Influence of Controlled Discharge from the Churchill River on the Oceanography of Groswater Bay, Labrador

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ABSTRACT

Bobbitt, J., and S. Akenhead. 1982. Influence of controlled discharge from the Churchill River on the oceanography of Groswater Bay, Labrador. Can. Tech. Rep. Fish. Aquat. Sci. 1097: iv + 43 p.

This study investigates changes in water properties in Groswater Bay due to the regulation of flow from the Churchill River. Since hydroelectric development, the flow rates of the Churchill River have approximately tripled during winter and decreased by about 30% in summer. Salinity profiles in Lake Melville and Groswater Bay show that the water structure in summer remains practically unchanged. The residual time of fresh water in the fjord was found to be of the order of several months, indicating that Lake Melville acts as an effective filter between variations in river flow and changes in Groswater Bay. A constriction at the Narrows controls the transfer of water between Lake Melville and Groswater Bay, and results in a choking coefficient of 0.2. Water properties found outside the Narrows could be traced as far south as Cape Porcupine but disappeared near Pack's Harbour in the presence of a more dominating water mass.

Key words: fjord, Lake Melville, Hamilton Inlet, hydroelectric development, Labrador, river discharge, salinity, oceanography, Churchill River

RESUME

Bobbitt, J., and S. Akenhead. 1982. Influence of controlled discharge from the Churchill River on the oceanography of Groswater Bay, Labrador. Can. Tech. Rep. Fish. Aquat. Sci. 1097: iv + 43 p.

La présente étude examine les changements dans les propriétés de l'eau survenus à la baie Groswater en raison de la régularisation de débit de l'eau du fleuve Churchill. Depuis le développement hydroélectrique, le débit de fleuve Churchill triple presque au cours de l'hiver et diminue d'environ 30 % en été. Les profils de salinité au lac Melville et à la baie Groswater montrent que la structure de l'eau ne change pratiquement pas au cours de l'été. On a trouvé que l'eau douce reste dans le fjord pendant plusieurs mois, ce qui indique que le lac Melville sert efficacement de filtre entre les périodes de variations du débit du fleuve et les changements à la baie Groswater. Un reserrement aux Narrows contrôle le passage de l'eau entre le lac Melville et la baie Groswater, ce qui entraîne un coefficient d'etranglement de 0.2. Les propriétés de l'eau constatées en-dehors des Narrows ont pu être retrouvées aussi loin au sud que Cap Porcupine mais avaient disparu près de Packs Harbour en présence d'une masse d'eau plus importante.

INTRODUCTION

CONCERN OF FISHERMEN

This study was contracted by the Department of Fisheries and Oceans (DFO) to investigate the effects of controlled hydro discharge from the Churchill River upon the water properties of Groswater Bay. Commercial fishermen in the region are concerned with the disappearance of cod from traditional fishing grounds and feel that the alteration in fresh water input to Lake Melville has changed the properties of the inshore water mass and the currents in Groswater Bay and farther south. For several years, they have sought to have the matter investigated.

The findings of this project supplement biological and hydrographic information collected by LGL Limited in Pack's Harbour and Domino areas during the summer of 1981, under an OLABS (Offshore Labrador Biological Studies) contract. The objectives of the LGL project are to measure biological and oceanographic variations at the two study sites and to determine how codfish respond to these variations as reflected in day to day changes in their availability to various gear types. Codfish catches at Domino in recent years have been excellent while those at Pack's Harbour have been atypically poor. Results of the LGL study will be available in June, 1982.

The present physical oceanographic study of Lake Melville and Groswater Bay will compare measurements made in the areas before and after the Churchill Development. The amount of fresh water in Lake Melville was calculated and the thickness and salinities of the top brackish layer compared, to determine whether the amount of vertical mixing has altered and whether the fresh water transport between Lake Melville and Groswater Bay has changed significantly. The effect of the Narrows was investigated to establish how effectively it acts as a control mechanism on the flow in Lake Melville and on the water properties in Groswater Bay. Data collected in Groswater Bay in the early 1950's and in 1981 were compared to show the magnitude of any differences that may have occurred.

GEOGRAPHY OF HAMILTON INLET

Hamilton Inlet, the largest inlet located along the Labrador coast, consists of three main water bodies known as Groswater Bay, Lake Melville, and Goose Bay (Fig. 1.1). Groswater Bay extends west for approximately 50 km, at which point it constricts into a narrow and shallow area about 22 km in length known as the Narrows (Fig. 1.4 and 1.5). At the extrance to Lake Melville, the Narrows becomes divided into two channels by Henrietta Island. The west channel is divided further by Eskimo Island. The most shallow cross section is 2 km south of the community of Rigolet with a depth of approximately 30 m and a width of 2.8 km. This cross section will be referred to throughout the report as the sill.

Lake Melville extends for 126 km from Pike Run (the channel east of Henrietta Island) to the mouth of Goose Bay. Goose Bay is a 22 km extension of Lake Melville with a basin depth of over 60 m. At the northeastern end of Lake Melville, the Backway extends east from Pike Run for about 22 km. The Backway is an arm of Lake Melville with a basin depth of 174 m (Coachman 1953).

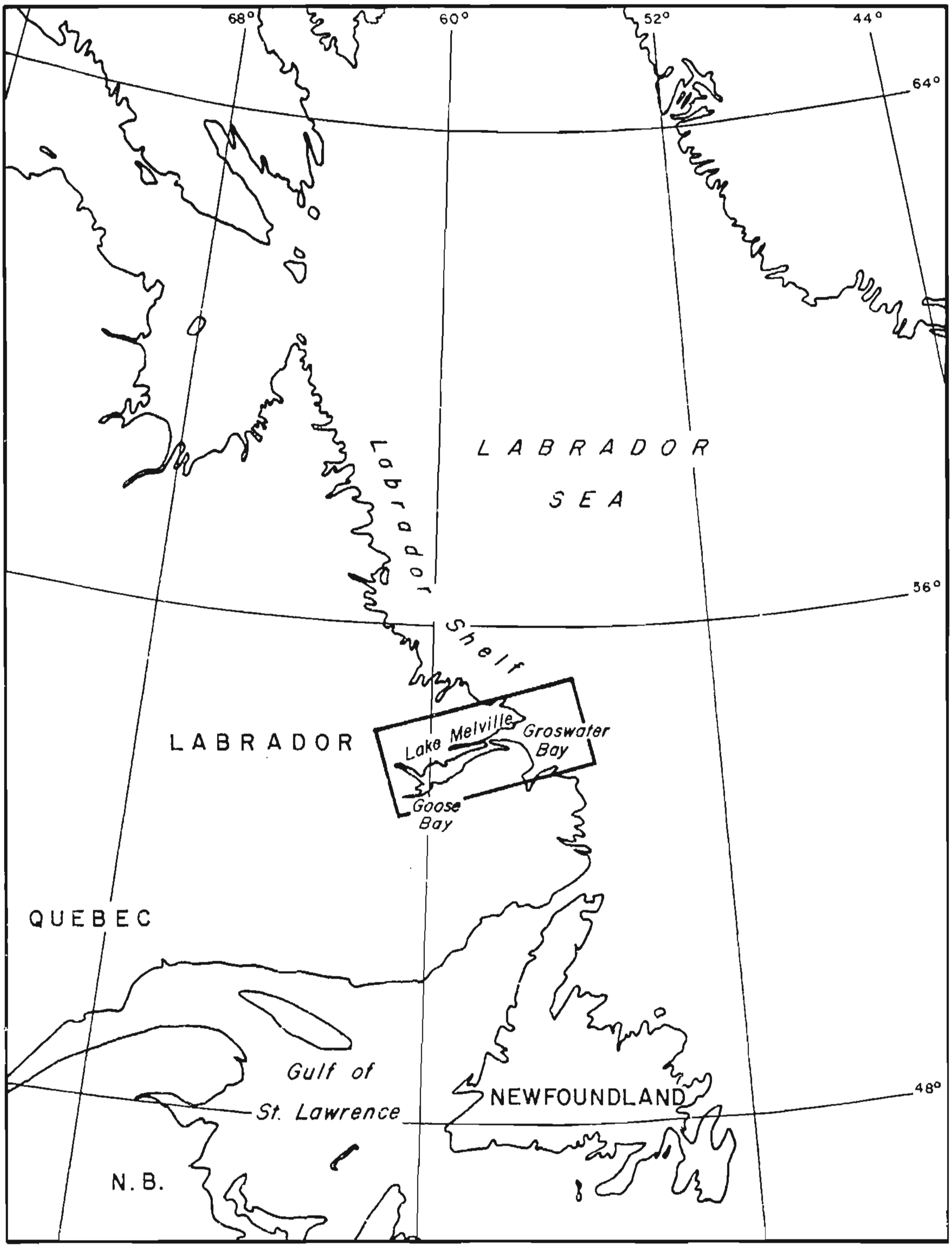


FIGURE 1·1 STUDY AREA

Lake Melville has a total length of approximately 180 km and a maximum width of more than 35 km at its southwestern end, making it an extremely large fjord. It has a basin depth of over 200 m. The shallow constriction at the Narrows restricts the exchange of water between Lake Melville and Groswater Bay. The dimensions of the constriction in relation to the size and depth of Lake Melville, causes Lake Melville to be classified as a landlocked fjord. Fresh water is discharged into the fjord at the southwestern end by four major rivers, the largest being the Churchill River. The other rivers, in order of size, are the Northwest, the Kenamu, and the Goose. The location of these rivers are shown in Fig. 1.2.

BACKGROUND ON THE CHURCHILL RIVER DEVELOPMENT

Construction of the hydro development of the Churchill River began in 1967 by Churchill Falls Labrador Corporation Limited (CFLCo), and was completed in December 1971. There were no large dams constructed but rather a series of dykes covering more than 65 km, the longest having a length of 6.1 km (Coté 1972). Prior to the Churchill development, dykes were constructed to form the Ossokmanuan Reservoir for the Twin Falls power development which began in 1960 on a tributary of the Churchill River. The Twin Falls power station was built to supply power for the mining development at Wabush and Labrador City.

In the Churchill development, dykes were built to link up countless existing lakes and hundreds of square kilometers of bog and muskeg to create the Smallwood Reservoir (Fig. 1.3), and smaller rivers were diverted to increase the water supply. From the Smallwood Reservoir, the water is released through various control structures. A section of the river was diverted in a new course along a series of lakes parallel to the original river bed so that it could descend over 300 m through penstocks into the power plant. Excess water is released through the Jacopie spillway and allowed to flow along the original route.

The initial drainage area was increased by approximately 11,400 km^2 through the construction of dykes at Orma and Sail Lakes (Coté 1972). The Orma Lake dykes divert some of the water which would otherwise flow into the Naskaupi River. Since the water of the Naskaupi River eventually ends up in Lake Melville, this diverted portion has little effect on the overall discharge in the Lake Melville fjord system. However, the Sail Lake dykes divert water which originally drained into Kanairiktok River, which empties into Kanairiktok Bay, located about 120 km northwest of Groswater Bay. The diversion of this water supply increases the total amount of fresh water flowing into Lake Melville.

FIELD PROGRAMS

The temperature and salinity data for this study were collected by survey parties aboard the Blue Dolphin from 1949 to 1952, the Investigator II in October 1952, and the Burin Bay in August 1981. Winter data were collected in March 1952 and 1953 as part of the Blue Dolphin expeditions.

The majority of the existing data was collected from 1949 to 1953 by the Blue Dolphin expeditions under the command of Captain David Nutt of Dartmouth College, New Hamshire and financed by the Arctic Institute of North America,

