RLO-1725-184
CONF-701064--1

UNIVERSITY OF WASHINGTON
DEPARTMENT OF OCEANOGRAPHY
and
DIVISION OF MARINE RESOURCES
Seattle, Washington 98105

Coastal Zone Processes and their Influence on Estuarian Conditions

28 October 1970

Nearshore and Estuarine
Zone Symposium
Portland, Oregon

by

Alyn C. Duxbury

Reference: M70:79
Oral Presentation prepared under
U. S. AEC Contract AT (45-1)-1725
and
NSF Grant GH-66 under the Sea Grant Program
...25-184
...r 1970

COASTAL ZONE PROCESSES AND THEIR INFLUENCE ON ESTUARIAN CONDITIONS

Introduction

A discussion of the estuarian and coastal zone is not complete unless the oceanic processes along the coast are also considered. On the basis of several premises, one can describe flushing rates or calculate the net circulation using salt and water budget equations in estuaries. However, estimates of this type are based on average conditions and thus are insensitive to the role that coastal waters may play in estuarian circulation, especially when short lived density-driven displacement enters into the problem.

One can readily calculate the volume transport in along the bottom of the Straits of Juan de Fuca and the volume transport out at the surface that are required to maintain the salt and water balance of the Straits of Georgia, Puget Sound estuarine systems. These transports can be shown to vary seasonally because of the changing freshwater discharge and the changing salinity of the incoming ocean water and outgoing surface water. The ability of the incoming water to flush the deep basins behind the shallow entrance sills is not just a function of its supply and salt content, but also a function of its temperature, which combines with the salinity to control its density. Only when the incoming water at depth is supplied in sufficient quantity and density can it displace the deep basin water behind isolating sills in the estuarian environment. Thus, flushing of the deeper estuaries is not necessarily a continuous process, but can be periodic and is related to oceanic processes that combine to place a dense water in position where it can flow inward to the estuarian system. In the Strait of Juan de Fuca case, the dense water must be raised sufficiently in the water column to clear the 180-m entrance sill of the Strait.

In other shallow coastal embayments such as Willapa Bay and Gray's Harbor, there are no deep basins isolated by shallow entrance sills. Thus, flushing is more of a continuous process. However, even here the changing characteristics of the ocean water presented to the bay entrance become important. The sudden appearance of a dense oceanic water at levels shallow enough to enter the channels leading to these embayments can cause a gravity flow into the bay that will bodily displace the water within the bay at a rate that is greater than that calculated from budget considerations. This type of flushing, unrelated to that required for salt and water balance or tidal exchange, can be regarded as both good and bad. It can be good if one considers that it is a mechanism for rapidly removing waste materials from a semi-isolated embayment or bad if the flushing leads to the displacement of water that contains the planktonic stage of some desired benthic organism such as oyster larvae.

The properties of the displacing water that make it dense, namely, high salinity and low temperature, may also create additional problems for biopopulations in an embayment. The biopopulations adapted to a warmer, less saline water may suffer considerably when a sudden flushing exposes them to a lower temperature-higher salinity water.

The properties of the oceanic water and the processes that act to present a variable type of oceanic water to the estuaries are part of near-coast ocean environment. Thus, for a full understanding of estuarian problems, we must also understand the coastal regime.

The Coastal Regime of Washington and Oregon

The coastal region of Washington and Oregon is located at about the same latitude as the center of the North Pacific West Wind Drift, the broad expanse of westward-moving water that is the northern side of the large North Pacific clockwise current gyre. This current often mistakenly referred to as the Japanese Current, divides as it approaches the coast, sending one branch northward to feed the Gulf of Alaska gyre and another branch southward to form a flow called the California Current. This latter flow, though not swift, is subtantial and enduring enough to carry water of the type found in the north central Pacific Ocean as far south as the tip of Baja, California.

The division of the West Wind Drift current into its two branches occurs about 11×10^2km, 600 n mi. off our coast. Thus, our immediate coastal region appears to be well removed from the direct influence of this major oceanic surface current. Indeed, our coastal region extending out to about 5×10^2km is characterized by weak and variable flows. Dynamic topographies that yield the mean ocean surface current relative to the 1000 decibar level in the same way atmospheric pressure charts are used to determine the wind field show that surface currents are variable at about 5 cm/sec^{-1} off shore, about 1/10 of a knot, and about twice that, closer to shore.

The low value of flow imposed by the oceanic scale currents in our coastal region allows the local processes for generating currents to become very important. Studies conducted in the coastal regions of Washington and Oregon point out that the local wind influence is instrumental in controlling the water circulation and that the seasonal cycle in the prevailing wind system produces a seasonal cycle in the coastwise flow and the properties of the seawater found near shore. A reversal in the nearshore surface current during winter is evident.

During the summer months, the North Pacific high pressure cell enlarges and migrates to a position where it, combined with the Canadian Continental low cell pressure, produces predominately northerly winds of light magnitude. During the winter the condensing of the North Pacific high and the development of the Aleutian low cell cause south winds of stronger magnitude to predominate along the coast. This cyclic reversal in the local wind field is what causes the reversal in the alongshore flow of the surface water. It also causes a reversal in the onshore and offshore component of the surface flow. During the winter, water from offshore is moved toward the coast and held locked in against the beach where it is mixed with fresh water issuing from the rivers and land drainage; and then it migrates northward. In the summer the surface water and river effluent are moved seaward from the coast and to the southwest. This onshore-offshore flow locally supplies seawater to the coast in the winter to cause downwelling and removes the surface seawater during the summer necessitating upwelling of deeper water to maintain continuity.

Fig. 4

Fig. 5

The movement of coastal water in response to the wind approximates that described in Ekman wind drift theory. That is, the surface water moves at an angle of about 45° to the right of the wind stress vector while the transport of water as integrated over the vertical column set in motion by the wind is about 90° to the right of the wind. The transport and surface current as determined from Ekman theory closely agree with that observed. Studies of the distribution of the Columbia River effluent under AEC support have shown that occasionally discrete cells of low salinity water are formed near the river mouth and migrate seaward as an identifiable mass of water. Their displacement over time nearly matches that predicted by Ekman drift in both speed and direction.

Fig. 6

The seasonal variation in the local surface currents greatly affects the type of water found adjacent to the coast where it exchanges with the estuaries. In the summer the offshore wind-induced transport causes coastal upwelling. Along the coast, this process brings water from depth up to the surface which has low temperatures and high salinities. This upwelled water in response to the removal of surface water seaward forms a barrier of dense water that isolates the effluent from the Columbia River from direct contact with the coast. At this time of year the Columbia River becomes the major source of dilution for the region as freshwater contribution from smaller coastal rivers is at a minimum. The surface salinity patterns clearly reflect upwelling during summer and the importance of the Columbia River as a singular diluting source.

Fig. 7

In the winter the northward and onshore set of the surface flow under the driving wind stress produces another distribution of properties. The prevailing wind pattern at this time of year is closely coupled with an appreciable increase in coastal precipitation. This increases the freshwater discharge of all coastal rivers into the nearshore environment and makes the Columbia River less evident as a single source of dilution. One therefore sees a dilute band of seawater held in against the coast and tending northward. The surface salinity distributions during winter are indicative of the flow.

Fig 8

The surface winds are usually stronger in winter than in summer. Thus, even though the local currents tend to reverse seasonally, the northward flow in winter is greater than the southward flow in summer. This aids in producing a net trend of coastal water to the north over the annual cycle. Another process also acts to promote a northward-tending flow especially at depth. The presence of the Strait of Juan de Fuca with its attached estuarian systems makes certain demands on the water at the coast. The water and salt budget equations show that an influx of bottom water into the Straits of Georgia, Puget Sound System is on the average about 13 x $10^4 m^3 sec^{-1}$, with a range from 6 x $10^4 m^3 sec^{-1}$ in winter to 26 x $10^4 m^3 sec^{-1}$ in summer. This is no small flow rate. At its mean value, it is more than 18 times the average annual discharge of the Columbia River. The outflow at the surface is equal to the inflow at depth plus the freshwater contribution. This influx at depth into the Straits and discharge at the surface acts to pull ocean water at depth along the coast toward the entrance enhancing a northward flow along the coast of Washington at all seasons. The kind of water at depth to flow toward the Strait of Juan de Fuca is evident in the migration patterns of seabed drifters that have been released along the coast and picked up on the beaches or at sea by bottom trawlers.

Fig. 9

The Seasonal Change in Water Properties at the Coast.

We should now consider the change in coastal water type that is associated with the seasonal wind reversal. To do this we will consider the characteristics of the water in the Strait of Juan de Fuca. In midwinter, February, data from a section across the Strait at Pillar Point show that at 50-m depth, water of 31.5 to 32 ^{o}/oo salinity increasing to 33.7 ^{o}/oo at 180-m depth, and isothermal at 8^{o}C is available as the incoming water to be mixed with outflowing water by tidal action on the sills. This water has a density range of about 24.94 to 26.27 in sigma-t units. In the summer the water occupying the same position has a salinity of 32^o/oo at 50 m increasing to about 33.9 ^{o}/11 at depth and a temperature structure that varies from 8^{o}C at 50 m down to about 6.3^{o}C at depth. This water has a density range of about 24.94 to 26.67. Clearly the densest water available for transport into the Straits at depth to be mixed with the outflowing surface water is found

Fig. 10

during the summer. Of equal importance is the higher salinity of the near surface water with which the deep water mixes during the late summer. This higher surface salinity is, of course, a result of the reduced freshwater discharge at this time of year and the deep water from the basins that is being displaced by the incoming dense water.

Thus, the densest water available at the sills in Puget Sound to displace the water at depth in the deep basins behind the sills is formed during late summer. In a season when coastal upwelling is particularly intense and widespread, and precipitation is low, a greater quantity of denser water can be formed to act as a flushing agent. If precipitation is high during a summer and coastal winds do not promote strong upwelling, there is a chance that an insufficient quantity of the dense water will be produced to thoroughly flush the deep isolated basins of a system such as Puget Sound.

The small shallow harbors having direct contact with the ocean along the Washington and Oregon coast are not as dependent on the quantity and density of the intruding seawater as Puget Sound is. These embayments do not have deep basins behind isolating sills that act as catch basins for dense water. The ratio of tidal prism volume to volume of water at MLW stand is large indicating that a considerable portion of the volume of the embayment at MSL is removed and added each tide cycle. Their extensive shallows and exposure to coastal winds, as well as the turbulence generated in the tidal stream at their entrances, combine to aid in vertical mixing and promoting exchange between the tidal prism and the residual water left at each low tide. The dilution of these shallow harbors by their rivers produces strong vertical density structure near the rivers that retards vertical mixing.

