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Data from NORPAC 55 in the northeastern Pacific Ocean showed that there is a subsurface oceanic frontal zone beneath the region of the subtropical convergence. Correlations of temperature with salinity and of temperature with oxygen demonstrated that the front separates two distinct water masses at depths where thermosteric anomalies vary between 125 and 70 \text{cl/t}. The front is a well-defined feature oriented approximately east-west at about 26°N between 125°W and 140°W. East of 125°W, the front was not well defined; a mixture of the two water masses filled the nearshore area from Point Conception, California, to Punta Eugenia, Baja California.

The oxygen minimum zone has been enriched with oxygen along the northern boundary of the frontal zone. This enrichment has been taken as evidence of vertical mixing. Vertical mixing was further
corroborated by the distribution of salinity. On isentropic surfaces, cells of low salinity coincided with the region of low oxygen just north of the frontal zone nearshore. The vertical mixing was most strongly indicated nearshore in the vicinity of Point Conception.

It is suggested that the source of intermediate-depth water along the west coast of the U. S. below about 300 meters is partly within the frontal zone. East of 125°W it is postulated that eastward flow in the frontal zone carries water into the coastal region. Evidence of this flow was given by geostrophic flow on the 100-cl/t surface.

The subsurface northward flow along the coast of Baja California was examined and compared with the subsurface flow north of Point Conception. The computations suggest that the poleward flow along Baja California is shallower and that the transport is smaller than the flow north of Point Conception. An attempt is made to estimate the magnitude of the transports carried by various parts of the system. The contributions from the front and from the coastal flow along Baja California are approximately 2.5 and 0.6 sverdrups respectively. These flows combine to make the total subsurface northward transport approximately 3.1 sverdrups north of Point Conception.
The Subsurface Frontal Zone beneath the Subtropical Convergence in the Northeast Pacific Ocean

by

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THE SUBSURFACE FRONTAL ZONE BENEATH THE SUBTROPICAL CONVERGENCE IN THE NORTHEAST PACIFIC OCEAN

INTRODUCTION

An oceanic frontal zone is defined as a zone of transition between two water masses of different types (see for example Neumann and Pierson, 1966). One example is the Antarctic Convergence, a frontal zone separating Antarctic Circumpolar water from Subantarctic water (Sverdrup, Johnson and Fleming, 1942). Major frontal zones are also present in the regions of the western boundary currents. The Gulf Stream front in the western North Atlantic and an analogous one in the western North Pacific (Kuroshio front) separate warm, saline Central water masses from the cooler water adjacent to the coasts.

There are several indications of frontal zones in the eastern Equatorial Pacific. The circulation of water along fronts in this region has been discussed by Cromwell and Reid (1956), Knauss (1957), Bjerknes (1961), Fedorov (1963) and Wyrtki (1966). There has been great interest in fronts in this region because the eastern Equatorial Pacific is a region of high biological activity.

It is the purpose of this paper to examine a previously undescribed frontal zone in the Northeast Pacific. This front occurs in the area between California and Hawaii, is found approximately in the region of the surface subtropical convergence as
located on Chart No. 5 of Dietrich and Kalle (1957), but is located at depths between 400 and 1200 meters. It is shown that this frontal zone separates water masses of different characteristics and that these differences are not apparent above about 400 meters or below about 1200 meters. Thus the frontal zone is subsurface only, and separates different intermediate waters of the North Pacific.

Sverdrup, Johnson and Fleming (1942) have shown a water mass boundary between upper water masses in this region. It is demonstrated that the frontal zone of this study is apparent not between the upper water masses but between water masses at intermediate depths. A careful search of the literature has indicated that this subsurface feature has previously gone unnoticed.

This thesis describes the water masses on either side of the frontal zone. The study is necessarily a 'climatic' one because the quantity of data is insufficient to describe in detail the temporal changes in the front's location and in its width.

A major significance of any front is the fact that the currents on either side must be convergent; otherwise, the steep gradients of properties across the front would decay (Defant, 1961). This study demonstrates that there is indeed quasi-horizontal convergence at the front maintaining the gradients of properties between the two water masses. Finally, the influence of the front on the circulation of intermediate-depth water adjacent to the west coast of the U. S.
is examined.

The characteristics of the two water masses on either side of the frontal zone were determined by examining correlations of temperature with salinity and temperature with oxygen. The distribution of salinity on surfaces of constant thermosteric anomaly (isentropic analysis) was used to demonstrate the flow of water adjacent to the west coast of the U. S. Temperature-salinity and temperature-oxygen diagrams, together with the distribution of salinity on isentropic surfaces, were the principal methods used to describe the front and adjacent waters.

A model of the circulation in the vicinity of the front is proposed. The circulation was determined through an analysis that assumes that the gradients of temperature and salinity within the frontal zone represent a balance between advection and mixing.
REVIEW OF PREVIOUS WORK PERTINENT TO THIS STUDY

Oceanography of the Northeast Pacific Ocean

Sverdrup, Johnson and Fleming (1942) have shown that the upper layers of the North Pacific Ocean contains four dominant water masses: the Pacific Subarctic, the Eastern North Pacific Central, the Western North Pacific Central and the Pacific Equatorial. These water masses are defined from about 100 to 200 meters below the surface to below 1000 meters. The West North Pacific Central water mass extends down to 700 meters. The Subarctic water mass may extend deeper than 1000 meters. Figures 1 and 2 are taken from Sverdrup, Johnson and Fleming (1942) to illustrate the regional extent and the temperature-salinity characteristics of these water masses. In the Transition Region along the west coast of the U. S., the near-surface waters are of Subarctic origin, but as they move southward they are continually modified by heating, evaporation and mixing. The region is a complicated boundary region with currents which are weak, seasonal, and probably strongly influenced by both local and large-scale winds (Wooster and Reid, 1963). Figure 1, showing the regional extent of the upper water masses, shows also where we may expect a front, or a zone of rapid transition from one water mass to another.
Figure 1. Regional extent of the North Pacific upper water masses (from Sverdrup, Johnson and Fleming, 1942).
Figure 2. Water masses of the North Pacific (from Sverdrup, Johnson and Fleming, 1942).
The gross features of the surface circulation in the North Pacific are shown in Figure 3, taken from Seckel (1962). Dietrich and Kalle (1957, p. 507-509) have regionally classified the world oceans by defining certain characteristics (direction, velocity and persistency) of the motion of surface currents. They have a line of convergence extending approximately from Point Conception, California, to the island of Hawaii. This line, the subtropical convergence, extends through a region of weak and variable currents. Currents flow eastward to the north of the line; they flow westward south of the line. The subtropical convergence coincides closely with our region of interest (see chart No. 5 of Dietrich and Kalle, 1957).

