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Oceanographic Surveys of Traitors Cove Revillagigedo Island, Alaska

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ABSTRACT

Traitors Cove is a small fiordlike estuary in southeastern Alaska. It is divided into two basins by a narrow constriction, where a reversing tidal falls forms. Four oceanographic surveys of the estuary between 1963 and 1965 showed that this tidal falls creates a region of strong turbulence and destroys the stratification of the water near it. Surface currents in the estuary are predominantly seaward on ebb tide and toward the head of the estuary on flood tide.

INTRODUCTION

Pink salmon (Oncorhynchus gorbuscha) and chum salmon (O. keta) spawn in the gravels of many of the streams of southeastern Alaska. In the spring, the juvenile fish emerge from the gravel and soon migrate downstream to salt water. Their first few weeks in salt water are a critical period in their life cycles. Probably a large portion of the total ocean mortality of these fish takes place during this period.

Relatively little is known of the oceanography of the salt-water areas in southeastern Alaska where this mortality occurs. This paper describes a study of water temperature, chemistry, and surface currents of such an area--Traitors Cove estuary near Ketchikan. Powers (1963) made a similar study of Little Port Walter estuary, Baranof Island, southeastern Alaska. Both estuaries are the sites of salmon research facilities of the Bureau of Commercial Fisheries.

Traitors Cove estuary (fig. 1) penetrates Revillagigedo Island, near Ketchikan. It is divided into two basins, Inner Bay and Outer Bay, by a narrow constriction which has a sill depth of 1 or 2 m. below mean low water. Because of the large range of the tides in the region and the limited capacity of the constriction, a reversing tidal falls forms at the constriction. Tidal currents are strong near the constriction. Inner Bay is about 5.9 km. long and 0.7 km. wide and has a maximum depth of 46 m. Several streams enter Inner Bay; the largest, Traitors River, empties into the head of this bay (fig. 1). Outer Bay is about 6.5 km. long and 1.3 km. wide and has a maximum depth of 130 m. Margareta Creek is the largest of several streams that enter this bay. Outer Bay is freely connected to Behm Canal over a sill 55 m. deep. Behm Canal is a large deepwater body connected to the Pacific Ocean through Clarence Strait and Dixon Entrance.

Traitors Cove lies in a maritime climate and receives large amounts of precipitation and runoff. Annual precipitation at Ketchikan, 40 km. south of Traitors Cove, is about 390 cm. (U.S. Weather Bureau, 1965); watersheds tributary to Traitors Cove probably receive similar amounts. Because discharge records for Traitors River are available only since June 1964, I include records from Fish Creek, a stream about 40 km. southeast of Traitors Cove which has suitable records. Discharge data for these two streams for the 10-day periods immediately before each survey of the estuary are shown in table 1.

Table 1.--Discharge of Traitors River and Fish Creek, Revillagigedo Island, Alaska. Data from U.S. Geological Survey (1963, 1964, 1965)

Dates	Mean discharge	
	Traitors River	Fish Creek
	M.^{3}/sec.	M.^{3}/sec.
August 13-22, 1963.......	--	1.5
April 6-15, 1964.........	--	12.9
June 5-14, 1964..........	11.8	22.7
Sept. 27 to Oct. 6, 1965.	5.5	8.3

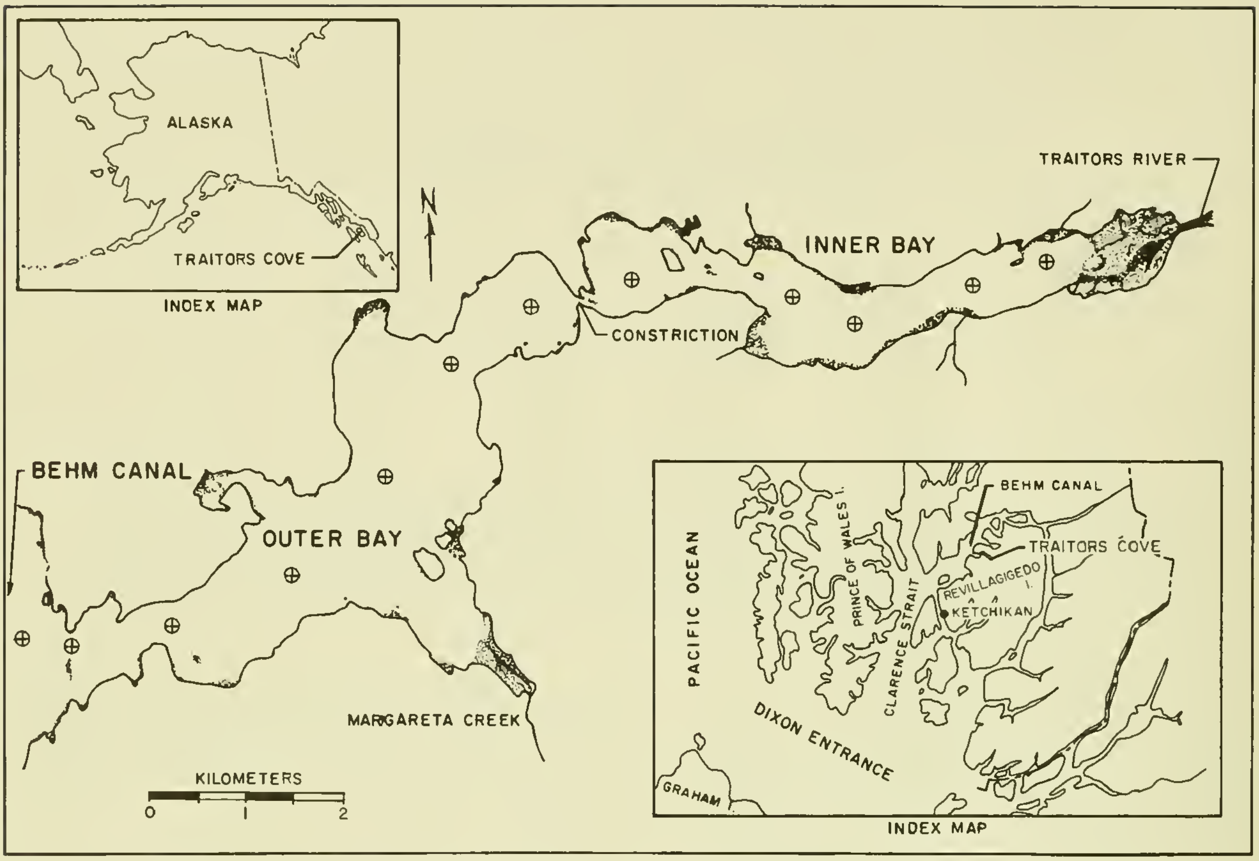

Figure 1.--Traitors Cove estuary, Revillagigedo Island, Alaska, and locations of stations where oceanographic surveys were made, 1963-65.

SAMPLING SCHEDULE

The oceanographic surveys of Traitors Cove estuary were made on August 21-22, 1963; April 14-17, 1964; June 13-15, 1964; and October 6-7, 1965.

On each survey we occupied 12 stations along the midchannel of the estuary (1 in Behm Canal, 6 in Outer Bay, and 5 in Inner Bay--see fig. 1). The stations in Behm Canal and Outer Bay were each occupied once--without regard to tidal conditions. The stations in Inner Bay were each occupied twice--once on the low tide and once on the high. We were not always able to complete the series of five stations in Inner Bay within the 2 hours between 1 hour before slack water and 1 hour after but completed them as soon as possible on the following tide. Also, we did not measure all of the oceanographic properties on every survey because personnel and equipment were limited. Water temperature, salinity, and transparency were measured on all four surveys; dissolved oxygen, phosphate, silicate, and chlorophyll a were determined on three of the surveys; and surface currents were observed intermittently between June 1964 and October 1965.

Table 2 shows the tide predictions for Inner and Outer Bays during the survey periods (U.S. Coast and Geodetic Survey, 1963, 1964, 1965). These predictions are only approximate and contain errors. For instance, on certain low tides the water level in Inner Bay is predicted to stand lower than the lowest level of water in Outer Bay on that tide. This situation is physically impossible, but the error involved is relatively small.

METHODS

We used conventional oceanographic methods on most of the surveys. Water temperature was determined by reversing thermometer, salinity by titration, concentration of dissolved oxygen by the Winkler method, and transparency by a white 30-cm. Secchi disk. Concentrations of silicate, phosphate, and chlorophyll a were determined by the methods of Strickland and Parsons (1960). On the October cruise we measured temperature and salinity with an Industrial Instruments Portable Induction Salinometer, Model RS-5.[1] This instrument measures to accuracies of about $\pm 0.4^{\circ}$ C. and ± 0.4 ‰.

