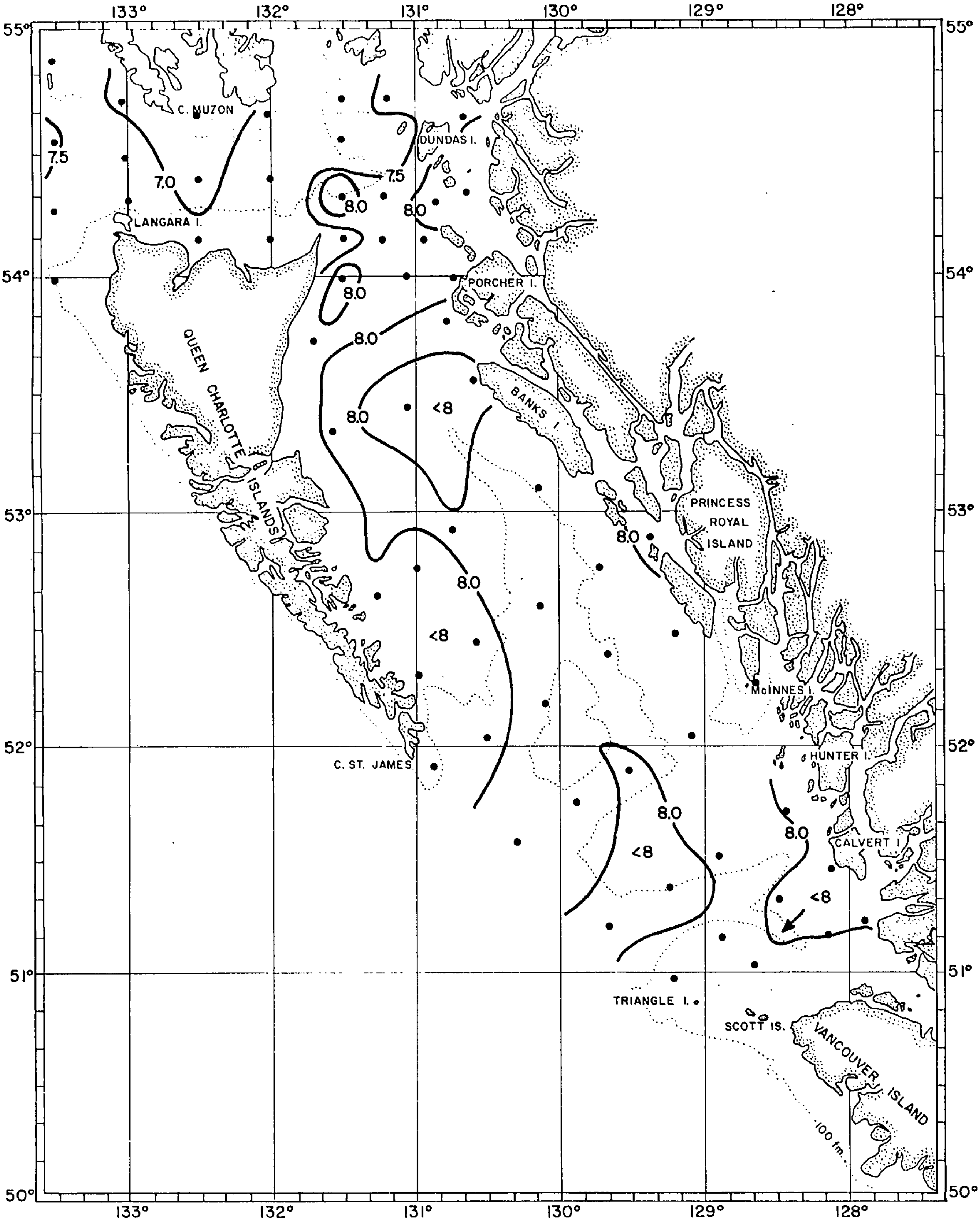


Fig. 53. Temperature (°C) distribution at 3 m depth, May 3-20, 1954 (arrows indicate direction of flow).

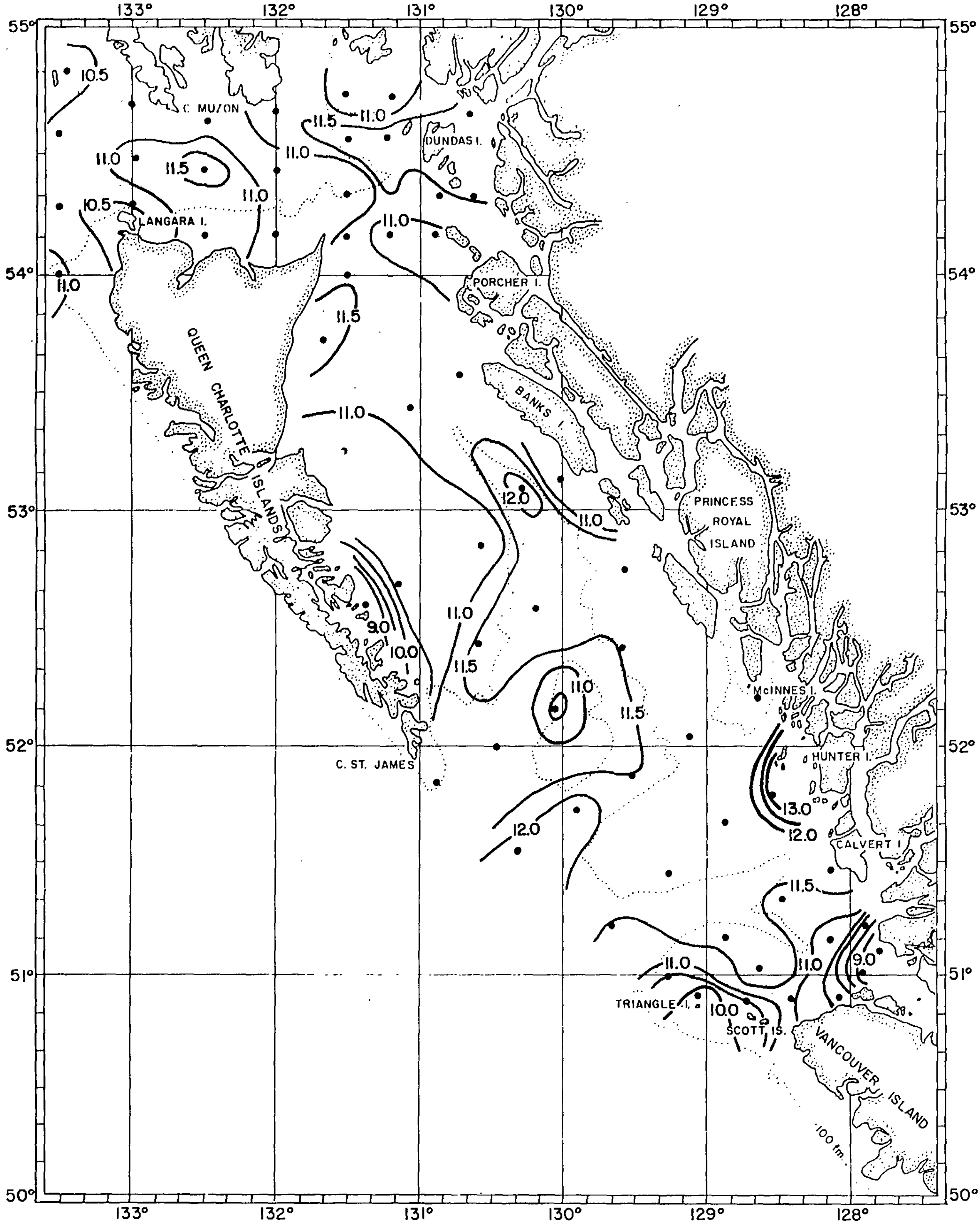


Fig. 54. Temperature (°C) distribution at 3 m depth, June 29-July 22, 1954.

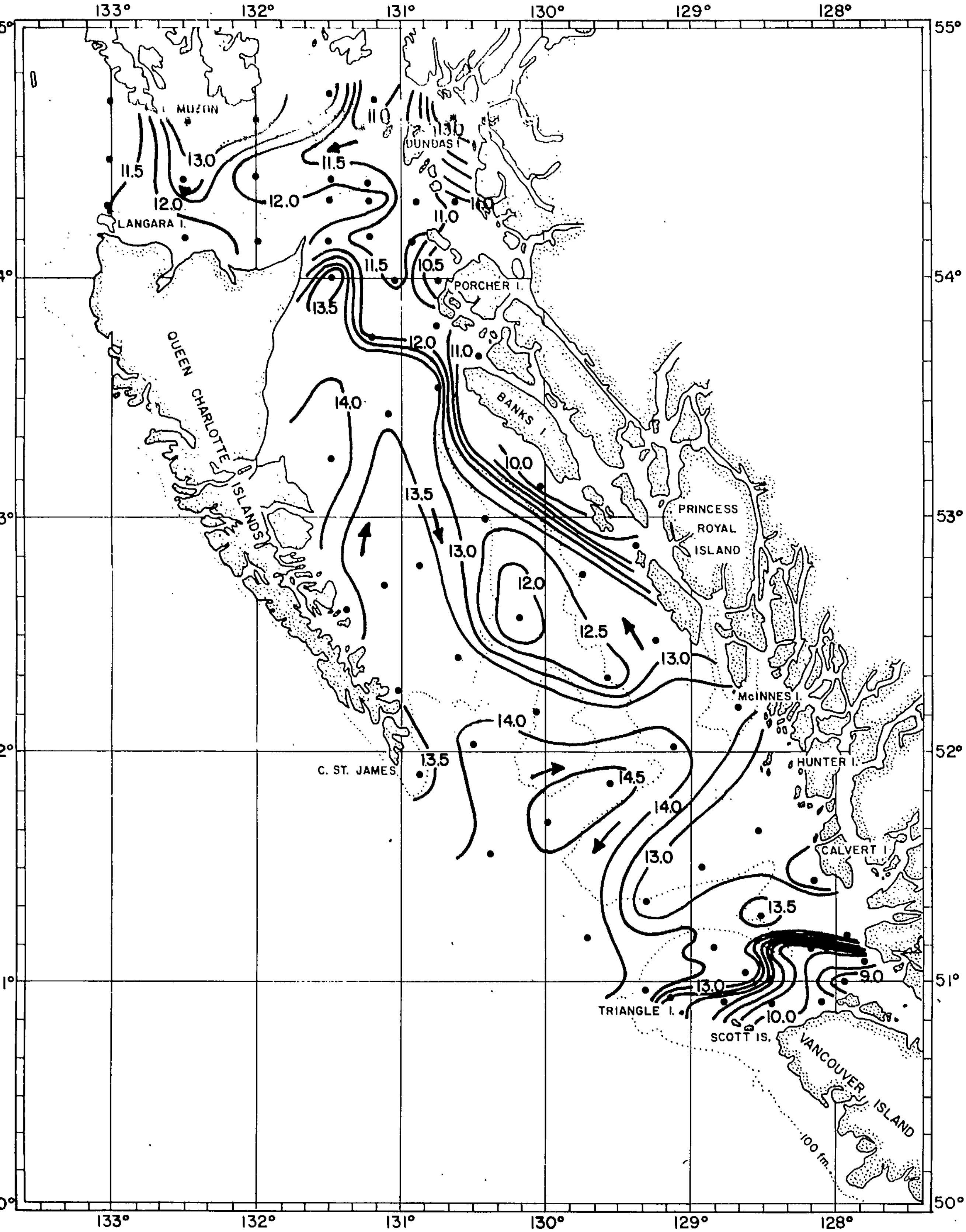


Fig. 55. Temperature (°C) distribution at 3 m depth, August 17-September 9, 1954 (arrows indicate direction of flow).

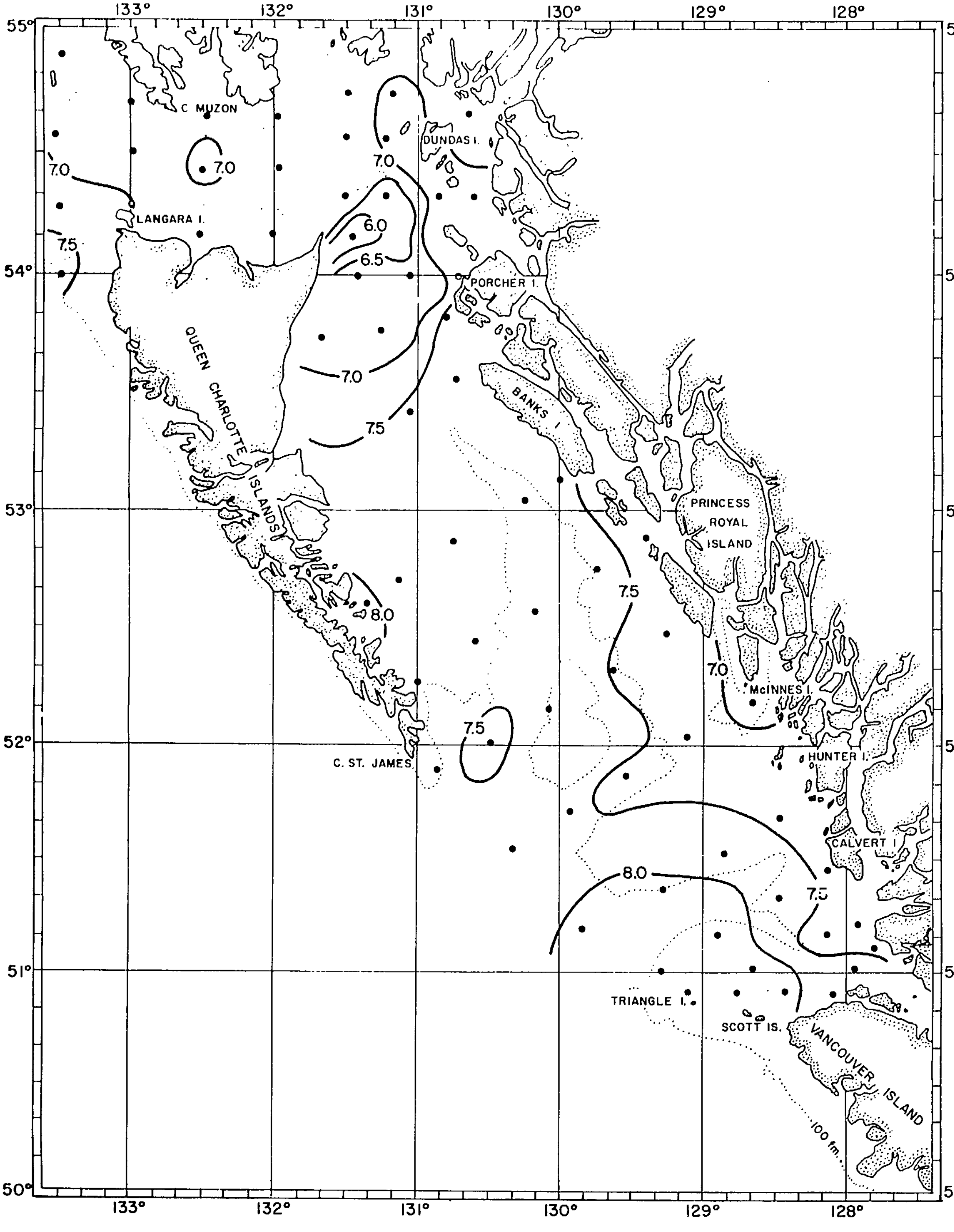


Fig. 56. Temperature (°C) distribution at 3 m depth, February 6-13, 1955.

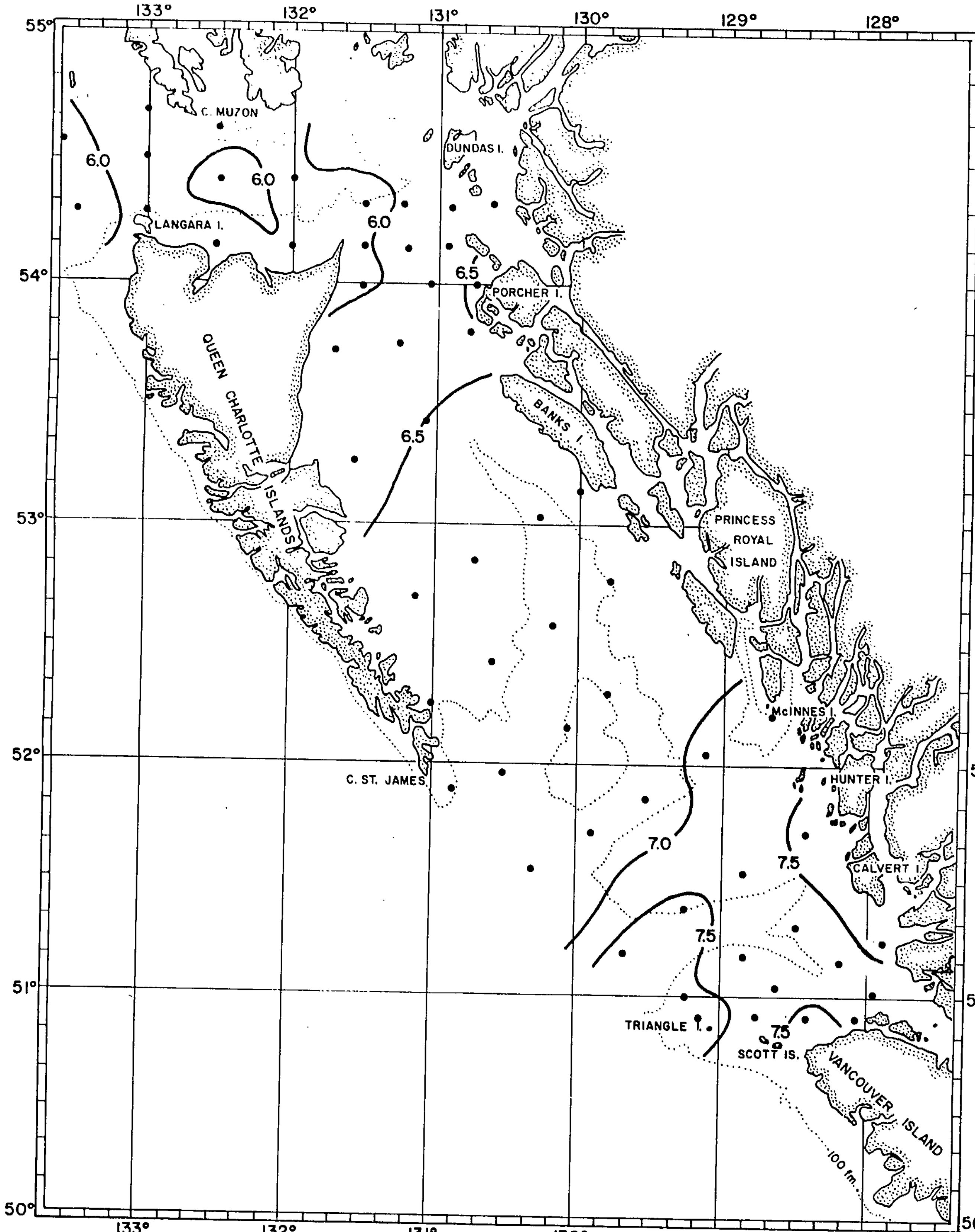


Fig. 57. Temperature (°C) distribution at 3 m depth, April 14-18, 1955.

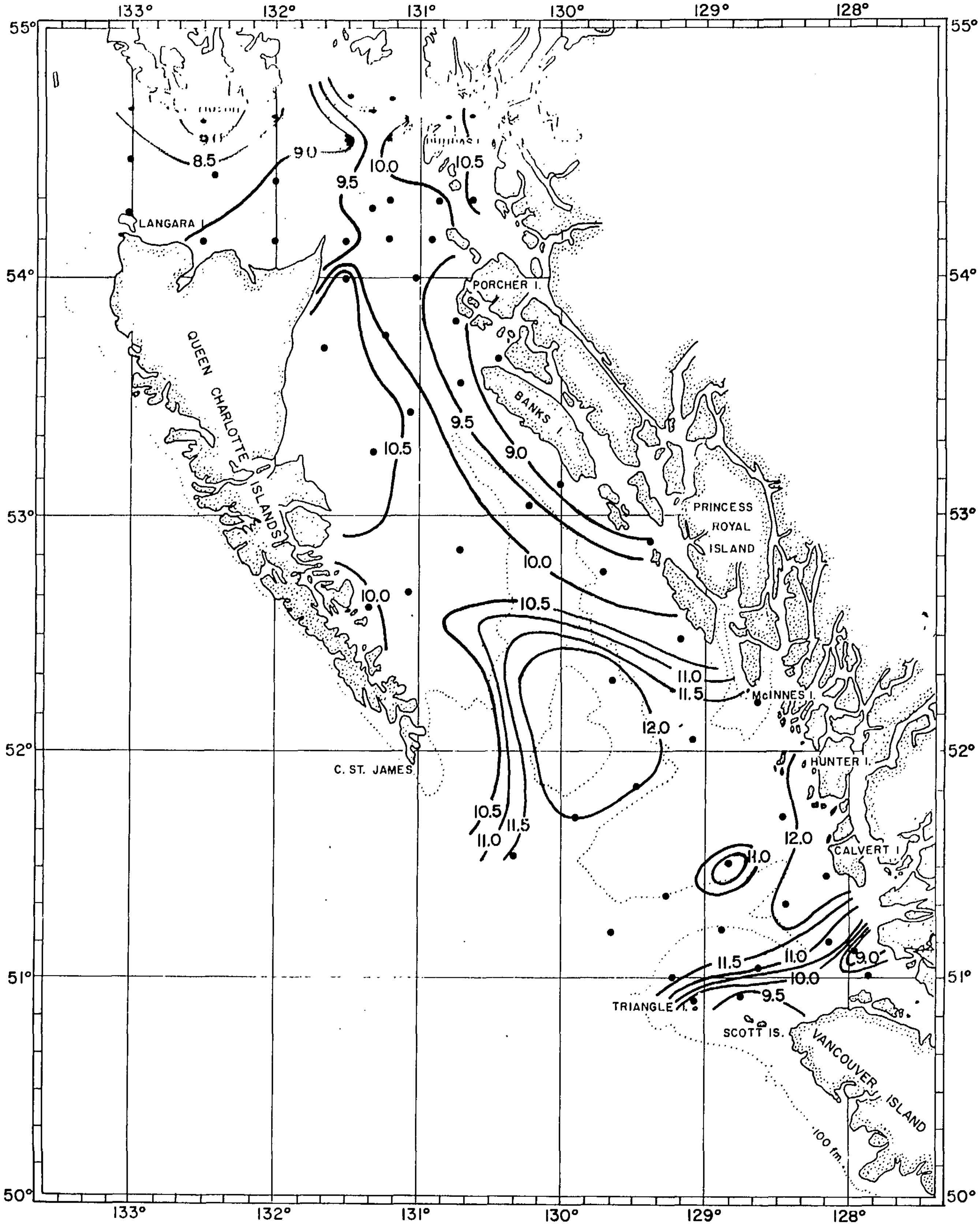


Fig. 58. Temperature (°C) distribution at 3 m depth, May 30-June 24, 1955.

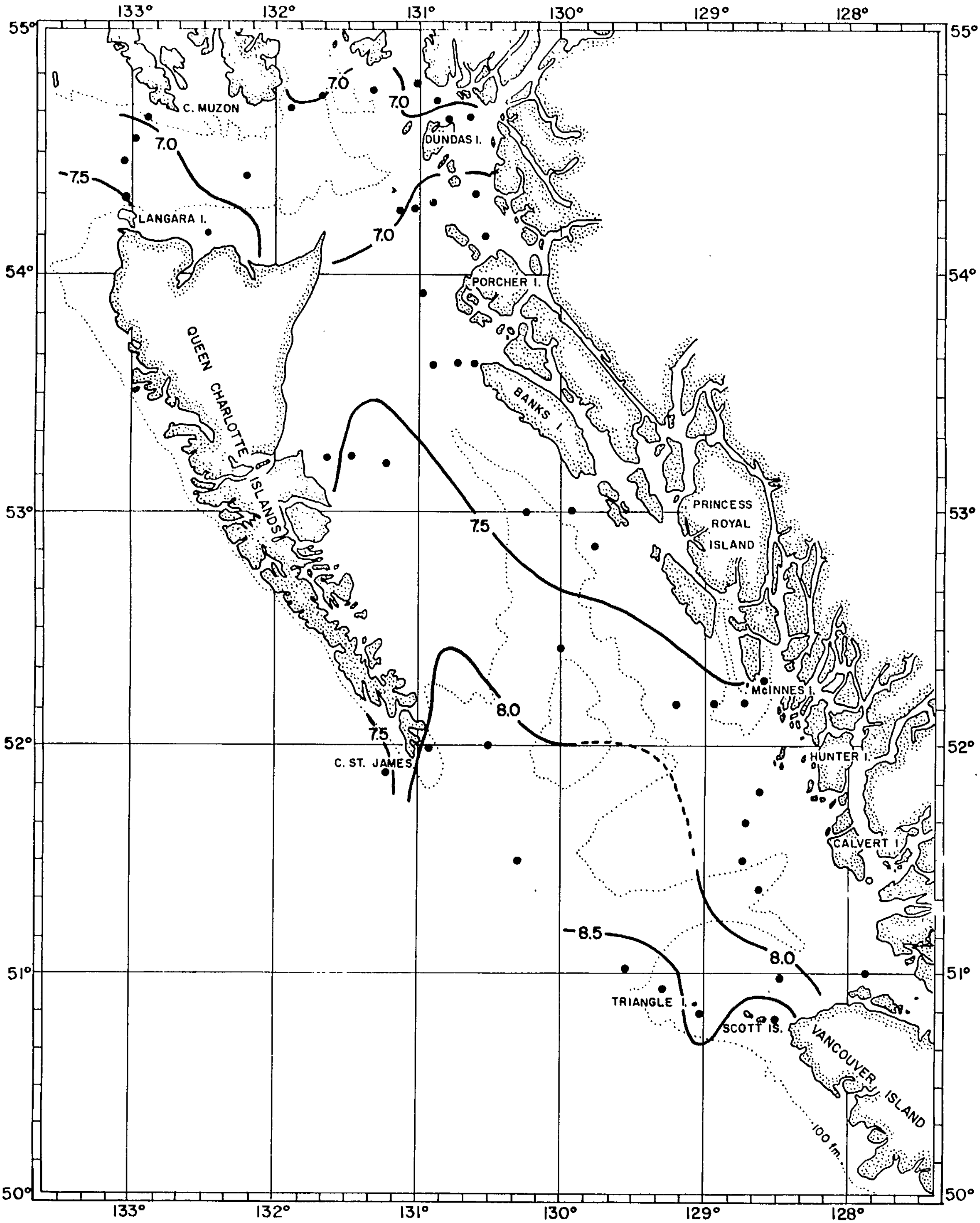


Fig. 59. Temperature (°C) distribution at 5 m depth, April 12-21, 1959.

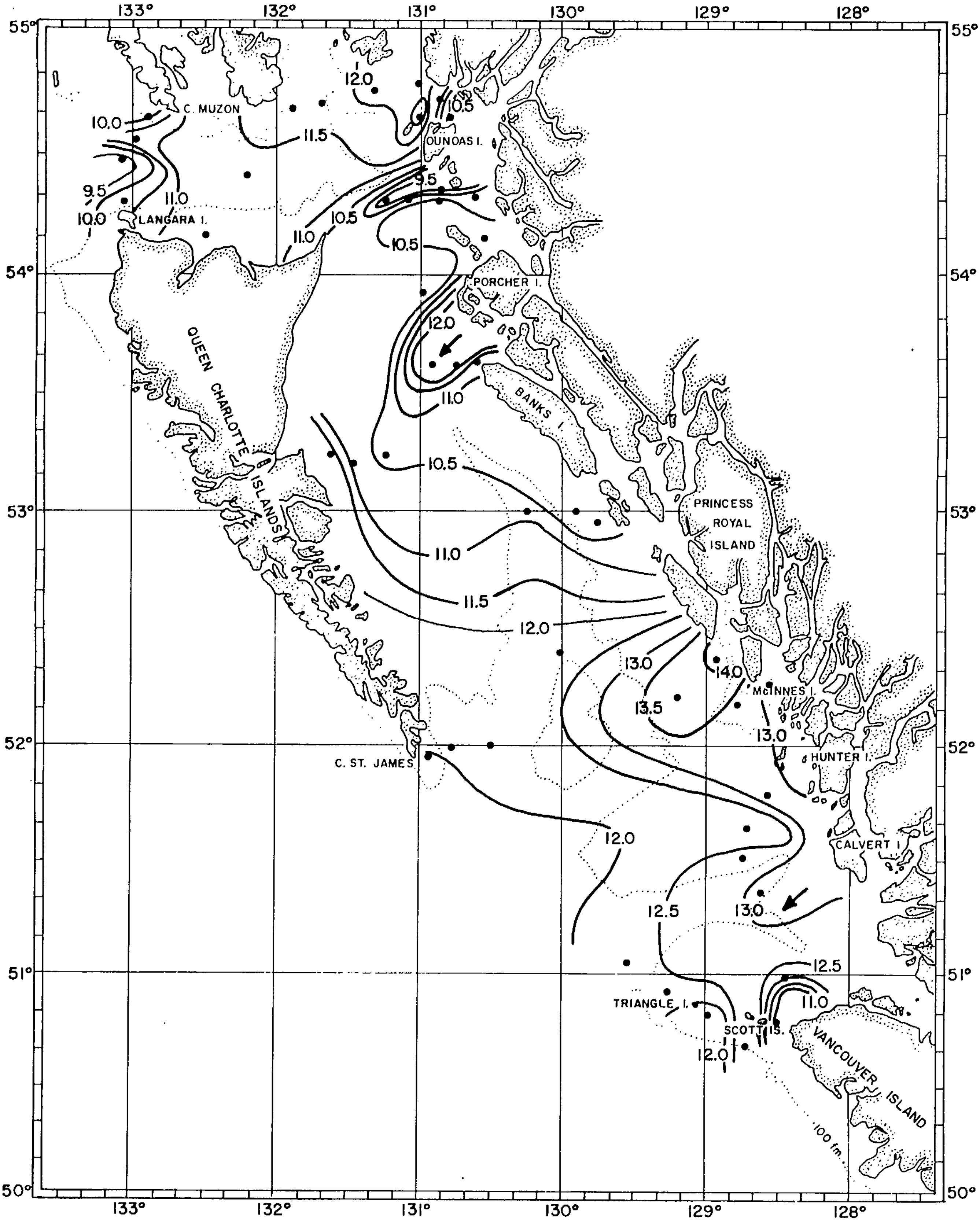


Fig. 60. Temperature (°C) distribution at 5 m depth, June 21-29, 1959 (arrows indicate direction of flow).

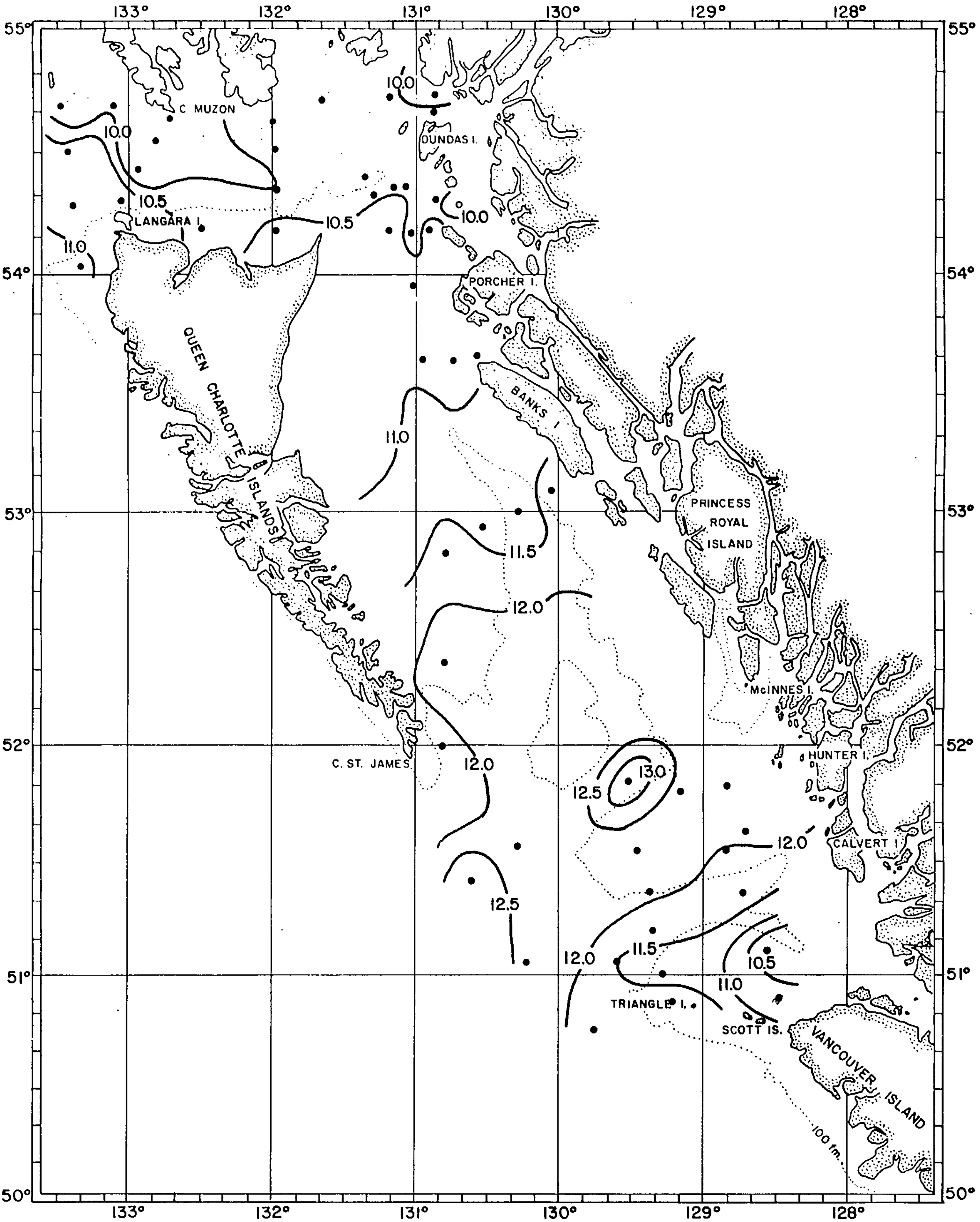


Fig. 61. Temperature (°C) distribution at 5 m depth, October 3-9, 1961.

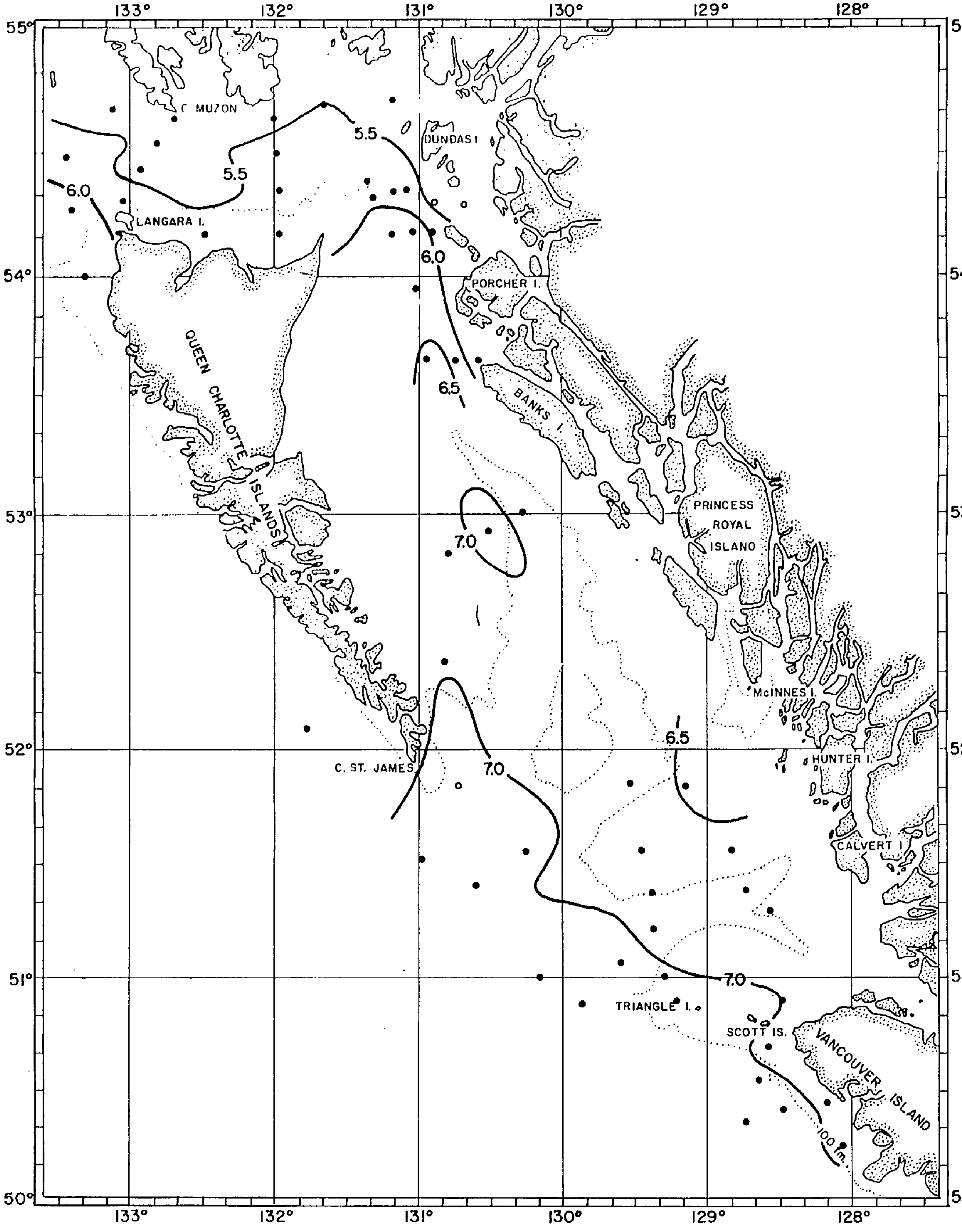


Fig. 62. Temperature (°C) distribution at 5 m depth, January 17-24, 1962.

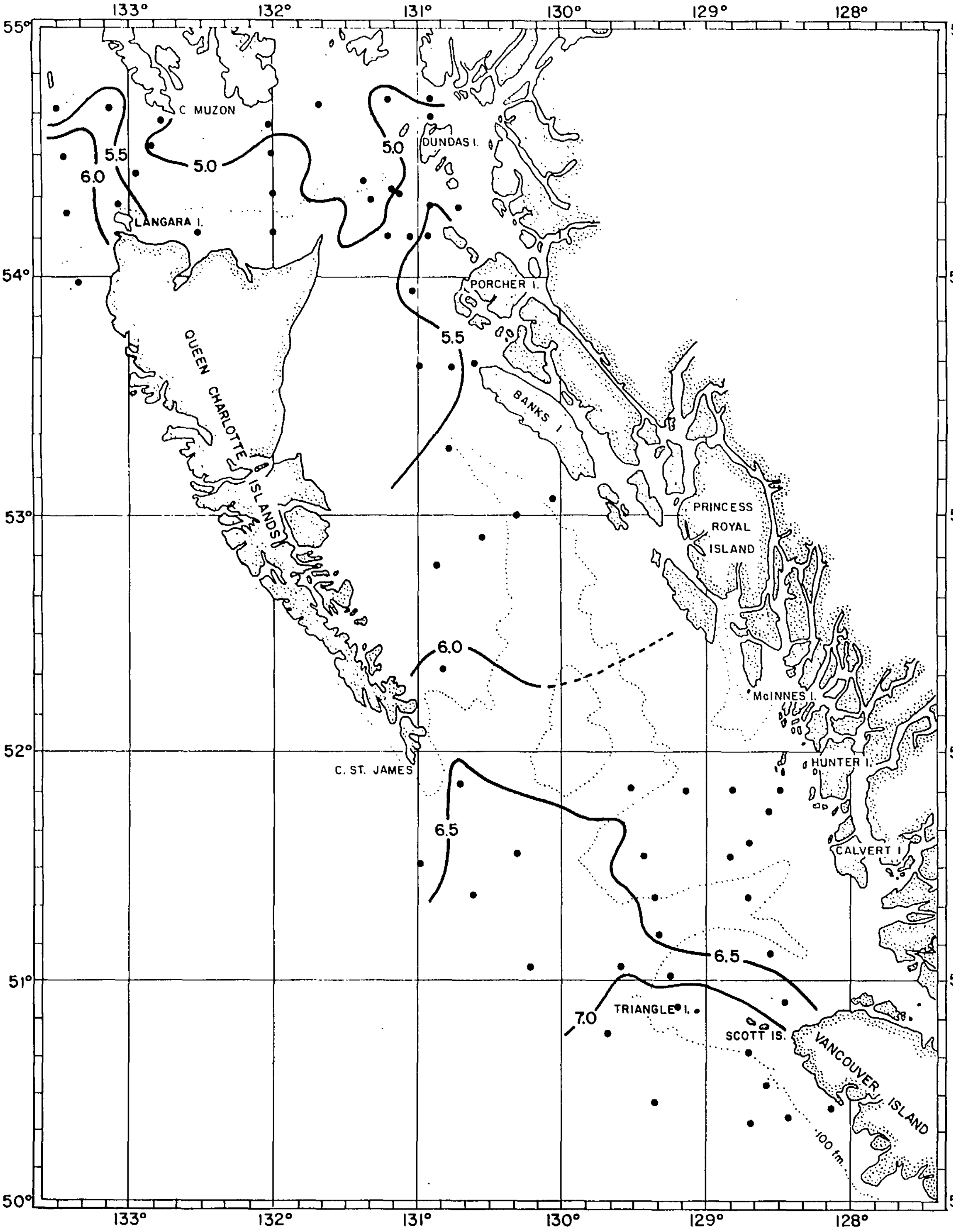


Fig. 63. Temperature (°C) distribution at 5 m depth, March 13-20, 1962.

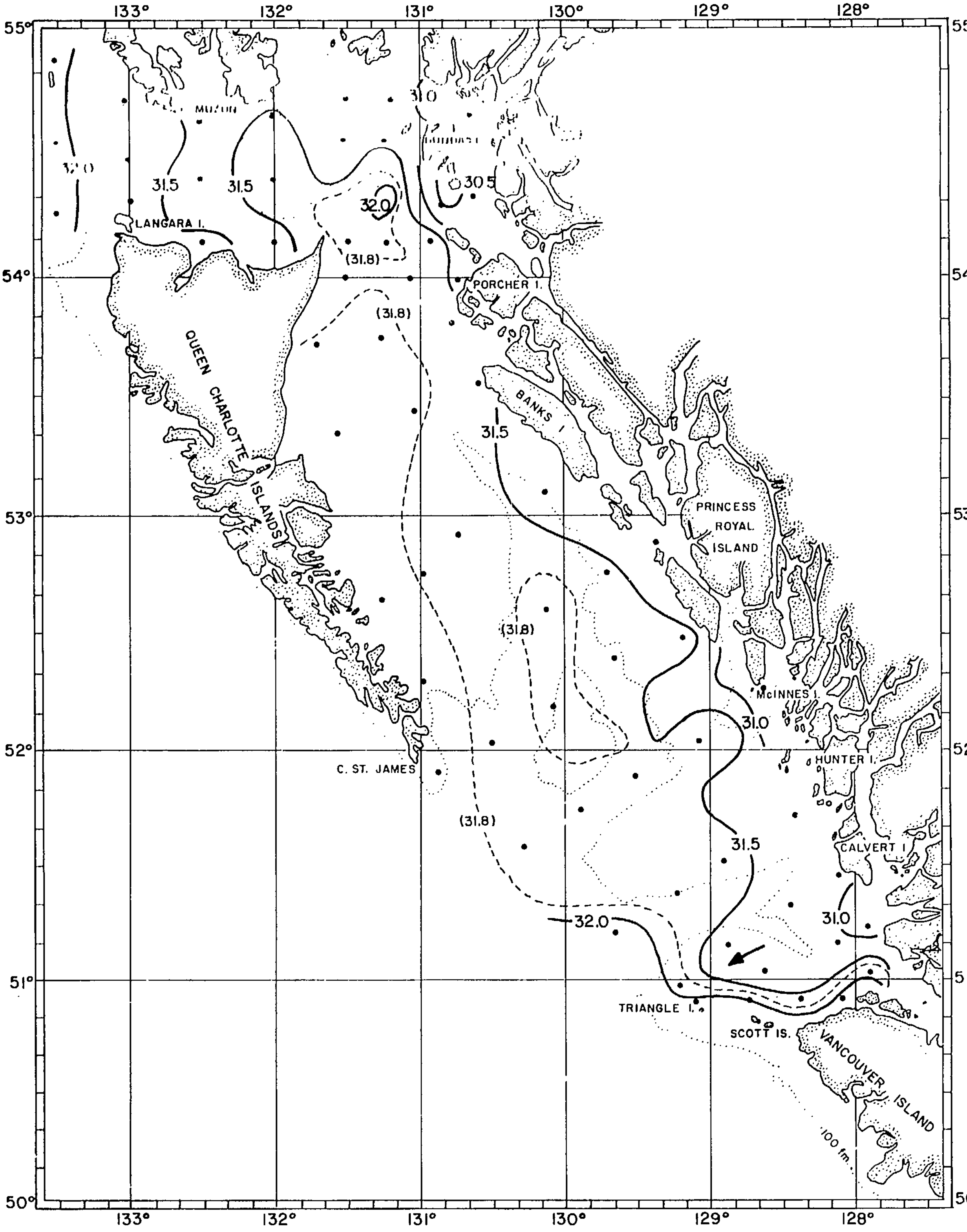


Fig. 64. Salinity (‰) distribution at 3 m depth, May 3-28, 1954 (arrows indicate direction of flow).

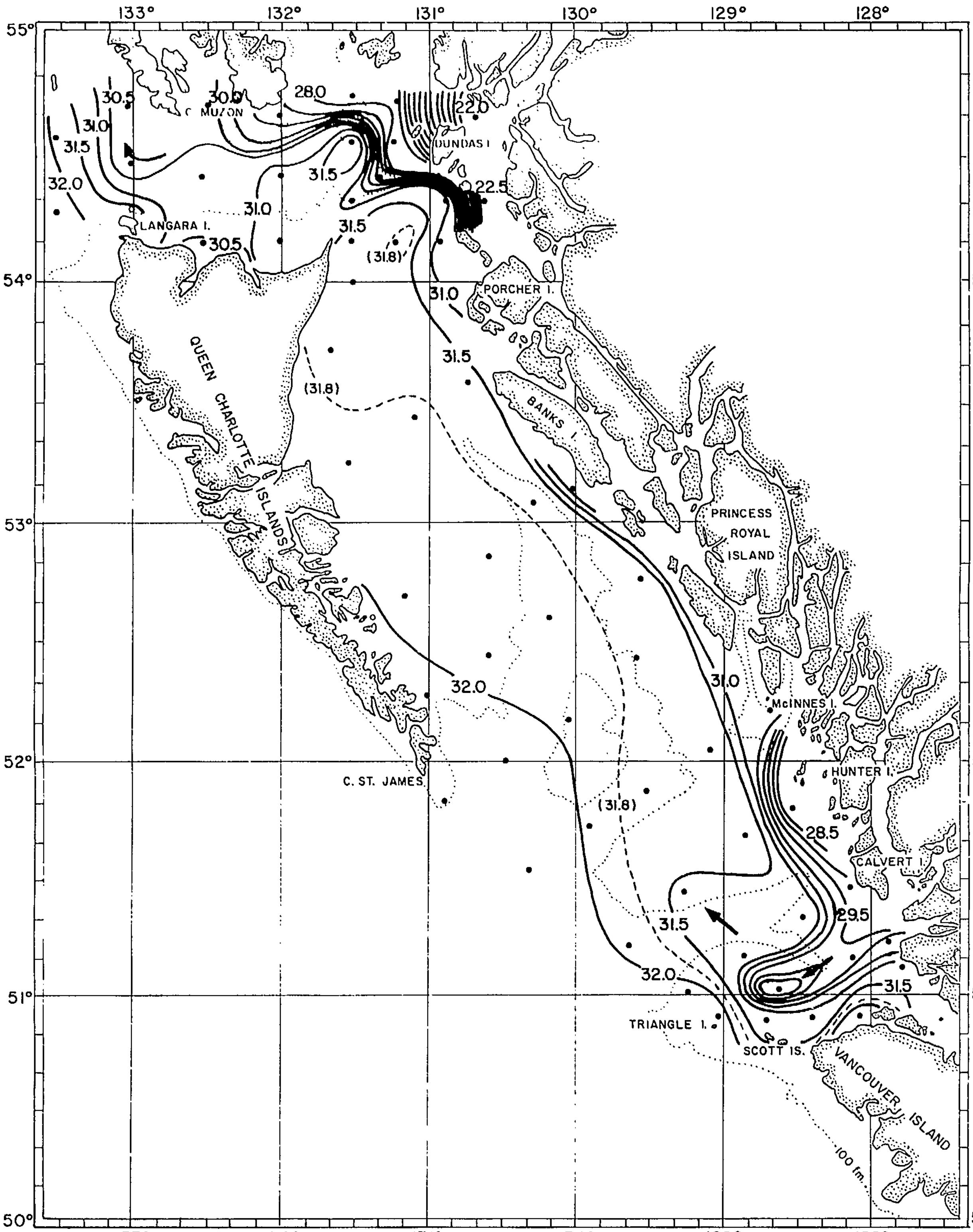


Fig. 65. Salinity (‰) distribution at 3 m depth, June 29-July 22, 1954 (arrows indicate direction of flow).

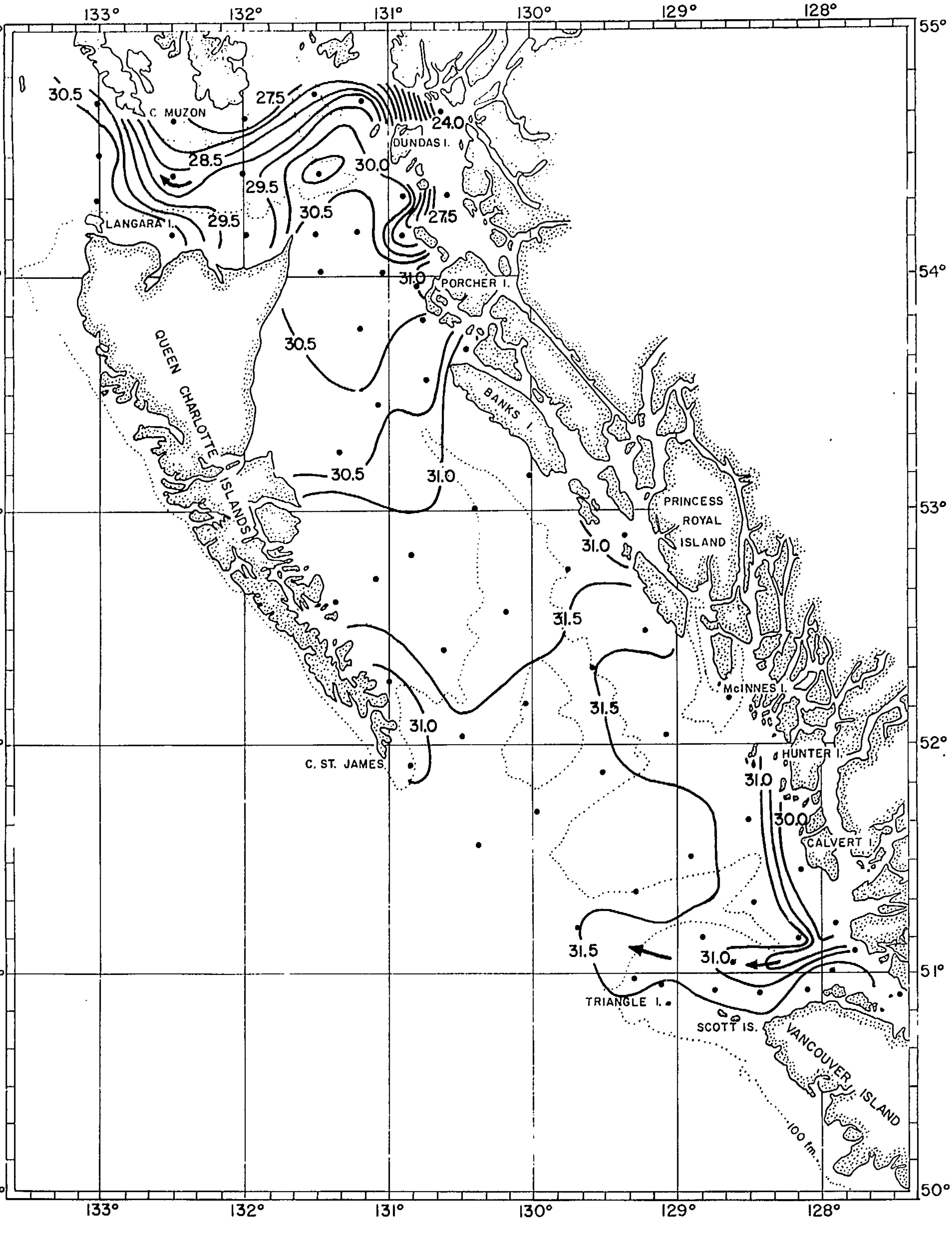


Fig. 66. Salinity (‰) distribution at 3 m depth, August 17-September 9, 1954 (arrows indicate direction of flow).

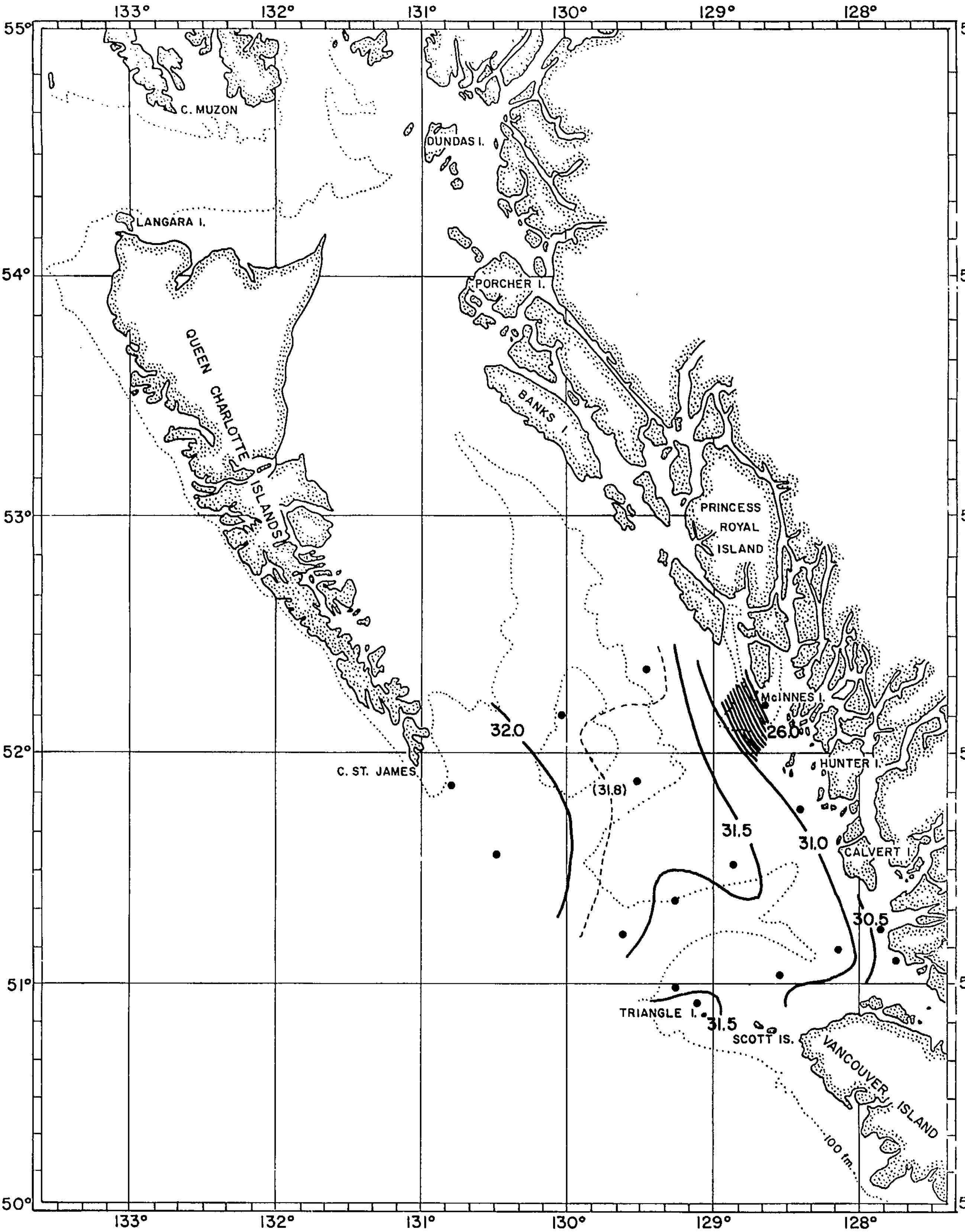


Fig. 67. Salinity (‰) distribution at 3 m depth, November 15-December 2, 1954.

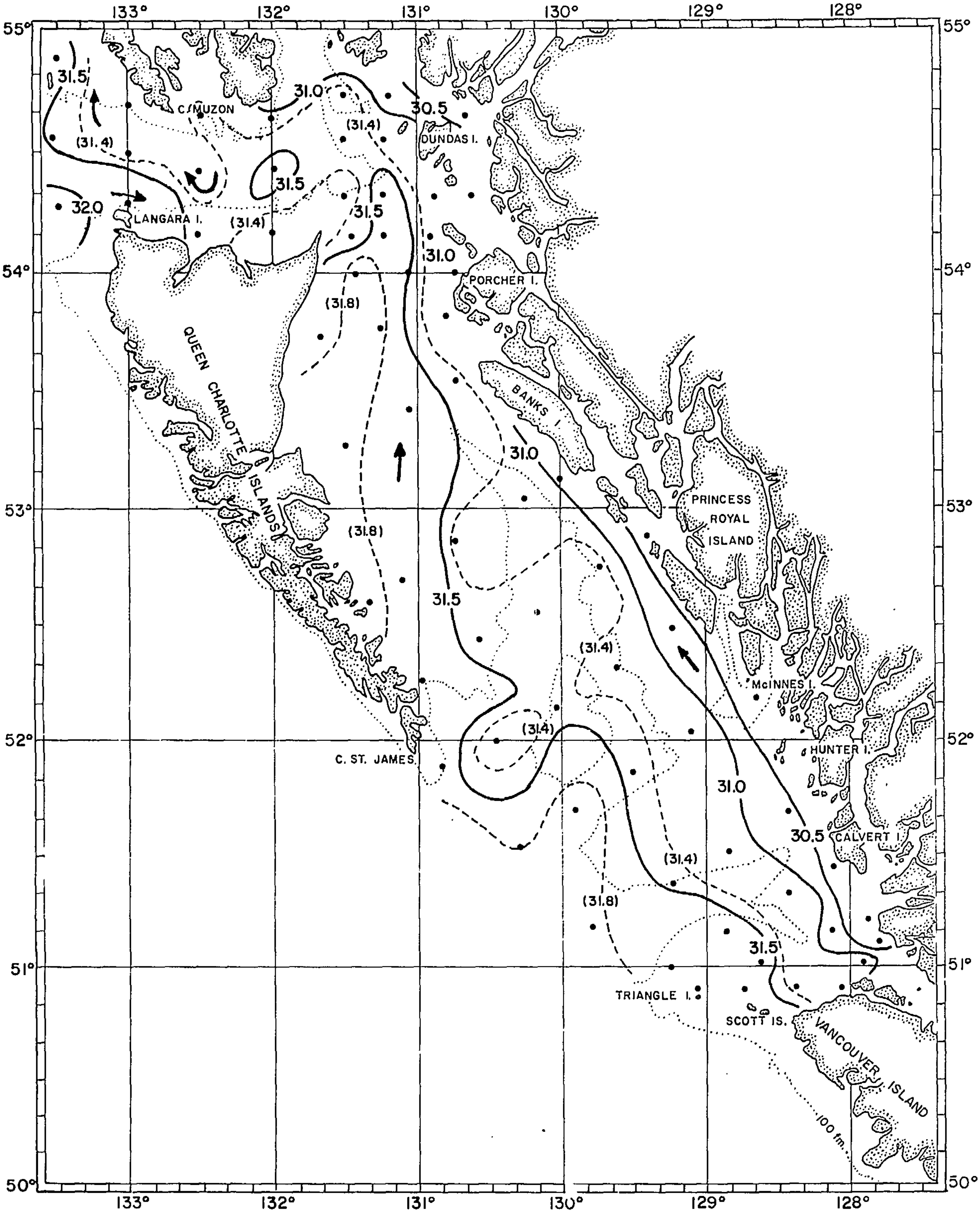


Fig. 68. Salinity (‰) distribution at 3 m depth, February 6-13, 1955 (arrows indicate direction of flow).