Below the upper water masses of the North Pacific, Sverdrup, Johnson and Fleming (1942) describe an Intermediate water. This water is characterized by a salinity minimum. The depth of the minimum varies between 300 and 800 meters. Sverdrup et al. (p. 717) published a chart of the depth and the salinity of the salinity minimum. In the eastern portion of the chart, there are two minima in salinity but only one set of isohalines. Reid (1965) states that the isohalines in the eastern portion of the chart by Sverdrup et al. correspond to the shallower of the two minima. Their chart shows no contours of either depth or salinity in the Transition Region because the water of lowest salinity is surface water.
Figure 3. Gross circulation of surface waters in the North Pacific (from Seckel, 1962).
Sverdrup, Johnson and Fleming (1942), Ichiye (1955) and Reid (1965) among others proposed that the Intermediate Water, after sinking in the area of the Polar Front, moves in an anticyclonic fashion matching that of the surface circulation of the central North Pacific. Others such as Uda and Koenuma (from Reid, 1965) have noted a salinity minimum under the Kuroshio and proposed a counter-current under the Kuroshio that transports the salinity minimum to the southwest. From mid-latitudes near Japan, the Intermediate Water spreads eastward towards North America.

**Subsurface Poleward Flow along the West Coast of the U. S.**

In the transition region of the North Pacific, there is evidence of subsurface poleward flow adjacent to the North American coast. The evidence is principally from the distribution of properties. Sverdrup and Fleming (1941), and Tibby (1941) were among the first oceanographers to concern themselves with this poleward movement. Tibby (1941) stated that the water in the subsurface countercurrent (counter to the equatorward surface flow) is a mixture of Pacific Equatorial and Subarctic water. He stated further that "the transport of warm, saline Equatorial water to the north . . ." is accomplished by the California Counter Current, present throughout the year at about 200 meters and below. Sverdrup and Fleming (1941) were less committed. Within the region of the southern
California coast, they defined two water masses, a "southern water" and a "northern water." They showed that the water adjacent to the coast could be a mixture of these two. This mixture is carried poleward in what Sverdrup and Fleming (1941) called the Coastal Deep Current. They demonstrated the presence of this current by the topography of the 100-and 200-decibar surfaces relative to 500 decibars.

More recently, Reid, Roden and Wylie (1958) stated that a subsurface countercurrent below 200 meters flows northward along the coast from Baja California to beyond Cape Mendocino. A discussion between J. L. Reid and Henry Stommel in 1960 adequately summarized what was known to that date and, for the most part, what is known today.

Stommel: The deep countercurrent you have mentioned is hard to define.
Reid: You do it essentially by the distribution of properties. Equatorial Pacific water is identified by certain temperatures, salinities, and a certain temperature-salinity relationship. It extends up from the Equator all along the coast.
Stommel: How deep is it?
Reid: It is found 200 meters below the surface. The thickness is uncertain since we use as a reference level the 1000 decibar surface, but it is at least 200 or 300 meters thick. Near the coast the deep salinities are higher than those offshore, and at lower latitudes we have a maximum in salinity that shows the northward intrusion of the high salinity water from the Equatorial Pacific.

Question: Low oxygen is a pretty good identifier?
Reid: Yes it is. The lowest oxygens are along the coast. Offshore the minimum oxygen value is higher and there is a tongue of high salinity and low oxygen water all the
way to the Aleutian Islands. Whether it is movement along the coast or movement up from deep water, I do not know.

Saur: This is year around?
Reid: Probably, since it is below 200 meters in depth. I have examined it only for July and August (Reid, 1960).

Fleming, in the same discussion, stated the possibility of the countercurrent extending to the surface in the winter (the surface flow being called the Davidson Current) but disappearing at the surface when northerly winds set in. Apparently this idea was first suggested by Sverdrup, Johnson and Fleming (1942).

Dodimead, Favorite and Hirano (1963) examined hydrographic data from 1955 to 1959 along the west coast of North America. The summer data (except 1958) of the 200-decibar surface relative to 1000 decibars exhibited a poleward flow off the Oregon - Washington coast. There is also evidence of this flow on the 500-decibar surface relative to 1000 decibars. The winter data of these years was inadequate to confirm the existence of poleward flow along the coast. Dodimead, Favorite and Hirano (1963) called this flow the California Undercurrent. They stated only that the source of waters off the west coast above San Francisco at depths below 300 meters "appears to be south of latitude 35°N..."

Oceanographers have been unable to better specify the origin and flow of the subsurface water adjacent to the west coast of the U. S. The present knowledge, including some references to
theoretical work, of poleward undercurrents along eastern oceanic boundaries is well summarized by Wooster and Reid (1963).

There have been some direct measurements of currents below 200 meters, notably those by Reid (1962), Reid (1963) and Stevenson (1966). These measurements were made by parachute drogues.

Reid (1962) laid drogues at a depth of 250 meters at 5-mile intervals on a line extending from 35°52’N, 124°29’W onshore to the 1000-fathom isobath off Monterey, California. The drogues were followed for 48 hours. Nearshore about 90 km from the coast, the flow was northward with a maximum speed of about 23 cm/sec. This flow was about 70 km wide. Offshore for the next 110 km, the flow was southwestward with maximum speeds to 26 cm/sec. Beyond here, the flow was unsteady, the direction changing from northeast to southeast at about 20 to 25 cm/sec. Reid labeled the inshore northward flow the California Countercurrent.

Reid (1963) later performed similar operations off northern Baja California. He followed 13 drogues at 250 meters for 48 hours or more placed along a line 110 km long extending southwestward from the 1000-meter isobath at 30 1/2°N. The drogues moved northwestward to westward at about 6 cm/sec along the inner 28 km of the line. Over the next 70 km, the drogues moved to the southwest at about the same speed. The inshore leg had negligible wind correction and agreed quite well with geostrophic calculations. The velocities
and widths of the currents off northern Baja California compared to those 700 km to the north (Reid, 1962) were considerably less.

A comparison of the widths and velocities of geostrophic currents and those of direct measurements led Reid (1963) to reinterpret the measurements off Monterey, California (Reid, 1962), and off Baja California. He interpreted both series to be measurements, not of a simple, steady, longshore countercurrent, but of eddies superimposed on a countercurrent that is better reflected by geostrophic computations. He stated that these eddies are similar to those on the surface attributed to the California Current.

Stevenson (1966) analyzed the data from 99 drogues placed at various depths between the surface and 500 meters at a location about 73 km offshore from Newport, Oregon. These measurements were made during 15 cruises from January, 1962, to September, 1965. The mean directions had a southward component at all depths but the average speed was very low. Flow with a northward component below 150 meters was indicated by only 6 drogues. Stevenson (1966) concluded that northward subsurface flow along the west coast off Oregon, at a distance of 73 km offshore, was not substantiated by his data.
Water Masses off Southern California

Sverdrup and Fleming (1941) analyzed the content of the subsurface water below 200 meters adjacent to the coast off southern California. Their data covered a region roughly bound by the coast and 123°W and between the latitudes 31°N to 35°N or approximately between Ensenada and Point Conception. Within this region they defined two extreme water masses, a "northern water" and a "southern water" (Fig. 4). The distinction between these two water masses was defined by correlations between temperature and oxygen and between temperature and salinity. Sverdrup and Fleming (1941) were careful to point out that had they examined a larger area, they might have found different extremes. The two water masses described in this thesis are similar to the "northern" and "southern" water described by Sverdrup and Fleming (1941) in the depths where delta-t is less than 125 cl/t.