[1] Trade name referred to in this publication does not imply endorsement of commercial product.

Table 2.--Heights and times of high and low tides of Inner and Outer Bays, Traitors Cove, Alaska, during oceanographic survey periods, 1963-65

Date	Outer Bay			Inner Bay		
	Time	Tide height		Time	Tide height	
		Feet	Meters		Feet	Meters
1963						
August 21	0229	16.6	5.5	0250	13.4	4.4
	0848	-1.8	-0.6	1016	-0.8	-0.3
	1508	15.6	5.1	1529	12.6	4.1
	2102	-0.7	-0.2	2230	0.4	0.1
August 22	0307	15.8	5.2	0328	12.8	4.2
	0921	-0.8	-0.3	1048	-0.4	-0.1
	1541	15.4	5.1	1702	12.4	4.1
	2140	1.0	0.3	2307	0.5	0.2
1964						
April 14	0229	18.6	6.1	0250	15.1	5.0
	0850	-2.9	-1.0	1018	-1.4	-0.5
	1511	16.4	5.4	1532	13.3	4.4
	2059	0.4	0.1	2227	0.2	0.1
April 15	0309	18.4	6.0	0330	14.9	4.9
	0936	-2.8	-0.9	1104	-1.3	-0.4
	1600	15.4	5.1	1621	12.4	4.1
	2141	1.5	0.5	2309	0.7	0.2
April 16	0353	17.6	5.8	0414	14.3	4.7
	1026	-2.1	-0.7	1154	-1.0	-0.3
	1654	14.2	4.7	1715	11.4	3.7
	2229	2.9	0.7	2357	1.4	0.5
April 17	0441	16.5	5.4	0502	13.4	4.4
	1123	1.1	0.4	1251	-0.5	-0.2
	1758	13.0	4.3	1819	10.4	3.4
	2327	4.3	1.4	--	--	--
April 18	--	--	--	0055	2.0	0.7
June 13	0322	17.8	5.8	0343	14.4	4.7
	1000	3.3	-1.1	1128	-1.6	-0.5
	1636	15.1	5.0	1657	12.2	4.0
	2212	2.9	1.0	2350	1.4	0.5
June 14	0415	16.5	5.4	0436	13.4	4.4
	1052	-2.1	-0.7	1220	-1.0	-0.3
	1730	14.6	4.8	1751	11.8	3.9
	2311	3.4	1.1	--	--	--
June 15	--	--	--	0039	1.6	0.5
	0512	15.0	4.9	0533	12.1	4.0
	1144	-0.7	-0.2	1312	-0.3	-0.1
	1827	14.2	4.7	1848	11.4	3.7
1965						
October 6	0500	1.7	0.6	0628	0.8	0.3
	1133	13.5	4.4	1154	10.9	3.6
	1725	4.0	1.3	1853	1.9	0.6
	2323	13.8	4.5	2344	11.1	3.6

Surface currents were measured with two sizes of biplane drogues. The larger consisted of two 60- by 60-cm. pieces of sheet metal that were crossed on one another. Because these drogues were supported in the upper 1 meter of water by a surface float, they are called "1-m. drogues." The other drogues had a similar design but were about a third as big and are called "35-cm. drogues." We released the 1-m. drogues in transects across the width of the estuary and determined their subsequent positions by approaching a drogue with a small boat and visually estimating its position. The 35-cm. drogues were used for special studies and for observations close to shore. Wind and tide conditions were recorded for each series of releases.

SEASONAL VARIATION OF OCEANOGRAPHIC PROPERTIES

Although the surveys were made in different years, I assume that they indicate the major oceanographic changes that occur seasonally in any year. Therefore, I present the results in a seasonal sequence regardless of the year of sampling. The data are presented in a series of figures (2-12) as contoured vertical sections. Outer Bay was sampled independently of tide stage. Inner Bay was sampled at high tide and at low tide, and the conditions at each stage are presented separately. The dots on the figures are the depths where measurements were made.

Temperature

The water in Traitors Cove has a marked seasonal thermal cycle--it is nearly isothermal vertically in winter, and a thermocline is present in summer. In April the water in the upper 30 m. in Outer and Inner Bays had only small thermal gradients (fig. 2); the temperature at this time ranged from 6.0° to 7.4° C.

By June, increasing insolation had warmed the surface water and formed a thermocline in both basins of the estuary (fig. 3). Water temperatures ranged from 9.6° to 13.5° C. at the surface and from 7.5° to 8.8° C. at 30 m.

Because of continued high insolation, water temperatures in August in the estuary were the highest observed (fig. 4). Maxima were 16.9° C. at the surface and 11.9° C. at 30 m.

On the October survey (fig. 5) the range of surface water temperatures was reduced to 8.8° to 10.2° C. These lower temperatures, in comparison with August, resulted from autumn cooling (indicated by lower air temperatures in October) and by vertical mixing (indicated by higher water temperatures at 30 m. than in August).

The deep water of Outer Bay cooled throughout the spring, summer, and fall. The temperature of the water at 75 m. in Outer Bay was 7.5° C. in April, 7.2° in June, 7.0° in August, and about 6.5° in October. This cooling is probably not a local feature, because the temperature of the water at 75 m. in Behm Canal followed a similar trend.

Salinity

The distributions of salinity in Traitors Cove show the presence of a surface layer with low salinity in summer and fall. This layer is formed by the mixing of underlying salt water with fresh water from runoff.

In April (fig. 6) the salinity of the surface water at the various stations ranged from 23.9 to 28.9 ‰ in Inner Bay and from 26.9 to 28.6 ‰ in Outer Bay. The salinity of the deep water (greater than 30 m.) was greater than 29.1 ‰ in both areas.

Because of greater runoff in June, the salinity stratification in both Outer and Inner Bays was more intense than in April (fig. 7). The salinity of the surface water at the stations in Inner Bay ranged from 5.4 to 17.0 ‰. Outer Bay, with surface salinities in the range 19.1 to 24.3 ‰, was less stratified than Inner Bay.

August 1963 was a month of unusually low rainfall throughout southeastern Alaska. (Ketchikan, for instance, received only 2.5 cm. of precipitation--about 9 percent of the long-term mean for August.) As a result of the low runoff, the salinity stratification in Inner Bay was poorly developed (fig. 8).

The salinity stratification of Outer Bay, however, was not greatly affected by the low local runoff. Large rivers in the region that drain into Behm Canal and other passages normally have peak discharges in July or August due to snowmelt. These rivers presumably supplied the fresh water which entered Outer Bay from Behm Canal and caused the salinity stratification there.

The net result of low local runoff and continued supply of low-salinity surface water from Behm Canal was that the salinity stratification in August was greater in Outer Bay than in Inner Bay--a reversal of the relation observed at other times during this study.

In October the local runoff was relatively large, and salinity stratification was intense (fig. 9). The salinity of the surface water ranged from 0.0 to 18.8 ‰ in Inner Bay and from 24.0 to 27.1 ‰ in Outer Bay. The salinity of the deep water (greater than 30 m.) was at least 30.0 ‰ in both bays.

Dissolved Oxygen

The concentration of dissolved oxygen was relatively high (at least 5.0 ml./l.) in the upper 10 m. of water during the April, June, and August surveys (dissolved oxygen was not measured in October). The deeper water had lower concentrations, but we found no evidence of stagnation.

In April (fig. 10), dissolved oxygen in surface waters ranged from 6.9 to 7.6 ml./l. The concentrations were higher in summer (figs. 11 and 12) and ranged from 7.1 to 8.9 ml./l. in June and 6.0 to 8.4 ml./l. in August.

Dissolved oxygen in the deep water of Outer Bay gradually decreased from spring to summer. Concentrations were about 5.2 ml./l. in April, 3.6 ml./l. in June, and 3.3 ml./l. in August. The decrease may have been caused by intrusion of water of lower oxygen content.

Phosphate

Concentration of phosphate was determined only during the April and June surveys. In April, concentrations in Outer Bay increased with depth from a range of 1.0 to 1.2 μg. at./l. (microgram atoms per liter) at the surface to about 1.9 μg. at./l. at 75 m. Phosphate values in Inner Bay ranged from 1.2 to 2.4 μg. at./l. in April, and although they also generally increased with depth, they were variable. In June, phosphate measurements were made at only two stations, and these values were from one-third to two-thirds of the April concentrations.

Silicate

Concentrations of silicate in April had distributions similar to those of phosphate. Concentrations in Outer Bay increased from the range 10 to 11 μg. at./l. at the surface to about 25 μg. at./l. at 75 m. The values in Inner Bay were more variable than in Outer Bay and increased with depth only near the head of the basin. In June, silicate concentrations were only one-half to one-tenth of their April values.