The seasonal change in the coastal water present off the mouths of these harbors and bays, however, does have an effect on the water properties within the embayments. In the wintertime coastal precipitation increases the flow of the rivers into these harbors to decrease their salt content and cause strong density stratification near their heads. In the case of Willapa Bay and Gray's Harbor, the effluent from the Columbia is directed northward along the coast to occupy a position off their mouths. Thus, in winter, fresh water is available to the harbors from both the landward and seaward side. In the summer the river discharge into the heads of these two harbors is reduced, and a high salinity-low temperature upwelled water is present off their mouths. This means that seasonally a fairly large fluctuation in salinity can occur while the temperature is buffered.

In the winter, water temperatures are controlled by local climatic conditions and by the temperature of freshwater sources. In the summer, however, the increase in temperature due to solar heating of the bay is somewhat offset by the introduction of the low temperature upwelled coastal water. Inspection of the data available in Willapa Bay and Gray's Harbor at midbay position shows that considerable scatter in surface and salinity values is found at the surface. These data, however, have been collected at all tidal stages and reflect a trend of elevated temperatures and lowered salinities during ebb stages and lowered temperatures and elevated salinities during flood periods in the summer. In the winter the ebb produces lowered temperatures and salinities, while the floodstage elevates both temperature and salinity. In the summer an occasional data point will show a very low temperature and high salinity, indicating the presence of upwelled oceanic water at the mid-channel observation point.

Temperature and salinity data uncorrected for tidal stage in Willapa Channel (Bendiksen) can be used to construct a T-S envelope that shows the seasonal change in water characteristics. The limits of salinity and temperature changes found in such an envelope may be used to judge the fitness of the water for sustaining a biopopulation. As an example, the adult Pacific oyster *Osteria gigas* has a known tolerance range to temperature and salinity.

Fig. 12 The larval stage has a smaller tolerance range for survival. This oyster also has a required temperature for spawning. These tolerance limits also

Fig. 13 can be drawn on a T-S diagram and superimposed on the seasonal T-S envelope for a harbor.

It is easy to understand from the comparison of these two envelopes that the summer introduction of cold upwelled coastal water into the harbor acts to suppress the temperatures below that required by the oysters for maintenance of the larval stage or reproduction at the mid-channel location. Thus, intensive coastal upwelling at a critical period may destroy the larvae or not allow reproduction to occur. During summer the temperatures of the shallow reaches remote from the mid-channel may or may not rise sufficiently to allow survival and spawning. Although I cite Willapa Bay here, similar processes occur at the other harbors along both the Oregon and Washington Coast. However, in harbors other than Willapa Bay and Gray's Harbor, dilution occurs primarily from rivers entering the heads of the estuaries. There is no single large river such as the Columbia to provide additional coastal wintertime dilution at their mouths.

The estuary of the Columbia River interacts with the open sea quite differently from the embayment-type estuaries where inflow and outflow are primarily tidal. In the Columbia estuary the large river flow limits the intrusion of a saltwater wedge at depth keeping it short of its fall line.

The normal intrusion of the salt wedge is limited between Tongue Point and the sea.

The large vertical velocity shear between the seaward-moving river water and the intruding saltwater wedge acts to maintain a sharp boundary between these two waters across which seawater is entrained upwards into the more turbulent mixed surface effluent. This erosion of saltwater from the wedge requires that the salt wedge be replenished. Thus, the inflow of saltwater into the river channel on the flood exceeds that required to move t wedge upstream. Outside of the river mouth, the flow of effluent extending to a depth of about 15 m also generates a velocity shear and entrainment of saltwater from below that is used to increase the salinity and volume of the effluent. Both within and without the estuary, the salt and water entrainment promote a localized upwelling of deeper water immediately around the mouth of the river and seaward of the mouth under the issuing jet. This upwelling is highly localized and is driven by processes unrelated to those affecting the more widespread wind-driven upwelling. The velocity shear upwelling should be strongest at periods of high discharge when entrainment increases.

The foregoing discussion establishes in general terms the manner in which the circulation and changes in the properties of coastal water control in part the physical processes in the bordering estuaries. We now need to consider some of the other aspects of the interplay between the ocean and estuaries.

The Nutrient and Gas Exchange Between Coastal and Estuarine Water.

Not only are water, salt, and heat exchanged between the estuaries and the coastal zone, but also all other dissolved substances carried in the water One class of substances of importance to the biological populations is nutrien another is the dissolved gasses. Other products such as pollutants, which are also important, will be neglected here. The most important of the dissolved gasses is oxygen. It is obvious that the displacement of the isolat deep basin water behind the sills in Puget Sound by the intruding dense wat in late summer also provides a mechanism by which aeration at depth is acco plished. However, the oxygen concentration of the intruding upwelled water at Pillar Point during the summer is low at 0.25 to 0.10 mg-at/L. Subseque mixing on the sills elevates this level to about 0.35 mg-at/L. The wintertime oxygen concentrations of the intruding water which has its source at lesser depths in the sea are higher, ranging from 0.45 to 0.25 mg-at/L. In late summer the intruding water, when mixed over the sills, has an oxygen content of about ^{o}0.4 mg-at/L. This oxygen is then carried to depth in the flushing process. If flushing of this deep water is not complete, then insufficient aeration and removal of accumulated organics and nutrients occ at depth.

Fig. 15

Fig. 16

Within the estuaries, land drainage and sewage disposal contribute a nutrient supply to the surface waters. As an example here, the Metro System of Seattle alone contributes on the average 2,730 lbs/day of nitrate-nitrogen, 8,260 lbs/day of ammonia-nitrogen, 5,200 lbs/day of total phospho and 4,200 lbs/day of orthophosphate as phosphorus to Puget Sound. An estimate of the total nutrient supply to Puget Sound and other estuaries is not available at this time. The coastal ocean water that enters the estuaries at depth also acts as a source of nutrients. It was stated earlier that the summer transport of seawater into the Straits of Juan de Fuca as estimated from continuity was $26 \times 10^4 m^3 sec^{-1}$. The inorganic phosphorus-phosphate content of this water averages about 2.5 µg-at/L. This means that about 6.5×10^8 µg-at sec^{-1} is delivered by advection to the Strait from the sea.

Fig. 7

An outward transport of nutrients in the surface layers is also occurring.

The harbors bordering the open coast also exchange dissolved gasses and nutrients with the coastal water. The amount of exchange is sensitive to the type of coastal water lying at the harbor mouth. During winter the coastal water is oceanic surface water mixed with the effluents of the local rivers. This water is usually well aerated by the stronger winter winds and wave action. Its low salinity, combined with wind mixing, tends to produce moderately high dissolved oxygen levels (0.5-0.6 mg-at/L). Its nutrient content is controlled in part by the typical concentrations found in the oceanic surface water, 5.50 μg-at/L for nitrate and 1.0 μg-at/L for inorganic phosphate. The river water present as the diluting agent may also add its contribution of nutrients if the river is a source of these materials.

In the summer when upwelling of subsurface water prevails under the lighter northerly winds, oxygen concentrations of the coastal water may drop appreciably and nutrient levels increase. Oxygen concentrations at depths where access can be gained into the estuaries can be as low as 0.2 to 0.3 mg-at/L. A specific example may be cited here when in August of 1963 samples were taken along the coast between Gray's Harbor and Long Beach. In 15 m of water off Grayland, the samples taken indicated that the seawater at 10 m depth had a temperature of 8.22°C, a dissolved oxygen content of 0.236 mg-at/L, and a salinity of 33.2 $^{\circ}$/oo. The collecting of samples on this occasion was prompted by a shellfish kill along the ocean beaches a short time before. If mixing and aeration of upwelled coastal water in the entrance zone to the harbors or along the ocean beach are not sufficient, the biopopulations may be subject to both depressed temperatures and low oxygen values. The nutrient values of the coastal upwelled water exchanging with the estuaries are elevated during the summer because of its deeper source.

Concentration values of 25 μg-at/L for nitrate, a fivefold increase over winter levels, are possible with a twofold increase of inorganic phosphate to 2 μg-at/L. Concentrations may be diminished to lower levels by *in situ* biological utilization near the sea surface if the upwelled water is retained in the photic zone prior to its exchange with the estuaries.

Conclusion.

Estuarian and coastal zone processes are interdependent. The estuaries demand water from the coastal zone for tidal processes and to maintain their average budgets of salt and water. The type of water present in the coastal zone to meet these demands is governed by coastal and oceanic conditions, and in the case cited here, is closely related to seasonal climatic changes. The presence of dense water at the estuary mouth increases the flushing potential of the deeper well-isolated basins by gravity flows, whereas the presence of less dense water does not. Mixing processes at the mouths of estuaries or across internal sills within estuaries that are dependent on tidal stream flow combine the inflowing oceanic water at depth with the outward-flowing dilute surface water in the estuary. Thus, the strength of the tidal currents and topography, combined with the properties of the surface water, also enter into the problem of flushing and exchange of water properties. It is a complex interaction dependent on many variables. Because of this, each estuary or embayment is unique unto itself and reacts to the whims of nature and man alike.

REFERENCES

Barnes, Clifford A., A. C. Duxbury, and Betty-Ann Morse, In Press, The Circulation and Selected Properties of the Columbia River Effluent at Sea, *Bioenvironmental Studies of the Columbia River Estuary and Adjacent Ocean Region*, (D. L. Alverson and A. T. Pruter ed.), U. S. Atomic Energy Commission Publication.

Budinger, T. F., L. K. Coachman, and C. A. Barnes, 1964, *Columbia River Effluent in the Northeast Pacific Ocean, 1961, 1962: Selected Aspects of Physical Oceanography*, University of Washington, Department of Oceanography Technical Report No. 99, Seattle.

Department of Oceanography, 1953-54, *Puget Sound and Approaches, A Literature Survey, Vol. I, II, III.*, University of Washington, Seattle.

Duxbury, Alyn C., In Press, Variability of Salinity and Nutrients off the Columbia River Mouth, *Bioenvironmental Studies of the Columbia River Estuary and Adjacent Ocean Region*, (D. L. Alverson and A. T. Pruter ed.), U. S. Atomic Energy Commission Publication.

Duxbury, Alyn C., Betty-Ann Morse, and Noel McGary, 1966, *The Columbia River Effluent and its Distribution at Sea*, University of Washington, Department of Oceanography Techical Report No. 156, Seattle.

Morse, B.-A., M. G. Gross, and C. A. Barnes, 1968, Movement of Seabed Drifters near the Columbia River, *Journal of the Waterways and Harbors Division*, American Society of Civil Engineers, 94(WW1): 93-103.

Redfield, A. C., 1950, Note on the Circulation of a Deep Estuary—the Juan de Fuca—Georgia Straits, *Proceedings of the Colloquium on the Flushing of Estuaries*, Woods Hole Oceanographic Institution: 175-177.