The northern water described by Sverdrup and Fleming (1941) appears to be from the mid-latitudes of the North Pacific. They speculated that the origin of the southern water is to the south of the region that they examined. They found "southern" water as far west as 146°E, south of the latitude of the Hawaiian Islands. (They did not suggest that southern water has been formed there; they did not state the source.)
Figure 4. The two water masses off southern California showing the comparison between southern and northern water as defined by Blanton (this study) and Sverdrup and Fleming (1941).
DATA AND METHODS

Data Sources

The principal source of data for this study is the station data from NORPAC 55 (Norpac Committee, 1960a and 1960b). NORPAC 55 data, for the most part, extends to depths of 1000 meters or more. The station locations are shown in Figure 5. These are the only data known to the author that cover the area of interest to such a high density in both space and time. All data were collected in the relatively short period one and one-half months.

Data for 1949 and 1950 (California, University, 1957 and 1960) also extend to about 1000 meters during some months, but the coverage is mostly restricted to east of 130°W longitude. These data are also used in discussing seasonal changes of the front close to shore. There are no seasonal data farther offshore, where the front is well defined.

Synthesis of Data

In order to present a description of the frontal zone, the station data along four sections shown in Figure 5 were analyzed. Correlations were made between temperature-salinity (T-S) and temperature-dissolved oxygen (T-O). In addition, salinity was
Figure 5. Location of the NORPAC stations used in this study. Sections and their station numbers used in the synthesis of the data are indicated.
mapped on surfaces of constant specific volume anomaly (delta-t).

**Correlation between Properties**

In the ocean, temperature, salinity, and dissolved oxygen values do not occur in all conceivable combinations but only in a limited number of particular combinations. To illustrate the particular combinations of properties found, oceanographers use so-called "characteristic" diagrams (Pickard, 1964). The most widely used characteristic diagram in descriptive oceanography is the T-S diagram (temperature versus salinity), first introduced by Helland-Hansen in 1916 (Sverdrup, Johnson and Fleming, 1942). He recognized the fact that when the temperatures and corresponding salinities of a subsurface water in a certain region are plotted against one another, the points usually fall on a well-defined curve (T-S curve). If the corresponding information from a hydrographically different region of the ocean were plotted, the T-S curve would appear different. Often the T-S curve is almost a straight line. (In the Central water masses, the T-S correlation is positive and nearly linear.) The interpretation of T-S curves and the information they yield on the formation and mixing of Central water masses have been discussed by Sverdrup, Johnson and Fleming (1942, p. 141-146). The formation and mixing of water masses with negative T-S correlations have not been adequately discussed in the literature.
Although not as widely used as T-S diagrams, temperature-dissolved oxygen (T-O) diagrams may also be used to distinguish water masses of different origin (see, for example, Metcalf and Stalcup, 1967). In some areas T-O correlations (and possibly salinity-oxygen correlations) may exhibit more distinctive features than are evident in T-S correlations. In the present study, both T-S and T-O diagrams are used to describe the differences found between the water masses on either side of the front.

Isentropic Analysis

It is generally accepted that flow in the subsurface regions of the ocean (those layers below the homogeneous surface layers) takes place mainly along surfaces of constant potential density. It has been demonstrated by Parr (1938), Montgomery (1938) and Sverdrup, Johnson and Fleming (1942) that surfaces of constant potential density in the ocean closely approximate isentropic surfaces. Fluid masses on a truly isentropic surface can be interchanged along the surface without altering the distribution of mass. The movement on isentropes specifies that any changes in density (or temperature) are adiabatic (i.e., the potential density is unchanged). Strictly, we must call constant potential density surfaces in the ocean quasi-isentropic surfaces because interchange of waters along these surfaces do, in fact, produce very small changes in the potential energy.
of the system, i.e., the distribution of mass is slightly altered. Montgomery (1938) has shown that this alteration is negligible; furthermore, he has shown that for the layers of the ocean with pressure less than about 1000 decibars (above 1000 meters), there is negligible error in approximating equal potential density surfaces by surfaces of equal sigma-t (or thermometric anomaly, delta-t). In this paper we call the flow along delta-t surfaces isentropic flow, and the determination of flow along the surfaces isentropic analysis.

Flow along constant potential density surfaces consists of advection (flow which retains or carries its properties without alteration) and lateral mixing. Investigators such as Parr (1938) and Sverdrup and Fleming (1941) demonstrated the importance of lateral mixing in explaining the distribution of properties. Parr (1936) presented evidence that mixing along isentropic surfaces was more important than mixing perpendicular to these surfaces.

Isentropic analysis is one of the principal tools used in this study in the interpretation of data in the vicinity of the front. The author has plotted salinity on delta-t surfaces. One can use temperature just as readily as salinity but it should be recognized that the use of both temperature and salinity is redundant since, when the field of one property is known on a potential density surface, the field of the second is completely determined. Obviously, properties along surfaces of constant depth will not display features identical to
those along isentropes for the major reason that the latter surfaces are not at constant depth. It is essential, therefore, to know the depth of an isentrope as well as the distribution of a property on it. The salinity (and other properties) on the isentrope were determined by a linear interpolation between standard-depth values of salinity. The interpolated values for each isentrope were written on maps showing each NORPAC station. Contours were drawn between these values to determine the distribution. In areas where interpretation was uncertain because of abnormally high or low values, at least two adjacent stations had to show high or low values compared with the nearby field of values before the feature was assumed real.

The salinity distribution on isentropes adjacent to the coast often exhibits tongue-like distributions. These tongues are customarily interpreted as coincident with axes of currents that advect properties. Neumann and Pierson (1966, p. 405-407) discuss the effects of advection and mixing on the production of tongue-like distribution of properties. They summarize the work of many investigators, such as Defant (1961), who have shown that tongue-like distributions in a steady state may be derived from advection balanced by mixing. Tongue-like distributions may also be produced by mixing alone. Moreover, currents uniform in magnitude along the plane of the tongue and currents with axes (non-uniform magnitude of velocities in the plane) will both produce tongue-like
distributions. These conclusions were originally the result of studies by Thorade in 1931 (Defant, 1961). It is apparent that one should have additional evidence to support the assumption that a tongue-like distribution is the result of a current along the axis of the tongue.

Sverdrup, Johnson and Fleming (1942, p. 503) discussed the fact that tongue-like distributions in the lateral plane usually are related to a pressure distribution such that the currents, rather than flowing along the tongue's axis, flow around the leading edge of the tongue. However, since mixing of the water inside the tongue with that outside tends to destroy the tongue, the tongue can only be a permanent feature if there is a net drift along the axis of the tongue. This slow replenishment maintains the tongue.

