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THE EXCHANGE OF DEEP WATER IN ALBERNI INLET

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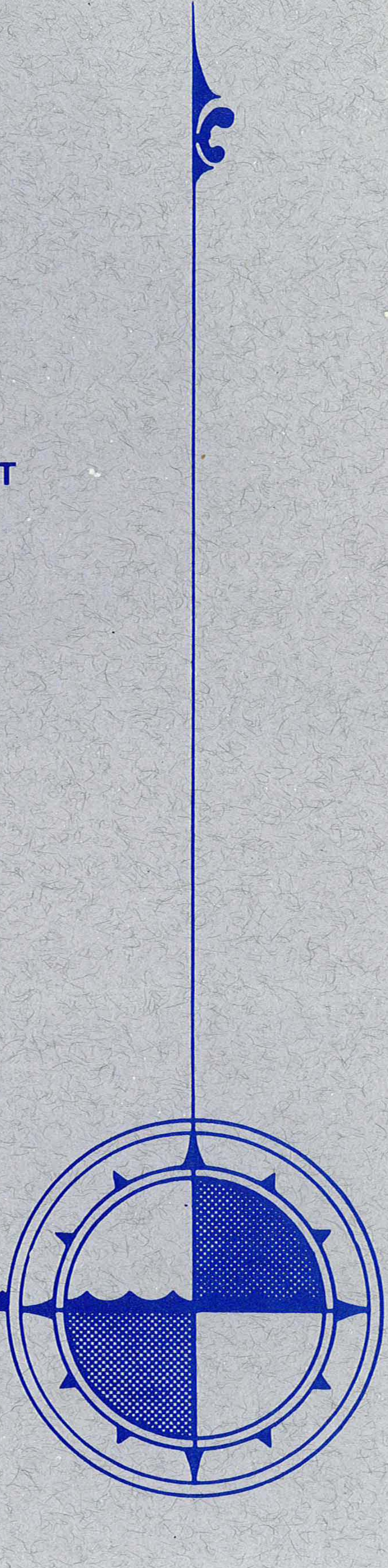

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THE EXCHANGE OF DEEP WATER IN ALBERNI INLET

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ABSTRACT

The deep water in Alberni Inlet appears to undergo renewal on an annual basis, with the replacement water arising from upwelling on the west coast. Available water property data are examined via time series plots and temperature-salinity diagrams for evidence to support this theory.

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INTRODUCTION

Alberni Inlet is located on the west coast of Vancouver Island, connecting with the Pacific Ocean through both Trevor Channel and Imperial Eagle Channel (Fig. 1). The total length is about 69 km, whichever channel is followed, and the mean width is about 1.3 km (Pickard, 1963). The system comprises a comparatively small inner basin at the east end of Alberni Inlet and a much larger outer basin extending westward to the ocean. The inner and outer basins are separated by a shallow sill at a depth of about 37 m, in the vicinity of Sproat Narrows. The extreme westerly end of the outer basin is separated from the ocean by another shallow sill, at a depth of about 40 m. However, there is a deeper waterway between the outer basin and the Pacific Ocean, via Imperial Eagle Channel and Junction Passage, where the shallowest depth is about 88 m. Junction Passage connects to Trevor Channel near the mid-point of the outer basin.

The harbour area immediately adjacent to Port Alberni, at the eastern end of the system, has been extensively studied for many years because of the existence of a pulp mill in that area. Much research has also been done in relation to the near-surface water of the inner basin, because the mill effluent is dispersed within this layer. Interest has now been aroused in the exchange of the deep waters in connection with dredge-spoil dump in the inner basin. There have been relatively few measurements actually made in the deep waters of either the inner or outer basin. The data have been due principally to Waldichuk *et al.* (1968), with some earlier measurements obtained by the Pacific Oceanographic Group (1957), and one comprehensive cruise by the Institute of Oceanography at the University of British Columbia (1959).

The data which are available strongly suggest an annual renewal of the deep water in both basins. The likely source of this water is upwelling on the Pacific coast. This phenomenon as a source of water for annual rejuvenation of the outer basin water was suggested as a possibility by Tully (1949). The suggestion was subsequently supported by Pickard (1963) on the basis of some additional observations.

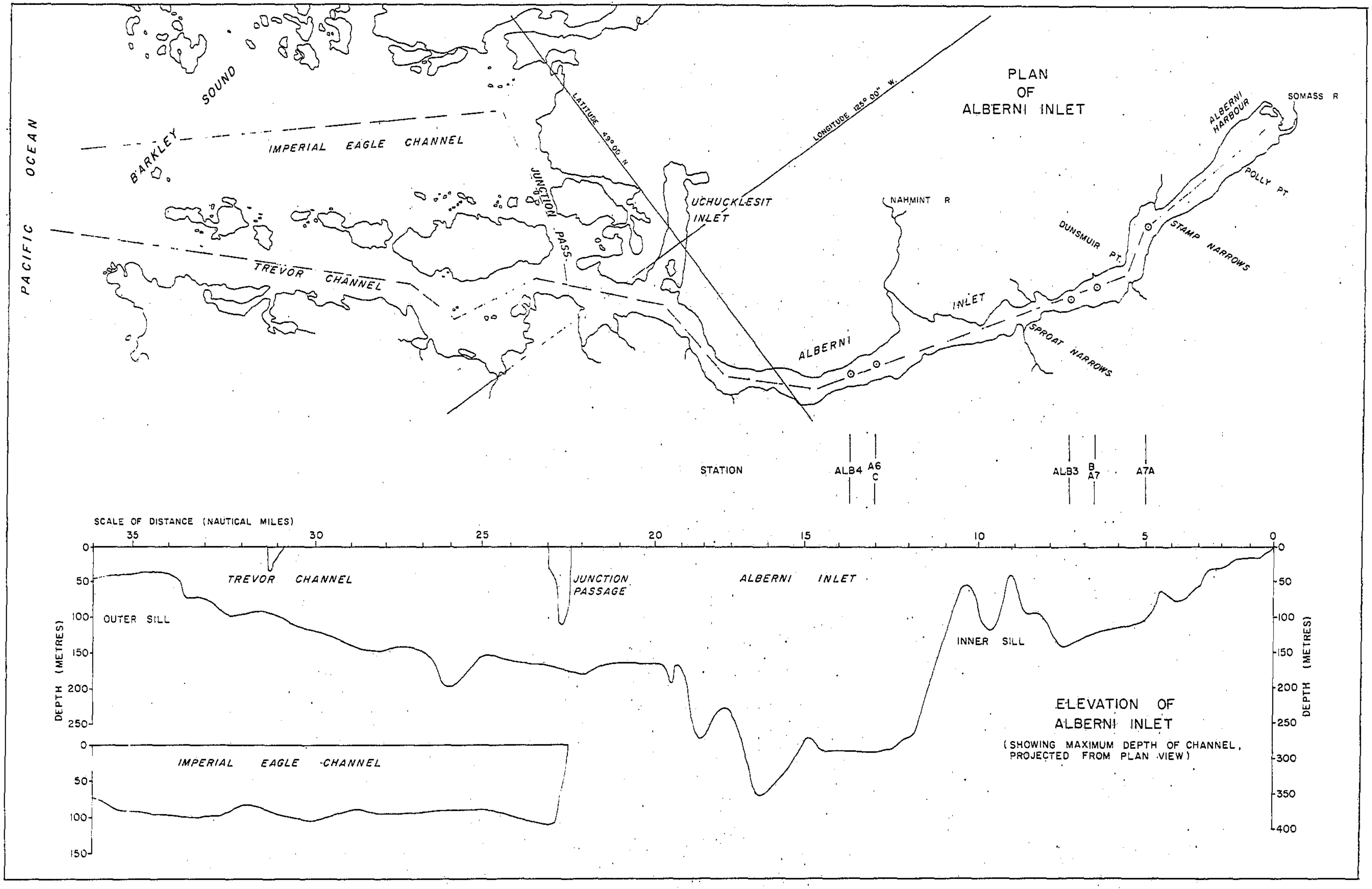

Figure 1. Plan view and longitudinal section of Alberni Inlet, showing station locations.