Stefansson, U., and F. A. Richards, 1963, Processes Contributing to the Nutrient Distribution of the Columbia River and Strait of Juan de Fuca, *Limnology and Oceanography*, 8(4):394-410.

Washington Department of Fisheries, *Observations of Seawater Temperatures, Density, and Salinity, State of Washington 1951-1957*, Hydrographic Data, Vol. 1, No. 2.

FIGURE CAPTIONS

Fig. 1--Surface Salinity and direction of surface flow in the Northeast Pacific Ocean.

Fig. 2--Dynamic topography of the near coastal zone, summer conditions.

Fig. 3--Dynamic topography of the near coastal zone, winter conditions.

Fig. 4--Mean surface wind vectors by month, 1961-1963.

Fig. 5--Frequency of northerly and southerly component winds by month.

Fig. 6--Average direction and magnitude of monthly Ekman transport, 1961-1963.

Fig. 7--Generalized distribution of Columbia River effluent as indicated by surface salinities, summer condition.

Fig. 8--Generalized distribution of Columbia River effluent as indicated by surface salinities, winter conditions.

Fig. 9--Release points and hypothetical paths of seabed drifters along the Washington coast.

Fig. 10--Temperature and slainity cycles at Pillar Point, Strait of Juan de Fuca, February 1953--March 1954.

Fig. 11--Surface salinities and temperatures observed in Willapa Channel (Bendiksen) 1954.

Fig. 12--Optimum salintiy and temperature ranges for O. gigas, the Pacific Oyster.

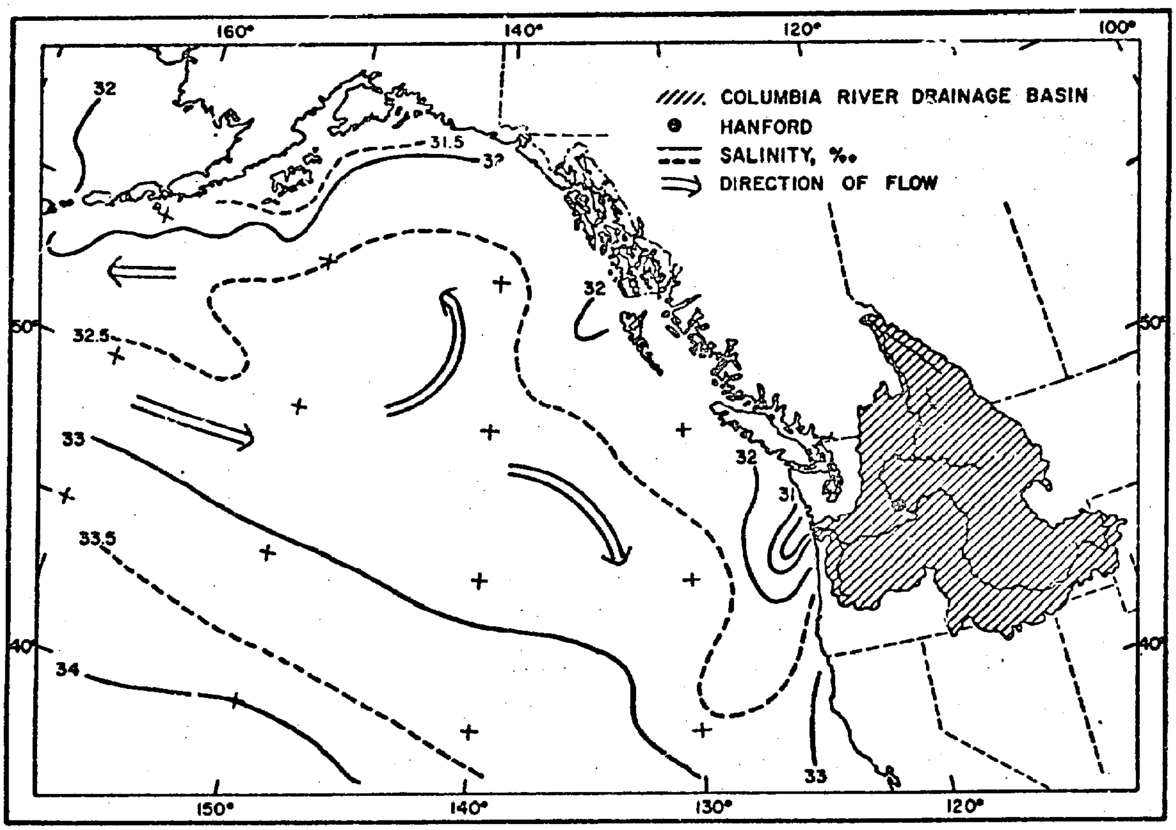
Fig. 13--A comparison of optimum salinity and temperature conditions for O. gigas and surface conditions observed in Willapa Channel.

Fig. 14--Vertical salinity structure in the Columbia River estuary, August 1963.

Fig. 15--Dissolved Oxygen content, mg-at/L, in the Strait of Juan de Fuca, July 1953.

Fig. 16--Dissolved Oxygen content, mg-at/L, in the Strait of Juan de Fuca, February 1953.

Fig. 17--Dissolved inorganic phosphate content, μg-at/L, July 1953.



160°
140°
120°
100°
COLUMBIA RIVER DRAINAGE BASIN
HANFORD
SALINITY, ‰
DIRECTION OF FLOW
32
31.5
32
32
32.5
33
32
31
33.5
34
33
50°
40°
150°
140°
130°
120°

ig. 1

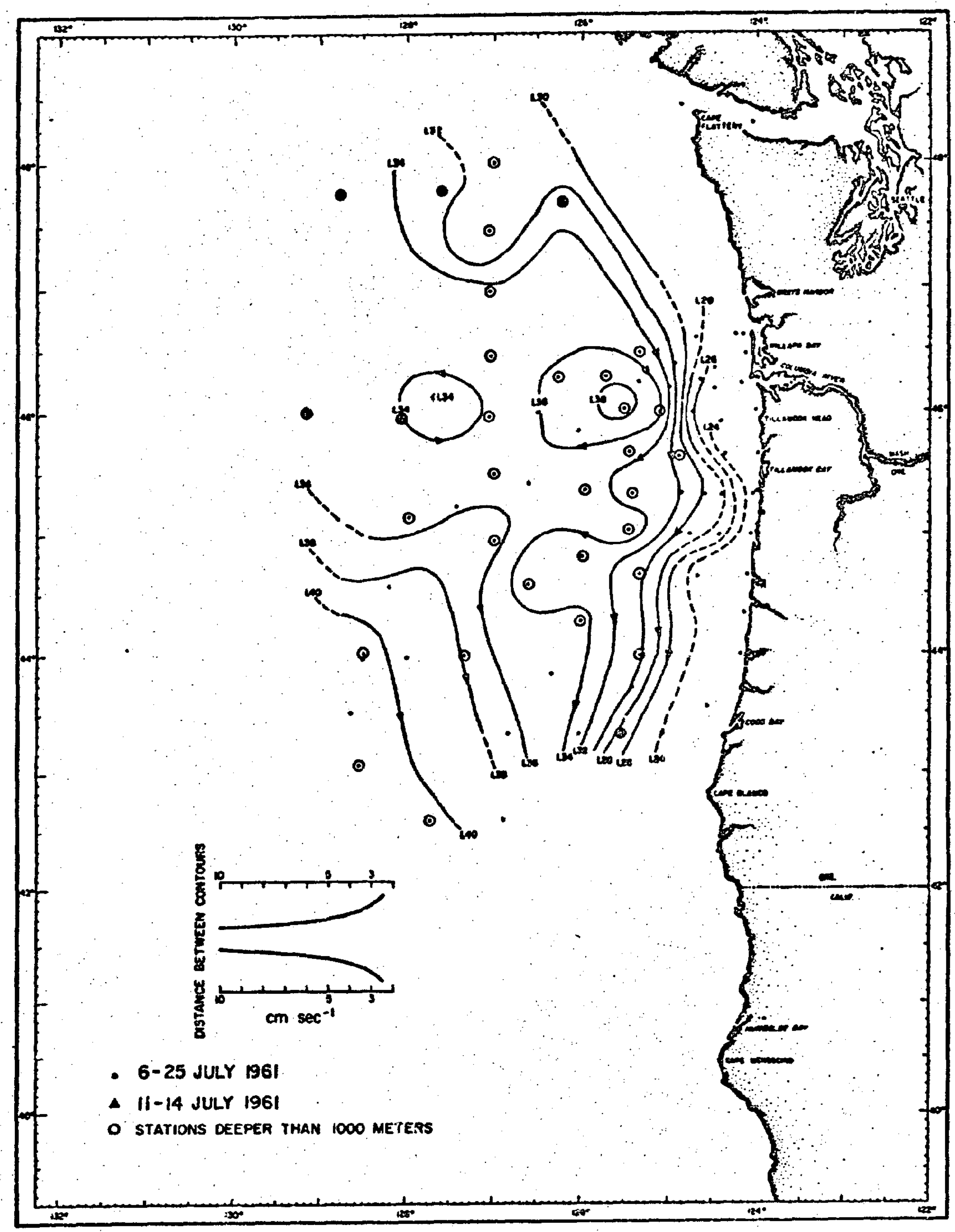

DISTANCE BETWEEN CONTOURS
cm sec-1
6-25 JULY 1961
11-14 JULY 1961
STATIONS DEEPER THAN 1000 METERS
COOS BAY
CAPE BLANCO
TILLAMOOK HEAD
COLUMBIA RIVER