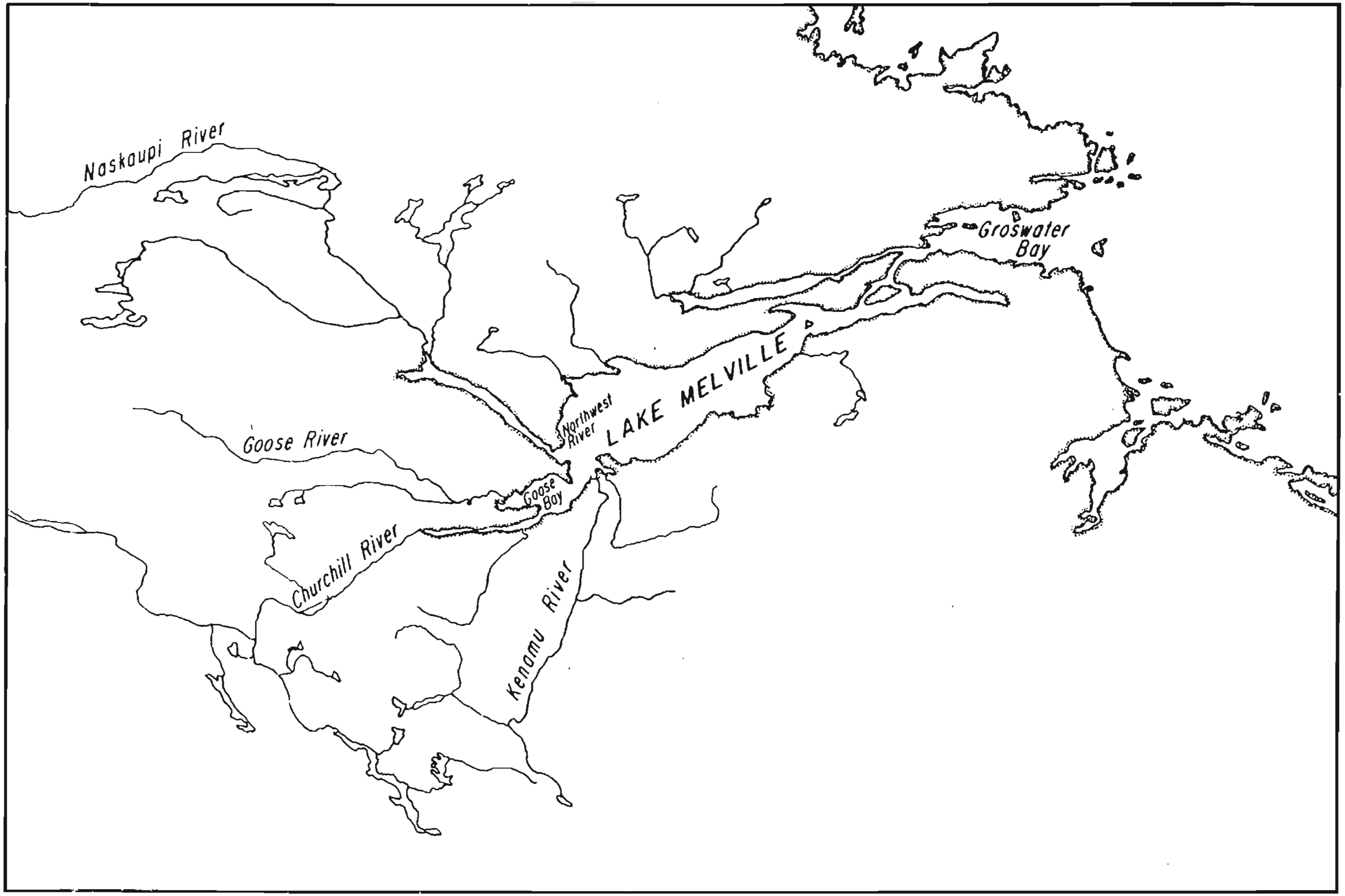


FIGURE 1·2 MAJOR RIVERS FLOWING INTO LAKE MELVILLE

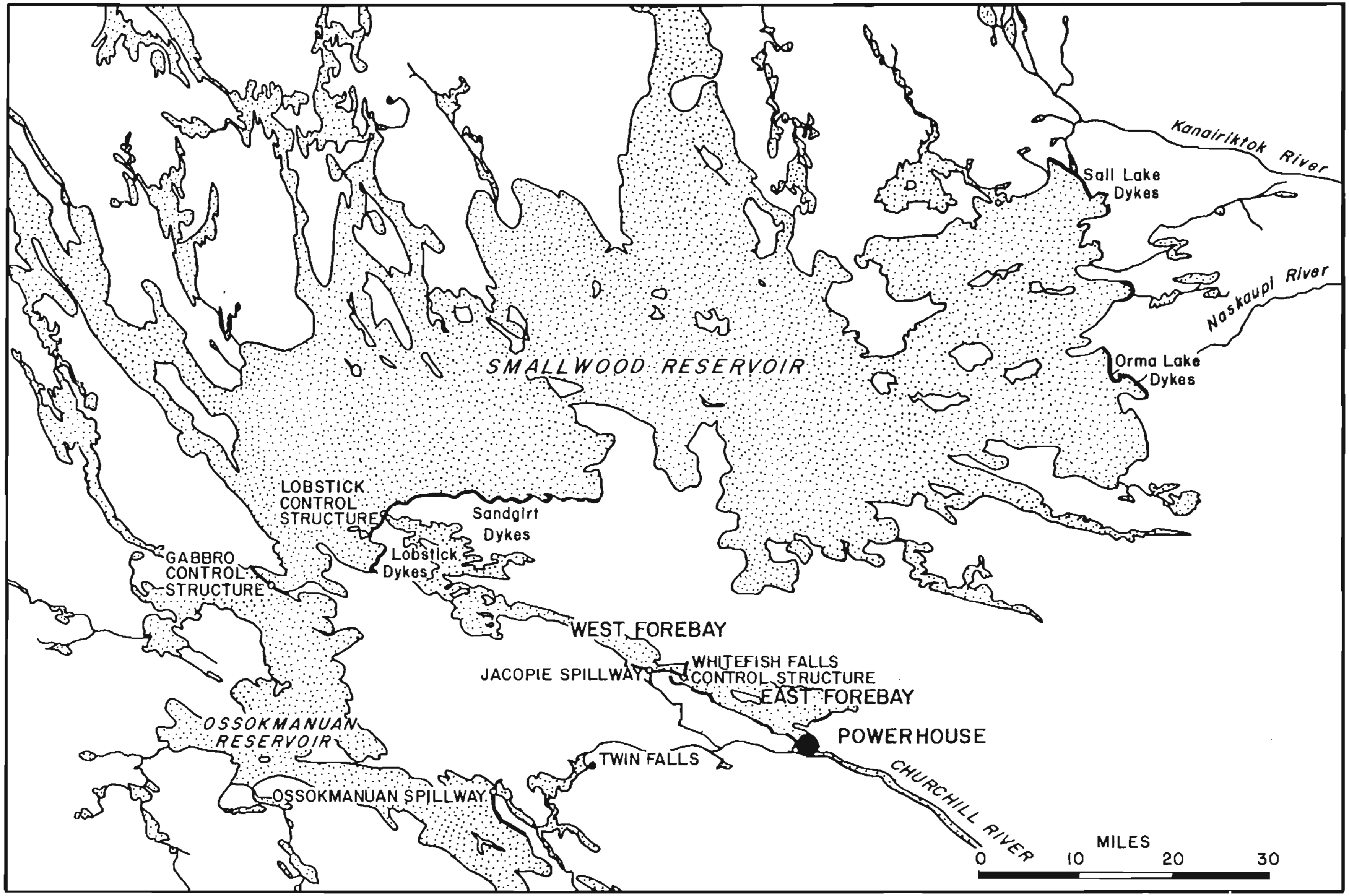


FIGURE 1·3 CHURCHILL RIVER DEVELOPMENT

the Office of Naval Research, the U.S. Hydrographic Office, and private sources. Measurements of salinity and temperature were taken throughout Hamilton Inlet during the periods July 4-29, 1950; August 18-28, 1950; July 6-29, 1951; August 13-28, 1951; June 29-July 12, 1952; August 19-28, 1952; and March 18 to April 10, 1953. A few stations were sampled as a preliminary survey during the summer of 1949. This constitutes an excellent data set as the sampling programs were well organized, and the selected grid of stations was re-sampled during consecutive summers. In addition, time series of bottle casts were carried out at the Narrows, Goose Bay bar, Terrington Basin bar, and a few points throughout Lake Melville to study changes during a tidal cycle. In all, 350 hydrographic samples were collected in Hamilton Inlet during the four summers, apart from that collected during the winter season. The major rivers were gauged during the expeditions to determine the fresh water volume being discharged into the fjord. Oxygen samples were sometimes taken from Lake Melville to give more information on the circulation system. The oceanographic data from the Blue Dolphin expeditions are currently being re-assembled and will be presented in a data report of this series as well as being archived in the Marine Environmental Data Service (MEDS). The data report will contain all the bottle data for salinities, temperatures, oxygens and phosphates, and will include tidal and current measurements made at various locations in Hamilton Inlet.

Additional data, before the Churchill development, were collected during October 13-16, 1952 by the Fisheries Research Board of Canada. Aboard the Investigator II four stations were sampled in Lake Melville and one in Groswater Bay. Since no recent data existed after the Churchill Development against which to compare the historical data, a survey was carried out during August 19-21, 1981, as part of this project. Bottle data were collected at 6 stations in Lake Melville and 3 stations in Groswater Bay, using the Burin Bay, a fisheries patrol vessel operated by the Department of Fisheries and Oceans.

The positions of the stations in Lake Melville are shown in Fig. 1.4 and those in Groswater Bay are shown in Fig. 1.5.

CIRCULATION IN LAKE MELVILLE

A GENERAL DESCRIPTION OF FJORD CIRCULATION

Fjord circulation depends on topography, fresh water discharge, wind, tide and external hydrography. The water in a fjord usually consists of two or three distinct layers. The upper layer consists of a mixture of the fresh river water and the underlying sea water that has been mixed upward by either entrainment or turbulence. The middle layer consists of sea water influenced by tides, and the bottom layer, if existent, contains water that is either stagnant or renewed only intermittently.

The brackish water at the surface has a net movement seaward and this produces a compensating inward flow at some deeper level. The seaward movement is due to the river water being introduced at the head of the inlet and producing a sloping free surface that is small but measurable. The compensating flow is controlled by the amount of sea water transferred to the upper layer by the entrainment process. The seaward flow of brackish water and the compensation current below are normally referred to as the estuarine circulation.

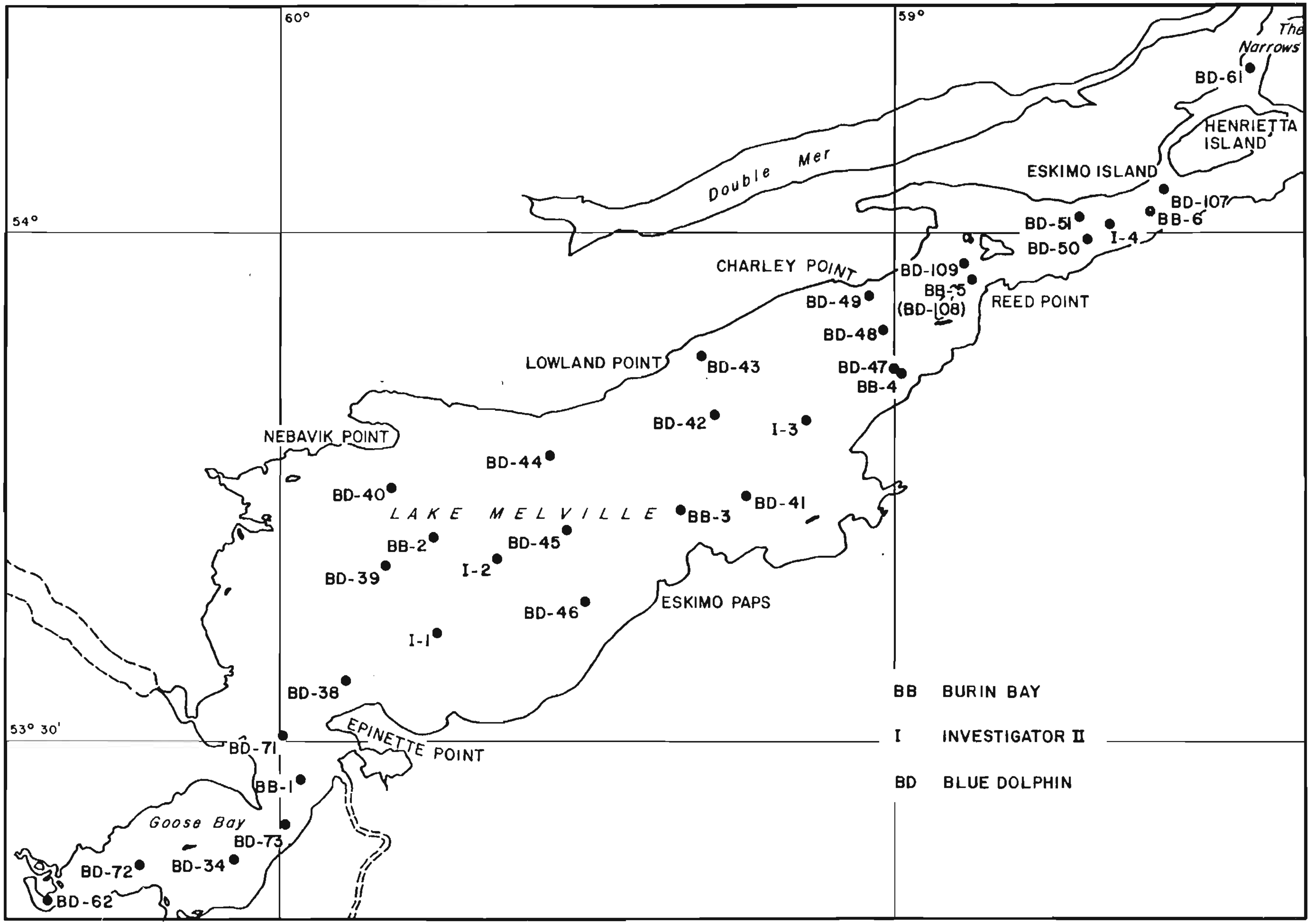


FIGURE I·4 STATIONS SAMPLED IN LAKE MELVILLE

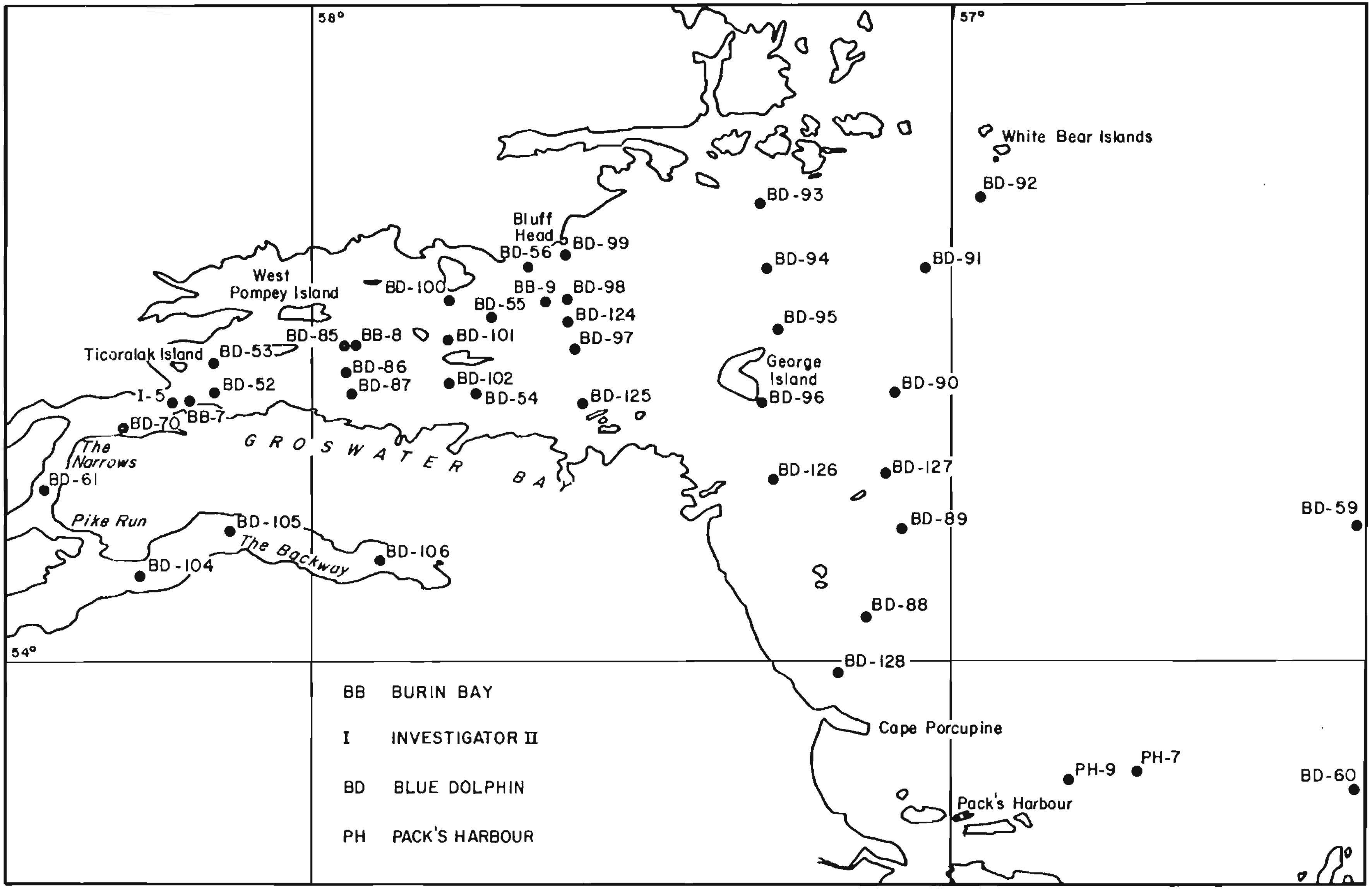


FIGURE 1·5 STATIONS SAMPLED IN GROSWATER BAY

In most fjords the salinity of the brackish layer gradually increased from head to mouth. In Lake Melville, due to the high discharge rates, the top layer has practically the same salinities throughout the fjord. This indicates that there is minimal vertical exchange between the brackish layer and the sea water due to entrainment. The thickness and salinity of the homogeneous section of the surface layer is strongly influenced by the wind conditions.

The flow of water within and through a fjord is produced by the sum of the tidal circulation, the steadier but usually weaker gravitational flow, and the widely variable wind-driven currents. During the action of winds, the eddy viscosity of initially stratified water will grow from particularly low to quite appreciable values, acting as an increasing frictional resistance to the flow (Gade 1976). However, the wind driven currents can reach significant magnitudes. Measured velocities in the range of 10% of the wind velocity are not uncommon (Rye 1973). Wind driven currents result from the direct effect of wind stress on the sea surface with the resulting current being dependent on the velocity and direction of the wind. The wind drift is usually predominantly in the direction of the wind with a tendency to align along the longitudinal axis of the fjord. The most significant effect of a predominant up-inlet or down-inlet wind upon the water surface is to produce an accumulation of water against the opposing boundary. This will produce a raising of the sea level in the area of the boundary and is usually referred to as a set-up. The sloping surface will produce a reversing current at deeper levels. In many instances, the current system in fjords becomes multi-layered.

The sea water which enters a fjord over the sill is carried upstream by mixing processes due to 1) horizontal advection from the current system, 2) density currents along the sloping isobaric surface, 3) horizontal diffusion and 4) horizontal turbulence created by friction at the boundaries and by shear stresses between the currents at different levels. Horizontal advection and vertical eddy diffusion are the dominant mixing processes in most fjords, with horizontal advection having a far greater influence. In most forms of horizontal dispersion, the effective mechanisms are based upon interactions between advective and turbulent processes (Gade 1976).

The intensity of turbulence controls the vertical distribution of salinity. In stratified waters, such as the halocline in fjords, the density gradient will resist the exchange of momentum and thereby reduce the vertical mixing. Mixing and entrainment across the interface is often the result of internal waves which are always present to some extent. Salt can be transferred to the upper layer through their breaking crests. In addition to short period internal waves being generated at the density interface, internal tidal motion can sometimes be present. It is expected that internal tidal motion may play a major role in the circulation of Lake Melville because the sill extends up to the stratified layer, so that a shear flow of appreciable magnitude may be produced.

The mixing and exchange of deep water in a fjord depends on the density of the water outside the sill in adjacent coastal regions. The presence of the sill prevents free exchange between the waters in the deep part of the fjord and the region outside, and may produce stagnant periods. The density of the deep water will decrease during stagnant periods because of the vertical flux of salt out of the deep water or heat into the deep water, or both

(Smethie 1981). When the density of the deep water is less than the density of the outside water at sill depth, flushing occurs. The exchange of the deep water is usually controlled by denser water being introduced to the region outside the sill during instances of offshore winds or by seasonal changes in the hydrographic structure.

FRESHWATER INFLOW

The freshwater content of the brackish upper layer of Lake Melville comes mainly from four major rivers; Churchill River, Northwest River, Kenamu River, and Goose River. Of these rivers, Churchill River accounts for over 60% of the freshwater inflow. Discharge rates for the four rivers, as determined by field survey parties during the Blue Dolphin expedition, are shown in Table 1, for years 1950-1953 (Coachman 1953). These data show that during spring run-off in May 1953 the discharge of the Churchill River was exceptionally high with a flow rate of 10,919 m^3/sec. The maximum flow, as measured by the Water Resources Branch of Inland Waters Directorate, usually occurred in June with a mean value of 5,122 m^3/sec for years 1954-1966. The minimum discharge was usually in April with a mean flow rate of 403 m^3/sec. The low value is due to the surface water of the Labrador plateau being mainly in the form of ice and snow during the winter months.

Table 1. Discharge rates in m^3/sec for the four major rivers flowing into Lake Melville, as measured by the Blue Dolphin expeditions.

Date	Churchill	Northwest	Kenamu	Goose
July, 1950	2,727	1,262	179	135
July, 1952	2,774	625	161	43
August, 1952	1,934	669	692	303
March, 1953	~226	366	7	5
May, 1953	10,919	1,800	290	532

Since the Goose and Kenamu Rivers have smaller drainage basins, their flow is irregular, reflecting local meteorological conditions. These two rivers together were found to usually contribute only about 5% of the freshwater flow, but after a storm in August, 1952 their contribution was approximately 28% of the discharge from the four rivers (Coachman 1953).

Daily flow rates of the Churchill River above Muskrat Falls have been measured by the Inland Water Directorate for the years 1954 to the present. The monthly mean values before and after the Churchill Falls development are shown in Table 2. The data for the years of construction (1967-71) were not included due to uncertainties associated with construction. However, during the construction period there were no anomalies in the flow rate. Table 2 shows that the monthly flow rates have changed considerably since the development.

The greatest differences are during the winter months. From December to April, the flow rates have approximately tripled those measured before development. During June and July, important months for the coastal fisheries, the flow rates have decreased by about 30%.

The Churchill River development has also changed the flow of the Naskaupi River, which flows into the Northwest River. The flow of the Naskaupi River has decreased during the winter and increased during the summer, the reverse situation to that of the Churchill River. To show the overall effect of development, the data for the Churchill and Naskaupi Rivers were combined and shown in Fig. 2.1. Since the flow of the Naskaupi River is so much less than that of the Churchill River, the curves of the combined data do not differ signicantly from those showing only the flow of the Churchill River.

Table 2. Mean monthly flows in m^3/sec above Upper Muskrat Falls, as measured by the Inland Waters Directorate.