UPWELLING AS A SOURCE

Upwelling along the west coast of Vancouver Island is known to occur in the summer months, apparently with great regularity, as reported by Tully (1949), Pickard (1953, 1963), Doe (1955) and Lane (1963). Beginning (usually) in the months of April or May and continuing through September, the winds along the coast blow predominantly from the north-west. The stress on the water surface causes a divergence resulting in, after the time lag involved in accelerating large water masses, a net transport offshore. The replacement waters arise in part, at least, from upwelling of the deeper ocean waters.

At some point, the upwelled water, with its relatively higher density, begins running into the outer basin of the inlet system via Junction Passage. It accumulates at a depth appropriate to its density. The resident water in the outer basin is then uplifted and eventually starts flowing into the inner basin, replacing some deep water there. In this case, one would expect a temperature-salinity (T-S) diagram to show that the deep water in the inner basin is the same as water from intermediate depths in the outer basin (providing the data were obtained at the appropriate time). A slight increase in oxygen levels could be expected because the mid-depth water normally contains more dissolved oxygen (DO) than the deeper water. If the process continues for a sufficient length of time, one would expect complete replacement of the outer basin water, below some depth which depends on the magnitude of the upwelling, with nearly homogeneous water having the properties of the upwelled coastal water, i.e. the salinity will be increased and the temperature decreased compared to the water originally resident in the basin. Likewise, there would be an increase in DO to a value which, while still not large, is relatively greater than the previous value. At this point, the "new" water in the outer basin might be in a position to spill over into the inner basin until it, too, becomes homogeneous in the deep water. If the upwelling process is very intense, higher density water should pour into the inner basin via both Junction Passage and the seaward end of Trevor Channel, hastening the exchange process. Since the nature of the upwelling may change somewhat over time, the basin water may not be completely homogeneous and there will likely be some differences in water characteristics between inner and outer basins. However, if complete renewal of deep water in both basins does occur in the same year, one would expect the T-S diagrams to show the same general trend (especially immediately after cessation of renewal) because the water is from the same source.

It is actually possible for upwelling to occur at any time of the year when the wind blows strongly from the north-west for a sufficient length of time. An exchange of basin water at intermediate depths may then occur, depending on the relative densities.

When exchanges are not actively occurring, then other processes take over. In particular, in the deep water, diffusive processes predominate. This results in a gradual reduction of salinity and an increase in temperature, in general. DO is also reduced by diffusion, but the situation here is further complicated by oxidation processes.

EXAMINATION OF TIME SERIES DATA

The first evidence for an annual renewal of inner basin water is shown in Fig. 2, where the available DO data at 100 m depth for eleven different years are plotted on a time axis spanning one year. The data are from a location at or near Stn. A-7A. Monthly values are available for the 1966 period and these are emphasized by connecting them with a solid line. While there is a sparsity of data in the late winter months, the tendency for samples taken during the other seasons, in all of the years, to fall approximately along the same curve is remarkable. This portion of the data represents a period when diffusive processes are holding sway. For each year, if water renewal had not occurred in the preceding spring season, then one would expect the DO in the deep water to have disappeared almost completely (on the basis of the rates of change implied by the data) unless the downward diffusion of oxygen was sufficient to hold it just above an anoxic state.

Similar plots are given for salinity (Fig. 3) and temperature (Fig. 4) at a depth of 100 m. In all of the plots, it is apparent that Alberni Inlet falls into the general behavioural classification of "saw tooth", as given by Pickard (1975) for various other British Columbia inlets, wherein there is an annual variation consisting of a rapid rise of the property values, followed by a slower decline. Especially in the 1966 data, there appears to be a definite lag between the onset of the increase in DO and the increase in salinity or decrease in temperature, as well as in the occurrence of peak values of these properties. A possible explanation for this is suggested below, during the consideration of depth-time plots. However, it should be pointed out here that the lag may not be as pronounced as it first appears to be, with the deception arising from the considerable length of time between samples.