Fig. 2

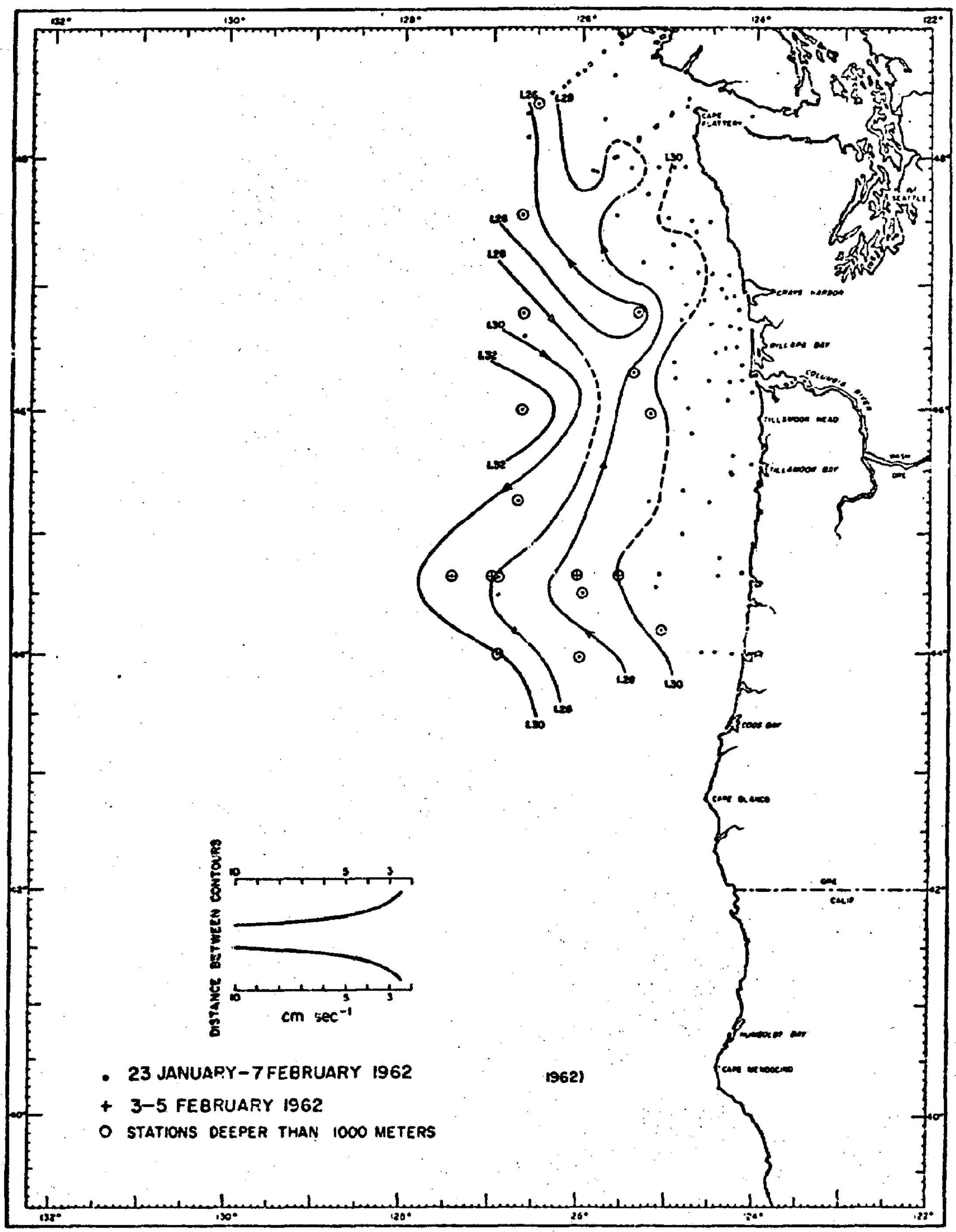

DISTANCE BETWEEN CONTOURS
cm sec⁻¹
• 23 JANUARY–7 FEBRUARY 1962
+ 3–5 FEBRUARY 1962
O STATIONS DEEPER THAN 1000 METERS
1962)
CAPE FLATTERY
SEATTLE
GRAYS HARBOR
WILLAPA BAY
COLUMBIA RIVER
TILLAMOOK HEAD
TILLAMOOK BAY
COOS BAY
CAPE BLANCO
ORE
CALIF
HUMBOLDT BAY
CAPE MENDOCINO

Fig. 3

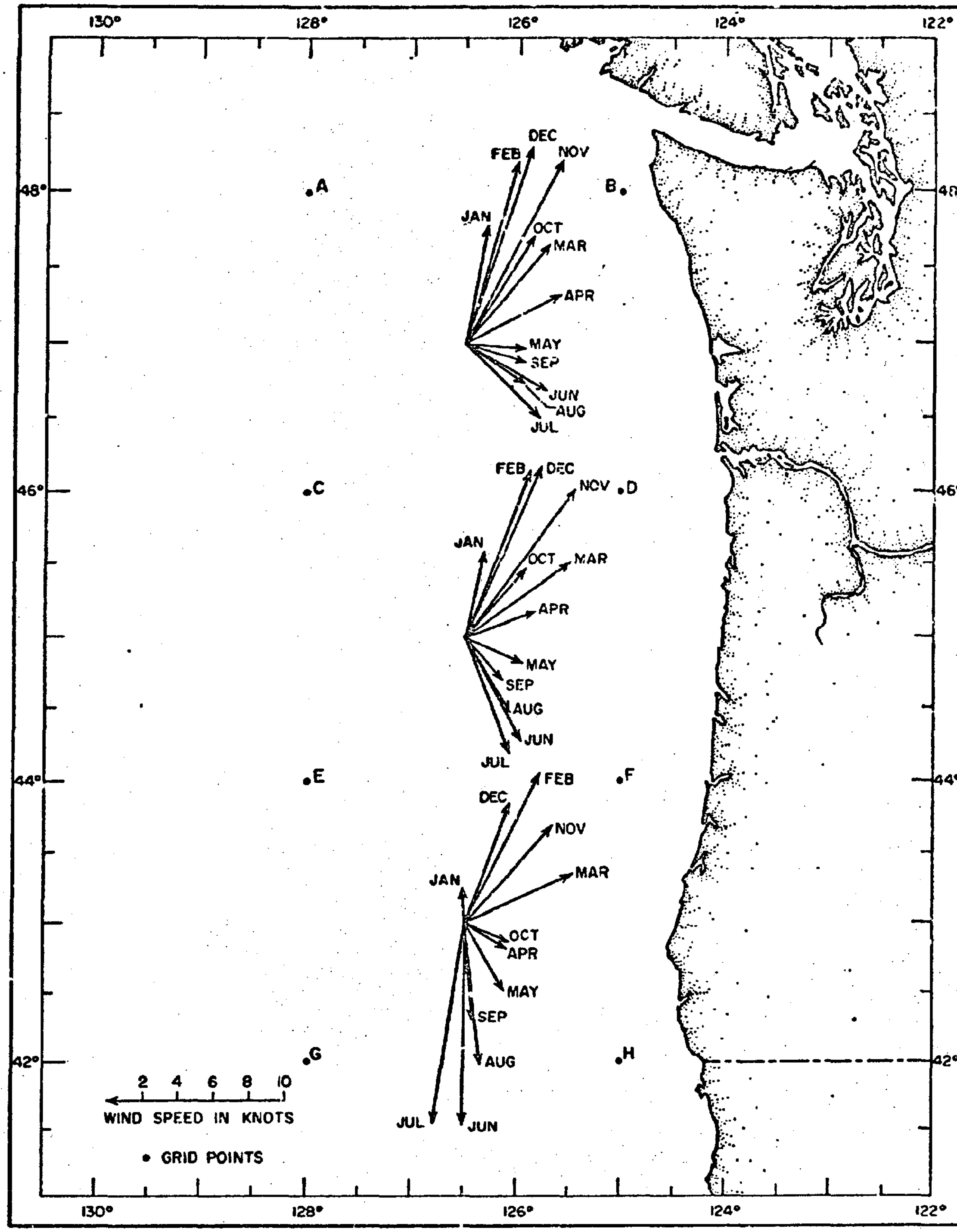

130°
128°
126°
124°
122°
48°
46°
44°
42°
A
B
C
D
E
F
G
H
JAN
FEB
DEC
NOV
OCT
MAR
APR
MAY
SEP
JUN
AUG
JUL
2 4 6 8 10
WIND SPEED IN KNOTS
• GRID POINTS

Fig. 4

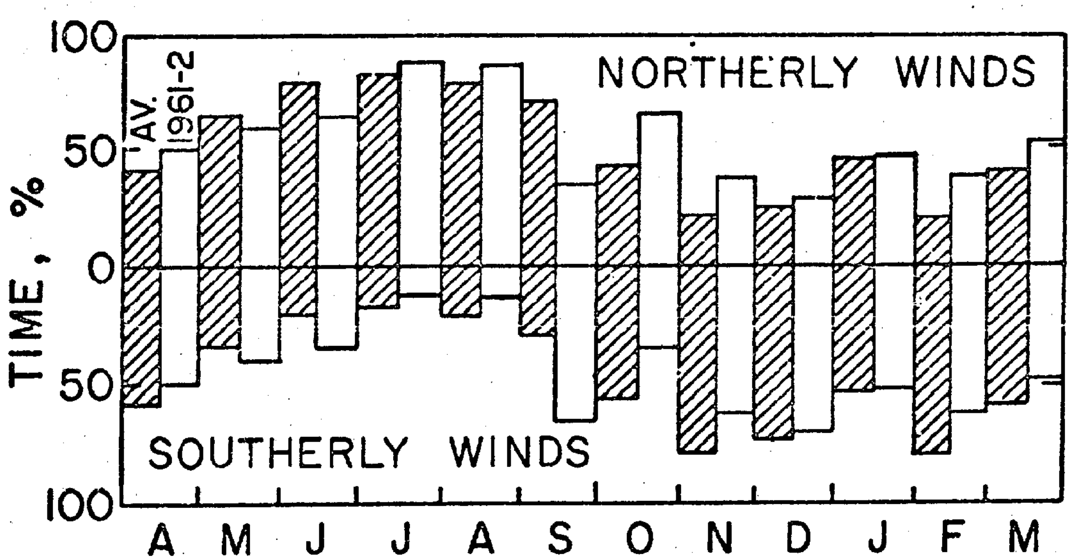
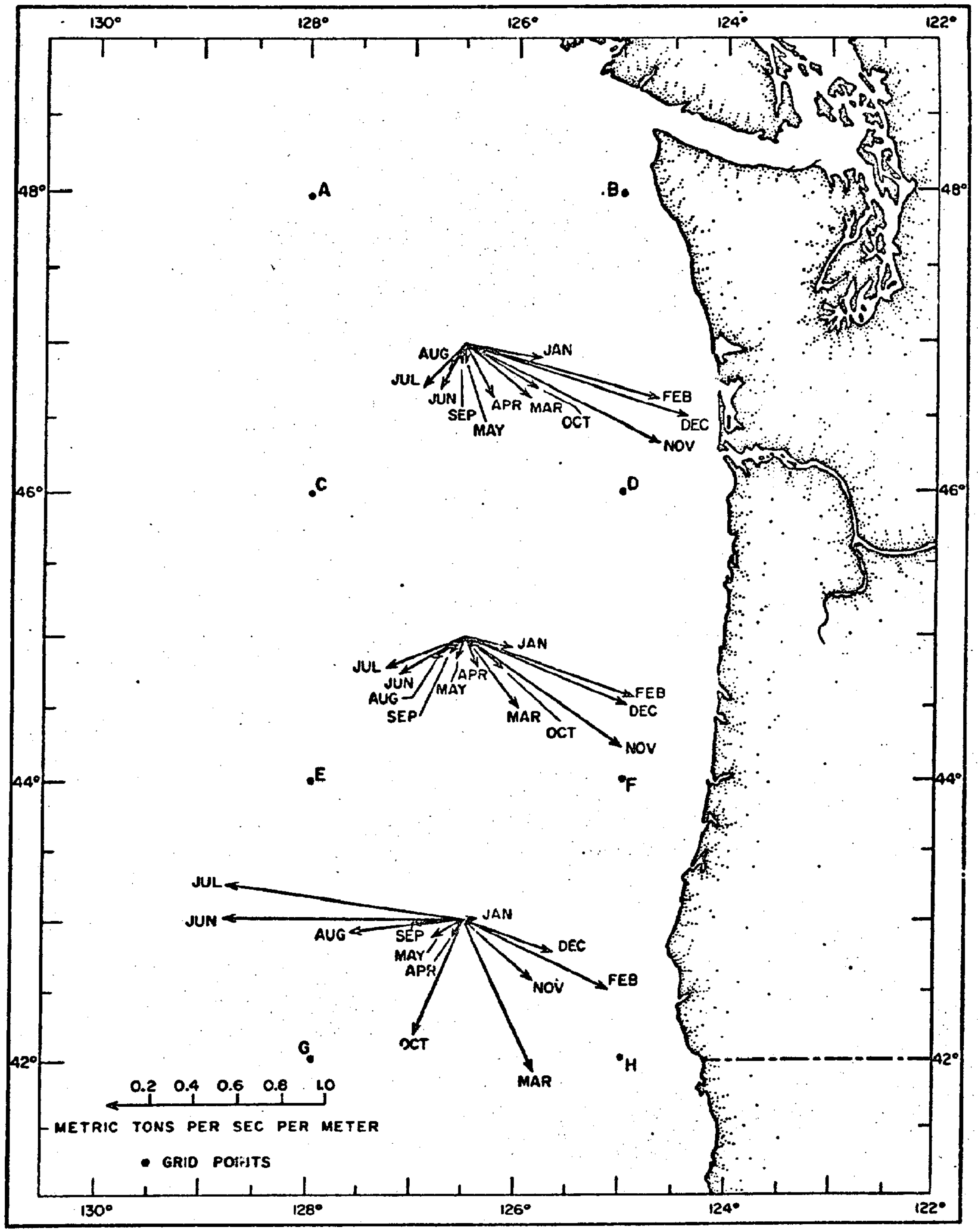