**Geostrophic Flow on Isentropic Surfaces**

Montgomery (1937) suggested a method for representing geostrophic flow on isentropic surfaces. This flow can be derived from a single quantity, the acceleration potential. This quantity is defined as

$$
\gamma_A = \phi_A + a_A p
$$

where \( \gamma \) is the acceleration potential of the surface \( A \), \( \phi \) is the anomaly of dynamic height for the surface above an assumed
reference level, \( \alpha \) is the specific volume (assumed constant over the surface), and \( p \) is the pressure on the surface. It can be shown that if the acceleration potential is plotted on a surface of constant specific volume, contours of equal acceleration potential represent the streamlines of geostrophic flow on that surface. The gradient of the acceleration potential is a measure of the velocity, \( \bar{v} \), or

\[
\bar{v} = \frac{1}{f} \nabla \alpha (\gamma_A) \times \hat{k}
\]

where \( \nabla_A \) represents the gradient measured along the isentropic surface, and \( \hat{k} \) is the unit vertical vector; \( f \) is the Coriolis parameter.

In this study, the data are mostly above 1000 meters, so we may assume that \( \alpha_A \) is adequately approximated by delta-\( t \). Furthermore, for the reason that there is insufficient data below 1000 meters, we take as a reference level the 1000-decibar surface. Reid (1961) and McAlister (1962) have independently shown that the use of 1000 decibars for the reference level is a good selection for the Northeast Pacific Ocean.
DESCRIPTION OF THE FRONT AND ITS ENVIRONS

The Characteristics of Northern and Southern Water Masses

Figure 6 shows T-S diagrams for stations along section AB. (The locations of sections are shown in Figure 5.) Section AB extends parallel to shore about 1500 km offshore. We concentrate on the portion of the T-S correlation at depths deeper than the delta-t surface of 125 cl/t (depths below approximately 400 meters). The portions of the curves below this layer, as distinct from those above, may be divided into two separate sets. This division is apparent if one compares the solid data points with the "open" points shown on the figures.

The two groups of stations have distinctive slopes to the T-S curves. Stations 116, 125 and 140 have slopes resembling a modified Equatorial Pacific water or "southern" water while the remaining stations have slopes defining a water which we will call "northern." Northern water resembles a modified Subarctic water.

T-S diagrams of stations along sections CD, EF and GH are shown in Figures 7, 8 and 9. Figure 7 shows T-S diagrams along section CD. Section CD is about 1000 km offshore from, and parallel to, the coast. Two water masses are evident, and they are practically identical to those in Figure 6.
Figure 6. T-S diagram for stations along section AB.
Figure 7. T-S diagram for stations along section CD.
Figure 8. T-S diagram for stations along section EF.
Figure 9. T-S diagram for stations along section GH.
Figures 8 and 9 consist of T-S diagrams along sections EF and GH respectively. Section EF is about 550 km offshore; GH is 200 km from the coast. Two water masses can be distinguished on sections EF and GH although their differences appear less distinct as one approaches Point Conception.

Thus, for each of the sections shown in Figure 5, there are two water masses distinguishable on T-S diagrams. These water masses lie at depths where delta-t varies between 125 and 60 cl/t. The two water masses are less distinct near the coast.

Figure 10 contains plots of the T-S pairs of all stations from NORPAC 55 data (Norpac Committee, 1960b) that had delta-t values between 125 and 60 cl/t, were more than 900 km offshore from Point Conception, and were within 1100 km of the boundary separating the two water masses. The inshore data have been omitted because a clear difference between the two water masses was not evident. By a least squares analysis, the regression of temperature on salinity for each water mass was determined. For southern water stations the slope was about minus eight degrees Celcius per part per thousand of salinity; for northern water stations the slope was about minus four degrees Celcius per part per thousand of salinity. The dashed lines on Figure 10 represent the regressions. The correlation coefficient (m) is lower for the southern water (m = -0.77) than for the northern mass (m = -0.91). (The greater "scatter" of T-S points in the
Figure 10. Linear regression of temperature on salinity computed for northern (---) and southern (-----) water masses. Data points are from stations greater than 900 km offshore. $m$ is the correlation coefficient.

- Southern water: Slope = $-7.89^\circ C/\%oS$  $m = -0.77$
- Northern water: Slope = $-3.95^\circ C/\%oS$  $m = -0.91$
southern water mass was also found in the study by Sverdrup and Fleming (1941).

T-O diagrams for stations along sections AB, CD, EF and GH are shown in Figures 11 through 14. A division of the T-O curves into two sets is apparent if one compares the solid data points with the "open" points shown on the figures. The temperature of the oxygen minimum describes this division, and this temperature can be approximated from the data on the T-O diagrams. In Figure 11, the temperature of the oxygen minimum (shown by solid data points) is between 3.5 and 4.0 °C while that of the southern water mass (shown by the open points) is around 5.5°C. At locations close to the coast, the curves are less distinct between the two water masses. Nevertheless, the curves in Figure 14 show two distinct minima. The northern water has a minimum oxygen temperature between 3.5 and 4.5°C. The minimum for the southern water is between 5.0 and 6.0°C.

**The Feature of the Dissolved Oxygen Distribution**

NORPAC observations of dissolved oxygen have been used to draw distributions of dissolved oxygen along sections AB, CD, EF and GH. Contours have been drawn by linear interpolation between observed values. The isograms of dissolved oxygen shown on Figures 15 through 18 include only the minimum oxygen layer where
Figure 11. T-O diagram for stations along section AB.
Figure 12. T-O diagram for stations along section CD.

Numbers represent depth of observation in hectometers.
STATION LIST

88-0  47- ●
112- △  54- △
121- ■  66- ■
74 - ●

Numbers represent depth of observation in hectometers.

Figure 13. T-O diagram for stations along section EF.
Figure 14. T-O diagram for stations along section GH.

Numbers represent depth of observation in hectometers.

STATION LIST
86 O   45 ●
95 △   52 △
110 ◊  63 ■
118 ◊  71 ←
Figure 15. Dissolved oxygen (ml/l) versus depth along section AB. Dashed lines are those of delta-t in °C/°C.
Figure 16. Dissolved oxygen (ml/l) versus depth along section CD.
Dashed lines are those of delta-t in °C/°C.
Figure 17. Dissolved oxygen (ml/l) versus depth along section EF. Dashed lines are those of delta-t in cl/t.
Figure 18. Dissolved oxygen (ml/l) versus depth along section GH. Dashed lines are those of delta-t in c1/t.
the dissolved oxygen content is 1.0 ml/l or less. Lines of constant
delta-t are superposed.