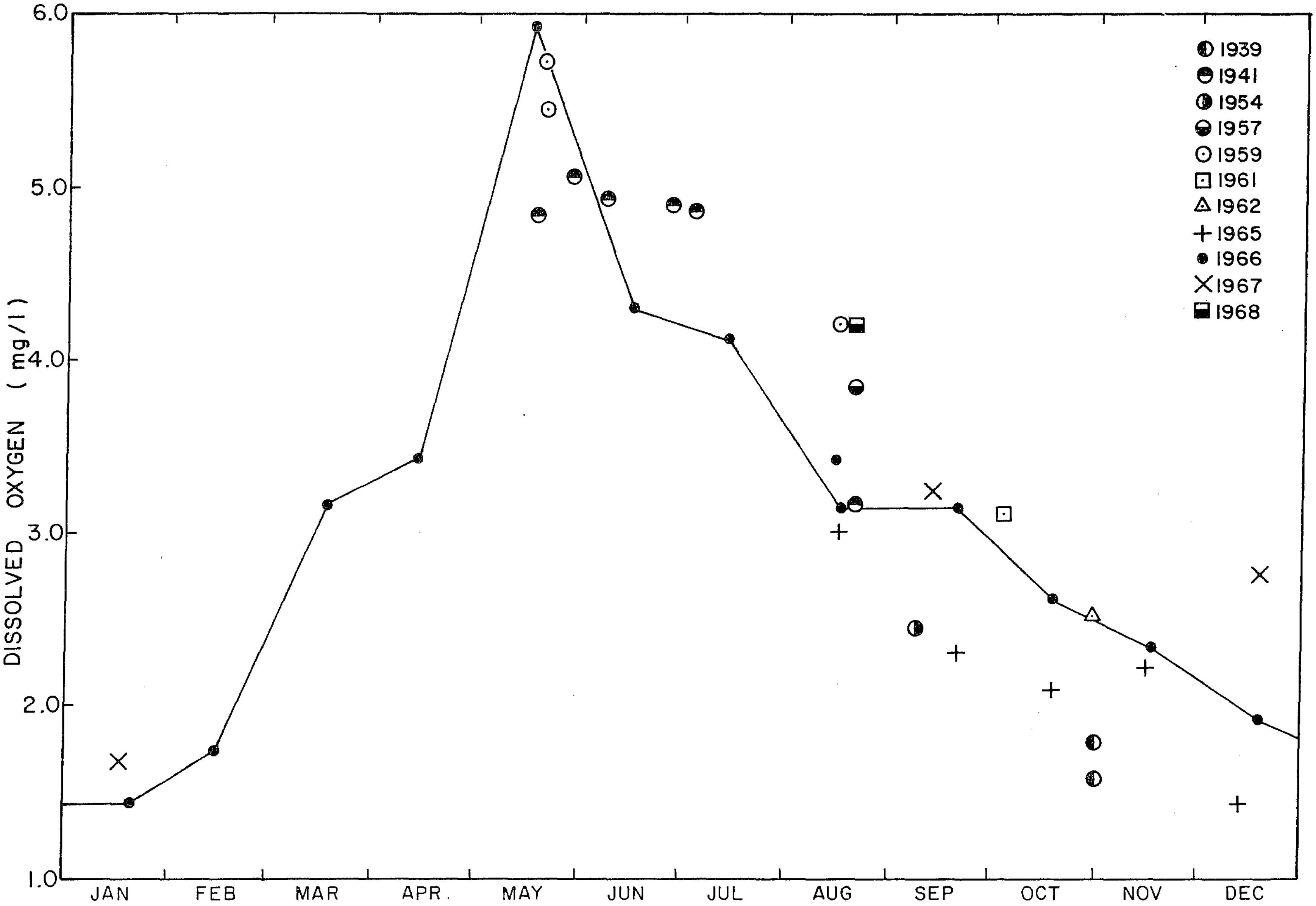

Figure 2. Annual variation of dissolved oxygen at a depth of 100 m in the inner basin of Alberni Inlet, 1939-1968.

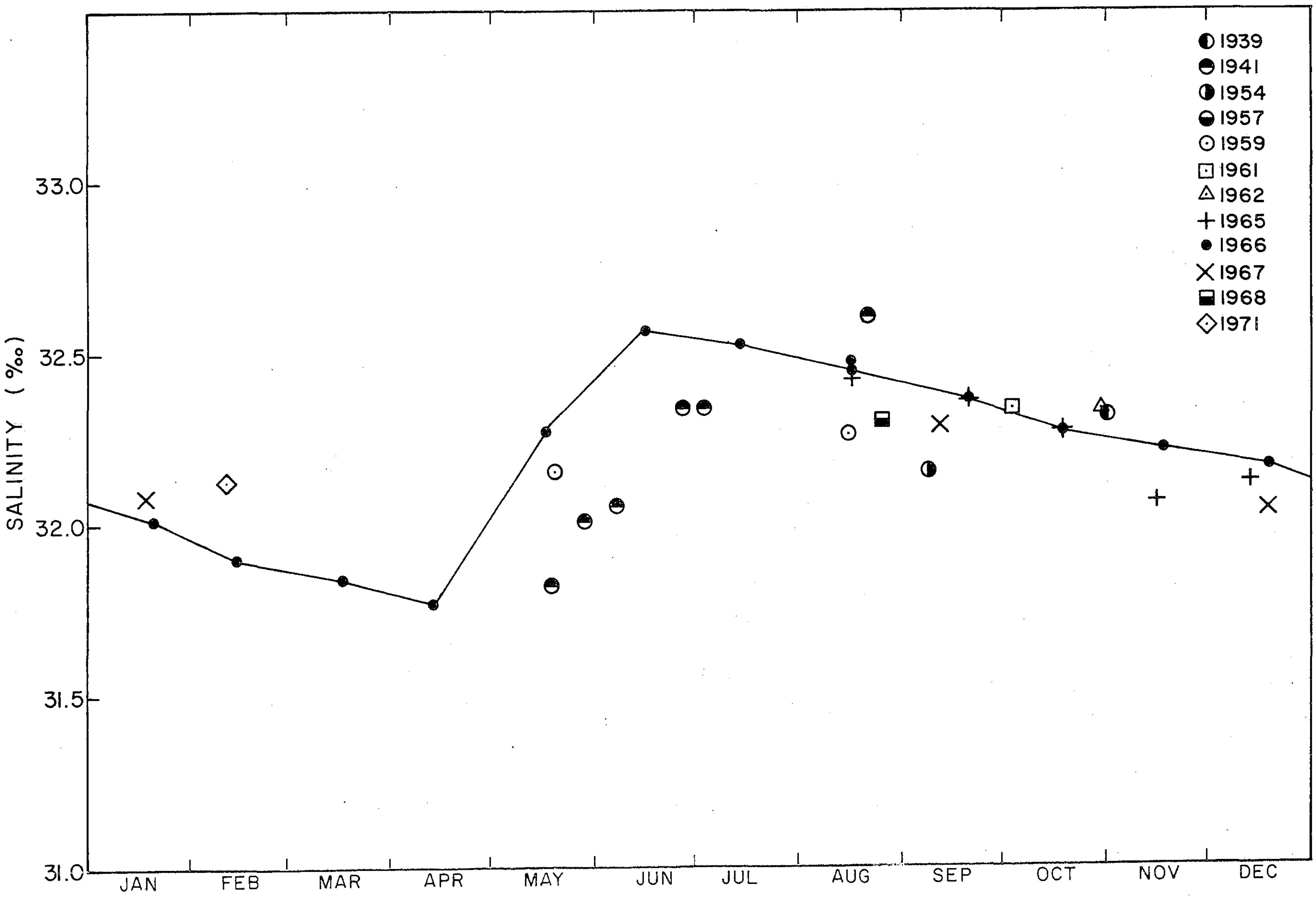

Figure 3. Annual variation of salinity at a depth of 100 m in the inner basin of Alberni Inlet, 1939-1971.