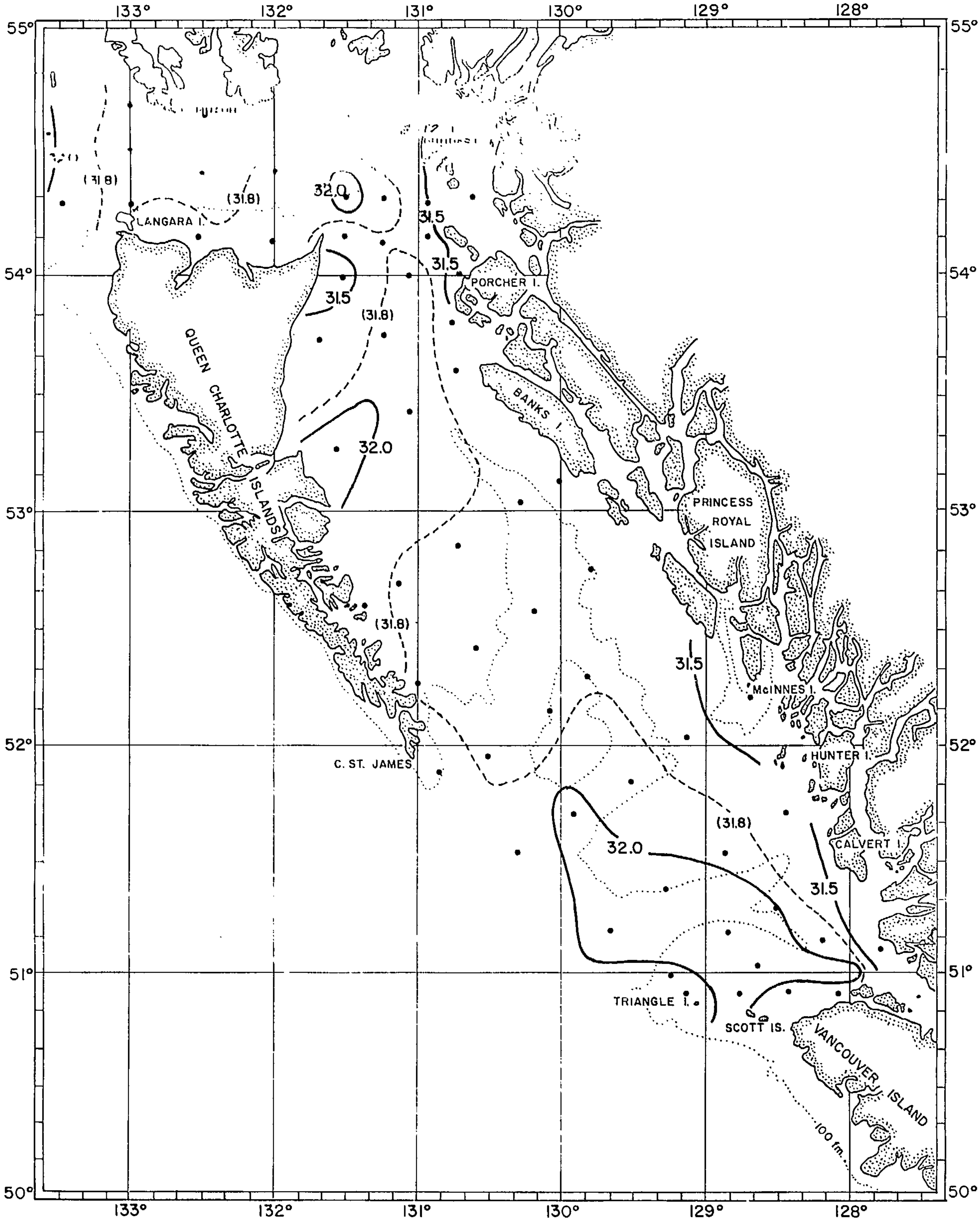


Fig. 69. Salinity (‰) distribution at 3 m depth, April 14-18, 1955.

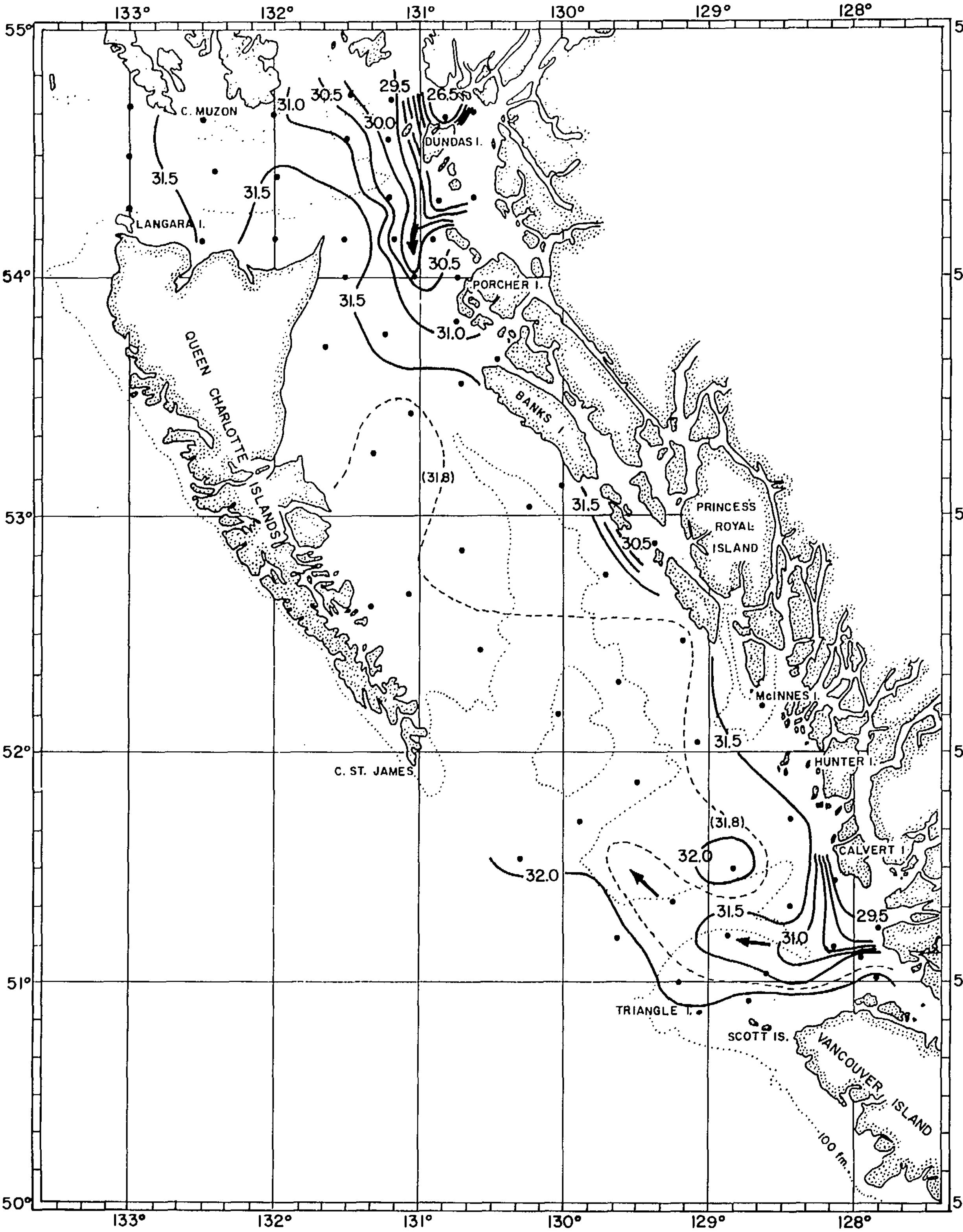


Fig. 70. Salinity (‰) distribution at 3 m depth, May 30-June 24, 1955 (arrows indicate direction of flow).

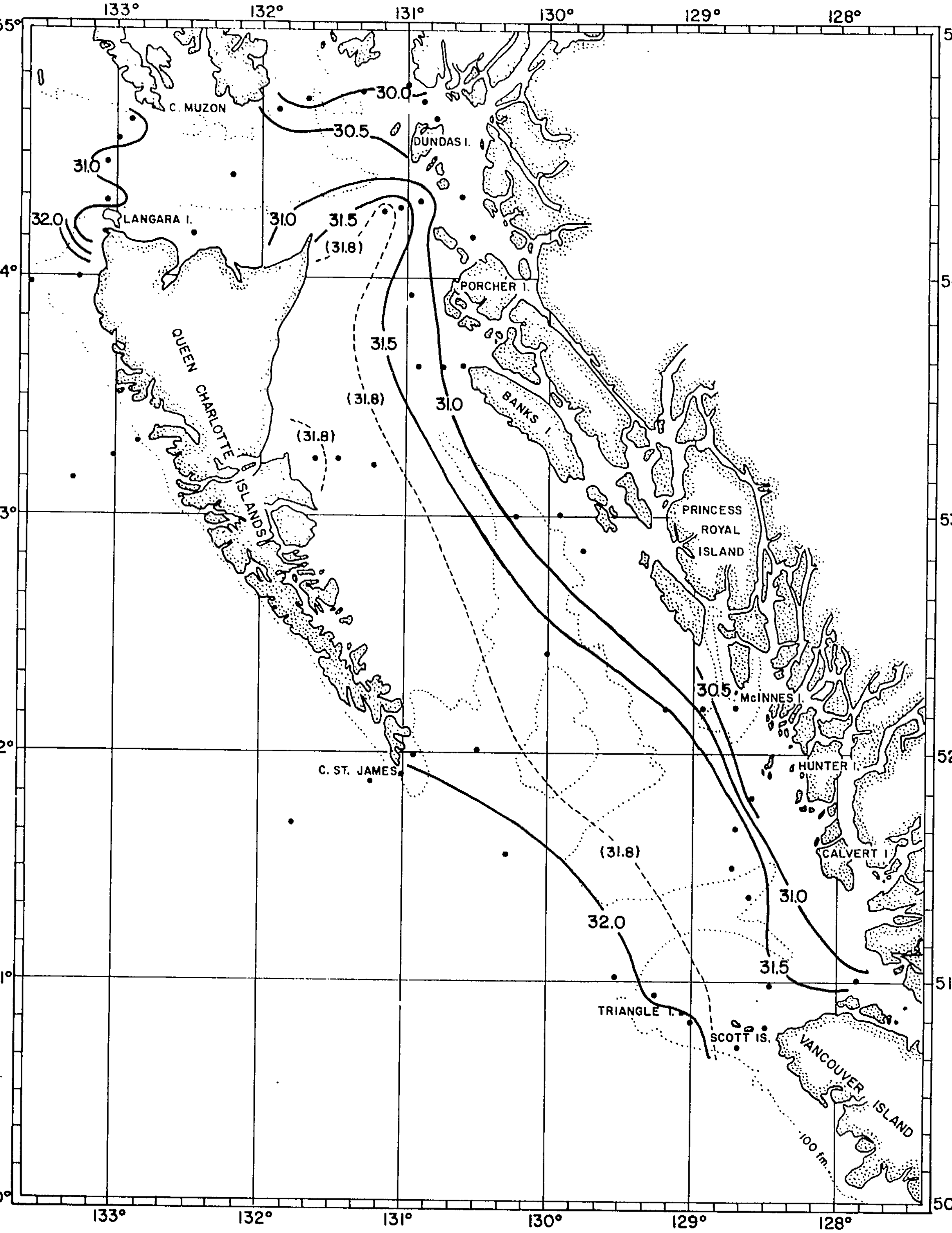


Fig. 71. Salinity (‰) distribution at 5 m depth, April 12-21, 1959.

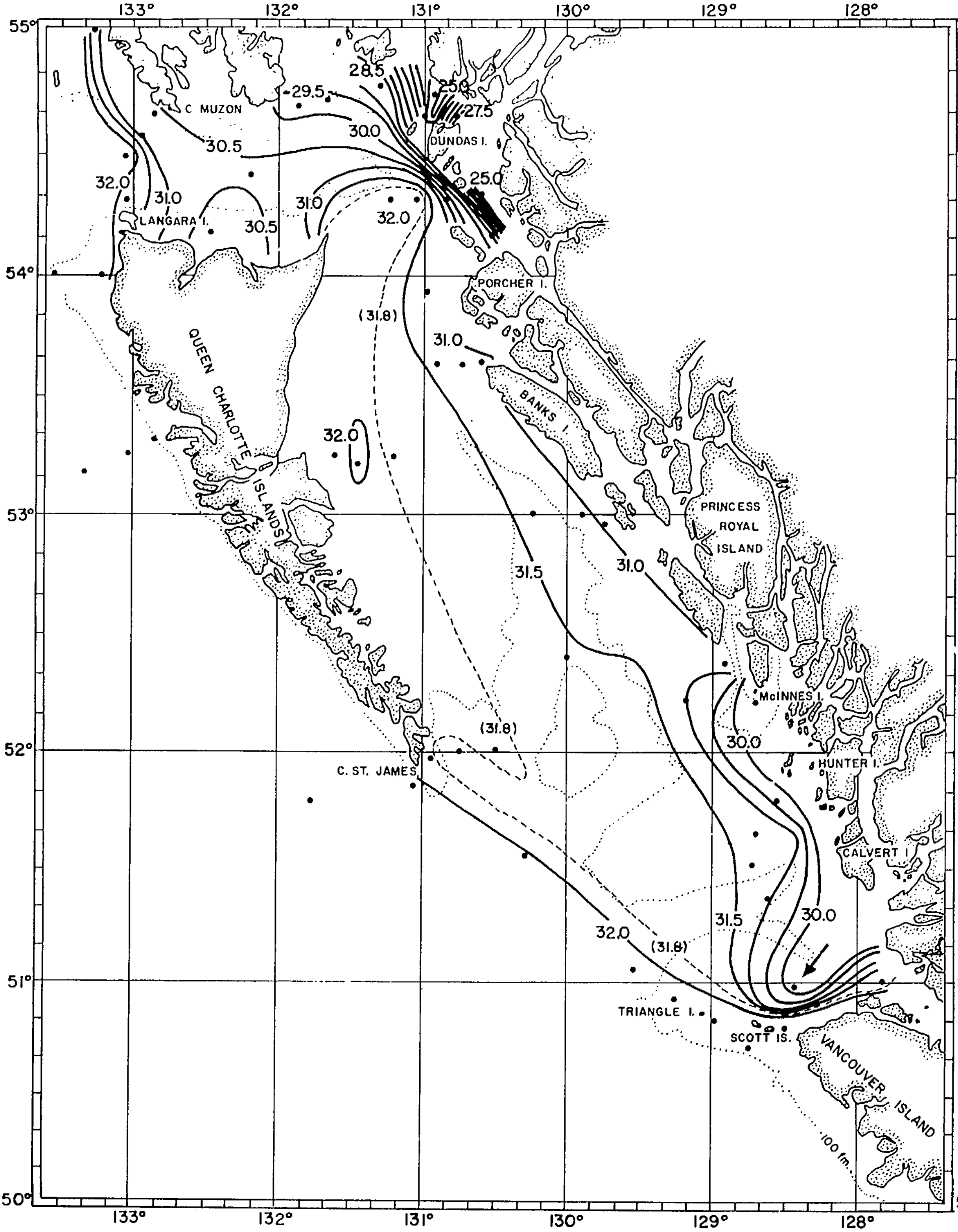


Fig. 72. Salinity (‰) distribution at 5 m depth, June 21-29, 1959 (arrows indicate direction of flow).

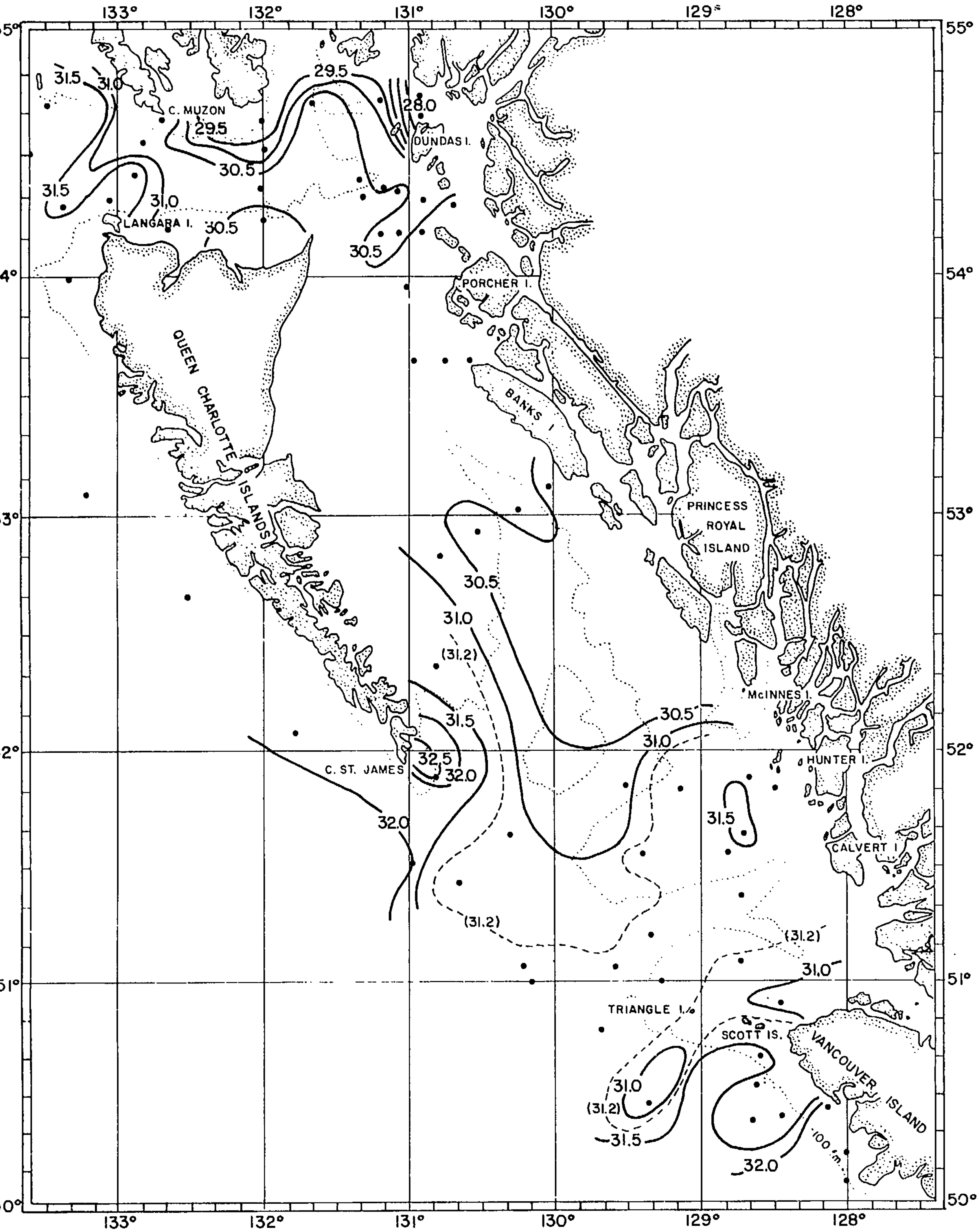


Fig. 73. Salinity (‰) distribution at 5 m depth, July 27-August 3, 1961.

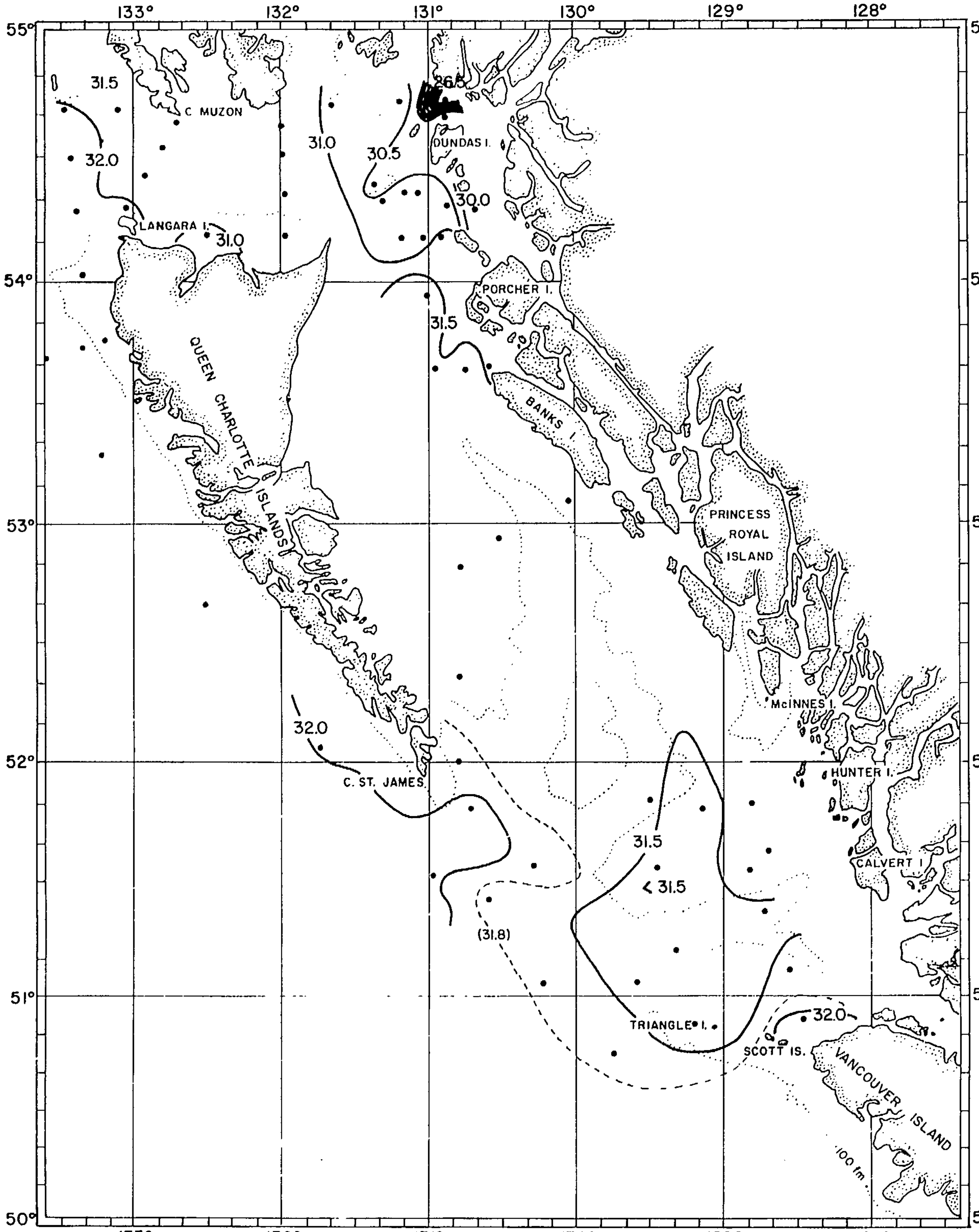


Fig. 74. Salinity (‰) distribution at 5 m depth, October 3-9, 1961.

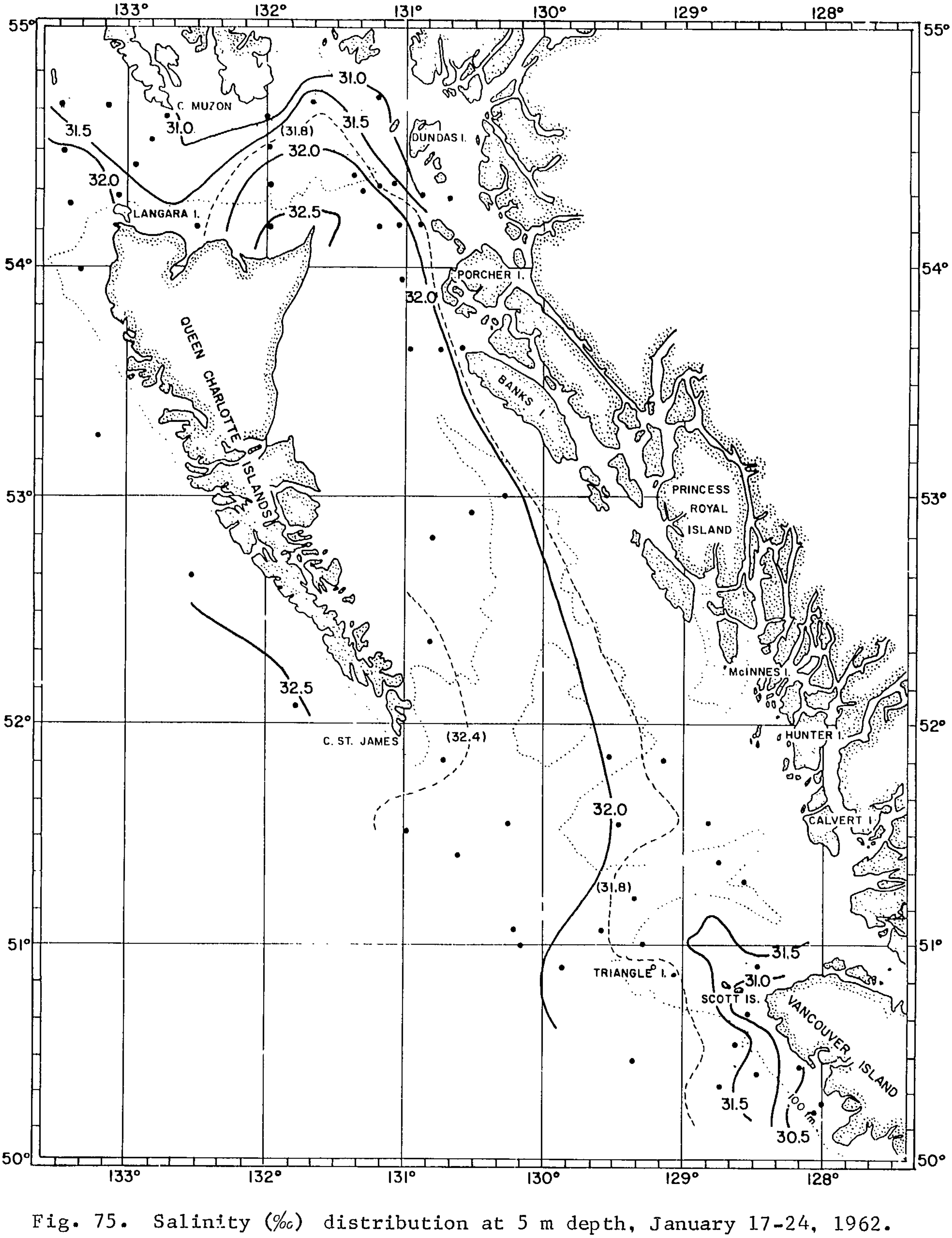


Fig. 75. Salinity (‰) distribution at 5 m depth, January 17-24, 1962.

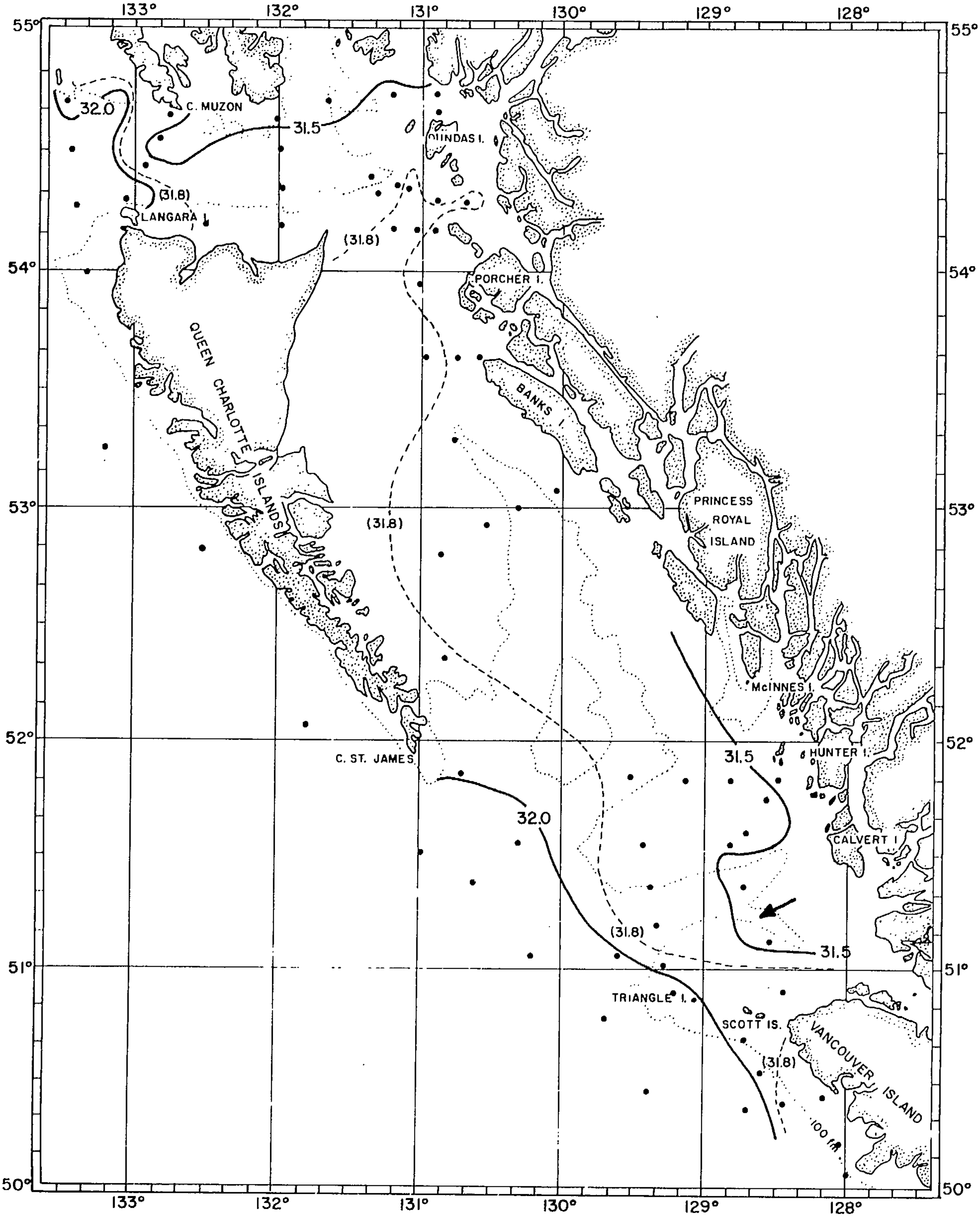


Fig. 76. Salinity (‰) distribution at 5 m depth, March 13-20, 1962 (arrows indicate direction of flow).

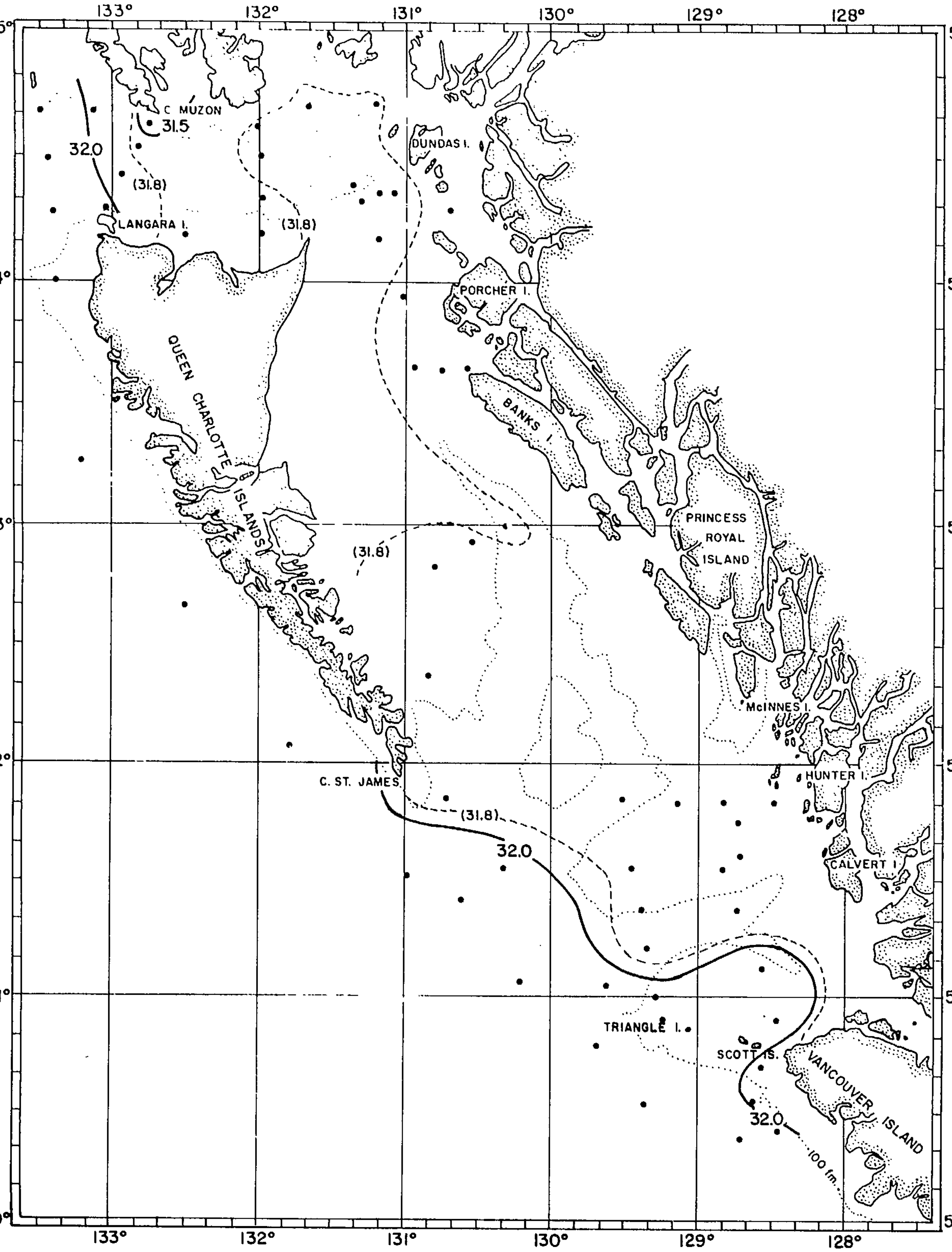


Fig. 77. Salinity (‰) distribution at 5 m depth, March 28-April 3, 1962.

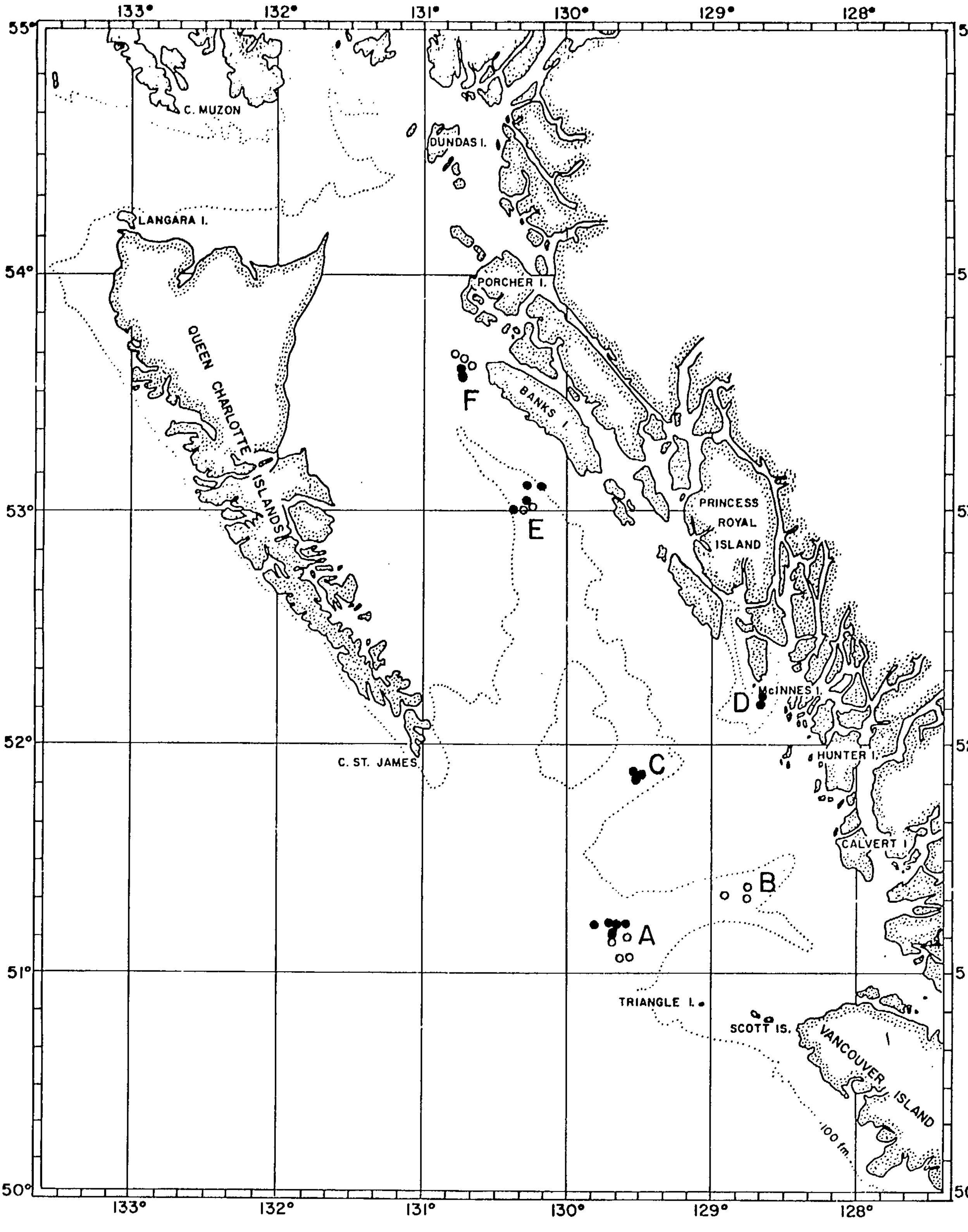


Fig. 78. Areas and stations selected to show the annual cycle of temperature, salinity, density and dissolved oxygen content in the subsurface waters of Queen Charlotte Sound and Hecate Strait (● 1954-55; o 1960-62).

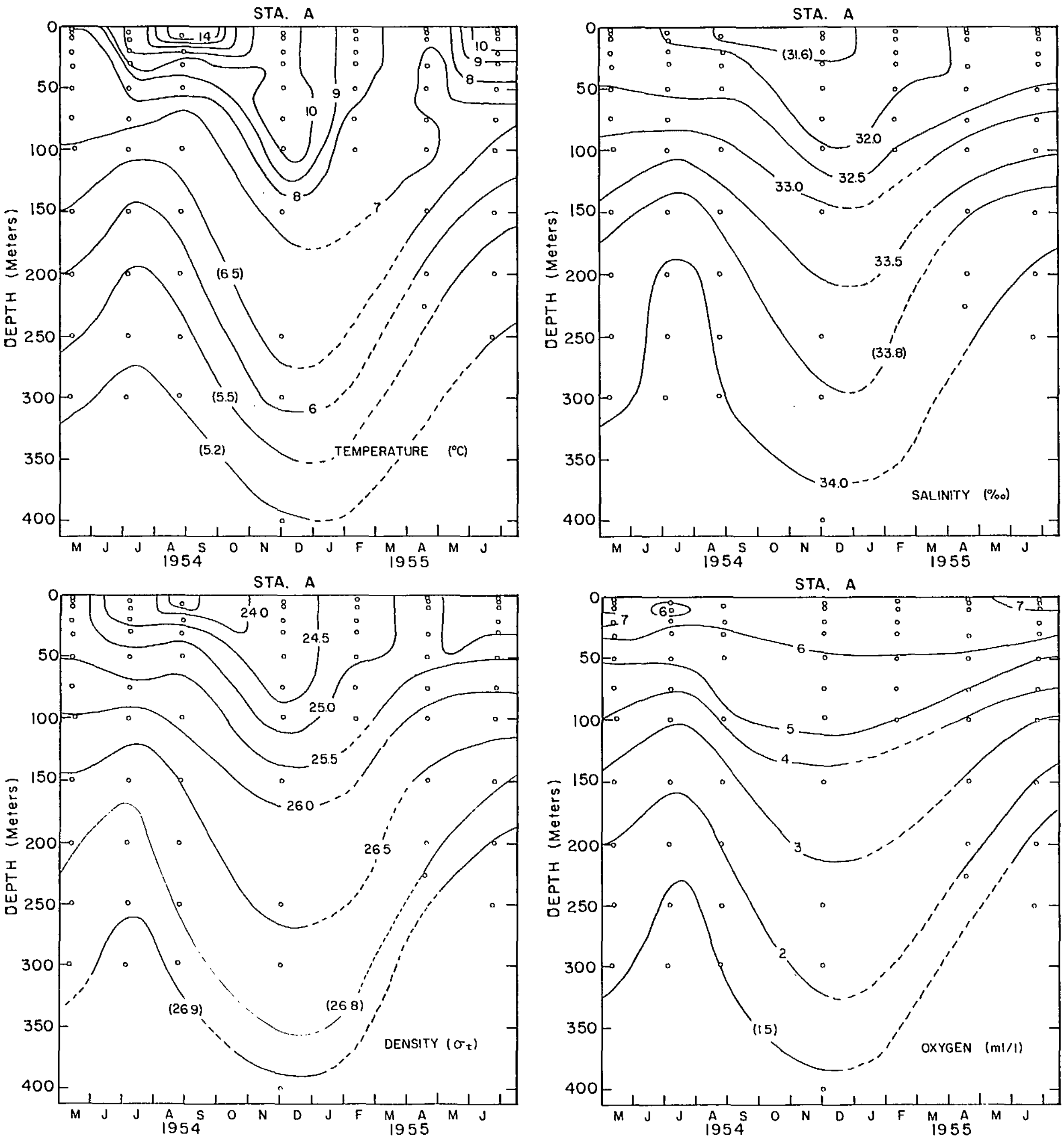


Fig. 79. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station A in Queen Charlotte Sound, 1954-55.

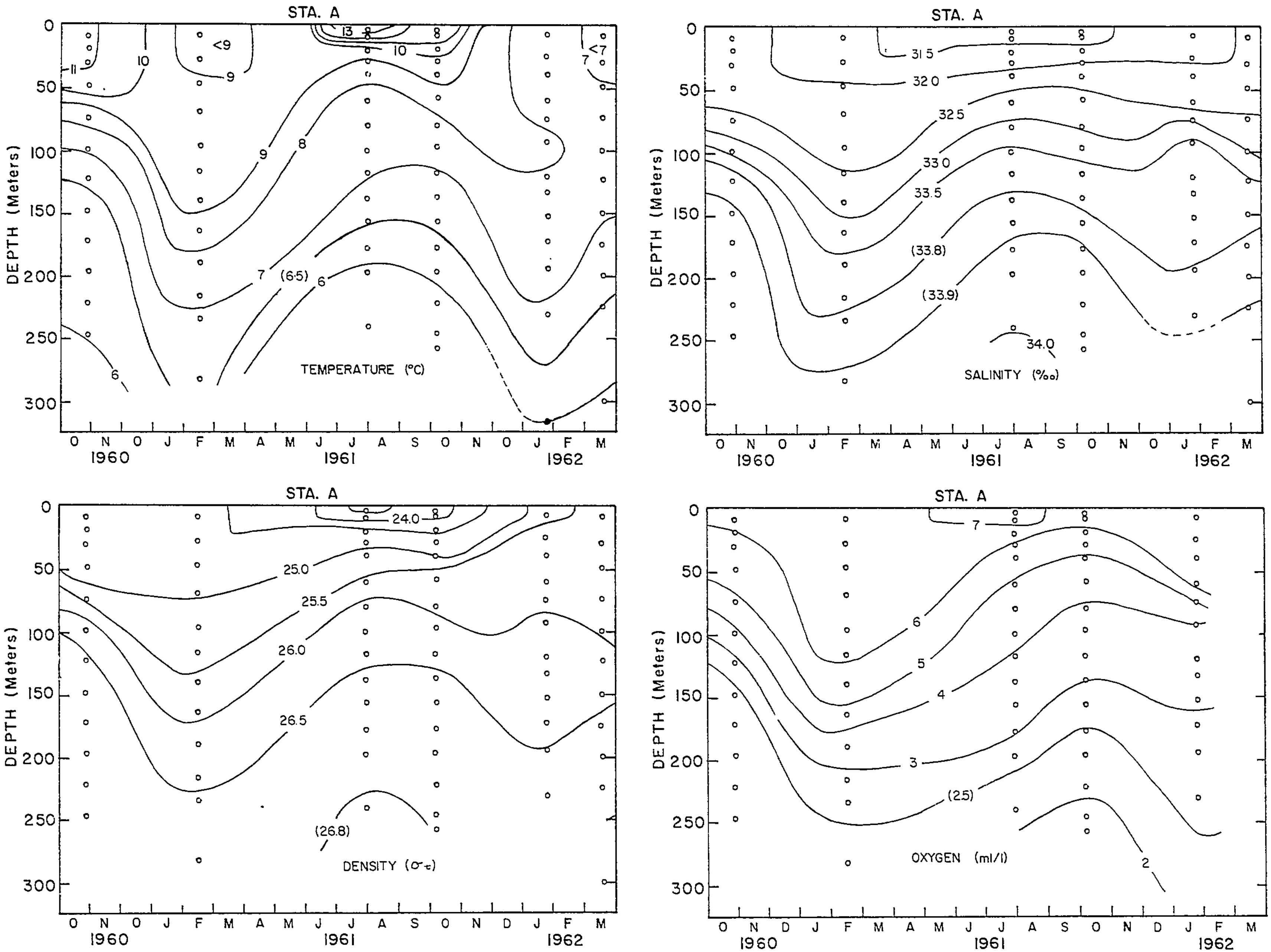


Fig. 80. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station A in Queen Charlotte Sound, 1960-62.

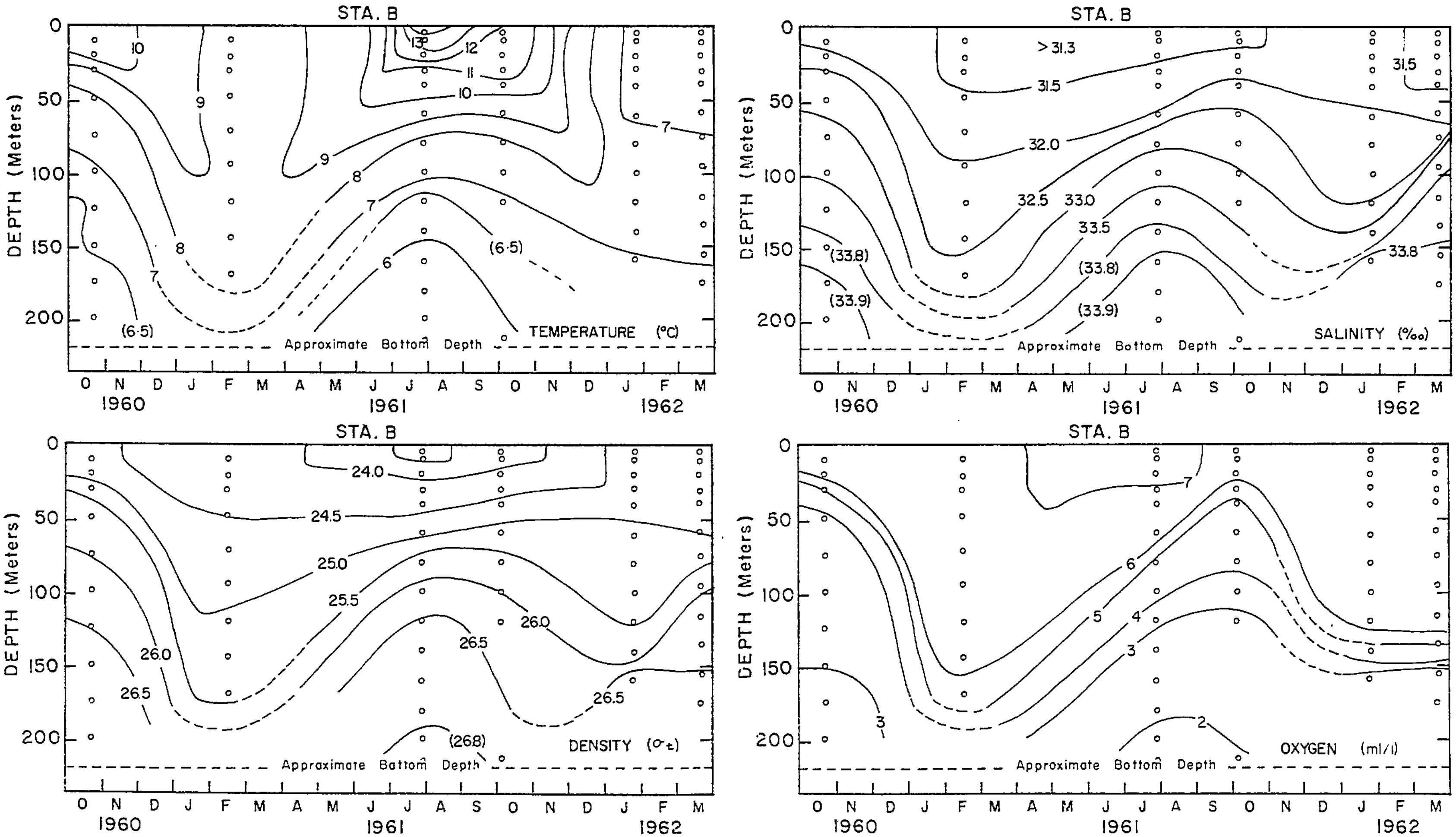


Fig. 81. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station B in Queen Charlotte Sound, 1960-62.

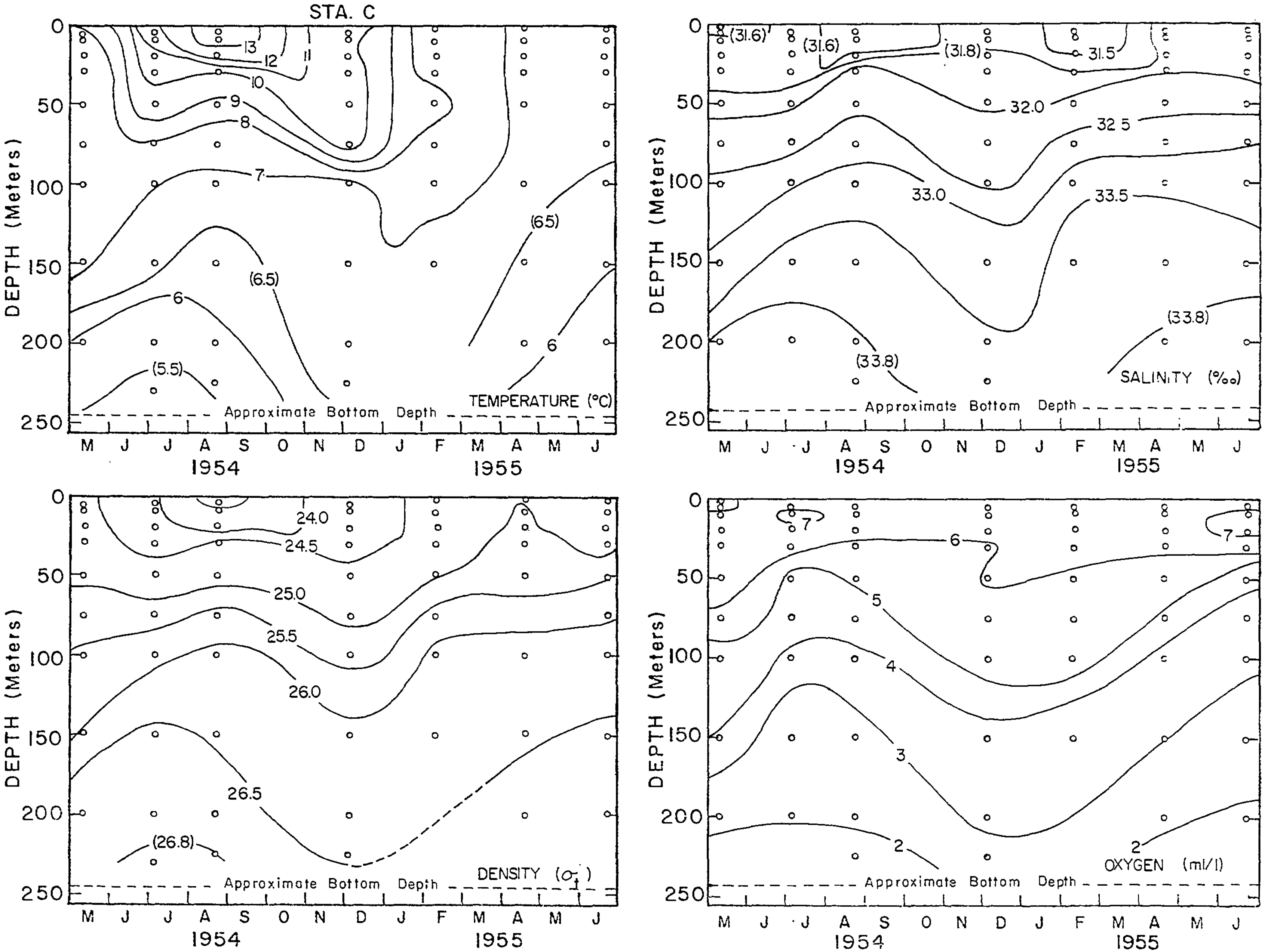


Fig. 82. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station C in Queen Charlotte Sound, 1954-55.

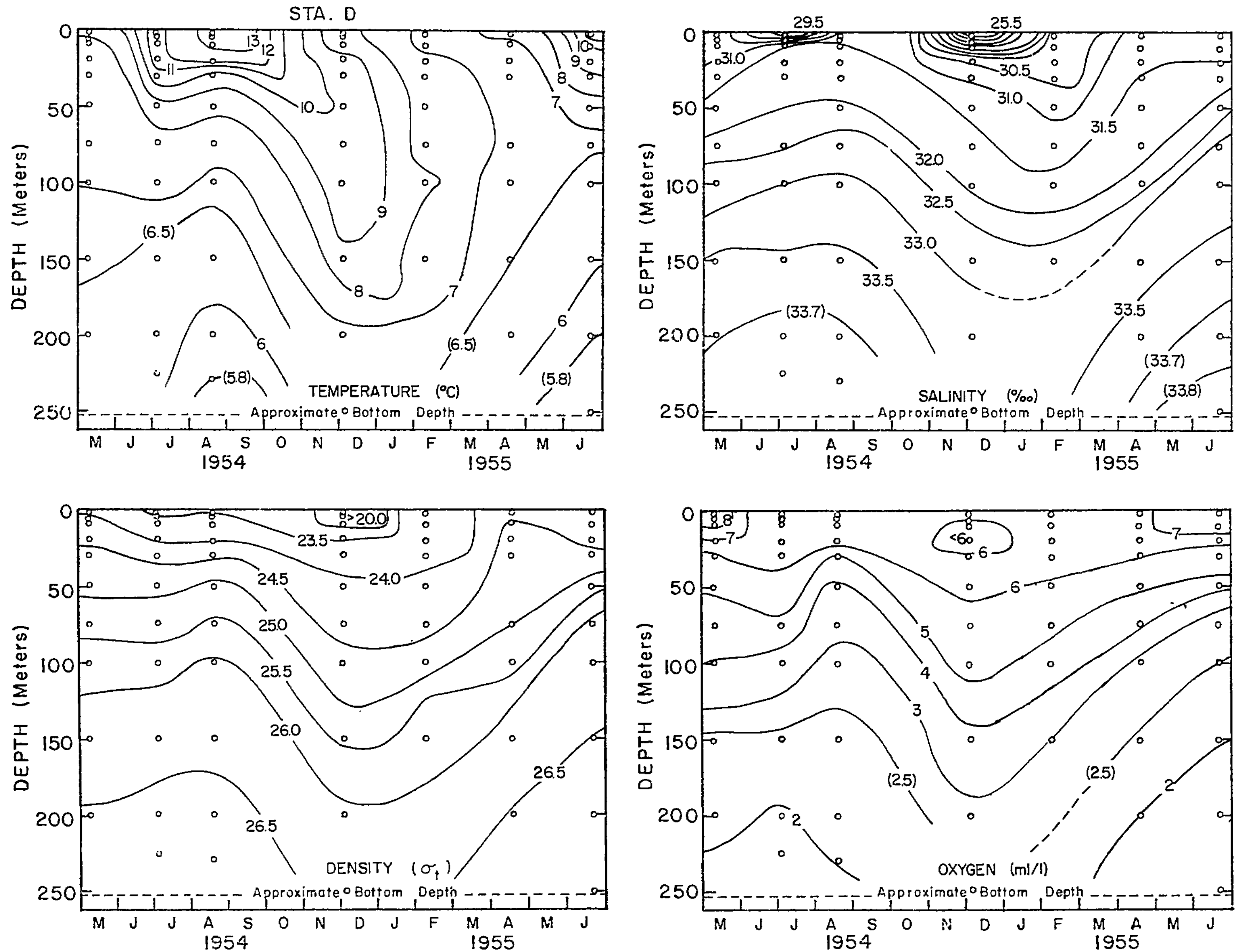


Fig. 83. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station D in Queen Charlotte Sound, 1954-55.

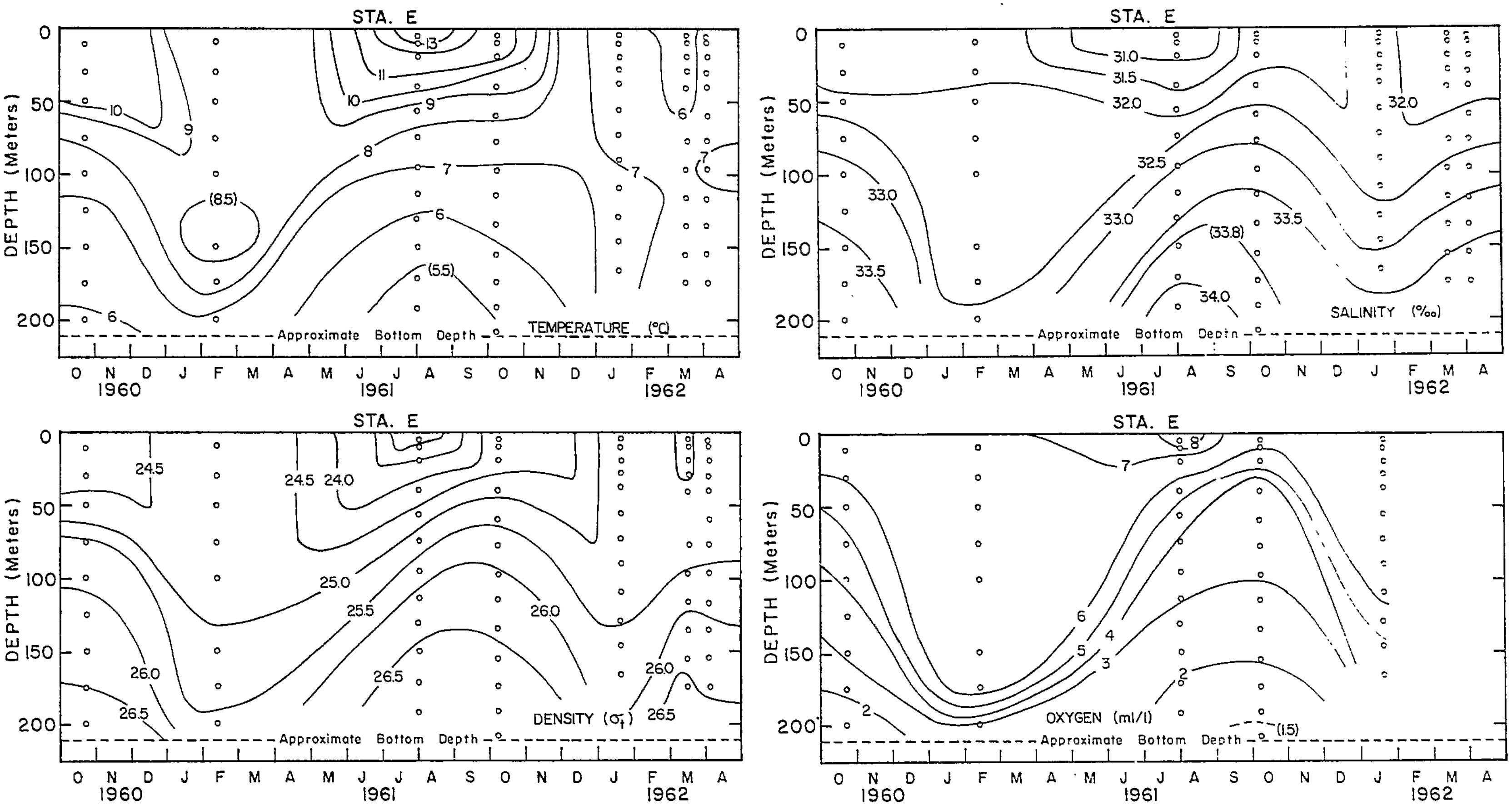


Fig. 84. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station E in Hecate Strait, 1960-62.

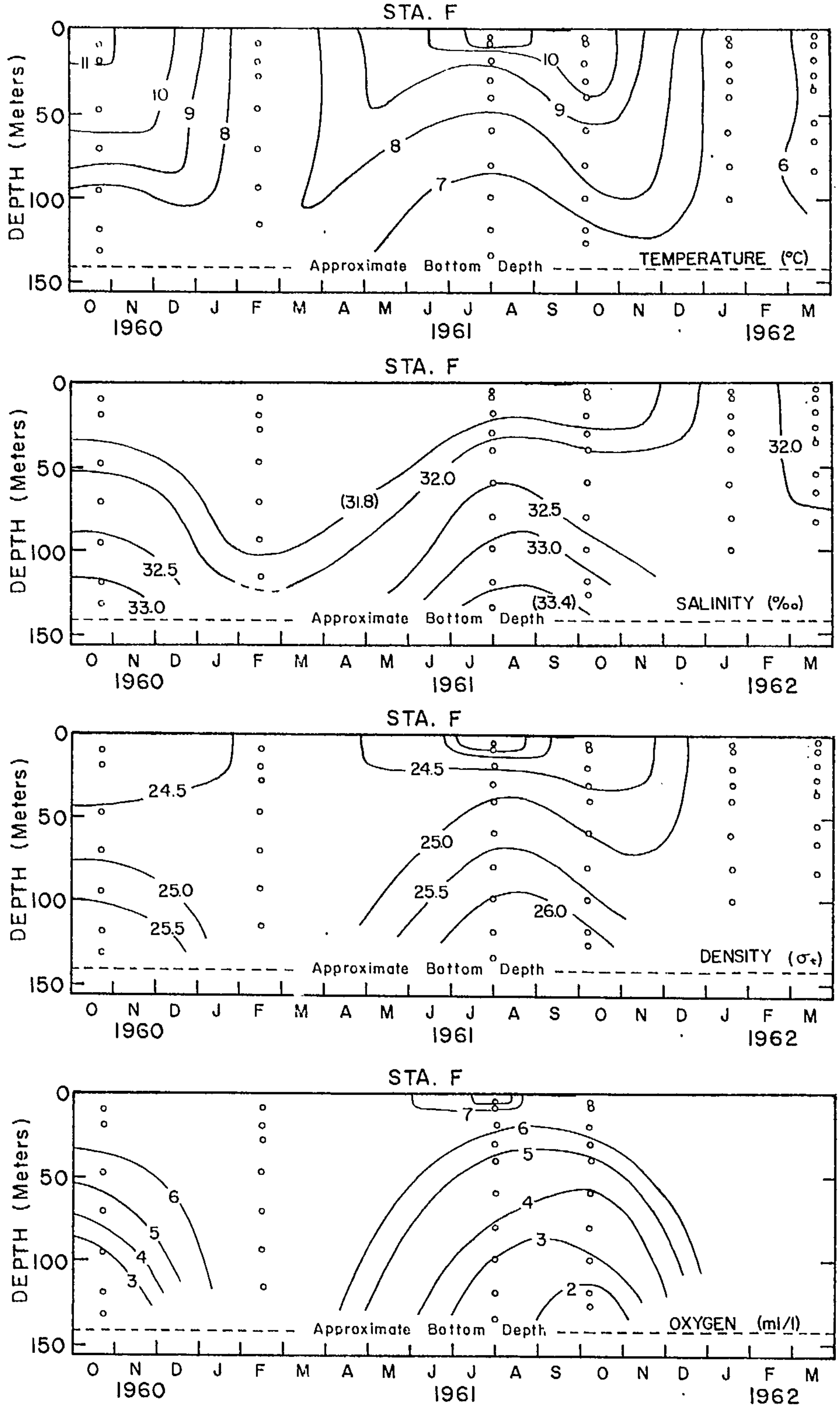


Fig. 85. Annual cycle of temperature, salinity, density and dissolved oxygen content at Station F in Hecate Strait, 1960-62.