Chlorophyll $\underline{a}$

The concentration of chlorophyll $\underline{a}$ in April in Outer Bay ranged from 0.14 to 0.91 μg./l. and in Inner Bay from 0.38 to 11.47 μg./l. Chlorophyll $\underline{a}$ was not measured in June, but a few measurements were made in August; they ranged from 0.18 to 0.83 μg./l. in Outer Bay and from 0.90 to 4.62 μg./l. in Inner Bay. On both surveys the concentration of chlorophyll $\underline{a}$ generally increased in a landward direction from Outer Bay to Inner Bay. The maximum concentrations were at depths of 5 or 10 m., and the minimum values were at 50 m. or greater.

Transparency

The transparency of the upper layers of water generally decreased from April to October. The average Secchi disk readings (in meters) for the four surveys were 9.0 in April, 4.9 in June, 6.0 in August, and 3.5 in October. On all four surveys the transparency generally decreased in a landward direction from Behm Canal to Outer Bay to Inner Bay. Average Secchi disk readings for the four surveys were 7.0 m. in Outer Bay and 4.7 m. in Inner Bay.

CIRCULATION

Traitors Cove fits the definition of a positive estuary (Pritchard, 1952)--the sum of runoff and precipitation is greater than the evaporation. In this type estuary the driving force of the net circulation is the hydrostatic head of the entering fresh water. Being less dense than sea water, the fresh water remains on the surface and flows seaward. Saline water from below is mixed or entrained upward into the surface layer (Tully, 1958). To compensate for the sea water entrained upward into the low-salinity surface layer and carried seaward, a net flow of sea water moves landward at depth. The net flow pattern is two layered--seaward on the surface and landward at depth.

The actual circulation in Traitors Cove is more complicated than this simple model because of the turbulence created by the constriction. This turbulence is strong enough to destroy almost completely the vertical density stratification of the water near it. The deep water of Inner Bay is created by this process and is a mixture of deep water from Outer Bay and the surface low-salinity waters from both Inner and Outer Bay. Normally most of the low-salinity water comes from runoff. On the August survey, however, under conditions of low local runoff into Inner Bay, much of the low-salinity water probably came from Behm Canal via Outer Bay.

On the June survey the deep water created by turbulence at the constriction did not reach the bottom of Inner Bay. On that survey we observed a water mass with temperature of about 10.5° C. and salinity of 26.5 ‰ between 5 and 12 m. depth in Inner Bay. It overlay a second water mass of about 8.7° C. temperature and 28.2 ‰ salinity (see figs. 3 and 7). Probably the first water mass was formed by mixing at the constriction, and its density was too low to displace the older bottom water in Inner Bay.

The turbulence is created at the base of the tidal falls. Because this falls reverses with the tide, the turbulence is created alternately in Inner and Outer Bays and mixes the water near the falls to vertical homogeneity. After tide reversal, runoff quickly reestablishes a surface brackish layer over the mixed water. This action was evident on the April and August surveys, when the water in Inner Bay near the constriction was vertically homogeneous on high tide (after a flood) and slightly stratified

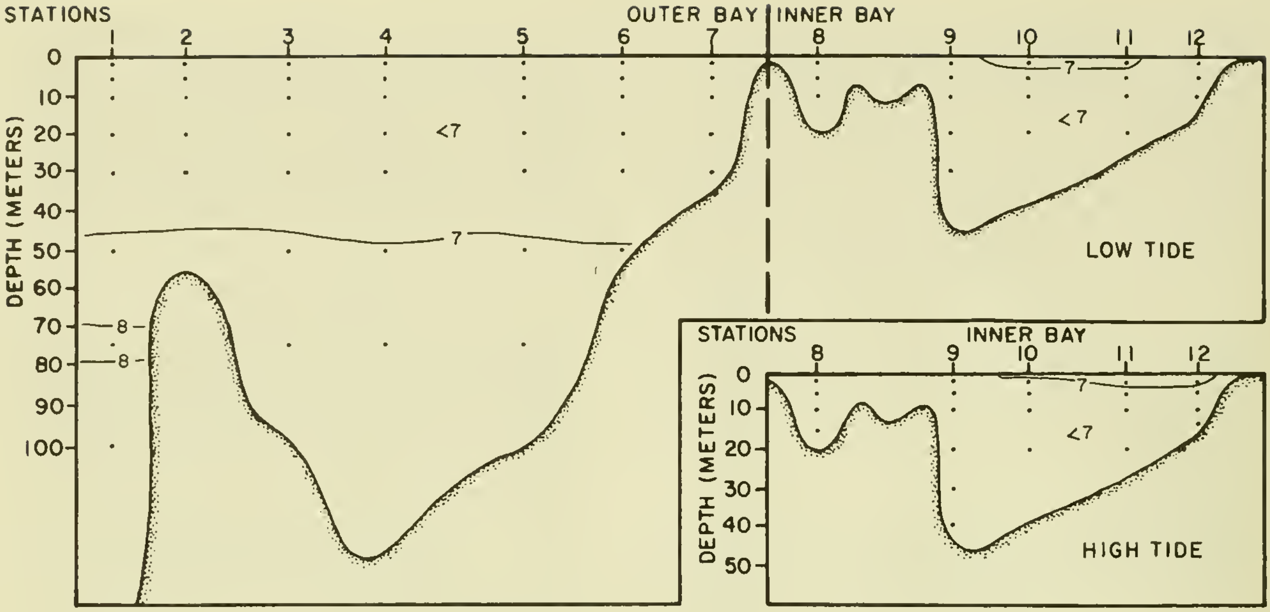

Figure 2.--Temperature (^{o}C.) of Outer and Inner Bays, Traitors Cove, Alaska, April 1964. (Time of surveys: Outer Bay--0850-1520 April 14. Inner Bay--low tide, 0950-1225 April 15 and 1130-1215 April 17; high tide, 1600-1750 April 15 and 1800-1830 April 17.)

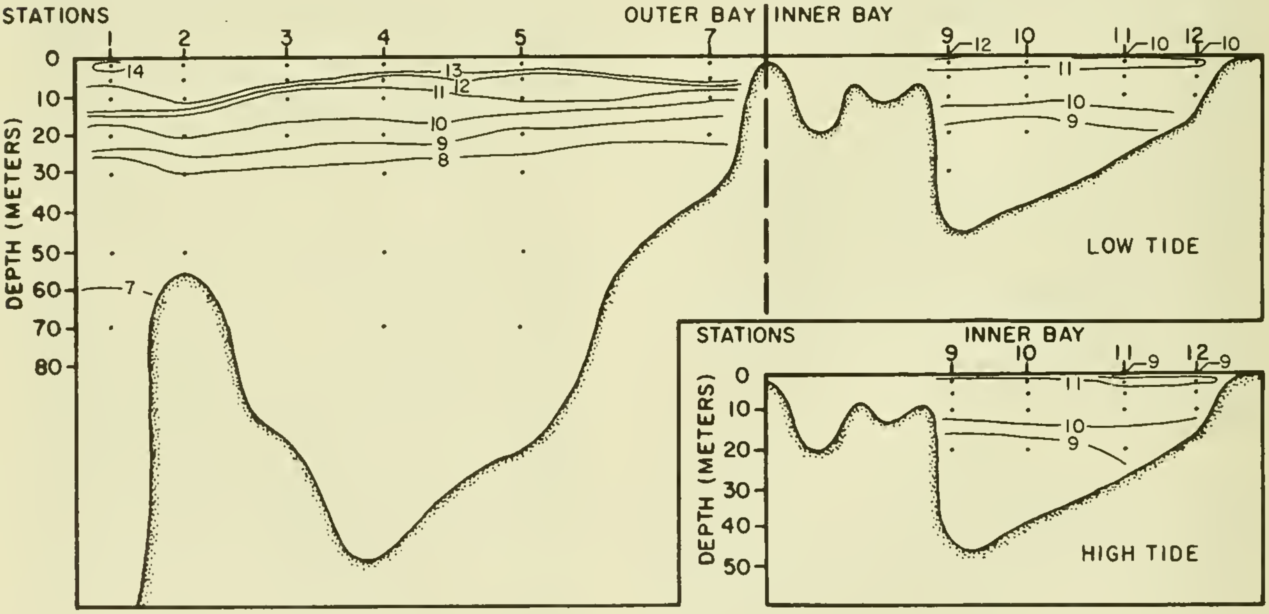

Figure 3.--Temperature (^{o}C.) of Outer and Inner Bays, Traitors Cove, Alaska, June 1964. (Time of surveys: Outer Bay--1520-1620 June 13 and 1015-1445 June 14. Inner Bay--low tide, 1240-1415 June 15; high tide, 1825-1855 June 14 and 0700-0730 June 15.)