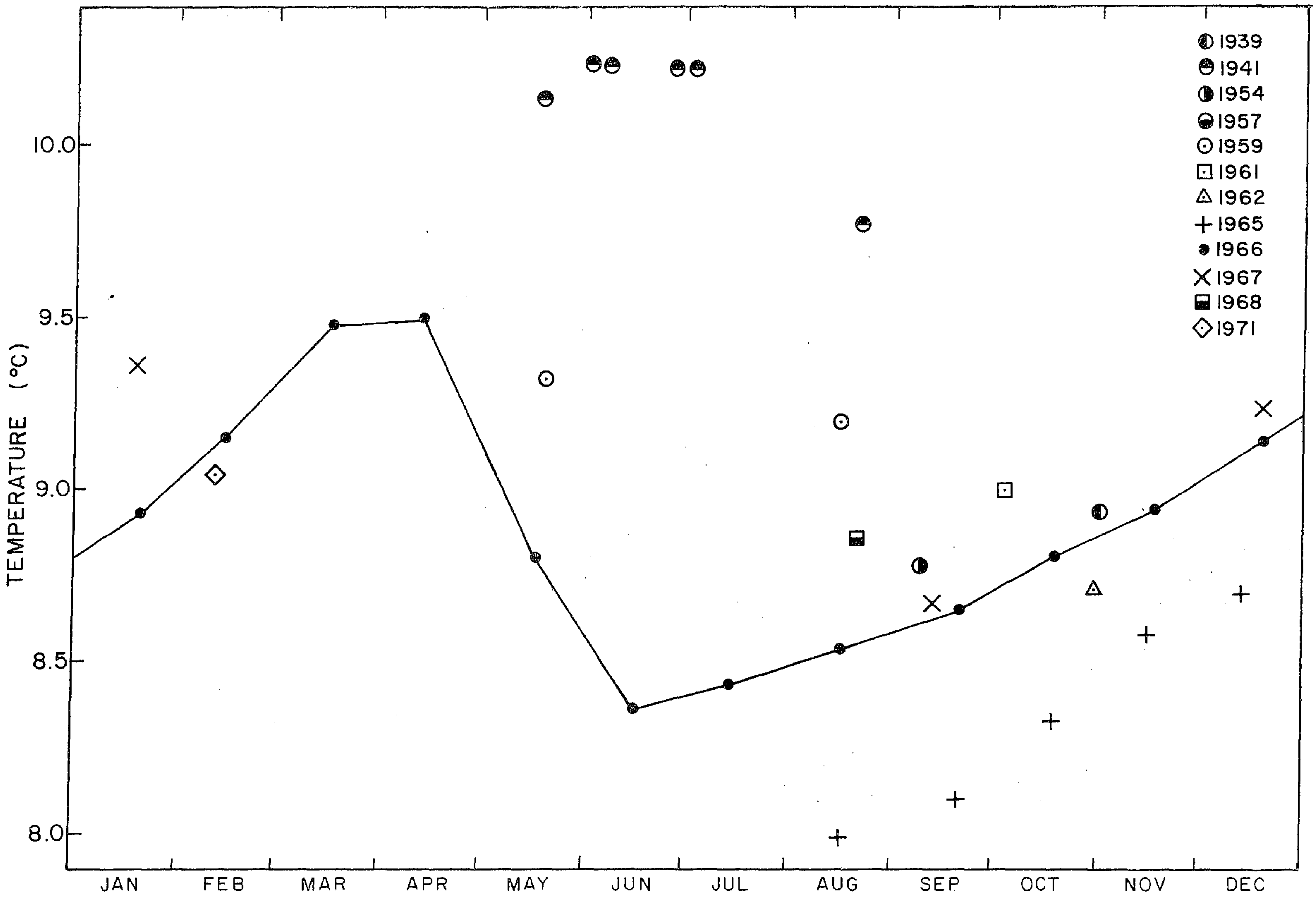

Figure 4. Annual variation of temperature at a depth of 100 m in the inner basin of Alberni Inlet, 1939-1971.

Fig. 5 is a depth-time plot for the density structure at Stn. A-7A in the inner basin, covering the period of July 1965 through January 1967. Density, as exemplified by specific gravity anomaly (sigma-T), generally follows the same trend as salinity. Fig. 6 is a similar plot for DO. These plots are derived from monthly samples at standard depths. At the beginning of the period in 1965, it is clear that there has been a recent renewal of all of the basin water below sill depth because of the relatively high density and because of the homogeneity indicated by both the sigma-T and DO plots. In October 1965, there is an indication of an incursion of water at a depth of about 50 m. This is shown by a slight uplift in the isopleths for both sigma-T and DO, due to the displacement upwards of the lower-density resident water with its particular DO content. In late January and early February of 1966, it is likely that water of approximately the same density as that at a depth of 75 m or so in the inner basin appeared at the sill and began running into the basin. This water had a slightly higher DO content than the resident water. Again, as the influx continued, the less dense water was displaced significantly upwards as shown by the sigma-T contours for 24.0 and less. The 24.5 contour was not affected at this time. The displacement is also shown in the DO contours, where water of relatively low DO content was raised to a much higher position in the water column. These data for Stn. A-7A are consistent with similar data from at least two adjacent hydrographic stations, supporting the supposition that the influxes are real rather than spurious products of aliasing. Given sufficient information about the basin geometry, it would be possible to calculate the approximate volumes of water involved in such mid-depth exchanges.

Moving into the upwelling season, apparently commencing about late March in 1966 and continuing into June, it is apparent from the plots that water of high density and high DO content was coming into the inner basin. At first, the upwelled water was relatively high in DO, increasing the inner basin content to a maximum of 6 mg/ℓ in May. As the upwelling continued even more strongly, bringing up water from greater depths off the west coast, the density was increased but the DO level was reduced. Thus, the density peaked in June, lagging somewhat behind the oxygen peak. At this time, the inner basin water had been completely exchanged, leaving it almost homogeneous below 20 m depth. While actual data is lacking for the outer basin during the same period, it can be assumed from the nature of the process that the outer basin water was also nearly homogeneous over much of its depth. In fact, it probably contained deep water of even greater density than that in the inner basin because of the much greater depth of the passage connecting the outer basin with the open ocean, a postulate supported by an examination of data obtained in August.

In October-November of 1966, a situation analogous to that observed at approximately the same time in the previous year prevailed. An incursion of water had occurred to a depth of about 60-70 m, resulting in a substantial uplift of the water property isopleths. Two sets of data obtained in September and December of 1967 (not shown in the figures) strongly suggest that a major influx also occurred in that year. Certainly, in contrast to the uncertainty about DO sources or sinks, one can only

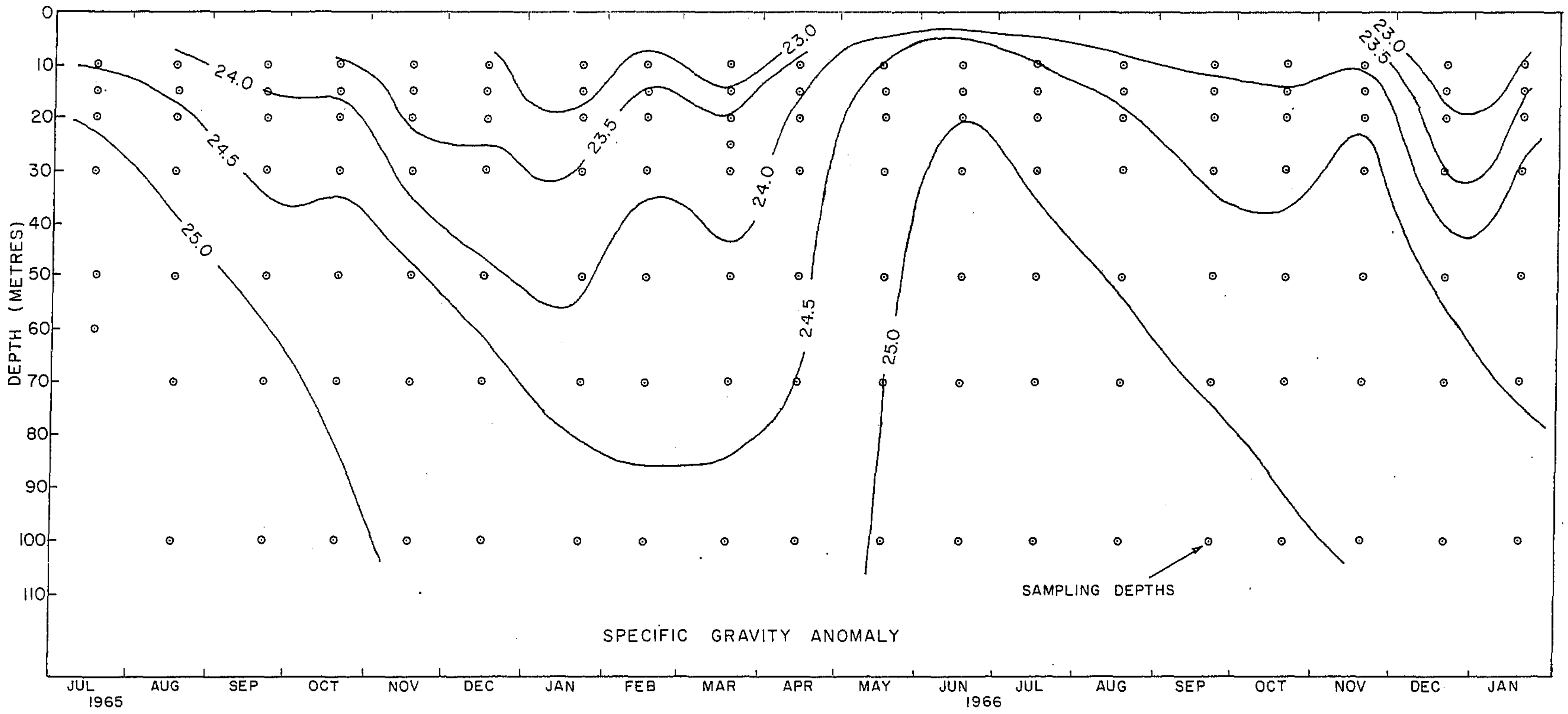

Figure 5. Time-depth contours for specific gravity anomaly at Stn A-7A, 1965-1966.