Month	Before development 1954-66	After development 1972-80
January	659	1,553
February	527	1,586
March	454	1,460
April	442	1,585
May	1,760	2,656
June	4,188	3,232
July	3,297	2,006
August	2,047	1,952
September	1,799	1,746
October	1,714	1,907
November	1,400	1,659
December	896	1,641

CONCENTRATION OF FRESHWATER AND ITS RESIDUAL TIME

The salinity structure and estuarine conditions in a fjord usually vary in response to the supply of fresh water from inflowing rivers. In order to compare the differences in Lake Melville, six stations inside the sill were sampled in August 1981, and the measurements compared to those taken in the early 1950's by the Blue Dolphin Expedition and Investigator II. Since there is less fresh water flowing into Lake Melville during the summer months, it was expected that there may be a reduced volume of fresh water in the fjord, and significant differences in the salinity structure.

The salinity profiles from the six stations sampled in August 1981 were compared with the profiles previously taken at nearby locations. Figures 2.2-2.7

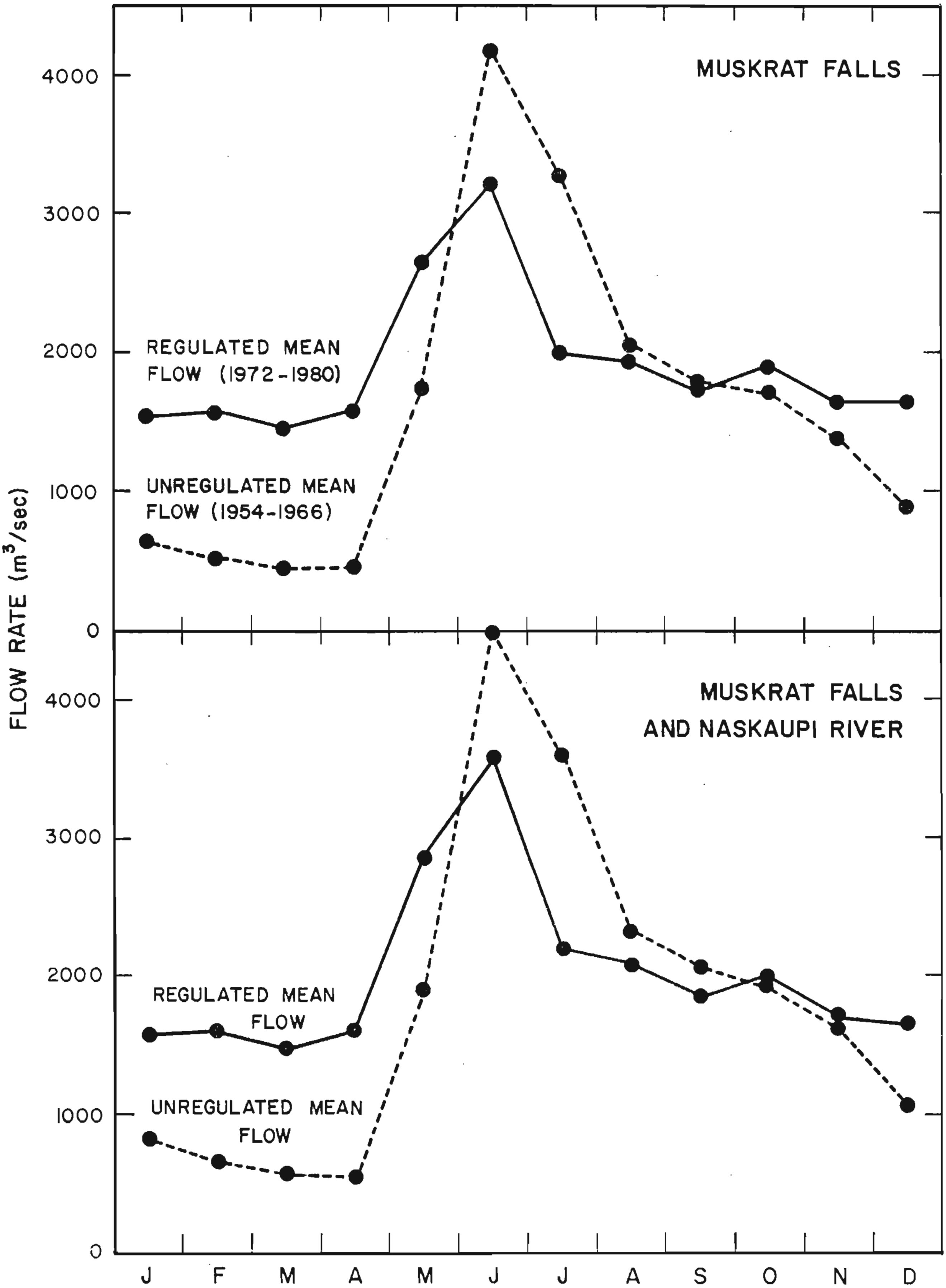


FIGURE 2·1

MEAN MONTHLY FLOWS BEFORE AND AFTER THE CHURCHILL FALLS DEVELOPMENT (data from the Inland Waters Directorate) show that at each location the profiles of the near-surface waters are remarkably similar, even though the fresh water inflow from the rivers has changed considerably. Due to estuarine processes and the dimensions of the fjord, the proportionate changes in the salinity distribution are less than in the river flow. The slight differences observed are in the range one would expect when sampling on different days during the same season, due to tidal stages, internal waves and wind mixing.

The calculated volumes of fresh water and the corresponding flushing times are summarized in Table 3. The results show that the volume of fresh water in Lake Melville during August 1981, was comparable to that found in the early 1950's. Only the fresh water volume in the upper 30 m was considered because most of the river water remained near the surface with the halocline occurring between 5 and 20 m. In addition, the sill is located at a depth of approximately 30 m, thus restricting the water below this depth from readily being removed from the fjord.

Table 3. Fresh water volumes and their respective flushing times.

Time	Fresh water volume (km^3)	River discharge (m^3/sec)	Flushing time (months)
July, 1950	40.274	4,303	3.6
August, 1951	34.515	~2,876	~4.6
July, 1952	44.203	3,603	4.7
August, 1952	35.130	3,598	3.8
October, 1952	33.146	3,089	4.1
August, 1981	41.054	2,739	5.8

The fresh water volume was determined by the following method. Lake Melville was divided into 4 to 18 segments depending on the number of stations sampled during each oceanographic survey. The area of each segment was extracted from hydrographic charts, and the concentration of fresh water calculated from the salinity profiles. The concentration C of fresh water was determined for 5 m depth intervals by the following formula $C = (S_0 - S)/S_0$, where S was the mean observed salinity in the 5 m depth interval, and S_0 the salinity of the sea water. The salinity of sea water was taken as 30$^\circ/_{oo}$, the salinity between 15 and 30 m at the station sampled just outside the Narrows.

The flushing time, or the average time for the river water to be removed from Lake Melville was determined from fresh water concentrations and the amount of discharge from the rivers. The river discharge was determined from the flow rates supplied by the Inland Waters Directorate, Churchill Falls Labrador Corporation Ltd., and the Blue Dolphin expeditions. The volume of