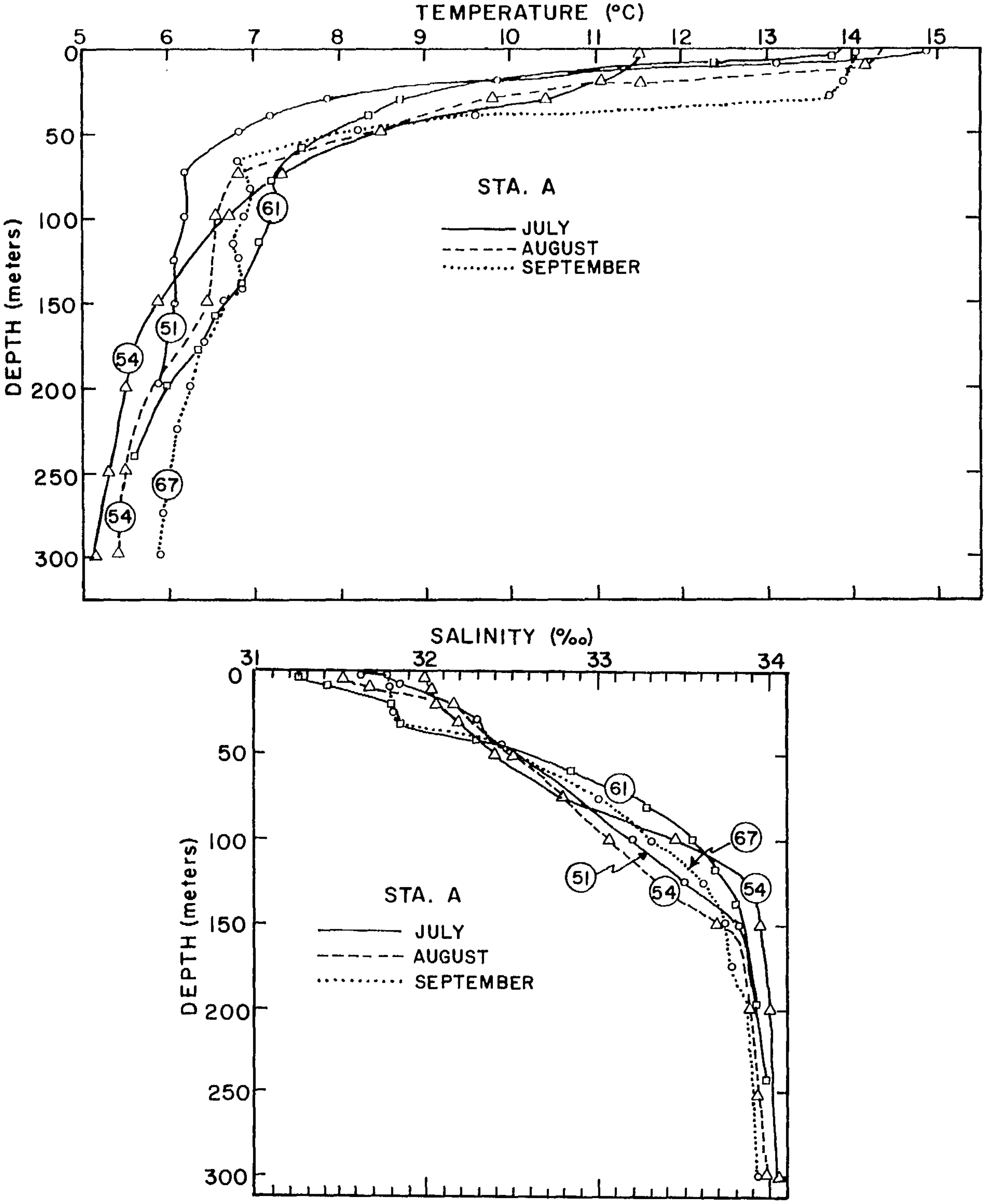


Fig. 86. Temperature and salinity structures at Station A in Queen Charlotte Sound, July-August (numbers in circles indicate year).

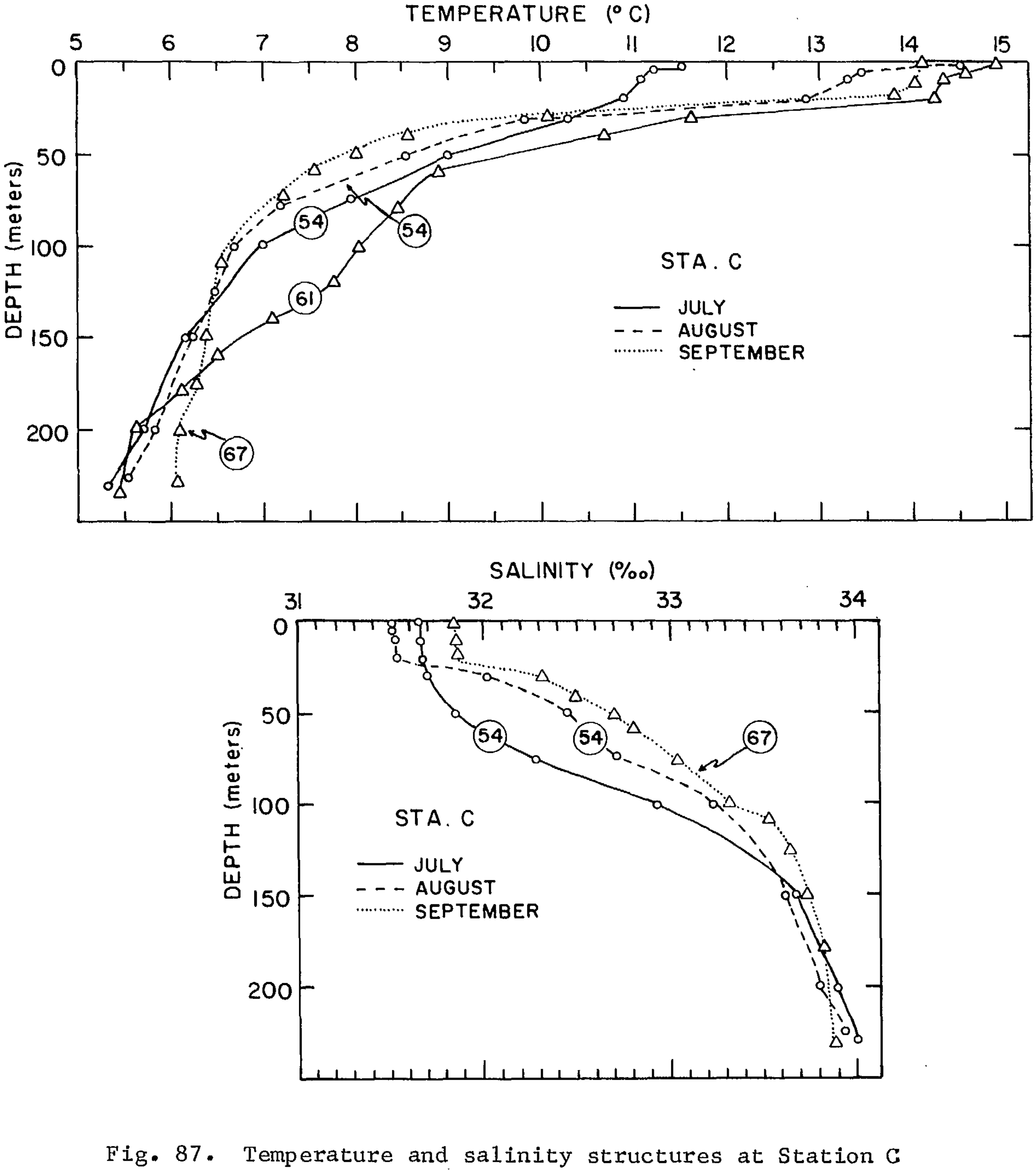


Fig. 87. Temperature and salinity structures at Station C in Queen Charlotte Sound, July-September.

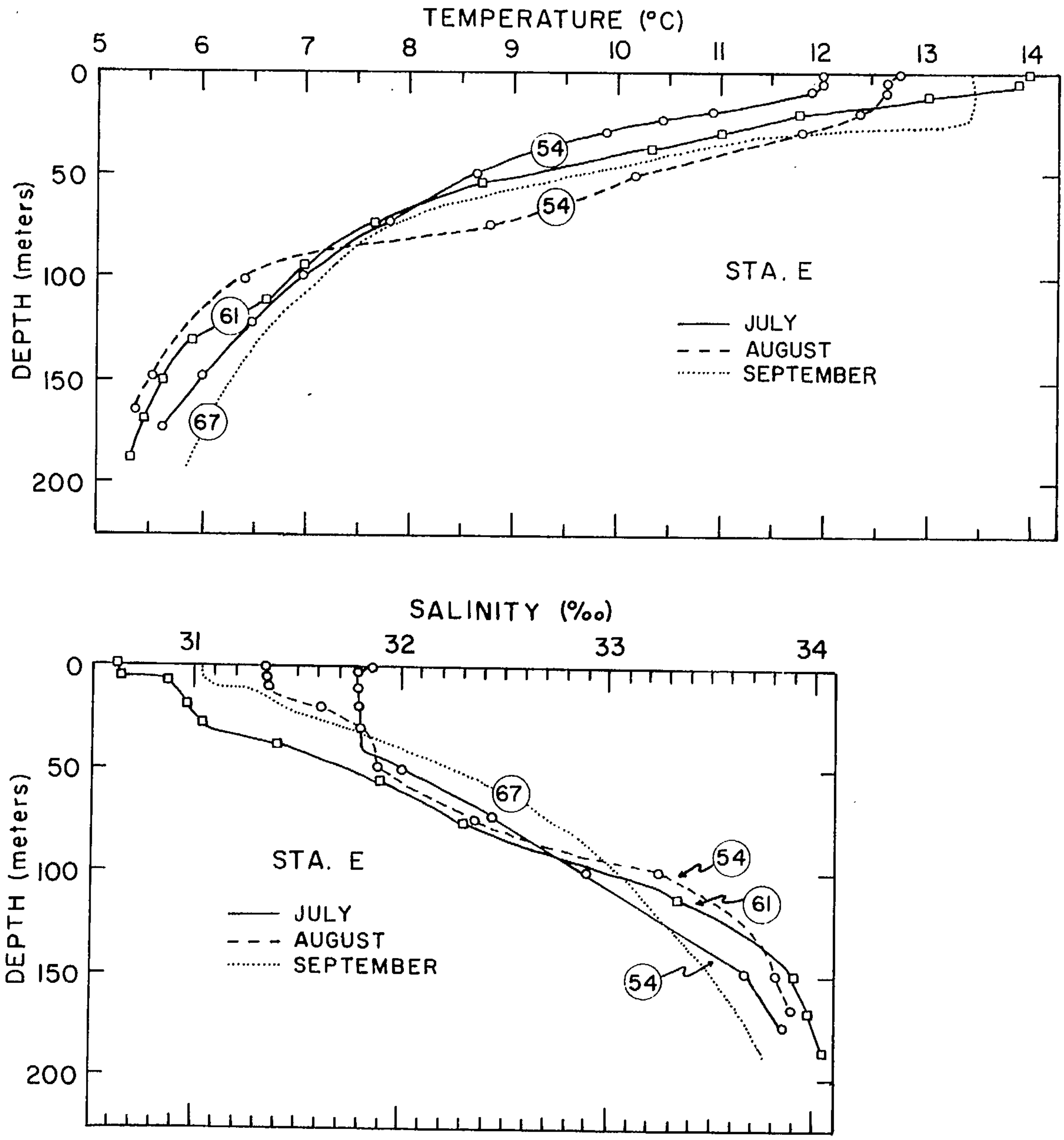


Fig. 88. Temperature and salinity structures at Station E in Hecate Strait, July-September.

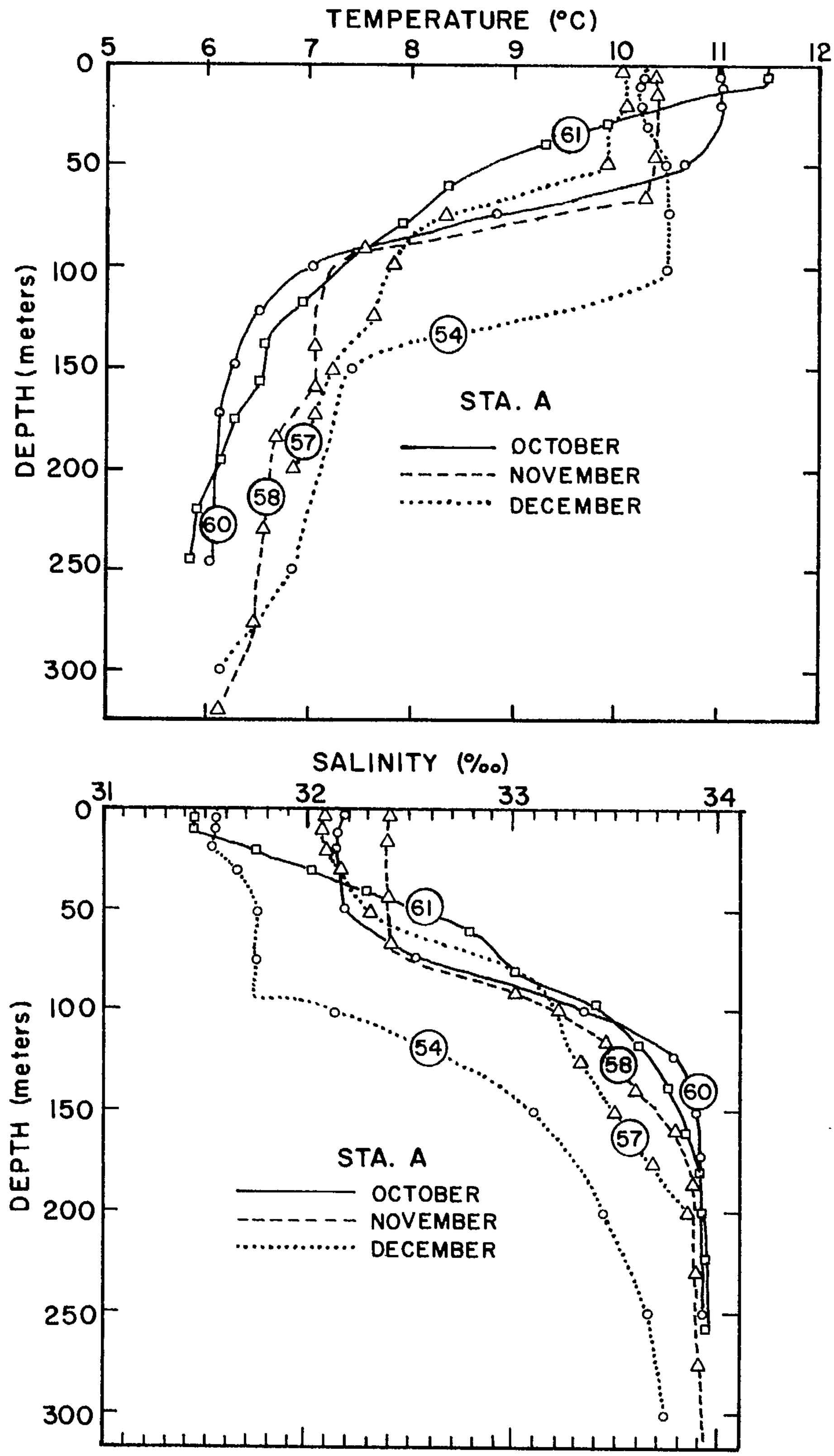


Fig. 89. Temperature and salinity structures at Station A in Queen Charlotte Sound, October-December.

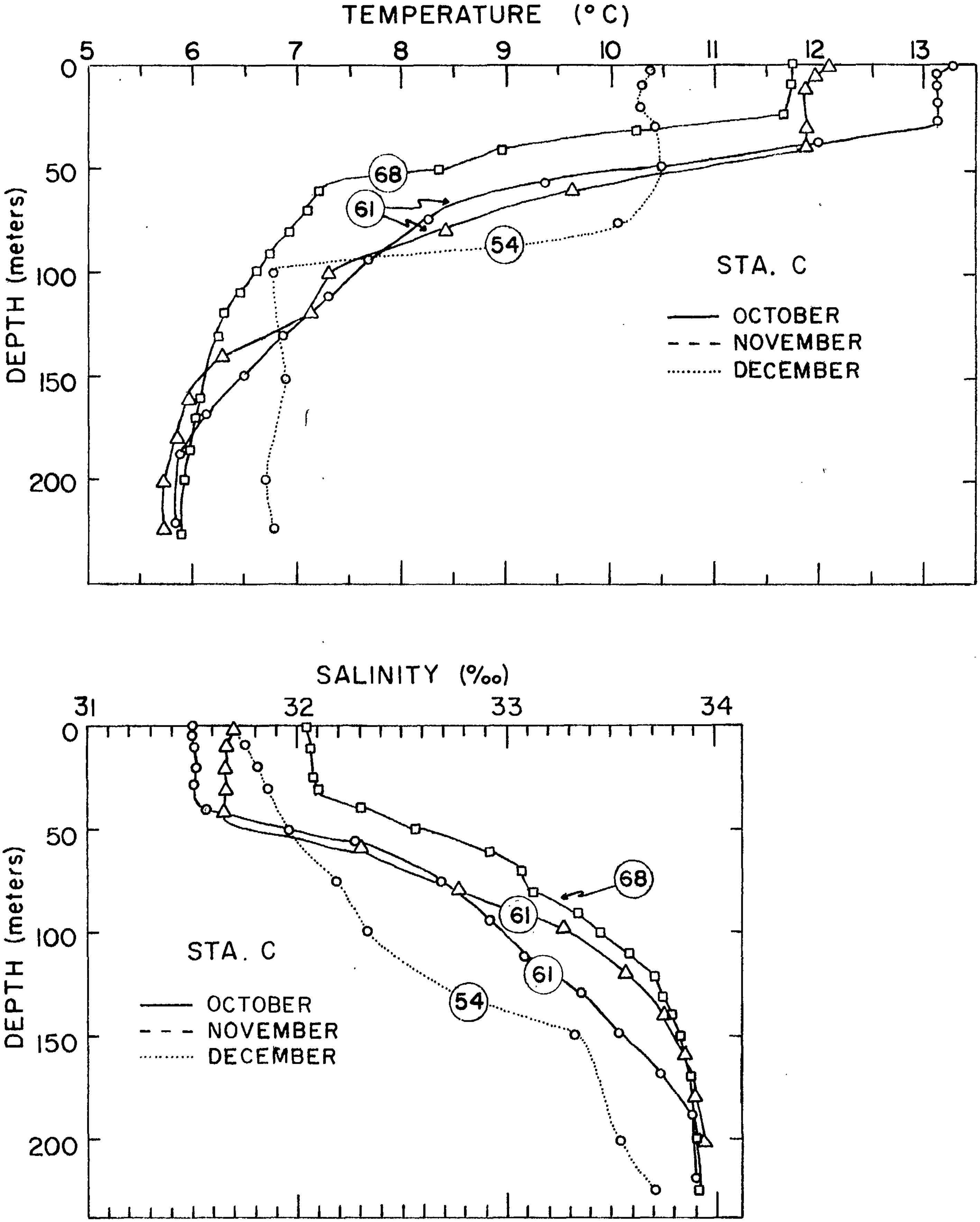


Fig. 90. Temperature and salinity structures at Station C in Queen Charlotte Sound, October-December.

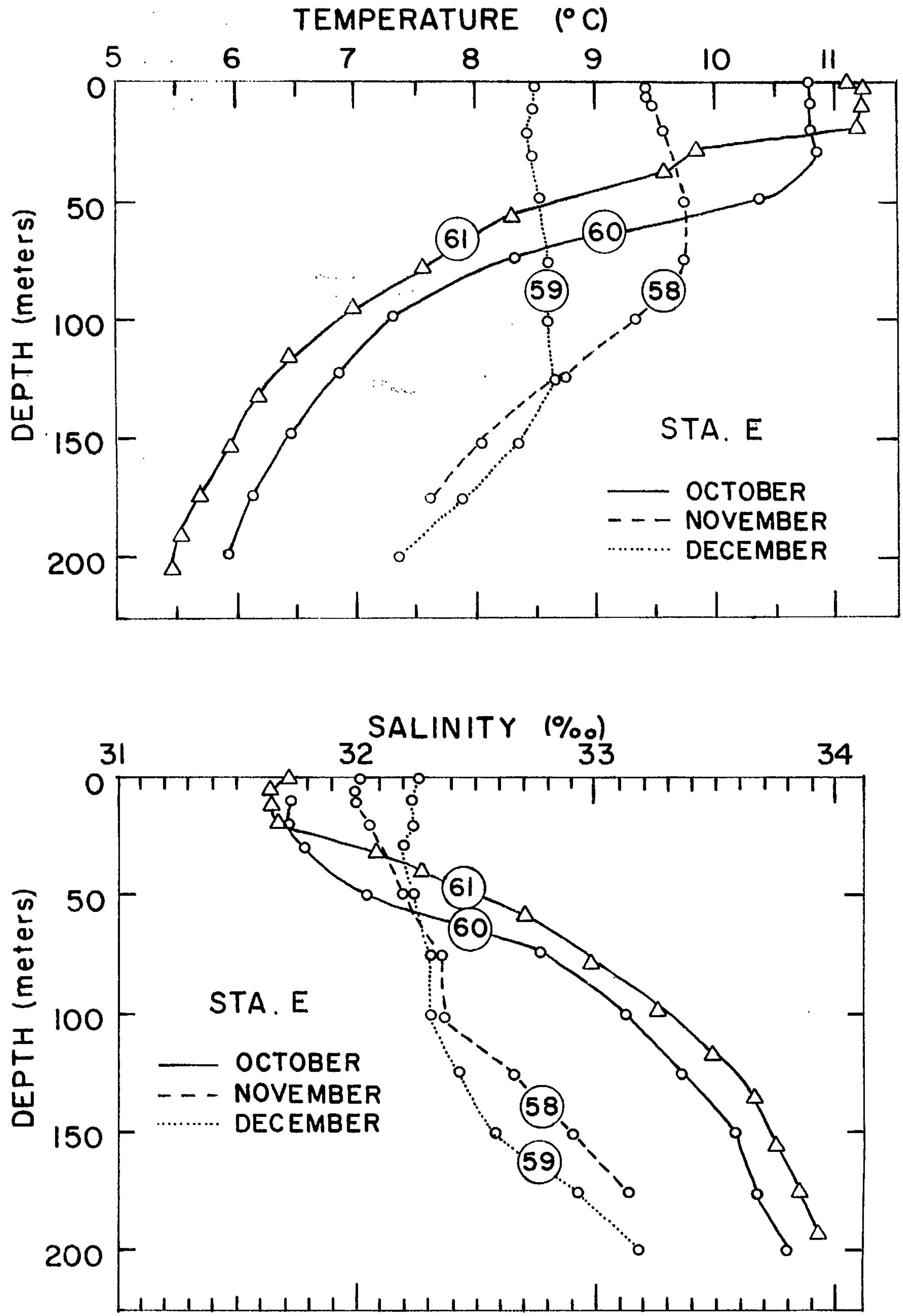


Fig. 91. Temperature and salinity structures at Station E in Hecate Strait, October-December.

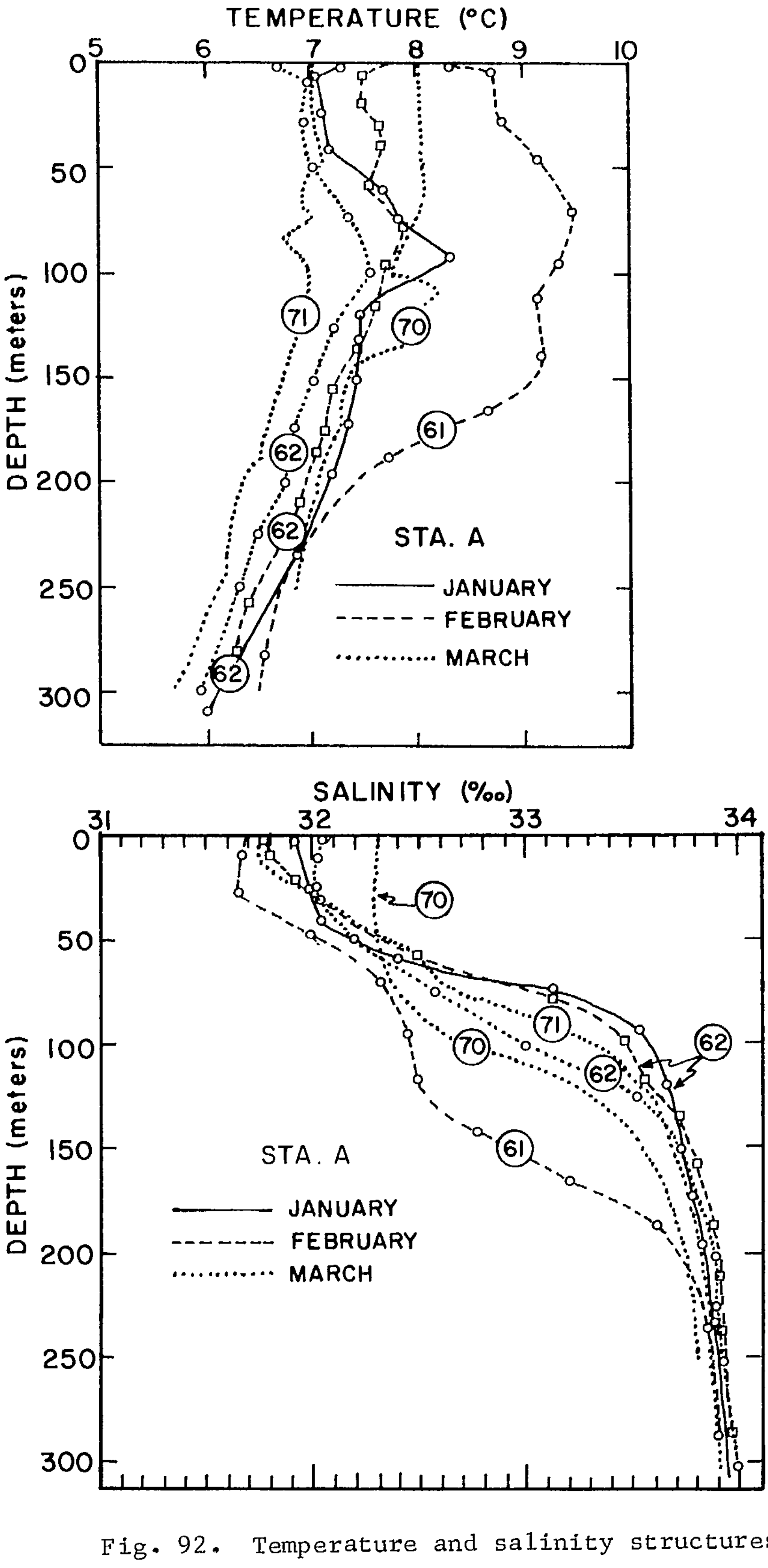


Fig. 92. Temperature and salinity structures at Station A in Queen Charlotte Sound, January-March.

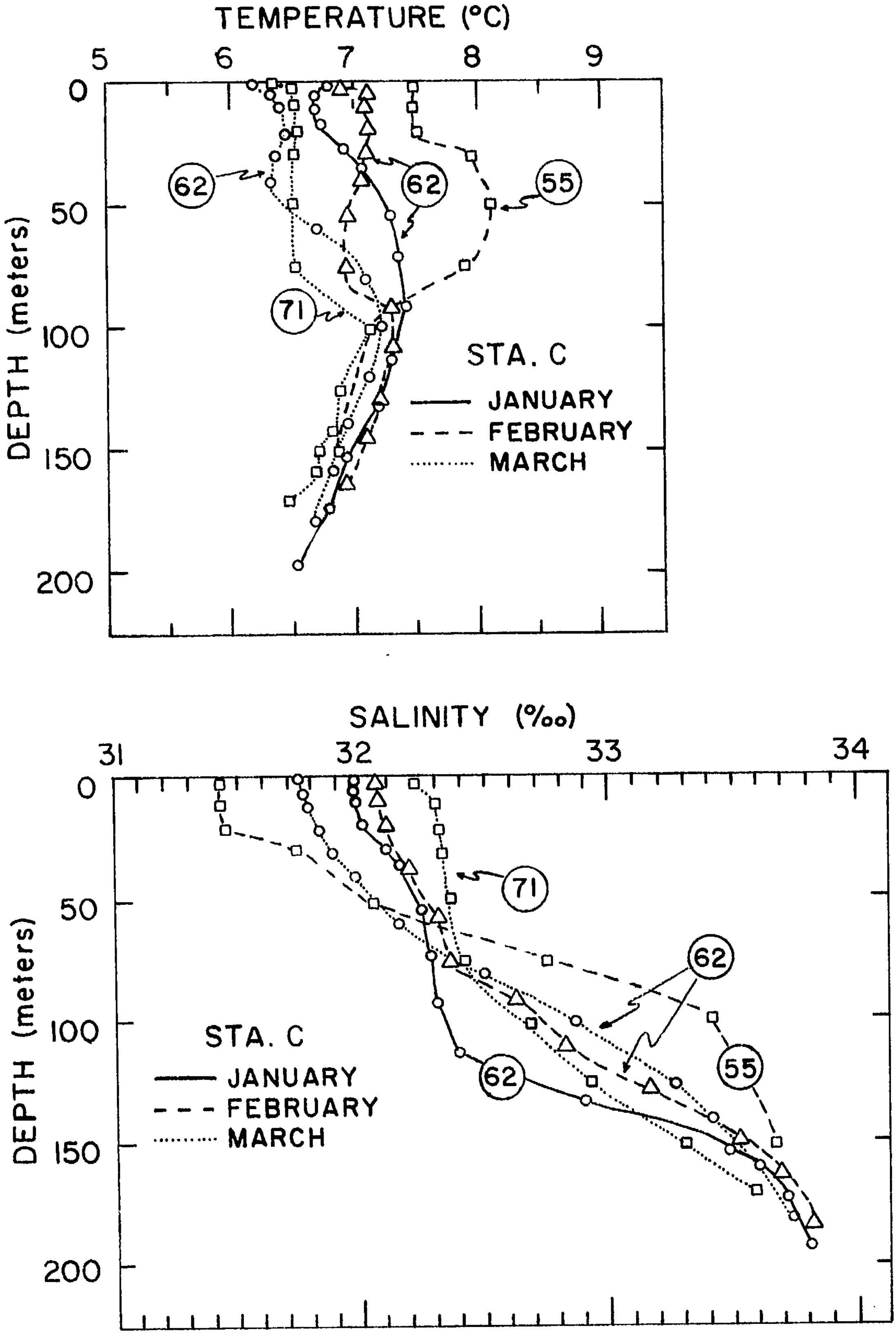
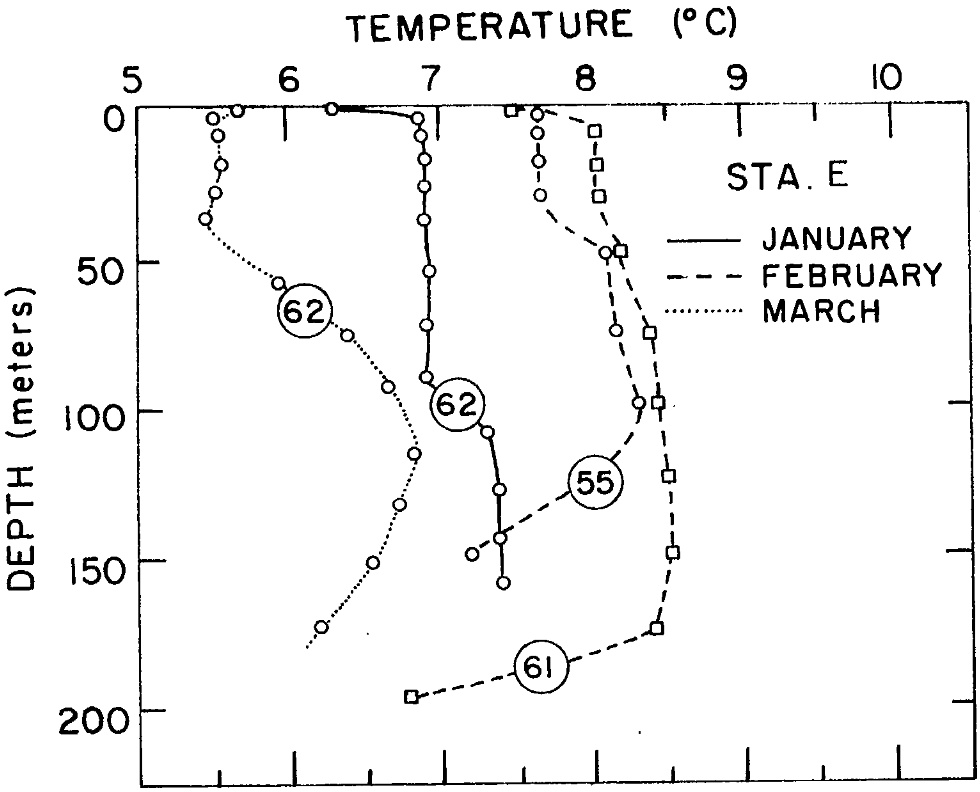


Fig. 93. Temperature and salinity structures at Station C in Queen Charlotte Sound, January-February.



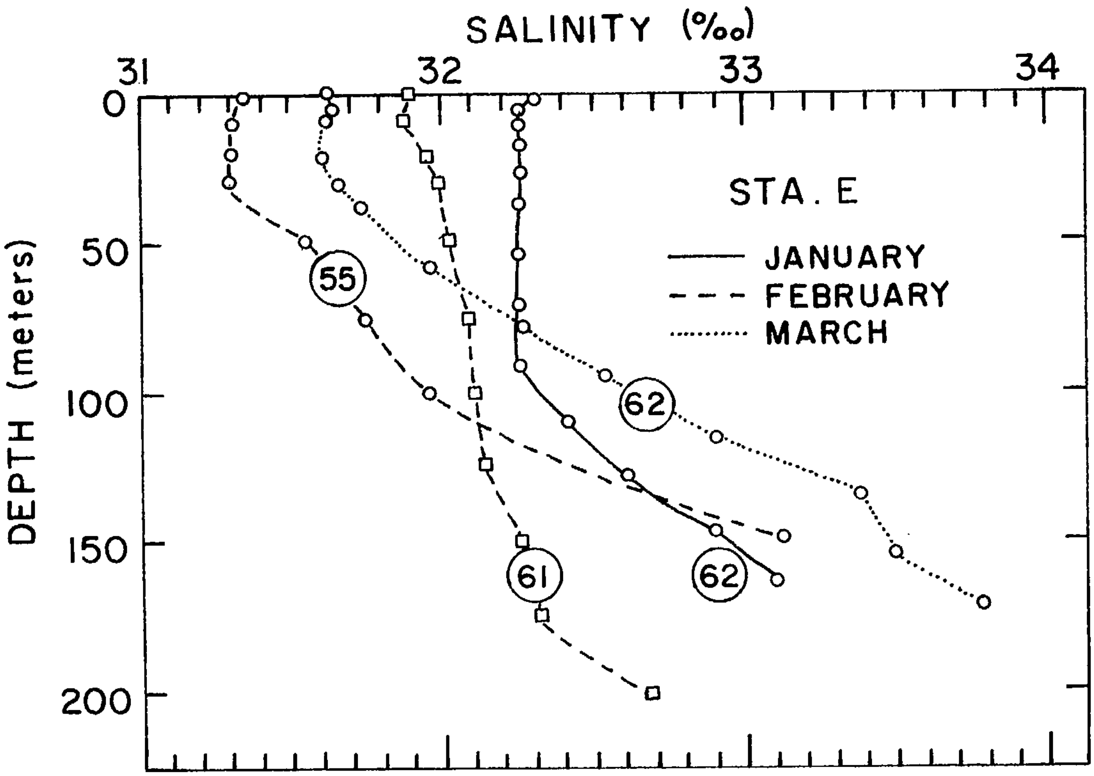


Fig. 94. Temperature and salinity structures at Station E in Hecate Strait, January-March.

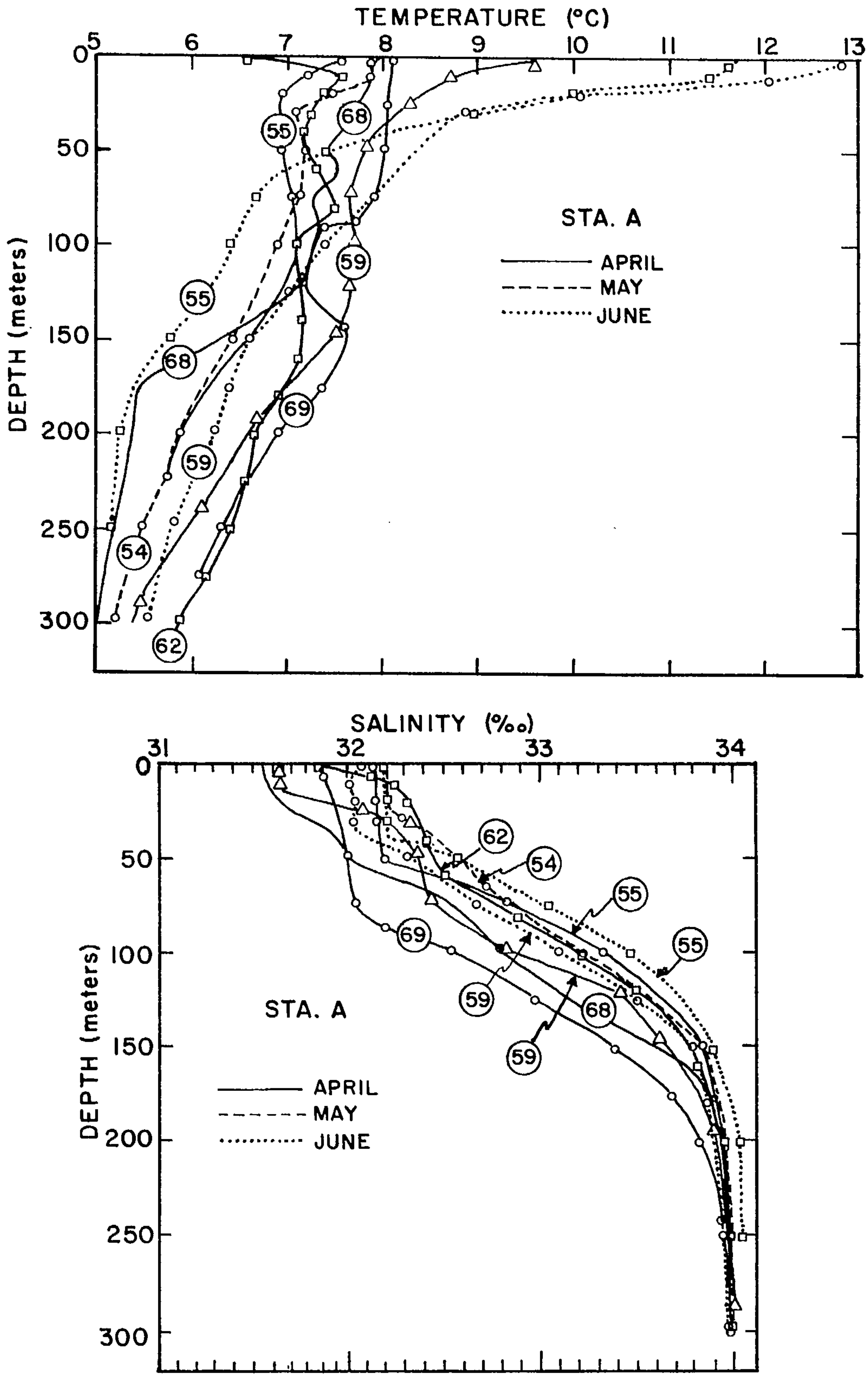
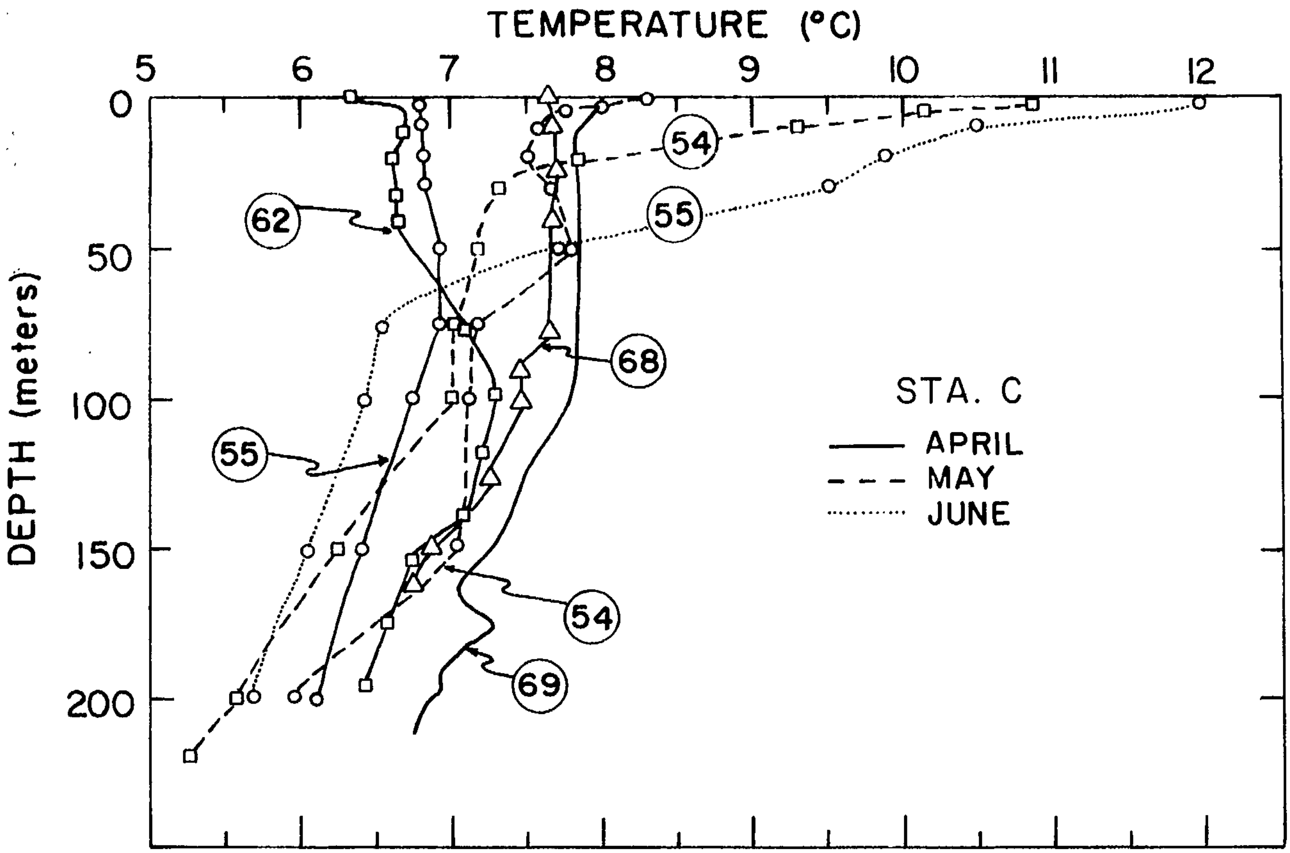


Fig. 95. Temperature and salinity structures at Station A in Queen Charlotte Sound, April-June.



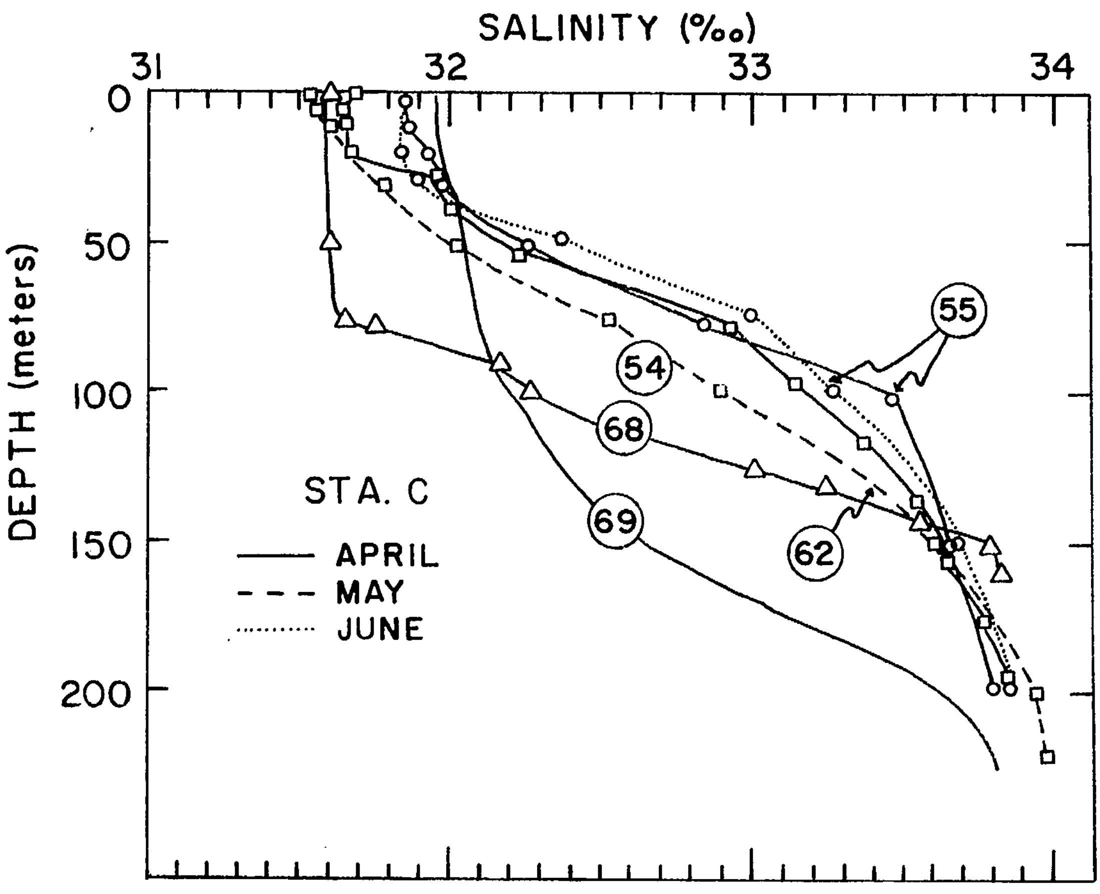
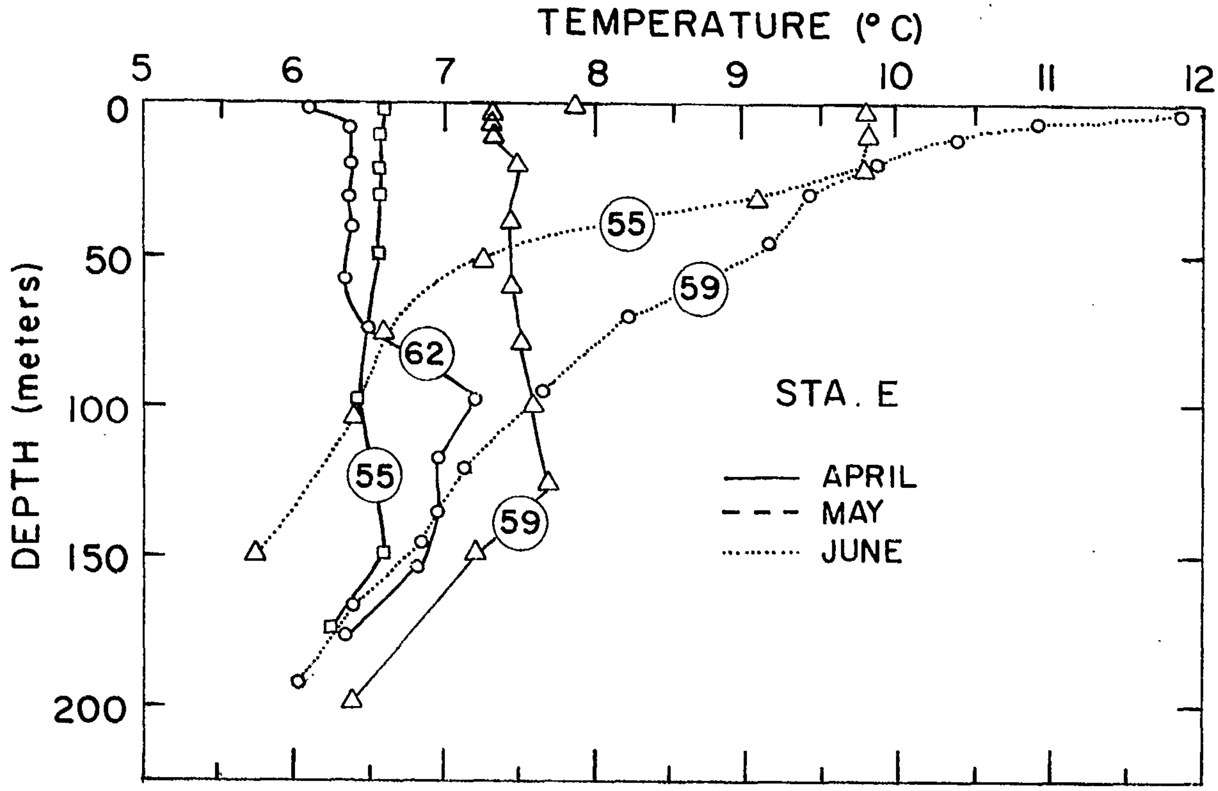


Fig. 96. Temperature and salinity structures at Station C in Queen Charlotte Sound, April-June.



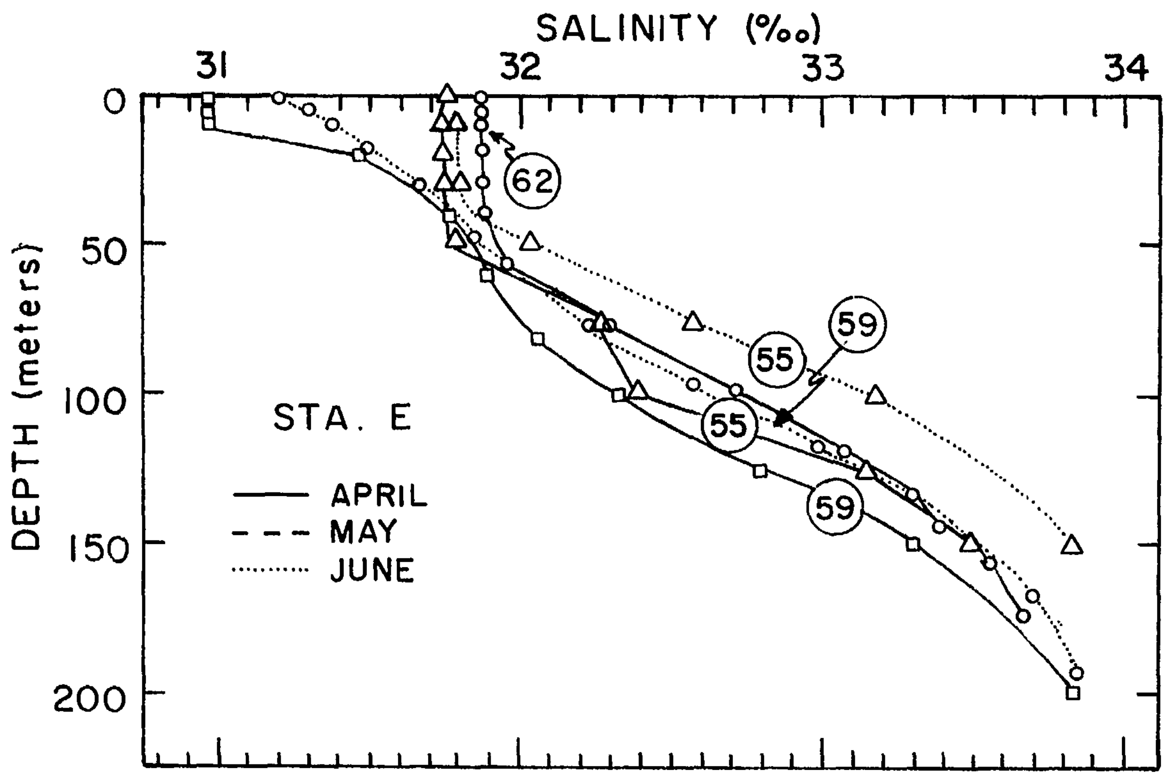


Fig. 97. Temperature and salinity structures at Station E in Hecate Strait, April-June.

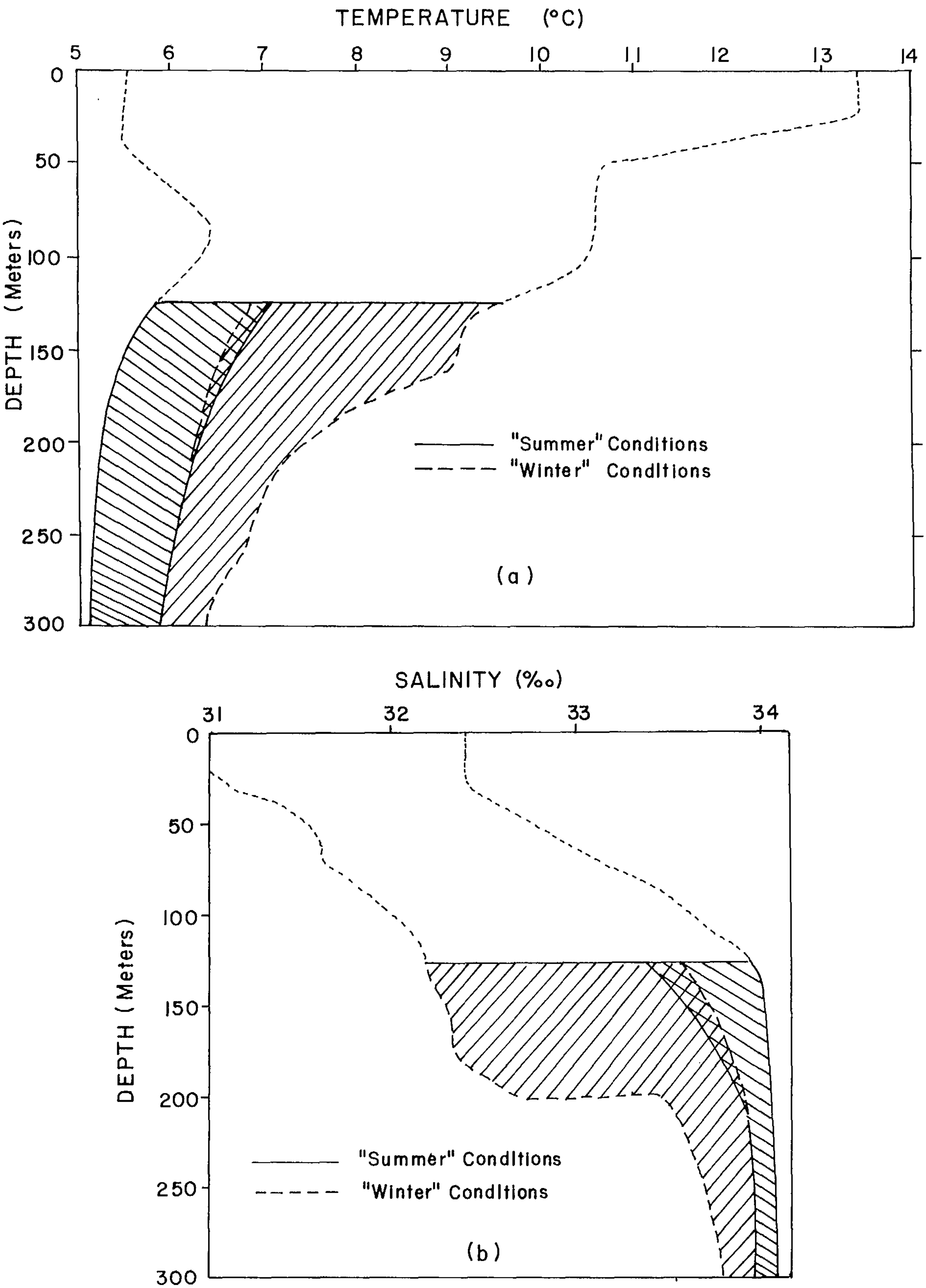


Fig. 98. Approximate ranges of "summer" and "winter" (a) temperature and (b) salinity conditions in the subsurface waters of Queen Charlotte Sound and Hecate Strait.

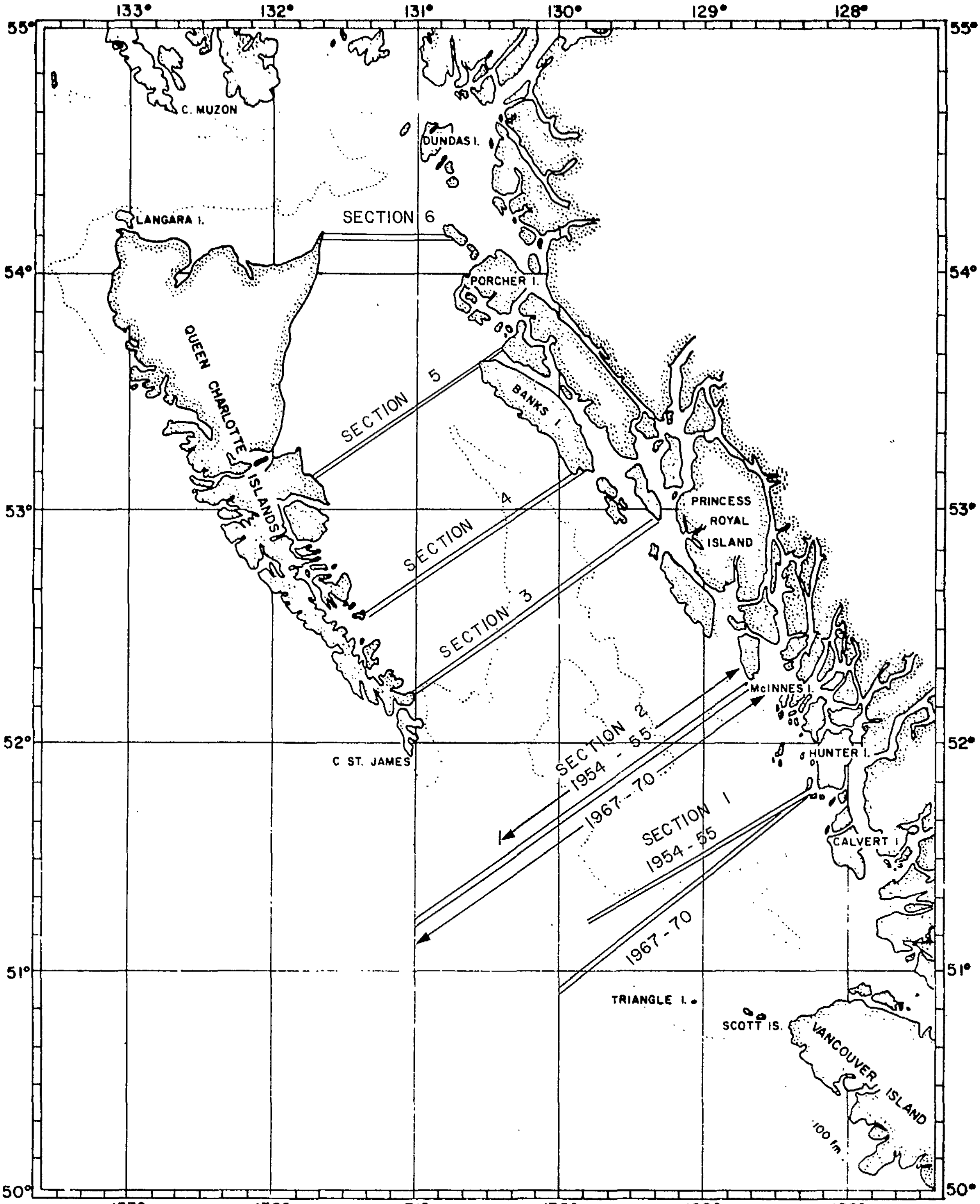


Fig. 99. Location of vertical sections presented in Figs. 100-141.