100
50
0
50
100
TIME, %
AV.
1961-2
NORTHERLY WINDS
SOUTHERLY WINDS
A M J J A S O N D J F M

Fig. 5



130°
128°
126°
124°
122°
48°
46°
44°
42°
A
B
C
D
E
F
G
H
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
0.2 0.4 0.6 0.8 1.0
METRIC TONS PER SEC PER METER
GRID POINTS

Fig. 6

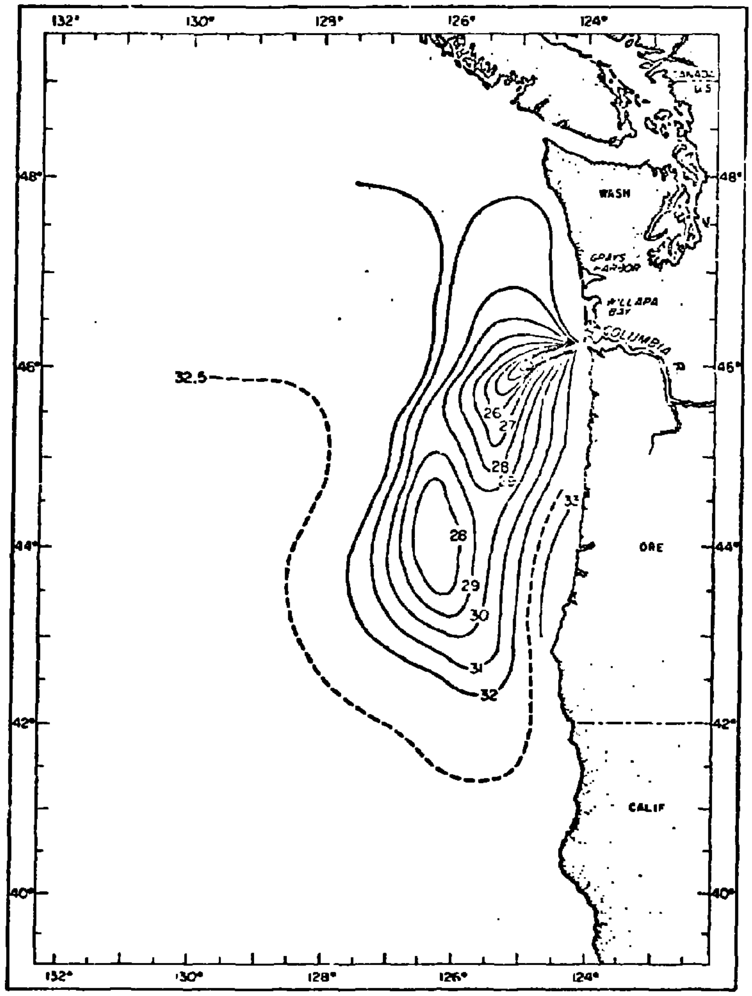
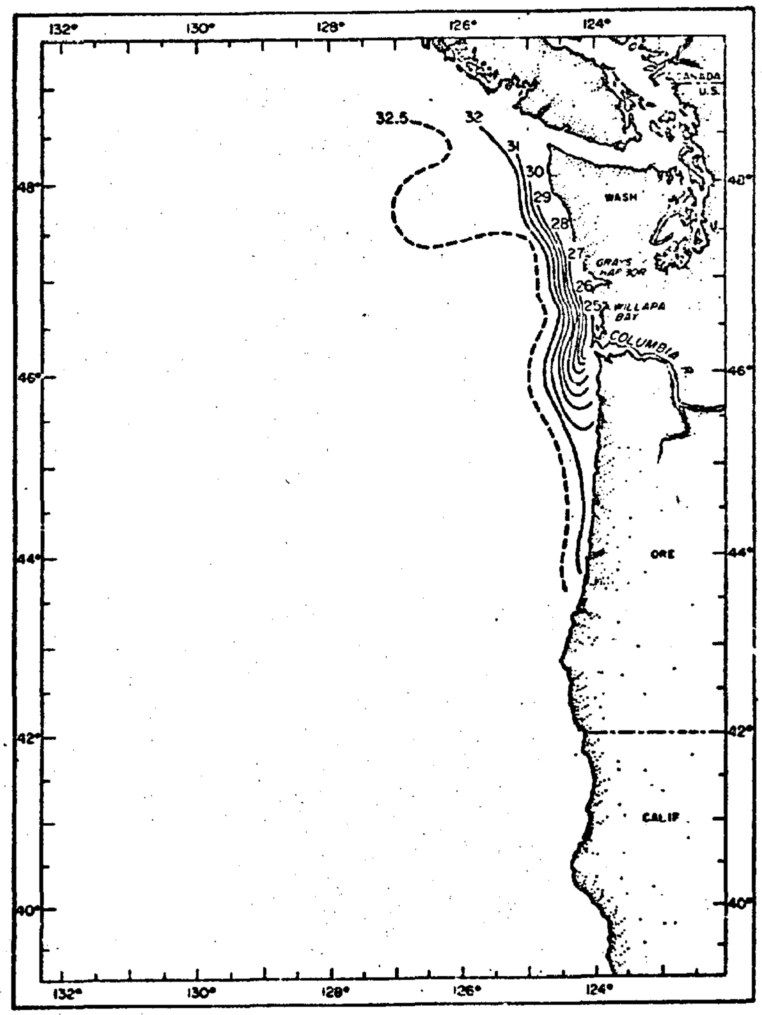

132°
130°
126°
124°
48°
46°
44°
42°
40°
128°
WASH
COLUMBIA
ORE
CALIF
32.5
26
27
28
28
29
30
31
32
33

Fig 7



132°
130°
128°
126°
124°
CANADA
U.S.
32.5
32
31
30
29
28
27
26
25
WASH
GRAY'S HARBOR
WILLAPA BAY
COLUMBIA
48°
46°
44°
42°
40°
ORE
CALIF