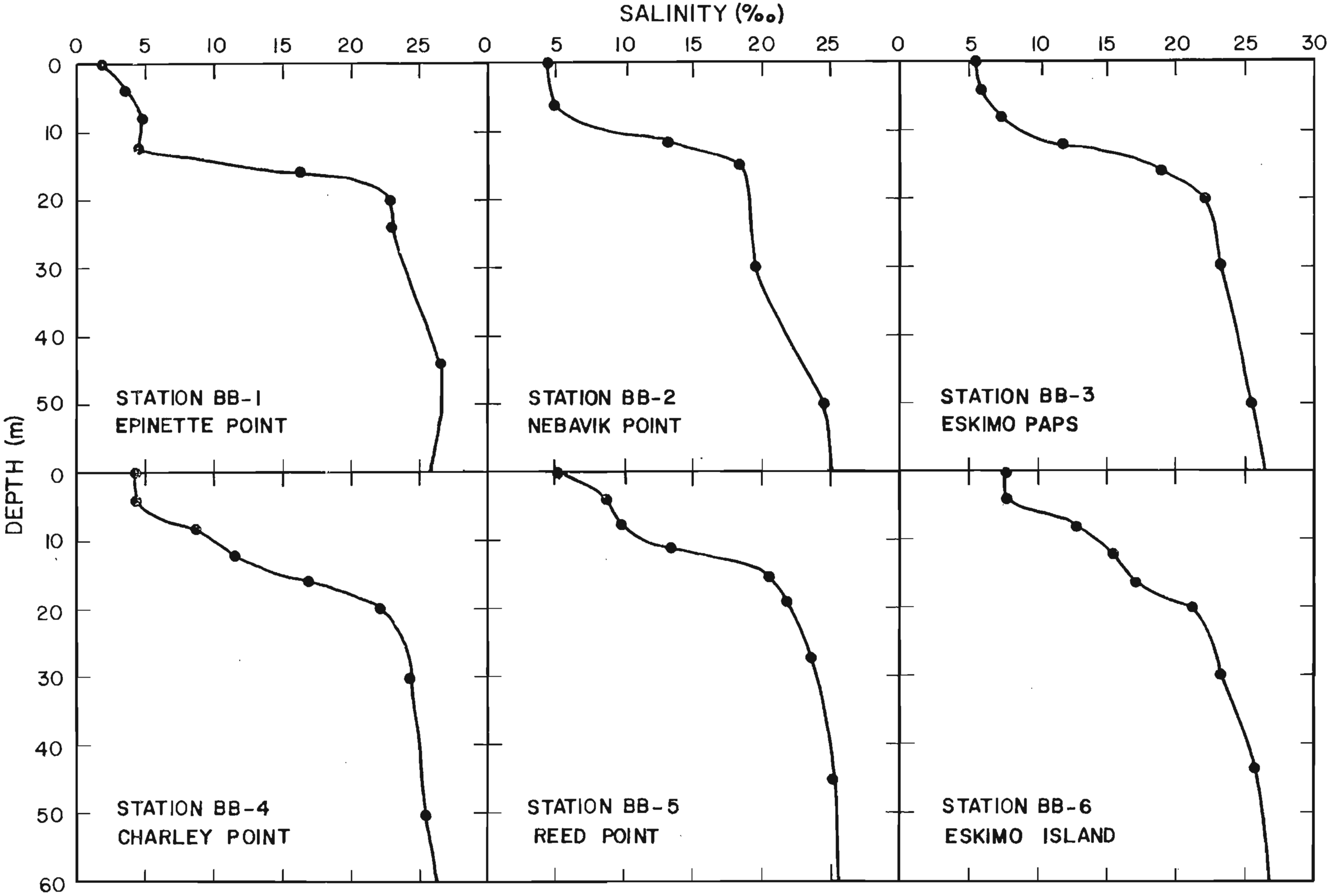


FIGURE 2·2
NEAR SURFACE SALINITY PROFILES IN LAKE MELVILLE
DURING AUGUST 19-20, 1981

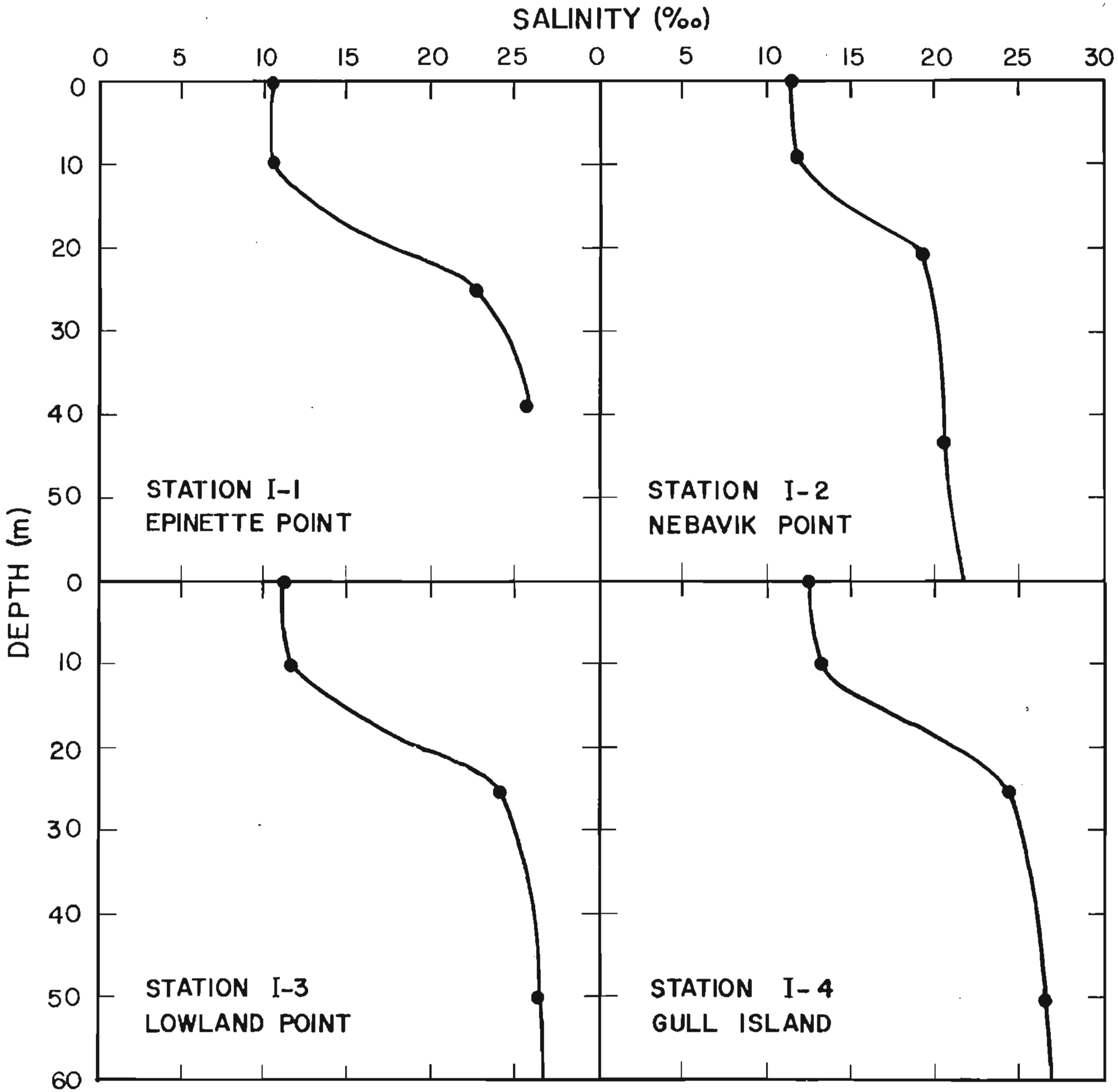


FIGURE 2·3
NEAR SURFACE SALINITY PROFILES IN LAKE MELVILLE
DURING OCTOBER 13-16, 1952

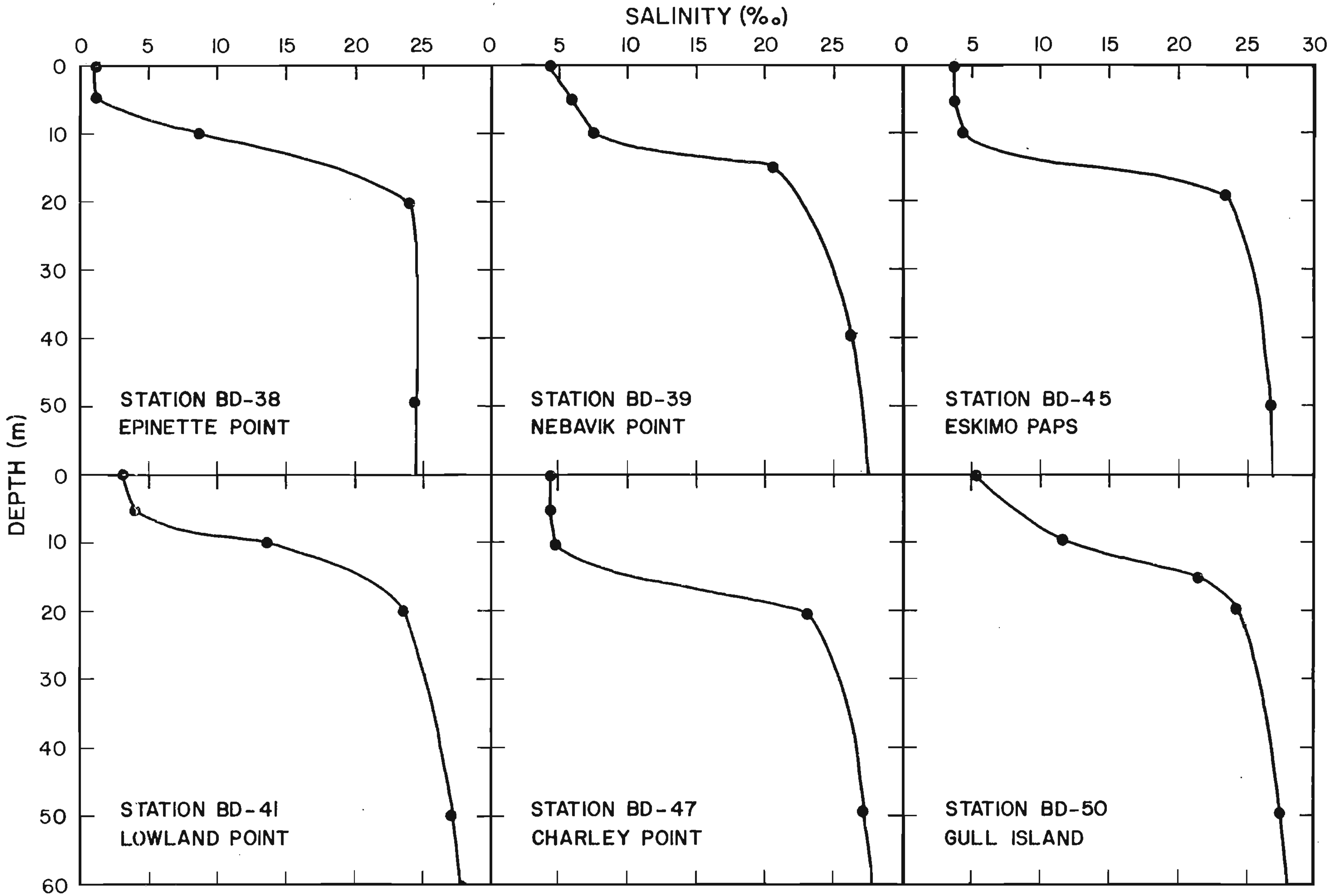


FIGURE 2·4
NEAR SURFACE SALINITY PROFILES IN LAKE MELVILLE
DURING JULY 8-13, 1950

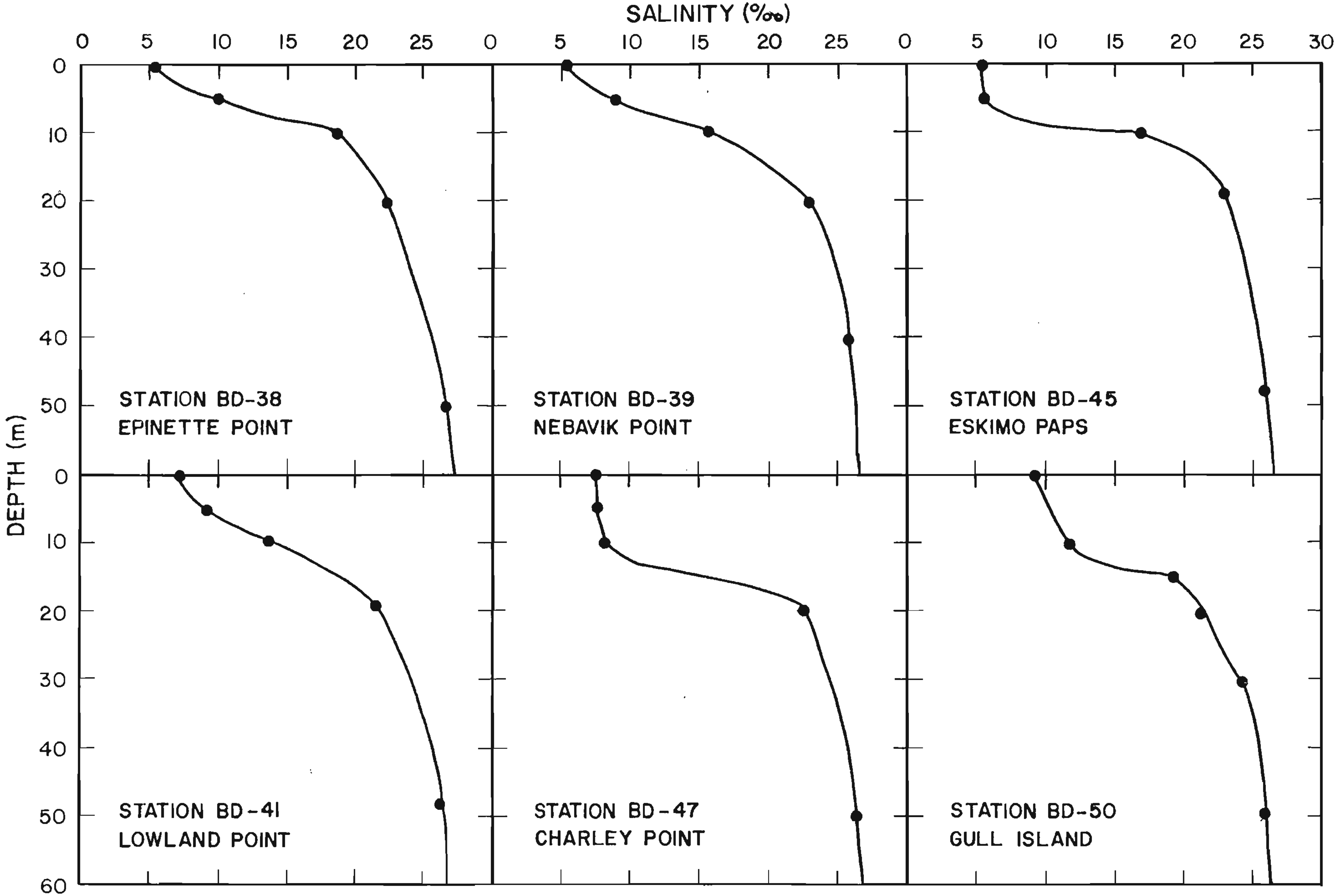


FIGURE 2·5
NEAR SURFACE SALINITY PROFILES IN LAKE MELVILLE
DURING AUGUST 21-22, 1951

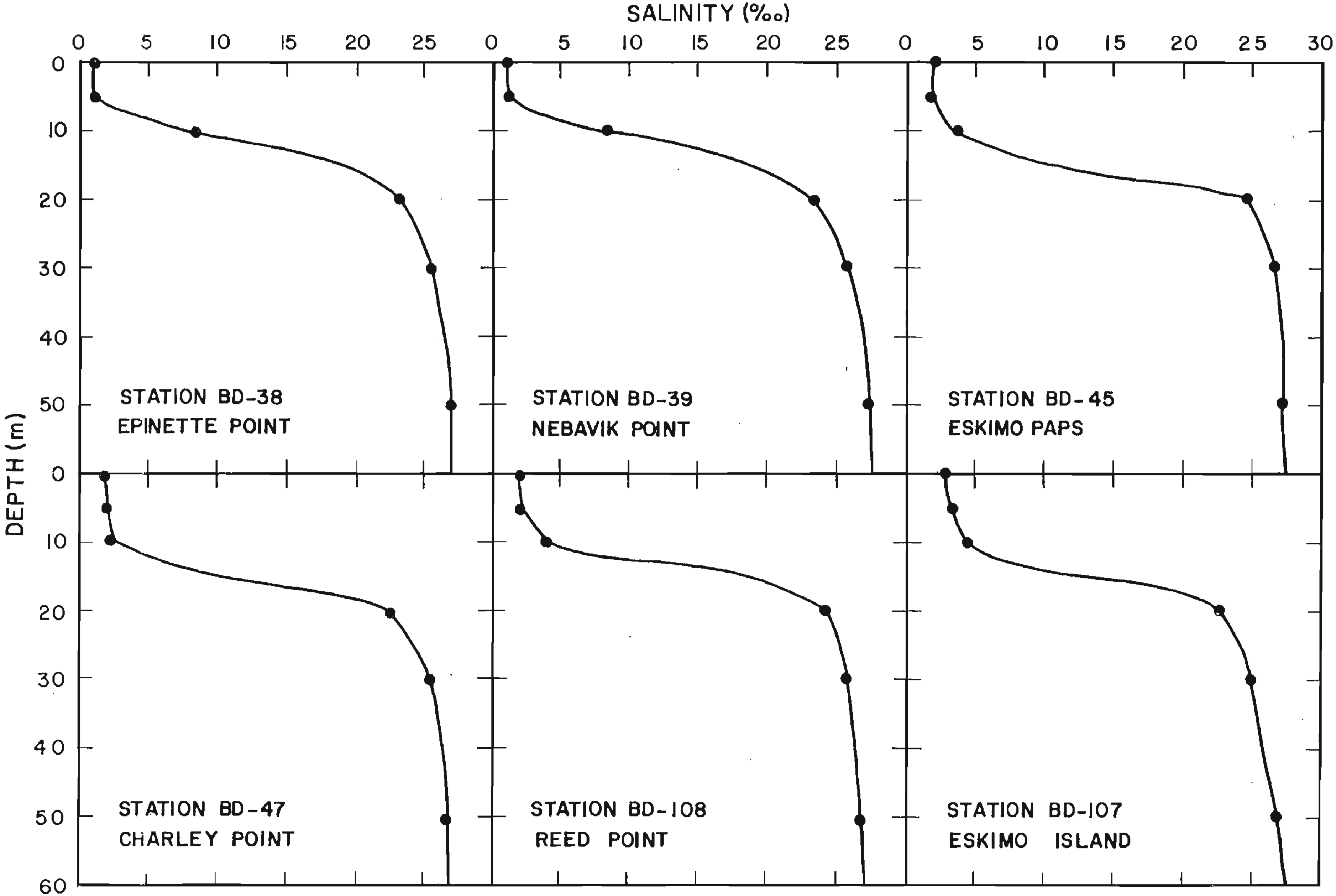


FIGURE 2·6
NEAR SURFACE SALINITY PROFILES IN LAKE MELVILLE
DURING JULY 4-6, 1952

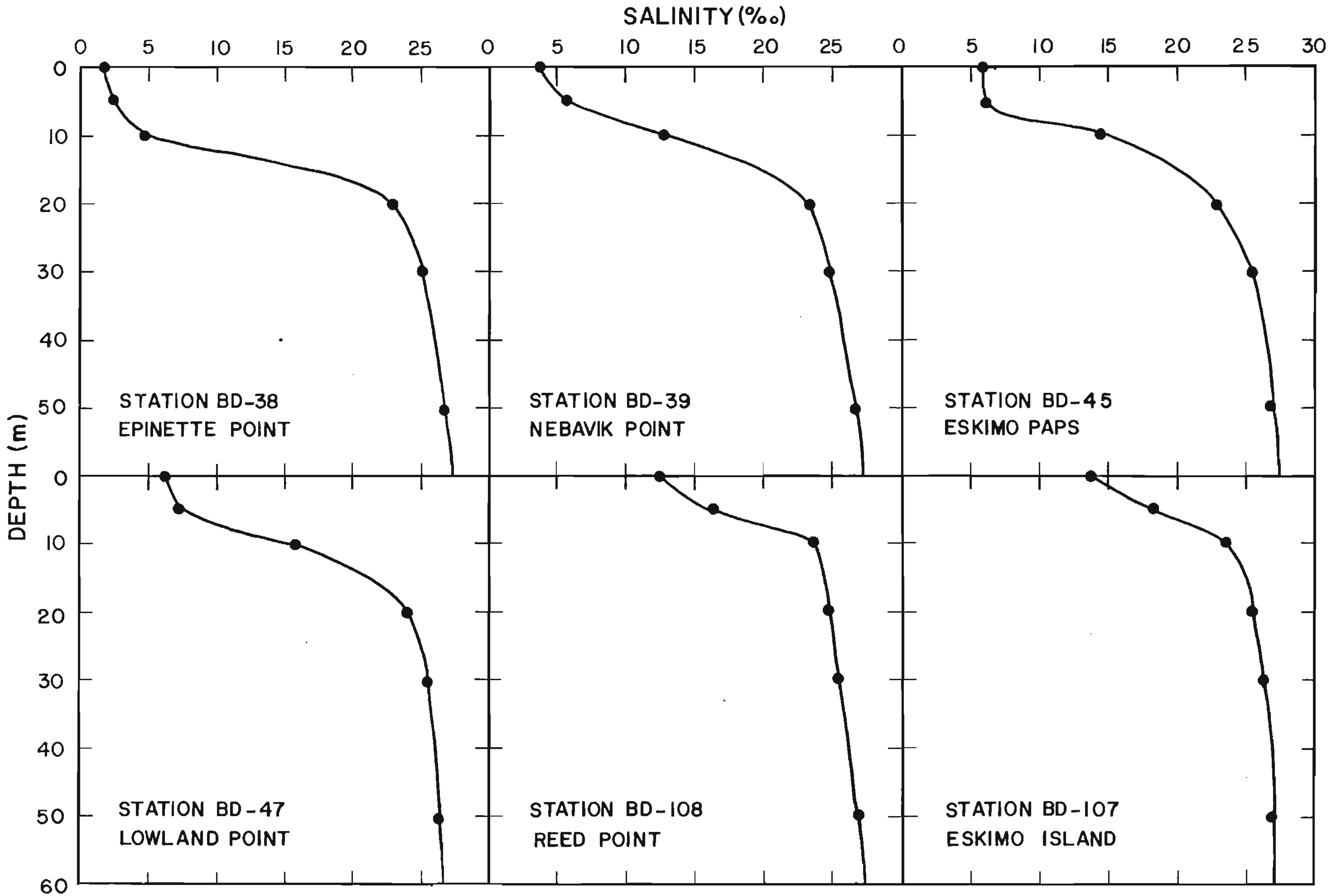


FIGURE 2·7
NEAR SURFACE SALINITY PROFILES IN LAKE MELVILLE
DURING AUGUST 21-24, 1952

river water flowing through any cross-section must equal the volume of water introduced by the river flow since the mean sea level throughout the fjord remains constant. The flushing time is the time required for the rivers to replace the fresh water volume and can be expressed by t = volume of fresh water/river discharge. By this method the flushing times before the Churchill development were found to vary from 3.6 to 4.7 months. In August, 1981, the flushing rate was 5.8 months due to the decrease in river flow. Since the quantity of fresh water within Lake Melville remains relatively unaffected, the volume of fresh water transferred to Groswater Bay on each tidal cycle must be less now than before development. During the winter the situation is reversed with much more fresh water being introduced into Lake Melville now than before development.

Since the fjord is large and the flushing times rather lengthly, Lake Melville tends to act as a buffer between variations in river flow and respective changes in salinity in Groswater Bay. This means that in the absence of exceptionally strong down-inlet winds, short-term variations in river flow should have negligible effect on the salinity in Groswater Bay.

DEEP WATER EXCHANGE

In order to get vertical exchange between fjord deep water and adjacent coastal water, the density of the water at sill depth and above has to be greater than that of the deep water in the fjord. Figure 2.8 shows that this condition exists for Lake Melville. The density of the water between 12 and 30 m at station BB-7 is greater than that found anywhere in Lake Melville. A similar situation existed in 1952 except that the density of the adjacent coastal water was slightly lower in that year. The high density of the water outside the sill suggests that the deep water is readily being flushed. However, the water below sill depth in Lake Melville is approximately 1-3 degrees colder than that of the adjacent coastal water, and having negative values below a depth of 100 m. T-S curves (Fig. 2.9) of the water masses on opposite sides of the sill show that the water properties are considerably different. If the water outside the sill, at sill depth and above, is mixed with that found at the same depth inside the sill, the resulting mixture will not have the properties of the water found below 30 m in the lake. The properties of the deep water can only be obtained through cooling. Even though the water properties indicate no exchange taking place during summer, the deep water is not stagnant. The oxygen values of the water below sill depth were found to vary between 7.2 and 7.8 ml/L at station BD-47 in August 1952. Similarly high oxygen values were found throughout the lake.

Since the incoming sea water has a salinity greater than 24.7$^\circ/_{oo}$, its density will increase with cooling. Therefore, the incoming water has to be cooled and mixed concurrently with a lower salinity water to get the properties found below sill depth in Lake Melville. This situation exists during the autumn and winter seasons, particularly in the region of the Narrows. The T-S curves in Fig. 2.10 indicate that vertical exchange can take place during the winter season. Moreover, the high oxygen values measured in 1952 suggests that complete exchange may occur over the winter period, even though there is a shallow constriction at the Narrows. In August, 1981, the deep water was slightly warmer by about 0.4°C. It had a salinity which was 0.8$^\circ/_{oo}$ (at a depth of 100 m) lower than that measured during August 1952. This variation