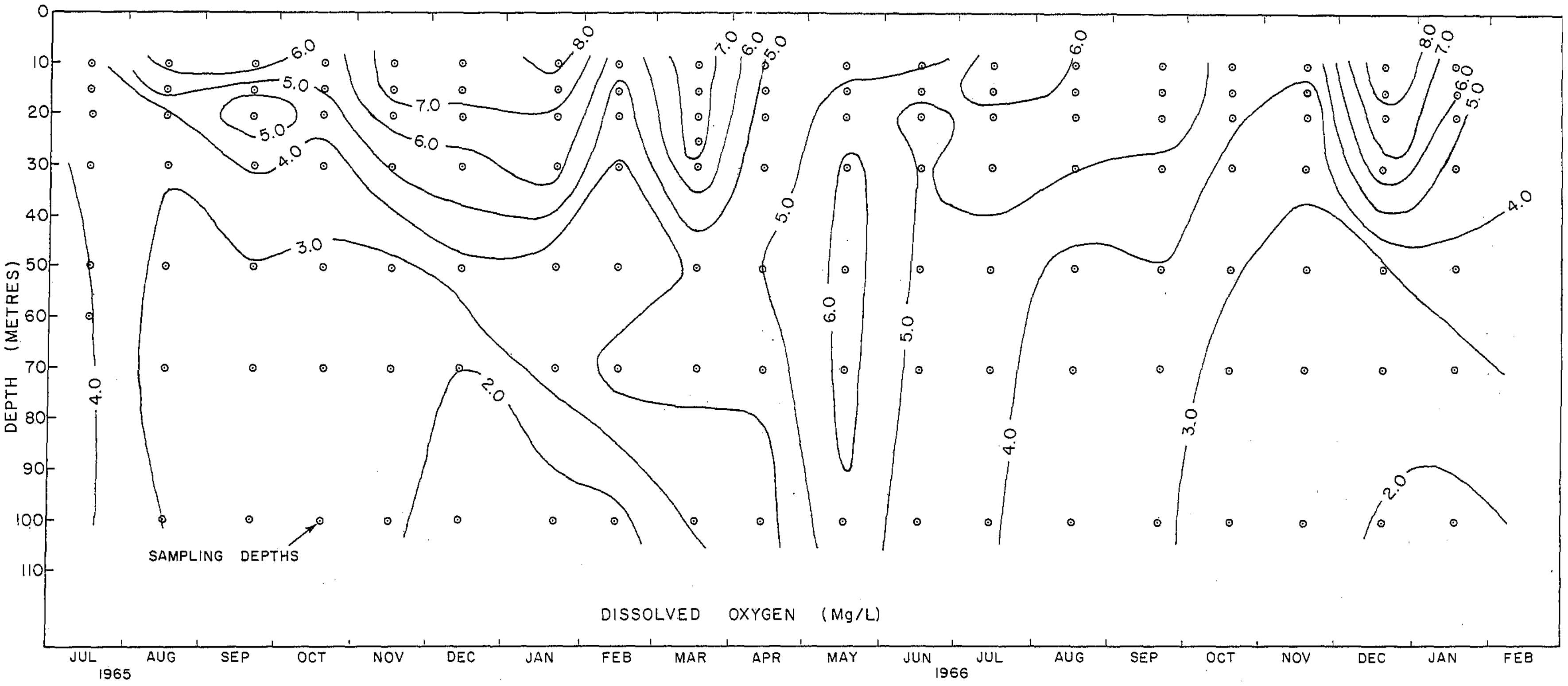

Figure 6. Time-depth contours for dissolved oxygen at Stn A-7A, 1965-1966.

expect the deep water to become less dense as time progresses. More particularly, the density of the water normally depends much more on salinity than it does on temperature and the only source for high salinity water is upwelling on the west coast. Judging again from the available data, it appears that salinity may be reduced by almost $1^{0}/oo$ per year by the downward diffusion of fresh water. On this basis, if an annual exchange did not occur, one would then expect to see in the following year values for salinity, at a depth of 100 m in the inner basin, of less than $31.1^{0}/oo$. In fact, the minimum value in any of the data sets is greater than $31.7^{0}/oo$.

TEMPERATURE-SALINITY RELATIONSHIPS

We now turn to an examination of T-S relationships. In nine instances in eight years, data are available simultaneously from stations in each of the inner and outer basins. Unfortunately, in only one case were the data obtained near the anticipated time of complete renewal of the basin water. In most cases, the data were taken well after such time. Thus, in any inter-basin comparisons, it is necessary to make allowances for the effect of diffusion and for the likelihood of higher density deep waters in the outer basin because of the Junction Passage connection to the coast. First, as an example of the kind of information one can gain about the water within a given basin, consider Fig. 7. Data are plotted for each of six months. For the initial three months, deep water changes are attributed to diffusion. By following the data point at a depth of 100 m, it can be seen that the density is decreasing. Then, an exchange process starts sometime in February, with denser water replacement occuring near 50 m. In March, the influx is apparent at 70 m. By mid-April, there has been a considerable increase in density at 70 m. The water at a depth of 100 m has not yet begun to increase in density, but the rate of reduction of this property by diffusion has been greatly reduced. In May, and again in June, a very substantial increase in density has taken place at all depths, indicating complete exchange of the basin water. The clustering of the data points shows the near homogeneity of the water mass. From this point on, the data (not plotted) again show a gradual reduction in density due to diffusion. For depths shallower than about 50 m, changes in water properties may be influenced by storms, run-off, entrainment and uplifted water from inflows at intermediate depths. Such changes are much more difficult to follow on a T-S diagram than are the deep water changes.