Fig. 8

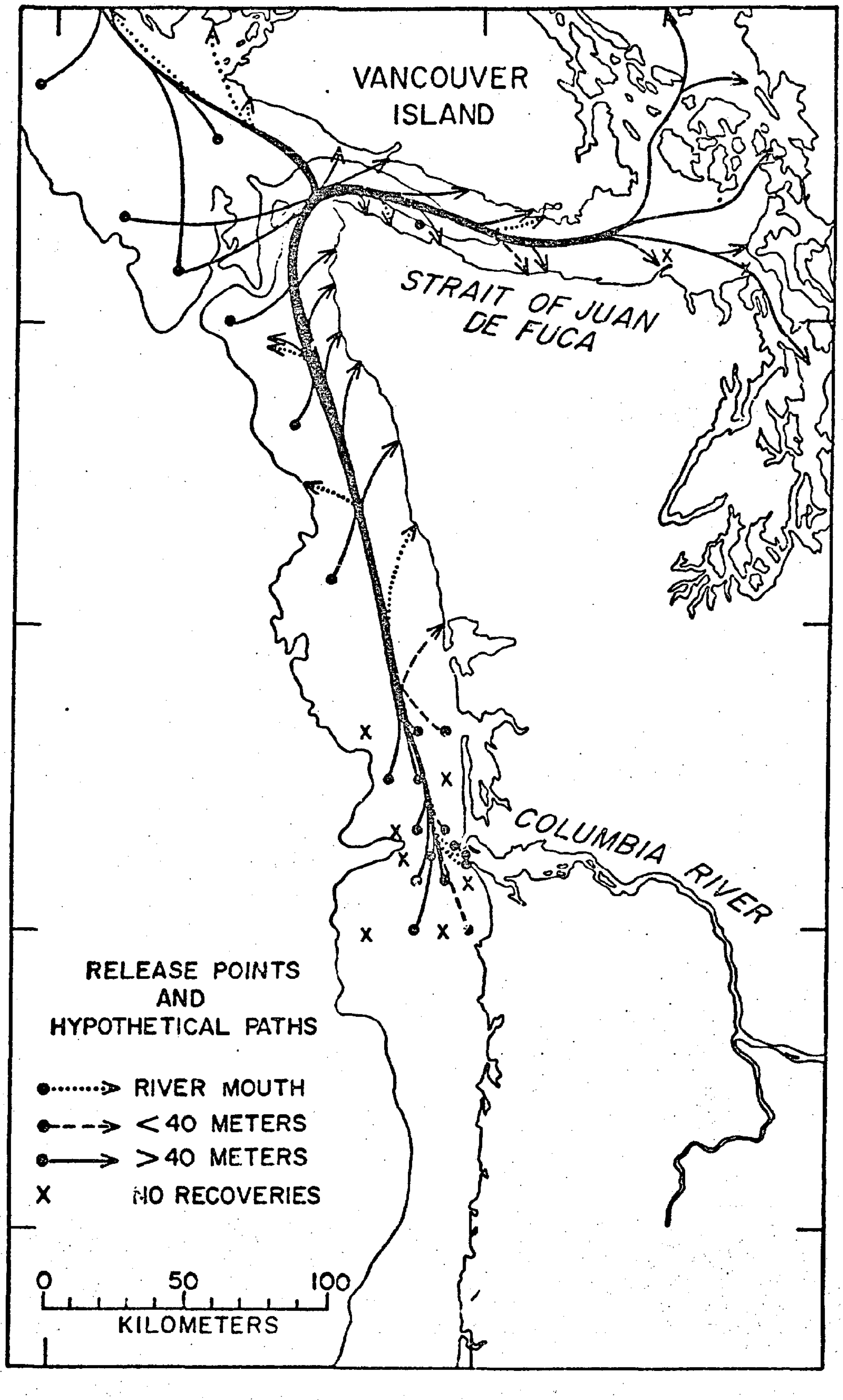
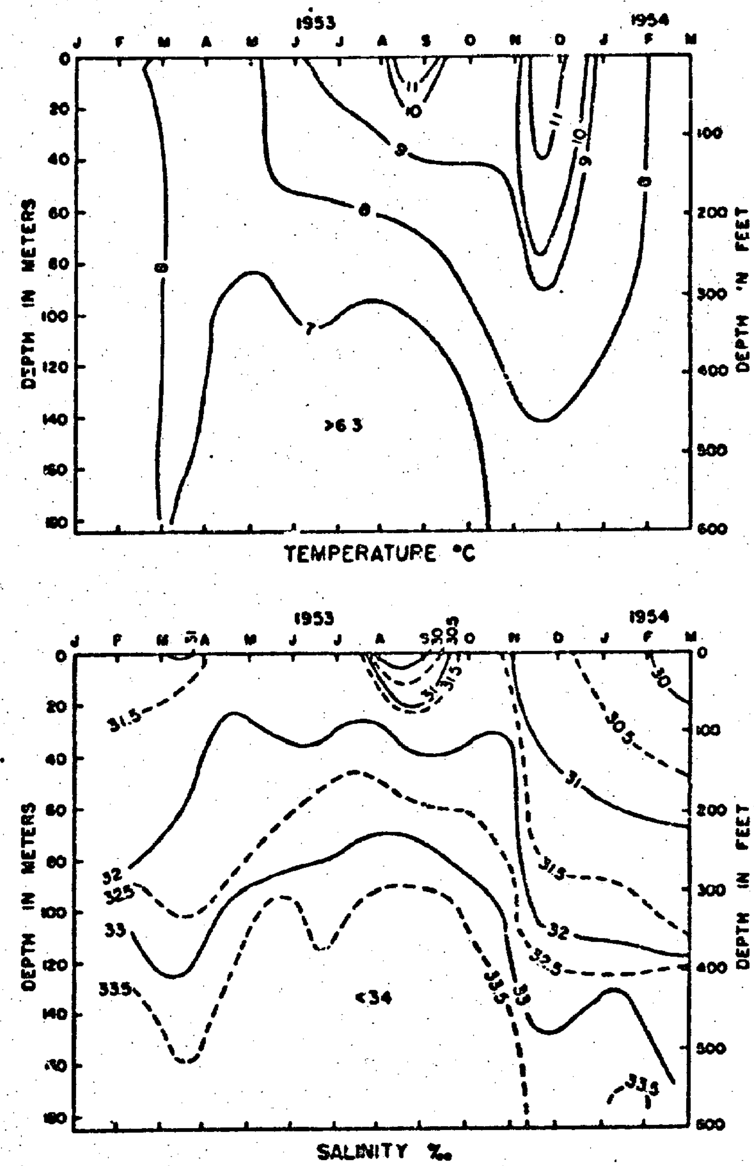

VANCOUVER ISLAND
STRAIT OF JUAN DE FUCA
COLUMBIA RIVER
RELEASE POINTS AND HYPOTHETICAL PATHS
RIVER MOUTH
<40 METERS
>40 METERS
X NO RECOVERIES
0
50
100
KILOMETERS