In all sections, it appears that the layer of minimum oxygen
has been "ventilated," i.e., it has been exposed to a source of oxygen
enrichment near the northern edge of the front. The T-O curves
(Figures 11-14) for those stations having an enriched oxygen
minimum zone have a minimum oxygen content at least 0.1 ml/l
higher than the other curves along the sections. A comparison of
Figures 15 through 18 shows that section GH closest to the coast has
the lowest oxygen content with large volumes of water having less
than 0.4 ml/l. However, the enriched oxygen minimum at station
71 on GH has an oxygen content greater than 0.6 ml/l. This content
is higher than the enriched oxygen minima in the other sections
farther offshore. Station 71 on section GH is closest to Point Con-
ception. That is, the area of the most intense "ventilation" occurs
in the region of Point Conception.

The enriched oxygen minimum occurs on the 80-cl/t surface
(depth of 750 meters) on section GH (Fig. 18). Offshore, on section
AB (Fig. 15) 1500 km from Point Conception, the enriched oxygen
minimum occurs at a depth of 800 meters at 80 cl/t.

It is certainly significant that the oxygen minimum on either
side of the enriched oxygen minimum lies on different delta-t sur-
faces. The northern minimum lies at the 80-cl/t surface; the
southern minimum lies at 100 cl/t. The depth difference between the two oxygen minima of the northern and southern water masses is about 200 meters. These facts imply that the two minima have different origins, thus offering further evidence of the different origins of the northern and southern water masses.

**Evidence for a Front between the Northern and Southern Water Masses**

Data from NORPAC 55 stations were examined to determine the following features at the depths where delta-t varied between 125 and 60 cl/t: (1) the southernmost stations which had northern water throughout the column, (2) the northernmost stations which had southern water throughout the column, (3) the stations which showed predominantly northern water overlying predominantly southern water, and (4) the stations showing an enriched oxygen minimum. This information is plotted on Figure 19.

West of section CD, 1000 km offshore, the transition from northern to southern water takes place somewhere within a maximum distance of 250 km, the station-spacing along sections AB and CD. East of section CD, the zone separating the two water masses must be about 750 km at the coast. The enriched oxygen minimum lies to the north of the frontal zone separating the northern and southern water masses.
• Station having northern water from 500 to 1200 m.
• Station having southern water from 500 to 1200 m.
Station having northern water over southern water.
□ Station having an enriched oxygen minimum zone.

Figure 19. Locations of stations that define the boundary between northern and southern water during NORPAC 55.
One may justifiably ask whether this front is a permanent feature or whether it may be peculiar to conditions prevailing during the time of NORPAC 55, that is, August and part of September, 1955. There were nine cruises between March and November, 1949, and eight cruises between February and September, 1950, with data that extended to 1000 meters and extended offshore to approximately section EF in Figure 5 (California, University, 1957 and 1960). These data were examined to see whether the temperature, salinity and dissolved oxygen data showed the existence of southern and northern water. No abrupt change from one water mass to the other was expected since the data were relatively close to shore, where there is not a clear difference between northern and southern water. Nevertheless, the temperature-salinity data indicated the presence of both northern and southern water.

Oxygen data are not as plentiful as the temperature-salinity data from the cruises in 1949-50. However, the oxygen data were examined to see if an enriched oxygen minimum was present during the time of the cruises. Data from section GH showed the enriched oxygen minimum to be present each month of the 15 months sampled. Its position varied from month to month in 1949 and 1950 (Table 1) from latitude 37°17'N in July, 1950 (farthest north), to 28°50'N in April, 1950 (farthest south). The average position of the enriched oxygen minimum for the 15 months was about 34°N or just offshore
Table 1. The position of the enriched oxygen minimum for the years 1949-50 along a line 200 km offshore (corresponding to section GH in Figure 5).

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Latitude (N)</th>
</tr>
</thead>
<tbody>
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</tr>
<tr>
<td></td>
<td>May</td>
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</tr>
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<td></td>
<td>June</td>
<td>32°15'</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>33°09'</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>37°03'</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>35°24'</td>
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<td>November</td>
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<td>37°17'</td>
</tr>
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<td>35°23'</td>
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Salinity Distribution on Isentropic Surfaces

The surfaces of 125, 100, 80 and 70 cl/t were selected for the examination of the salinity distribution on isentropic surfaces.

Salinity on the 125-cl/t Surface

The distribution of salinity on the 125-cl/t surface is shown in Figure 20. Throughout the area, the depth of this surface ranges from 600 meters at approximately 30°N, 155°W to less than 350
Figure 20. Salinity (%) and depth (meters) of the 125-cl/t surface. Stippled area defines the front.
meters adjacent to the coast. The salinity of this surface varies from 33.9% in the north to about 34.5% adjacent to the coast of Baja California. Stippling on Figure 20 and in the following figures shows the position of the frontal zone.

Some of the most interesting features are the tongues of high salinity extending up the west coast of the U. S. These tongues have their origin within the wide portion of the frontal zone, that is, the eastern portion adjacent to the coast. The axes of these tongues are located about 150 km offshore and their depths are about 350 meters. There is also a tongue extending offshore from San Francisco. This tongue gives the appearance of having "split off" from the tongues extending northward.

South of the frontal zone, there are tongues of high salinity extending northward from Punta Eugenia, Baja California. These tongues are located at depths between 350 and 400 meters and their axes lie up to 150 km offshore. They appear to be separate and smaller features than the tongues originating from the eastern end of the frontal zone.

Salinity on the 100-cl/t Surface

Figure 21 shows the distribution of salinity on the 100-cl/t surface. The depth of this surface ranges from 800 meters at about 30°N, 155°W to depths of less than 550 meters adjacent to the
Figure 21. Salinity (%) and depth (meters) of the 100-cl/t surface. Stippled area defines the front.
coast. The salinity on this surface varies from 34.1% in the north to a maximum of 34.5% off the coast of Baja California. There are cells of lower salinity (not shown in Figure 21 because the contour interval is too large) in the vicinity of Point Conception. It is not certain if they are real since there is a possible error of 0.02% in salinity data (Norpac Committee, 1960b). There are tongues of high salinity extending up the coast. The axes of the tongues are located about 200 km from the coast and are at a depth of about 550 meters. As in Figure 20, there is a tongue that appears to have split off from the tongue adjacent to the coast near Point Conception. There are very small tongues near the coast of Baja California, but they are definitely weaker than those extending northward from the frontal zone.

Salinity on the 80-cl/t Surface

Figure 22 shows the salinity distribution on the 80-cl/t surface. The depth of the surface ranges from over 1000 meters at 35°N, 160°W to less than 750 meters just off Point Conception. Salinity varies from approximately 34.3% in the northwest corner of the area to 34.5% in the south. There is a cell of low salinity just offshore and to the north of Point Conception. Its existence is uncertain.

This surface also shows tongues of high salinity extending up
Figure 22. Salinity (‰) and depth (meters) of the 80-clt surface. Stippled area defines the front.
the west coast of the U. S. These tongues originate in the eastern portion of the frontal zone, just as do those on the preceding two surfaces. The distance from the coast to the axes of the tongues averages about 400 km and the tongues themselves are about 200 km wide. The depths range from 750 to 800 meters. There is a tongue extending offshore from San Francisco to the northwest, just as in Figures 20 and 21.