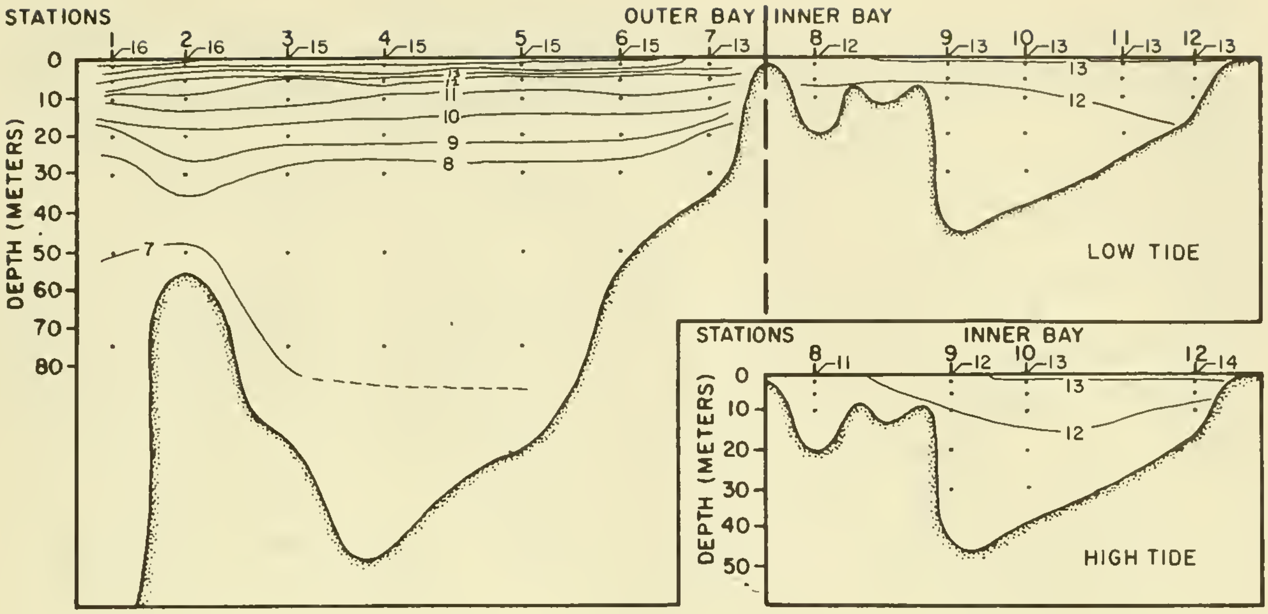

Figure 4.--Temperature (°C.) of Outer and Inner Bays, Traitors Cove, Alaska, August 1963. (Time of surveys: Outer Bay--1728-1305 August 21. Inner Bay--low tide, 0945-1215 August 22; high tide, 1525-1710 August 22.)

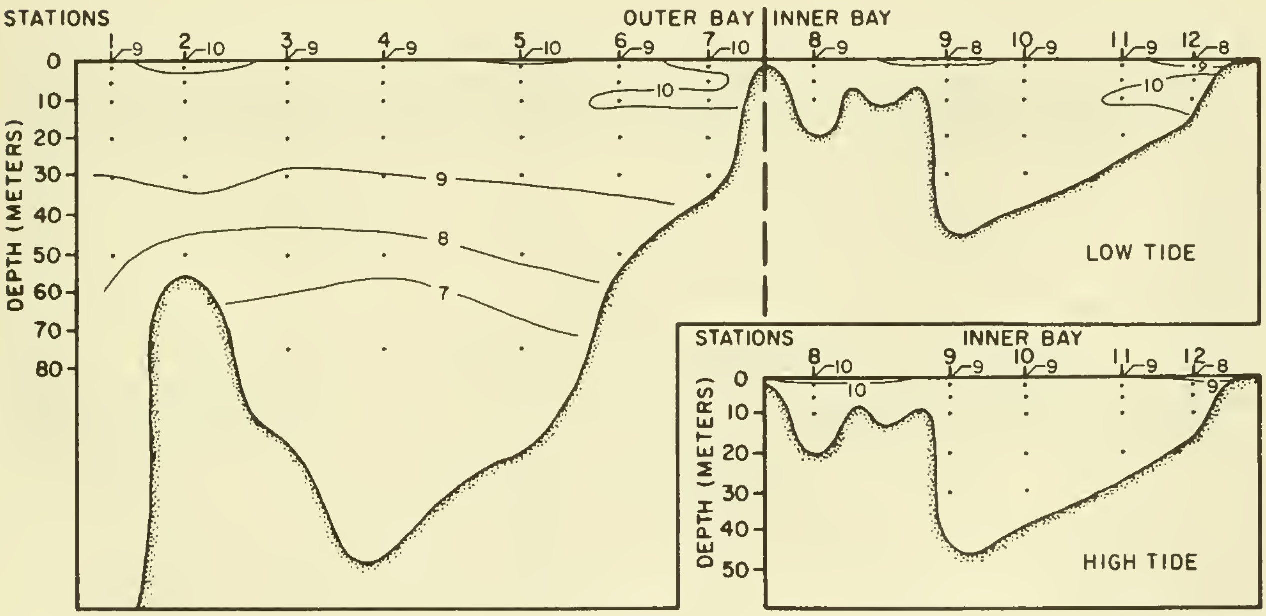

Figure 5.--Temperature (°C.) of Outer and Inner Bays, Traitors Cove, Alaska, October 1965. (Time of surveys: Outer Bay--1015-1200 October 6. Inner Bay--low tide, 0525-0620 October 6; high tide, 1225-1345 October 6.)

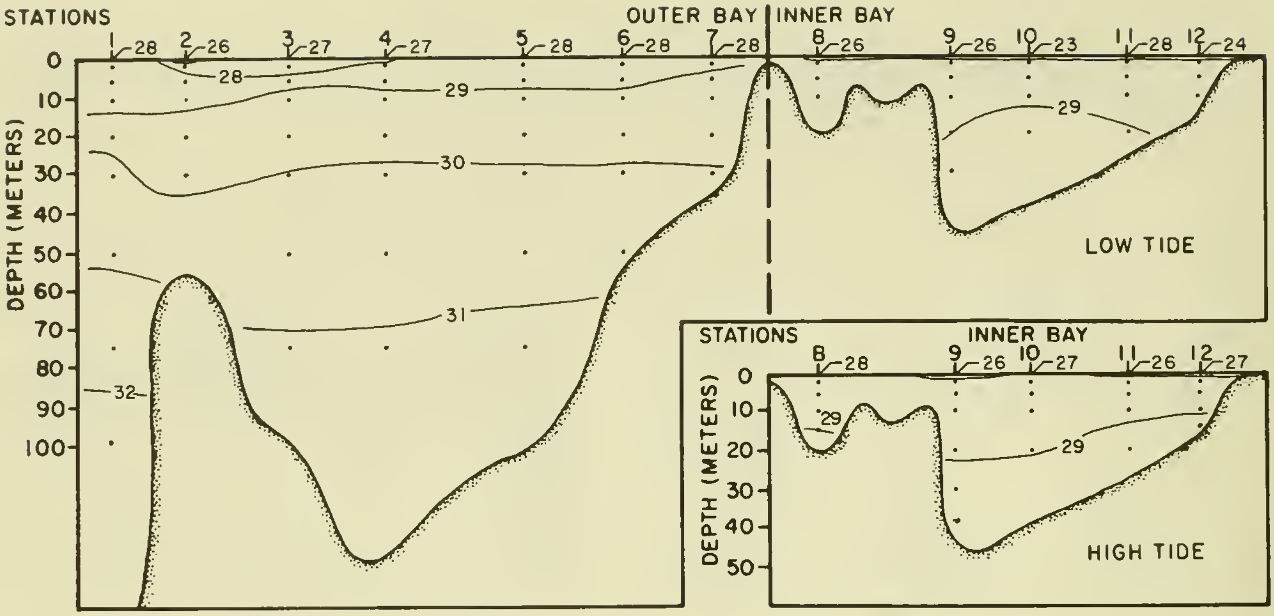

Figure 6.--Salinity (^{0}/oo) of Outer and Inner Bays, Traitors Cove, Alaska, April 1964. (Time of surveys: Outer Bay--0850-1520 April 14. Inner Bay--low tide, 0950-1225 April 15 and 1130-1215 April 17; high tide, 1600-1750 April 15 and 1800-1830 April 17.)