fig. 9



LEGEND

TEMPERATURE

PUGET SOUND

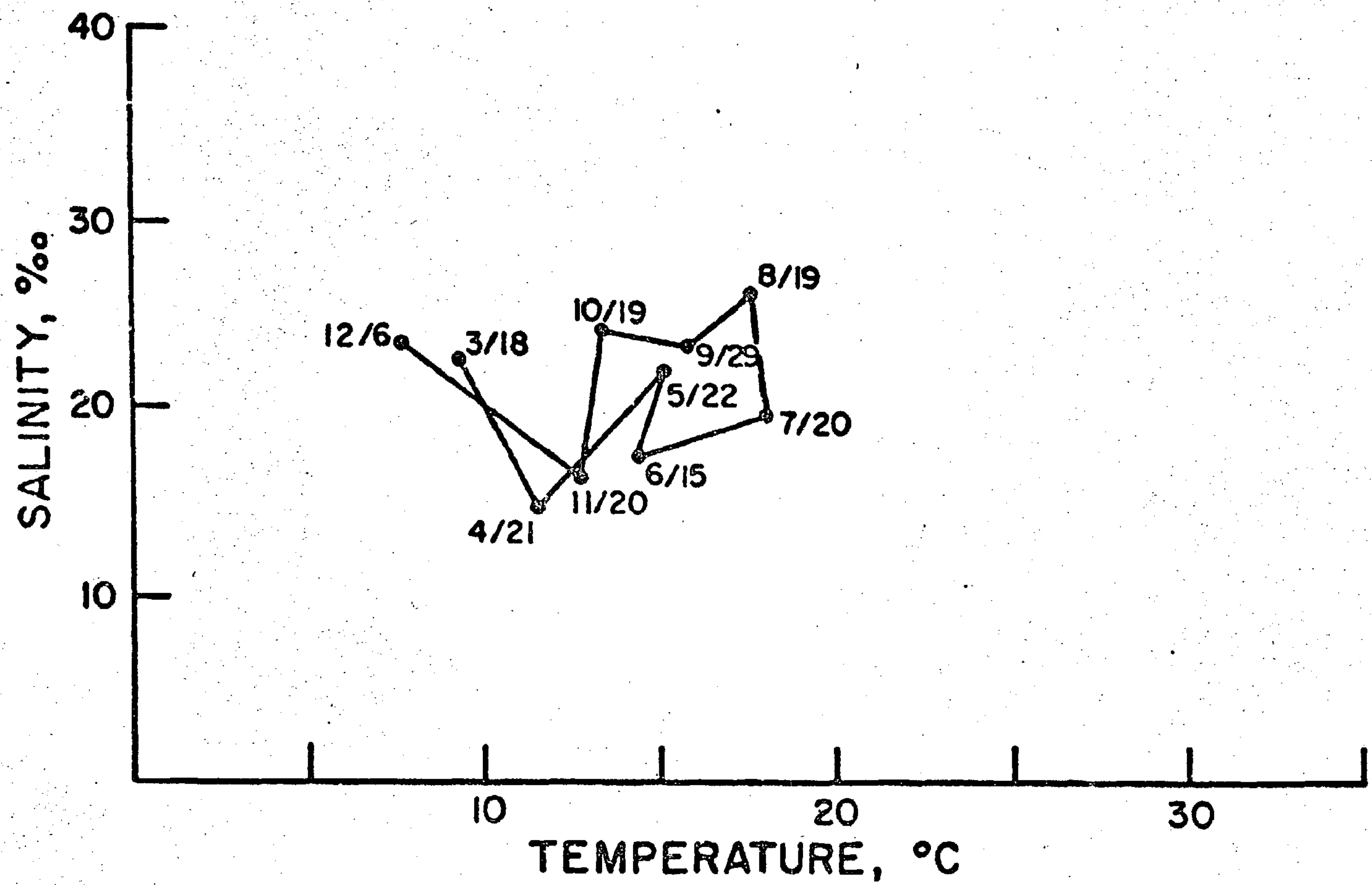
PILLAR POINT

TEMPERATURE AND SALINITY CYCLES

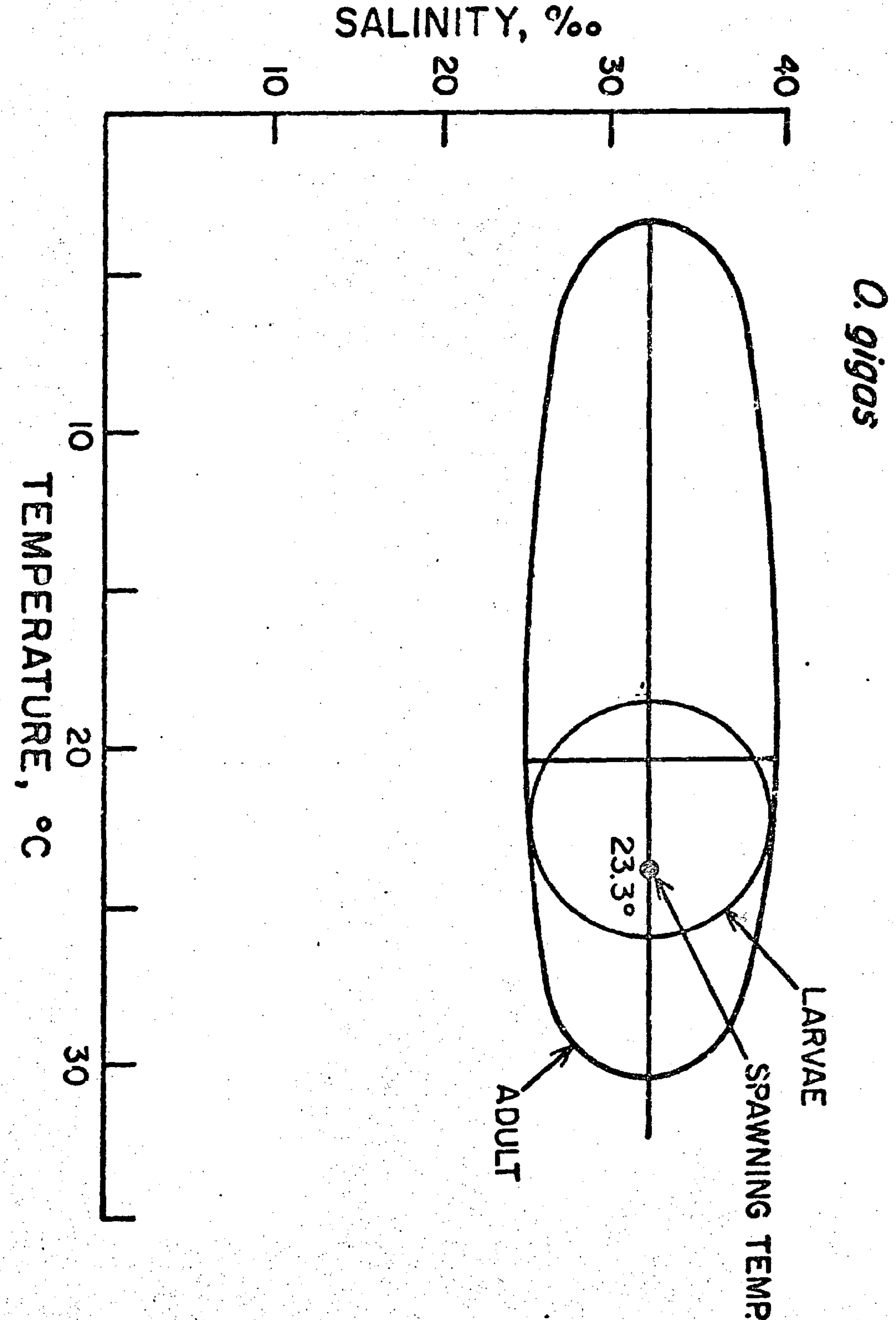
FEBRUARY 1953 — MARCH 1954

Fig. 10

Fig. 11

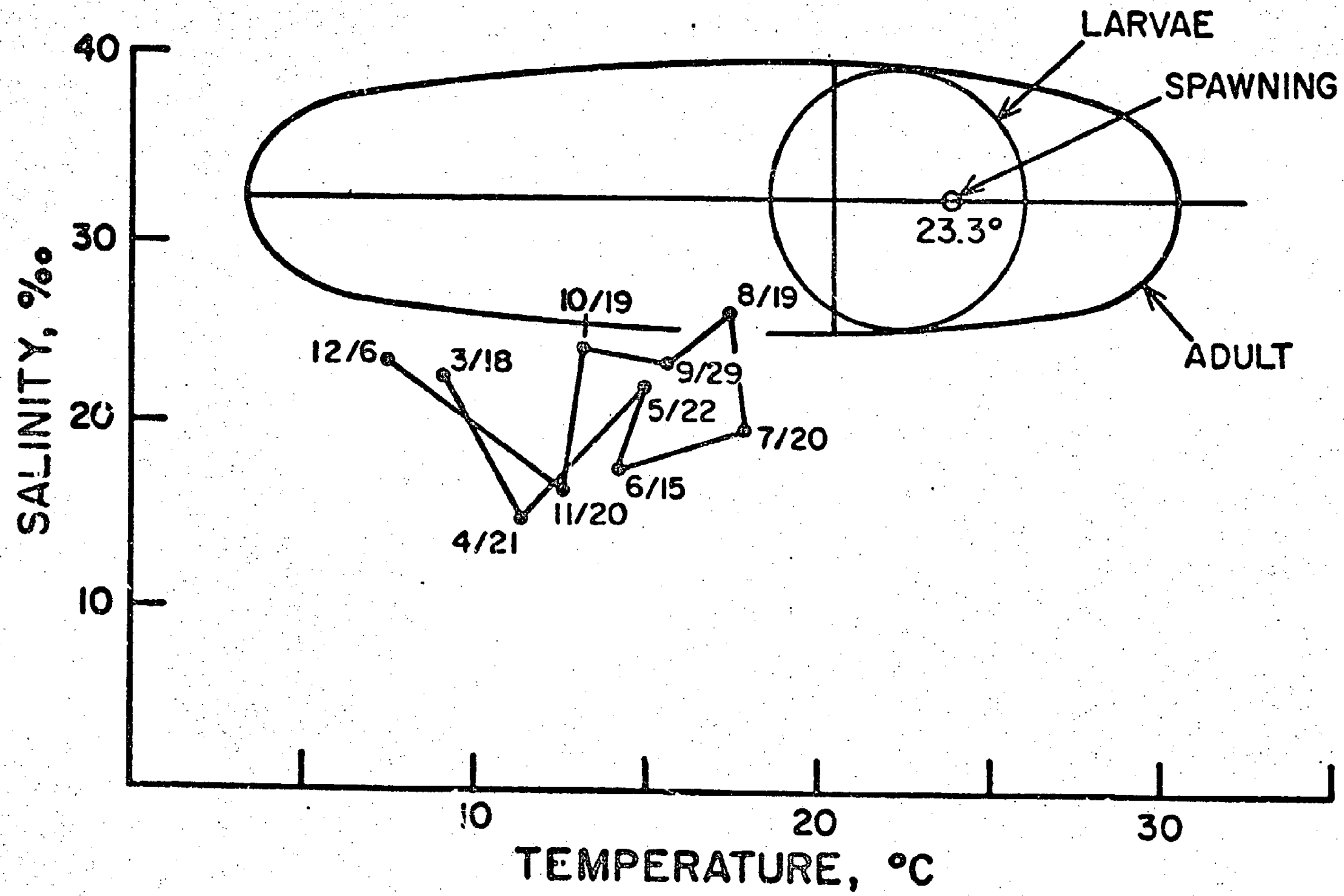


40
30
20
10
SALINITY, ‰
12/6
3/18
4/21
11/20
10/19
5/22
6/15
9/29
8/19
7/20
10
20
30
TEMPERATURE, °C



O. gigas
SALINITY, ‰
10
20
30
40
TEMPERATURE, °C
10
20
30
23.3°
LARVAE
SPAWNING TEMP.
ADULT

Fig. 12


LARVAE
SPAWNING
23.3°
ADULT
SALINITY, ‰
40
30
20
10
TEMPERATURE, °C
10
20
30
12/6
3/18
4/21
11/20
10/19
5/22
6/15
9/29
8/19
7/20

'G. 13

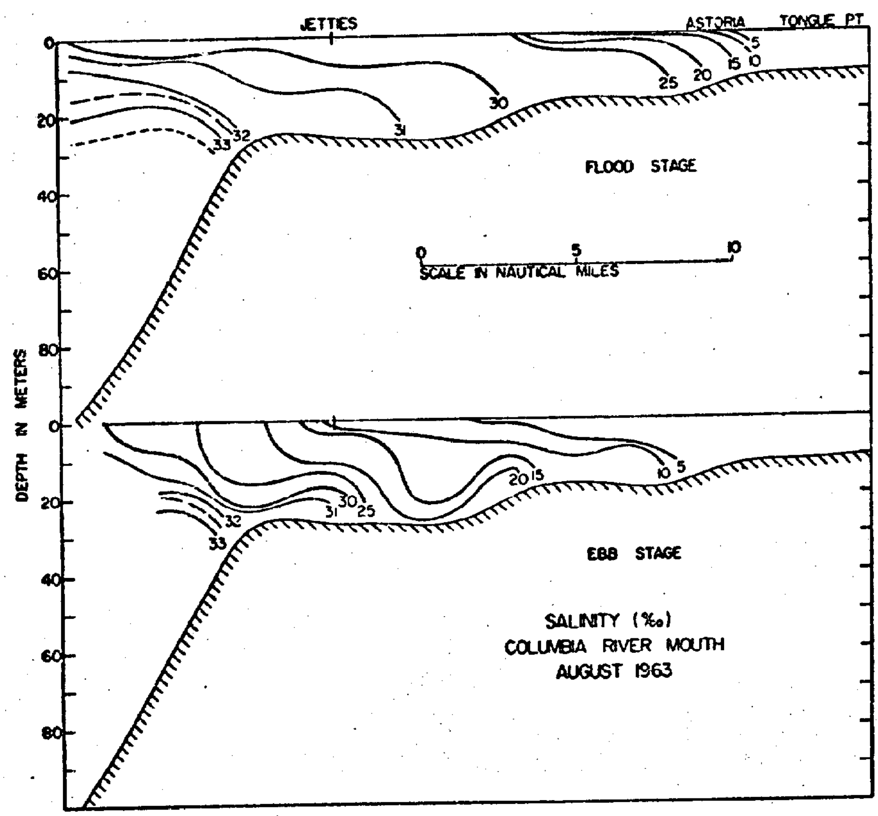
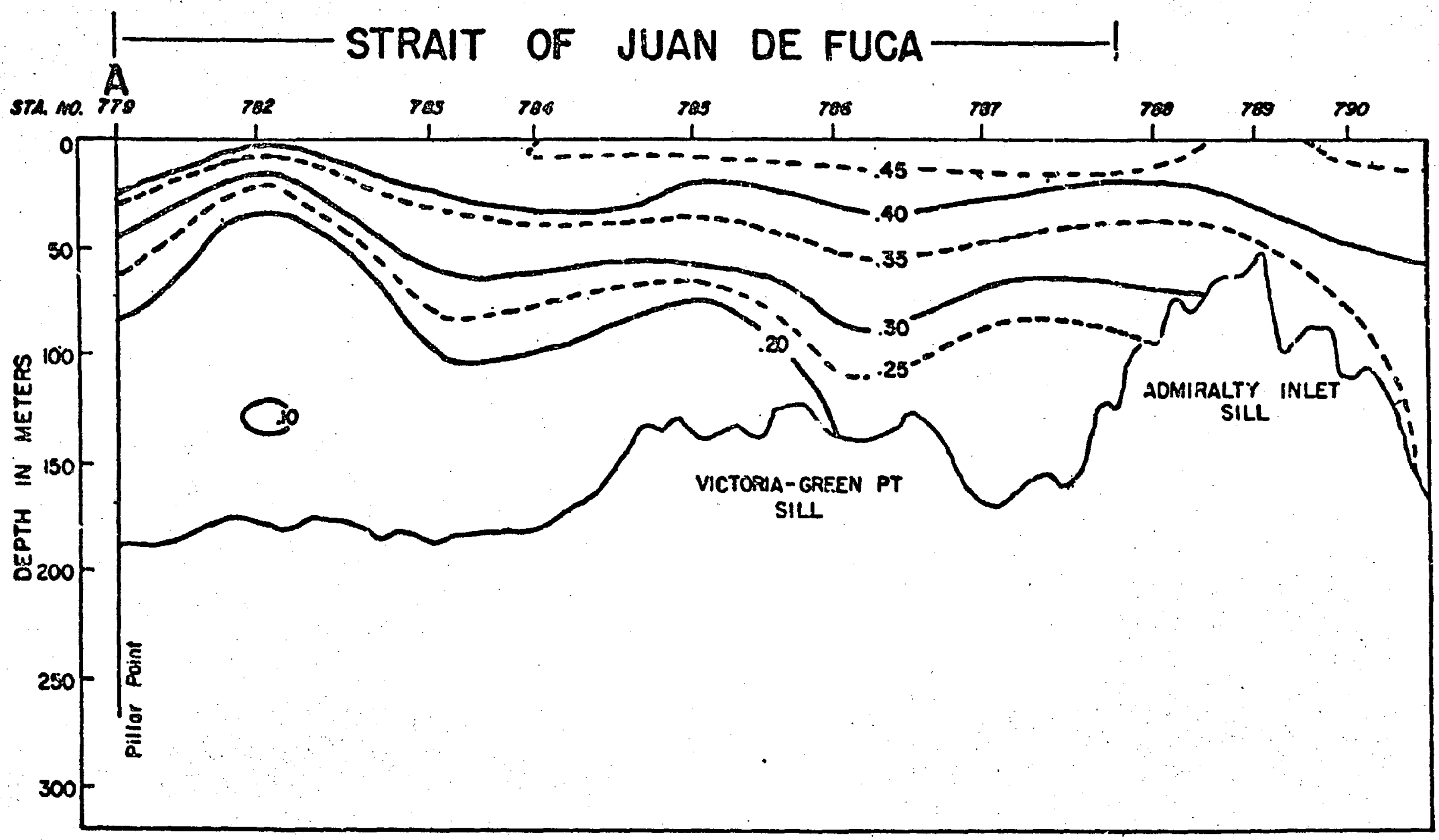