In the south portion of the frontal zone next to shore, there is a weak indication of tongues extending southward, at least to Punta Eugenia.

**Salinity on the 70-cl/t Surface**

The distribution of salinity on the 70-cl/t surface is shown in Figure 23. This surface is the deepest studied. Its depth ranges from 1100 meters in the western portion of the area to approximately 950 meters near the coast. The salinity varies from 34.4‰ in the northwest to greater than 34.5‰ adjacent to Baja California.

Tongues of high salinity water originate from the eastern portion of the frontal zone and extend northward along the coast. The axes of the tongues are about 300 km from the coast. An extension to the northwest is apparent north of Point Conception, although it is not as noticeable as those on the shallower surfaces. The depth of the tongues is close to 950 meters. There is little
Figure 23. Salinity (%) and depth (meters) of the 70-cl/t surface. Stippled area defines the front.
evidence, if any, of tongues along the coast of Baja California south of 30°N.

**Salinity at Depths Shallower than the 125-cl/t Surface**

In the layers of 70 through 125 cl/t, a strong gradient in salinity is evident near the frontal zone. This gradient is stronger on the 125-cl/t surface (Figure 20) and gradually weakens with depth. A study of the distribution of salinity on the 150- and 200-cl/t surfaces indicates that the gradient of salinity above the frontal zone decreases as the depth decreases. However, the gradient increases with decreasing depth as one proceeds toward the southeast to the coast of Baja California. On the 150-cl/t surface, tongues of high salinity less than 200 km from the coast and at a depth of 250 meters extend northward along the coast of Baja California up as far as Ensenada. There are no tongues extending up the coast of the U. S.

On the 200-cl/t surface, there are broad (widths between 500 and 1000 km) tongues of low salinity extending southward along the west coast of the U. S. The depth of this surface is around 100 meters near the coast.

**Geostrophic Flow**

This section presents the description of geostrophic flow on the surfaces of 125 and 100 cl/t. Below these surfaces, the gradient of
acceleration potential, which is directly proportional to the geostrophic velocity, is too weak to give meaningful results. The acceleration potential in units of $10^3 \text{ cm}^2/\text{sec}^2$ is plotted in Figures 24 and 25. The gradients on the 125- and 100-cl/t surfaces are small and velocities above 1 cm/sec are rare.

It is not expected that the geostrophic velocities calculated on the 125- and 100-cl/t surfaces will be accurate to better than 1 or 2 cm/sec because of the inaccuracies in the determination of temperature and salinity. However, the acceleration potential can give us good indication of the direction of flow even though the speed of flow is usually less than 1 cm/sec in depths below 400 meters. This is so because we consider the field of acceleration potential represented by several adjacent stations. The field as a whole may show a gradient of acceleration potential, thus indicating a direction in flow, even though the difference in potential between any two adjacent stations may be below the threshold of accuracy. If the trend of the field is relatively regular, we can estimate the speeds from the contour intervals.

Flow on the 125-cl/t Surface

In general, the flow on the 125-cl/t surface (Figure 24) shows anticyclonic flow in the central region of the study area. In the western portion of the frontal zone, the predominantly southerly flow
Figure 24. The acceleration potential \((10^3 \text{ cm}^2/\text{sec}^2)\) on the 125-c1/t surface. Stippled area defines the front.
Figure 25. The acceleration potential \(10^3 \, \text{cm}^2/\text{sec}^2\) on the 100-cl/t surface. Stippled area defines the front.
changes rather abruptly to westward flow. Flow in the eastern portion is irregular. Within 300 km from the coast, the gradient of acceleration potential indicates northward flow along the coast. This flow appears to be divided into large eddies at Punta Eugenia, Point Conception and off the Oregon coast. The depth of the surface along the coast is approximately 350 meters.

Flow on the 100-cl/t Surface

West of 125°W, the flow is generally westward to the north of the frontal zone (Fig. 25). To the south of the frontal zone, particularly in the eastern portion, the flow is generally to the northeast toward the coast of the U. S. and Mexico. North of the western portion of the frontal zone, there is some indication of a change in flow direction from southerly flow to westward flow as in Figure 24. Within 300 km of the coast, there is an indication of northward flow. Flow adjacent to the coast is divided into eddies as in Figure 24. The flow on this surface is irregular compared to that on the 125-cl/t surface.

Flow at Depths Shallower than the 125-cl/t Surface

On the 150-cl/t surface (not shown), the gradient of acceleration potential indicates mostly anticyclonic circulation. Adjacent to the coast, the flow is southward except at Baja California where
there is an indication of northward flow between Punta Eugenia and the international border. Above this on the 200-cl/t surface, the flow is southward all along the west coast of the U. S. and Mexico except at the tip of Baja California.

Summary

An analysis of temperature, salinity and oxygen data from NORPAC 55 has demonstrated the existence of two water masses in the layers where delta-t varies between 125 and 60 cl/t. The two water masses, southern water and northern water, are separated by a frontal zone. West of 125°W the front is less than 250 km wide. Near the coast, the width of the frontal zone markedly increases to about 750 km.

Southern and northern water as defined in this study are different water masses than those described by Sverdrup and Fleming (1941) for coastal waters. The comparison is shown in Figure 4 and reveals that their two water masses extend over a greater temperature-salinity range. The definition of southern and northern water in this paper employs more data both in quantity and extent than were available to Sverdrup and Fleming (1941). Their data were collected within 250 km from shore. The data used in the regression analysis to define northern and southern water extended greater than 1500 km offshore, and all data within 900 km of the coast were omitted.
The distribution of salinity on isentropic surfaces has shown that tongues of high salinity water lie along the coast of the U. S. in depths where delta-t varies between 70 and 125 cl/t. Above 125 cl/t, there is no evidence of these tongues along this coast. These tongues apparently originate in the wide, eastern portion of the frontal zone. There are weak tongues of high salinity along the coast of Baja California. These are evident only in the depths where delta-t is 125 and 150 cl/t.

In the depths where delta-t is 100 and 125 cl/t, geostrophic flow was predominantly northward adjacent to the coast of the U. S. and Mexico. Above this, on the 150-cl/t surface, northward flow was indicated only along the coast of Baja California. In the relatively shallow waters where delta-t is 200 cl/t, the flow was southward along the entire coast from Washington-Oregon to the tip of Baja California.
PROPOSED MODEL OF THE FRONTAL ZONE AND ITS CIRCULATION

The Water Mass Structure along the Frontal Zone

The results of the distribution of salinity on isentropic surfaces were replotted in terms of relative salinity along each of the sections whose locations are shown in Figure 5. This method of presentation was used by Parr (1938). An example of the relative salinity distribution along section AB, 1500 km offshore, is given in Figure 26. The highest salinity ($S_h$), found in the southern portion of each isentropic surface, is assumed to be the least-mixed state of the tropical water contributing to the system; the lowest salinity ($S_1$), found in the northern portion, is the least-mixed state of the Subarctic water north of the Polar Front. $S_h$ and $S_1$ usually have different values for each of the isentropes considered. The relative salinity ($S_r$) is an expression of the amount of tropical water present at any location along an isentrope, given in percent, or

$$S_r = \frac{(S - S_1)/(S_h - S_1)}{100},$$

where $S$ is the salinity at the location where $S_r$ is calculated.