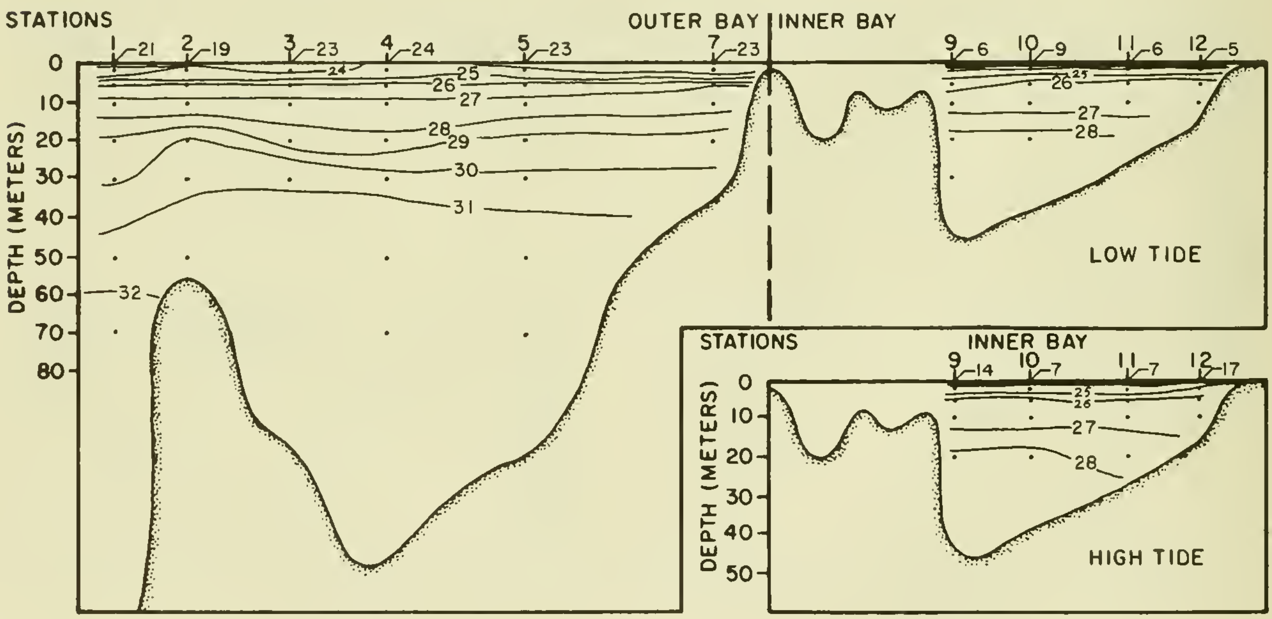

Figure 7.--Salinity (^{0}/oo) of Outer and Inner Bays, Traitors Cove, Alaska, June 1964. (Time of surveys: Outer Bay--1520-1620 June 13 and 1015-1445 June 14. Inner Bay--low tide, 1240-1415 June 15; high tide, 1825-1855 June 14 and 0700-0730 June 15.)

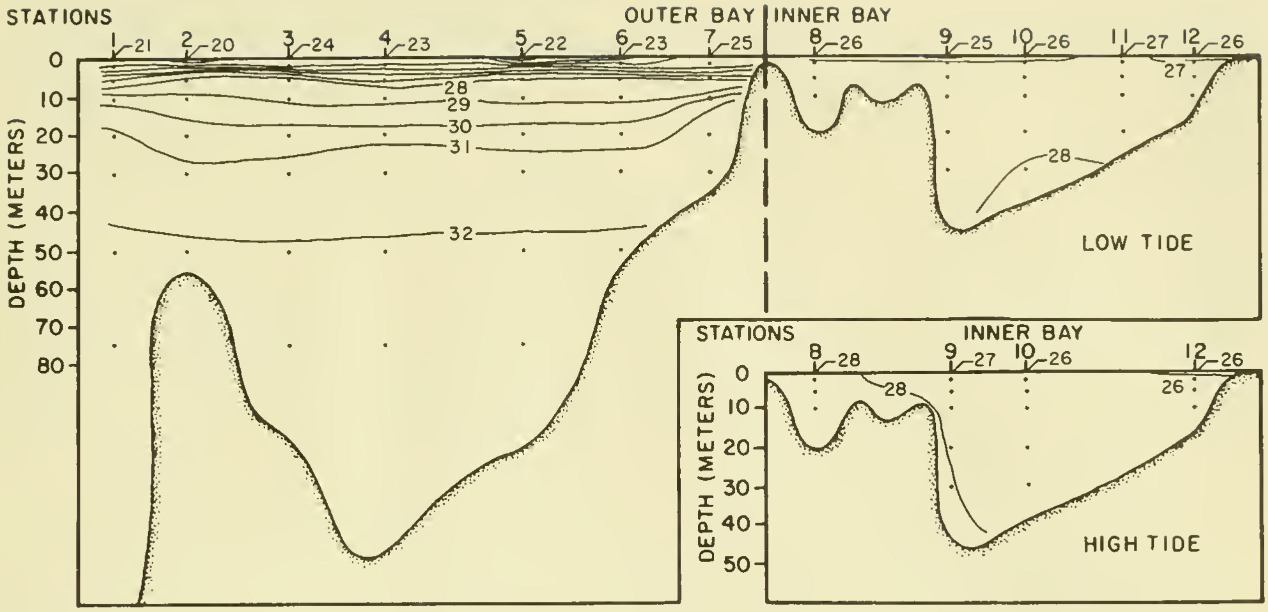

Figure 8.--Salinity ($^{o}/oo$) of Outer and Inner Bays, Traitors Cove, Alaska, August 1963. (Time of surveys: Outer Bay--0728-1305 August 21. Inner Bay--low tide, 0945-1215 August 22; high tide, 1525-1710 August 22.)

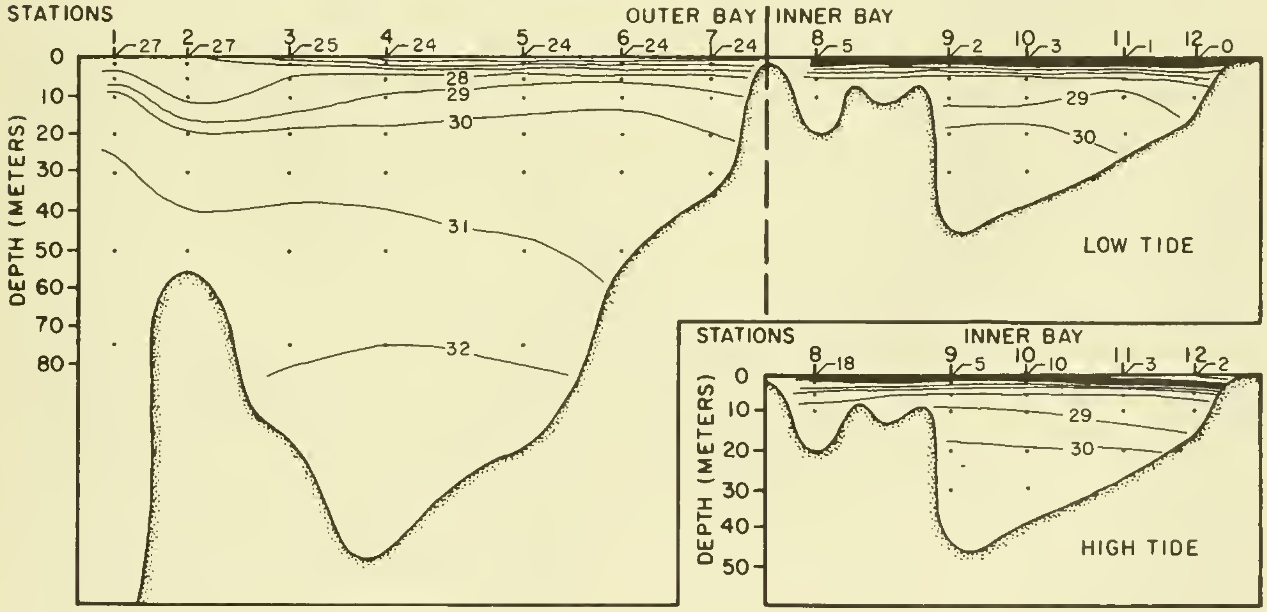

Figure 9.--Salinity ($^{o}/oo$) of Outer and Inner Bays, Traitors Cove, Alaska, October 1965. (Time of surveys: Outer Bay--1015-1200 October 6. Inner Bay--low tide, 0525-0620 October 6; high tide, 1225-1345 October 6.)