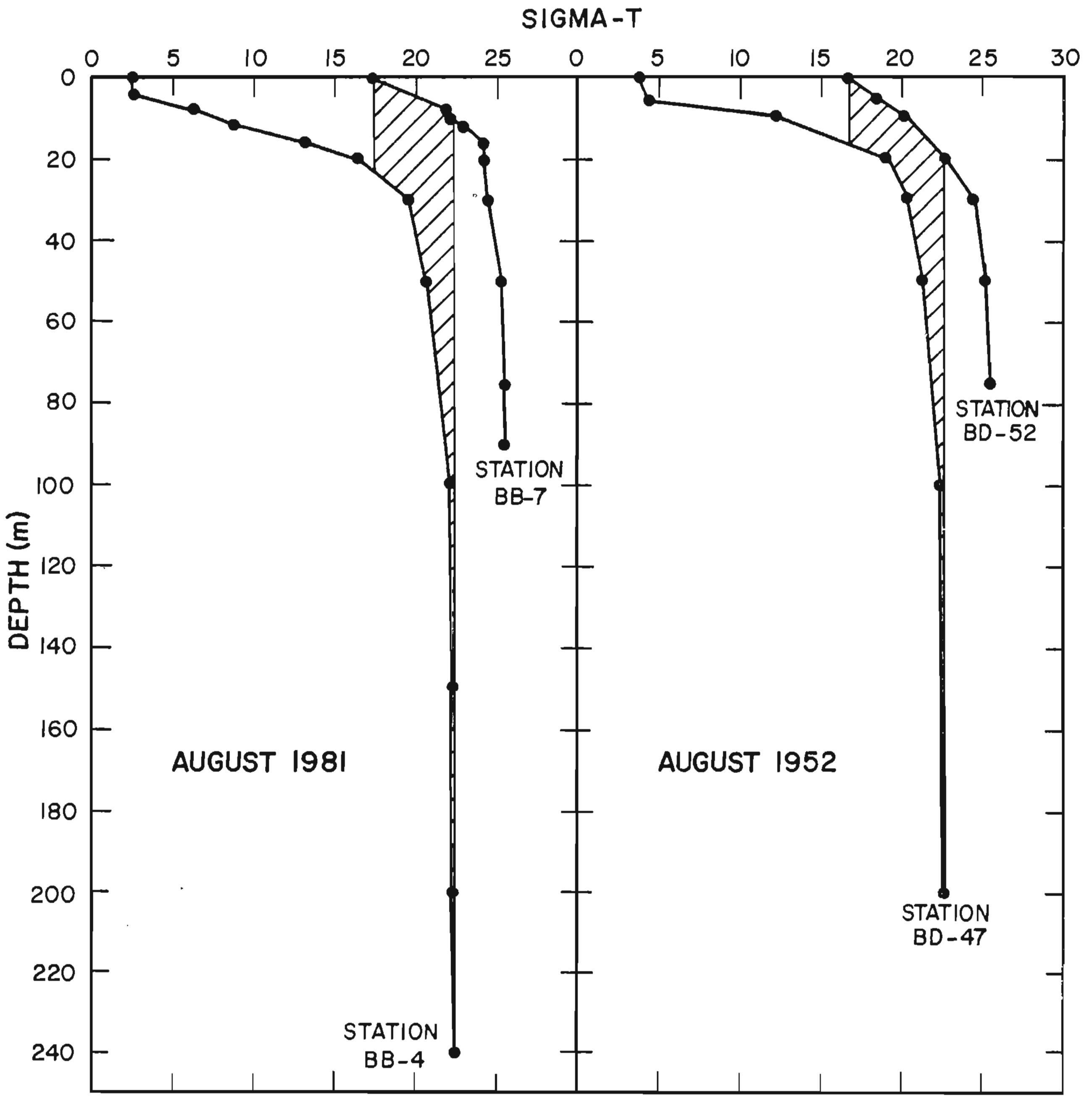


FIGURE 2.8

COMPARISON OF SIGMA-T PROFILES IN LAKE MELVILLE AND OUTSIDE SILL

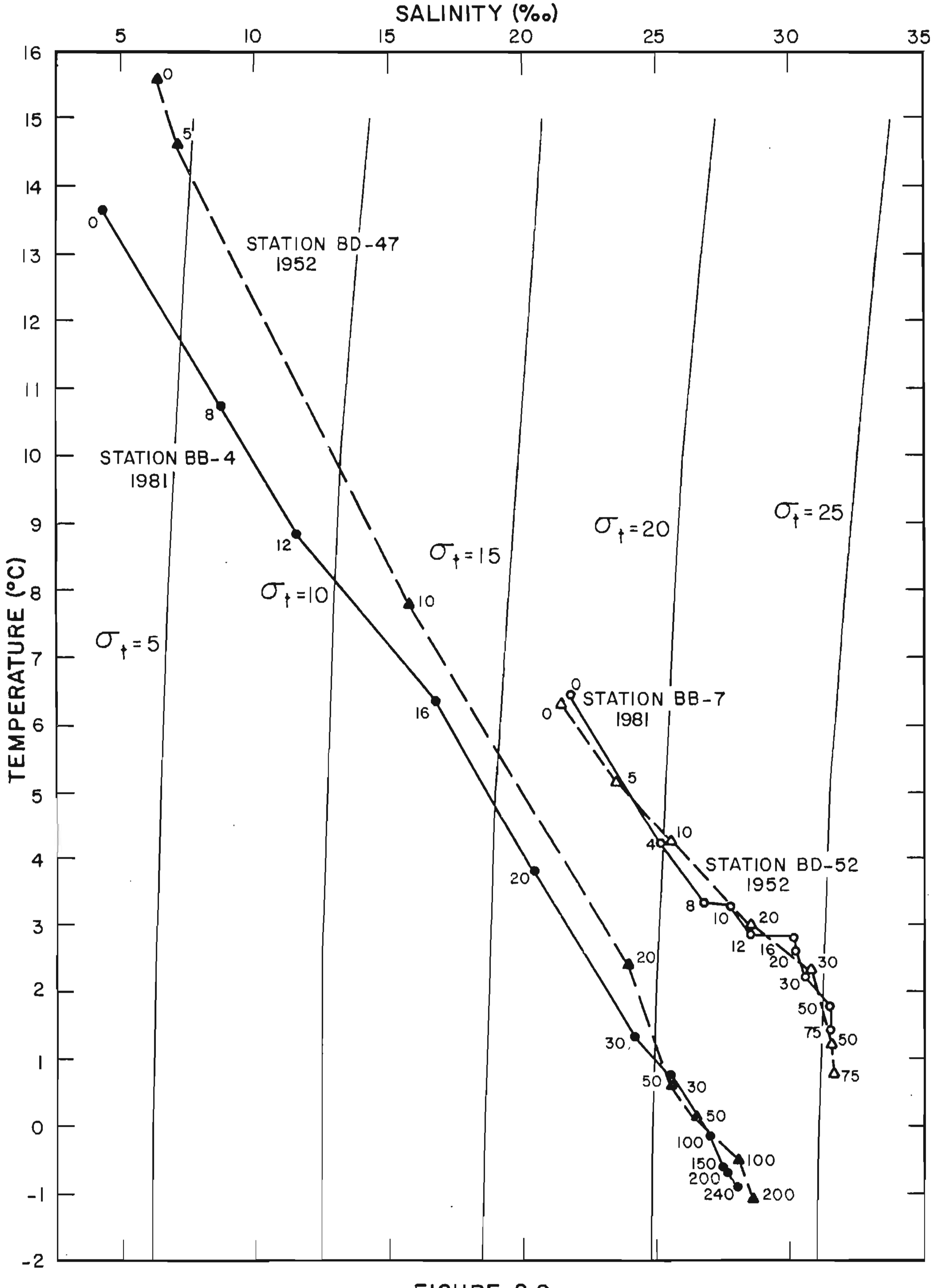


FIGURE 2·9

T-S CURVES OF WATER MASSES IN LAKE MELVILLE AND OUTSIDE THE SILL DURING AUGUST 1952 AND 1981

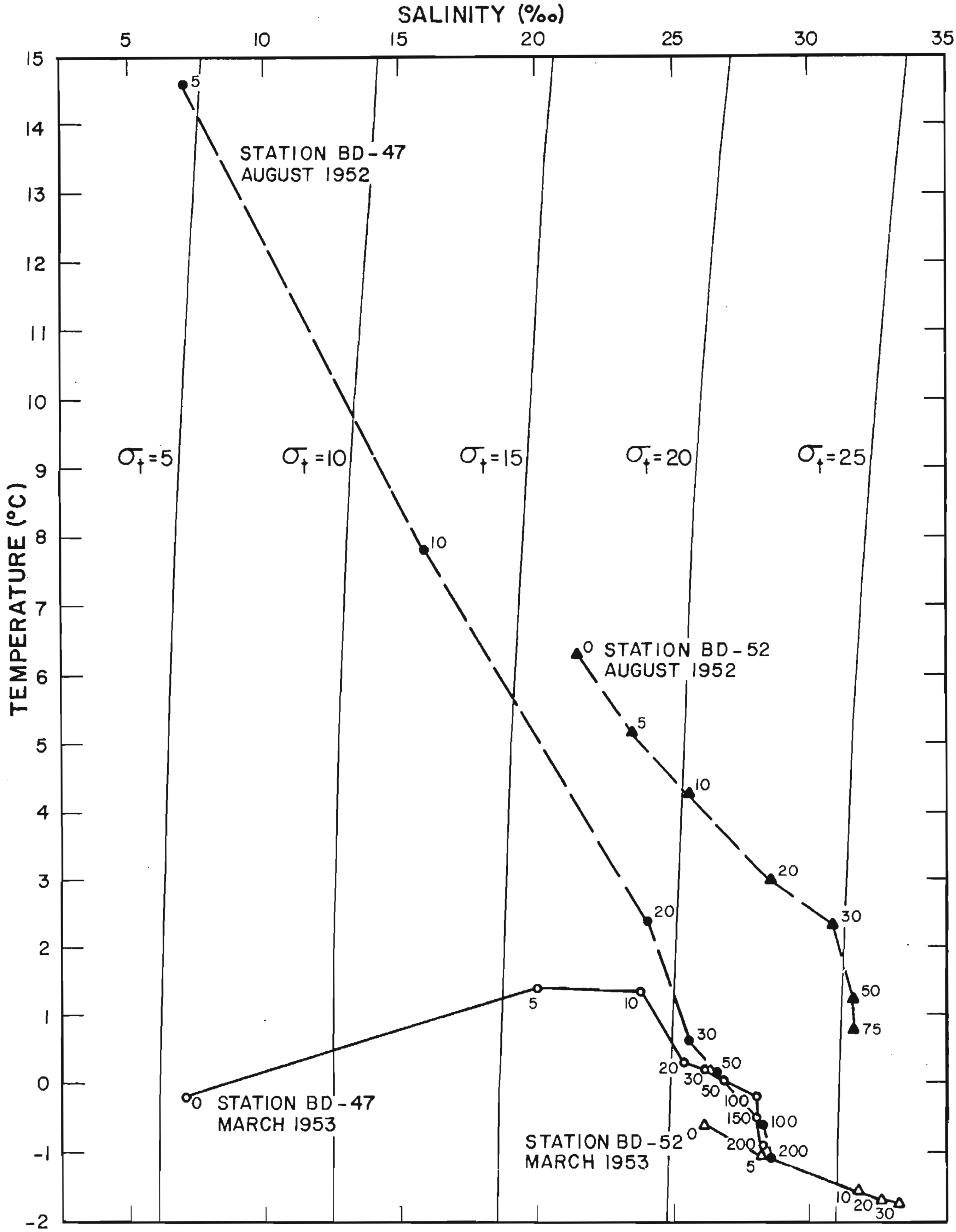


FIGURE 2.10

T-S CURVES OF WATER MASSES IN LAKE MELVILLE AND OUTSIDE THE SILL DURING AUGUST 1952 AND MARCH 1953 may be a normal yearly difference but more probably is due to different mixing conditions caused by the larger volume of river water discharged during the winter since the Churchill development. Oxygens were not measured in 1981, so there is no indication of whether or not the deep water is still being completed renewed during the autumn and winter seasons. However, since winter is relatively lengthly in this area, there is no reason to suspect that complete exchange is not taking place. In most cases for which data are available the deep water renewal of a fjord basin is a relatively rapid event, which is often completed within the course of a few weeks (Gade 1973).

EFFECTS OF THE NARROWS

TIDAL CHOKING

The Narrows, located between Lake Melville and Groswater Bay, has a sill depth of 30 m, a width of 2.8 km, and a length of 22 km. This constriction dampens the rise and fall of the tide from 1.3-2 m in Groswater Bay to 0.2-0.5 m in Lake Melville (Nutt 1963). This gives a choking coefficient of approximately 0.2 where the choking coefficient is defined as the ratio of the inside tidal height to the outside tidal height. The choking coefficient is not a constant, for it will show some deviations due to non-symmetry of the outside mixed, mainly semi-diurnal tidal amplitudes and to natural variations in such parameters as river flow and wind conditions. In general, the choking coefficient decreases as the tidal amplitude increases (Glenne and Simensen 1963).

In landlocked fjords, the shape of the inside tidal curve is different from the outside tidal curve. A tidal curve with a peaked inflow and a rounded outflow is often typical. This effect is caused by the variation in cross-sectional area of the channel with decreasing tidal amplitude.

Due to the constriction and the large river discharge, the mean water level within Lake Melville must be higher than the mean water level in Groswater Bay. This causes the period of tidal inflow (flood) to be shorter than the period of outflow (ebb). In the Narrows on July 4, 1950, ebb current was found to last for 8½ hr and flood current for 6¼ hr (Nutt 1951). Moreover, the tidal phase inside Lake Melville was delayed compared to the tidal phase in Groswater Bay. High water occurred in Groswater Bay when it was low water in Goose Bay at the head of the fjord, and vice versa (Nutt 1963).

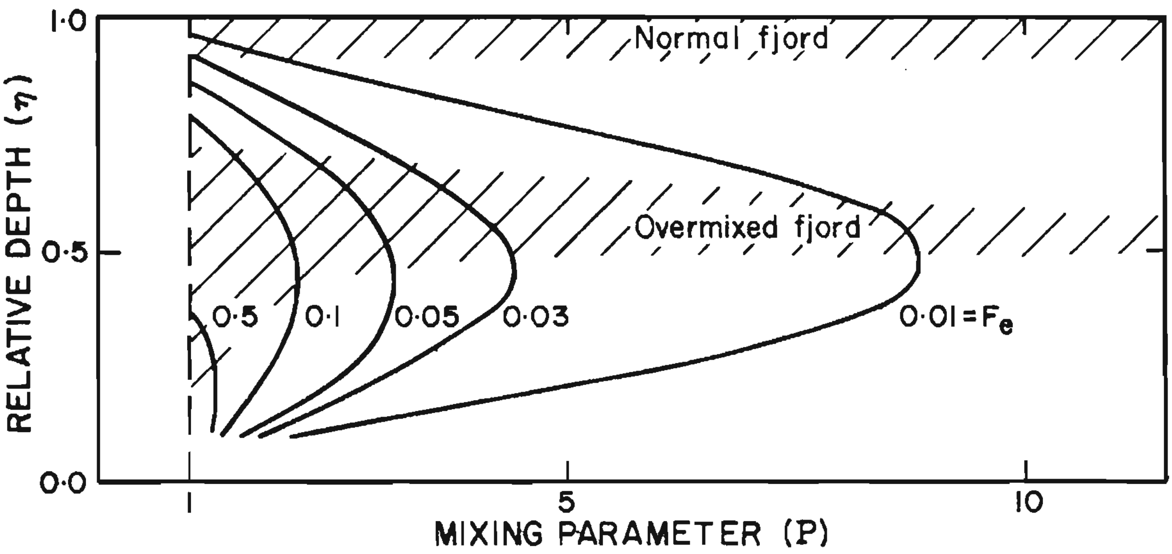
In addition to changing the shape of the tidal curve and the tidal phase, sills and narrows can also enhance inlet currents. On July 24, 1950, ebb current in the Narrows was found to have a speed of 5 knots and flood current had a speed of 4 knots. On July 18, 1951, a flood current of 6 knots and a ebb current of 6.6 knots was reported. In general, maximum flood velocities are larger than ebb velocities for landlocked fjords with large river discharge (McClimans 1978). This implies that a larger energy flux is transferred to the fjord than to the sea. The current velocities in the Narrows indicate that the reverse situation may exist for Lake Melville. However, the constriction at the Narrows can convert an enormous amount of tidal potential energy to kinetic energy for use in turbulent mixing on both sides of the construction. McClimans (1978) found that for frictionless tidal flow, the maximum energy flux will be transferred to the fjord when the tidal range within the fjord is 0.707 times as large as the external tidal range. This value is expected to be different in the case of Lake Melville because the length of the Narrows is too long to neglect frictional effects. However, the choking coefficient of approximately 0.2 indicates that tidal kinetic energy is not very effective in driving the circulation or in producing mixing in the fjord.

HYDRAULIC CONTROL MECHANISMS

The transport between Lake Melville and Groswater Bay is controlled by the salinity stratification, the barotropic tide, and the dimensions of the constriction. The transport capacity of a constriction is dependent on whether or not the flow is subcritical. Stommel and Farmer (1952, 1953) dealt with the transport capacity of a constriction between an estuary and the sea, for subcritical flow, and introduced a concept called overmixing. Overmixing refers to a state such that if the mixing energy is increased, the salinity of the upper layer cannot increase beyond a certain value. This means that there is an upper limit to the transport capacity of the system with respect to a two-layer exchange. Stigebrandt (1977, 1981) expanded on the concept of overmixing to show that this internal hydraulic control is important to the circulation in fjords. The critical condition for overmixing occurs when the interfacial Froude number $F_{d1}^2 + F_{d2}^2 = 1$ (at the mouth of the fjord) where $F_{di}^2 = U_i^2/g'H_i$, i = 1,2 in the upper and lower layer, respectively. U is the current velocity, H is the layer depth, and $g' = g\ \Delta\rho/\rho$ where $\Delta\rho$ is the density difference between the two layers.

This condition is satisfied and the constriction acts as an internal hydraulic control for stationary currents and negligible frictional effects. When the constriction has considerable length, such as the Narrows, the frictional effects can become important and the transport capacity can decrease.

Stigebrandt (1981) presented solutions to the equation developed by Stommel and Farmer for different values of the estuarine Froude number (Fe). The estuarine Froude number (Fe) = $Q_f/(g\ \Delta\rho/\rho)^{\frac{1}{2}}\ B_m\ H_m^{\ 3/2}$ where Q_f = volume flux of fresh water. B_m and H_m are the width and depth of the constriction, respectively. For a constant river discharge to a fjord, the F_e value is constant. For Lake Melville, using a typical summer discharge rate of 3,000 m^3/sec, the estuarine Froude number is approximately 0.02. According to the solution curves (Fig. 3.1) presented by Stigebrandt (1981) and the salinity



$\eta = \frac{H_2}{H_2 + H_1}$, $P = \frac{S_2}{S_2 - S_1}$ WHERE 1 – UPPER LAYER
2 – LOWER LAYER

FIGURE 3·1

THE SOLUTION CURVES OF THE STOMMEL & FARMER EQUATION FOR DIFFERENT VALUES OF THE ESTUARINE FROUDE NUMBER, F_e (from Stigebrandt, 1981) distribution (Fig. 3.2), the Narrows can fit into this overmixed condition provided that the barotropic tidal current is small.

The hydraulic control and overmixing will be eliminated during the times the barotropic tidal currents, superimposed on the estuarine circulation, are strong enough to give a one way directed flow (Stigebrandt 1977). The transport capacity of the constriction will then increase. The barotropic flow becomes important when its velocity is greater than $\frac{1}{2}\,(g'H)^{\frac{1}{2}}$. For this condition, the flow is alternating barotropic and baroclinic, or just barotropic (Stigebrandt 1977). This means that in the case of the Narrows, the internal hydraulic control ceases to be important when the tidal current is greater than 2 knots. Since a current of 6 knots has been measured in this area, it is to be expected that the flow often exceeds 2 knots.