The available data have served to point out that the water in both basins generally exhibited considerable differences in properties from year to year, but in any given year there was a strong correspondence in water properties between inner and outer basins. This suggests, as previously postulated, that consistent renewal of the deep water in both basins was occurring from the same source. Figs. 8 and 9 are given here as specific illustration of this in four particular years. For each year, a T-S curve is shown for a station in each basin. The correspondence of water types

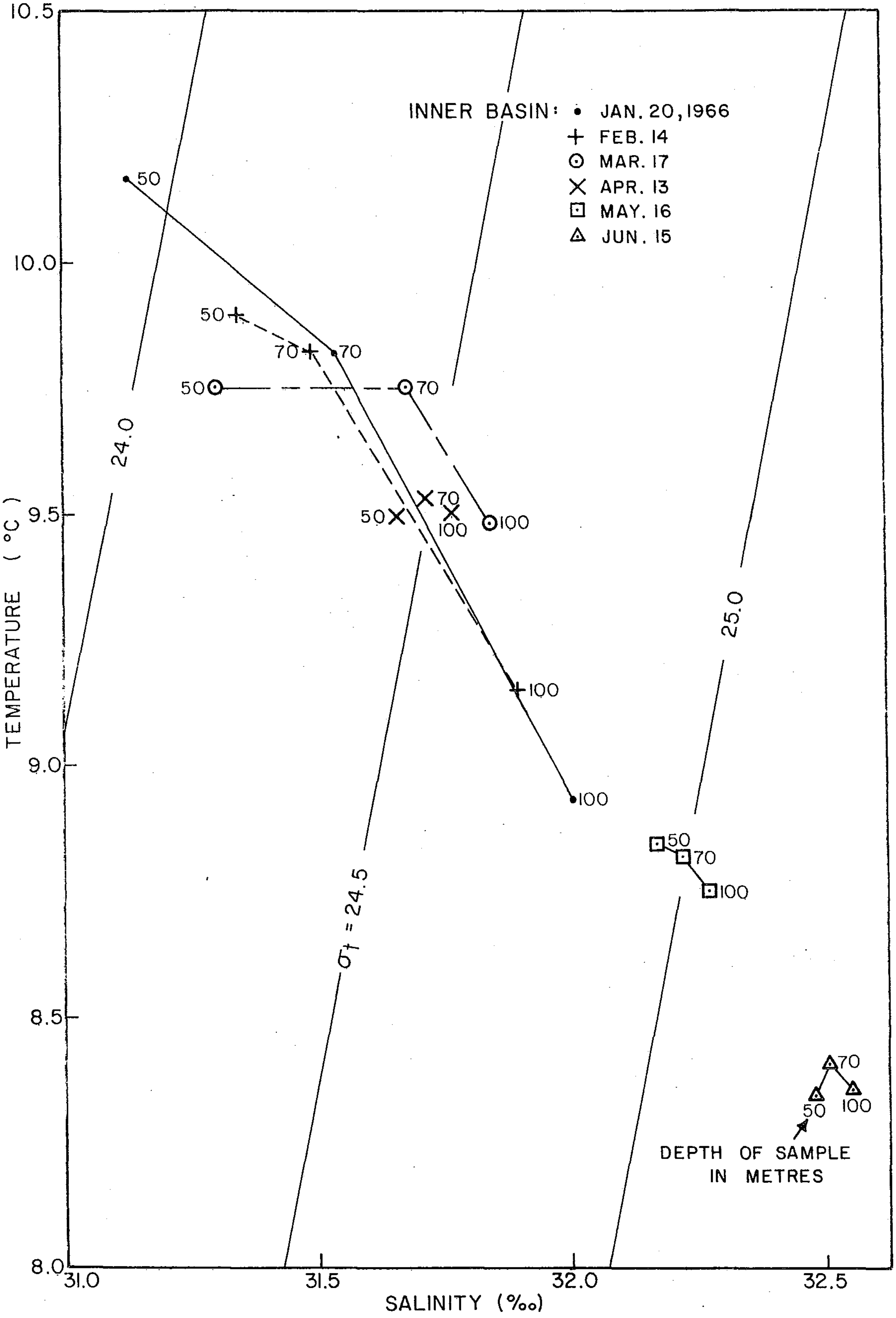

Figure 7. T-S diagram for the inner basin of Alberni Inlet, 1966.

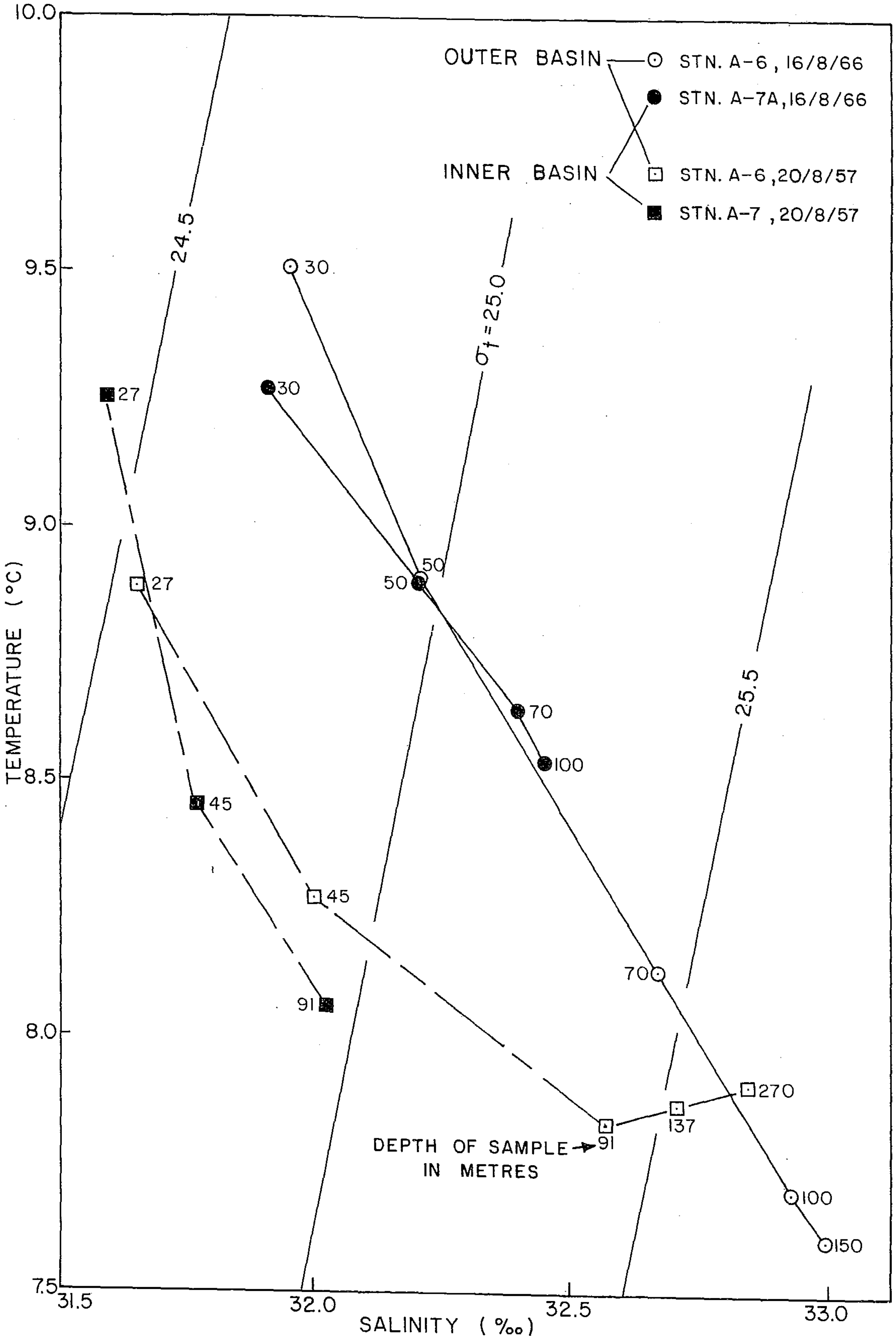

Figure 8. T-S diagram for the inner and outer basins of Alberni Inlet, 1957 and 1966.