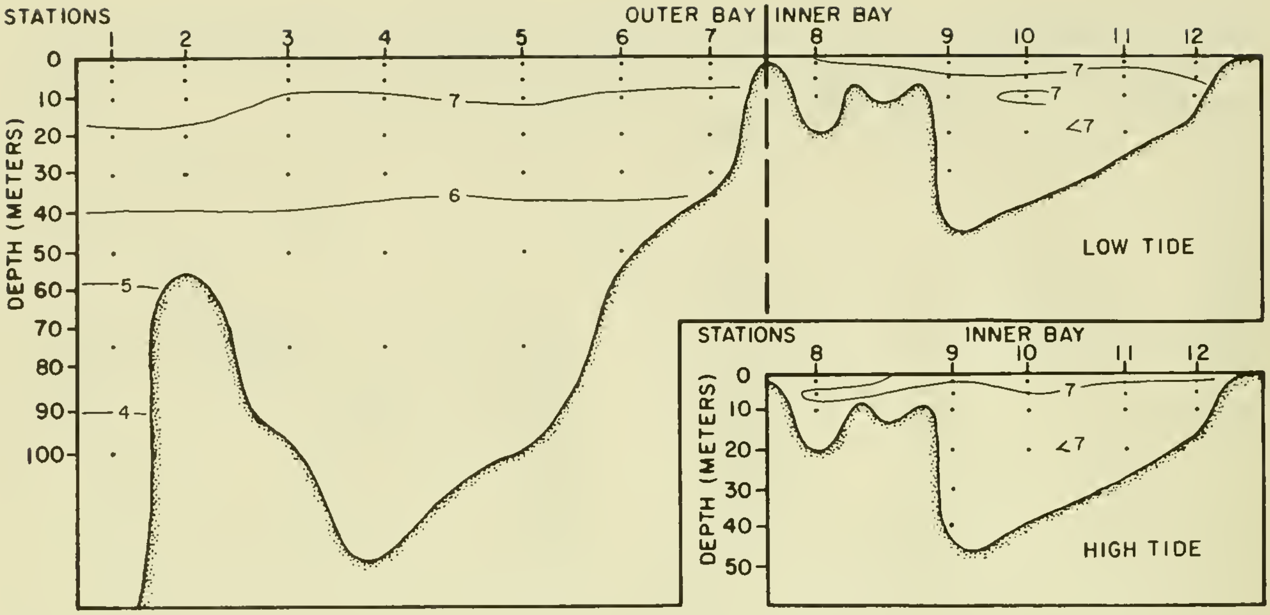

Figure 10.--Dissolved oxygen (ml./l.) of Outer and Inner Bays, Traitors Cove, Alaska, April 1964. (Time of surveys: Outer Bay--0850-1520 April 14. Inner Bay--low tide, 0950-1225 April 15 and 1130-1215 April 17; high tide, 1600-1750 April 15 and 1800-1830 April 17.)

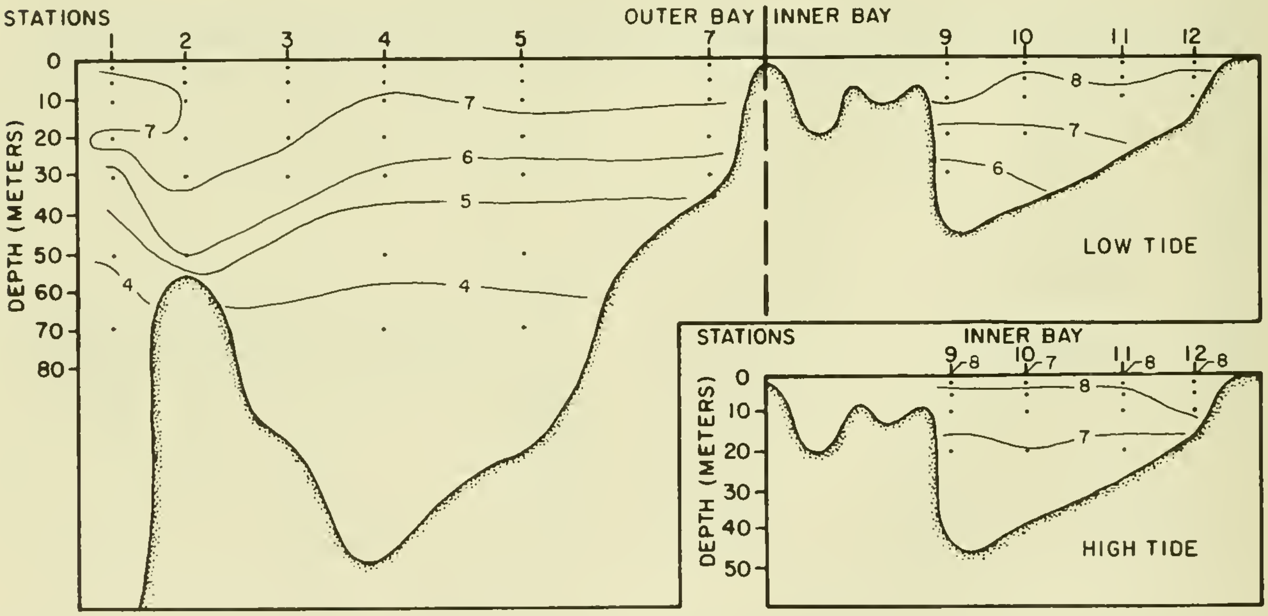

Figure 11.--Dissolved oxygen (ml./l.) of Outer and Inner Bays, Traitors Cove, Alaska, June 1964. (Time of surveys: Outer Bay--1520-1620 June 13 and 1015-1445 June 14. Inner Bay--low tide, 1240-1415 June 15; high tide, 1825-1855 June 14 and 0700-0730 June 15.)

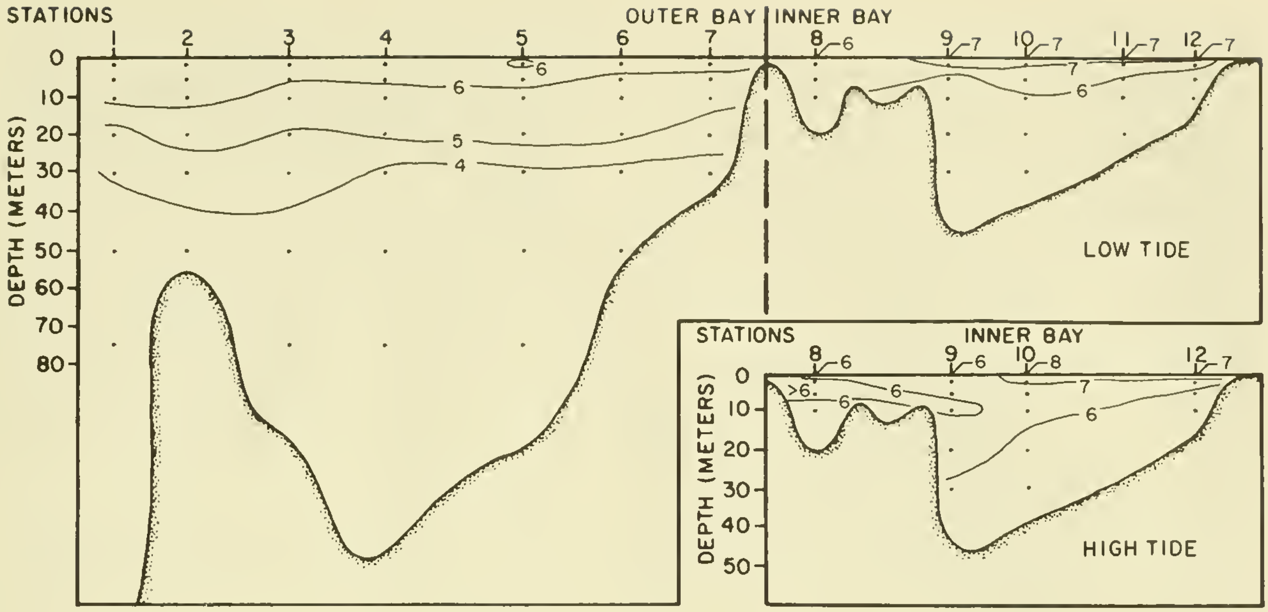

Figure 12.--Dissolved oxygen (ml./l.) of Outer and Inner Bays, Traitors Cove, Alaska, August 1963. (Time of surveys: Outer Bay--1728-1305 August 21. Inner Bay--low tide, 0945-1215 August 22; high tide, 1525-1710 August 22.)

on low tide (after an ebb). On the October survey, local runoff on both tides was sufficient to cause stratification in Inner Bay about half a kilometer from the falls.