Moreover, the flow in the Narrows probably goes from subcritical to supercritical over each tidal cycle. The condition for supercritical flow is that the current be greater than $(g'H)^{\frac{1}{2}}$, or greater than 3.4 knots in the Narrows. For this situation, internal waves are not generated at the sill and the flow is similar to that expected when stratification is absent (Stigebrandt 1980). In supercritical flow, the flow expands on the lee side of a constriction and a jet develops with the momentum balance occurring between the nonlinear field accelerations and the Reynolds stresses. For certain combinations of sill depth and thickness of the upper layer, the jet may undergo an internal hydraulic jump (Stigebrandt 1980). When flow separation occurs, kinetic energy is lost to turbulence. The hydraulic jump on the lee side of a sill can generate internal waves that propagate in groups with a weak interaction between them; and may be considered as a train of solitary waves (Farmer and Smith 1978).

The jet on the lee side of a constriction can be important for turbulent vertical mixing, both in Lake Melville and in Groswater Bay, depending on the stage of the tide. Turbulent mixing in the vicinity of the Narrows is probably a large factor in why the salinity stratification of the upper layer is practically constant throughout the fjord. Therefore, in addition to restricting the flow below sill depth, the Narrows play a major role in the conversion of tidal potential energy to kinetic energy for turbulent mixing and circulation on both sides of the sill.

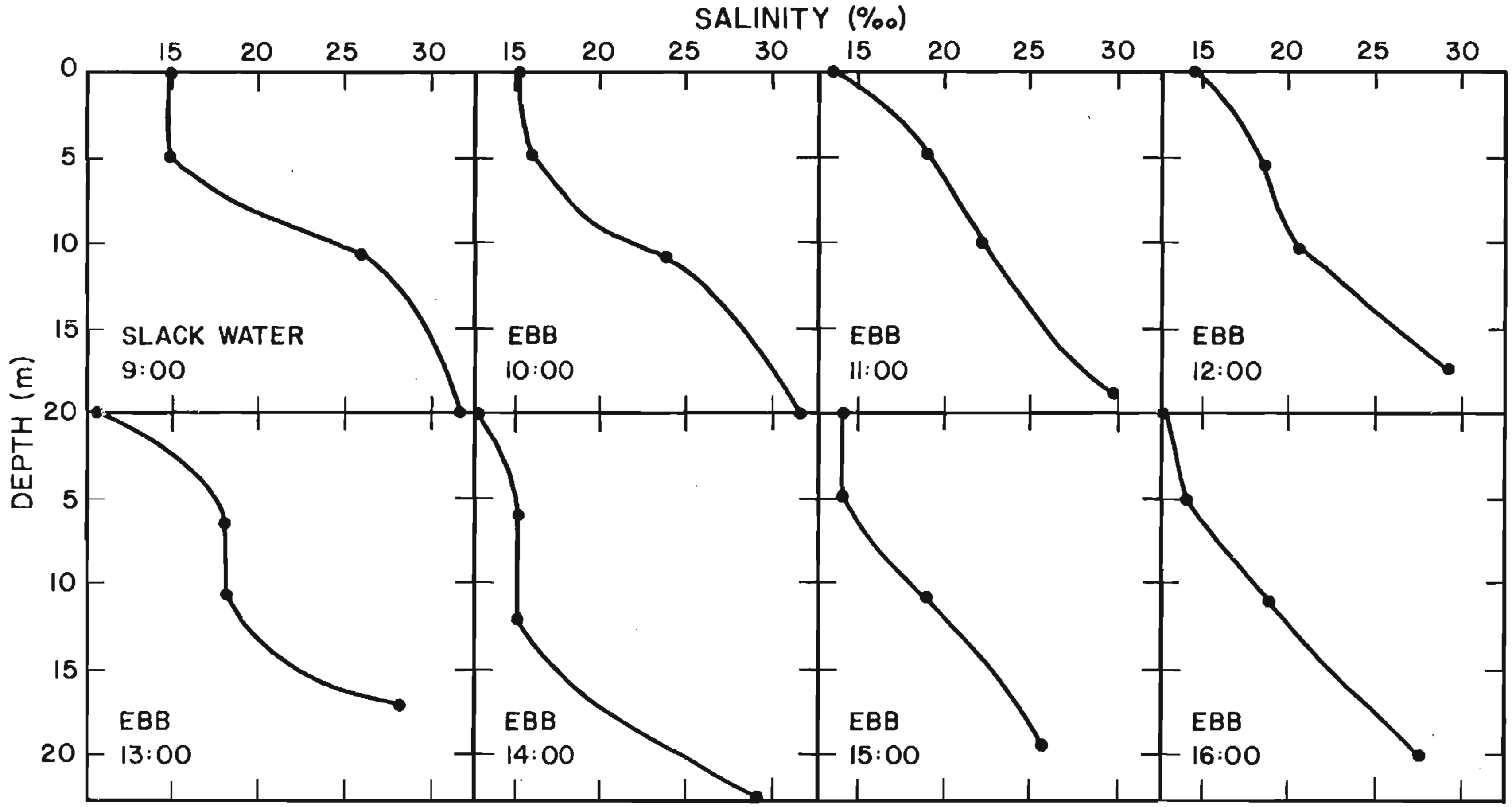


FIGURE 3·2

SALINITY TIME-SERIES AT STATION BD-61 IN THE NARROWS
ON JULY 24, 1950
(continued)

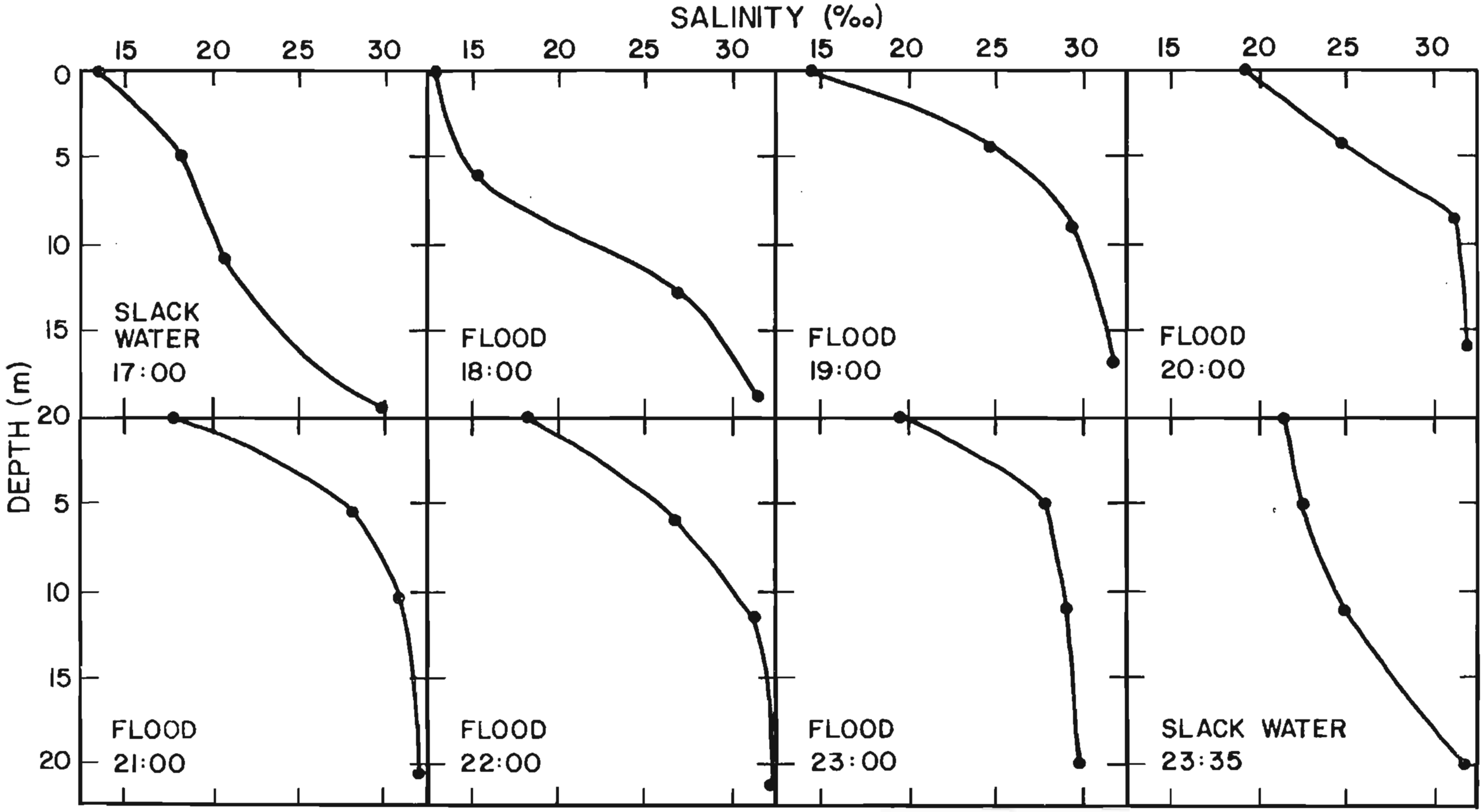


FIGURE 3·2 (continued)

WATER PROPERTIES IN GROSWATER BAY

WATER PROPERTIES OUTSIDE THE NARROWS

The water properties, before and after the Churchill development, were compared for stations located offshore Ticoralak Island (Fig. 1.5), at the head of Groswater Bay. Since these stations were situated immediately outside the Narrows, any changes in the water structure of Groswater Bay that were due to the Churchill development would be reflected at this location.

The stations were sampled during July 1950, August 1952, October 1952, September 1979, and August 1981. In addition to the Blue Dolphin, Investigator II, and Burin Bay surveys that were mentioned earlier, this location was also sampled on September 9, 1979 during the Offshore Labrador Biological Studies (OLABS). Figure 4.1 gives the temperature and salinity profiles for these stations.

These profiles show that the properties of the water in 1979 and 1981 are within the natural variations found before the Churchill development. An interesting feature is that the water had a higher salinity in July than in August even though there was more fresh water in Lake Melville during the month of July. This may be a consequence of the long flushing times as previously calculated.

A comparison of the data in August 1952 and August 1981 shows that the salinity of the water in the upper 30 m was 1 to 2 parts per thousand higher in 1981 than in 1952, even though there was slightly more fresh water in Lake Melville during 1981. This variation was expected due to the lower discharge rate from the Churchill River during the summer of 1981 than before development, resulting in a lower volume of water flowing from Lake Melville to Groswater Bay. This information adds to the previous results that additional fresh water in Lake Melville is not readily transferred out of the fjord.

The temperature in the upper 30 m in 1979 and 1981 was 0 to 1 degrees colder than in August 1952, and below 30 m the reverse occurred. This slight difference is insignificant for this location, and within the range of normal yearly variations. The high temperature of approximately 4°C throughout the water column on October 6, 1952 indicates the onset of convective overturn which occurs in coastal regions during autumn.

WATER STRUCTURE IN GROSWATER BAY

In August 1981, the water properties in Groswater Bay were sampled at stations BB-8 and BB-9, located offshore West Pompey Island and Bluff Head, respectively. The water properties at station BB-8 sampled on August 20, 1981 were compared with those at station BD-85, sampled on August 24, 1951. At this station in 1981, the water was slightly colder and had a slightly lower salinity than in 1951 (Fig. 4.2). This feature was also evident at station BB-9 when compared with station BD-98, sampled on August 27, 1952 (Fig. 4.3).

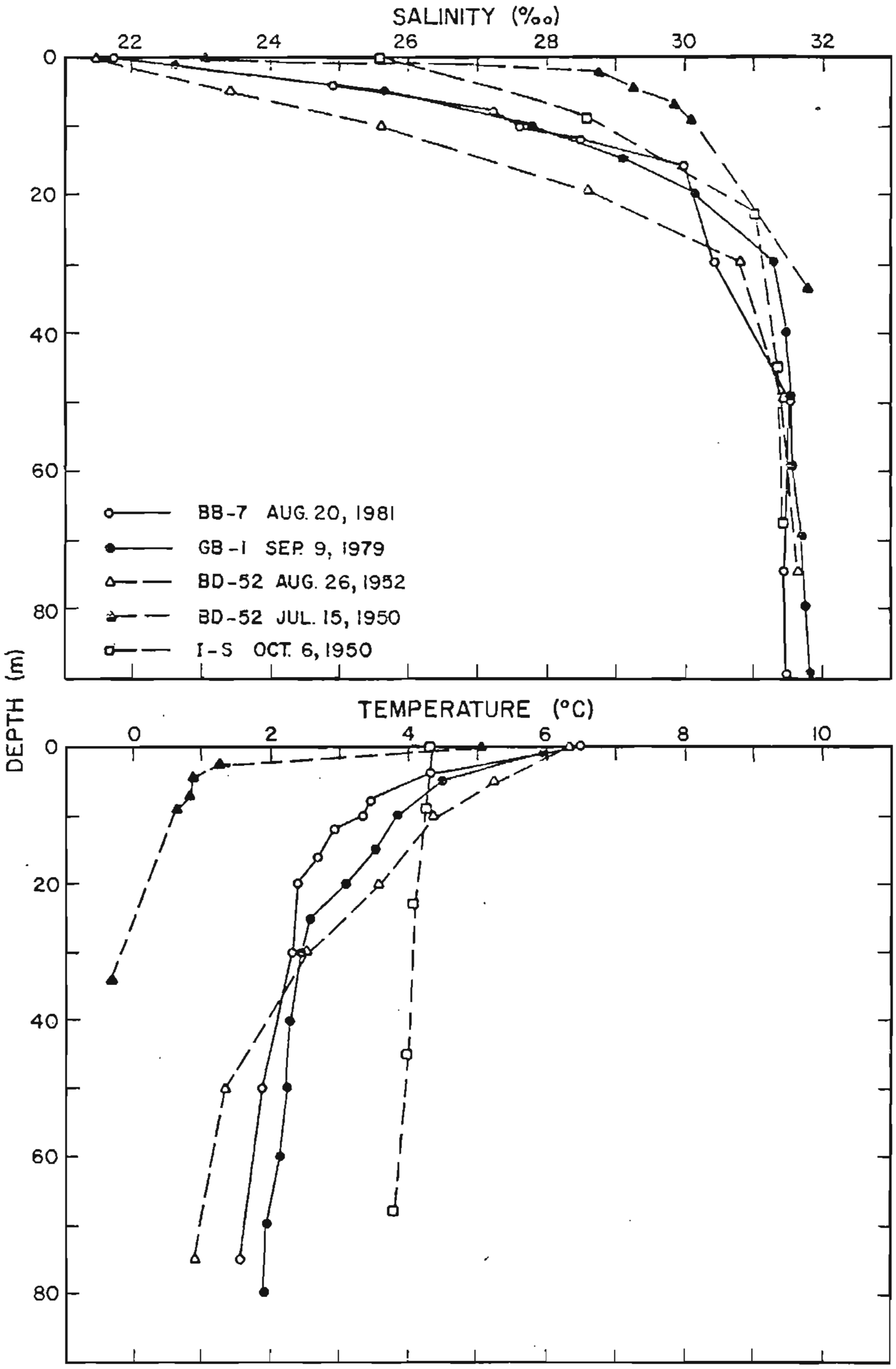


FIGURE 4·1
SALINITY AND TEMPERATURE PROFILES OUTSIDE THE NARROWS

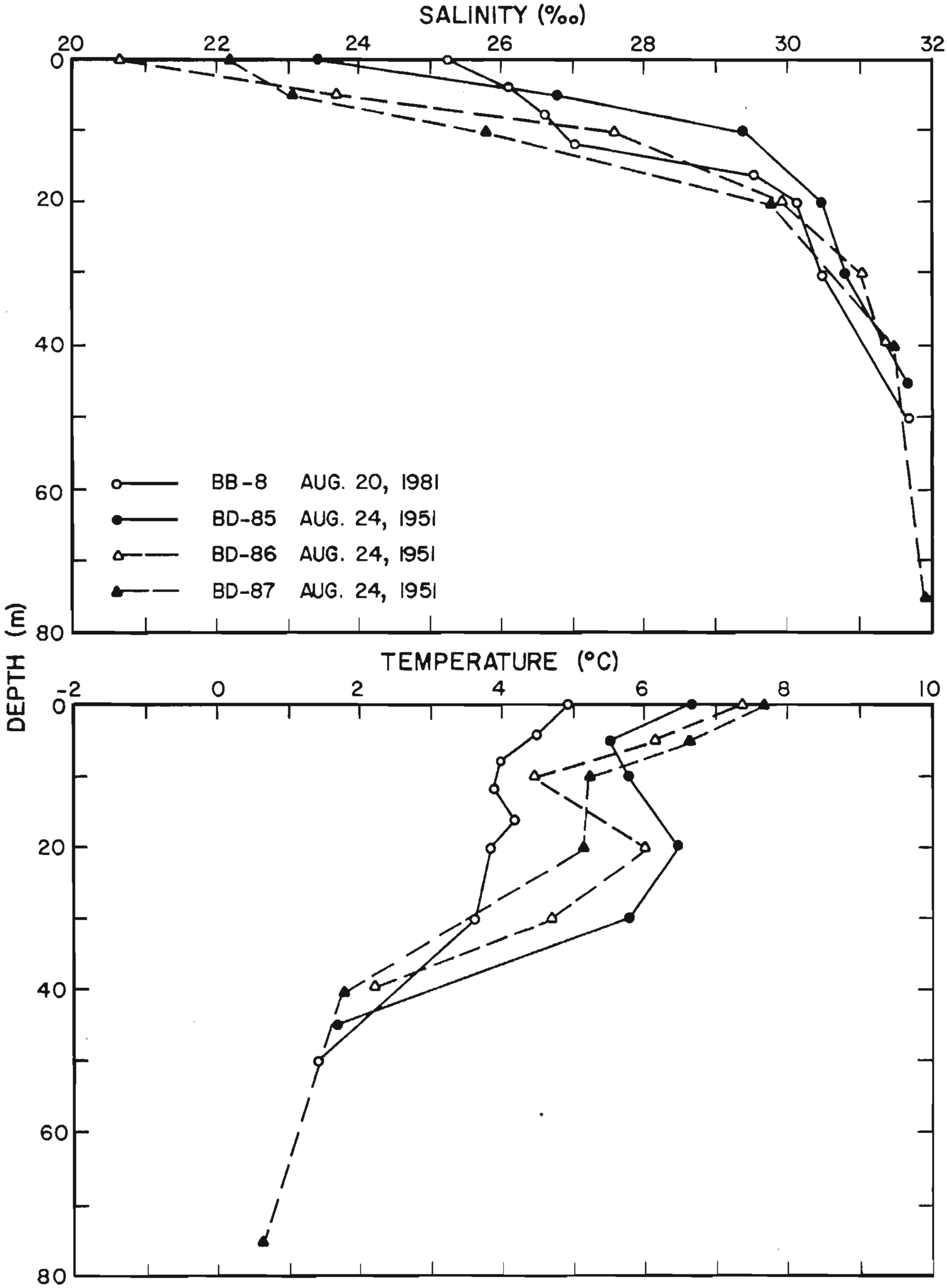


FIGURE 4·2

SALINITY AND TEMPERATURE PROFILES FOR STATION BB-8 (1981) AND FOR THE WEST POMPEY ISLAND SECTION (1951)