In section AB (Figure 26) the front is suggested by the rapid change in relative salinity in depths between 400 and 800 meters between stations 101 and 116. The diagram vividly illustrates that the front, although in the region of the subtropical convergence (see
Figure 26. The relative salinity (%) for section AB. Dashed lines are those of delta-t in cl/t.
chart No. 5 of Dietrich and Kalle, 1957), does not intersect the sea surface. The water above the front is in the region of the California Current Extension, and there are no fronts in this near-surface zone that would inhibit relatively free horizontal exchange of waters along the section.

Diagrams like Figure 26 were drawn for each of the sections shown in Figure 5. These diagrams, along with the T-S curves for each of the stations along each section, aided in the drawing of Figures 27 through 30. In these figures, the stippled areas represent frontal zones between water masses. Currents into the section are designated by $\otimes$, currents out of the section by $\odot$.

Figure 27 shows the water mass structure along section AB. The manner of drawing the boundaries between different types of water shows that there are actually several fronts in the area. We concern ourselves here with the front between northern and southern water. The front along section AB shows northern water to be present between 400 and 1000 meters north of station 101. Between this station and station 116, there is a mixture of northern and southern water. Above the front there appears to be a continuous band of relatively high-salinity water at depths between 250 and 400 meters. (The high salinity band gradually disappears 500 km north of station 78.)

The current directions shown in Figure 27 (and in the following
Figure 27. Schematic water mass structure for section AB, 1500 km offshore.
Figure 28, Schematic water mass structure for section CD, 1000 km offshore.
Figure 29. Schematic water mass structure for section EF, 500 km offshore.
Figure 30. Schematic water mass structure for section GH, 200 km offshore.
three figures) were determined from geostrophic currents (Figs. 24 and 25) and from results to be presented later. Above the salinity maximum zone, we find the surface water of the California Current Extension. Within this water is the shallow salinity minimum discussed by Reid (1965), among others.

Figure 28 shows the schematic distribution of the water masses about 500 km closer to shore (section CD) than in the previous figure. Some differences are apparent. The front is still rather strong, and the lower depths look much the same as in Figure 27. However, above 600 meters, the northern water appears to be over-running southern water. The zone of relatively high salinity above the front can be traced southward to the Equatorial Pacific water mass. The salinity maximum weakens and finally disappears about 200 km north of station 68. Equatorial Pacific water appears at the southern edge of section CD.

The character of the frontal zone along section EF (Fig. 29) is markedly different. The boundary of mixed southern and northern water has widened to approximately 750 km above a depth of 800 meters. The northern water is actually over-running the southern water. The mixed water has penetrated northward as far as Point Conception. Conditions above 300 meters are not appreciably different from those farther offshore. There is a weak front between southern and Equatorial Pacific water.
The well-defined frontal zone found offshore is practically unrecognizable in Figure 30. A front is apparent between southern and Equatorial Pacific water, but it should not be confused with the front between northern and southern water. Southern water extends northward past Point Conception at depths of around 1000 meters. The bulk of the water below 200 or 300 meters in the region north of the Mexican border is a mixture of northern and southern water. There appears to be significant "upwelling" of southern water just north of Point Conception.

The principal result to be emphasized here is that the front as a well-defined feature gradually breaks down as one approaches within 500 km from shore. Once the front breaks down, there is freer mixing of northern and southern water. The northern water, as shown in Figures 29 and 30, probably extends adjacent to the coast no farther equatorward than Point Conception. The unmixed southern water penetrates northward close to shore as far north as station 63, north of Point Conception. Below 600 meters, the mixture of northern and southern water extends northward beyond Cape Mendocino. (Note that the southern boundary between southern water and Pacific Equatorial water closely corresponds to the end of the Transition region shown in Figure 1.)

The enriched oxygen minimum zone (Figure 19) appears to be associated with the northern boundary of the frontal zone and
apparently marks the southern limit of northern water. The "ventilation" of the oxygen minimum zone was more intense nearest to Point Conception. Sverdrup and Fleming (1941) and many biologists have recognized that Point Conception acts as a boundary of some nature as far as surface currents were concerned. Indications here are that it may be a boundary of deeper extent than previously supposed. The distributions of oxygen and water masses suggest that vertical mixing at Point Conception weakens offshore. The enriched oxygen minimum is also weaker offshore, and it may be a remnant of the vertical mixing closer to shore. There is evidence of some upwelling offshore in section EF (Figure 29), but it is not as strong as in section GH. These indications of weakening as one proceeds offshore suggest (1) that either the vertical motions themselves decrease or (2) that there are no appreciable vertical motions offshore and that the higher maximum in the oxygen minimum and the upwelled mixture of northern and southern water are simply carried by currents from the region of Point Conception to the offshore area. Geostrophic flow near Point Conception at a depth of 550 meters does not show offshore currents, but they may be too weak to detect.

There is other evidence of vertical motion close to Point Conception. Figure 22, showing the distribution of salinity on the 80-cl/t surface, contains a closed isohaline of low salinity water
near Point Conception. (The salinity distribution on the 125- and 100-cl/t surfaces also shows closed isohalines of low salinity when the contour interval is decreased to 0.02 part per thousand of salinity.) Parr (1938) pointed out that closed curves of temperature, salinity or oxygen on isentropic surfaces are evidence of vertical motion. Values of low salinity in our data show that water has been transported downward in the areas of low salinity. The only place from which such low salinity can come is from above. There are no closed isohalines west of 125°W, thereby suggesting that vertical motions that change the property distributions significantly are sufficiently strong only close to Point Conception.

The Offshore Circulation West of 125°W

In a well-formed front, mixing acts to reduce the gradient of properties. In order to maintain the front between two water masses in the presence of mixing, the two water masses must be continuously supplied, i.e., they must be convergent. The purpose of this section is to examine the gradient of properties in the frontal zone where it is well defined.

Flow Balanced by Advection and Mixing

For a conservative property in an incompressible fluid, the existence of a stationary pattern of concentration, s, requires a
balance between advection and turbulent diffusion or mixing. This balance may be expressed as

\[ \rho \overline{v} \nabla s = A_H \nabla^2 s + A_V \nabla^2 s, \]

where \( \rho \) is the density, \( \overline{v} \) is the velocity, \( \nabla s \) is the gradient of the property, \( \nabla_H^2 s \) and \( \nabla_V^2 s \) are the second derivatives of the property in the horizontal and vertical directions, and \( A_H \) and \( A_V \) are the coefficients of eddy diffusion for horizontal and vertical mixing respectively.