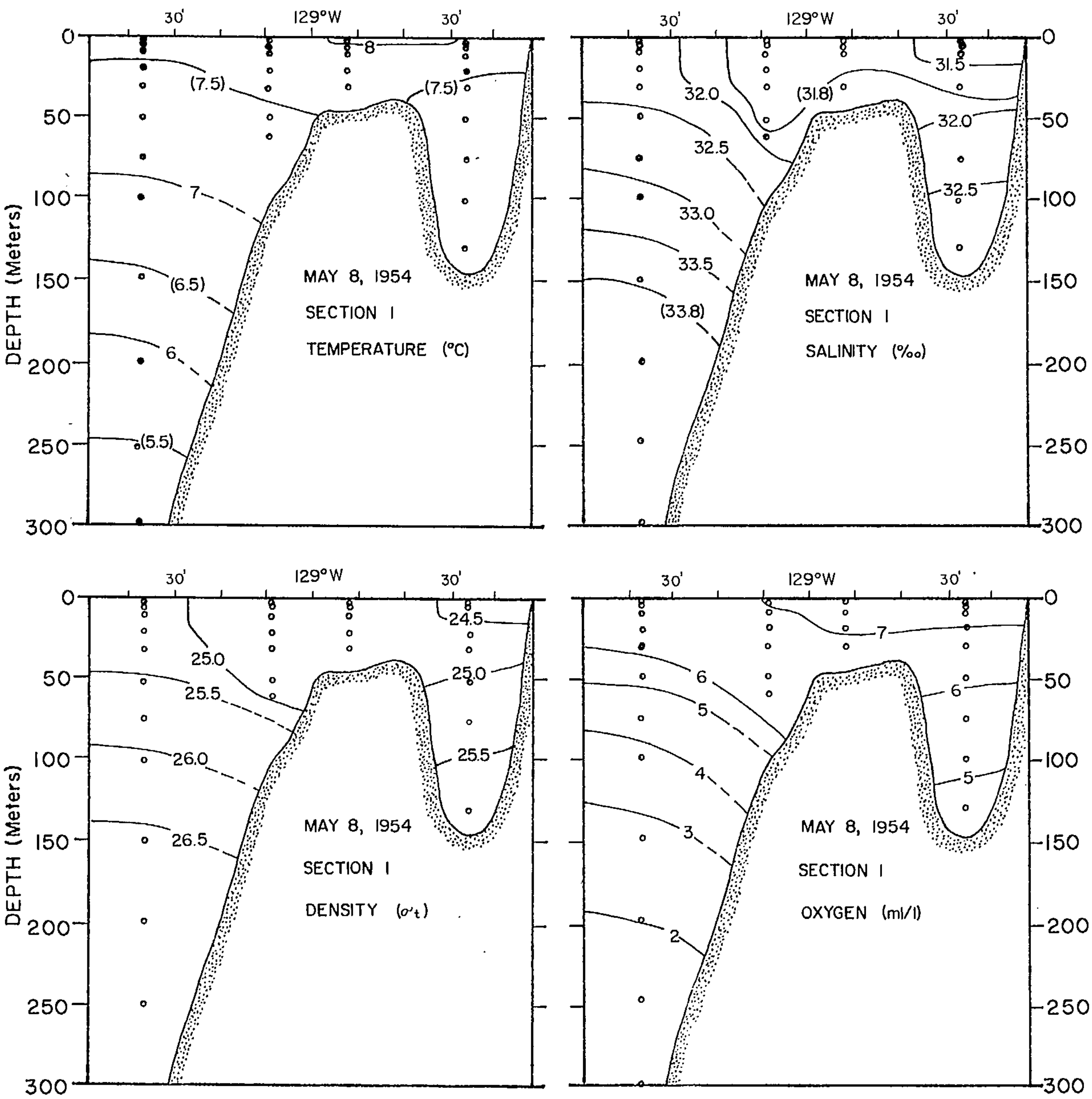


Fig. 100. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, May 8, 1954 (see Fig. 99 for location of sections).

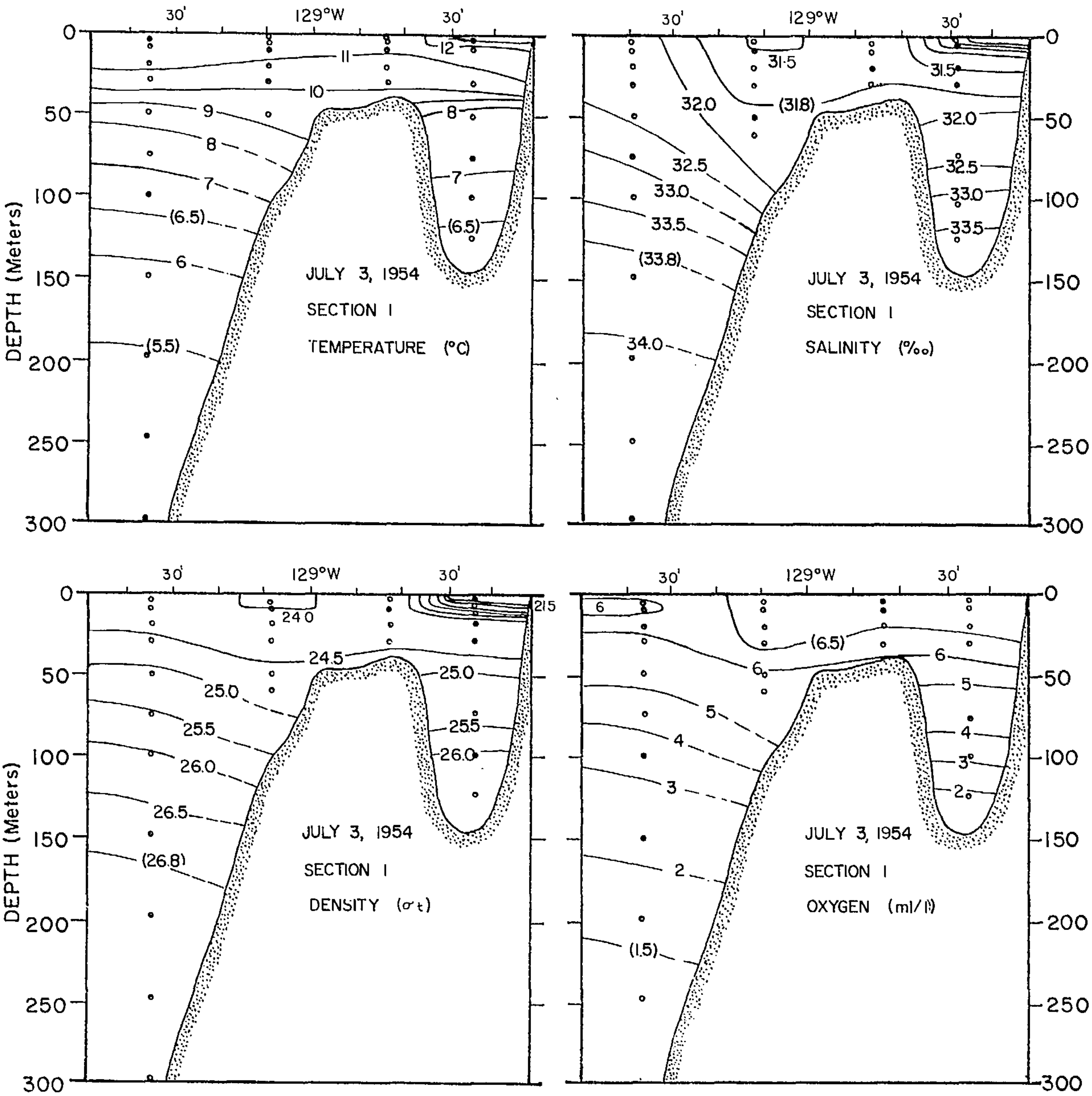


Fig. 101. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, July 3, 1954.

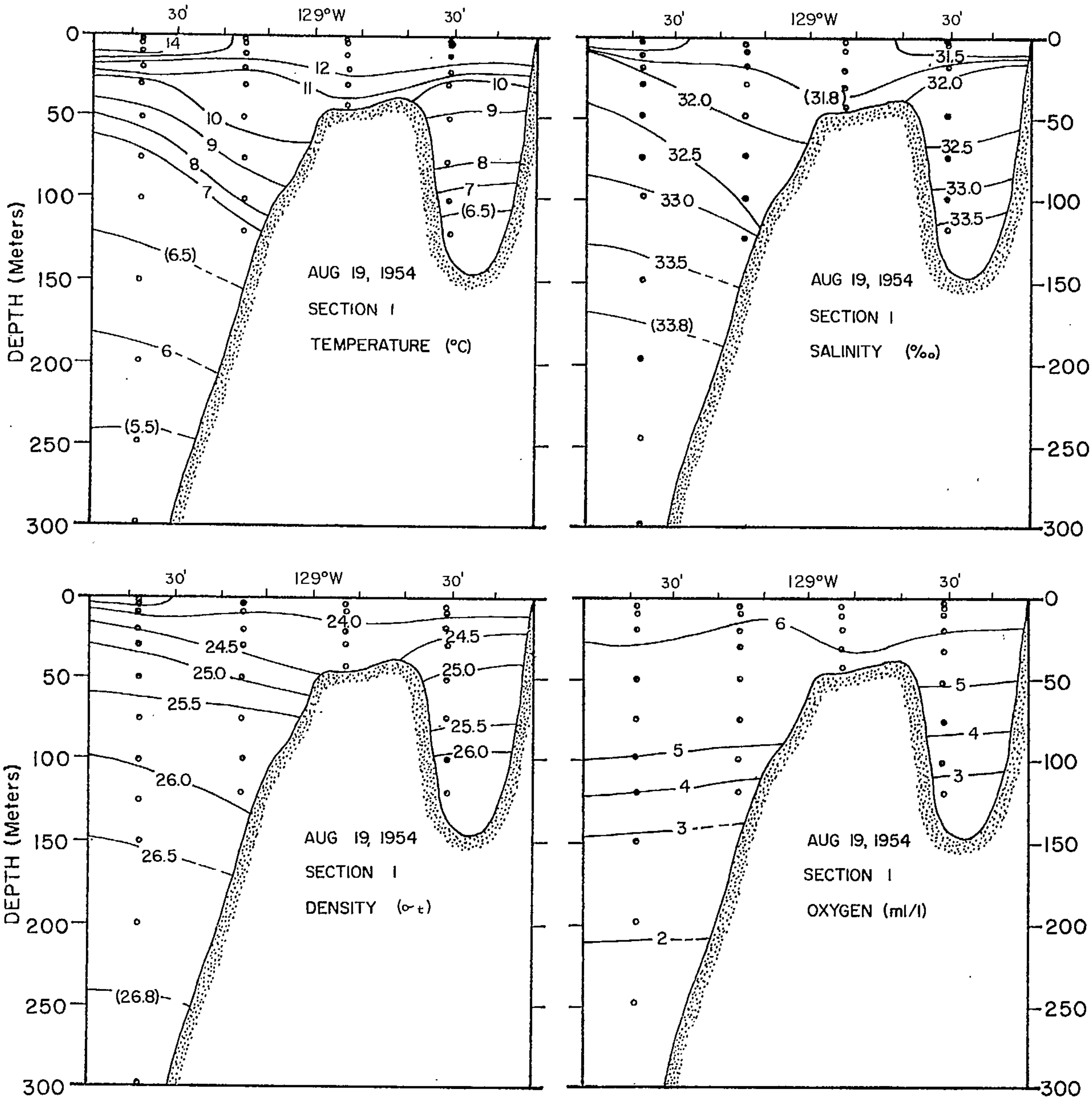


Fig. 102. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, August 19, 1954.

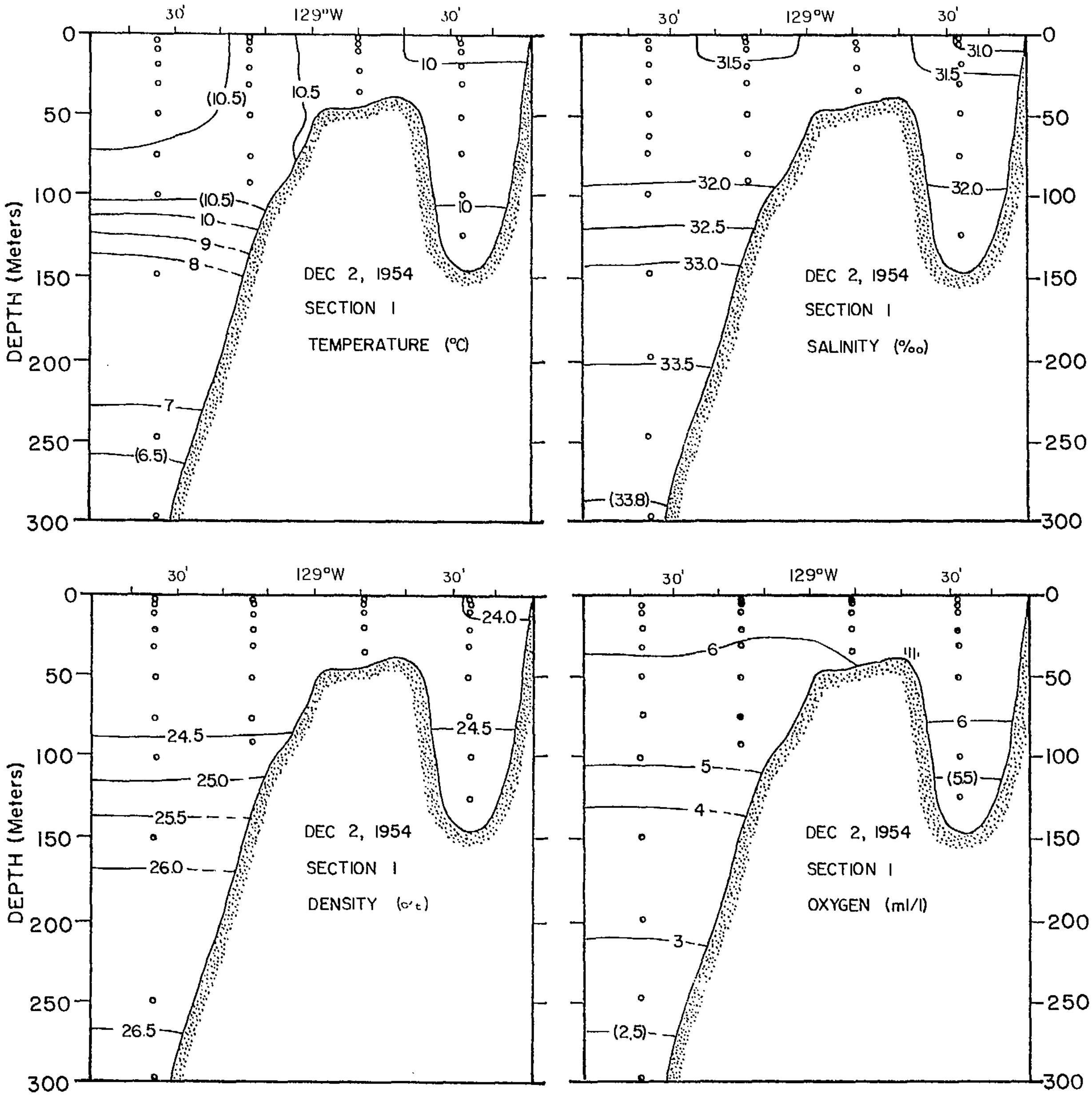


Fig. 103. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, December 2, 1954.

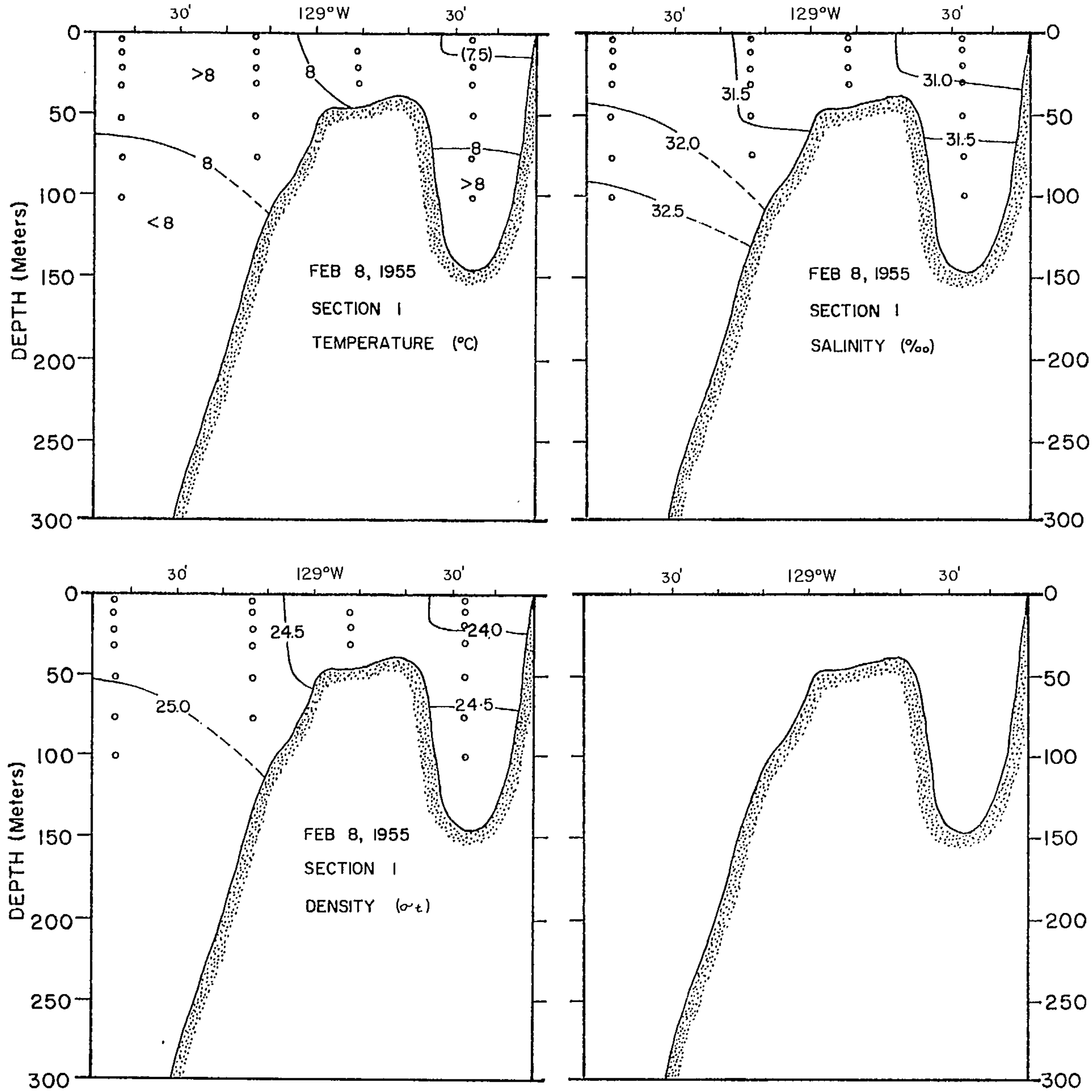


Fig. 104. Vertical sections of temperature, salinity and density in Queen Charlotte Sound, February 8, 1955.

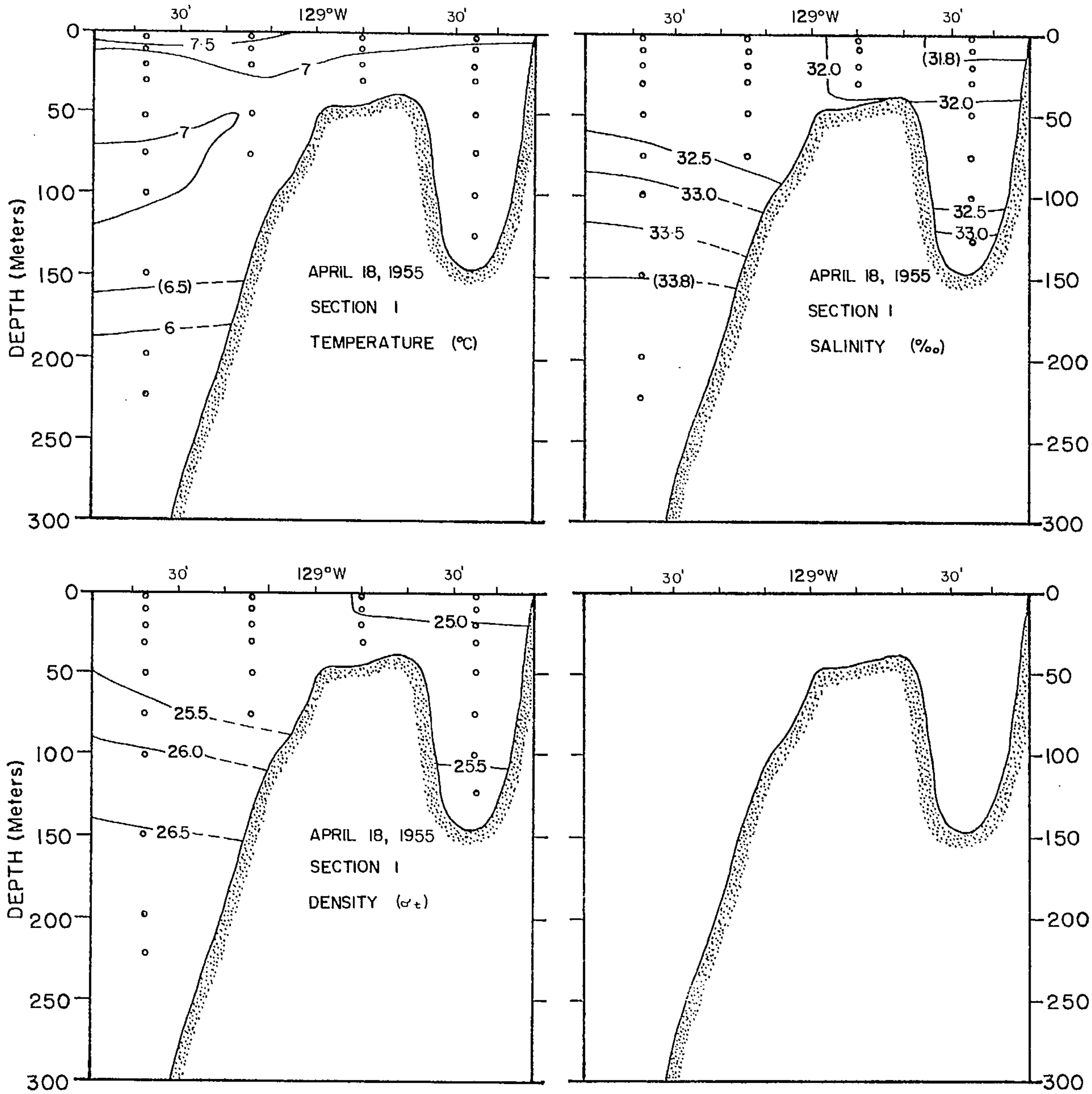


Fig. 105. Vertical sections of temperature, salinity and density in Queen Charlotte Sound, April 18, 1955.

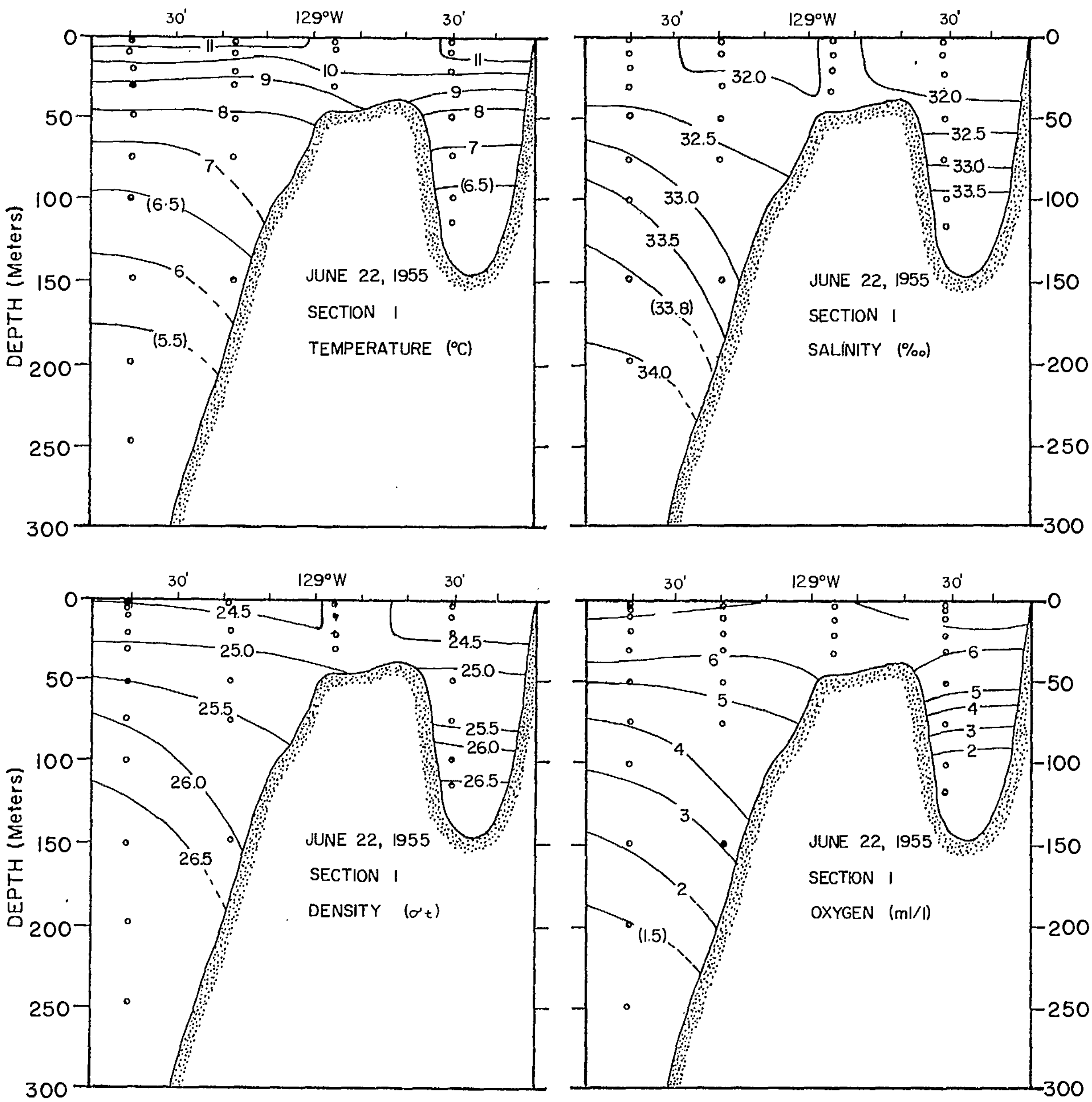


Fig. 106. Vertical Sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, June 22, 1955.

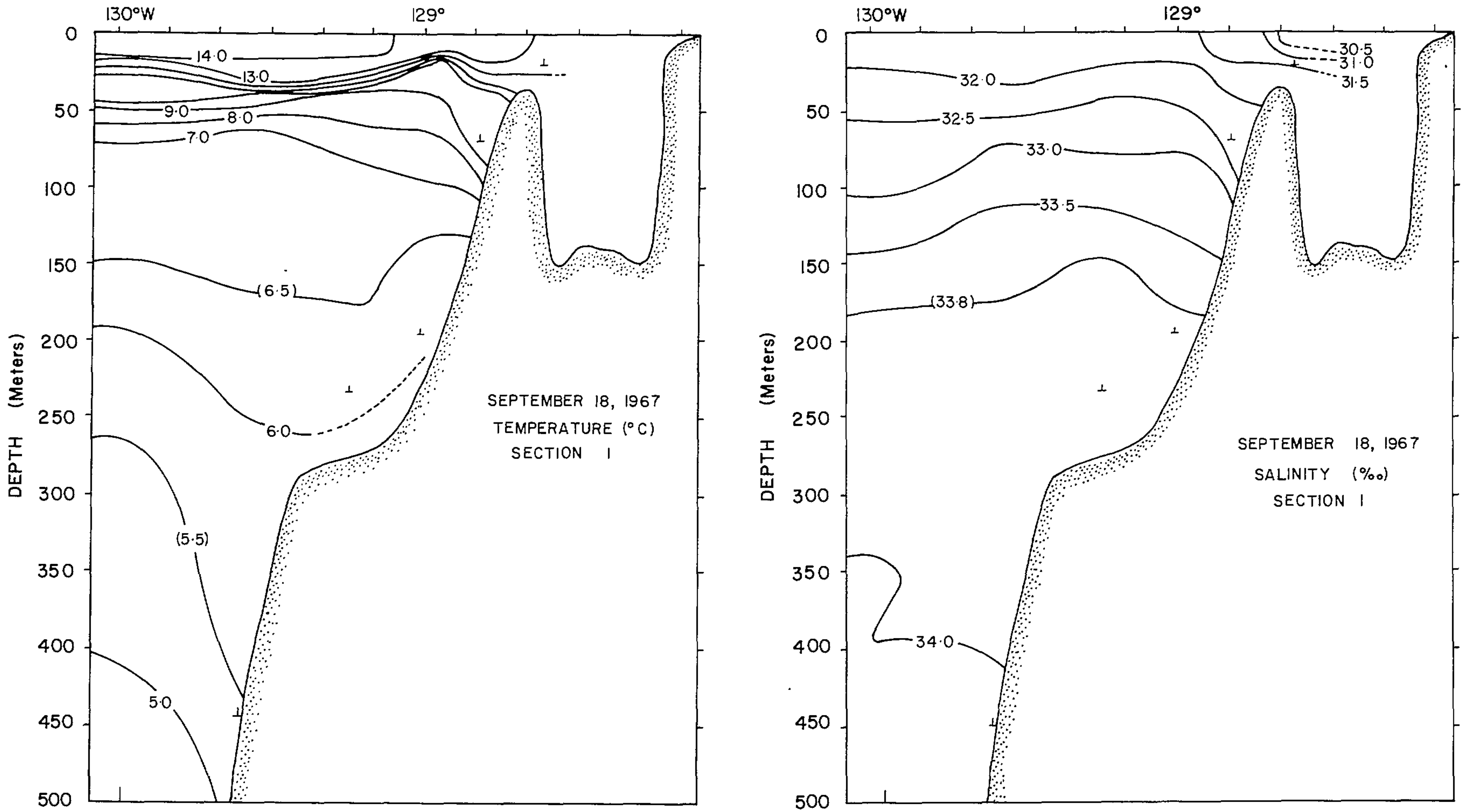


Fig. 107. Vertical sections of temperature and salinity in Queen Charlotte Sound, September 18, 1967.

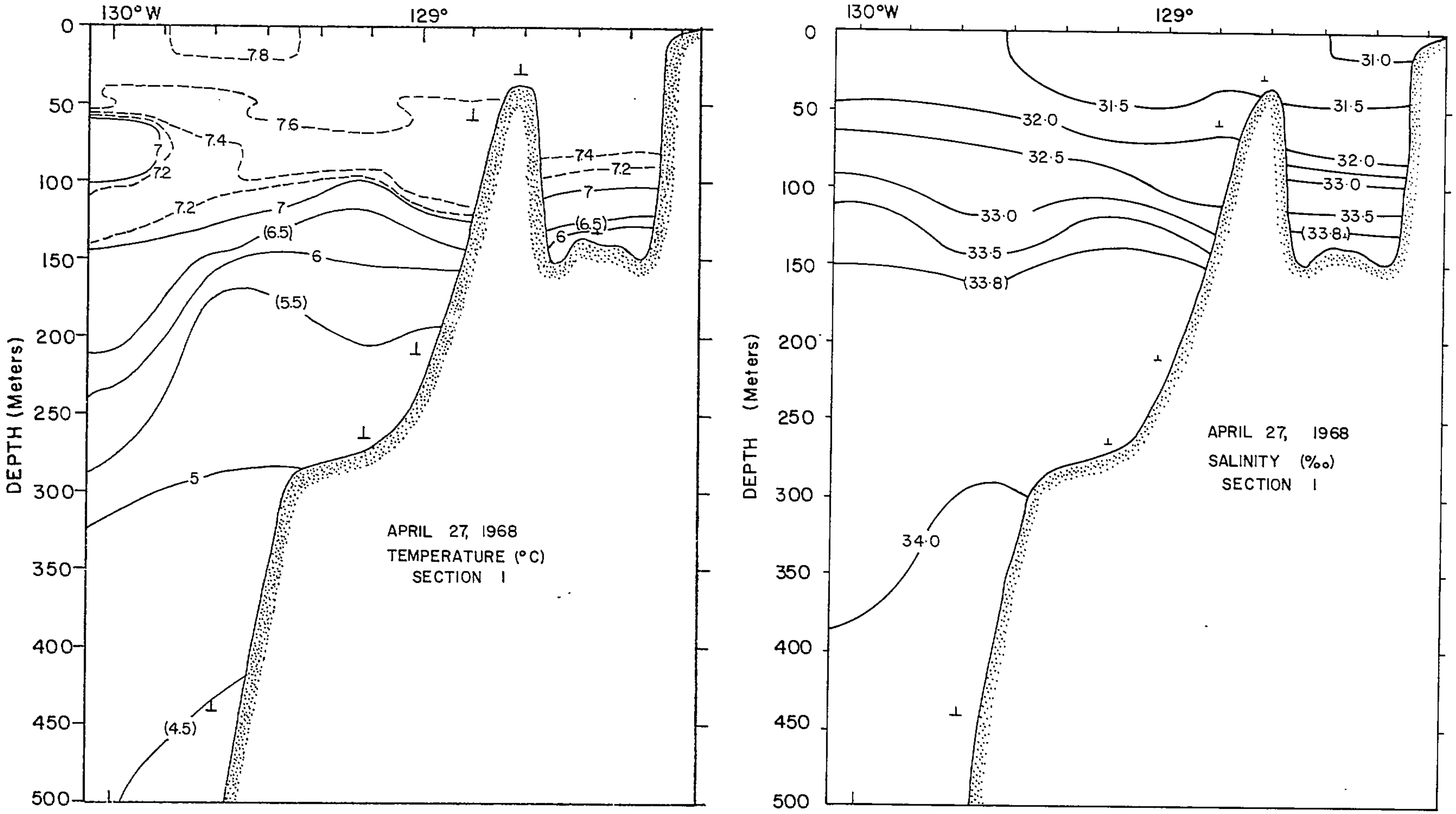


Fig. 108. Vertical sections of temperature and salinity in Queen Charlotte Sound, April 27, 1968.

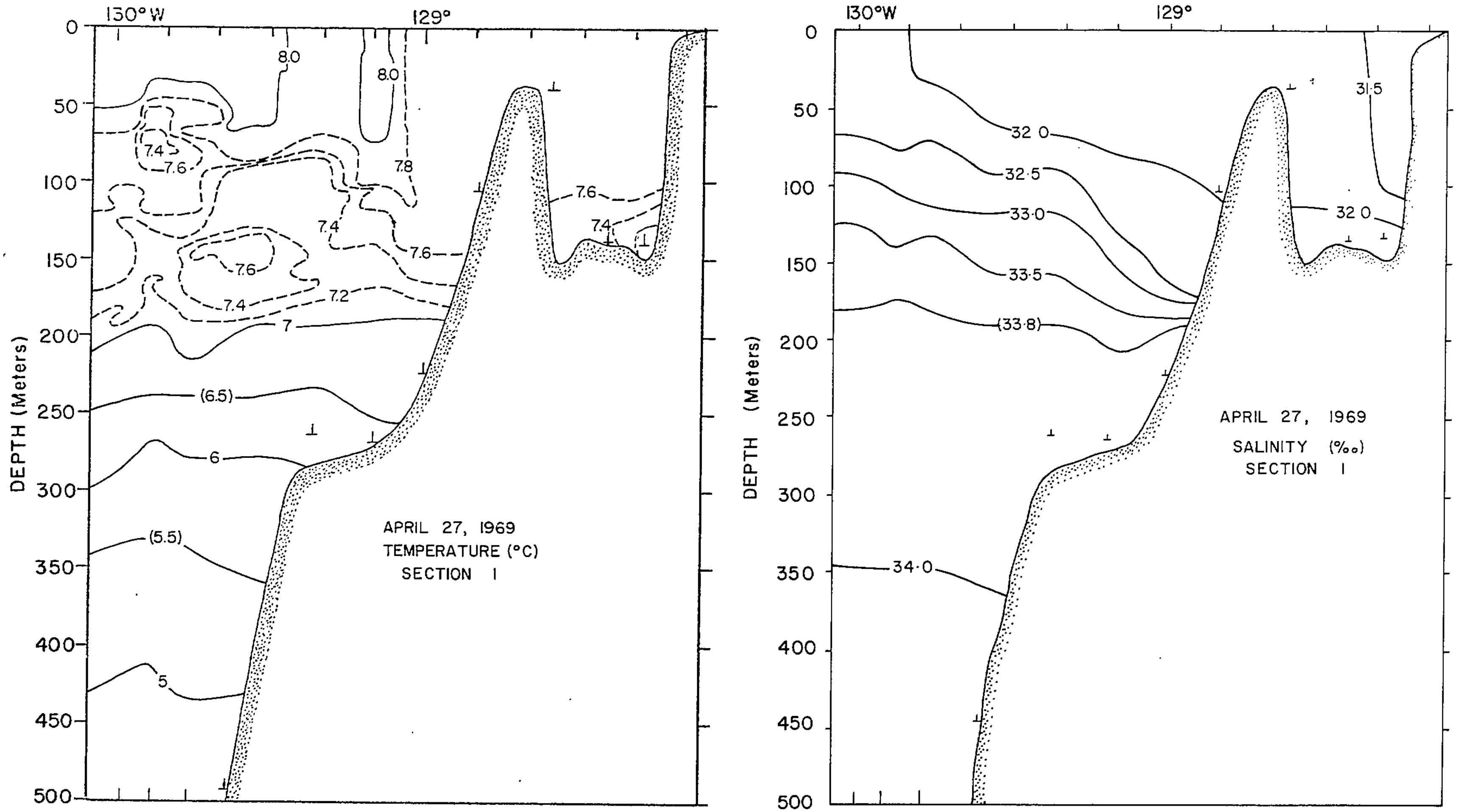


Fig. 109. Vertical sections of temperature and salinity in Queen Charlotte Sound, April 27, 1969.

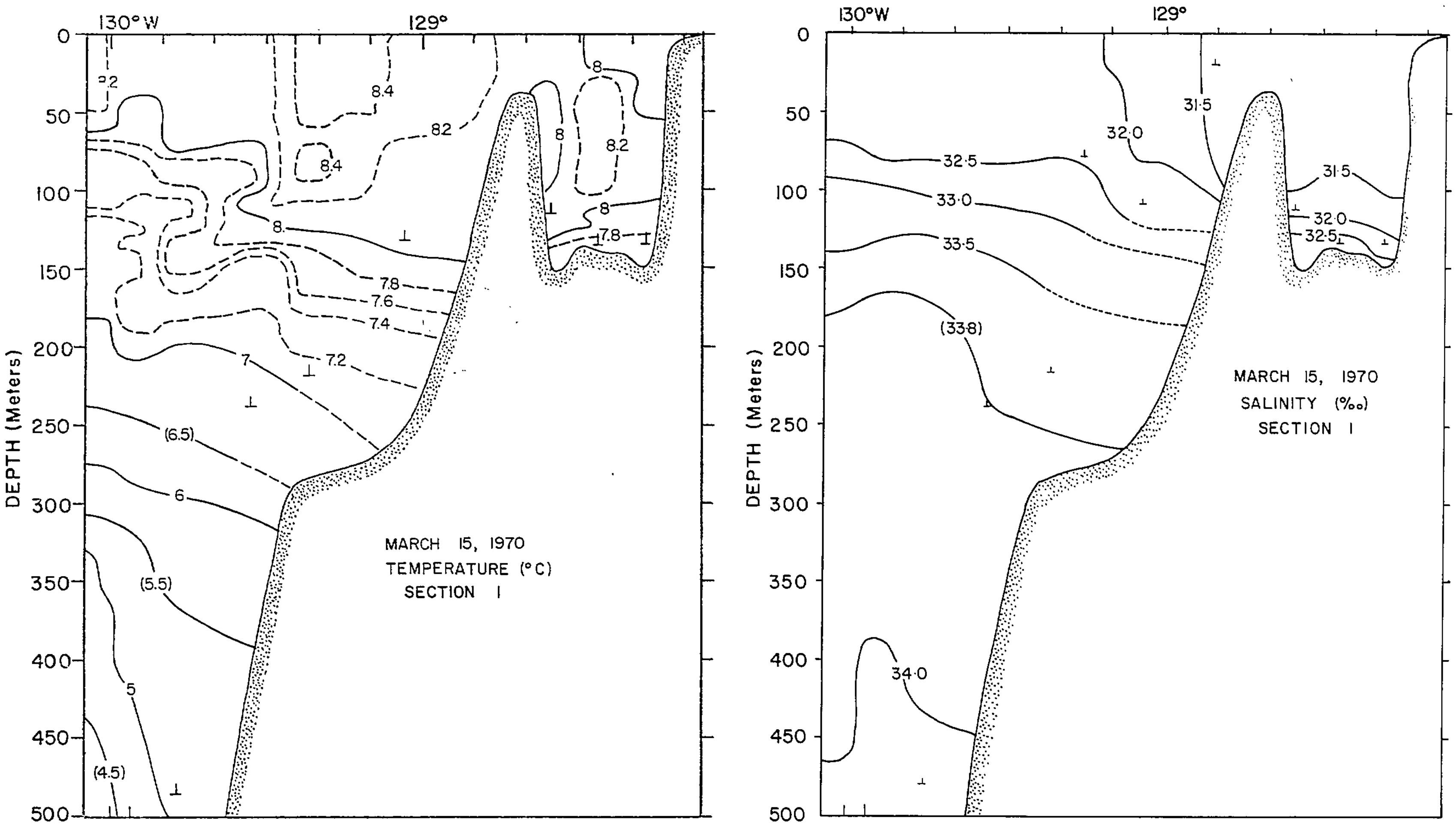


Fig. 110. Vertical sections of temperature and salinity in Queen Charlotte Sound, March 15, 1970.

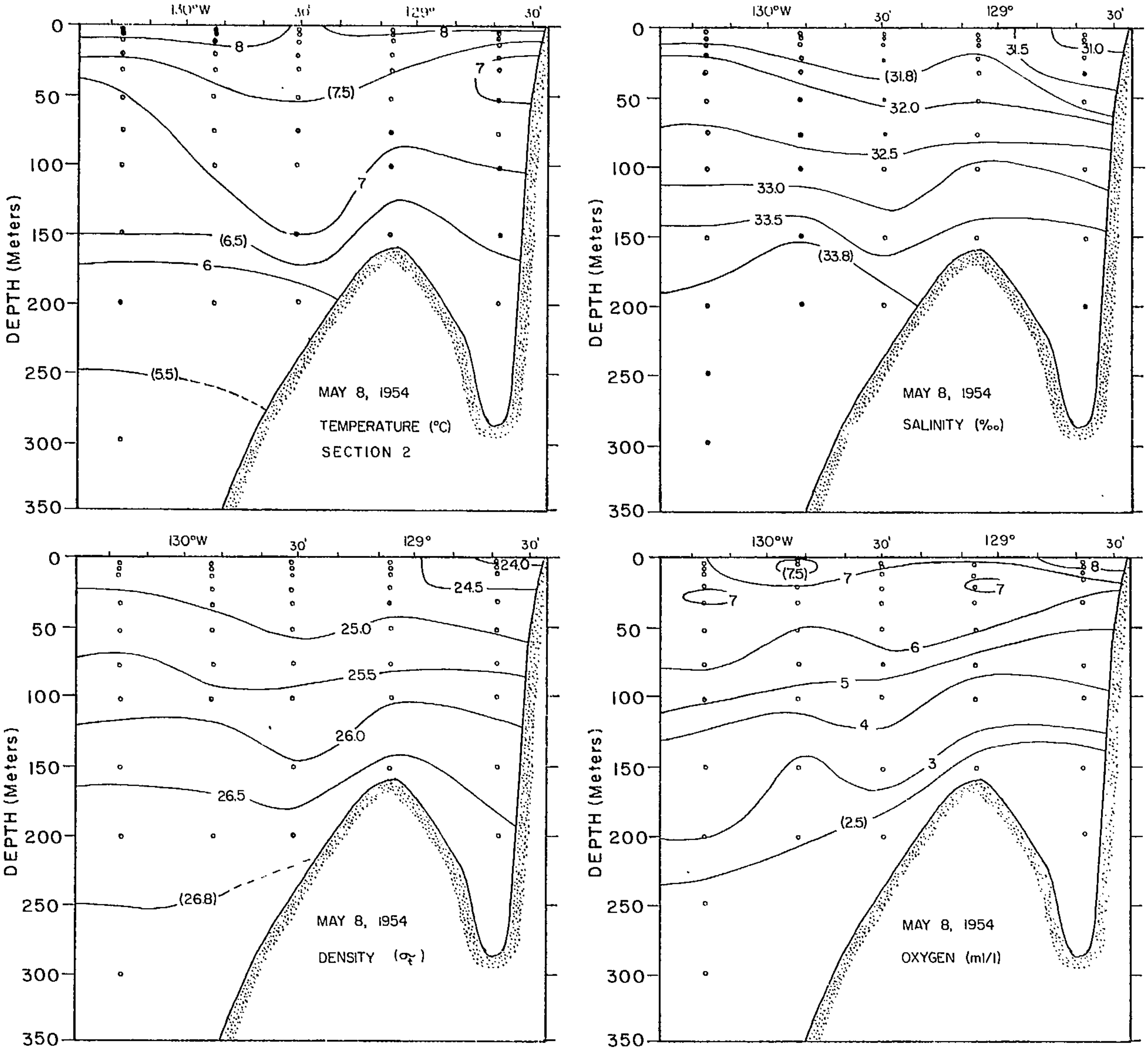


Fig. 111. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, May 8, 1954.

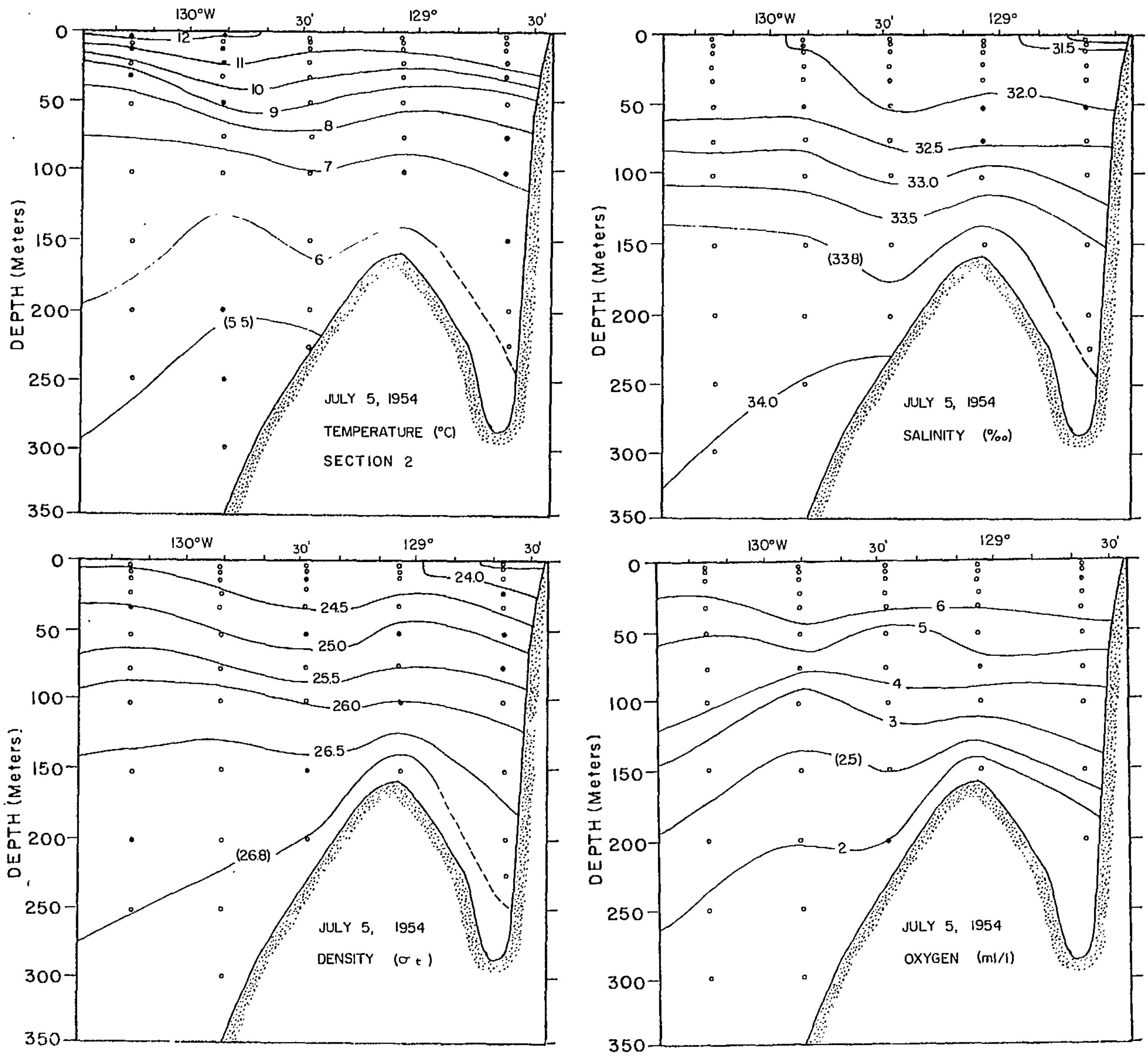


Fig. 112. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, July 5, 1954.

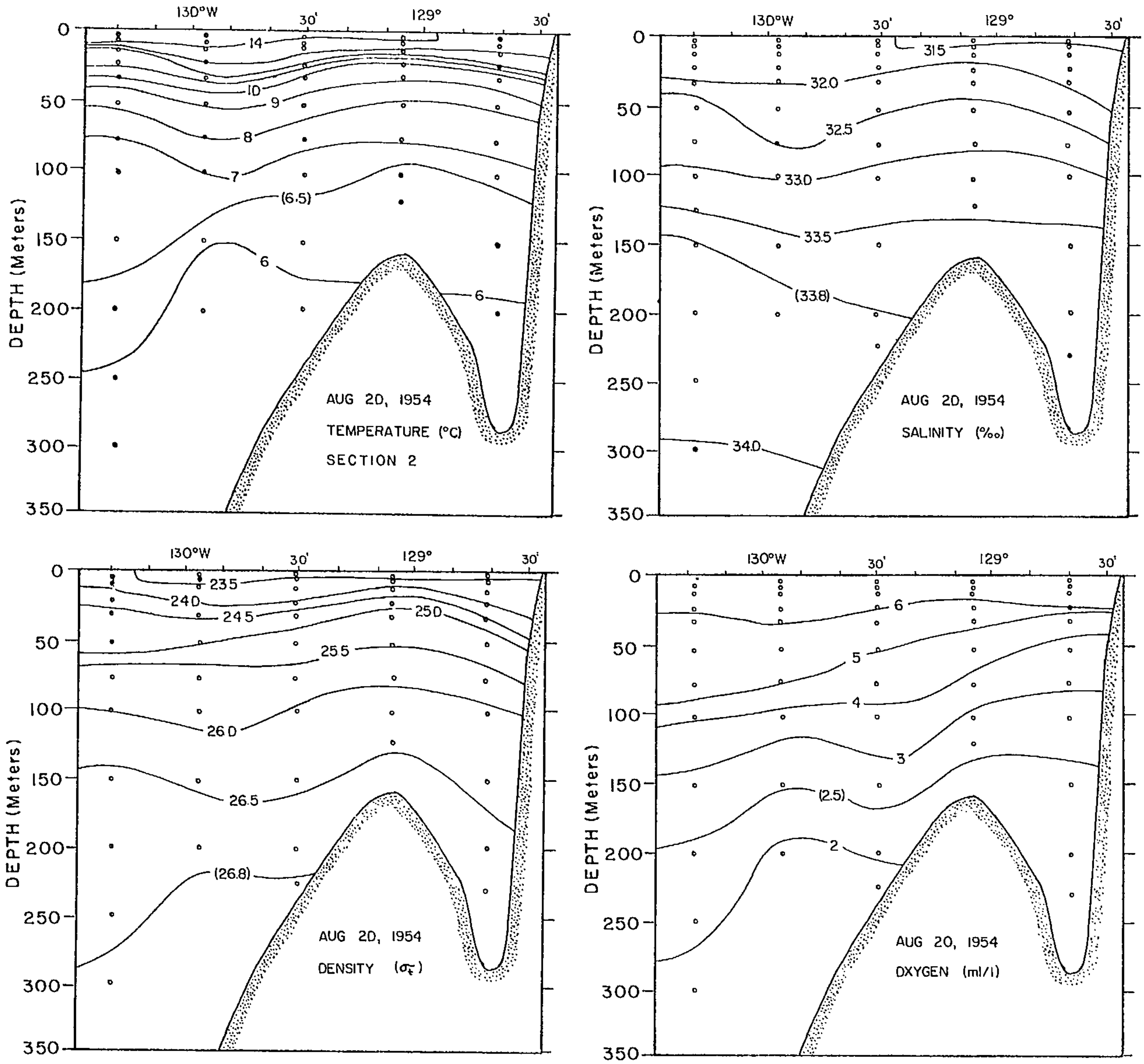


Fig. 113. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, August 20, 1954.

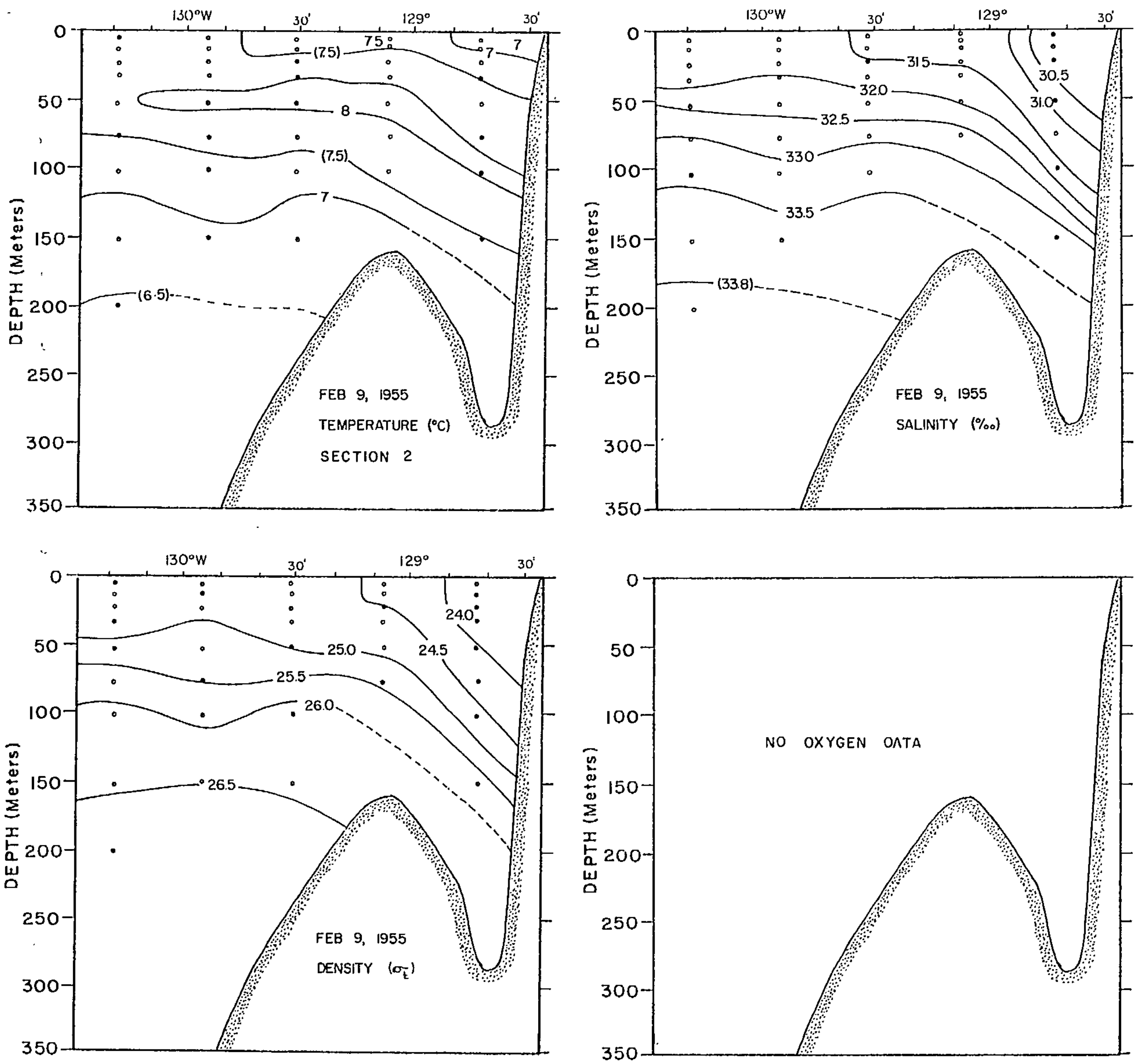


Fig. 114. Vertical sections of temperature, salinity and density in Queen Charlotte Sound, February 9, 1955.

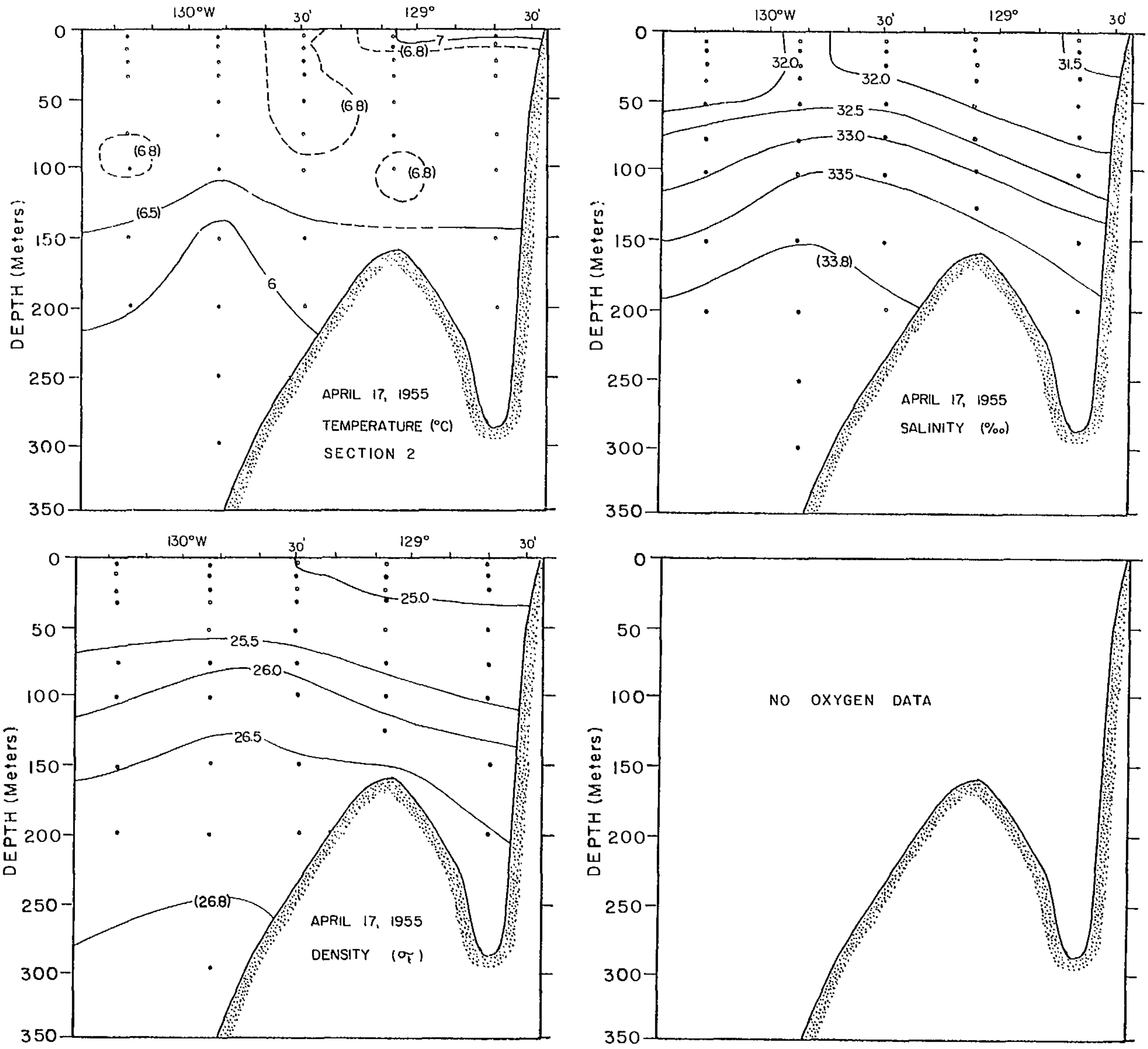


Fig. 115. Vertical sections of temperature, salinity and density in Queen Charlotte Sound, April 17, 1955.

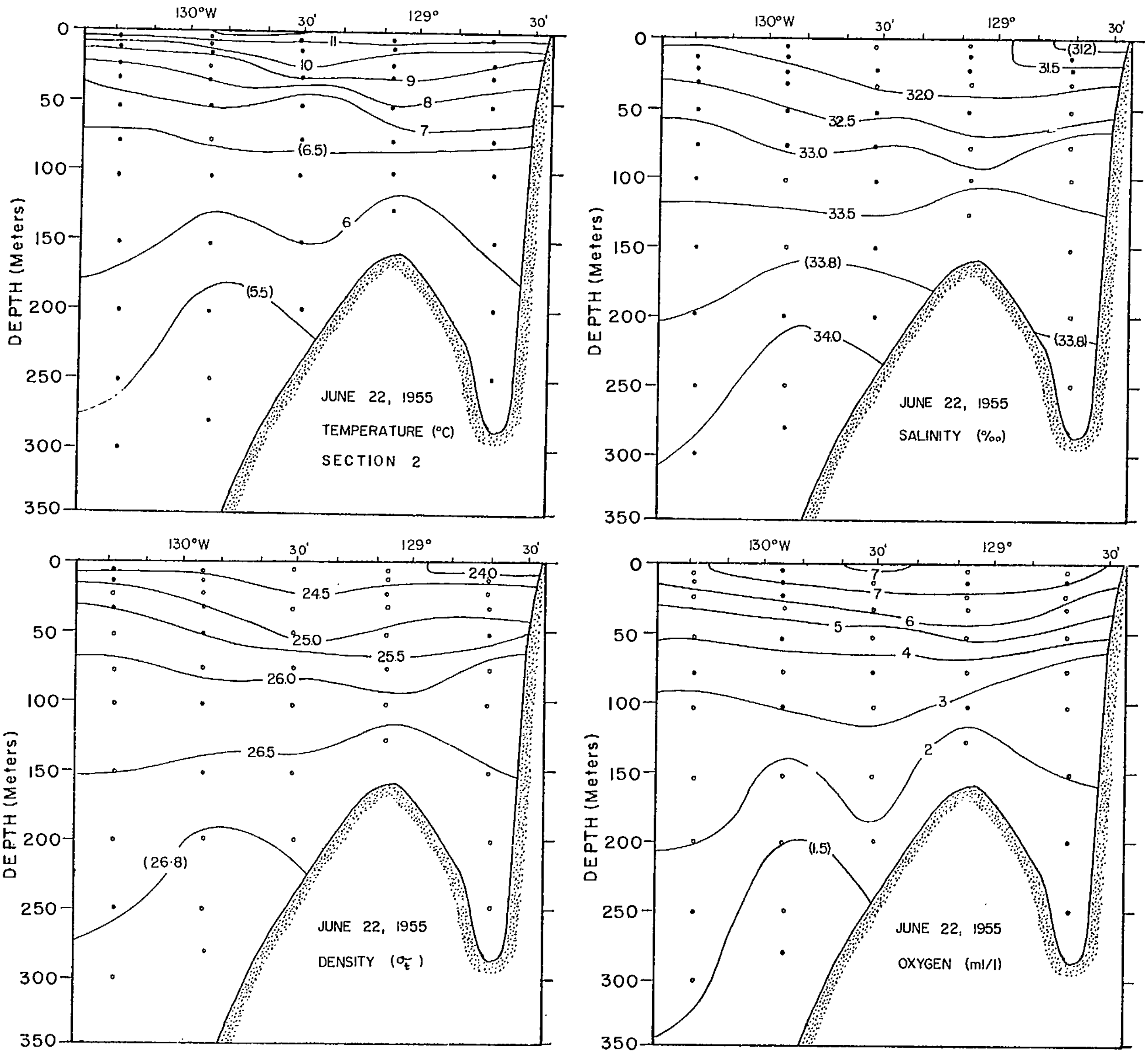


Fig. 116. Vertical sections of temperature, salinity, density and dissolved oxygen content in Queen Charlotte Sound, June 22, 1955.