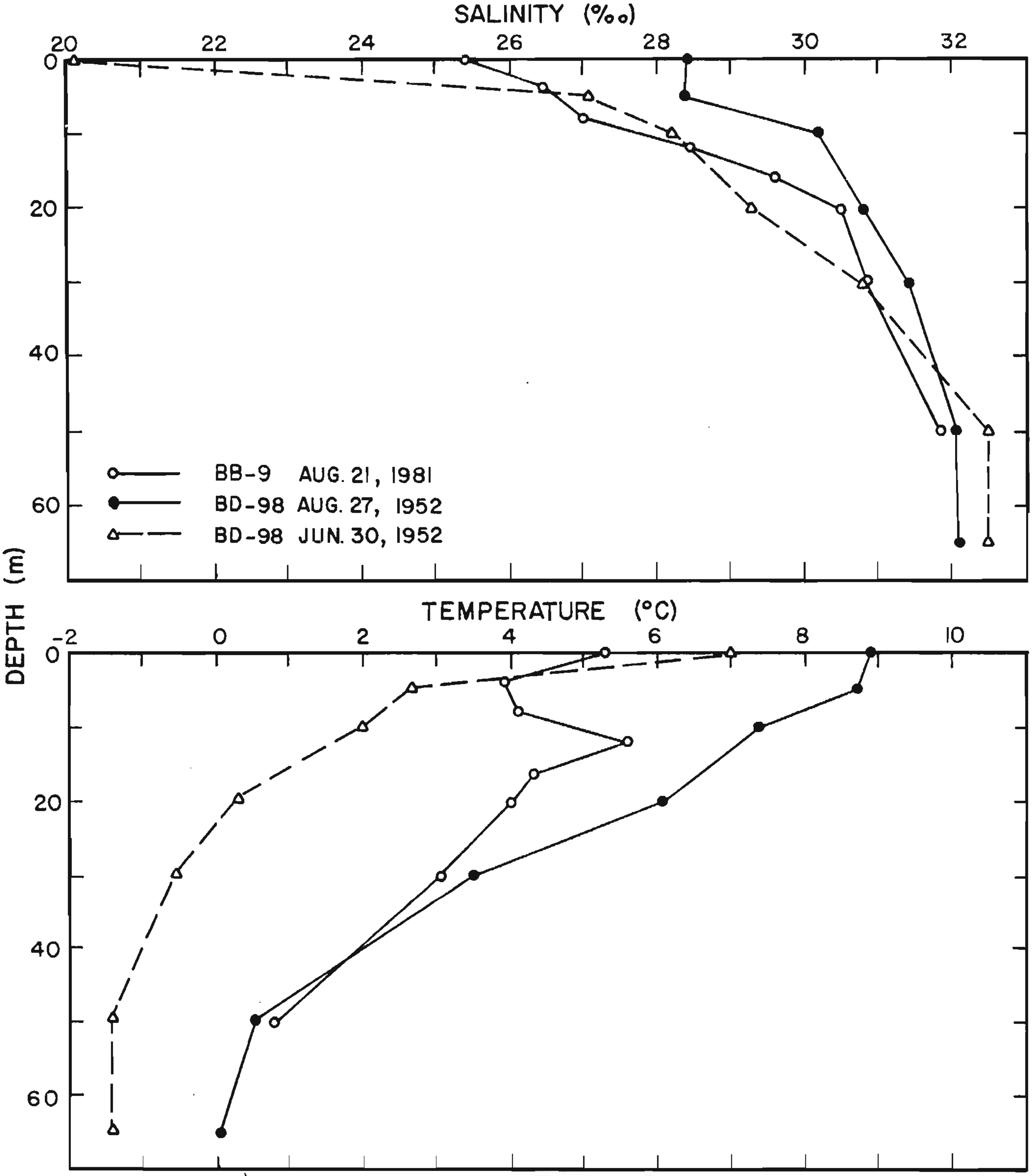


FIGURE 4·3

COMPARISON OF SALINITY AND TEMPERATURE PROFILES AT STATION BB-9 (1981) AND STATION BD-98 (1952)

Figure 4.2 also shows profiles of temperature and salinity at three stations along a cross-section of Groswater Bay, offshore Pompey Island. The profiles show that in a direction from north to south, the water becomes slightly colder and has a lower salinity indicating that the influence of the Churchill River is felt more strongly along the southern shore. This feature is also evident in Fig. 4.4 which presents profiles of temperature and salinity along a cross-section at the mouth of Groswater Bay, in the vicinity of George Island.

The profiles for the outer cross section between Cape Porcupine and White Bear Islands are shown in Fig. 4.5. Again, all profiles show that the water above a depth of 30 m tends to decrease in salinity from north to south, clearly showing that the Churchill River can influence the water properties as far south as Cape Porcupine, the most southerly station in the data set for this area. Through mixing at the Narrows, the temperature of the Lake Melville mixed water was less than that at the other stations further north where the influence of the fjord water could not be detected.

VARIATIONS IN WATER PROPERTIES IN THE VICINITY OF PACK'S HARBOUR

The water properties at station BD-88 (located offshore Cape Porcupine), sampled on June 29, and August 28, 1952, where compared with those measured near Pack's Harbour on the same dates in 1981 by LGL Limited. The profiles of temperature and salinity in Fig. 4.6 show striking differences in both parameters. For June 29, the temperatures were similar but the salinities were 1 to 2 parts per thousand higher in 1981. By August 28, the salinity throughout the water column had increased and showed a difference of 1.5 to 5.5 parts per thousand as compared with station BD-88 in 1952. Below 15 m, the temperature was 1 to 4 degrees warmer in 1981. Some of this difference may be attributed to geographical location because the station near Pack's Harbour was located approximately 25 km southeast (but downstream) of station BD-88. Since the water properties found outside the Narrows could be traced for 75 km, similar properties should have been sampled at Pack's Harbour in the absence of mixing with a more dominating water mass.

Figure 4.7 shows the T-S curves of the water properties sampled at four stations in 1952 and station 7 at Pack's Harbour in 1981. The four stations presented in this diagram were located along the southern shore of Groswater Bay from just outside the Narrows to Cape Porcupine. The four stations show mixing within the upper 20 m between the fresher fjord water and saltier sea water, and below 30 m the salinities were comparable at all stations. The T-S curve of the measurements from Pack's Harbour show a different water mass. At this location the water is warmer and saltier. This implies that variations in the water properties and structure near Pack's Harbour are more dependant on mixing with some other water mass than with the water from Groswater Bay. Warm, high salinity water is a characteristic of the water mass along the continental slope and in the troughs of the Labrador Shelf, such as the Cartwright Saddle.

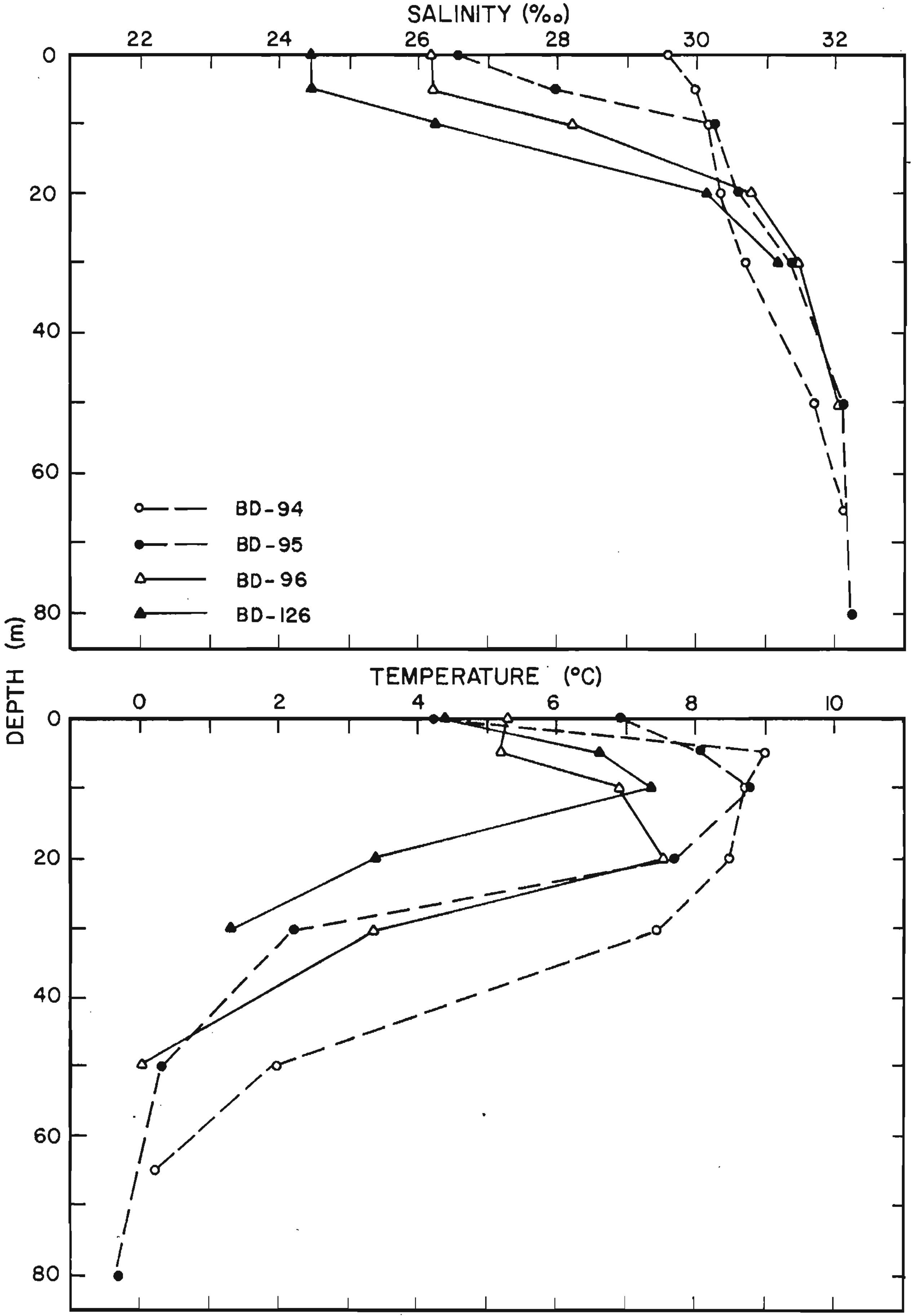


FIGURE 4·4

SALINITY AND TEMPERATURE PROFILES FOR THE GEORGE ISLAND SECTION ON AUGUST 27, 1952

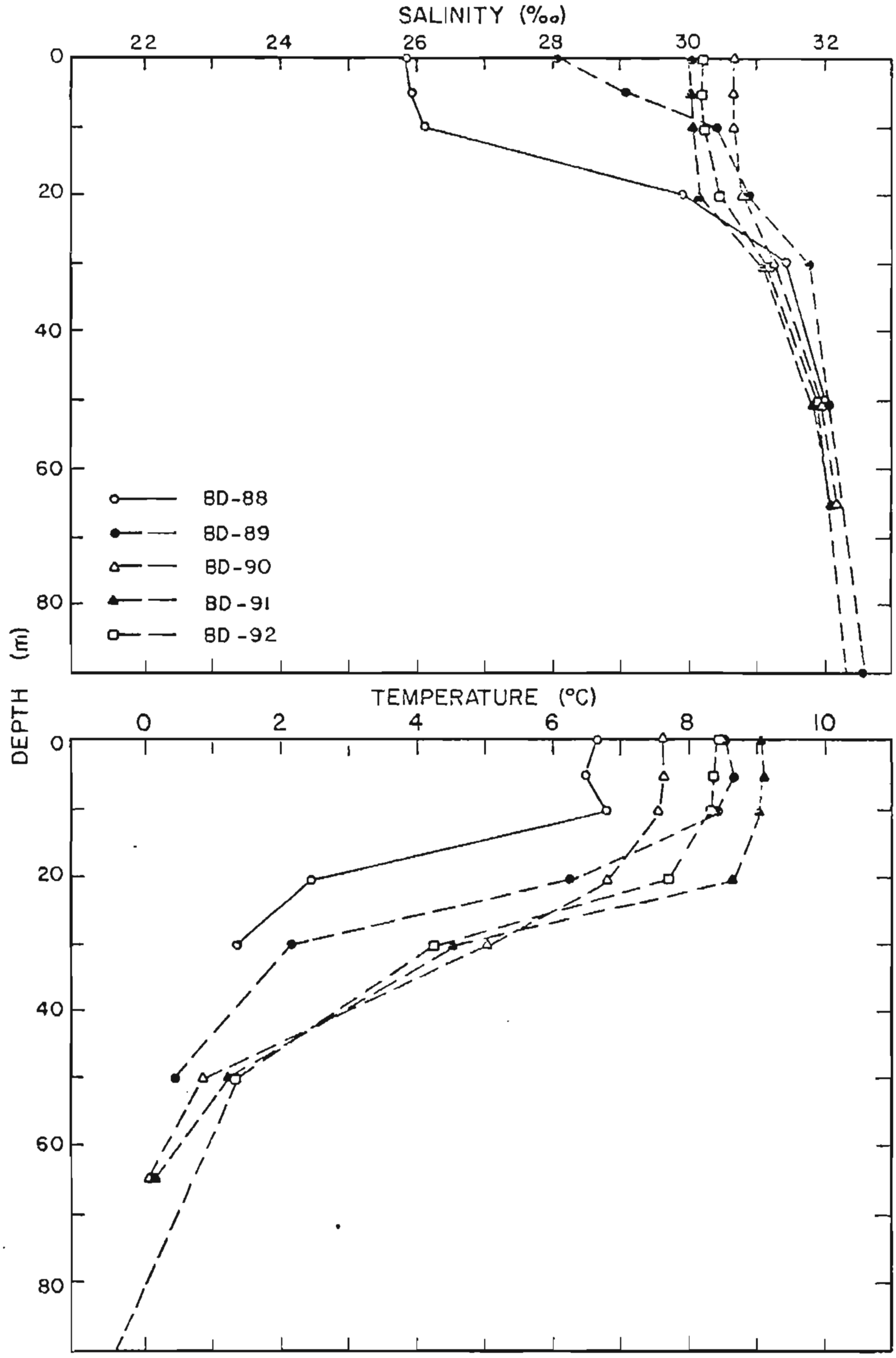


FIGURE 4·5

SALINITY AND TEMPERATURE PROFILES FOR THE OUTER SECTION (CAPE PORCUPINE TO WHITE BEAR ISLAND) ON AUGUST 28, 1952

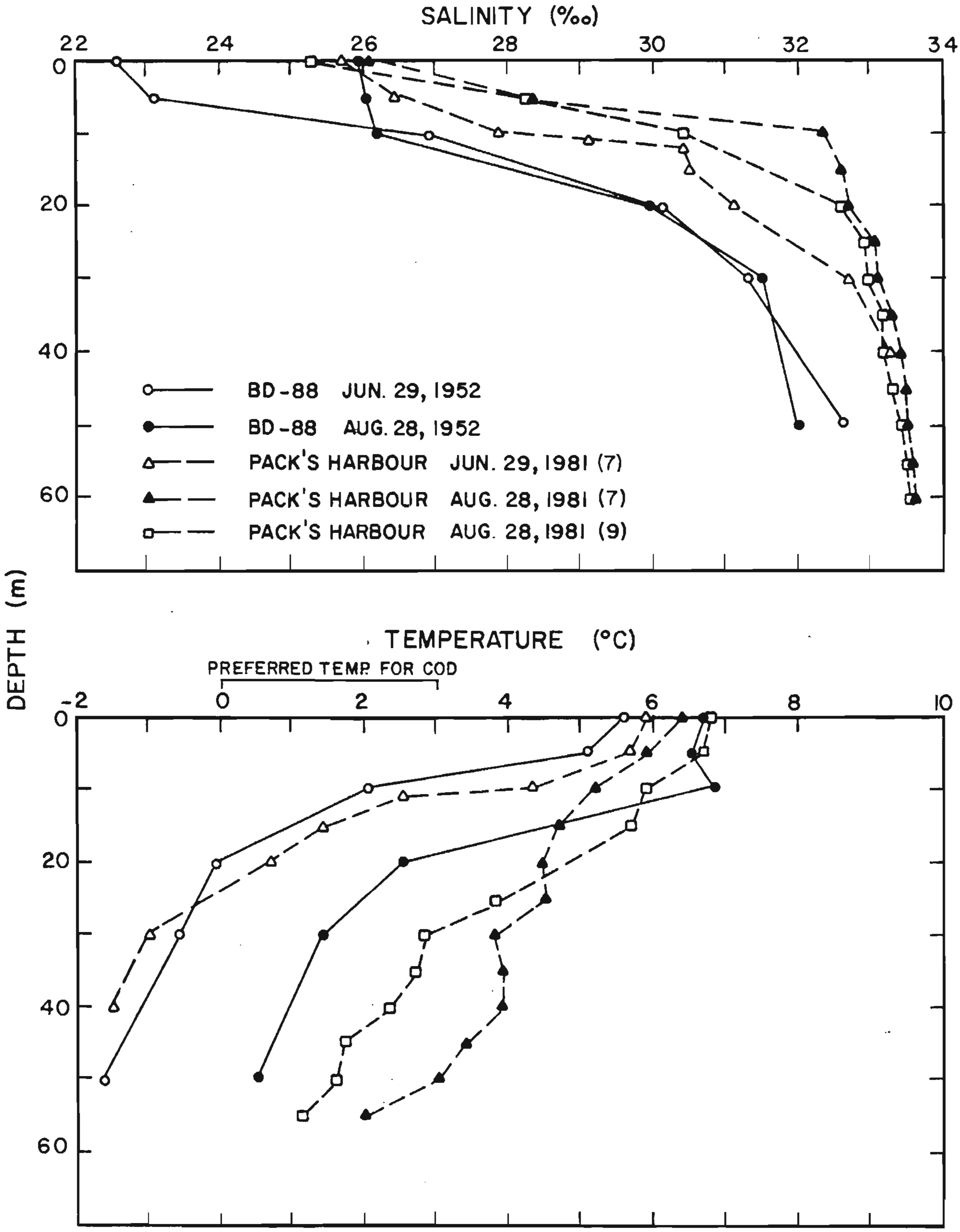


FIGURE 4·6

COMPARISON OF DATA AT BD-88 (1952) AND PACK'S HARBOUR (1981)