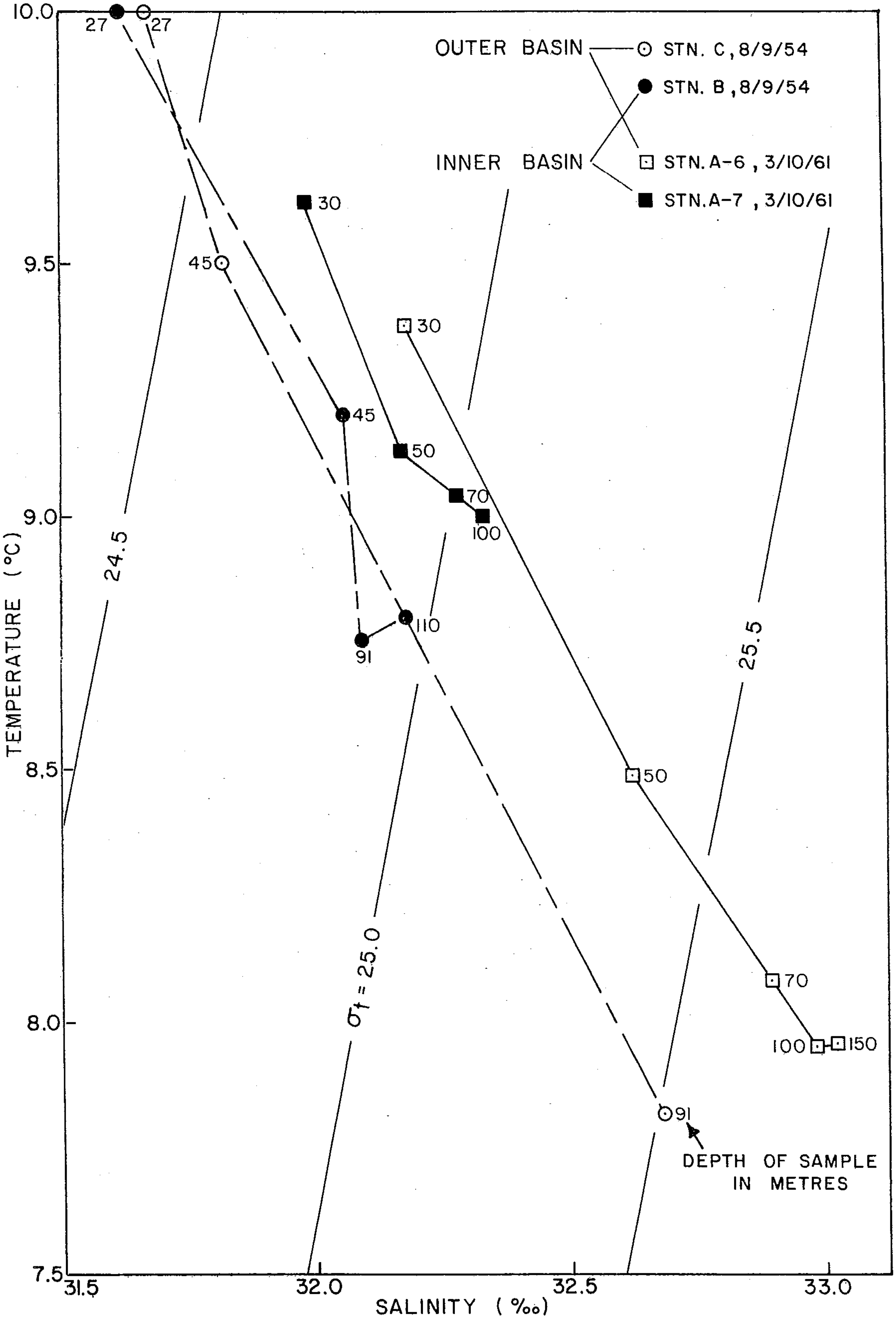

Figure 9. T-S diagram for the inner and outer basins of Alberni Inlet, 1954 and 1961.

is indicated by the proximity of the inner and outer basin curves to one another, again making allowances for the effects previously noted. In addition, further confirmation is given for another two years in two subsequent T-S diagrams (Figs. 10 and 11).

The T-S diagram in Fig. 10 presents the data obtained for both basins on two occasions in 1959. For the outer basin, the water in May was considerably less dense than it was in the following August, indicating an influx at some time during the intervening period. The water below a depth of 50 m, in August, was all of higher density than any of the water resident in the basin in May. Above 50 m, that water mass shows different properties in August than in May, indicating that replacement had occurred over the whole depth of the basin. For the inner basin, the density of the water at a depth of 100 m in August corresponded approximately to the outer basin water at 30 m in the same month. Since there was no question of accessibility, the depth of the sill separating the basins being about 37 m, one assumes that the same water mass was involved, spilling into the inner basin to a depth appropriate to its density. Further reinforcement of this suggestion is provided by the DO values, which were 4.22 mg/ℓ in both instances, and by the fact that the August T-S curves were nearly coincident and quite different in slope from the May curves. Therefore, it appears likely that complete replacement of the water in both basins occurred, from the same eventual source.

An earlier occasion on which some concurrent data occurs for both basins is 1941. The T-S curves are shown in Fig. 11. The character of the water in the outer basin (Stn. C) appears, from an examination of additional intervening sets of data, to have been changing more or less continuously over the period shown, i.e. from May into July. Thus, it seems that water upwelling on the coast was running into the outer basin for much of this period, replacing and uplifting the resident water. The July data suggest that nothing very drastic was yet occurring in the inner basin, although the water at sill depth seems to be sufficiently dense to be capable of flowing into the basin to a depth of about 100 m. Whatever may have happened at this point, it is certain that flushing of the inner basin had been accomplished before the end of August. The replacement water corresponds in properties to that found below sill depth in the outer basin in July. The inference is that upwelled water continued to run into the outer basin for some portion of the July-August period, raising the water from 50 or 60 m to sill depth. This water then proceeded to flush out the inner basin. Of particular interest in 1941 is the fact that temperatures throughout the water column in both basins were appreciably higher than those observed at any other time. The year 1941 was also one of unusually high temperature in the eastern Pacific Ocean, as demonstrated by the daily seawater samples taken at west coast lighthouses (Hollister, 1972; Tabata, 1976).