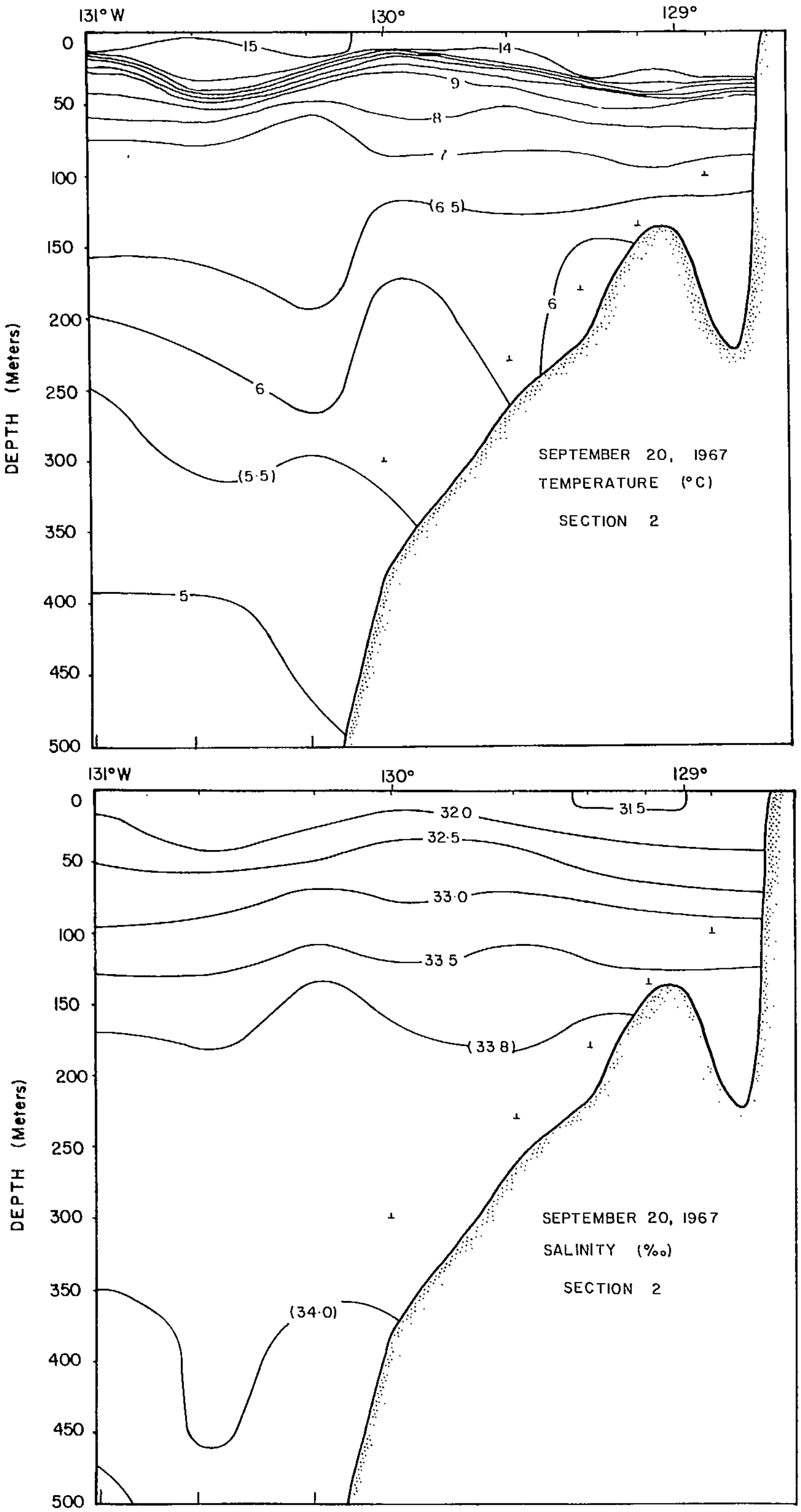


Fig. 117. Vertical sections of temperature and salinity in Queen Charlotte Sound, September 20, 1967.

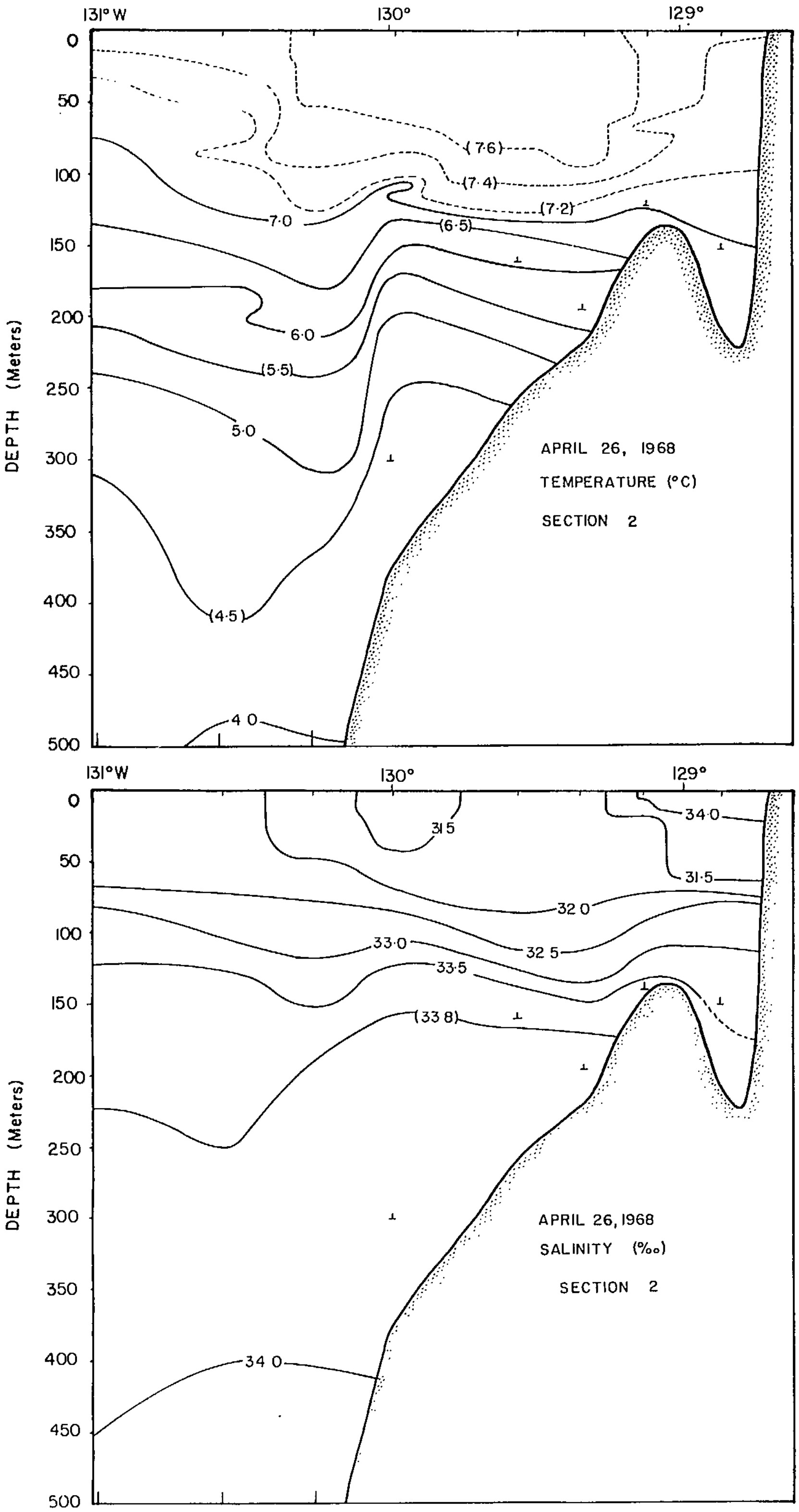


Fig. 118. Vertical sections of temperature and salinity in Queen Charlotte Sound, April 26, 1968.

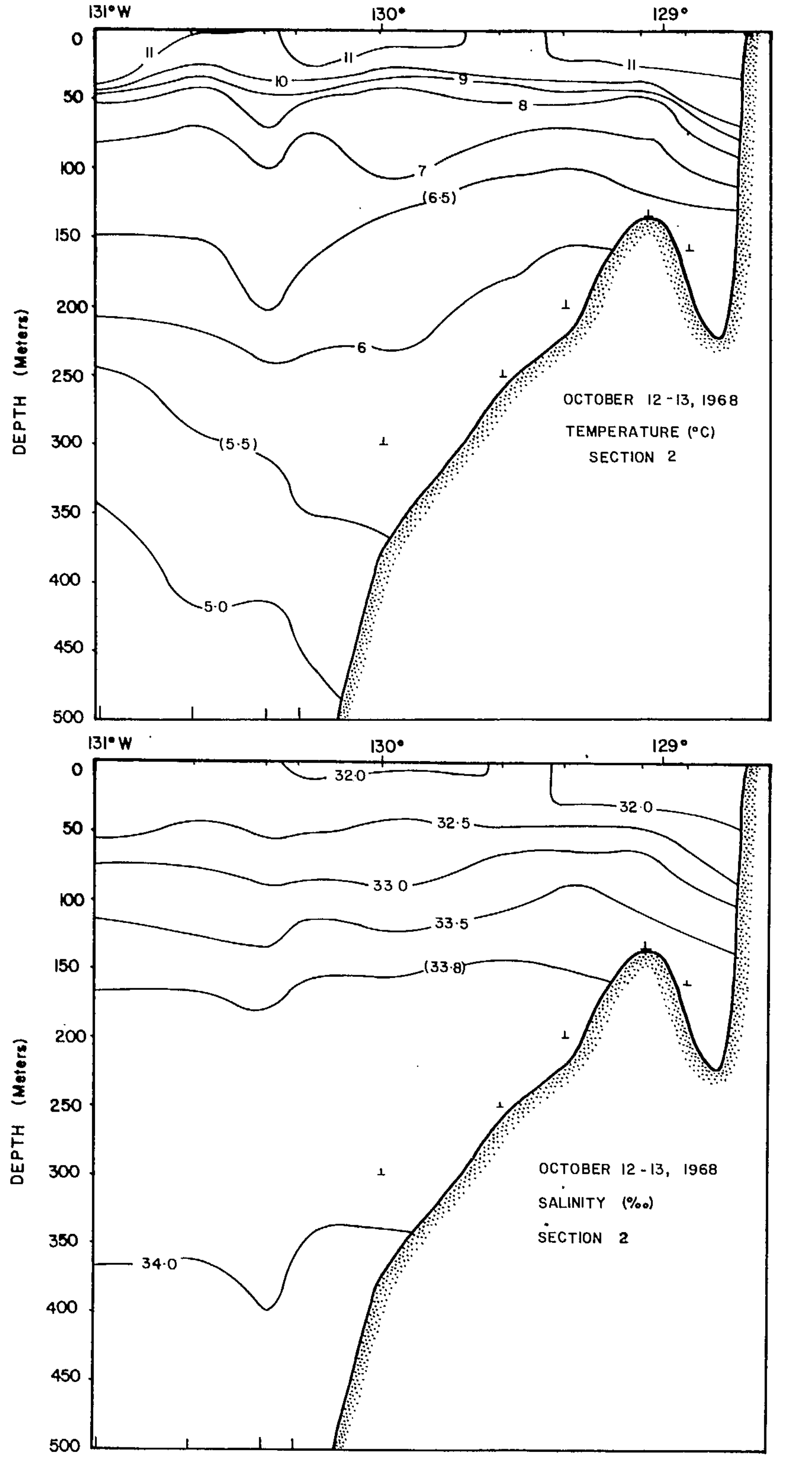


Fig. 119. Vertical sections of temperature and salinity in Queen Charlotte Sound, October 12-13, 1968.

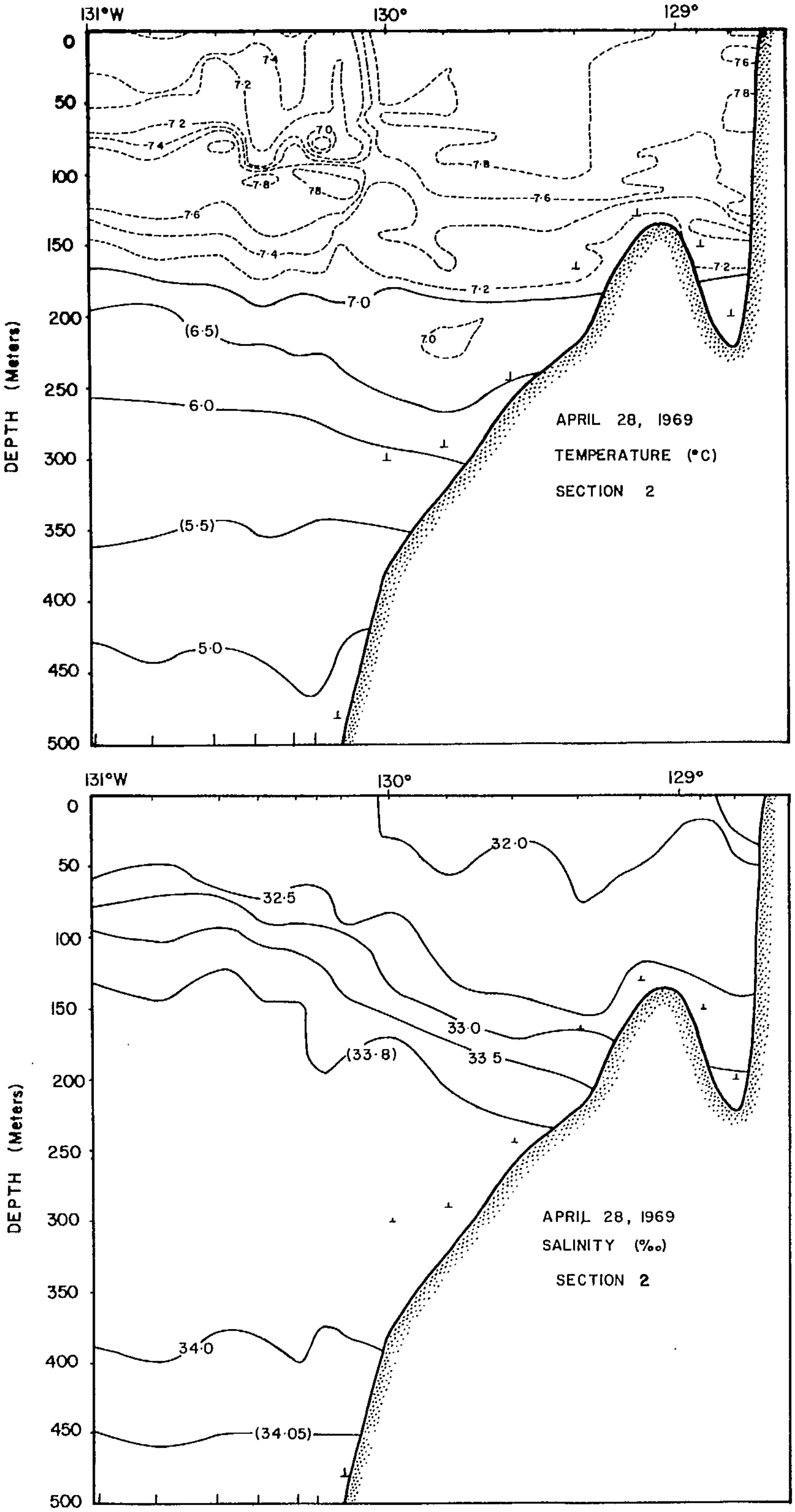


Fig. 120. Vertical sections of temperature and salinity in Queen Charlotte Sound, April 28, 1969.

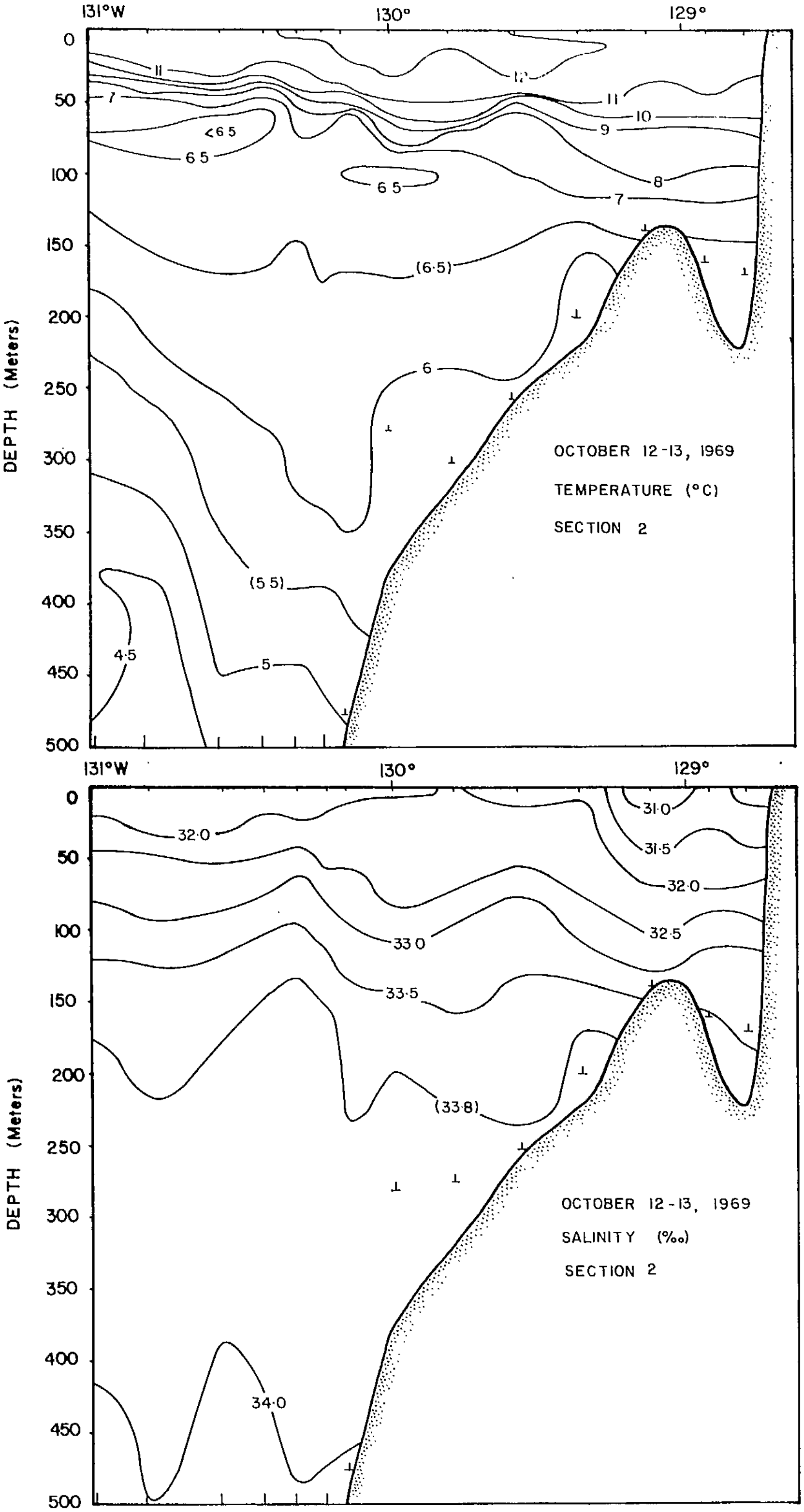


Fig. 121. Vertical sections of temperature and salinity in Queen Charlotte Sound, October 12-13, 1969.

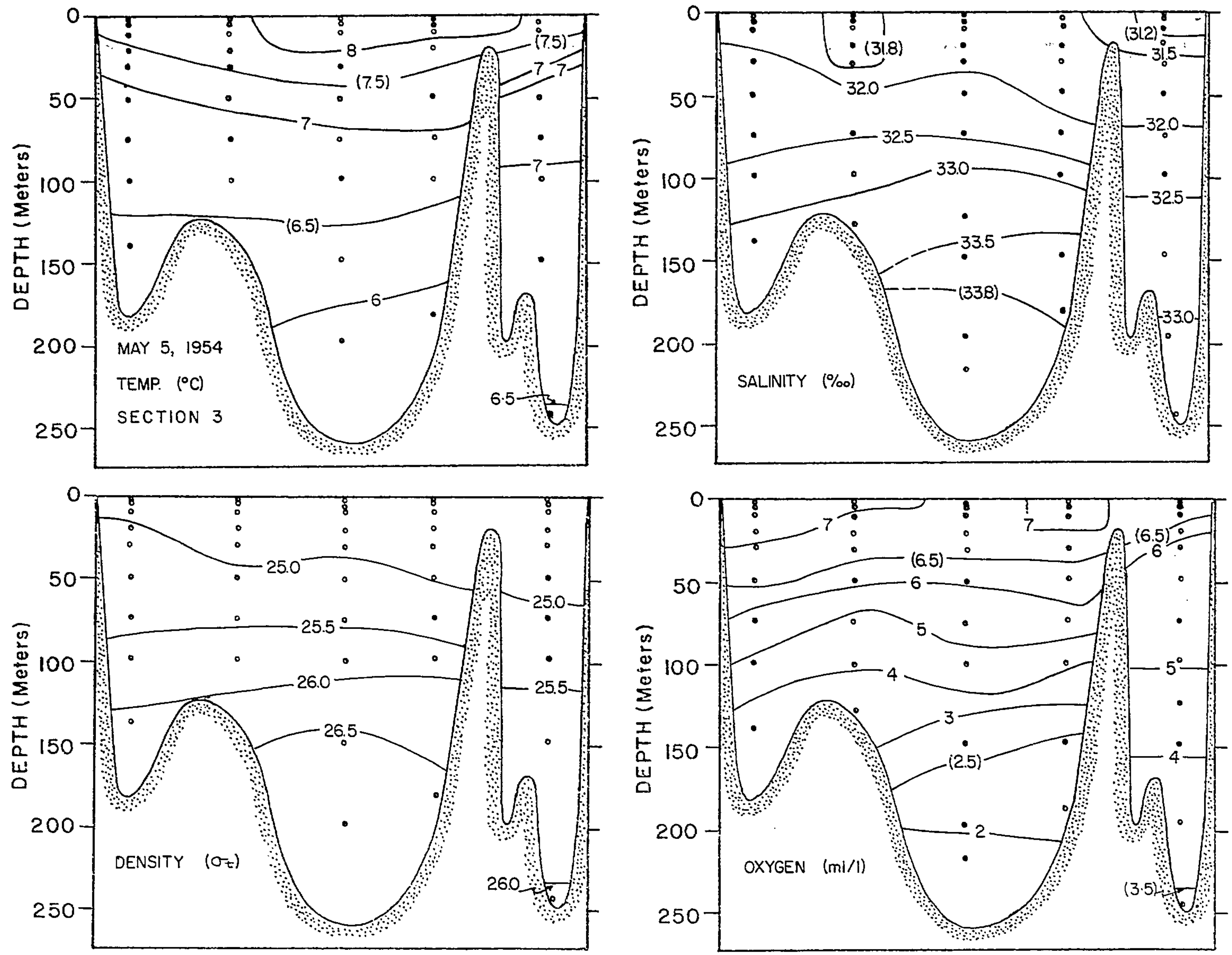


Fig. 122. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, May 5, 1954.

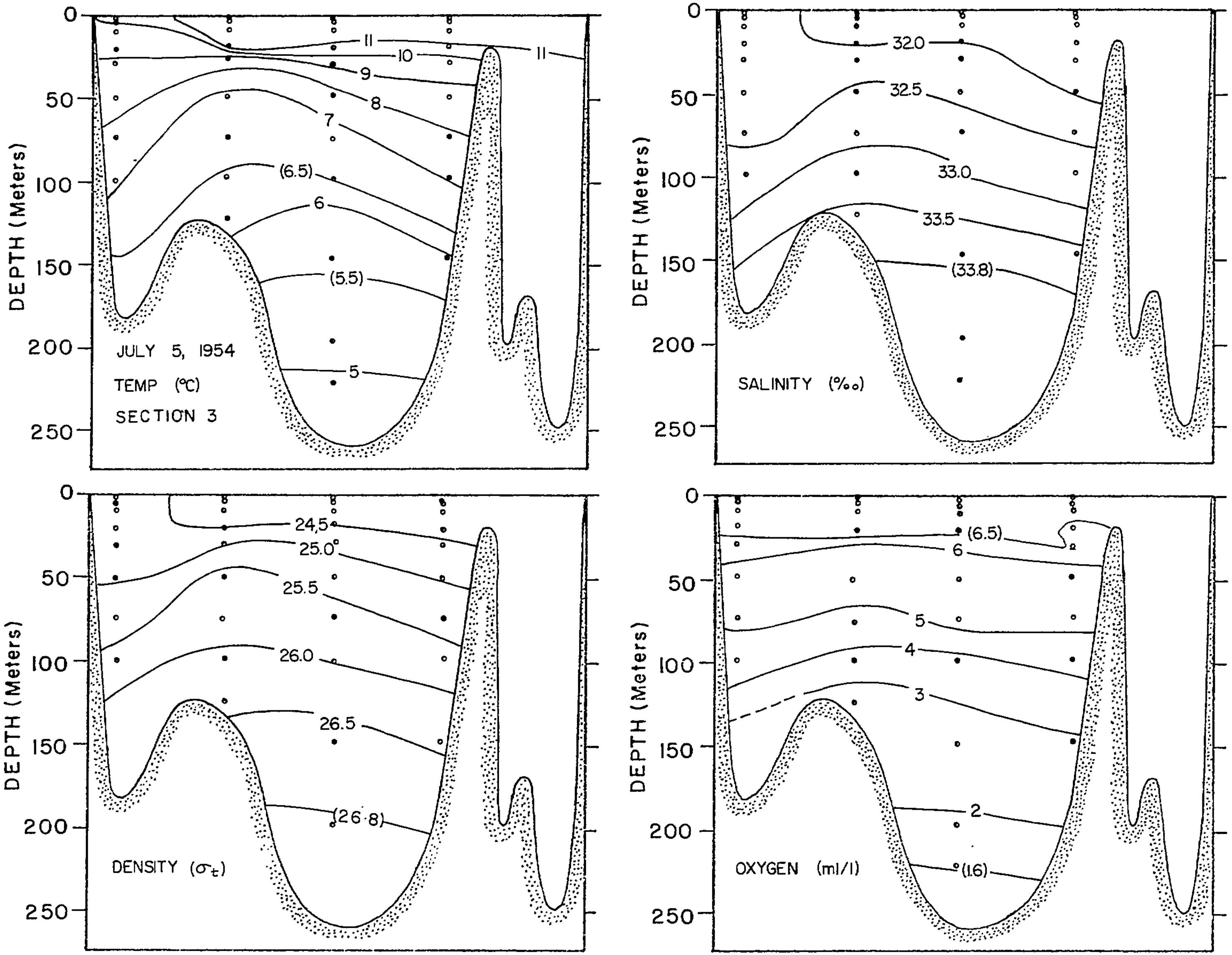


Fig. 123. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, July 5, 1954.

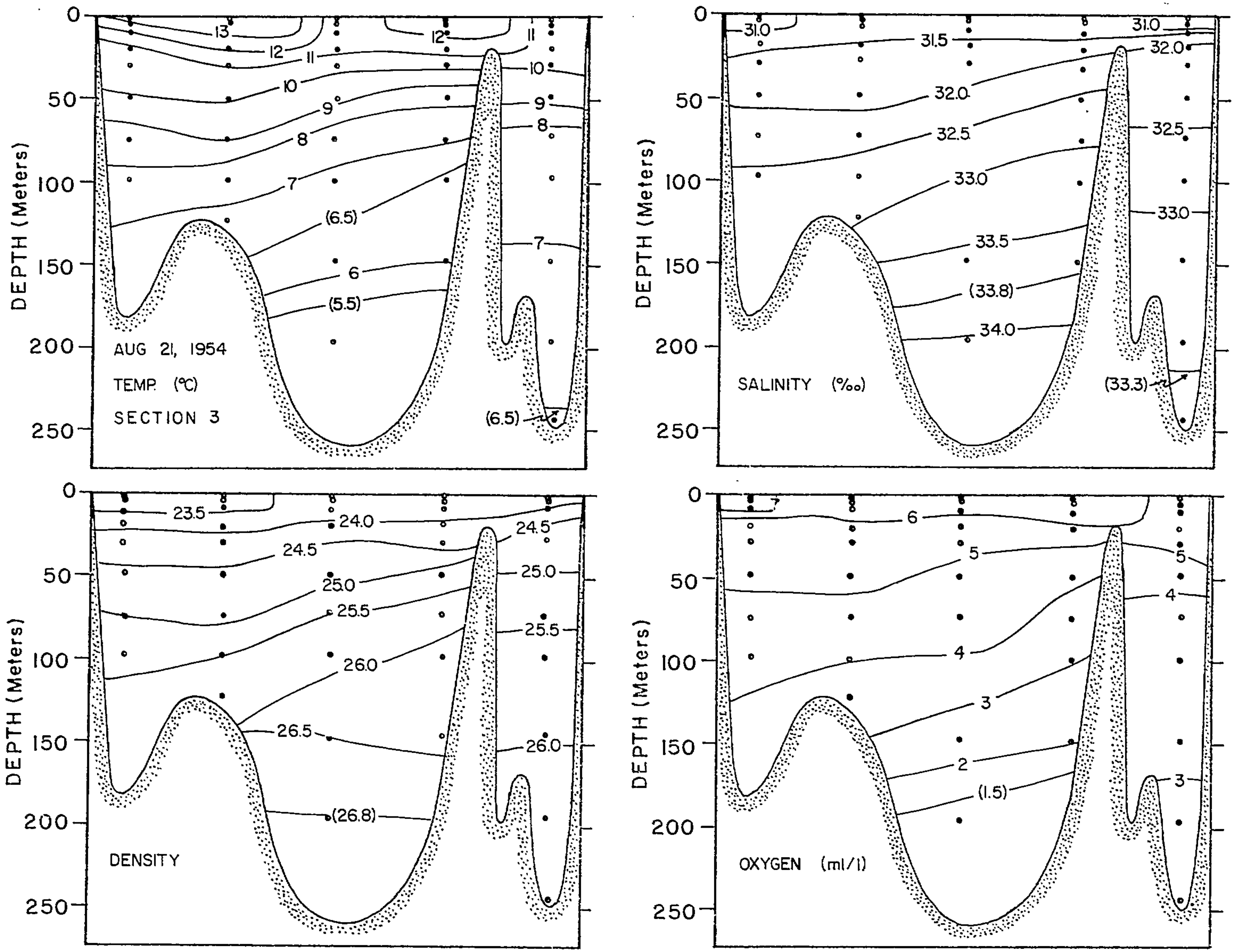


Fig. 124. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, August 21, 1954.

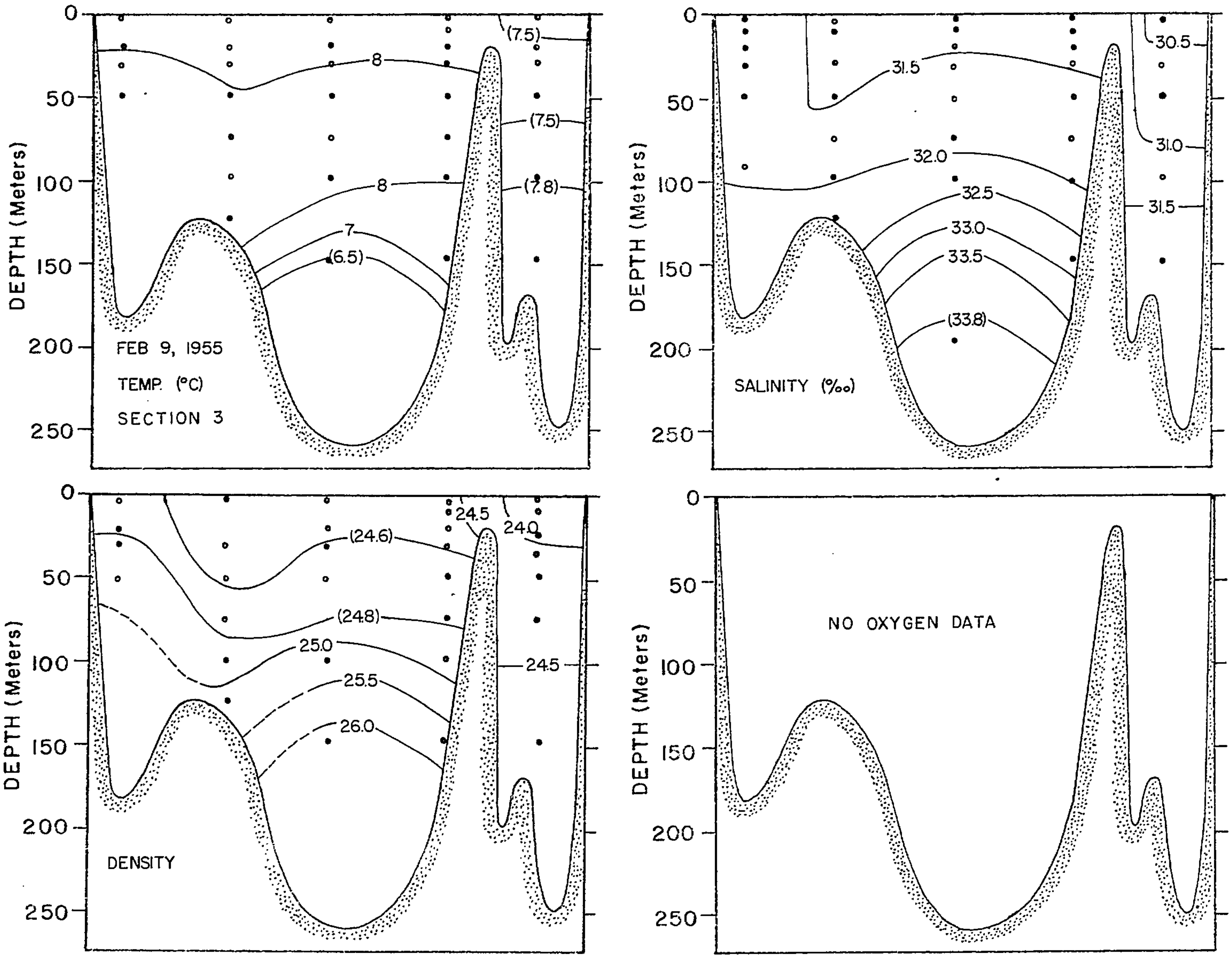


Fig. 125. Vertical sections of temperature, salinity and density in Hecate Strait, February 9, 1955.

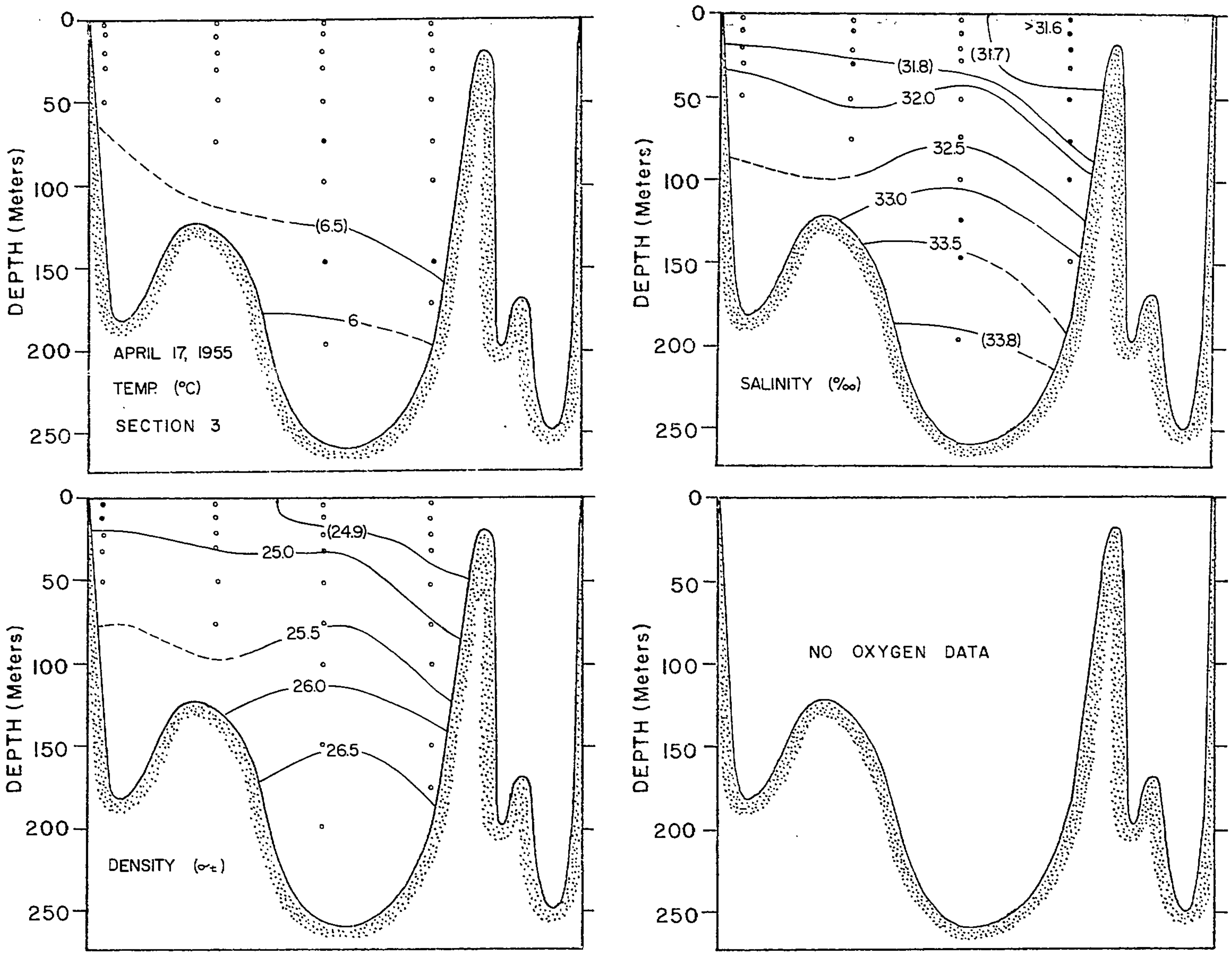


Fig. 126. Vertical sections of temperature, salinity and density in Hecate Strait, April 17, 1955.

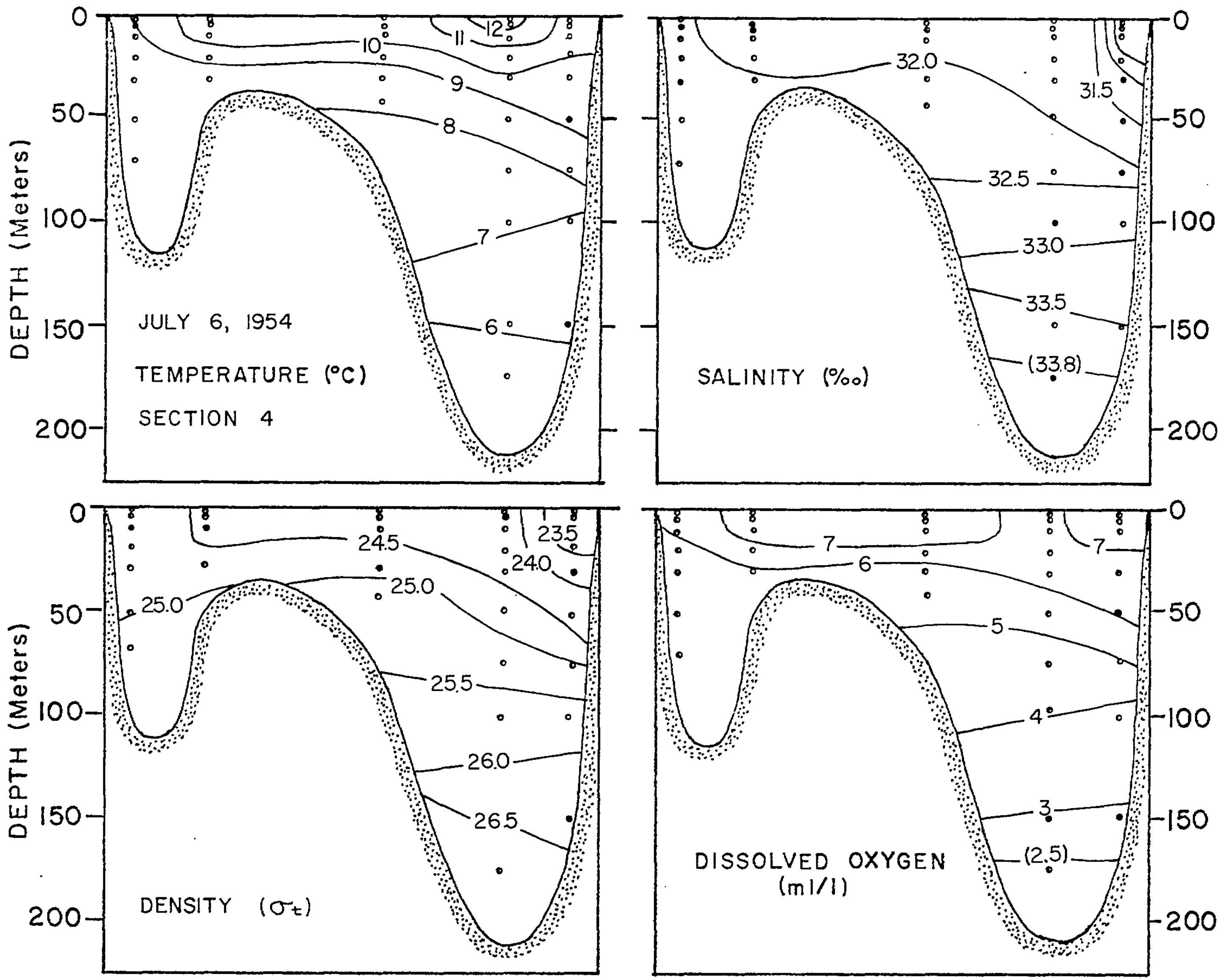


Fig. 127. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, July 6, 1954.

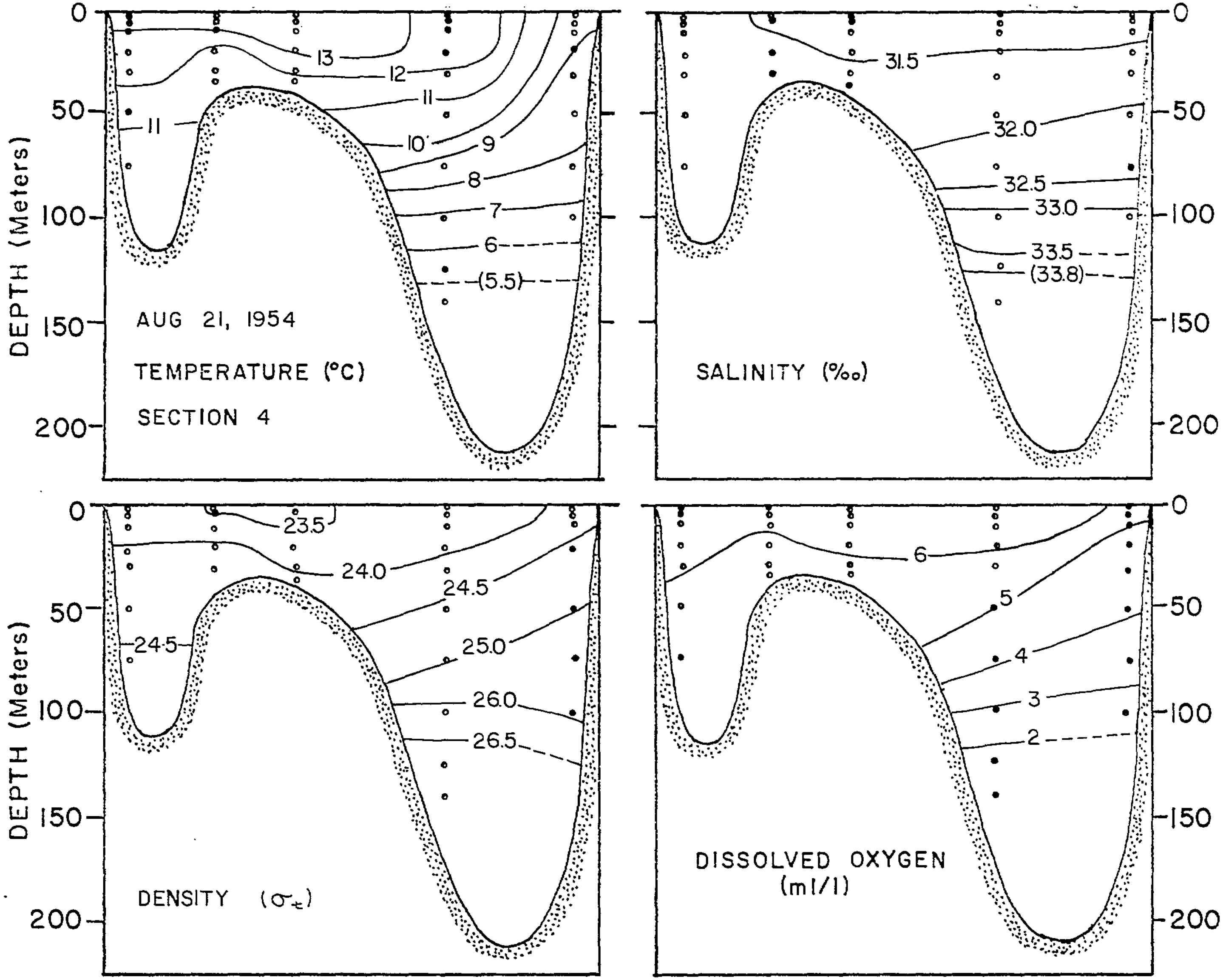


Fig. 128. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, August 21, 1954.

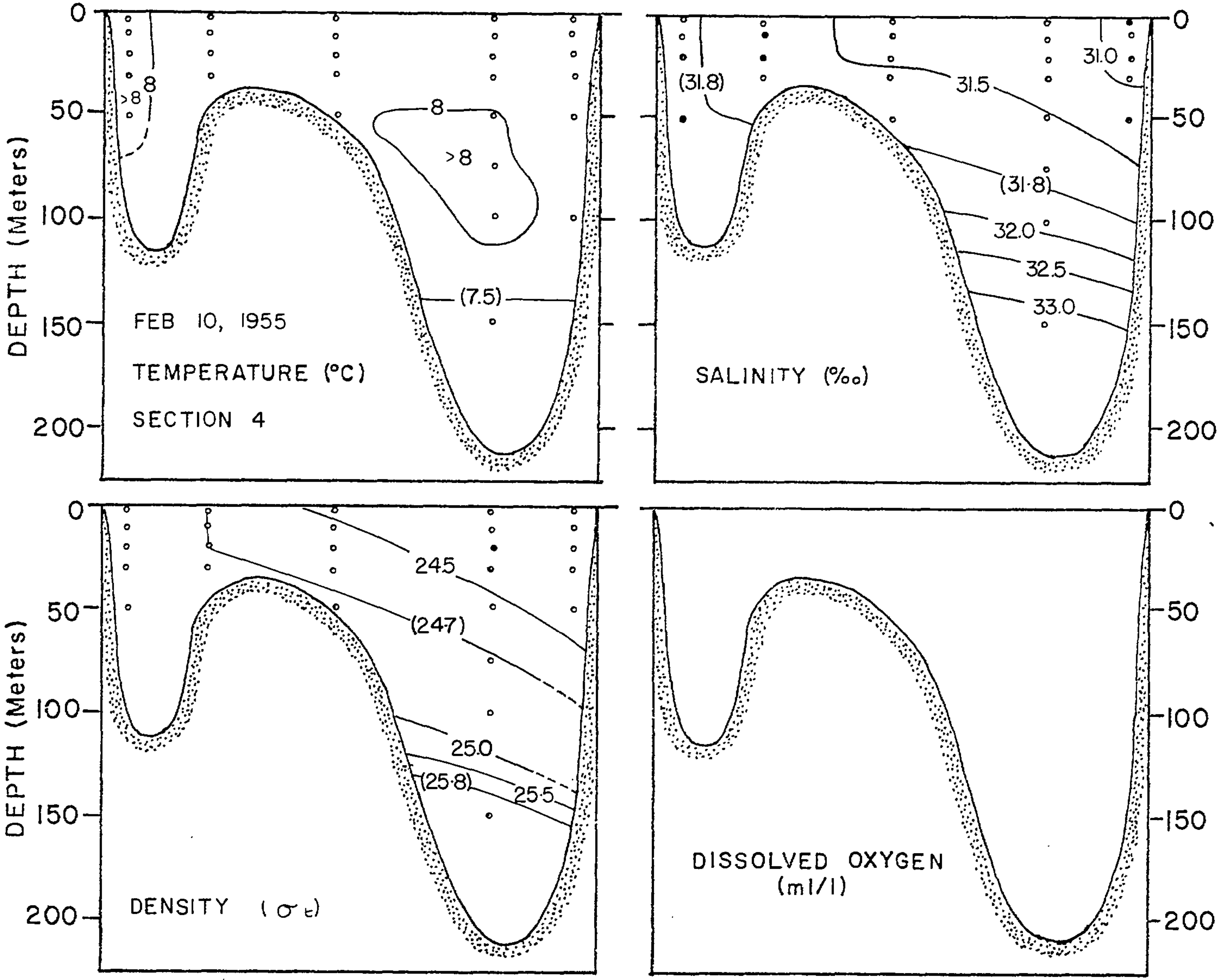


Fig. 129. Vertical sections of temperature, salinity and density in Hecate Strait, February 10, 1955.

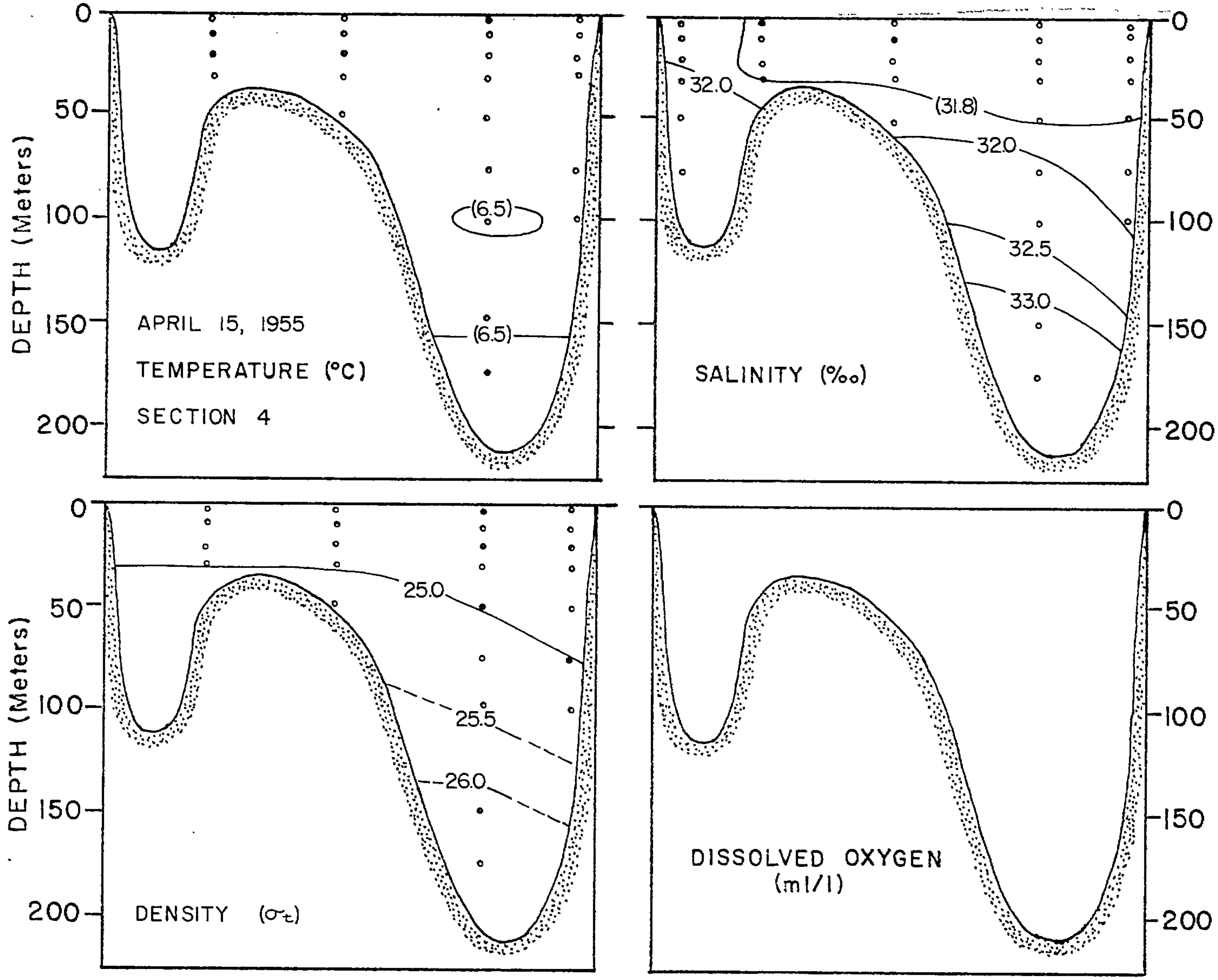


Fig. 130. Vertical sections of temperature, salinity and density in Hecate Strait, April 15, 1955.

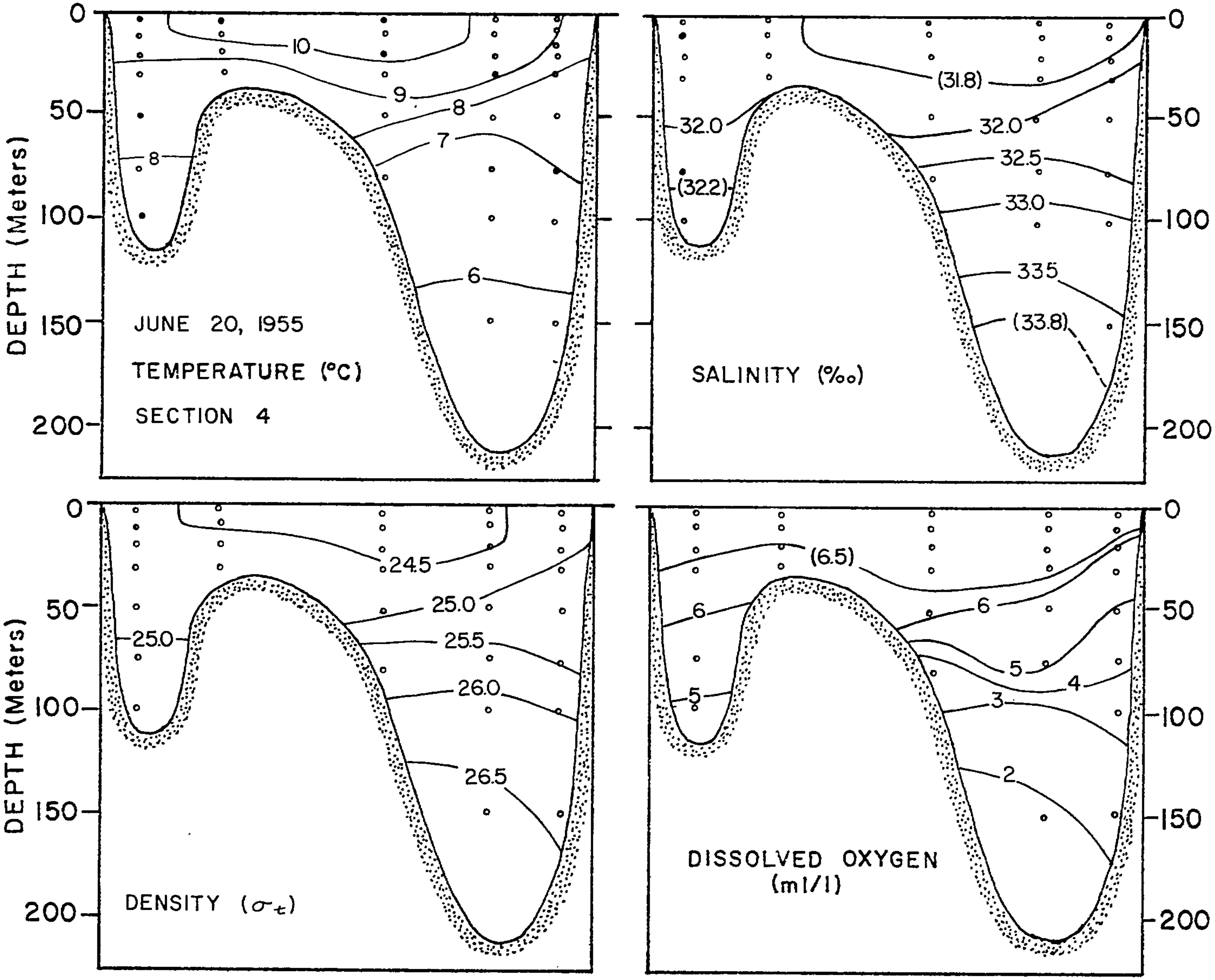


Fig. 131. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, June 20, 1955.

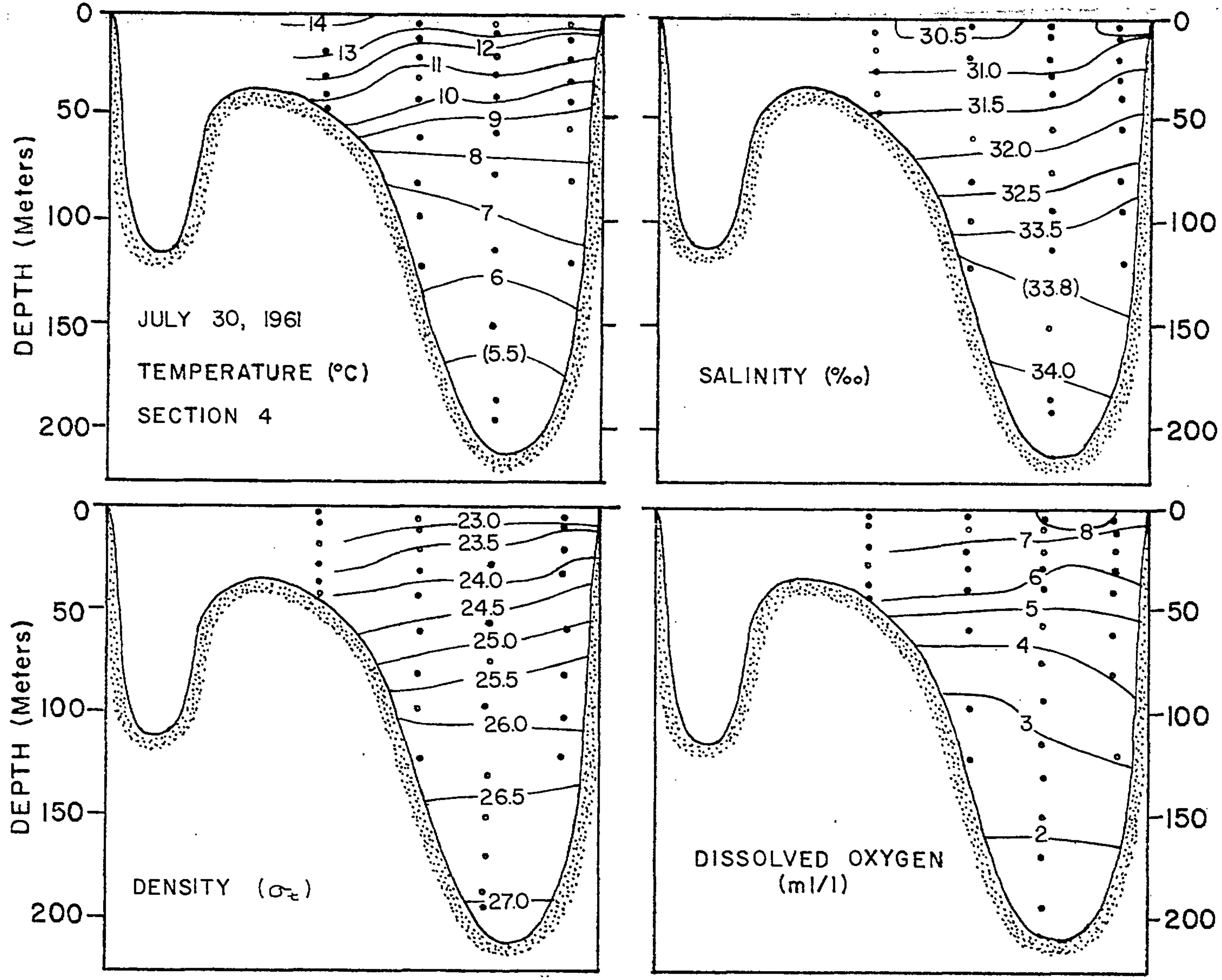


Fig. 132. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, July 30, 1961.