The action of the water flowing over the 55-m. sill at the outer entrance of Outer Bay is different from that of the action of water at the sill at the constriction. The 55-m. sill does not cause strong turbulence but merely blocks the entrance of water from Behm Canal into Outer Bay at depths greater than 55 m. For example, in April and August the 75-m. water in Behm Canal was more saline and contained less dissolved oxygen than water at the same depth in Outer Bay. Being more saline and hence more dense, the water at 75 m. in Behm Canal cannot rise up and pass over the 55-m. sill to enter Outer Bay. On the other hand, Behm Canal water at depths of 55 m. or less moves easily into Outer Bay. The density of the deeper (greater than 55 m.) water of Outer Bay is thus governed by the density of the water at 55 m. in Behm Canal. If denser water were to appear at or above the sill depth, it would flow over the sill and replace the bottom water of Outer Bay.

The deep water of Outer Bay had general seasonal trends in its properties. From April to October the temperature of this water decreased, the salinity increased, and the concentration of dissolved oxygen decreased. (The only exception to this pattern was salinity, which was slightly less in October than August.)

These trends in oceanographic properties are results of wind-driven movements of surface water along the coast. In winter, southeasterly winds are strong and persistent. They force the coastal surface waters shoreward by Coriolis deflection and cause a downwelling along the coast. In summer, the southeast winds relax and may shift to northerly. This change in wind relaxes the onshore transport and may cause slight offshore transport of surface waters. Reduced onshore transport in turn allows a moderate upwelling of deep waters. This upwelled water is cold, saline, and low in oxygen, and gradually flows into the coastal inlets at depth. It is the slow intrusion of this water that causes the decrease in temperature, increase in salinity, and decrease in dissolved oxygen in Outer Bay from April to October. The properties of the deep water of Auke Bay near Juneau, Alaska, were attributed to the inflow of water at depths for similar reasons (U.S. Federal Water Pollution Control Administration, 1966).

TIDAL EFFECTS

In addition to its effect on circulation in the estuary, the constriction influences the tidal regime of Traitors Cove in four major ways. First, the limited capacity of the constriction restricts the volume of water that can move into and out of Inner Bay during a tidal cycle and hence reduces the tidal range of Inner Bay with respect to that of Outer Bay. The tide tables (U.S. Coast and Geodetic Survey, 1965) list a mean tidal range of 3.44 m. in Inner Bay and 4.11 m. in Outer Bay.

Second, the constriction causes the ebb tide in Inner Bay to last longer than the flood tide. On our surveys the ebb and flood tides averaged

430 and 320 minutes in Inner Bay and 372 and 382 minutes in Outer Bay.

Third, the constriction causes the times of high and low slack waters in Inner Bay to lag behind those of Outer Bay. The tide tables (U.S. Coast and Geodetic Survey, 1965) list high and low waters in Inner Bay as 21 and 88 minutes behind those of Outer Bay. These lag times are approximate and depend on the height of the tide in question. For example, on a neap tide (3-4 m. range) at Traitors Cove the times of high and low water were both 40 to 50 minutes later in Inner Bay than in Outer Bay. On spring tides (5-6 m. range) the times of high and low slack waters were 50 to 70 and 90 to 120 minutes later in Inner Bay than in Outer Bay. These data, which were provided by personnel of the Bureau of Commercial Fisheries Biological Field Station at Traitors Cove, also show that the duration of the ebb becomes greater as the tidal range increases.

Fourth, the constriction creates exceptionally strong tidal currents that affect the distribution of bottom sediments in its vicinity. Jay Quast (Auke Bay Biological Laboratory), who made a series of scuba dives in the area near the constriction in Outer Bay in April 1964, found that the floor of the constriction was bare rock and was free of sediments and debris, probably because of tidal currents. He noted a depression floored with bare rock and large boulders at the foot of the falls in Outer Bay; the bottom graded into flat cobbles, gravel, and finally sand at greater distances from the constriction. The steep rock shore across from the constriction has undercut ledges presumably cut by currents of the ebb tide. Figure 13 is a sketch of Quast's observations of the bottom sediments and topography.

SURFACE CURRENTS

Between 1964 and 1965, drifts of 70 surface drogues were followed under various conditions of wind and tide to determine the general patterns of surface currents. The times and positions of these drogues were used to calculate current velocities. Because the positions of the drogues were not determined precisely, the calculated velocities are probably accurate to about 20 percent--probably adequate when one considers the highly variable nature of the surface currents. Most of the data are from observations of 1-m. drogues, although a few observations were made with 35-cm. drogues very near shore. Therefore, the observations generally represent currents in the top 1 m. of water.

Because the surface currents obviously depended on tidal condition, I present the patterns for ebb and flood tides (figs. 14 and 15). In preparing the figures, I compensated for the effects of wind by reducing the apparent velocity of the currents by about 20 percent when the wind and tide were in the same direction, and increasing the velocity by about 20 percent when the wind opposed the tide.

Currents in both bays of Traitors Cove were predominantly seaward during the ebb tide and landward during the flood tide. Minor exceptions were eddies formed near shore in the lee of land projections during both tides. In Outer Bay, currents were weaker than in Inner Bay and occasionally appeared more dependent on wind than on tide. In both bays, currents near high and low stages of the tide were generally weak (less than 5 cm./sec.), variable, and dependent on winds.

At the head of Inner Bay, currents during the flood tide had speeds less than 15 cm./sec. and were normally directed up-inlet; in contrast, during the ebb tide currents were directed down-inlet and had speeds of 20 to a maximum of 27 cm./sec. During both tides currents appeared to be strongest on the southern shore. Three or more eddies appeared during the ebb along the north shore of Inner Bay.

Pronounced gyres formed at the foot of Inner Bay during the flood tide and at the head of Outer Bay during the ebb. These gyres rotated counterclockwise; maximum velocities were 20 to 40 cm./sec. Flow through the constriction was turbulent and, although not measured, was very fast.

During flood tide, currents in Outer Bay were generally landward and their speeds were 10 to 25 cm./sec.; during the ebb, currents were variable in direction and weaker. One series of drogues followed irregular and rotating paths. Another series released during an ebb tide moved landward rather than seaward because of an up-channel wind--the current was too weak to overcome the effect of the wind.

SOME EFFECTS OF THE SURFACE CURRENTS

At the head of Inner Bay the surface water is slowly backed up the river during flood tide and released rapidly during ebb tide. This motion has several important consequences on the oceanography of the estuary.

First, the fresh-water layer on the surface flowed seaward rapidly during the ebb tide and caused surface salinity to be lower at the time of low tide than at high tide (figs. 6, 7, and 9). This situation was not apparent in August during the period of very low runoff (fig. 8).