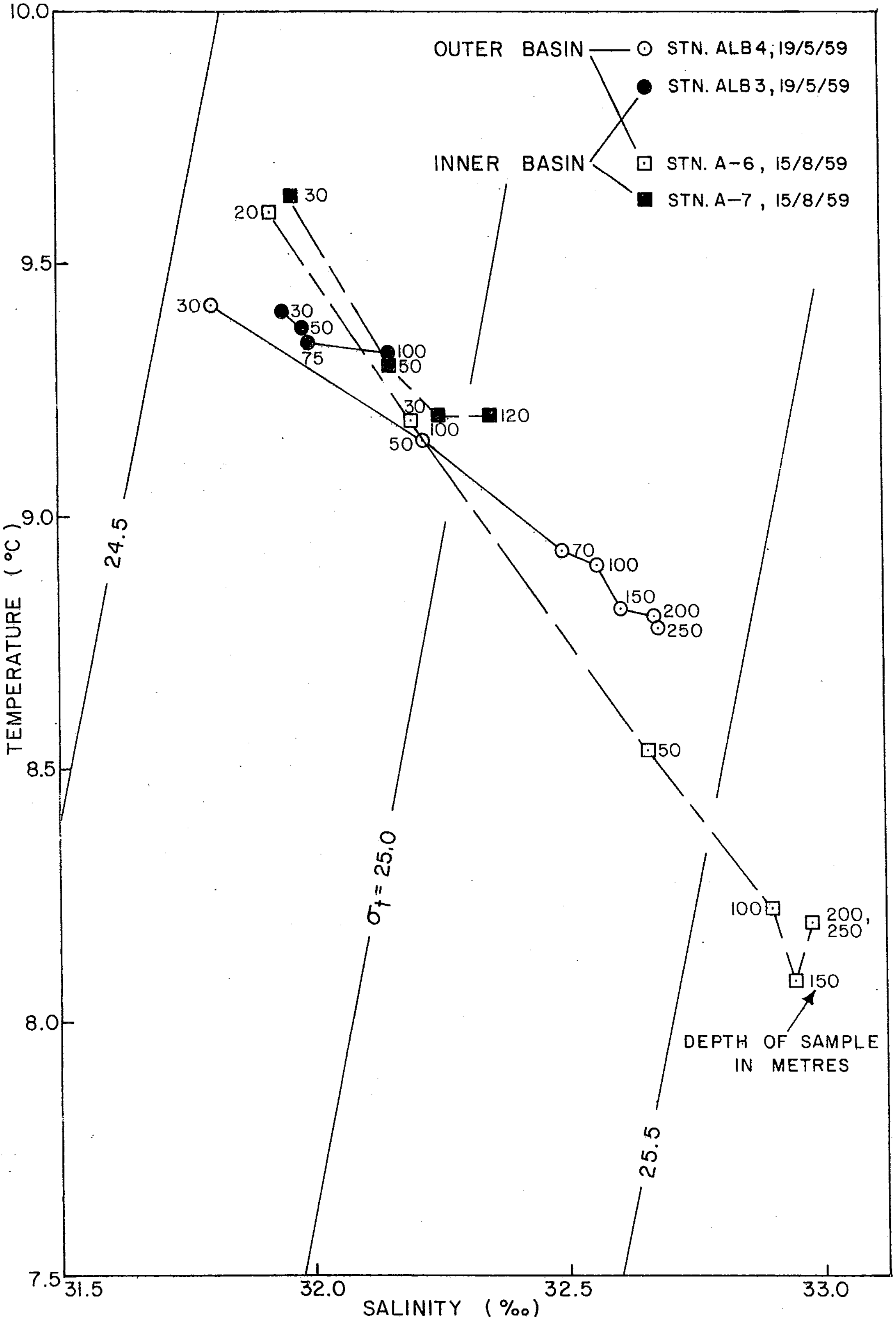

Figure 10. T-S diagram for the inner and outer basins of Alberni Inlet, 1959

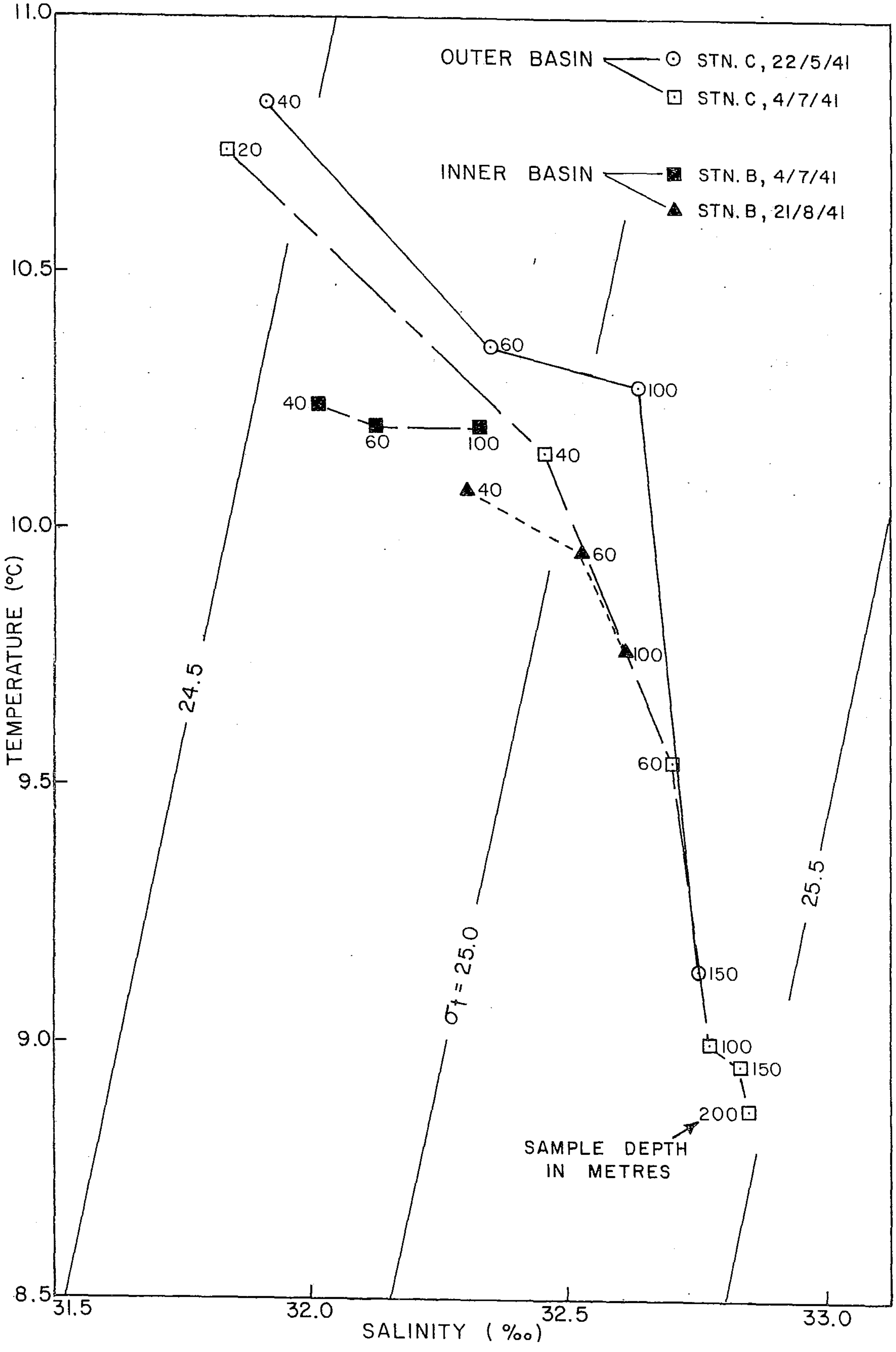

Figure 11. T-S diagram for the inner and outer basins of Alberni Inlet, 1941

CONCLUSION

In most years for which data are available, there is substantial evidence to indicate that a complete renewal of the water in both the inner and outer basins of Alberni Inlet has occurred in that year. There is a further implication, because of the prevailing magnitudes of water property values and the effect that diffusion would have on these values, that renewal has also occurred in each year preceding a year for which data were obtained. The only reasonable source of new water is upwelling of deep ocean water off the west coast. Also, the period during which the flushing of the basins begins would seem to coincide with the onset of the upwelling season. Since an apparently invariable annual cycle of winds is the chief cause of upwelling, it seems very likely that an annual cycle of renewal of the waters of Alberni Inlet will also prevail.

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