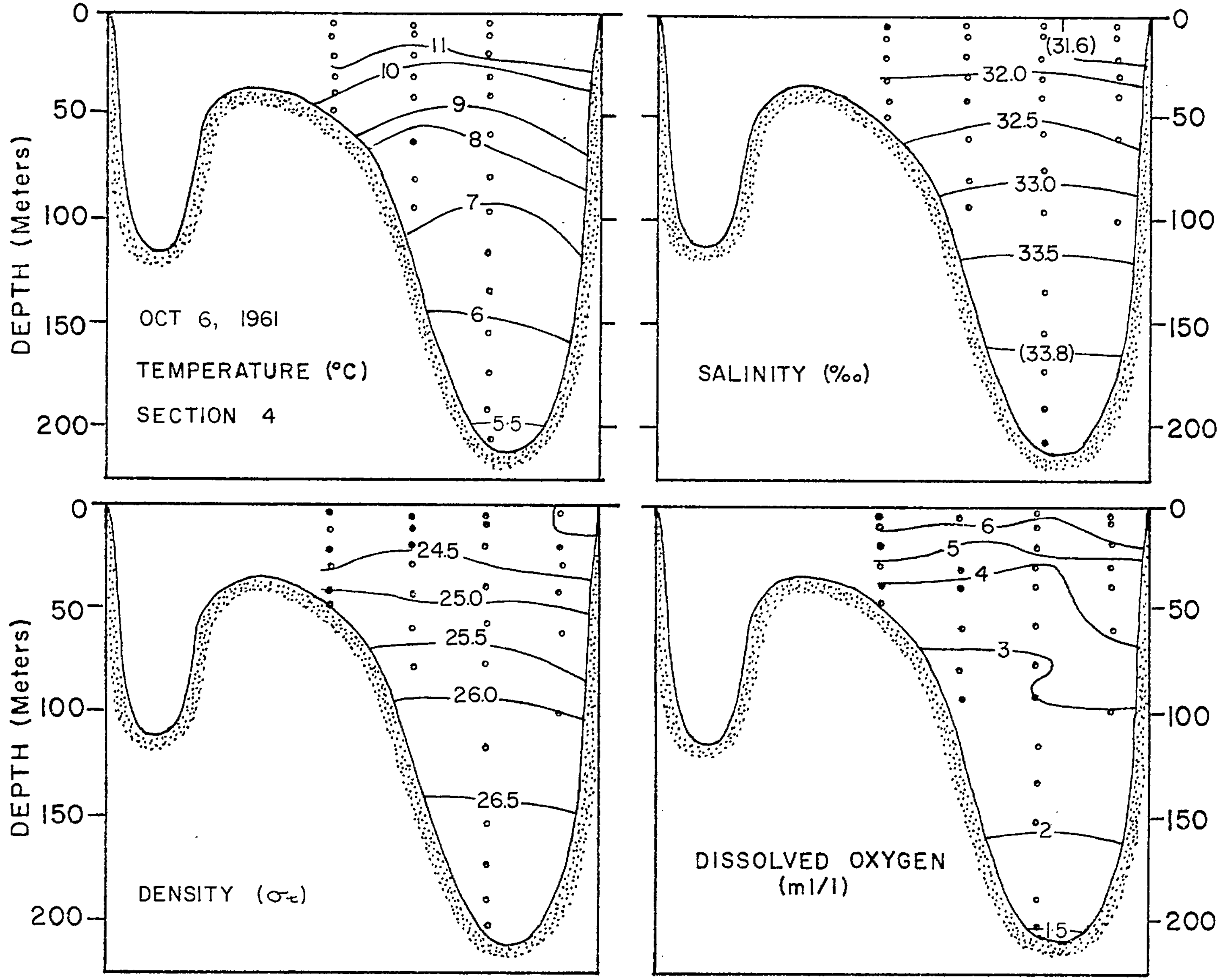


Fig. 133. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, October 6, 1961.

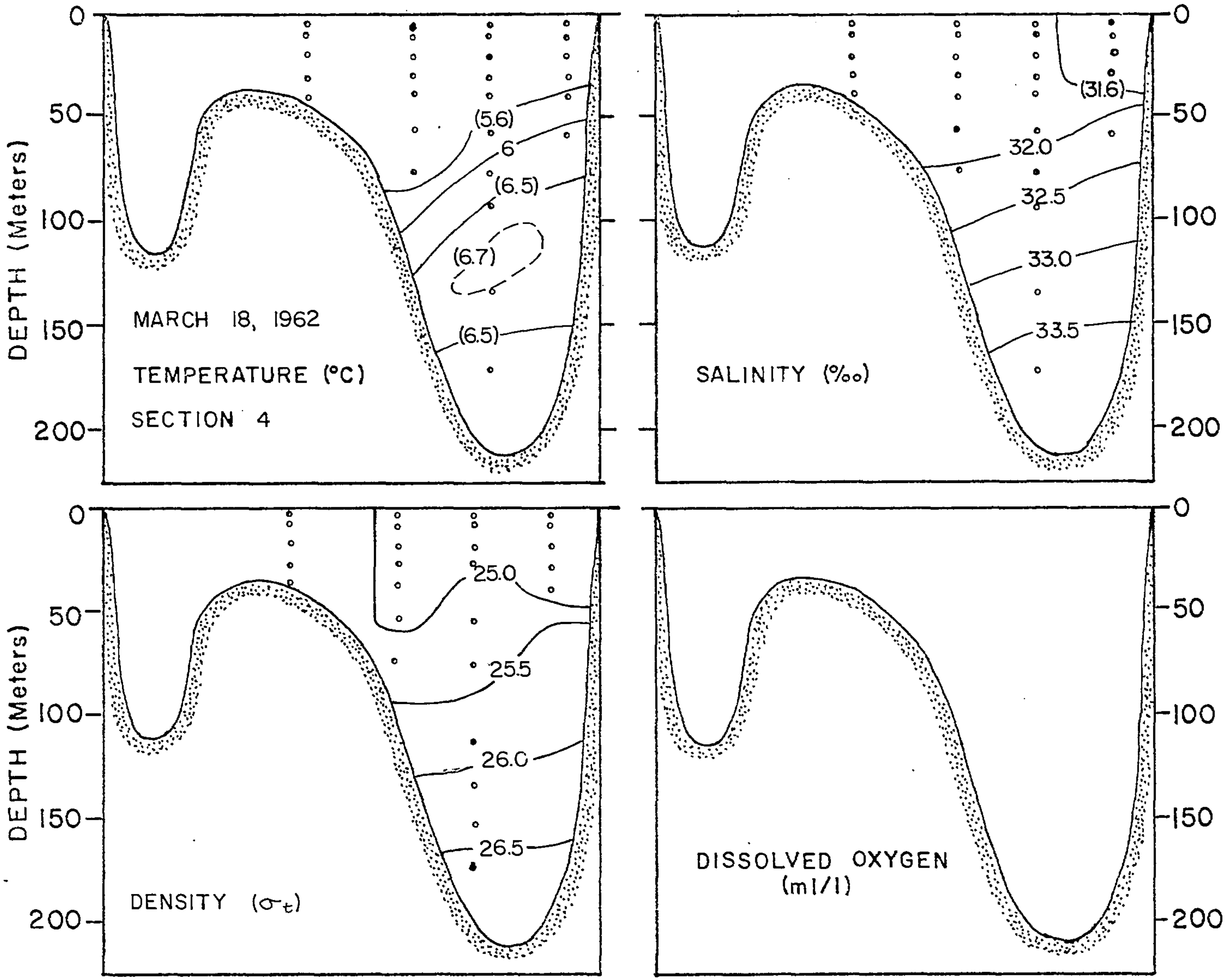


Fig. 134. Vertical sections of temperature, salinity and density in Hecate Strait, March 18, 1962.

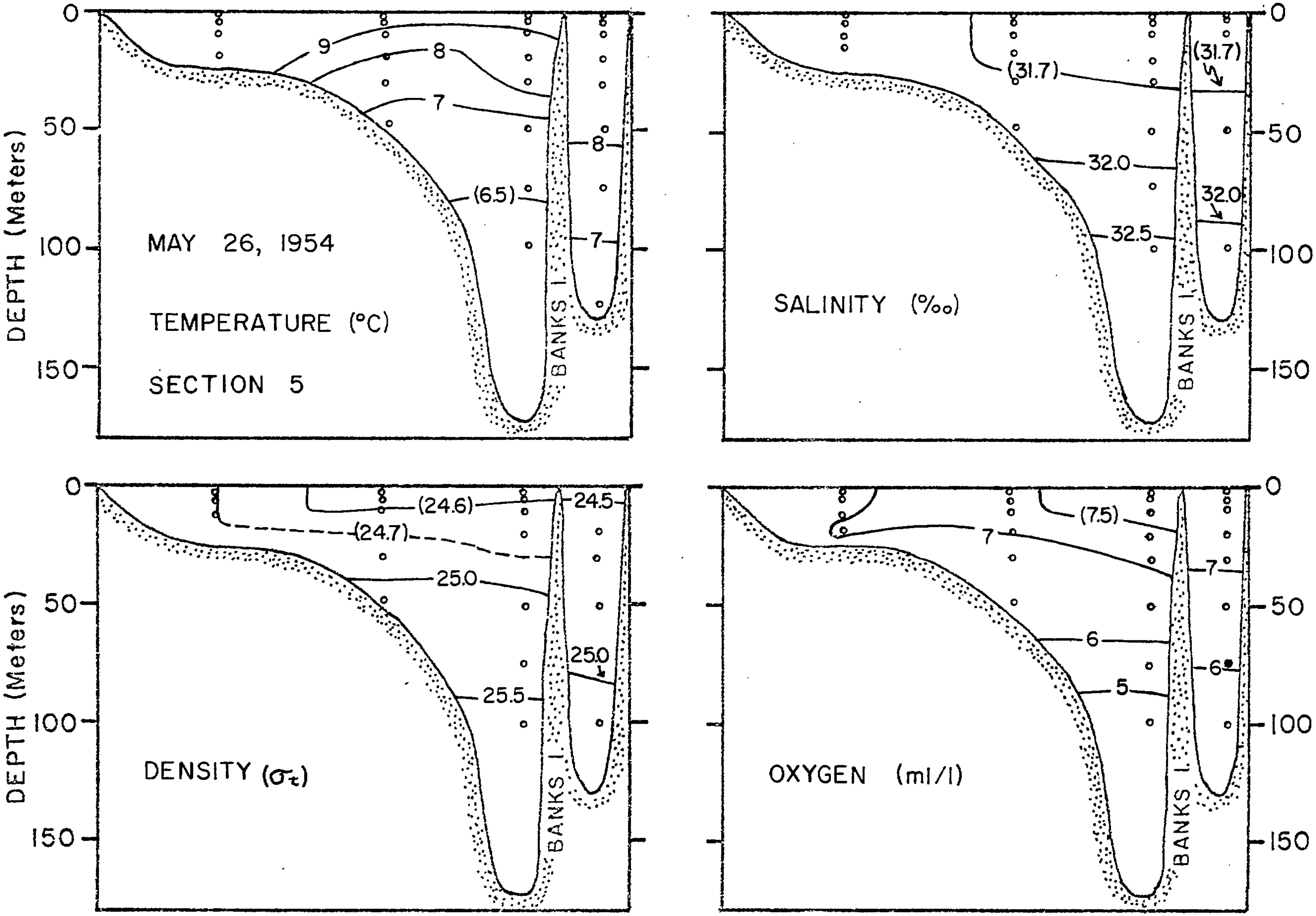


Fig. 135. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, May 26, 1954.

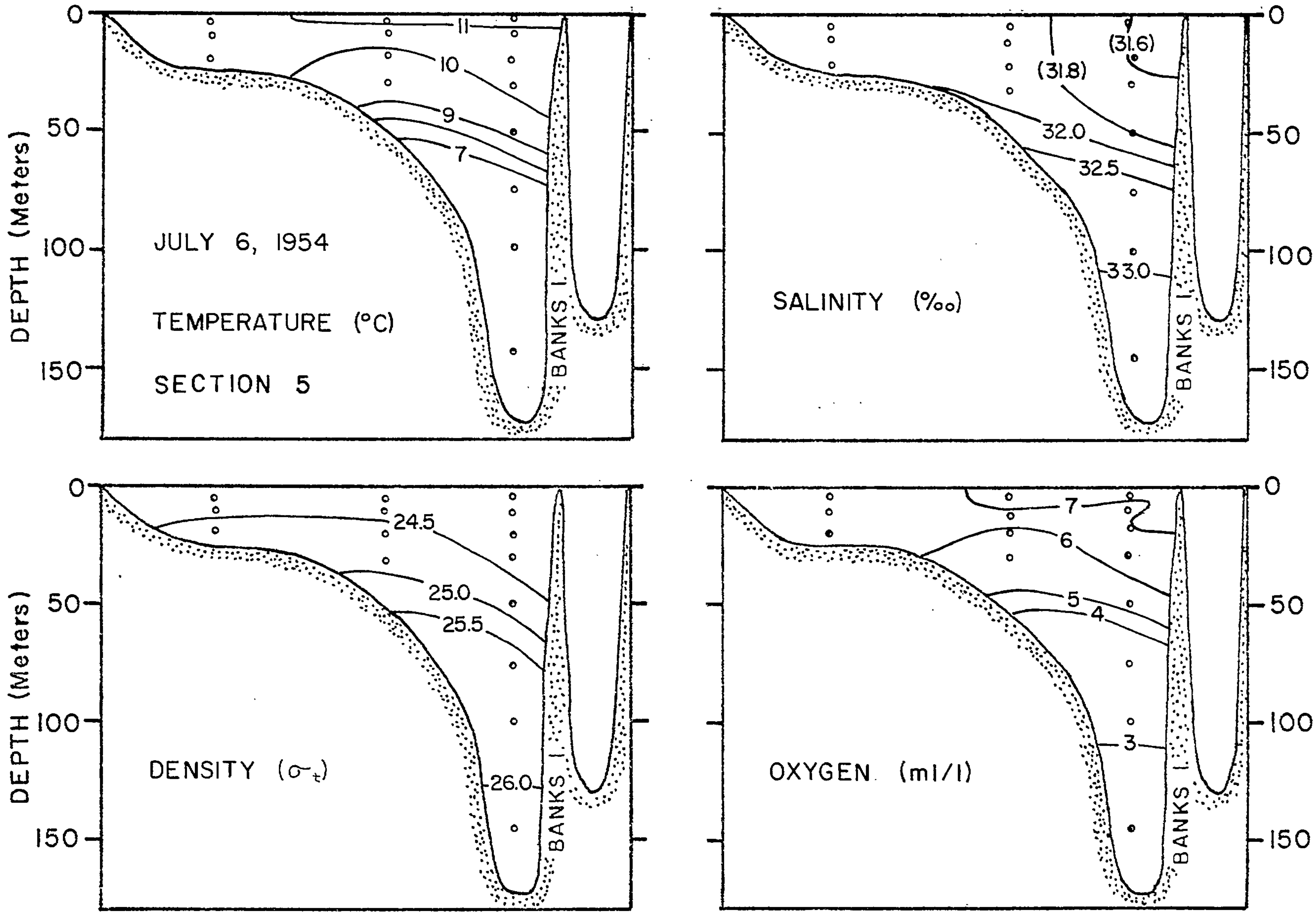


Fig. 136. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, July 6, 1954.

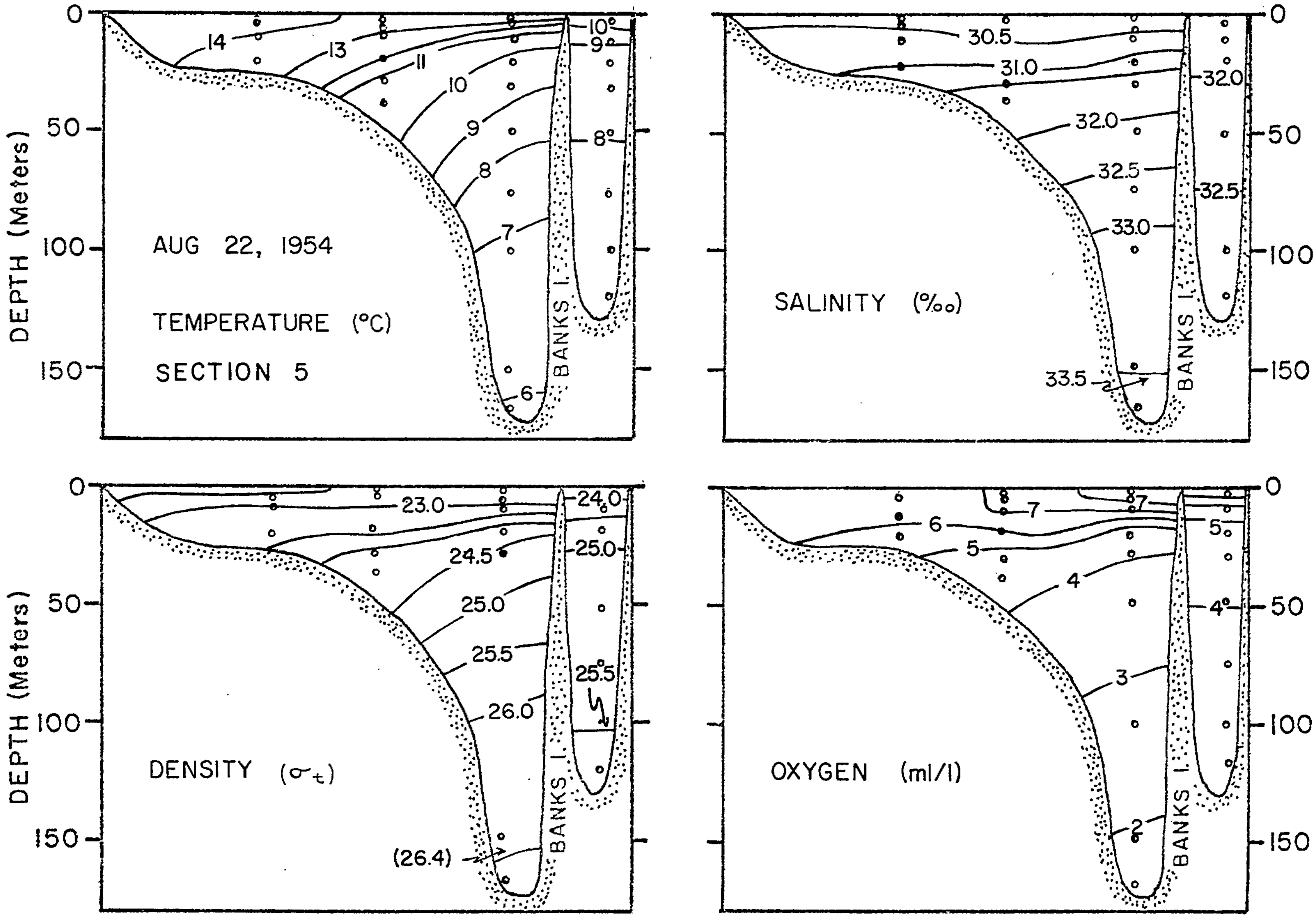


Fig. 137. Vertical sections of temperature, salinity, density and dissolved oxygen content in Hecate Strait, August 22, 1954.

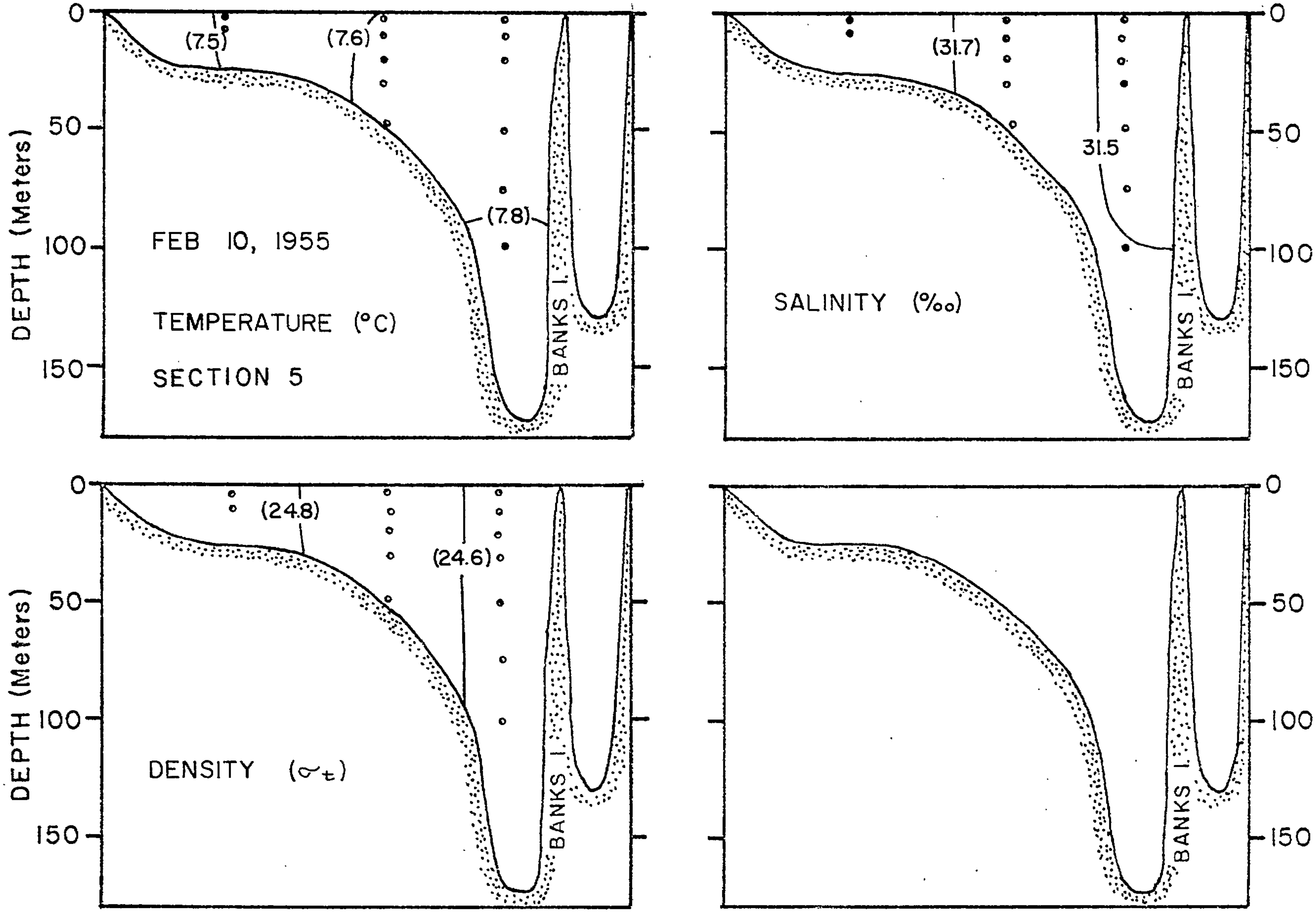


Fig. 138. Vertical sections of temperature, salinity and density in Hecate Strait, February 10, 1955.

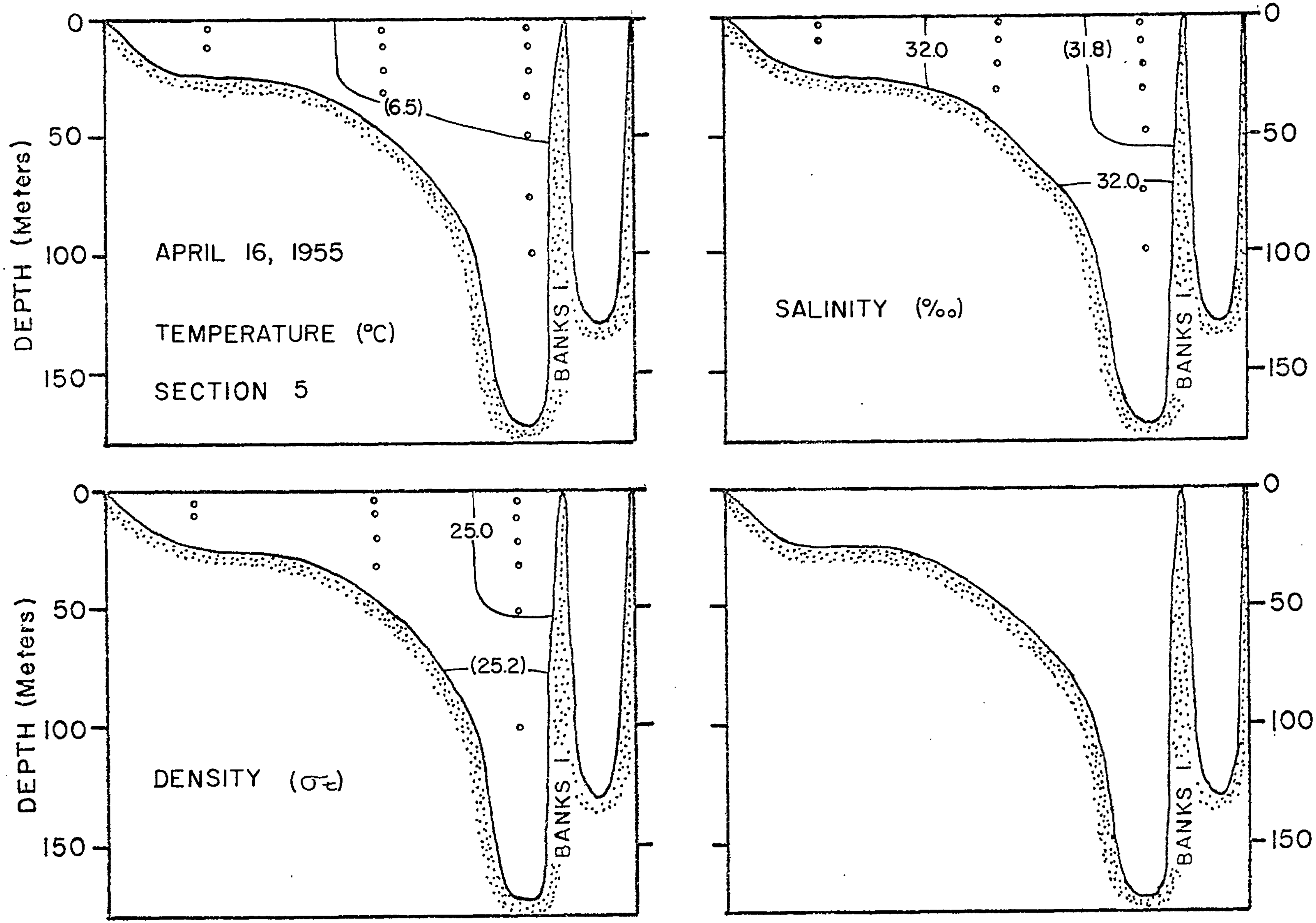


Fig. 139. Vertical sections of temperature, salinity and density in Hecate Strait, April 16, 1955.

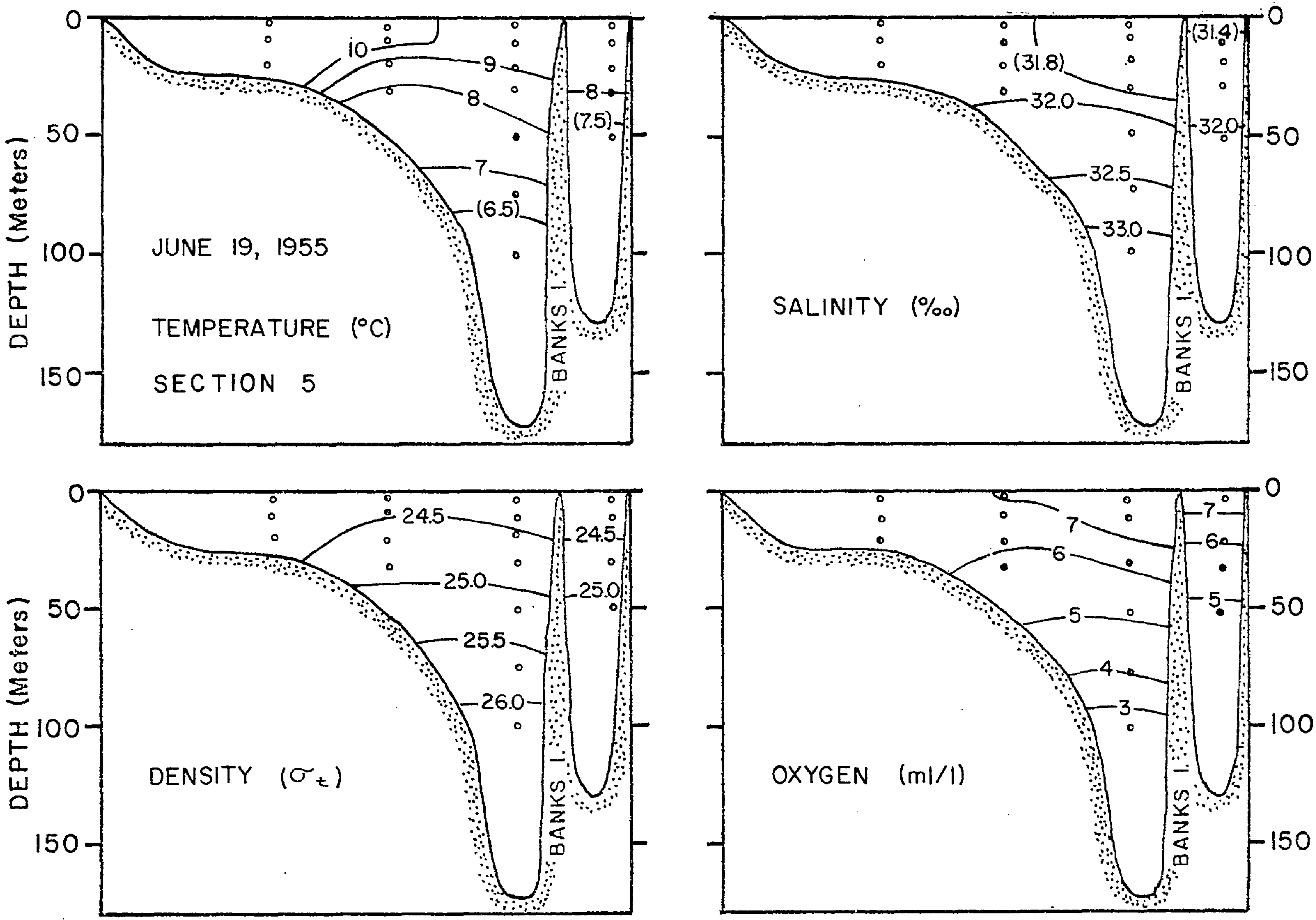


Fig. 140. Vertical sections of temperature, salinity, density and dissolved oxygen content. June 19, 1955.

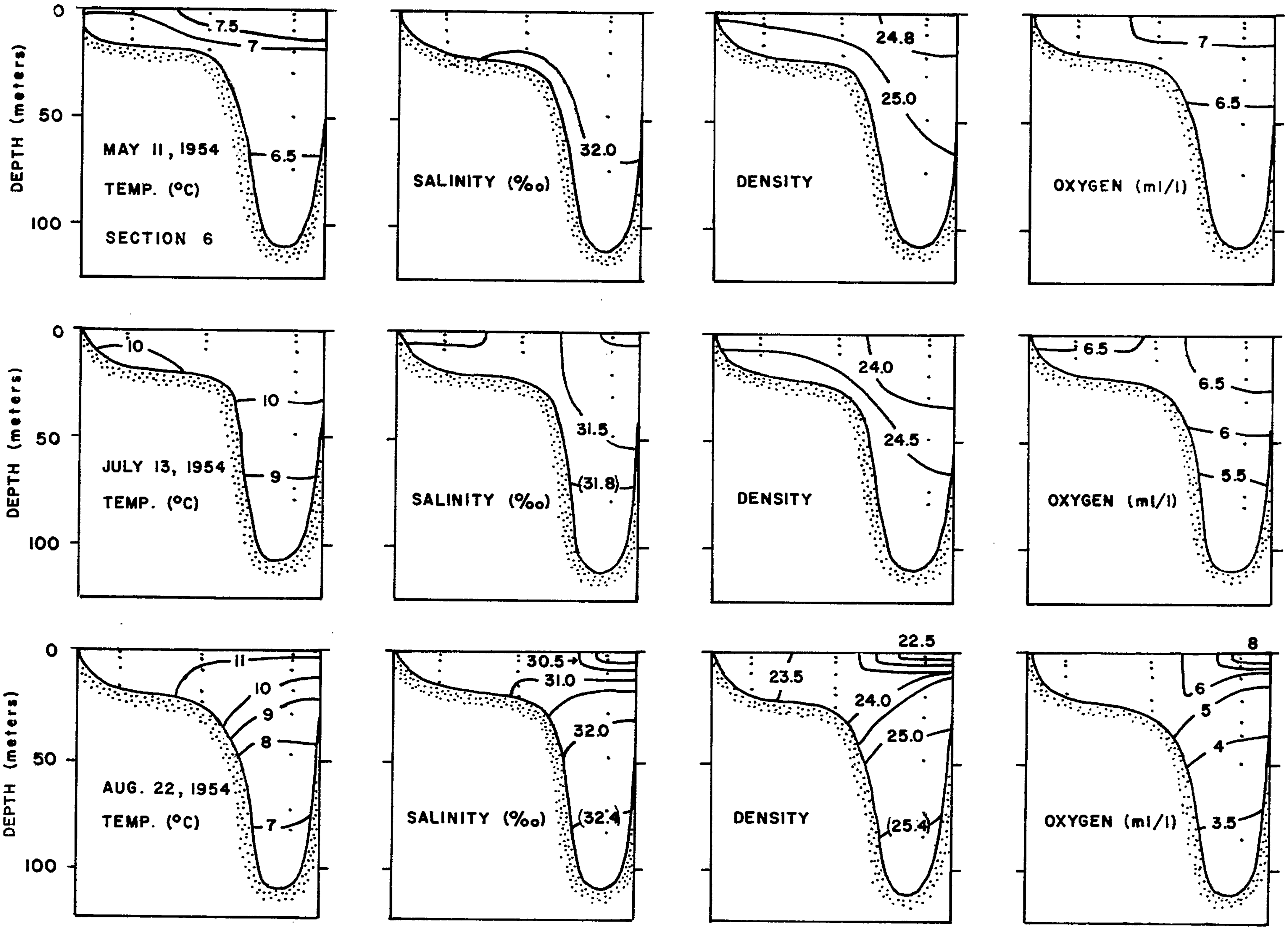


Fig. 141. Vertical sections of temperature, salinity, density and dissolved oxygen content, May 1954-June 1955.

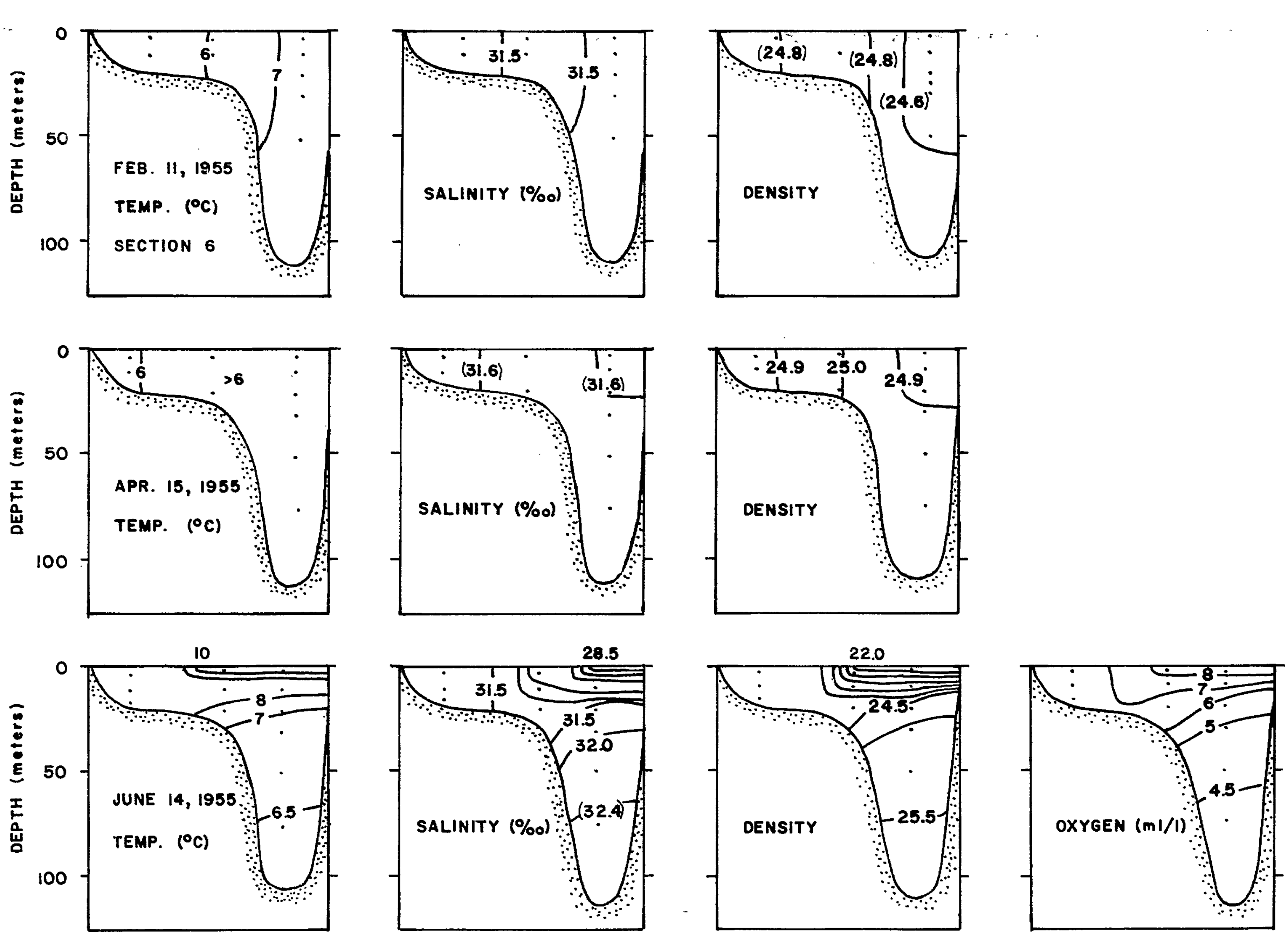


Fig. 141 (cont'd).

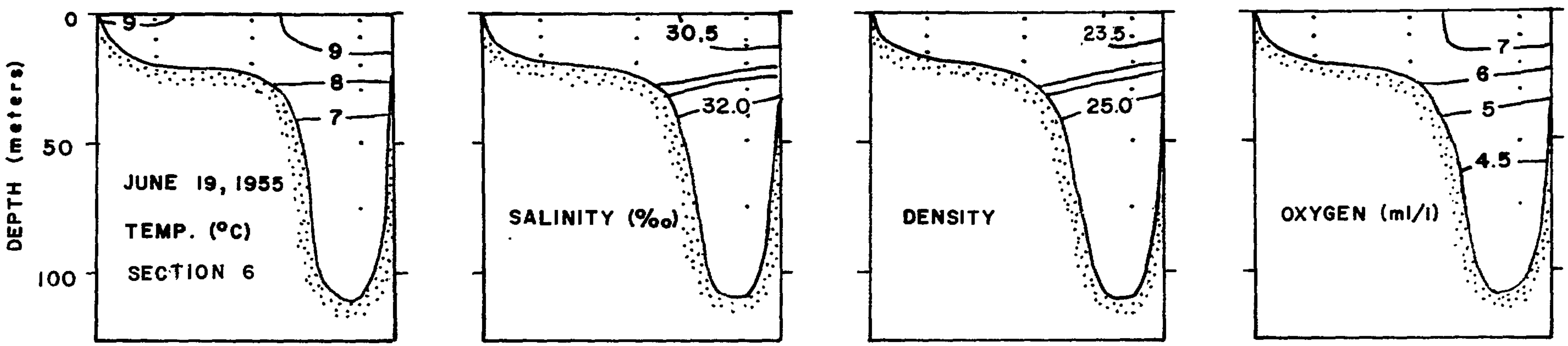


Fig. 141 (cont'd).

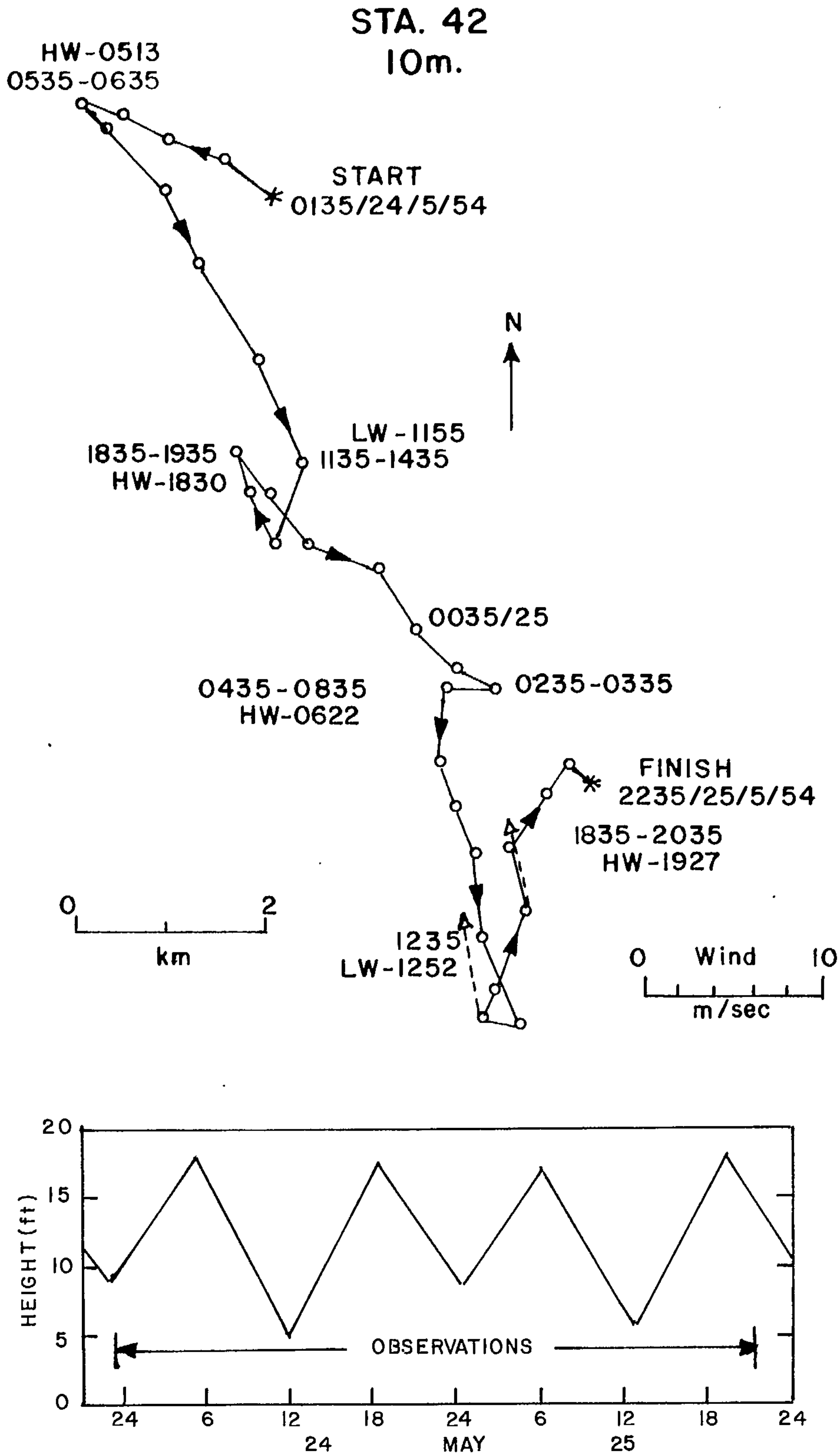


Fig. 142. Progressive vector diagram of tidal currents at 10 m depth at Station 42 in Hecate Strait, May 24-25, 1954 (dashed lines and arrows indicate wind velocities; predicted tides are those for Prince Rupert) (see Fig. 13 for Station positions).

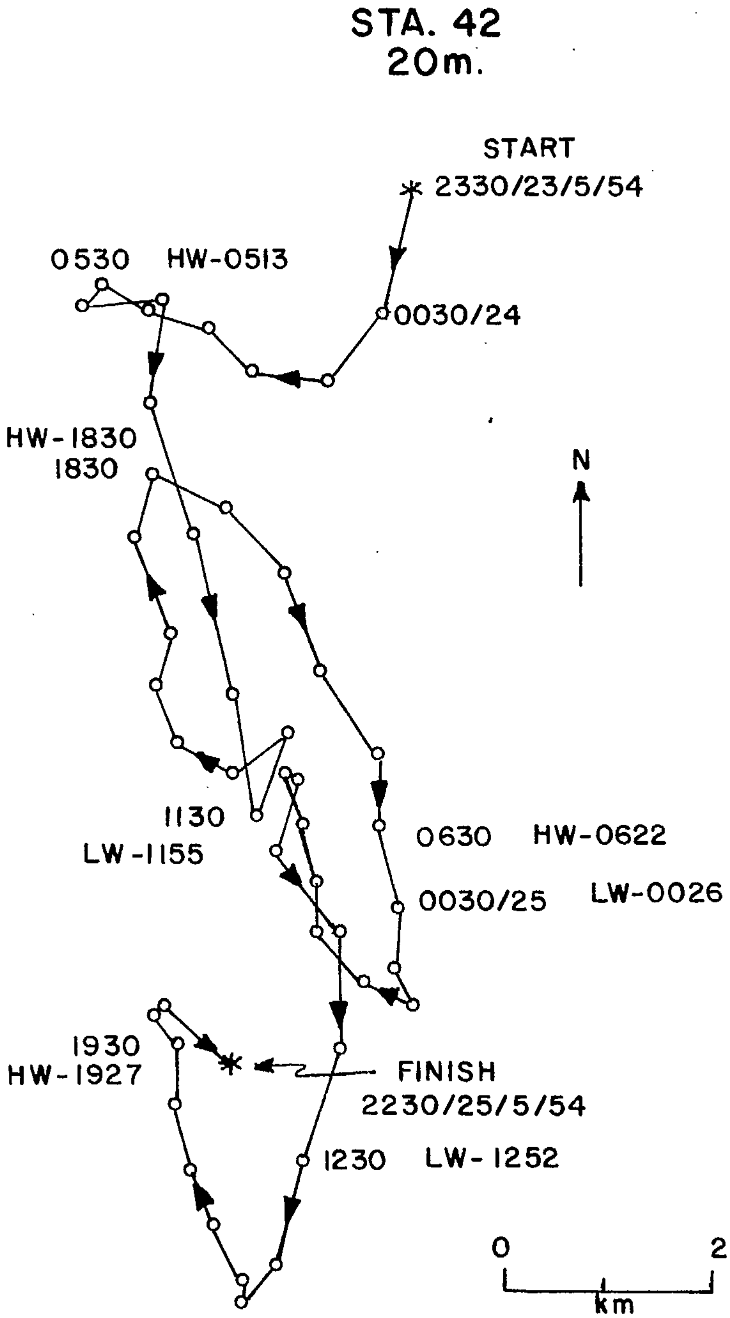


Fig. 143. Progressive vector diagram of tidal currents at 20 m depth at Station 42 in Hecate Strait, May 23-25, 1954.

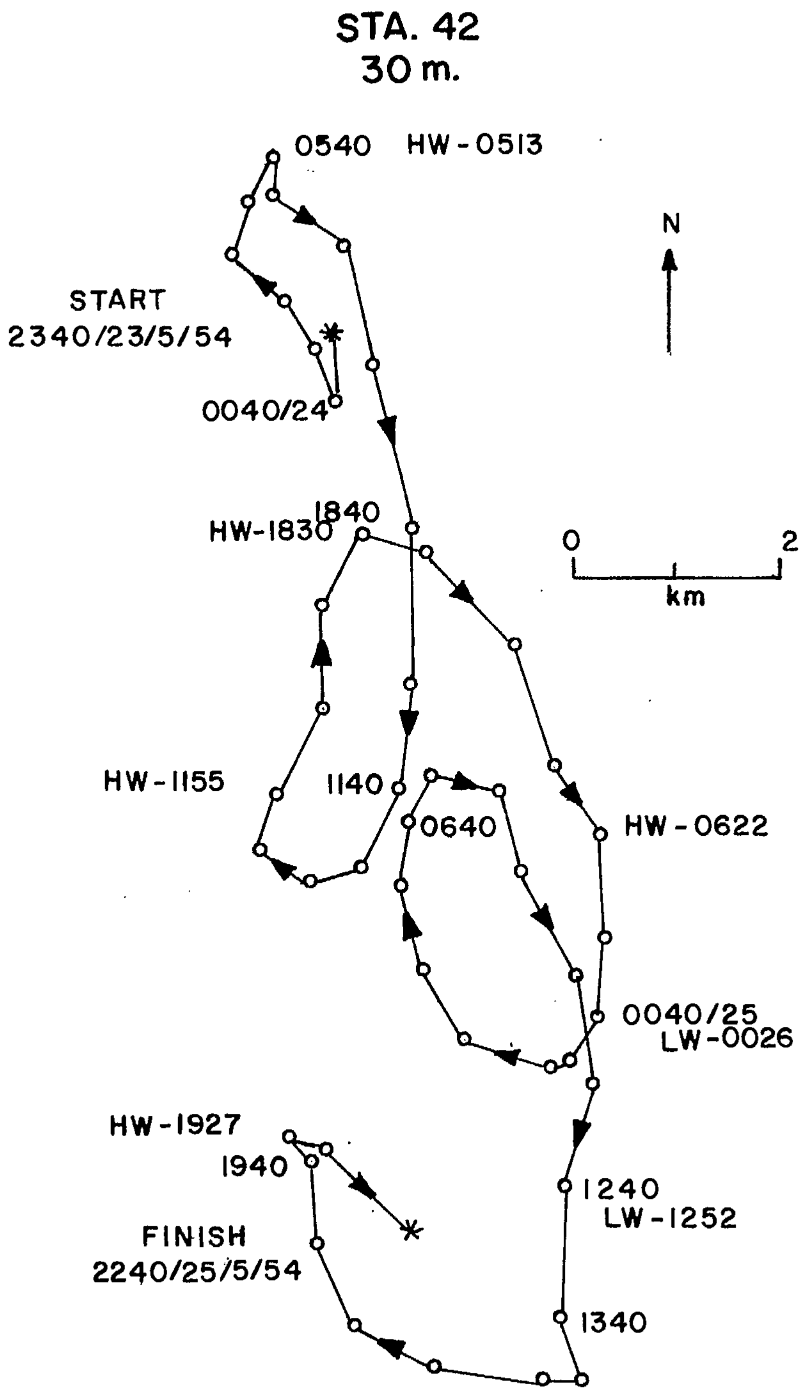


Fig. 144. Progressive vector diagram of tidal currents at 30 m depth at Station 42 in Hecate Strait, May 23-25, 1954.

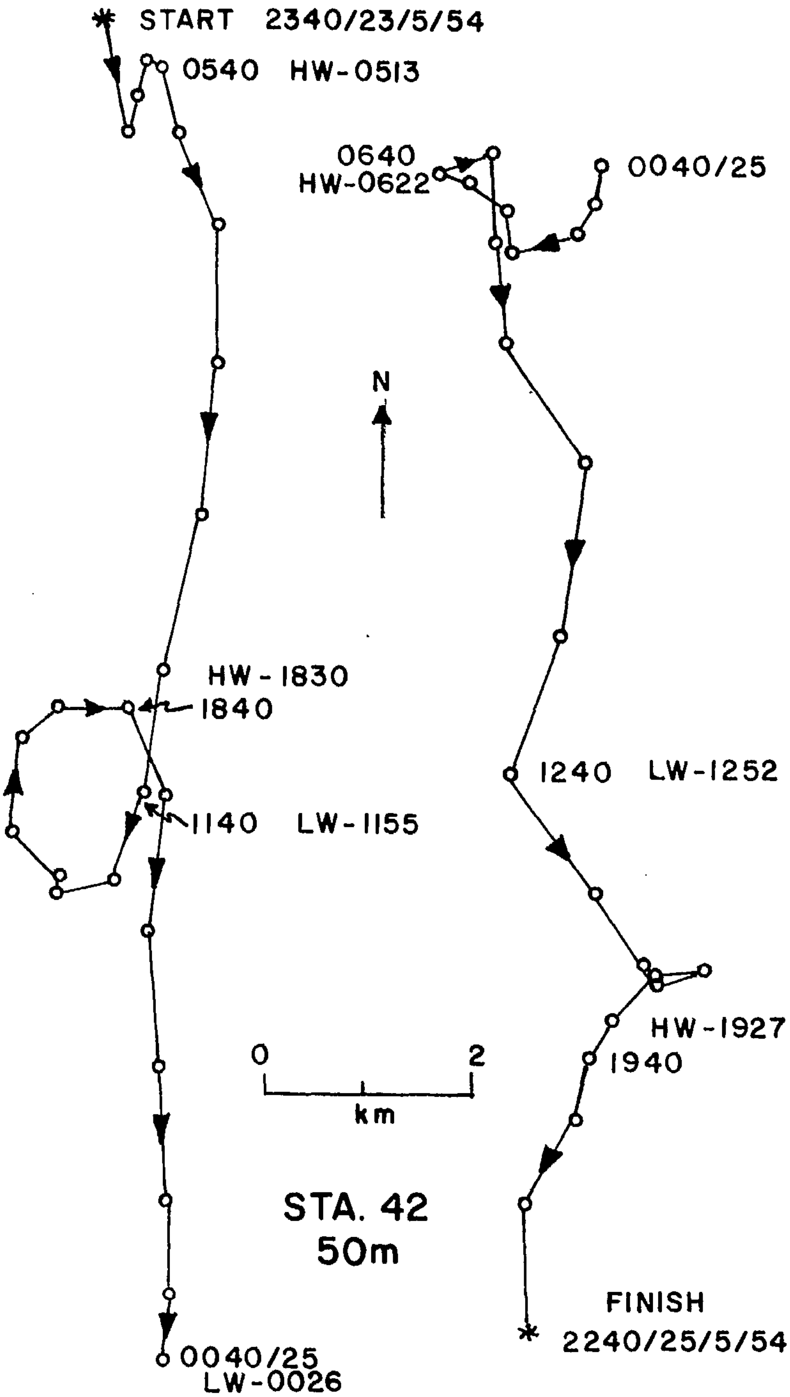


Fig. 145. Progressive vector diagram of tidal currents at 50 m depth at Station 42 in Hecate Strait, May 23-25, 1954.

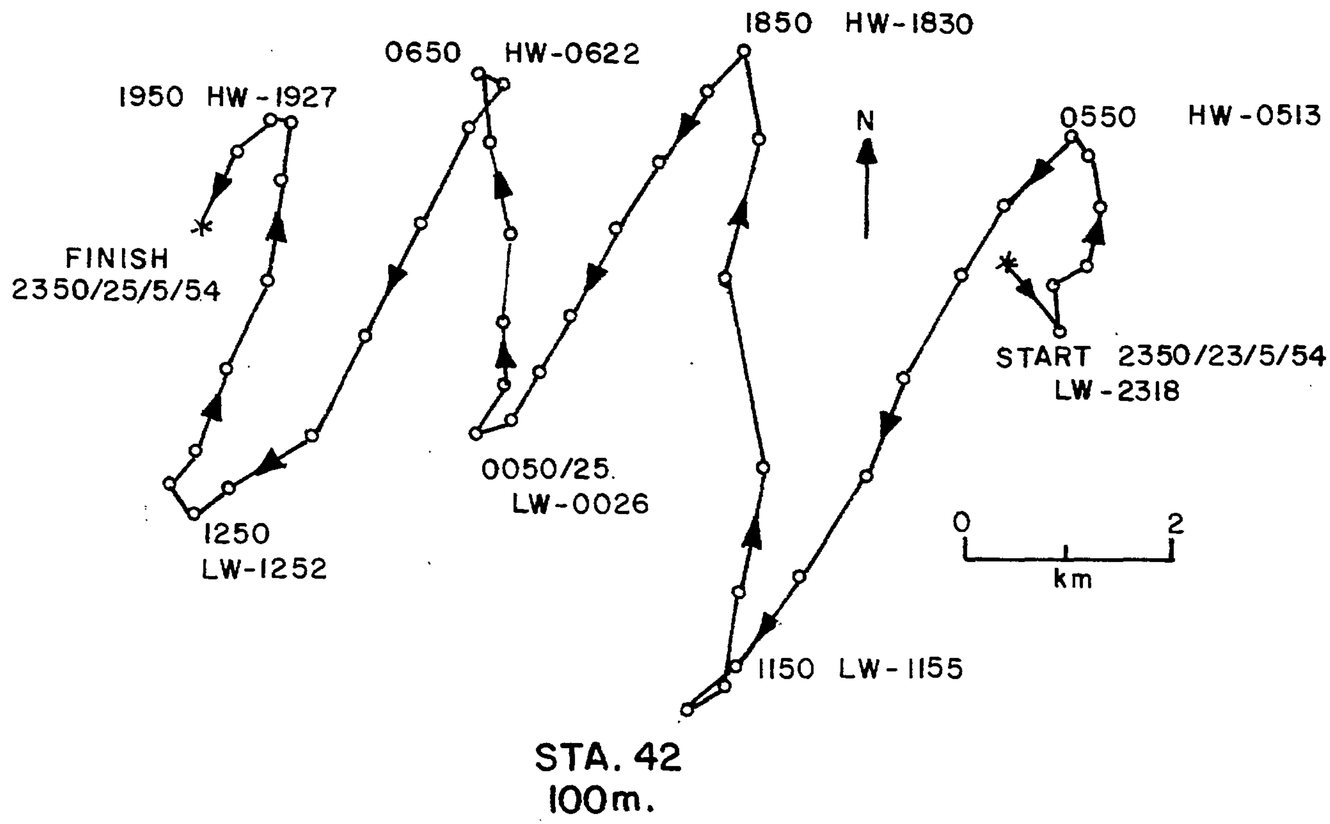


Fig. 146. Progressive vector diagram of tidal currents at 100 m depth at Station 42 in Hecate Strait, May 23-25, 1954.

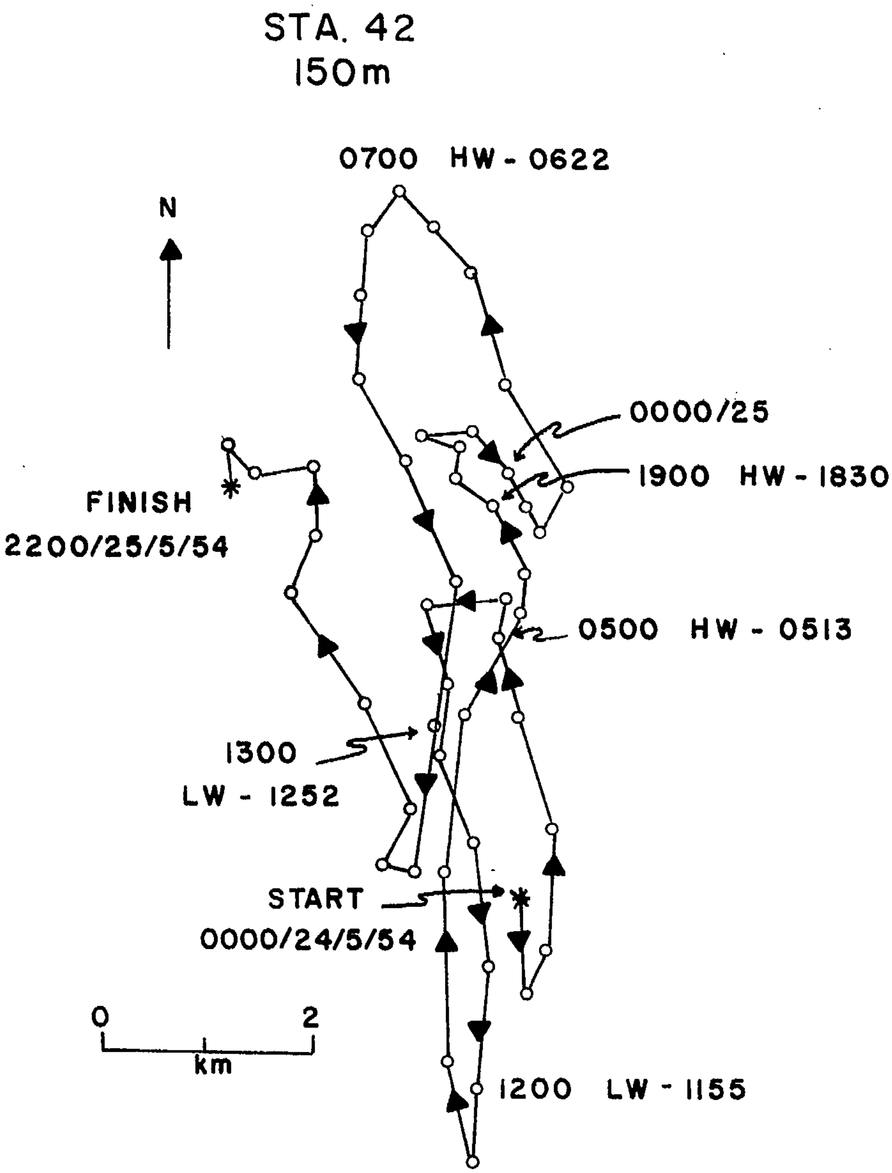


Fig. 147. Progressive vector diagram of tidal currents at 150 m depth at Station 42 in Hecate Strait, May 24-25, 1954.