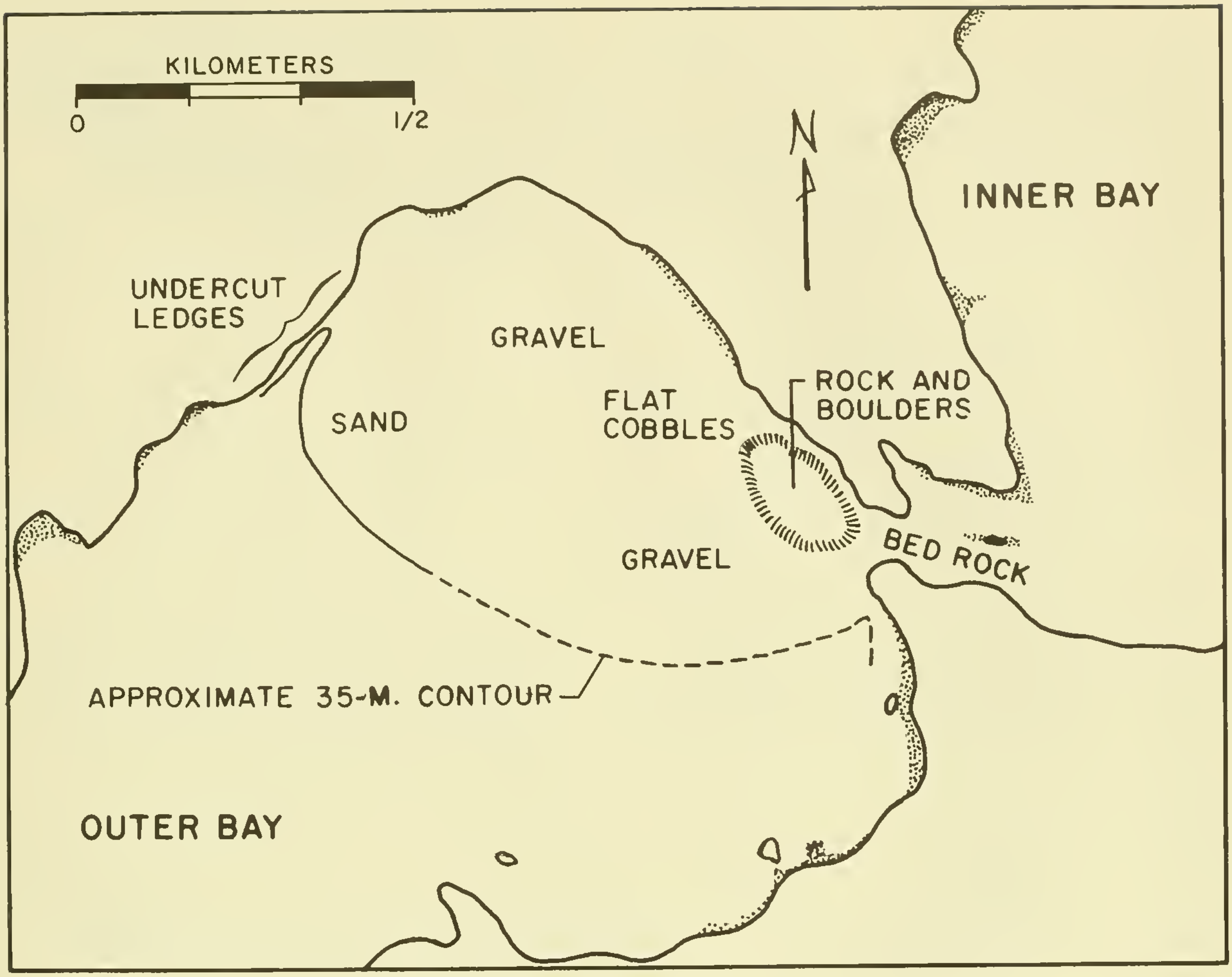

Figure 13.--Bottom sediments and topography of area near constriction between Inner and Outer Bays, Traitors Cove, Alaska.

Second, because seaward surface transport was greater during the ebb than during flood tides, a greater amount of vertical entrainment or upwelling occurred at the head of Inner Bay during the ebb. This upwelling resulted in a greater transport of nutrients from the deep water of Inner Bay to the head of the bay during ebb tide than during flood tides and was probably the cause of two situations that we observed: (1) higher concentrations in April of phosphate and silicate at the head of the bay at low tide than at high, and (2) higher concentrations in April of chlorophyll a near the head of Inner Bay at low tide (range 1.10-11.47 μg./l.) than at high (range 0.68-1.18 μg./l.)--possibly because of detritus or phytoplankton in the upwelled water.

The upwelling near the head of Inner Bay may explain the general decrease in the transparency of water in Traitors Cove proceeding from Behm Canal toward the head of Inner Bay. This decrease may have been caused by increasing concentrations of phytoplankton proceeding landward. This possibility is supported by the increasing concentrations of chlorophyll a in August in samples from Behm Canal landward.

The seaward movement of fresh water at the surface of Inner Bay allowed the formation of a temperature maximum layer there in June (fig. 3). As cool fresh water entered from Traitors River, it overrode the denser, though warmer, saline water of Inner Bay, which resulted in a cold layer at the surface overlying

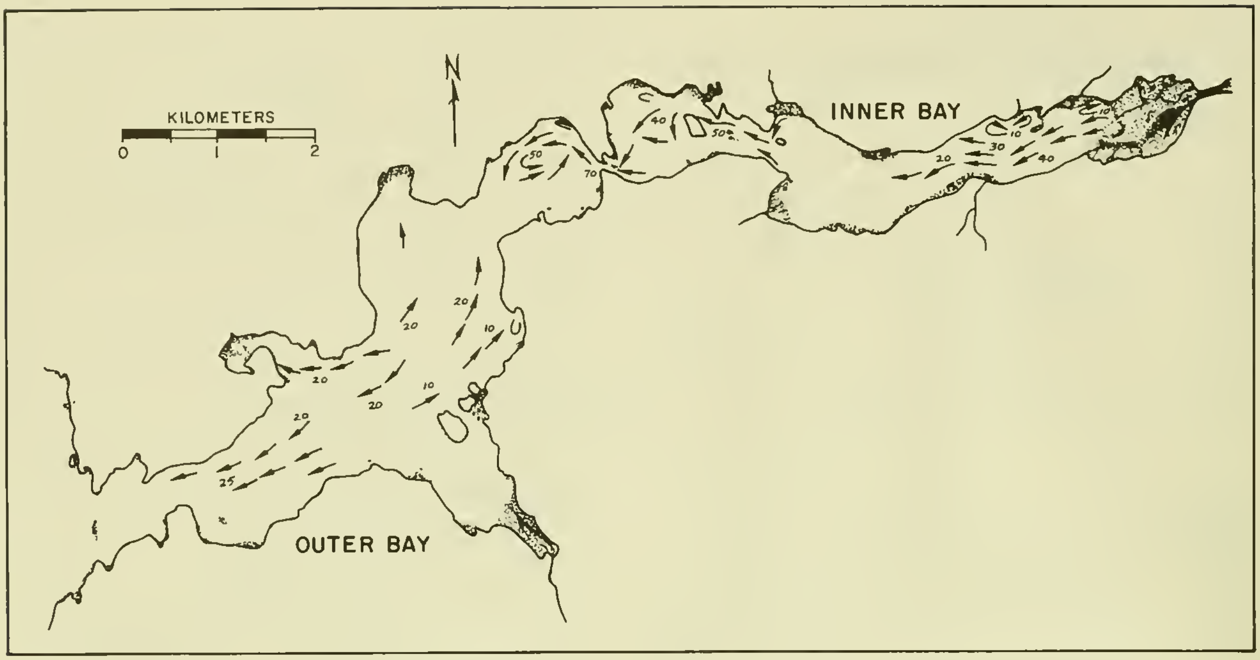

Figure 14.--Surface currents at ebb tide, Inner and Outer Bays, Traitors Cove, Alaska, 1-m. drogues. The numbers indicate current speed in centimeters per second.

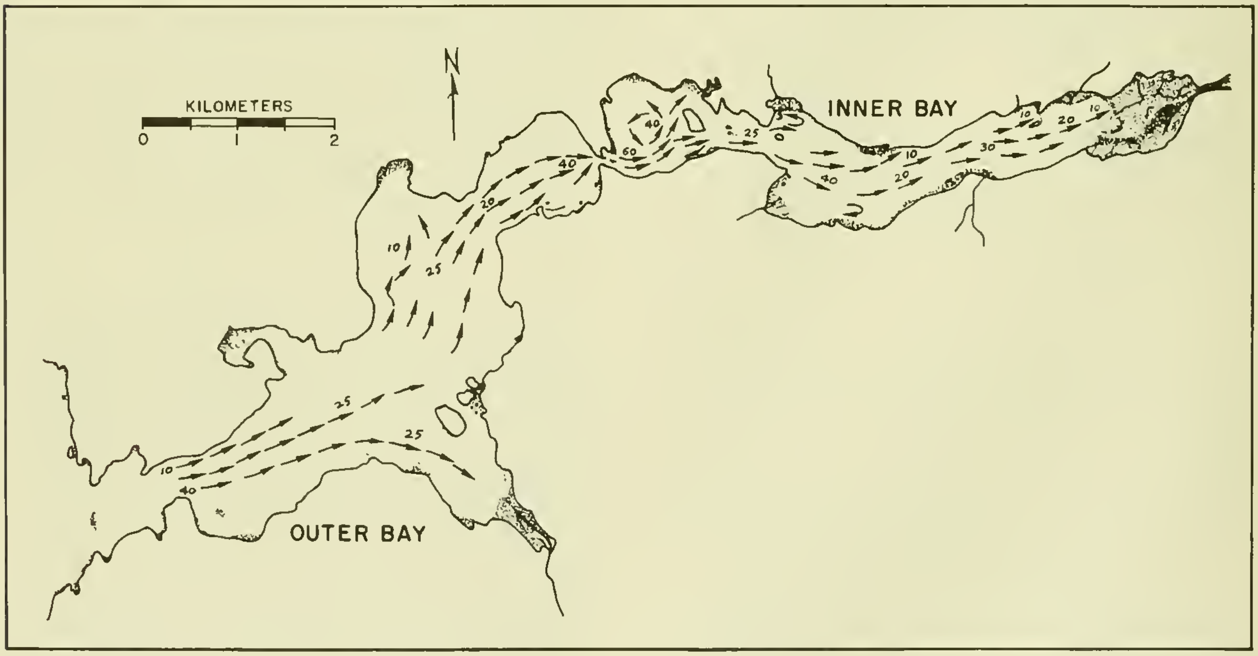

Figure 15.--Surface currents at flood tide, Inner and Outer Bays, Traitors Cove, Alaska, 1-m. drogues. The numbers indicate current speed in centimeters per second.

a warmer layer at 1 to 2 m. Because this layer in turn overlay cold deep water, a temperature maximum layer was formed.

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