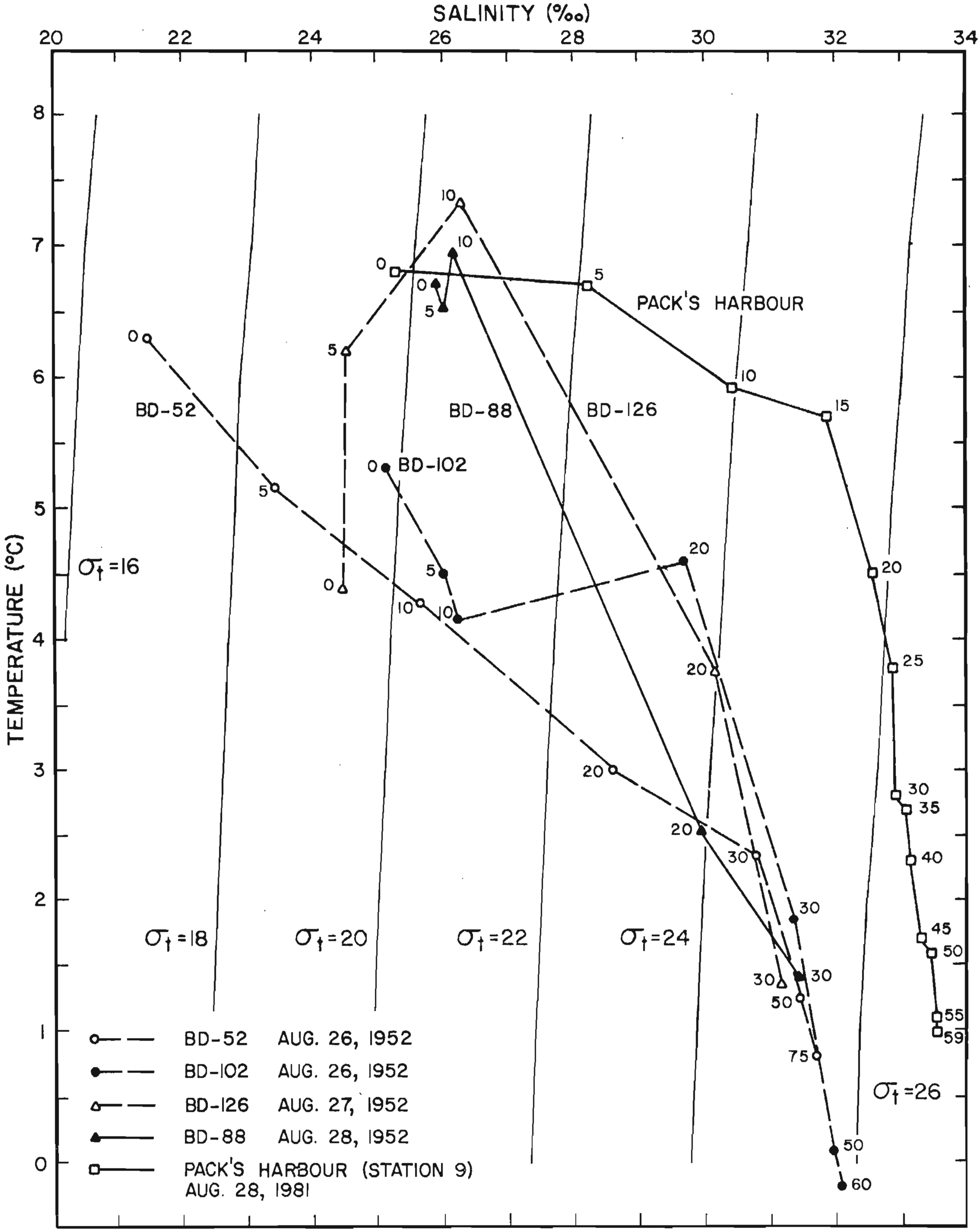


FIGURE 4·7

T-S CURVES OF WATER PROPERTIES FROM OUTSIDE THE NARROWS TO CAPE PORCUPINE (1952) AND PACK'S HARBOUR (1981)

CONCLUSIONS

SUMMARY OF RESULTS

This study demonstrates conclusively that variations in freshwater discharge do not alter the water properties in Groswater Bay during the summer months. Measurements made in Hamilton Inlet during the early 1950's and in August 1981 were compared to reach this conclusion.

The freshwater discharge has changed since the completion of the Churchill development in 1971. The freshwater flow has significantly increased during the winter and decreased during the summer. From December to April, the flow rates of the Churchill River have approximately tripled and during June and July they have decreased by about 30%. The overall quantity of freshwater has increased by about 300 m^3/sec. due to the diversion of water which originally flowed into the Kanairiktok River.

The fresh water volume in Lake Melville was found to be comparable in August 1981 to that during the months of July and August in the early 1950's. There was slightly more fresh water in August 1981, 41 km^3 as compared with 35 km^3 in August 1952. However, the river discharge in August 1981 was 2,739 m^3/sec compared with 3,598 m^3/sec in August 1952. This indicates that even though there was slightly more fresh water in Lake Melville, this extra water does not get transferred to Groswater Bay. This was confirmed by salinity profiles at a station located just outside the Narrows. The residual time of the fresh water in Lake Melville was calculated and found to vary from 3.6 to 4.7 months in the early 1950's and 5.8 months in August 1981. These long flushing times indicate that Lake Melville acts as an effective filter between variations in river flow and changes in Groswater Bay.

Salinity profiles of the near surface water throughout Lake Melville were compared to look for changes in the salinity structure. The profiles showed that the water structure was similar at all locations. At specific depths, the salinity of the water did not noticeably increase from head to mouth as normally found in most fjords. This indicates that horizontal advection and turbulent mixing are more important than vertical mixing by entrainment. To find out whether river water was being mixed into the deeper waters of the fjord, deep water exchange was addressed. The analysis showed that that water below sill depth did not have the properties of the summer water in Groswater Bay, and that this deep water could only be formed during autumn and winter months.

An investigation of the circulation which may occur in the Narrows showed that the transport through the Narrows was not limited by a phenomenon called overmixing. However, the geometry of the Narrows severely restricts the tidal inflow such that the tidal height in Lake Melville is about one fifth of that in adjacent coastal waters. The Narrows is also an area of intense mixing where the low salinity surface water of Lake Melville becomes mixed with sea water from Groswater Bay. This mixing results in producing a higher salinity in the surface water of Groswater Bay than would otherwise exist. In addition, the currents in the Narrows are strong enough to produce supercritical flow and jet streams on both sides of the sill, providing energy for turbulent mixing. The Narrows controls the flow out of Lake Melville and prevents fluctuations in river flow from being transferred to Groswater Bay and farther south.

A comparison of the water properties in Groswater Bay shows that in the region outside the Narrows, the water structure was similar in August 1981 to that in the early 1950's. If there had been changes in Groswater Bay due to the regulation of the Churchill River, these changes would have been most noticeable at this station. Lower salinity water was found along the southern shore of Groswater Bay compared to other locations in Groswater Bay, and this water could be traced as far south as Cape Porcupine, the most southerly station in the 1950's data set for this area. This indicates that if the Narrows did not act as a control on the circulation in Lake Melville, there would definitely be changes in the Groswater Bay area due to fluctuations in freshwater discharge, thus justifying the fishermen's concern.

At Pack's Harbour in 1981, the water properties are significantly different than those found offshore Cape Porcupine in 1952. T-S curves of the water properties at Pack's Harbour and for locations along the southern shore of Groswater Bay show striking differences, and indicate that at Pack's Harbour the water properties are dependant on mixing with some other water mass than with the water from Groswater Bay.

RESPONSE TO FISHERMEN'S OBSERVATIONS

In September 1981, interviews were made with fishermen of the Pack's Harbour area to get their personal opinions of environmental conditions which may be affecting the poor inshore fishery of this area. These opinions and observations are outlined in an unpublished document (Saunders 1981) produced by an OLABS field worker in Happy Valley, Labrador. Since these observations offer clues to the source of the problem, comments on the observations and opinions, with respect to physical oceanographic parameters, will be presented in this section.

The most interesting view was that the inshore currents had changed since the late 1960's. An increased number of large icebergs inshore is one indicator of this change in currents. The observations reflect the possibility that the current system on the Labrador Shelf has changed in response to climatic variations. The 1970's have been a period of increased wind strengths and low atmospheric pressures. Conceivably, the Pack's Harbour area could be sensitive to climate change due to its location inshore of the Cartwright Saddle, an area where the ratio of the two dominating water masses may alter. Unfortunately, the circulation on the Labrador Shelf is not well understood, so that the effects of climatic variations are difficult to assess.

It was a common feeling among fishermen that during recent years there have been more northerly winds during July. This can be easily verified by an analysis of the local wind conditions measured by the Cartwright weather station. Changes in local wind conditions would affect the hydrographic properties of the shallow waters.

Most fishermen felt that the tides are changing. Since tides are an astronomical phenomenon and predictable, this observation may be related to changes in water levels due to storm surges.

The observation that there was more ice in the 1970's coincides with present knowledge, with 1972 and 1974 being extreme years. Most of the observations point to climate change rather than changes resulting from the Churchill development, but since the construction on the Churchill River coincided with changes in climate, it is understandable for fishermen to question the influence of the Churchill development.

Changes in water colour and the absorption of radiation were not addressed in this study due to a lack of recent measurements. Secchi disc observations are available from the Blue Dolphin expeditions so that any future measurements can be compared. It is quite possible that the turbidity or colour of the surface water in Lake Melville has been altered, but it is doubtful whether this could have much affect at Pack's Harbour, since the dominating water mass at Pack's Harbour does not originate from Hamilton Inlet.

ACKNOWLEDGEMENTS

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APPENDIX 1: BOTTLE DATA COLLECTED ABORD THE <u>BURIN BAY</u> DURING AUGUST 19-21, 1981

Station: BB-1 (53°32.3'N, 60°21.5'W)
Time (GMT): 1715, August 19, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	1.73	14.93	0.51
4.0(1)	3.59	13.95	2.08
8.0(1)	4.83	12.97	3.18
12.0(1)	4.65	13.02	3.04
16.0(1)	16.16	5.76	12.78
20.0(1)	22.70	1.77	18.19
24.0(1)	22.78	1.61	18.26
24.0(2)	14.32	12.58	10.56
44.0(2)	26.44	0.20	21.24
69.0(2)	25.43	1.21	20.39

Station: BB-2 (53°42.0'N, 59°45.2'W)
Time (GMT): 2100, August 19, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	4.65	14.44	2.83
6.0(1)	4.98	13.21	3.26
12.0(1)	13.09	13.85	10.20
16.0(1)	18.19	4.27	14.48
15.9(2)	4.65	13.85	2.92
19.8(2)	6.84	12.04	4.86
29.8(2)	19.54	4.06	15.56
49.6(2)	24.36	1.11	19.54
74.4(2)	26.05	0.39	20.92
23.1(2)	26.86	0.02	21.58

Station: BB-3 (53°44.1'N, 59°22.2'W)
Time (GMT): 2300, August 19, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	5.57	13.99	3.61
4.0(1)	5.76	13.84	3.78
8.0(1)	7.14	11.89	5.11
12.0(1)	11.60	8.36	8.98
16.0(1)	18.90	3.46	15.09
20.0(1)	22.17	1.81	17.76
30.0(2)	23.06	1.44	18.49
50.0(2)	25.53	0.62	20.49
75.0(2)	26.56	0.14	21.33
100.0(2)	27.30	-0.22	21.94
150.0(2)	27.59	-0.58	22.18
193.0(2)	27.74	-0.79	22.31

Station: BB-4 (53°52.2'N, 58°59.4'W)
Time (GMT): 1240, August 20, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	4.34	13.65	2.71
4.0(1)	4.34	13.71	2.70
8.0(1)	8.64	10.74	6.42
12.0(1)	11.53	8.84	8.88
16.0(1)	16.75	6.38	13.19
20.0(1)	20.27	3.78	16.15
30.0(1)	24.08	1.37	19.31
50.0(2)	25.27	0.75	20.28
75.0(2)	26.35	0.26	21.16
100.0(2)	27.11	-0.13	21.78
150.0(2)	27.47	-0.60	22.08
200.0(2)	27.56	-0.72	22.16
240.0(2)	27.80	-0.89	22.36

Station: BB-5 (53°57.1'N, 58°53.1'W)
Time (GMT): 1645, August 20, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	5.08	13.58	3.29
3.8(1)	7.67	11.62	5.56
7.5(1)	9.64	10.53	7.22
11.3(1)	13.36	8.09	10.38
15.0(1)	20.37	5.49	16.11
18.1(2)	20.77	5.31	16.44
18.8(1)	21.70	4.82	17.21
27.2(2)	23.31	3.13	18.60
45.3(2)	25.06	1.29	20.09
68.0(2)	26.61	0.12	21.37
90.6(2)	27.16	-0.13	21.82
135.9(2)	27.60	-0.60	22.18

Station: BB-6 (54°01.3'N, 58°35.0'W)
Time (GMT): 1745, August 20, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	7.73	12.34	5.51
3.9(1)	7.79	12.39	5.47
7.9(1)	12.96	9.21	9.95
11.8(1)	15.40	7.98	11.98
15.8(1)	17.11	7.10	13.41
19.7(1)	21.22	5.20	16.80
29.5(1)	23.06	4.28	18.32
43.3(2)	25.62	1.85	20.51
65.0(2)	27.17	0.52	21.81
86.6(2)	27.42	0.20	22.02
129.9(2)	27.62	-0.04	22.19
173.2(2)	27.66	0.28	22.21
207.8(2)	27.66	0.30	22.21

Station: BB-7 (54°14.5'N, 58°11.7'W)
Time (GMT): 2040, August 20, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	21.68	6.44	17.05
4.0(1)	25.02	4.24	19.88
8.0(1)	27.27	3.34	21.73
10.0(2)	27.62	3.32	22.01
12.0(1)	28.53	2.85	22.77
16.0(1)	30.12	2.86	24.03
20.0(2)	30.14	2.79	24.06
30.0(2)	30.39	2.28	24.29
50.0(2)	31.46	1.82	25.17
75.0(2)	31.38	1.44	25.13
90.0(2)	31.43	1.41	25.17

Station: BB-8 (54°17.7'N, 57°56.2'W)
Time (GMT): 2215, August 20, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(2)	25.27	4.99	20.01
4.0(2)	16.11	4.48	20.72
8.0(1)	26.61	4.07	21.15
12.0(1)	27.08	3.89	21.53
15.9(1)	29.50	4.18	23.43
19.9(1)	30.10	3.85	23.94
29.9(1)	30.46	3.65	24.24
49.8(1)	31.68	1.42	25.37

Station: BB-9 (54°20.7'N, 57°37.9'W)
Time (GMT): 1215, August 21, 1981

Depth	Salinity	Temperature	Sigma-t
1.0(1)	25.43	5.29	20.11
4.0(1)	26.45	3.88	21.04
8.0(1)	27.03	4.10	21.48
12.0(1)	28.47	5.60	22.48
12.0(2)	26.95	4.04	21.43
16.0(1)	29.51	4.28	23.43
16.0(2)	28.82	5.82	22.72
20.0(1)	30.44	3.74	24.21
20.0(2)	29.53	4.34	23.44
30.0(2)	30.80	3.06	24.56
50.0(2)	31.79	0.80	25.50

Note: (1) - 1st bottle cast
(2) - 2nd bottle cast.