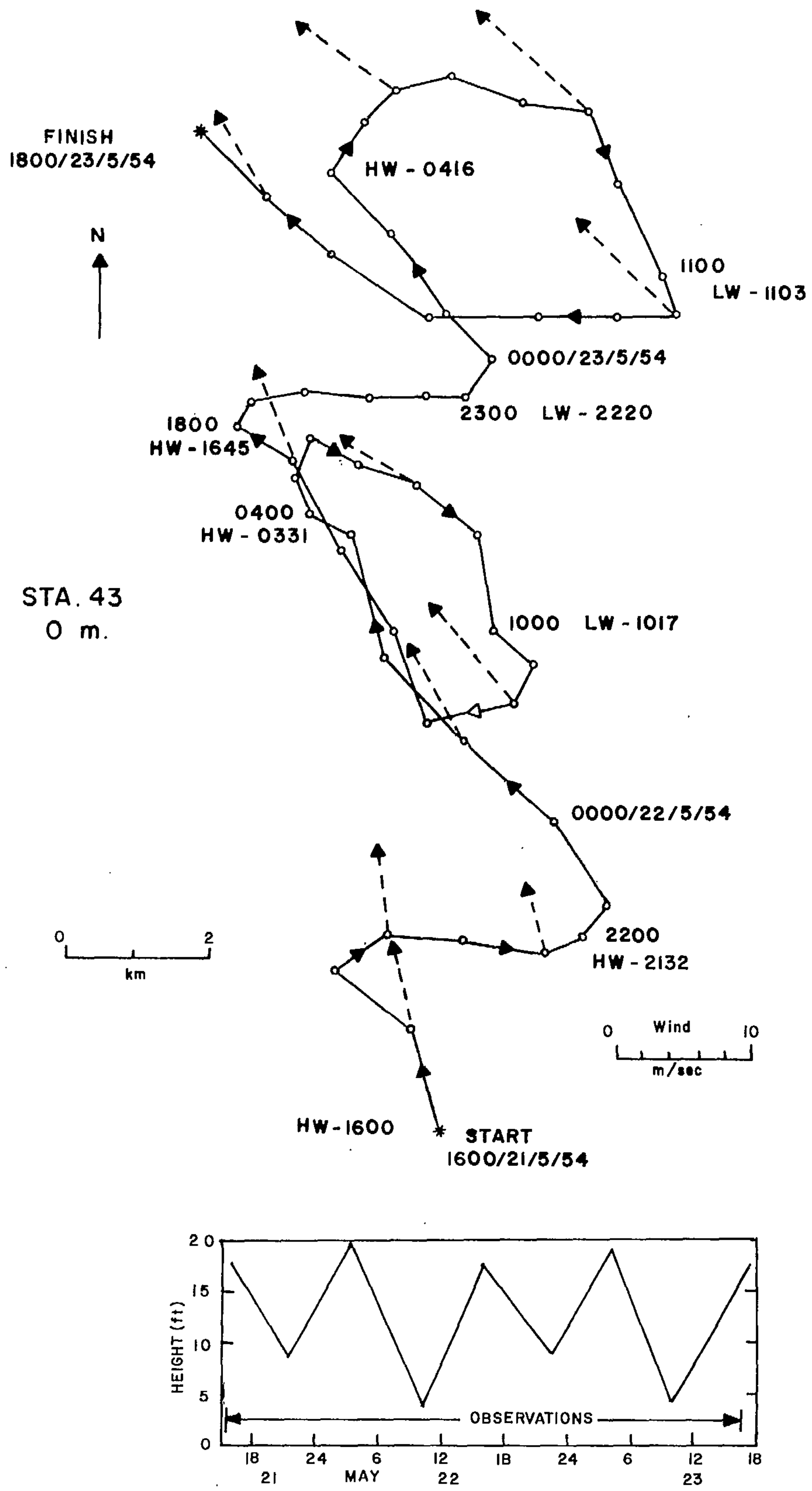


Fig. 148. Progressive vector diagram of tidal currents at 0 m depth at Station 43 in Hecate Strait, May 21-23, 1954.

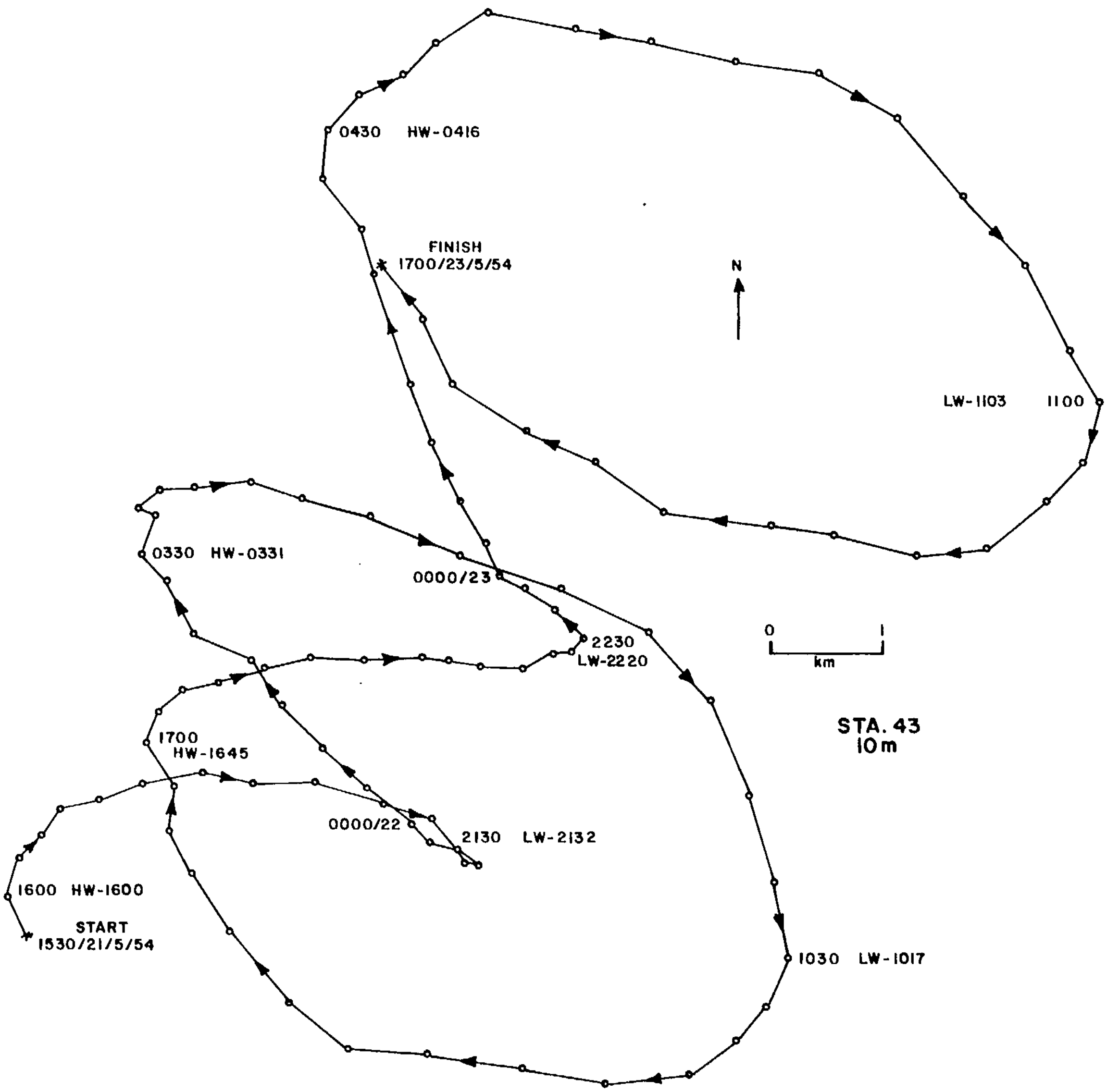


Fig. 149. Progressive vector diagram of tidal currents at 10 m depth at Station 43 in Hecate Strait, May 21-23, 1954.

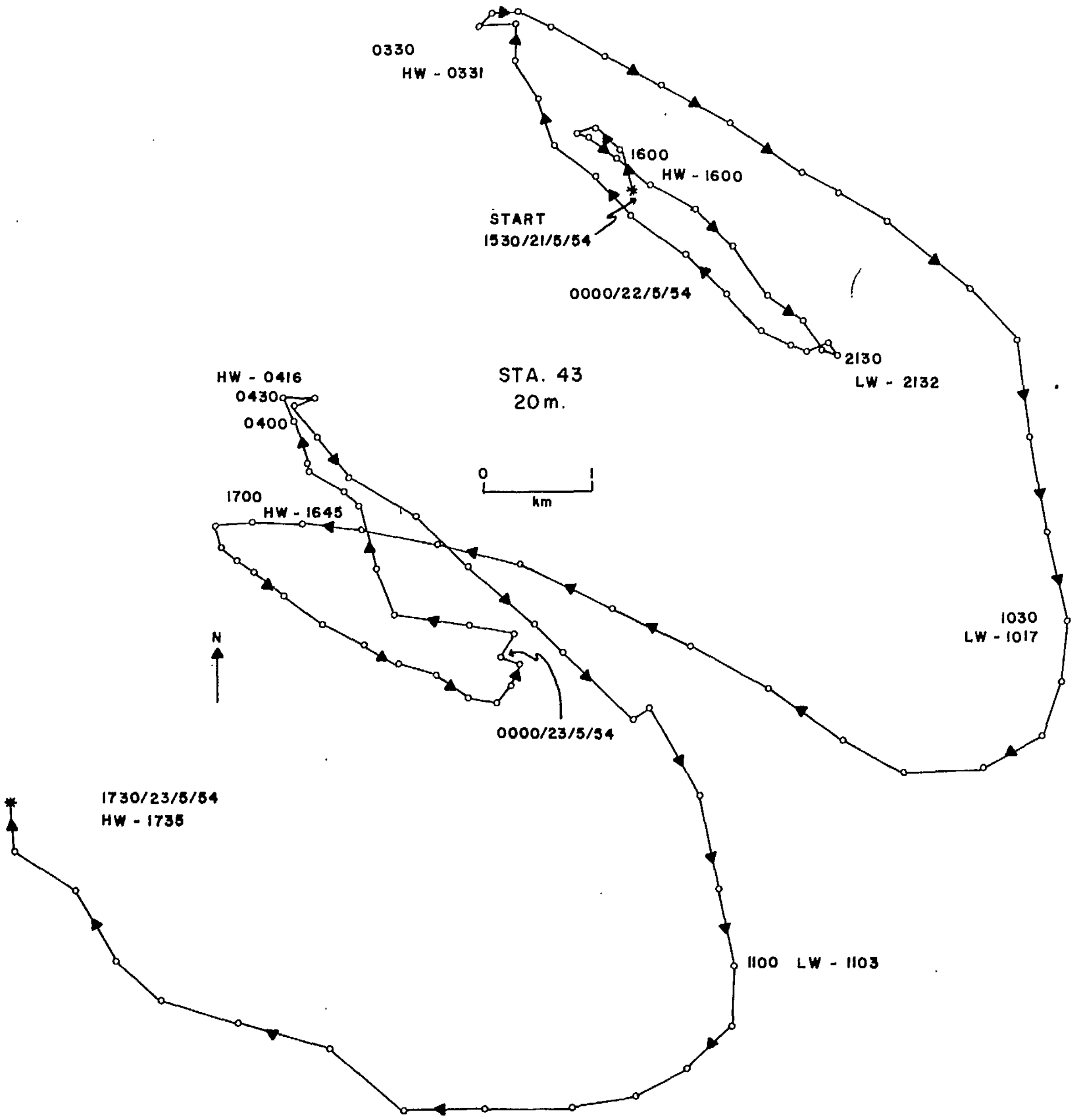


Fig. 150. Progressive vector diagram of tidal currents at 20 m depth at Station 43 in Hecate Strait, May 21-23, 1954.

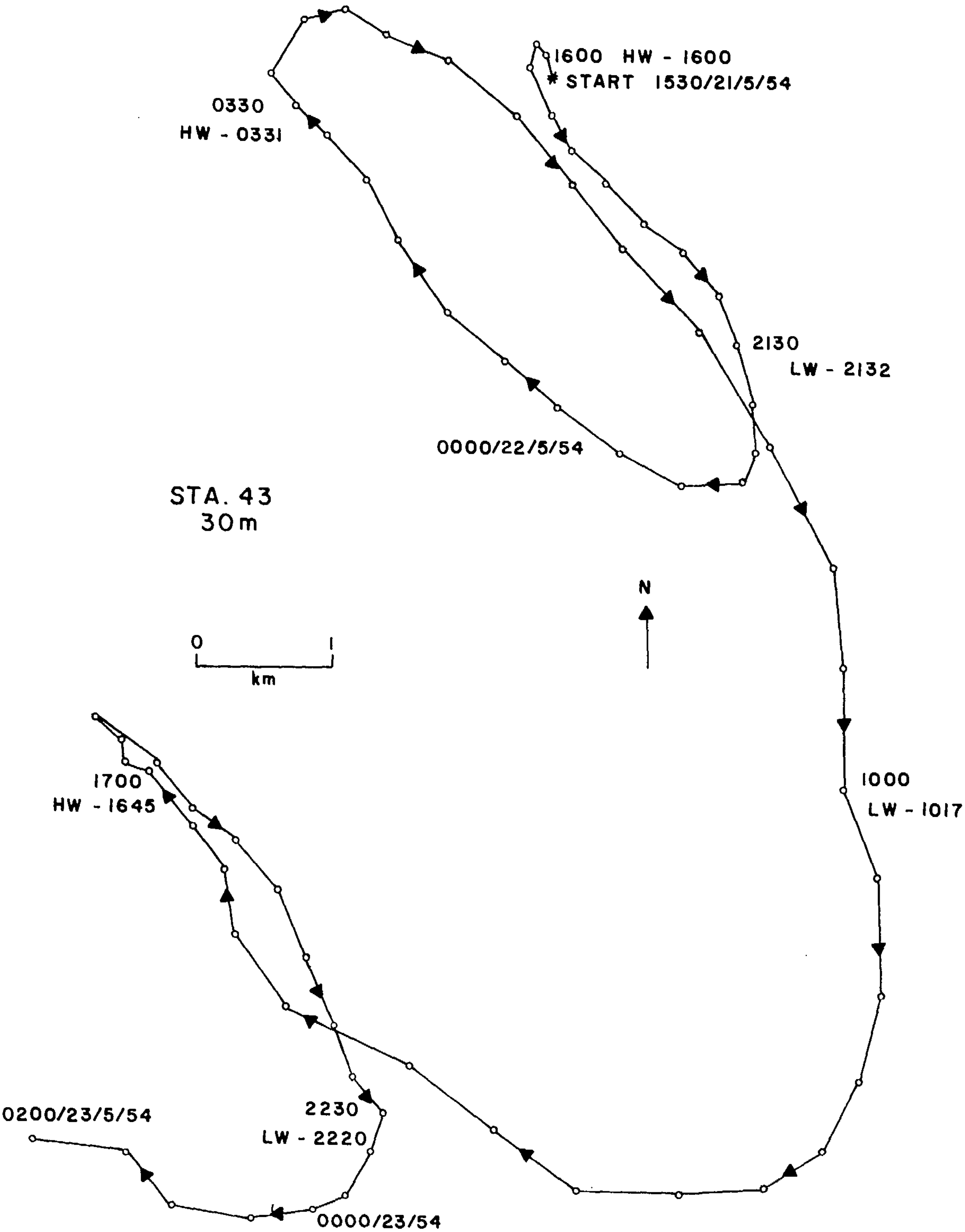


Fig. 151. Progressive vector diagram of tidal currents at 30 m depth at Station 43 in Hecate Strait, May 21-23, 1954.

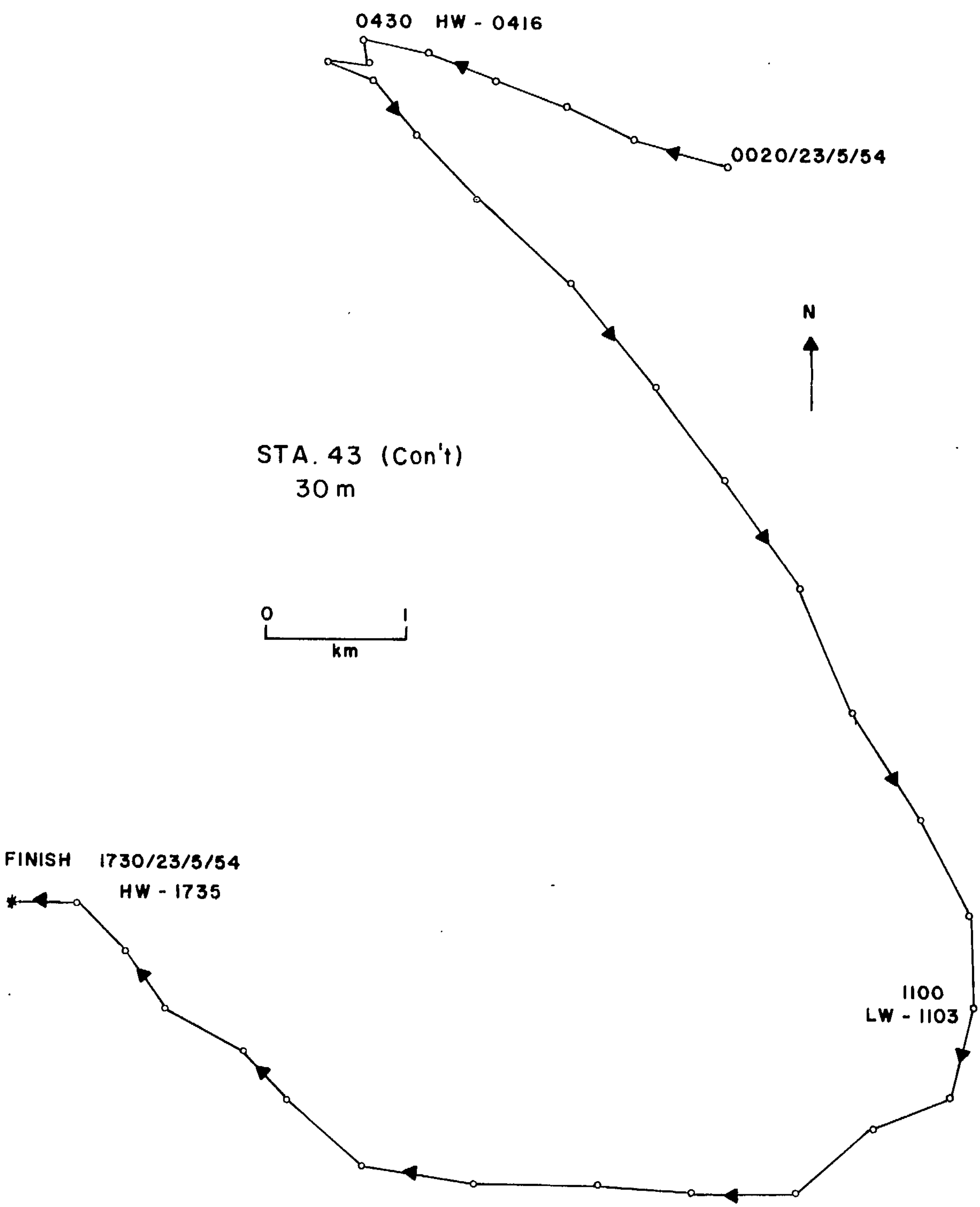


Fig. 151 (cont'd).

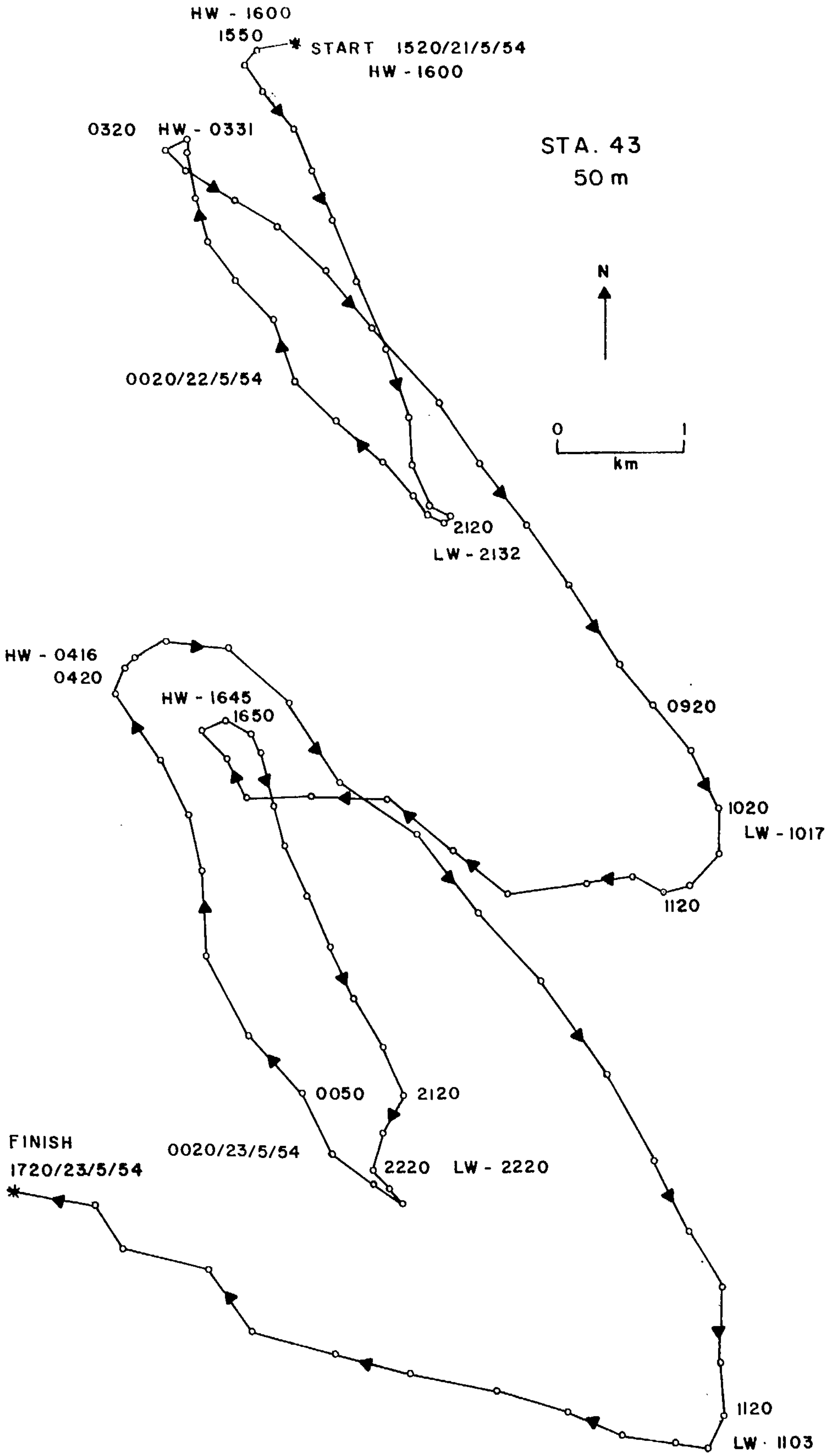


Fig. 152. Progressive vector diagram of tidal currents at 50 m depth at Station 43 in Hecate Strait, May 21-23, 1954.

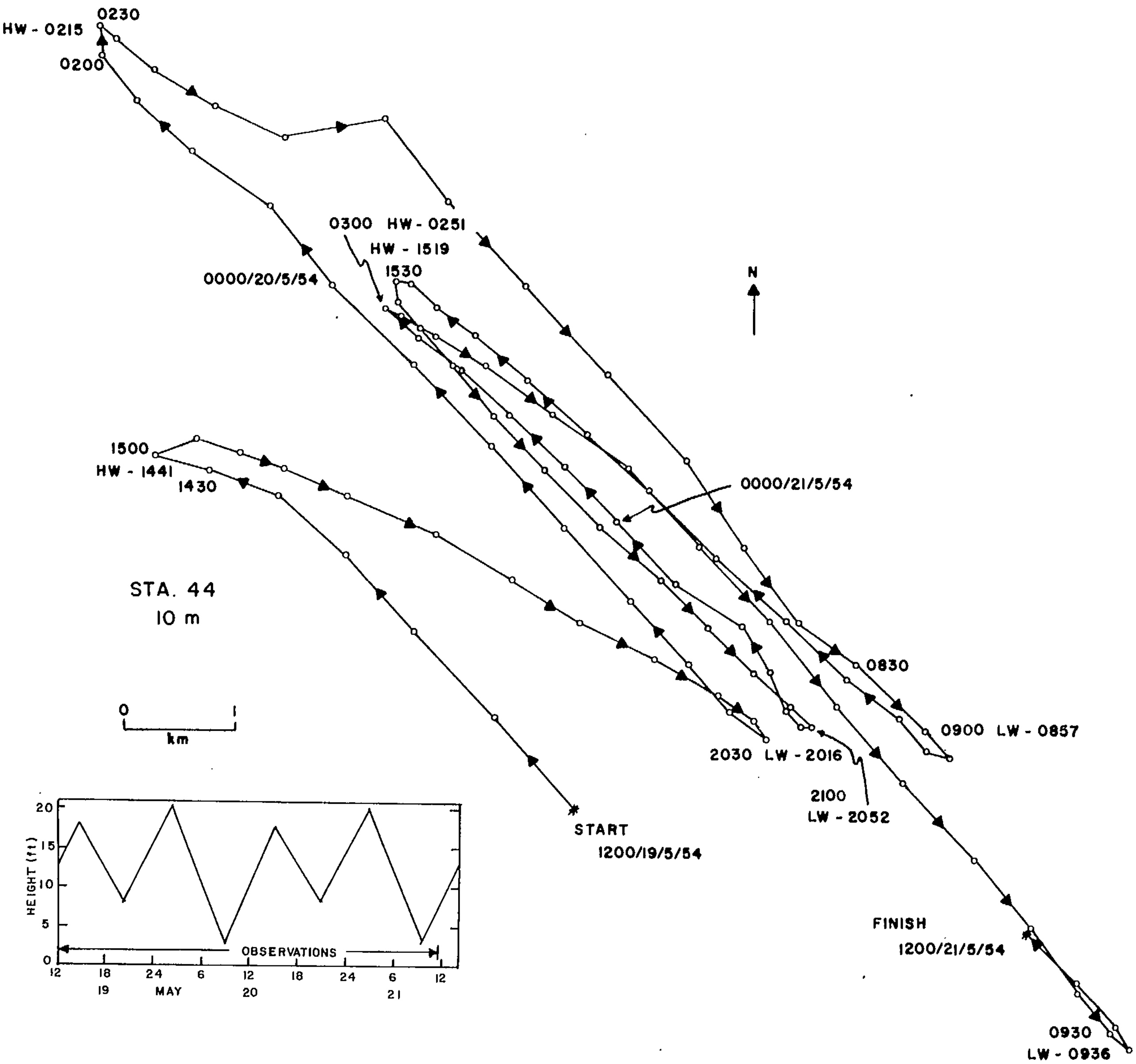


Fig. 153. Progressive vector diagram of tidal currents at 10 m depth at Station 44 in Hecate Strait, May 19-21, 1954.

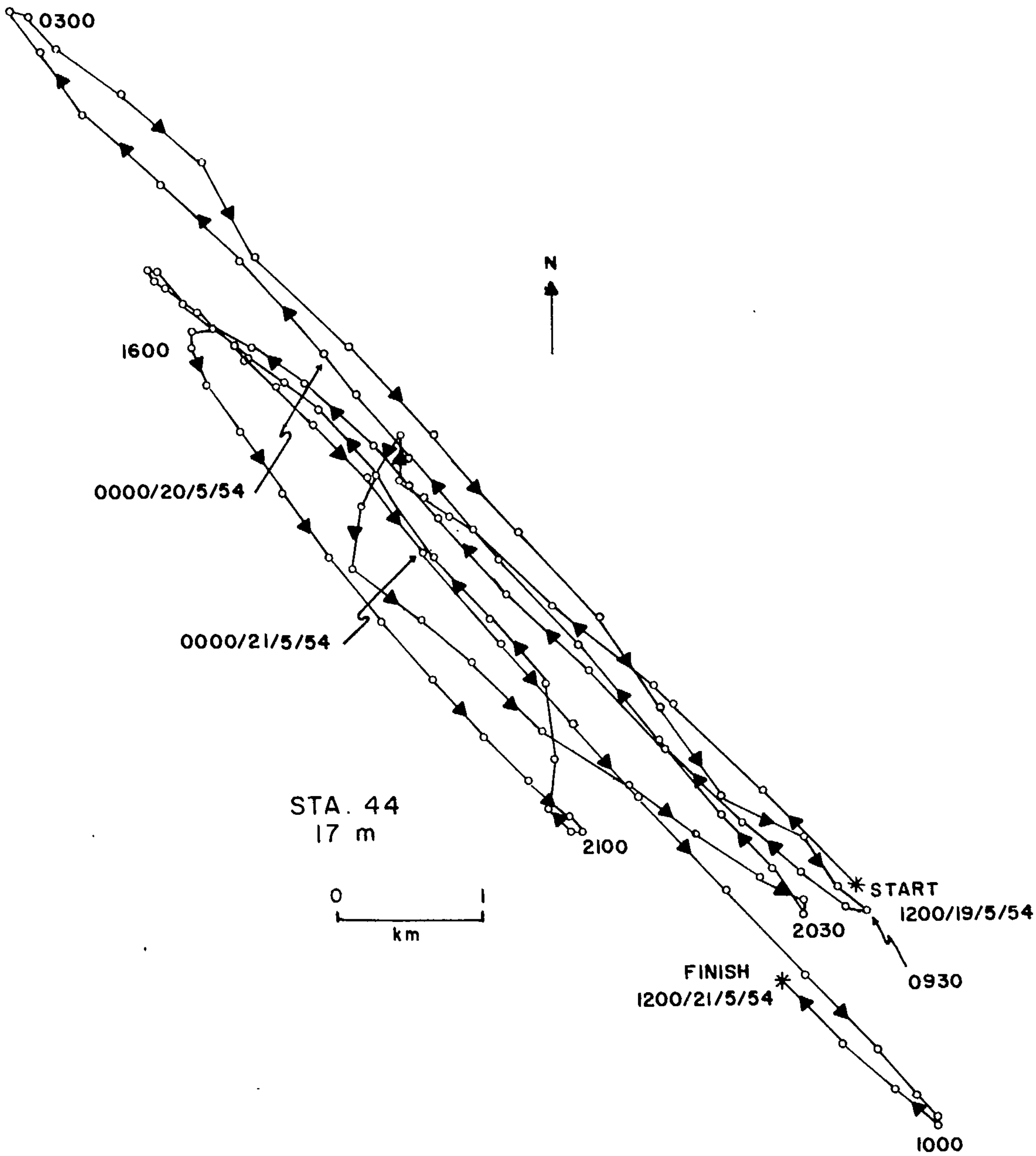


Fig. 154. Progressive vector diagram of tidal currents at 17 m depth at Station 44 in Hecate Strait, May 19-21, 1954.

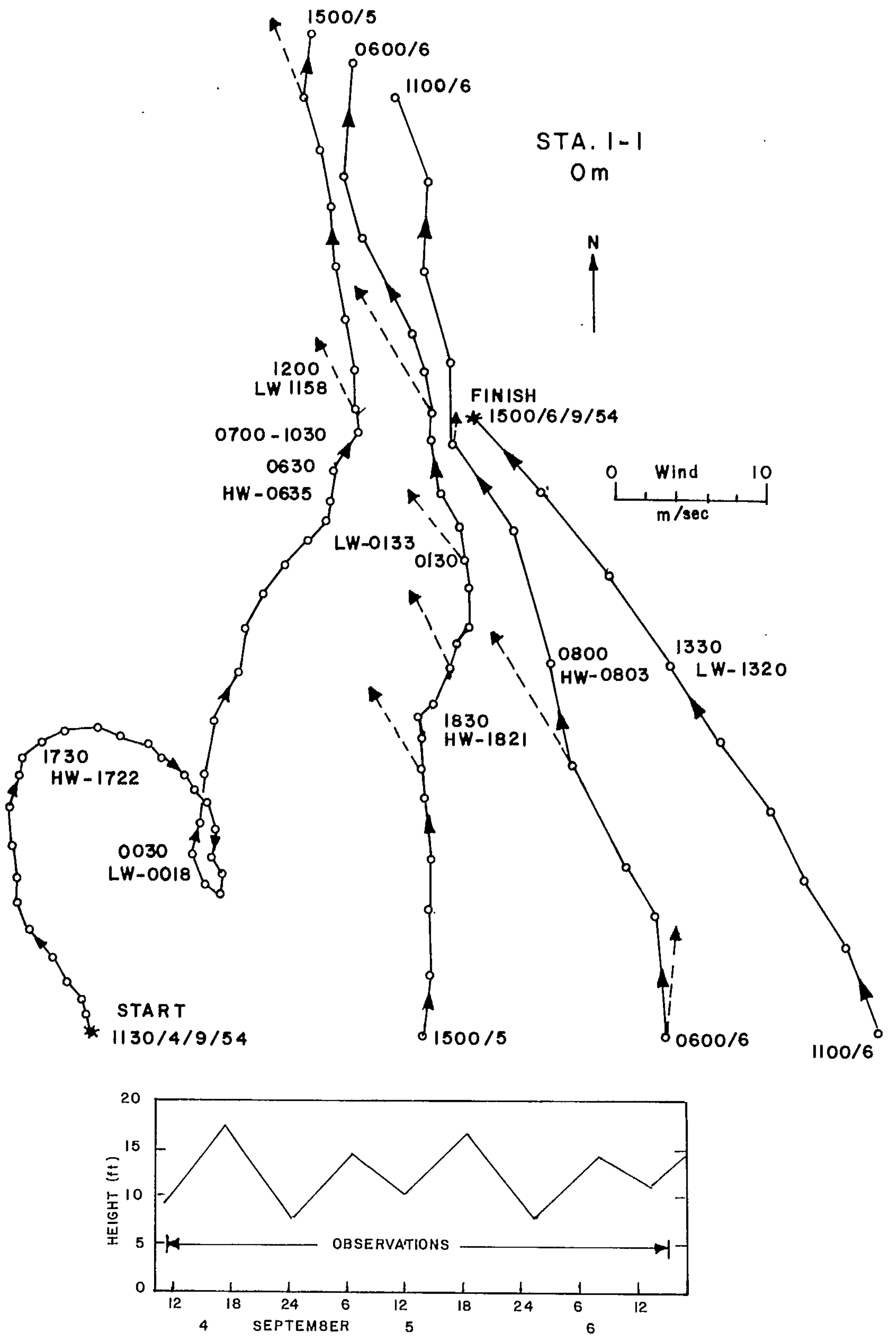


Fig. 155. Progressive vector diagram of tidal currents at 10 m depth at Station I-1 in Hecate Strait, September 4-6, 1954.

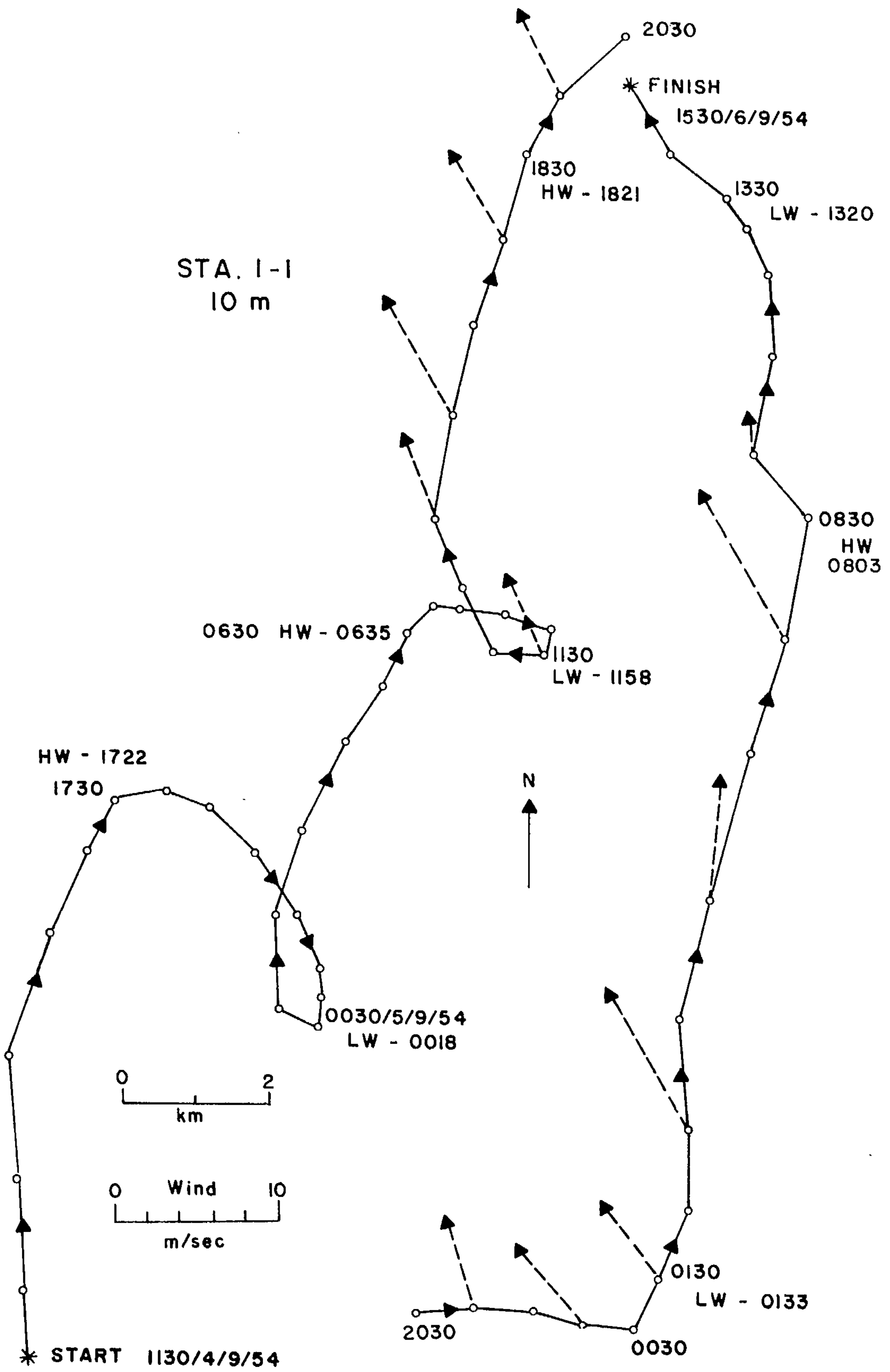


Fig. 156. Progressive vector diagram of tidal currents at 10 m depth at Station I-1 in Hecate Strait, September 4-6, 1954.

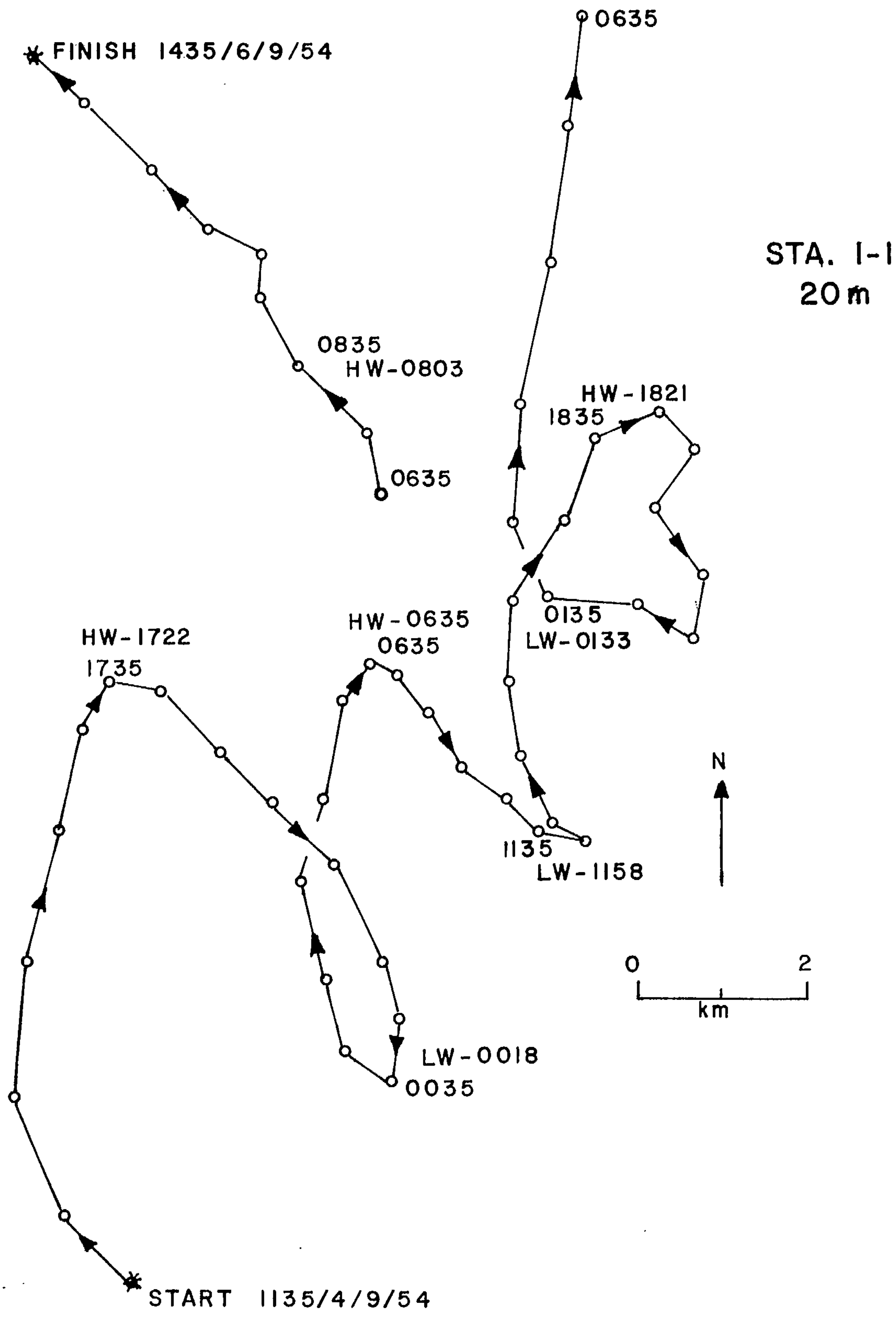


Fig. 157. Progressive vector diagram of tidal currents at 20 m depth at Station I-1 in Hecate Strait, September 4-6, 1954.

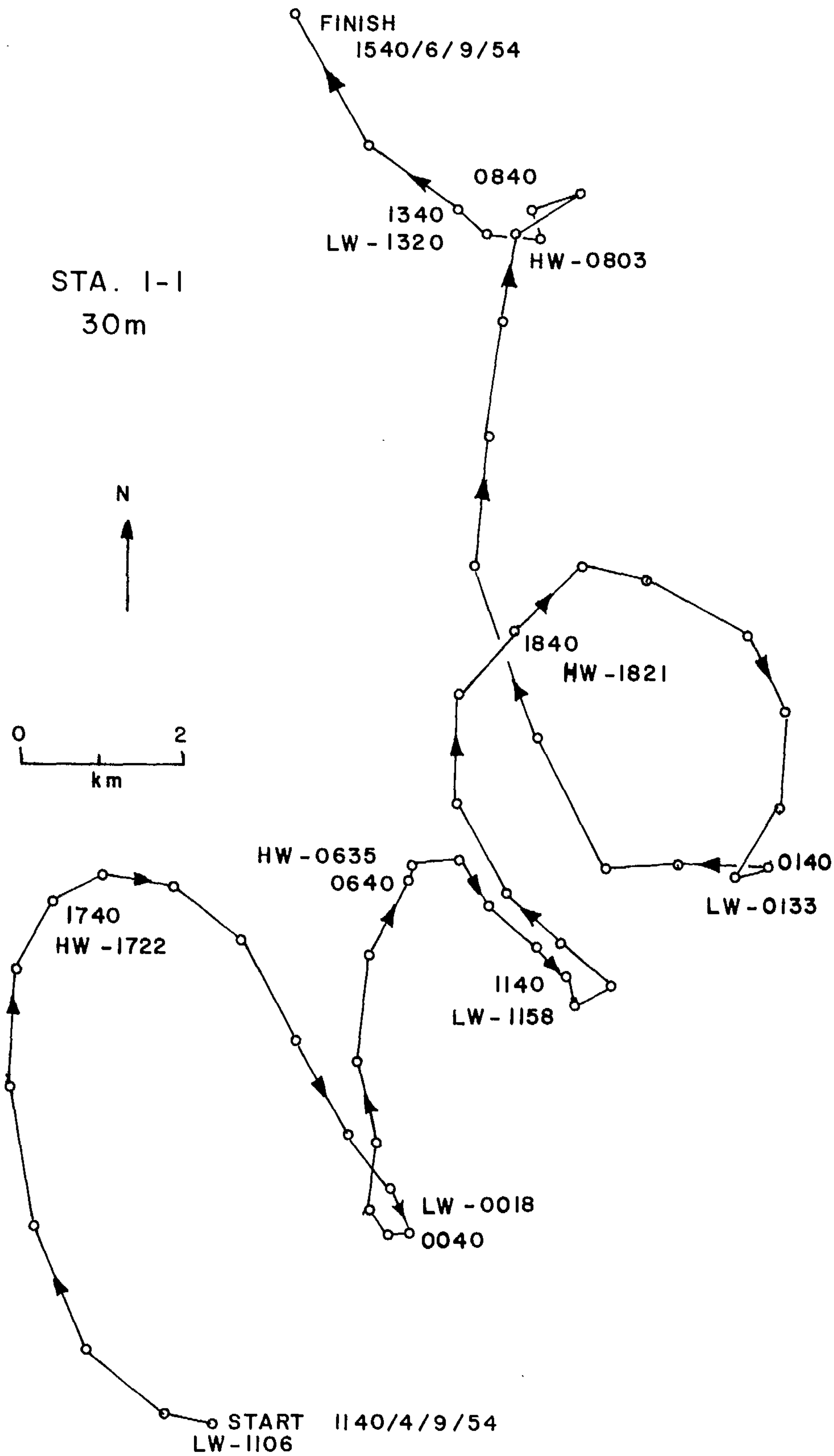


Fig. 158. Progressive vector diagram of tidal currents at 30 m depth at Station I-1 in Hecate Strait, September 4-6, 1954.

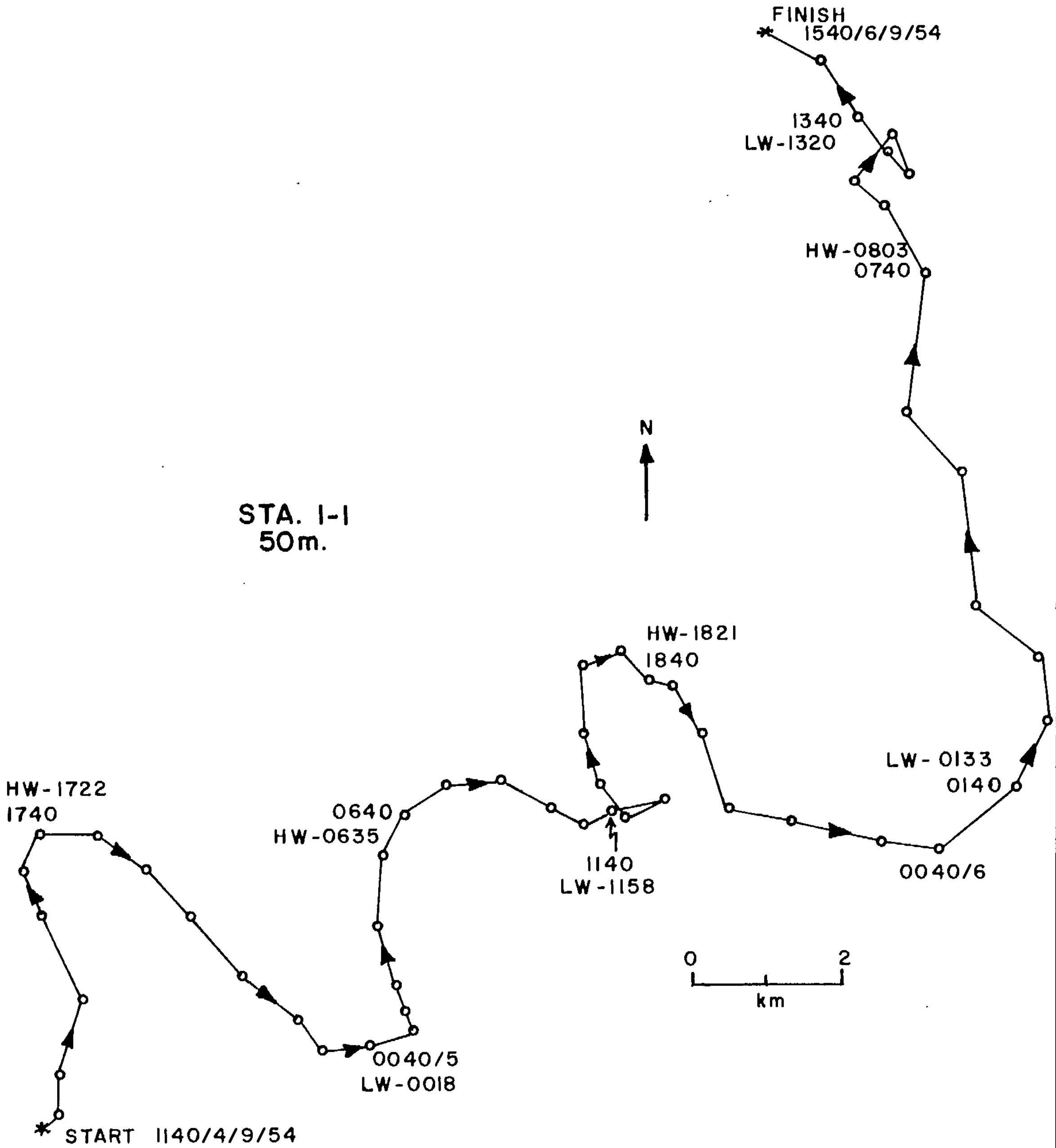


Fig. 159. Progressive vector diagram of tidal currents at 50 m depth at Station I-1 in Hecate Strait, September 4-6, 1954.

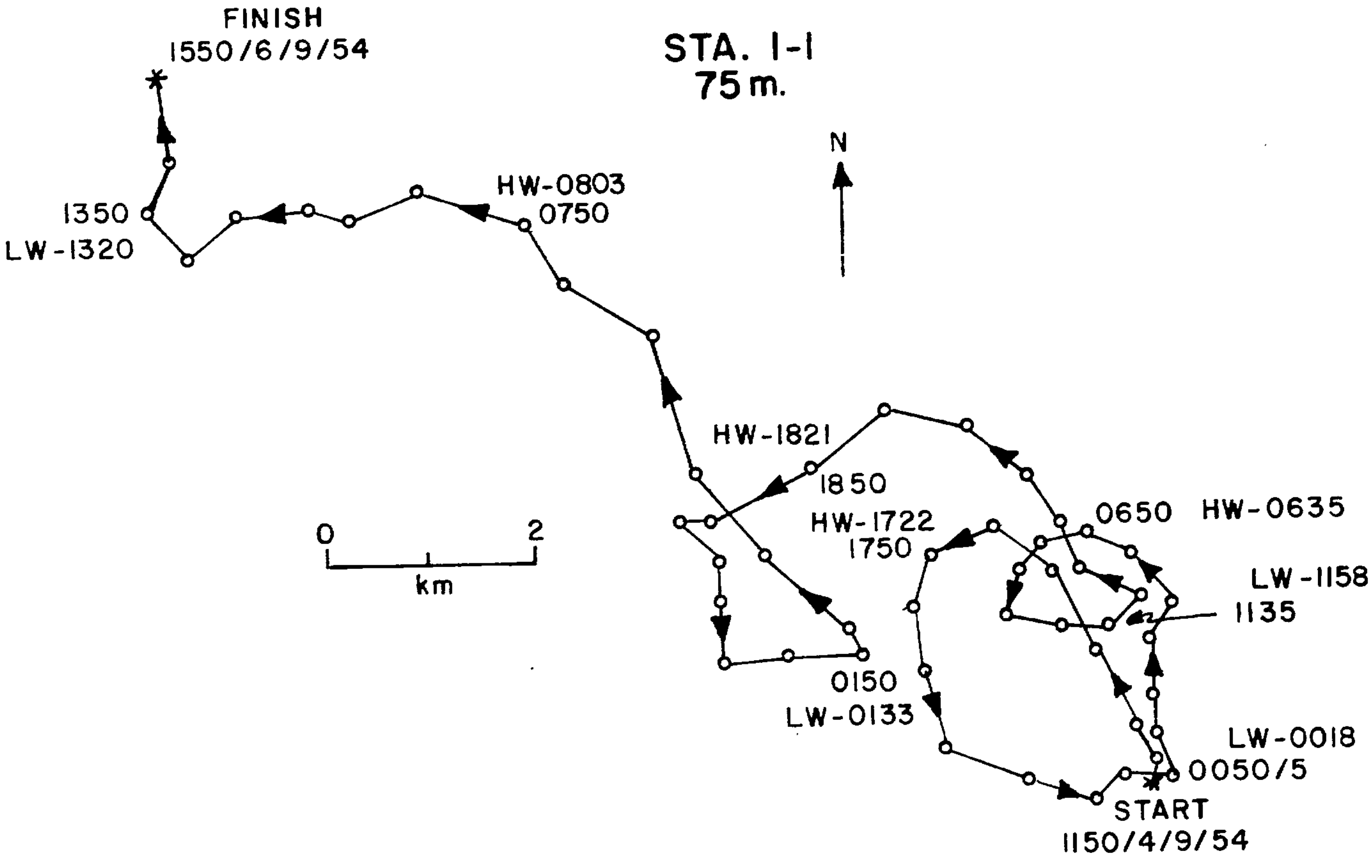


Fig. 160. Progressive vector diagram of tidal currents at 75 m depth at Station I-1 in Hecate Strait, September 4-6, 1954.

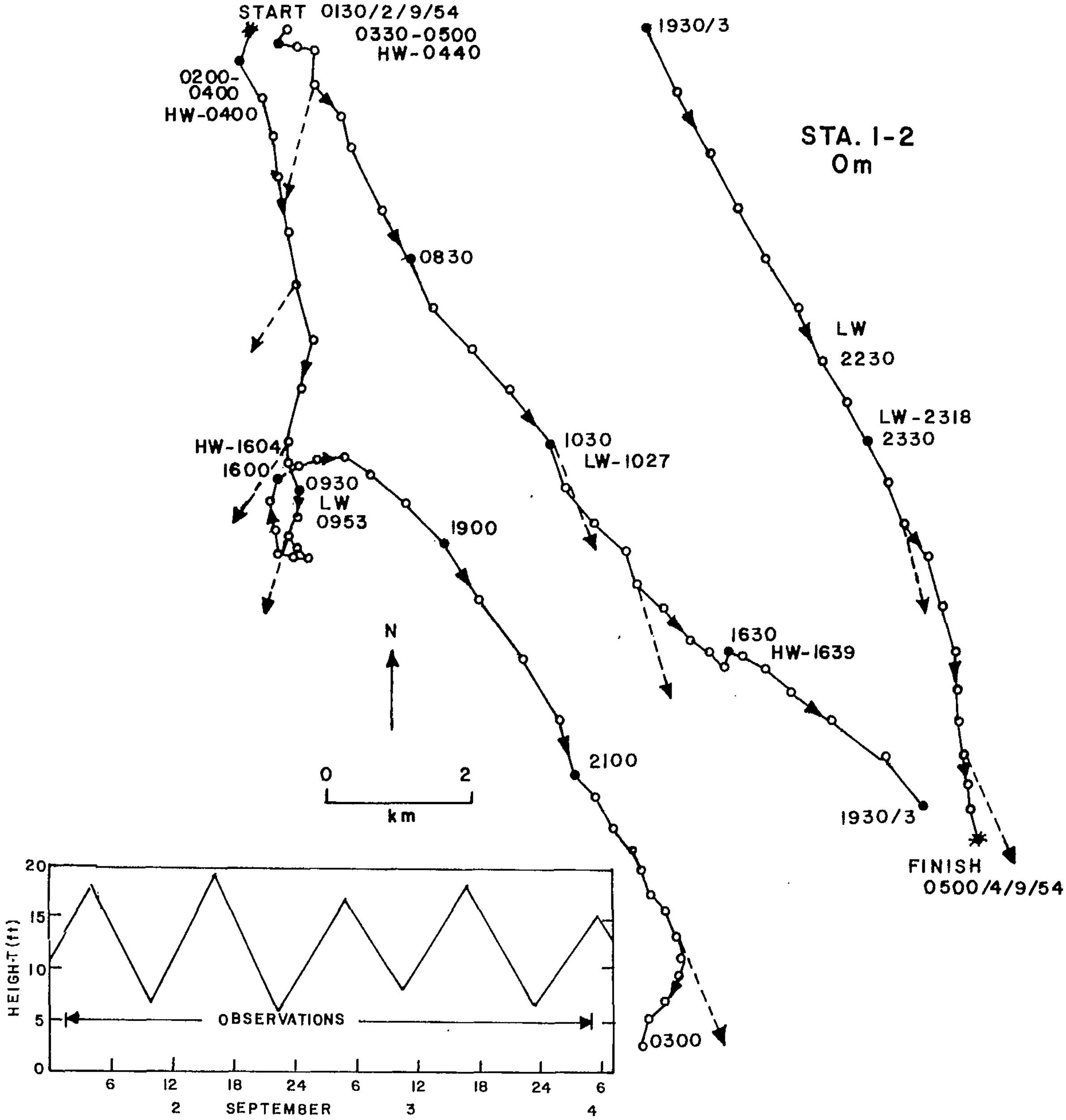


Fig. 161. Progressive vector diagram of currents at 0 m depth at Station I-2 in Hecate Strait, September 2-4, 1954.

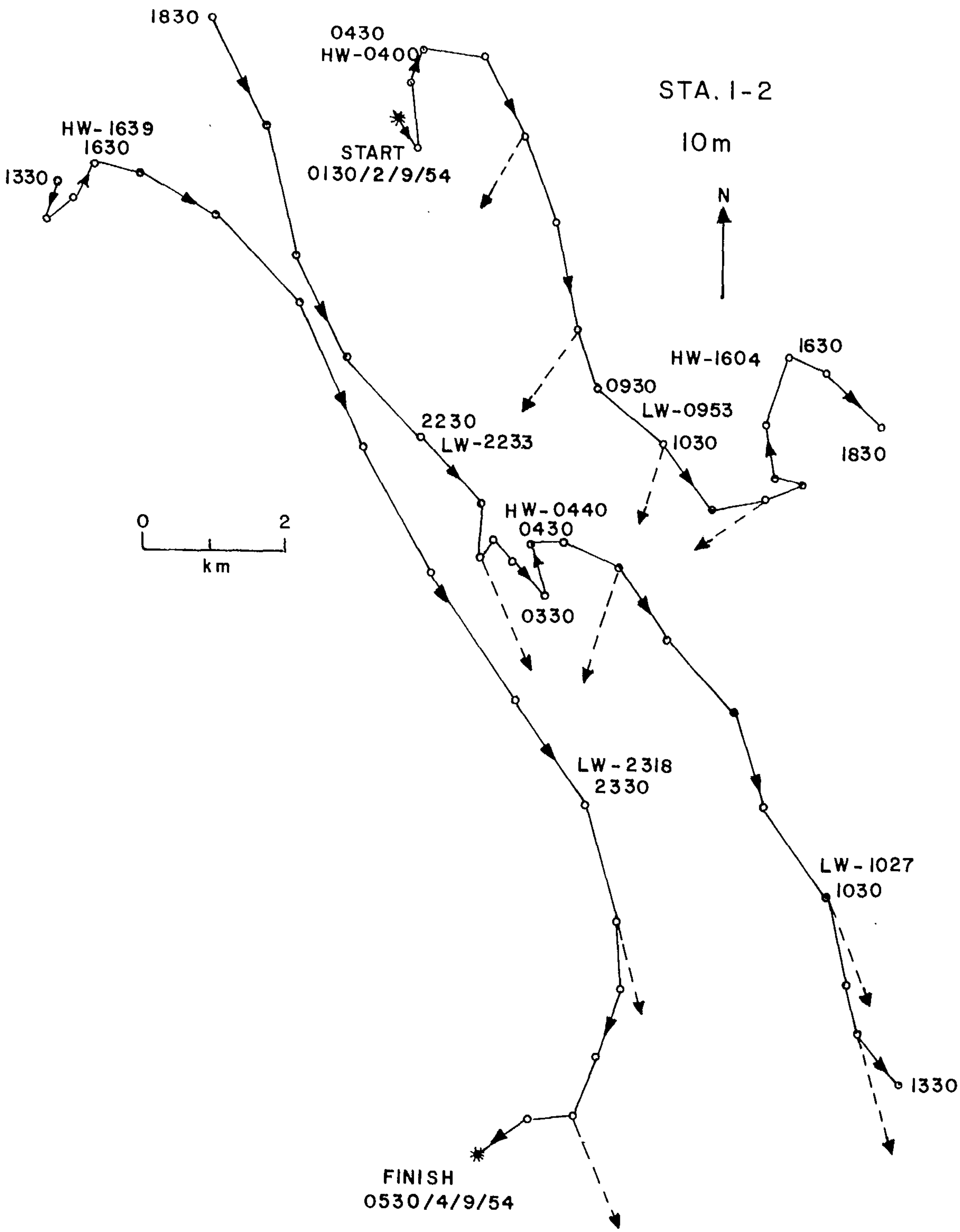


Fig. 162. Progressive vector diagram of tidal currents at 10 m depth at Station I-2 in Hecate Strait, September 2-4, 1954.