JETTIES
ASTORIA
TONGUE PT
FLOOD STAGE
0 5 10
SCALE IN NAUTICAL MILES
DEPTH IN METERS
EBB STAGE
SALINITY (‰)
COLUMBIA RIVER MOUTH
AUGUST 1963

Fig. 14


STRAIT OF JUAN DE FUCA
A
STA. NO. 779
782
783
784
785
786
787
788
789
790
0
50
100
150
200
250
300
DEPTH IN METERS
.45
.40
.35
.30
.25
.20
.10
Pillar Point
VICTORIA-GREEN PT
SILL
ADMIRALTY INLET
SILL

G. 15

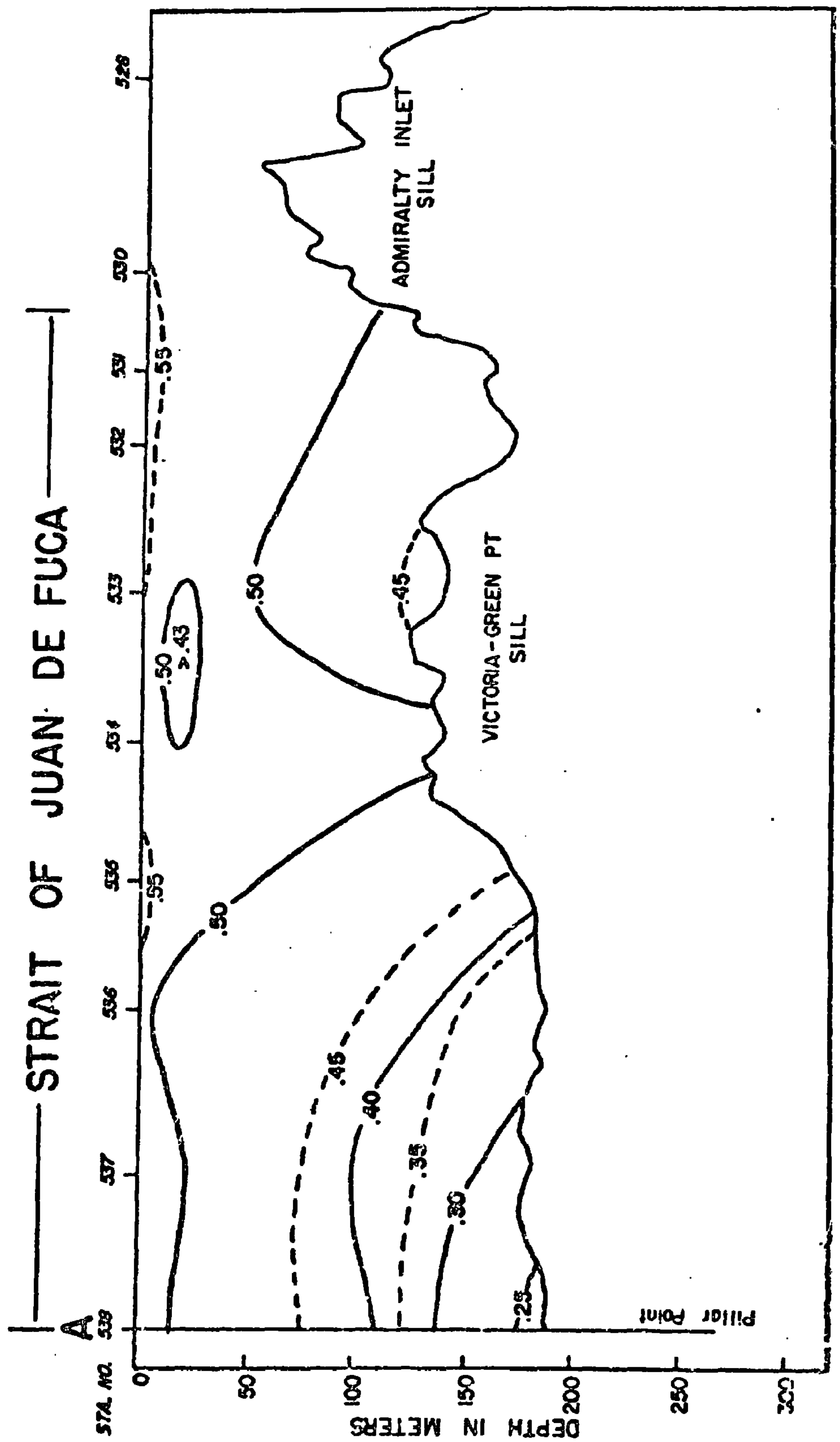
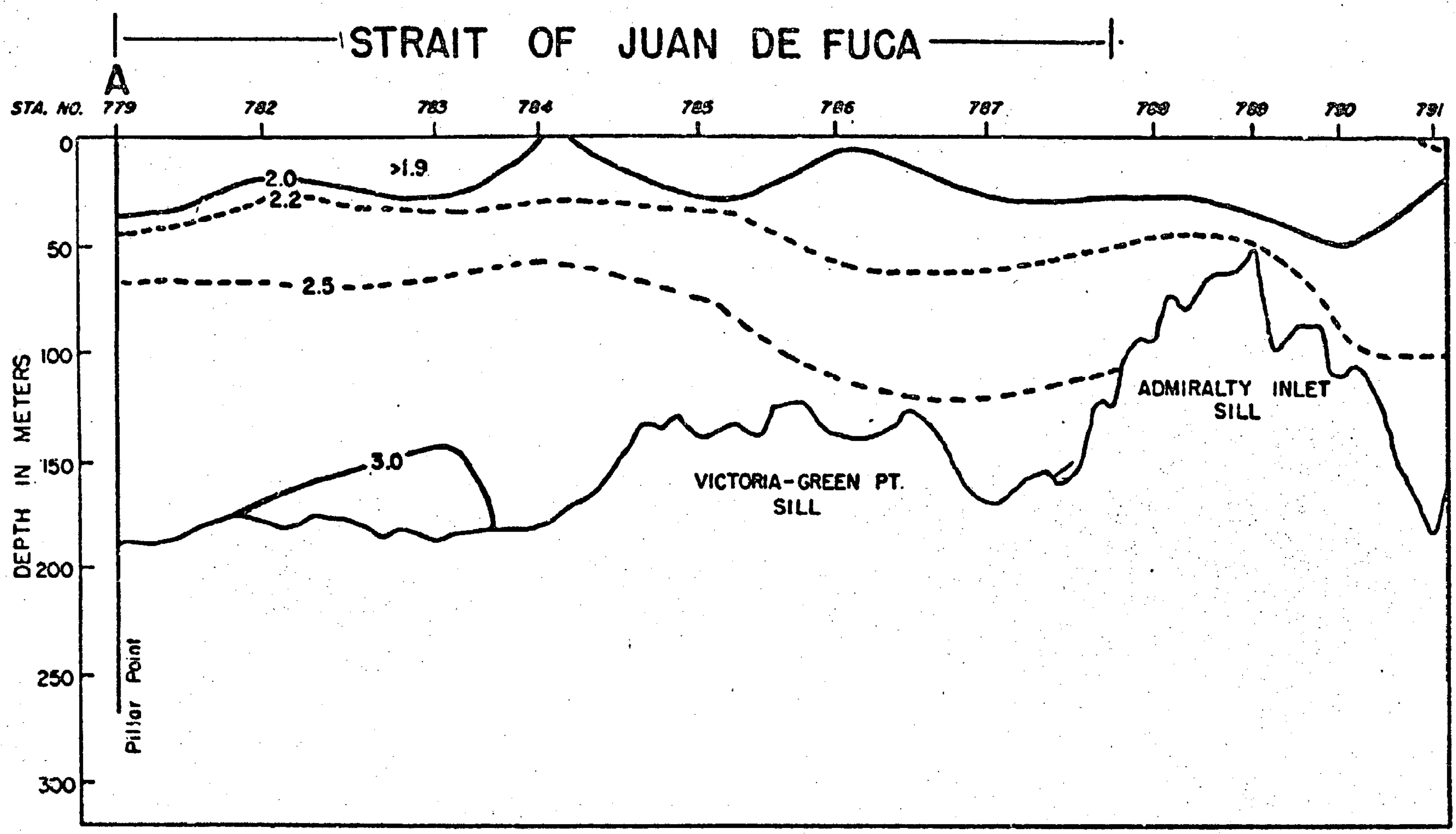

STRAIT OF JUAN DE FUCA
A
STA. NO. 538
537
536
535
534
533
532
531
530
528
DEPTH IN METERS
0
50
100
150
200
250
300
.55
.50
.45
.40
.35
.30
.25
.50
>.43
.45
.50
.55
VICTORIA-GREEN PT SILL
ADMIRALTY INLET SILL
Pillar Point

FIG 16



STRAIT OF JUAN DE FUCA
A
STA. NO.
779
782
783
784
785
786
787
788
789
790
791
DEPTH IN METERS
0
50
100
150
200
250
300
>1.9
2.0
2.2
2.5
3.0
Pillar Point
VICTORIA-GREEN PT.
SILL
ADMIRALTY INLET
SILL

FIG. 17

END

DATE FILMED

2 / 29 / 72