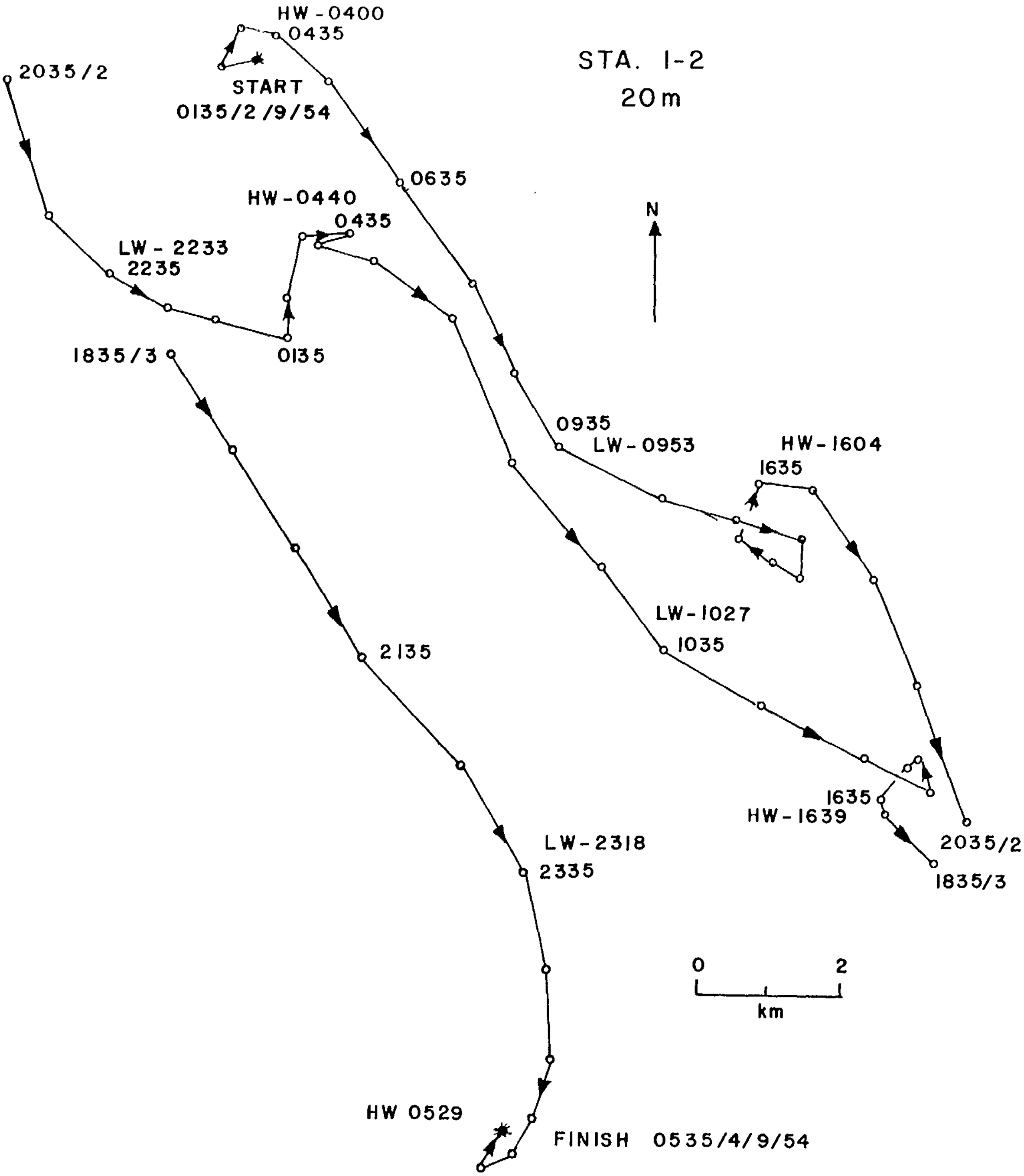


Fig. 163. Progressive vector diagram of tidal currents at 20 m depth at Station I-2 in Hecate Strait, September 2-4, 1954.

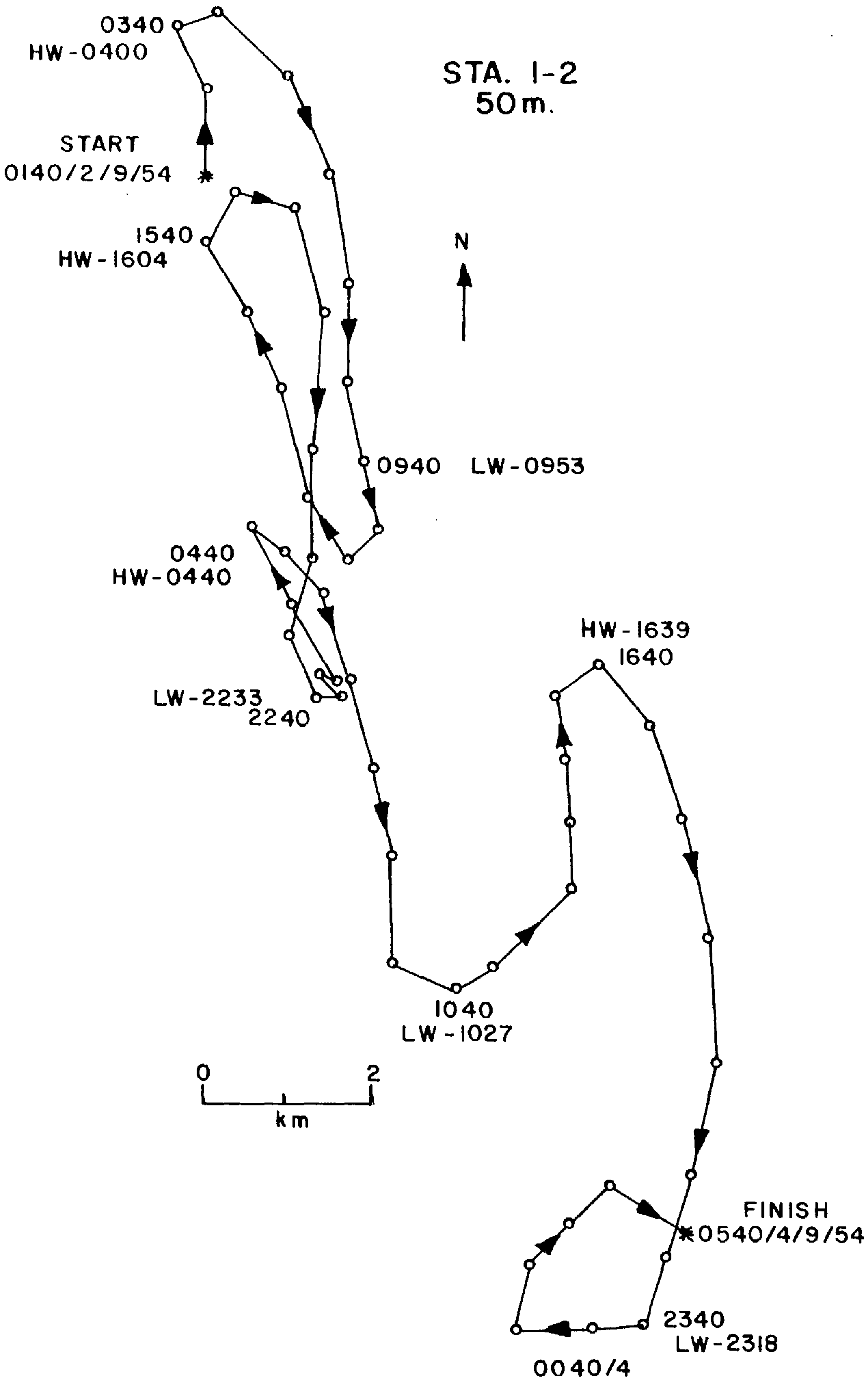


Fig. 164. Progressive vector diagram of tidal currents at 50 m depth at Station I-2 in Hecate Strait, September 2-4, 1954.

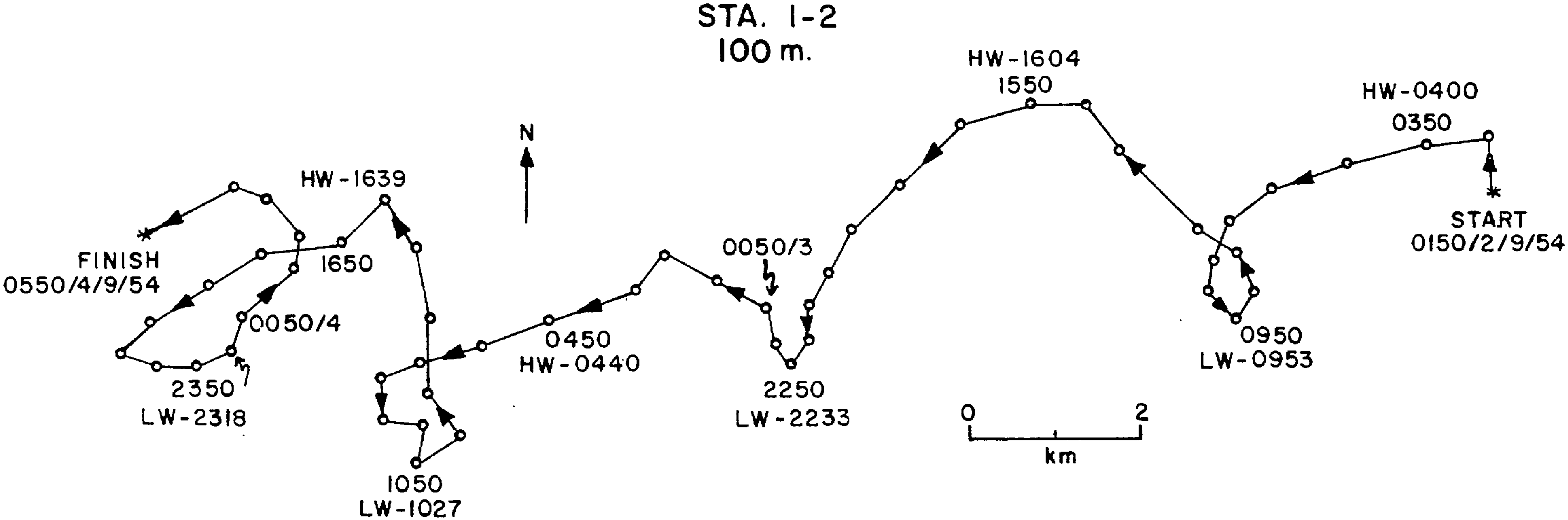


Fig. 165. Progressive vector diagram of tidal currents at 100 m depth at Station I-2 in Hecate Strait, September 2-4, 1954.

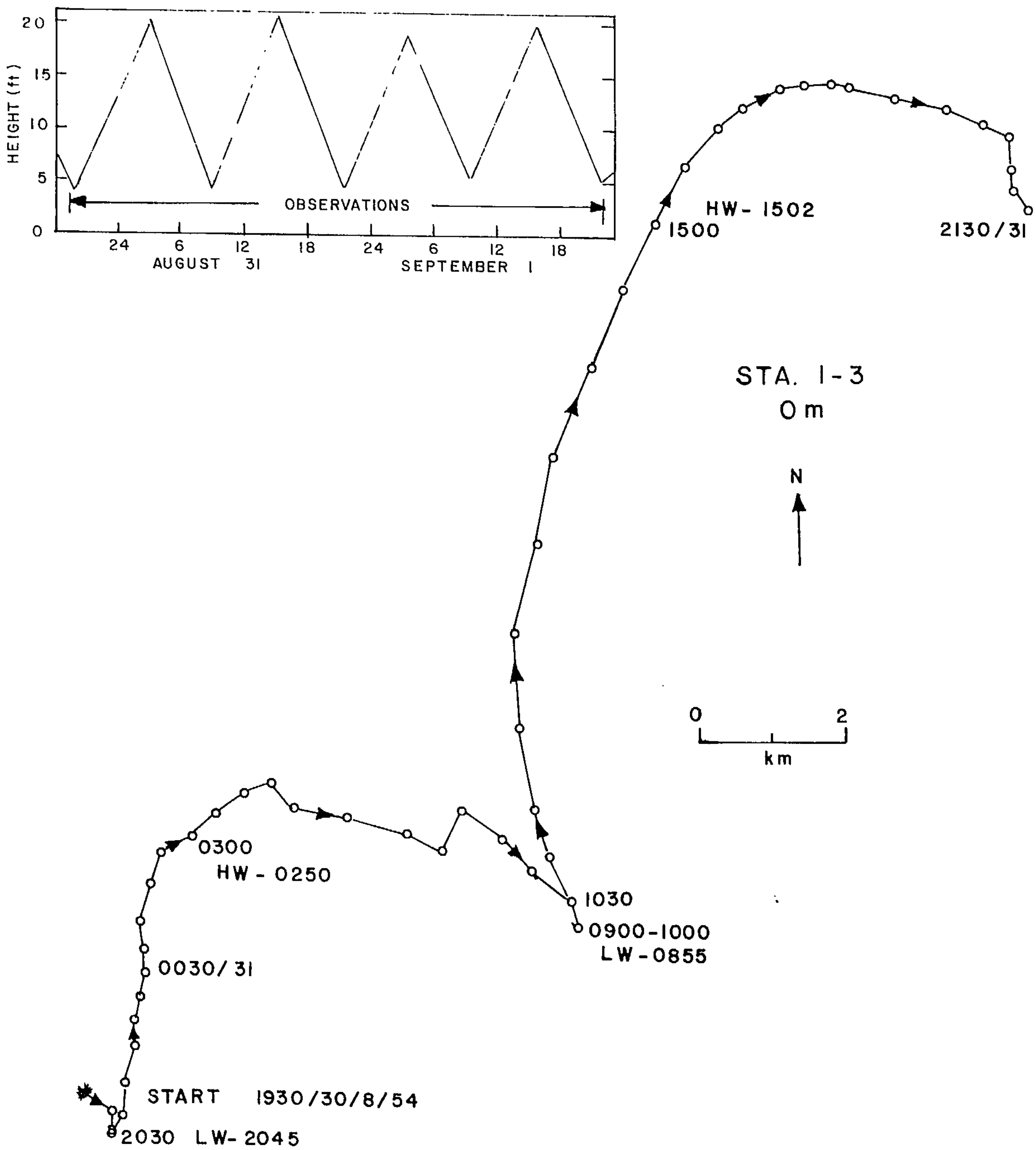


Fig. 166. Progressive vector diagram of tidal currents at 0 m depth at Station I-3 in Hecate Strait, August 30-September 1, 1954.

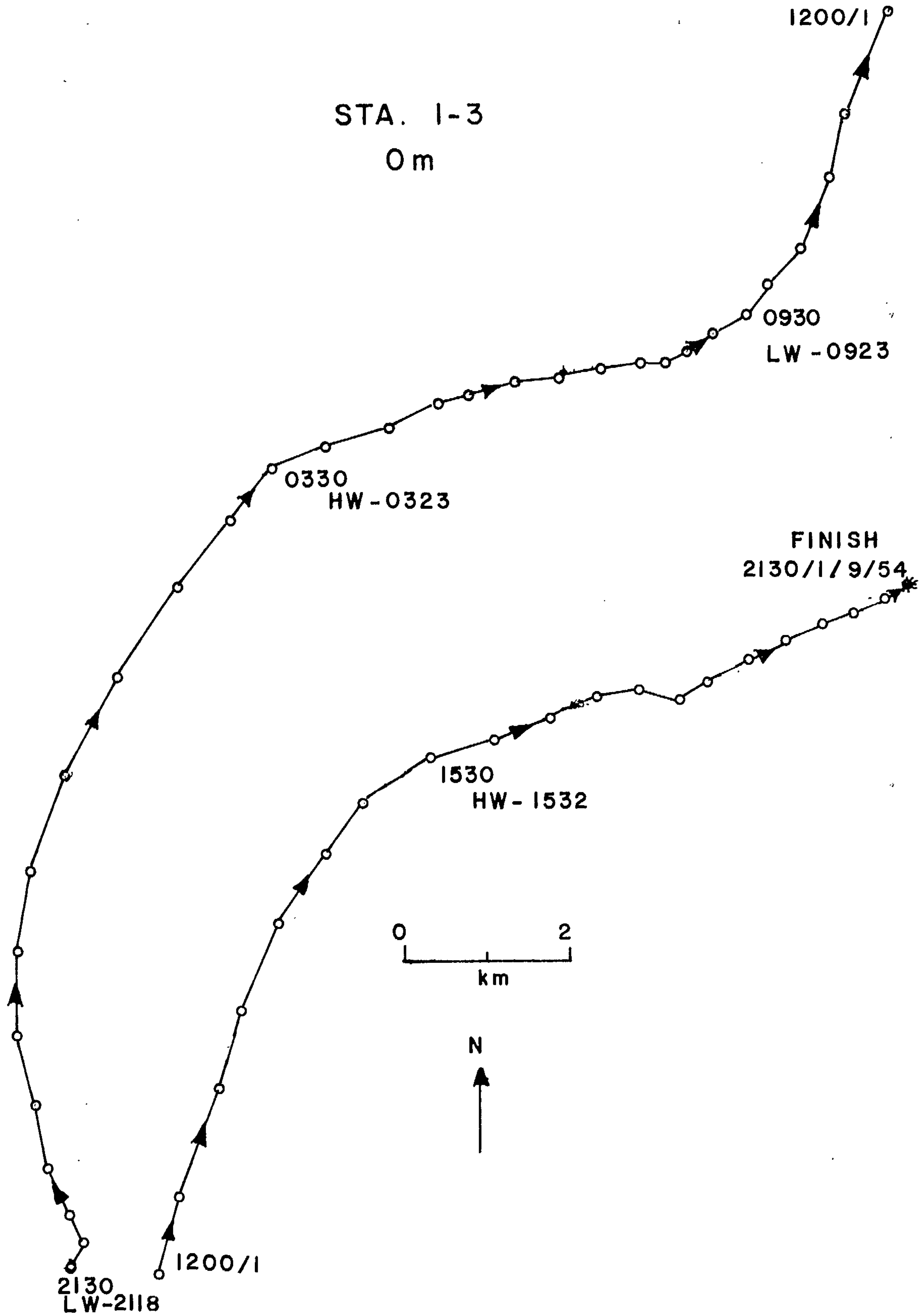


Fig. 166 (cont'd).

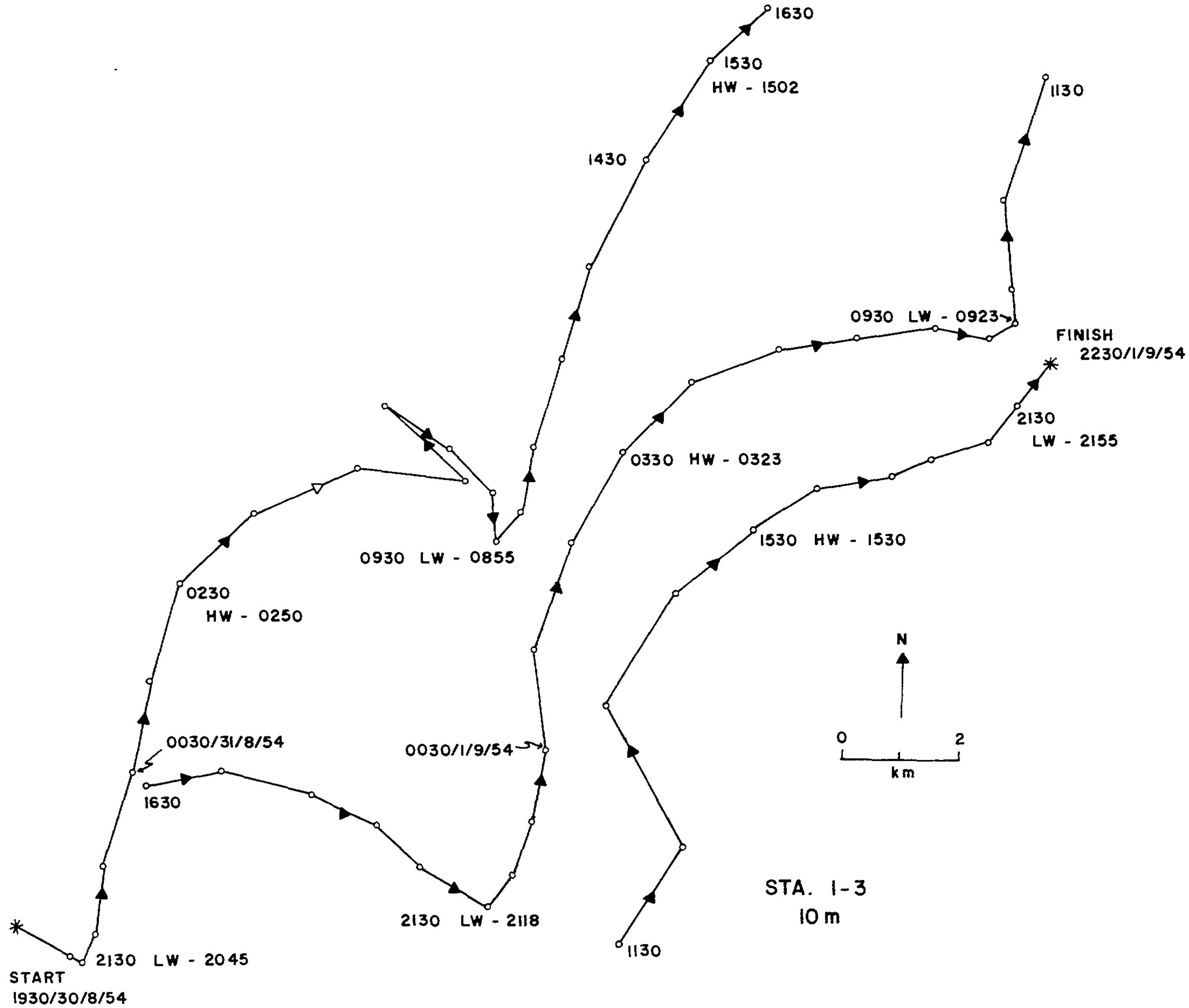


Fig. 167. Progressive vector diagram of tidal currents at 10 m depth at Station I-3 in Hecate Strait, August 30-September 1, 1954.

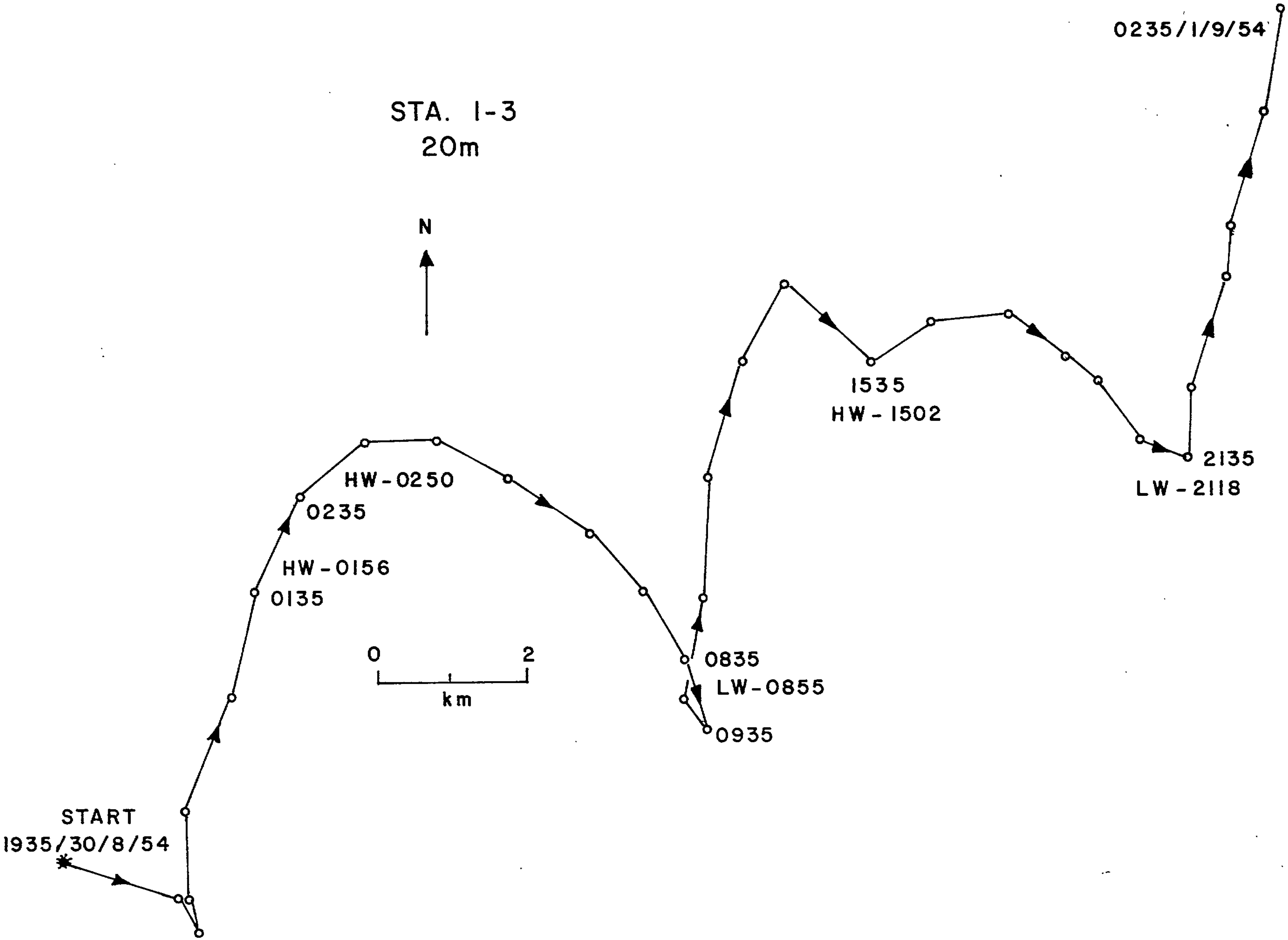


Fig. 168. Progressive vector diagram of tidal currents at 20 m depth at Station I-3 in Hecate Strait, August 30-September 1, 1954.

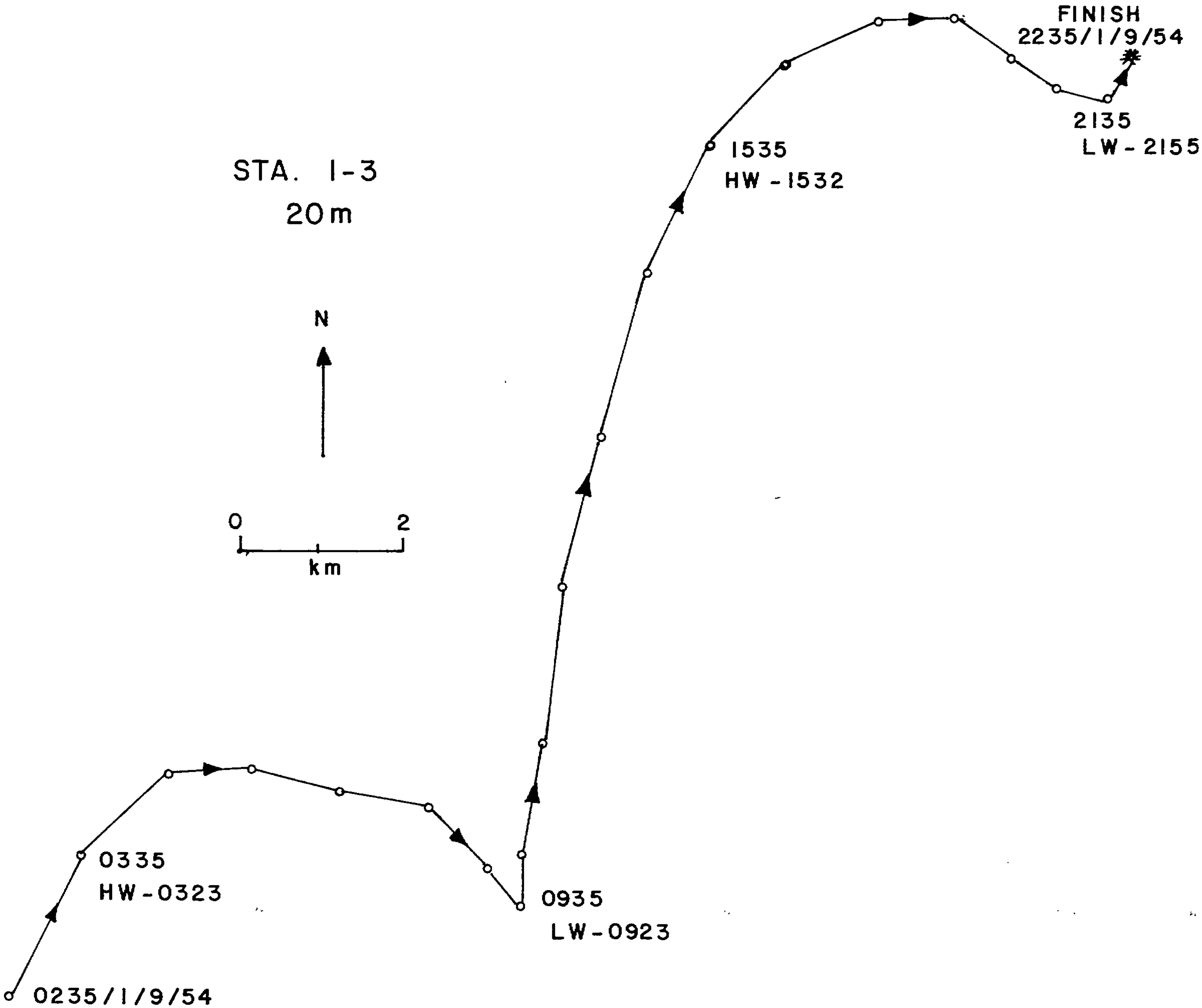


Fig. 168 (cont'd).

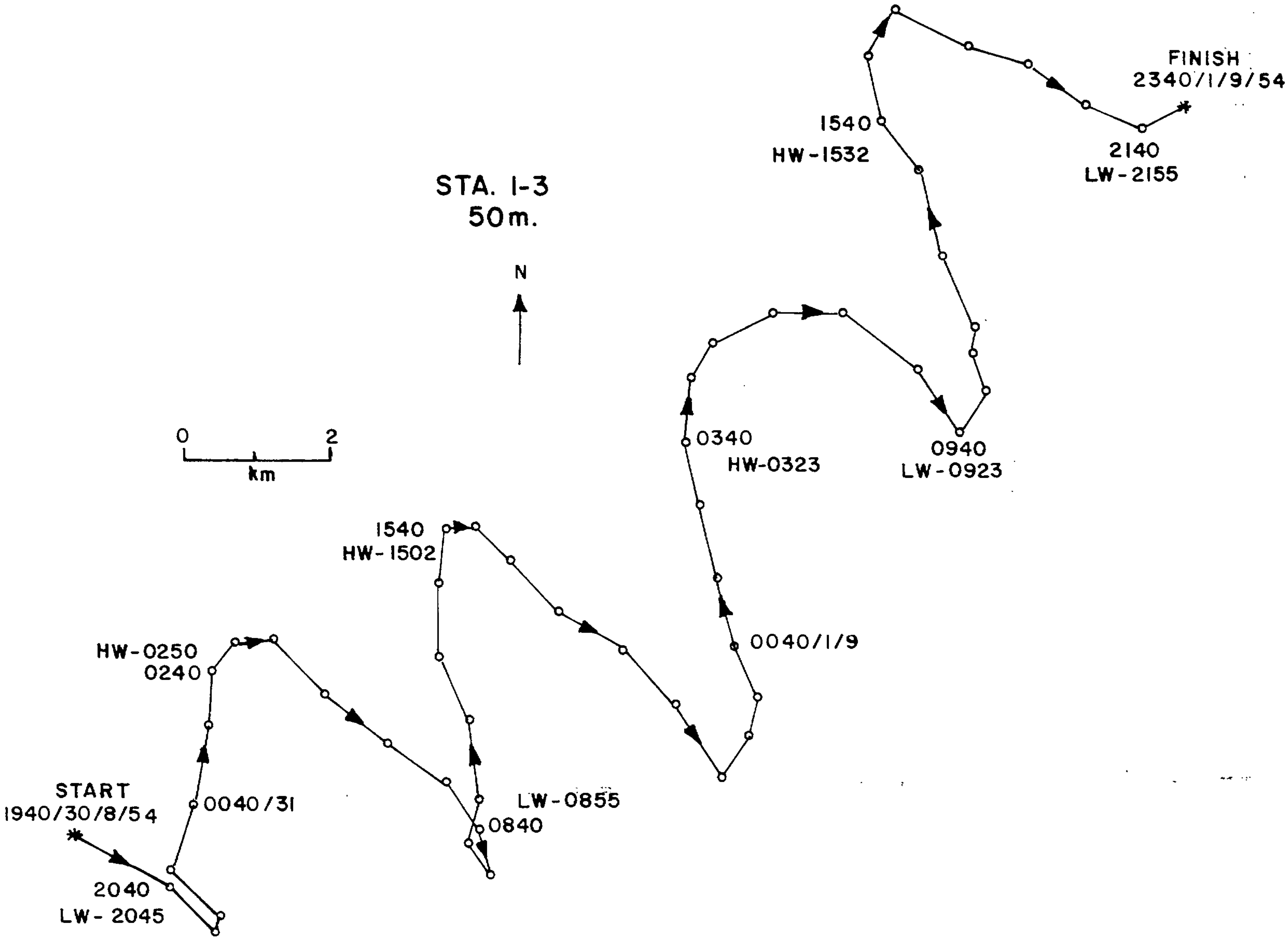


Fig. 169. Progressive vector diagram of tidal currents at 50 m depth at Station I-3 in Hecate Strait, August 30-September 1, 1954.

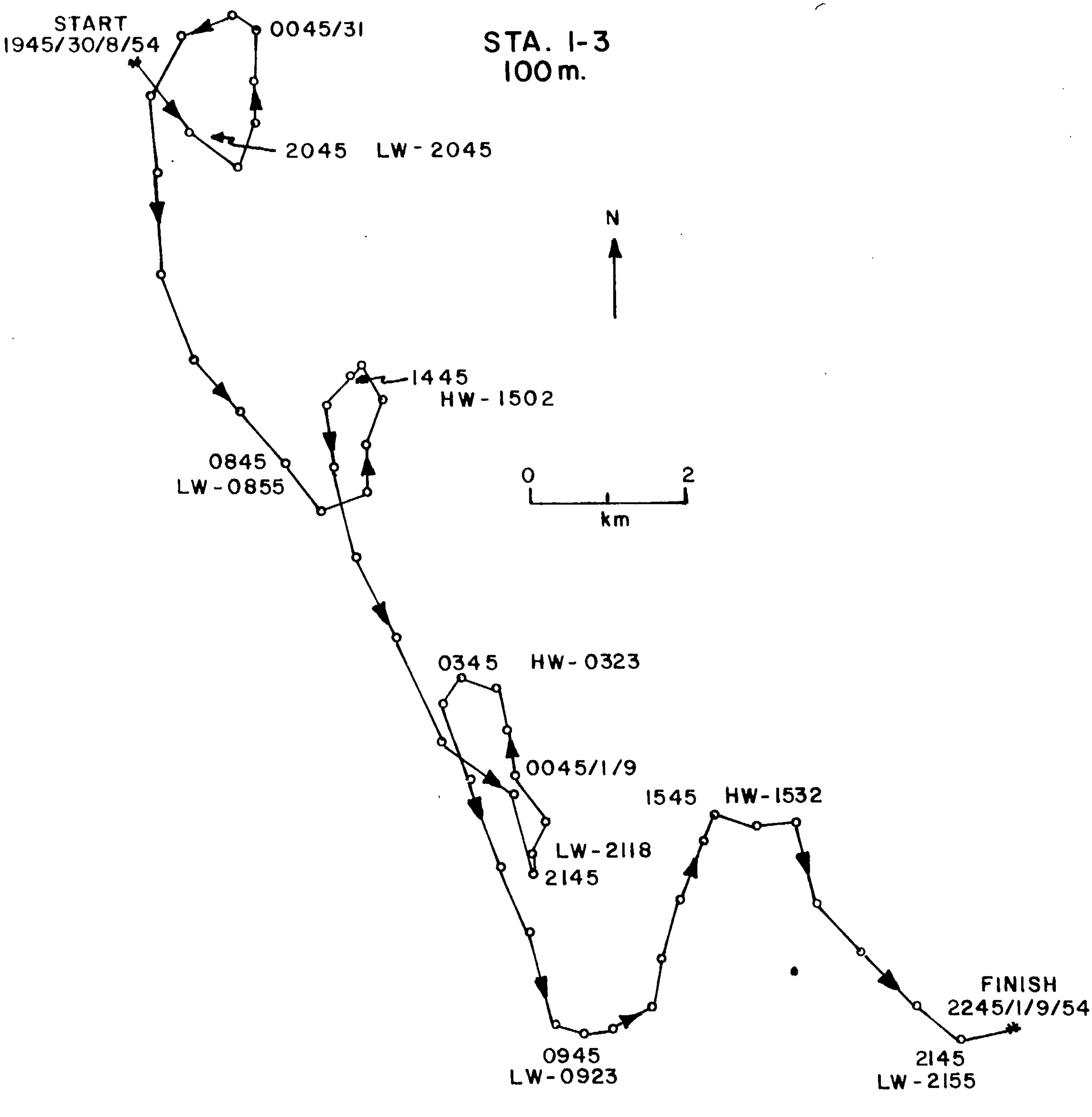


Fig. 170. Progressive vector diagram of tidal currents at 100 m depth at Station I-3 in Hecate Strait, August 30-September 1, 1954.

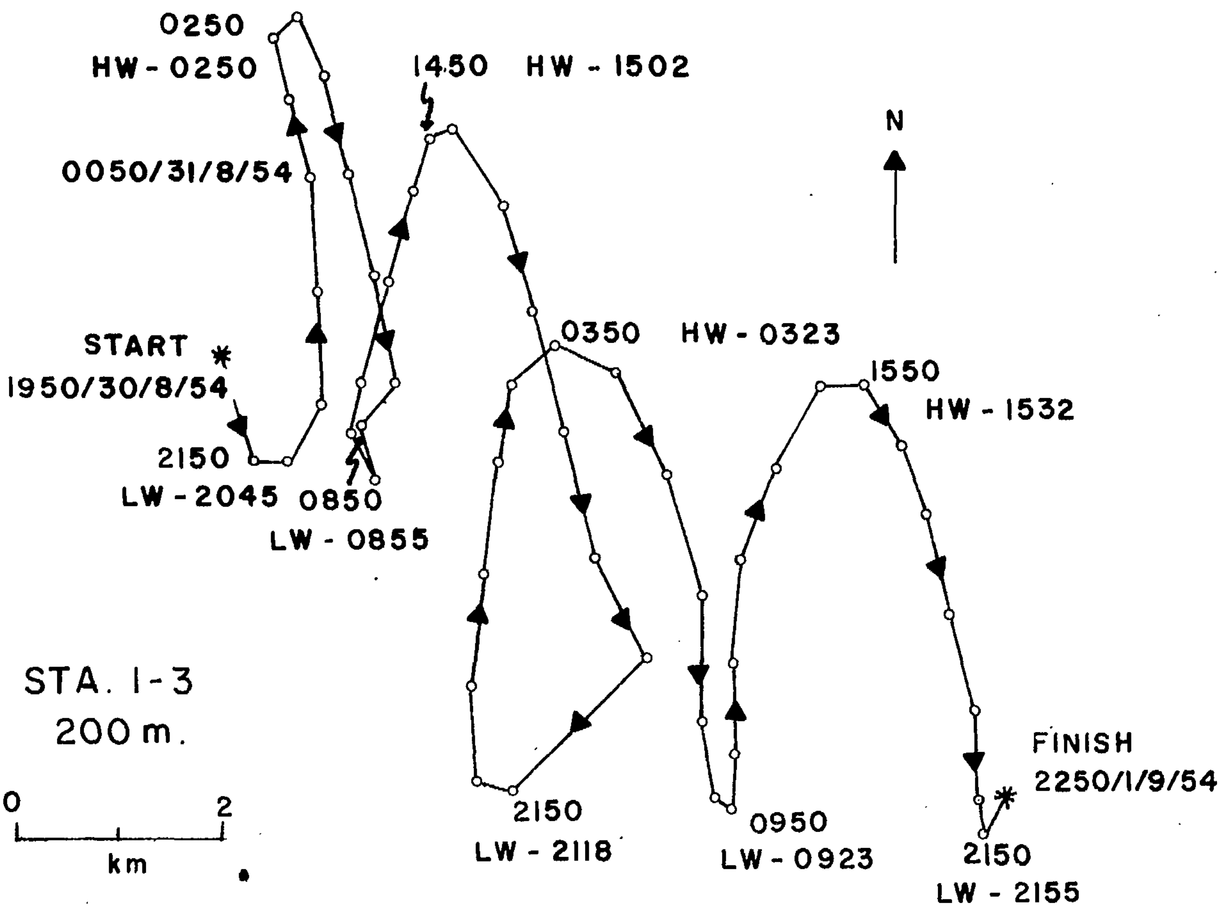


Fig. 171. Progressive vector diagram of tidal currents at 200 m depth at Station I-3 in Hecate Strait, August 30-September 1, 1954.

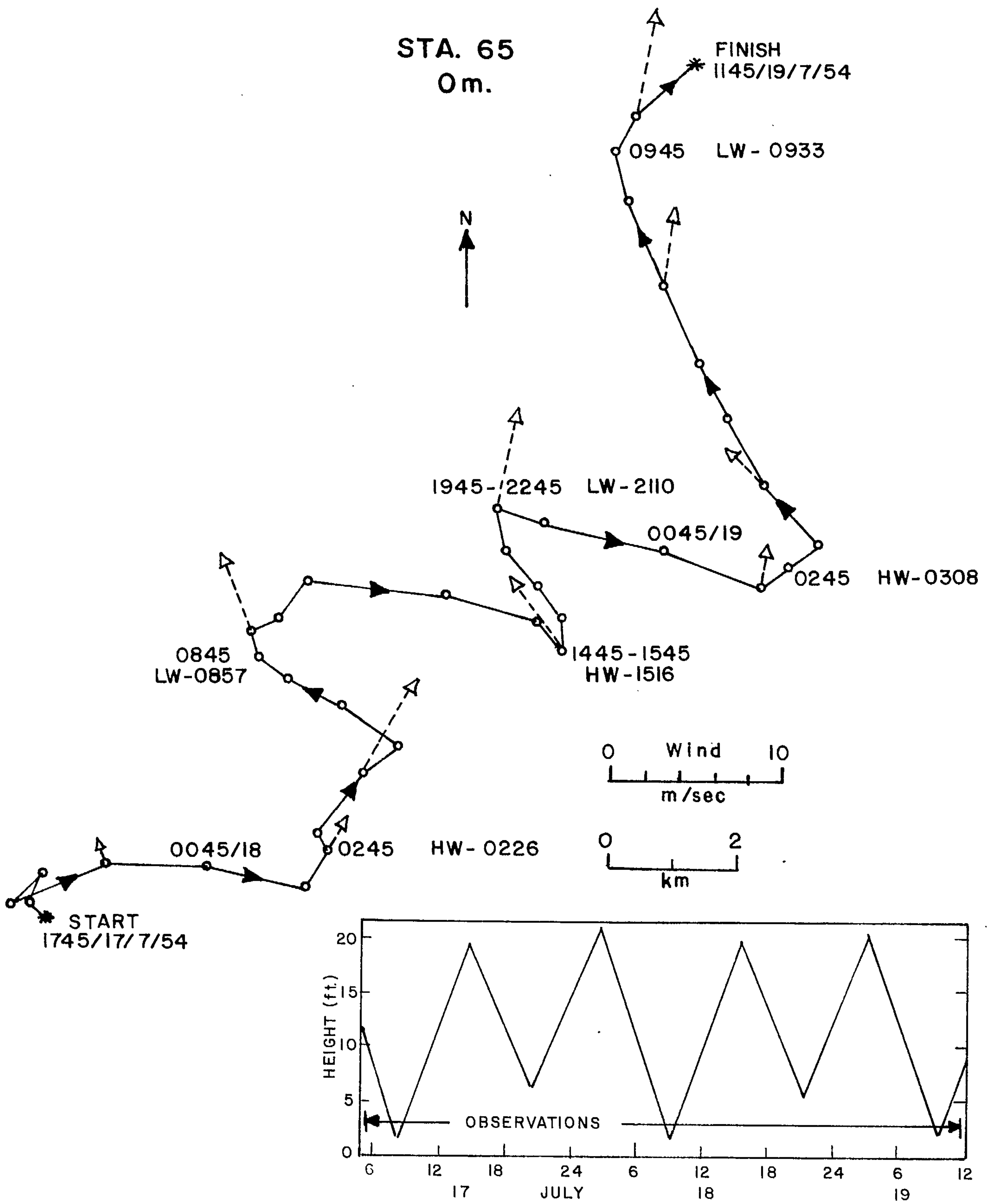


Fig. 172. Progressive vector diagram of tidal currents at 0 m depth at Station 65 in Dixon Entrance, July 17-19, 1954.

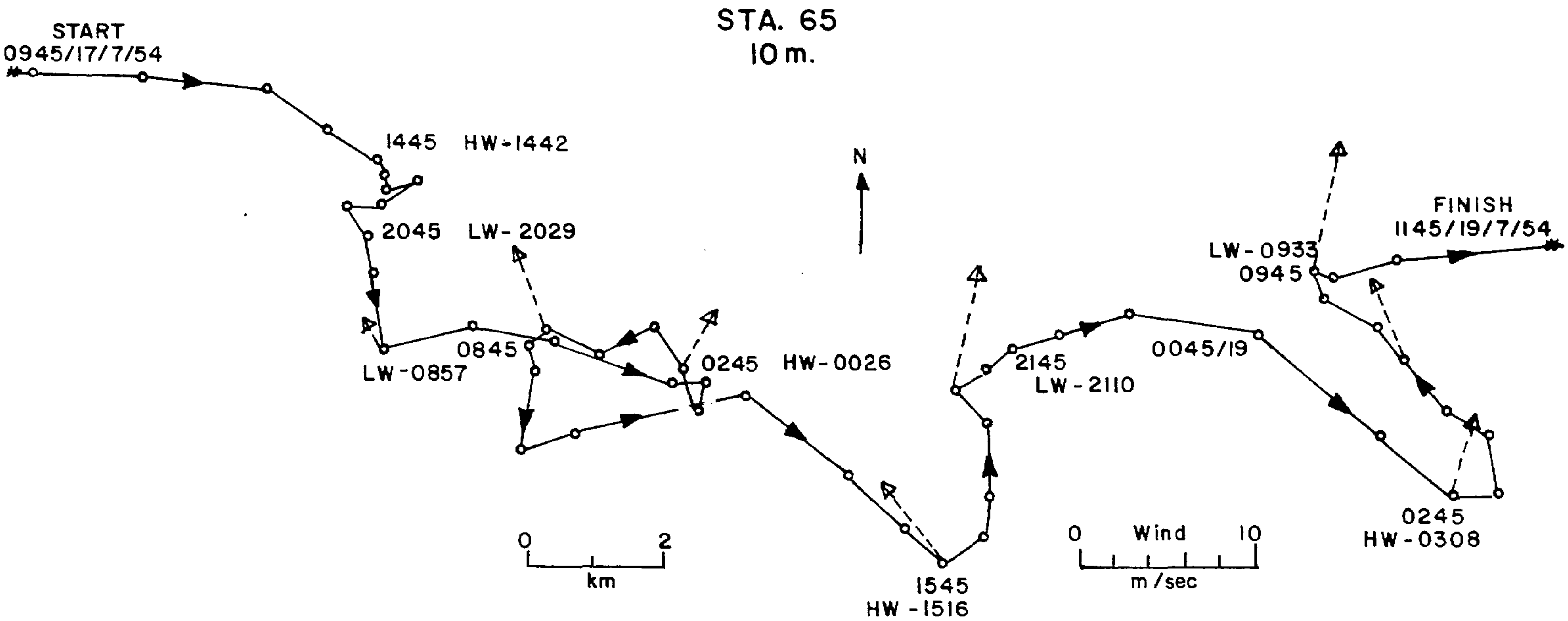


Fig. 173. Progressive vector diagram of tidal currents at 10 m depth at Station 65 in Dixon Entrance, July 17-19, 1954.

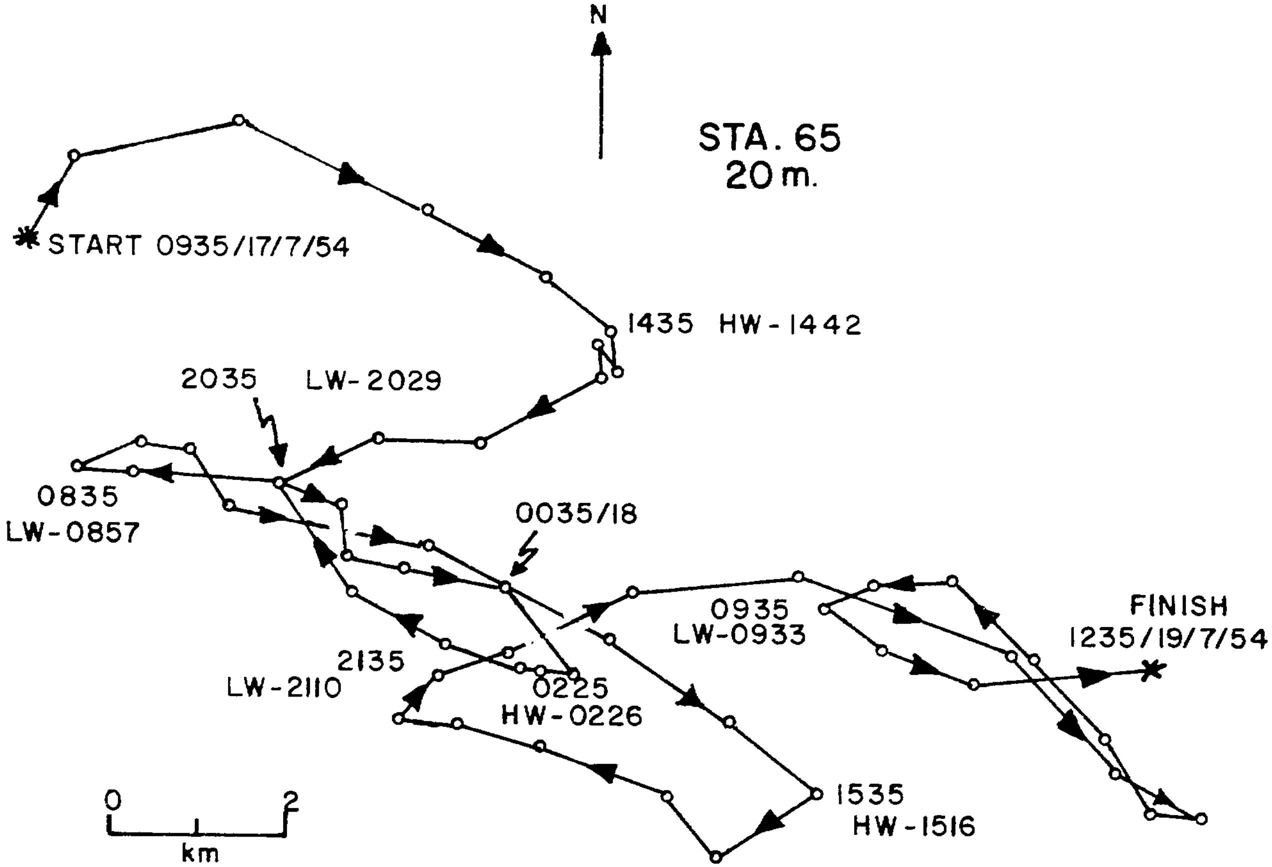


Fig. 174. Progressive vector diagram of tidal currents at 20 m depth at Station 65 in Dixon Entrance, July 17-19, 1954.

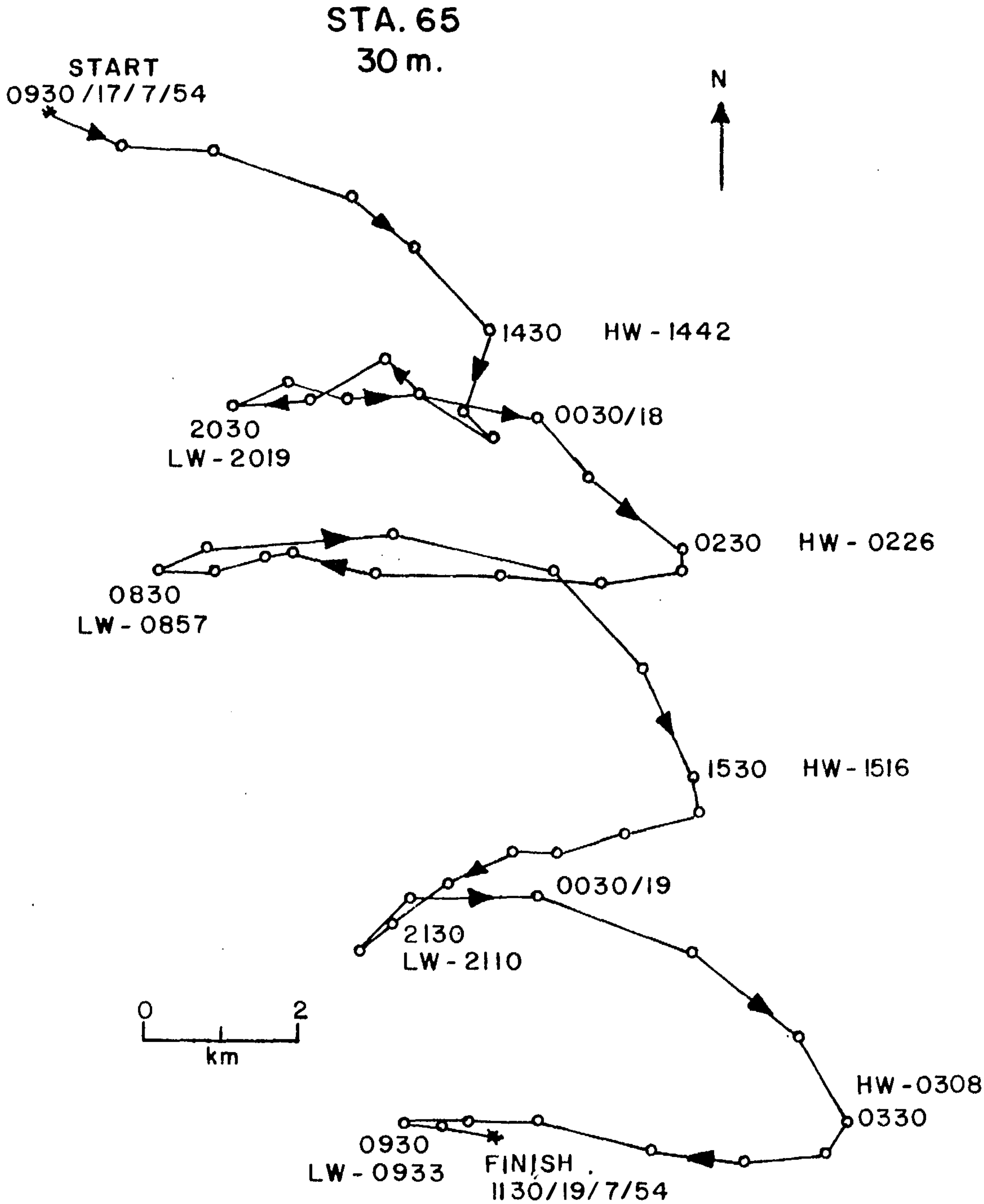


Fig. 175. Progressive vector diagram of tidal currents at 30 m depth at Station 65 in Dixon Entrance, July 17-19, 1954.

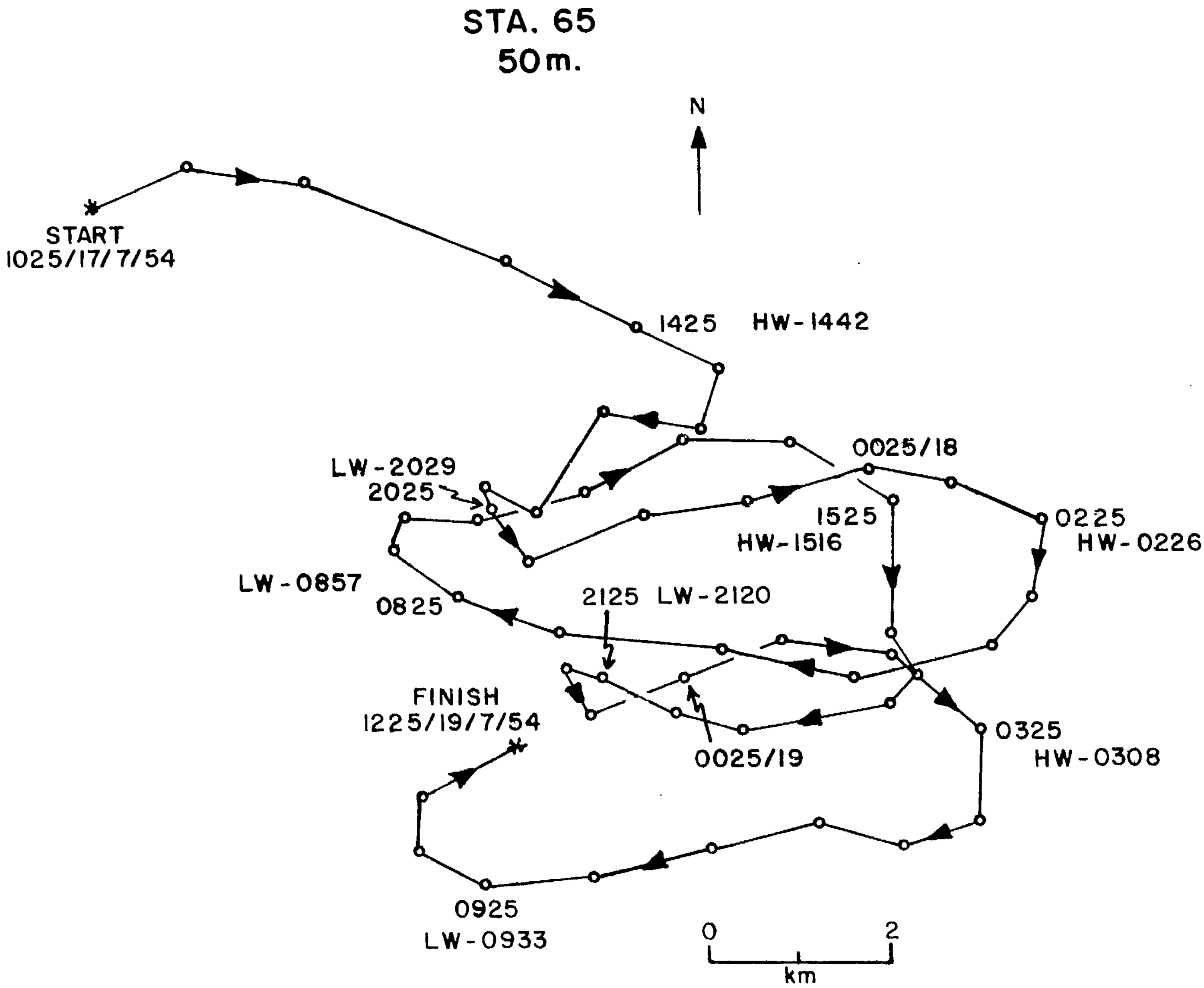


Fig. 176. Progressive vector diagram of tidal currents at 50 m depth at Station 65 in Dixon Entrance, July 17-19, 1954.

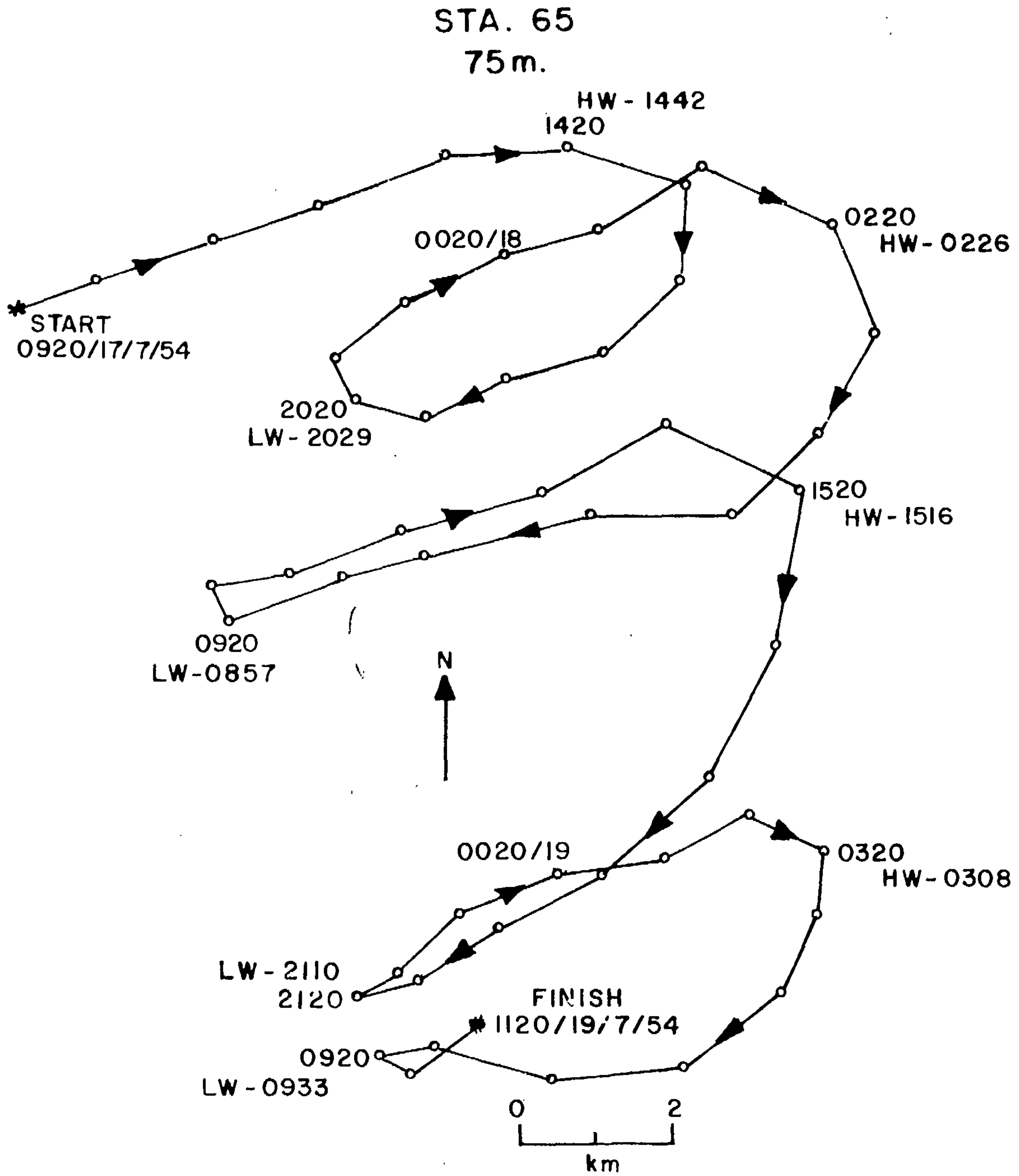


Fig. 177. Progressive vector diagram of tidal currents at 75 m depth at Station 65 in Dixon Entrance, July 17-19, 1954.