In the depths of the front 1000 to 1500 km offshore, temperature (T) and salinity (S) represent concentrations of heat and salt, both of which may be considered conservative below the surface. Consider the frontal zone oriented so that the x-axis extends parallel to the frontal surface towards the coast (approximately eastward). The y-axis is perpendicular to the frontal surface and is positive to the north. The z-axis is positive downward. We assume that gradients of T and S vanish along the x-axis. We can therefore write the above equation as two equations in S and T, or

\[ \rho v_S y + \rho w_S z = A_H S_{yy} + A_V S_{zz} \]

and

\[ \rho v_T y + \rho w_T z = A_H T_{yy} + A_V T_{zz}. \]
Here, $v$ and $w$ are the $y$ and $z$ components of velocity respectively, and the subscripts on $T$ and $S$ denote partial differentiation. From NORPAC 55 data we can estimate the first and second derivatives of temperature and salinity in the frontal region. There have been many calculations of $A_H$ and $A_V$ in various regions of the ocean. Neumann and Pierson (1966) suggest that typical values in the deep ocean are $A_V = 1 \text{ gm/cm/sec}$ and $A_H = 10^6 \text{ gm/cm/sec}$. The latter agrees well with the value of $A_H$ calculated by Sverdrup and Fleming (1941) for the California Current region between depths of 200 and 400 meters ($A_H = 2 \times 10^6 \text{ gm/cm/sec}$). For this study, $A_V$ and $A_H$ are taken as 1 and $10^6 \text{ gm/cm/sec}$ respectively. Therefore the above pair of equations have two unknowns, $v$ and $w$, and can be solved simultaneously.

Taking the density of sea water, $\rho$, as approximately 1 gm/cm$^3$,

$$
\begin{vmatrix}
D_S & S_z \\
D_T & T_z \\
\end{vmatrix}
v =
\begin{vmatrix}
S_y & D_S \\
T_y & D_T \\
\end{vmatrix}
\quad \text{and} \quad
w =
\begin{vmatrix}
S_y & S_z \\
T_y & T_z \\
\end{vmatrix}
$$

where $D_S = A_H S_{yy} + A_V S_{zz}$ and $D_T = A_H T_{yy} + A_V T_{zz}$.

$T_{yy}$, $T_{zz}$, $S_{yy}$, $S_{zz}$ were determined for each station along section AB from horizontal and vertical profiles.
of temperature and salinity. The front was best delineated along section AB. Then $v$ and $w$ were calculated at several depths for locations on either side of the front using the last two equations for $v$ and $w$. Table 2 presents the results.

Table 2. North-south and vertical velocities on either side of the front calculated for a section 1500 km offshore.

<table>
<thead>
<tr>
<th>Station</th>
<th>Depth (m)</th>
<th>North-south velocity (cm/sec)</th>
<th>Vertical velocity (Direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>300</td>
<td>$&lt;0.1$ north</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>0.7 north</td>
<td>downward</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>$&lt;0.1$ south</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>0.1 south</td>
<td>upward</td>
</tr>
<tr>
<td>116</td>
<td>300</td>
<td>2.2 south</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>$&lt;0.1$ north</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.3 north</td>
<td>-0-</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>$&lt;0.1$ north</td>
<td>upward</td>
</tr>
<tr>
<td>101</td>
<td>300</td>
<td>2.3 south</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>0.3 south</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.2 south</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>-0-</td>
<td></td>
</tr>
<tr>
<td>Between 78 and 101</td>
<td>300</td>
<td>$&lt;0.1$ north</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>3.9 south</td>
<td>upward</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>0.9 north</td>
<td>downward</td>
</tr>
<tr>
<td></td>
<td>900</td>
<td>0.4 north</td>
<td>-0-</td>
</tr>
</tbody>
</table>

The horizontal and vertical profiles of temperature and salinity from which their first and second derivatives were estimated are, at best, poorly defined. The station spacing along AB was 250 km and data were spaced no closer than 100 meters vertically.
Therefore it is difficult to attach much significance to the magnitudes of the velocities tabulated in Table 2 since they are dependent upon the magnitudes of the first and second derivatives of temperature and salinity. What may be significant is that the sign of the gradients indicates some consistency in direction for horizontal and vertical velocities. The same calculations were performed for an \( A_H = 10^7 \) gm/cm/sec. This had no effect on the directions although the magnitudes of the velocities changed.

The arrows in Figure 27 reflect the results of this analysis. The important feature is the convergence shown at depths between 500 and 900 meters. Another important result is the upward motion along the northern and southern edge of the frontal zone.

Convergence at the frontal zone is also suggested by Figures 24 and 25 which show geostrophic flow on the 125- and 100-cl/t surface. Where the front is well formed (section AB), southward flow to the north of the front turns abruptly westward so that \( \partial v/\partial y \) is negative; assuming that \( \partial u/\partial x \) is approximately zero, the horizontal divergence is negative, that is, there appears to be convergent flow.

Flow Parallel to the Front

Geostrophic flow in Figures 24 and 25 indicates that the water in the depths where delta-t is 125 and 100 cl/t goes mostly westward
north and south of the front where it is well formed. Presumably the water in the mixed zone goes westward also as part of the general westward circulation. Rough estimates of the acceleration potential gradient in the frontal region indicate that westward velocities are on the order of 0.5 cm/sec.

Inshore from section CD, 1000 km from the coast, the velocity pattern changes. The gradient of the acceleration potential suggests that convergence is no longer present. This may explain why the gradients of properties are much weaker in the frontal zone east of 12.5°W. Moreover, on the 100-cl/t surface, there is good indication of a weak northeastward flow onshore (Fig. 25). Along section EF, 500 km from the coast, the onshore velocity estimated from the acceleration potential gradient on the 100-cl/t surface is between 0.5 and 1.5 cm/sec. Acceleration potential gradients are negligible in the frontal region at depths below the depth of the 100-cl/t surface. The 125-cl/t surface does not have onshore flow 500 km from the coast, but the flow on this surface is onshore in section GH, 200 km from shore.

A rough calculation of the onshore transport through the section 200 km offshore is possible if we assume that the average velocity throughout that part of the section showing onshore flow is about 0.5 cm/sec; the width of the section is about 750 km with a thickness of approximately 300 meters. This section thus has a
transport of approximately 1.1 sverdrup \((1.1 \times 10^{12} \text{ cm}^3/\text{sec})\).

This estimate neglects any flow that may occur below 550 meters. If we increase the depth of the section to 700 meters (including depths between 550 and 1000 meters) and assume that the average velocity throughout the section is 0.5 cm/sec onshore, the transport is 2.6 sverdrups.

Summary

Flow near the frontal zone west of 125°W must be convergent in order for the front to maintain itself. This convergence was indicated both by the geostrophic flow pattern and by an analysis of diffusion and advection of heat and salt near the frontal zone. West of 125°W, the mixed water in the frontal zone is carried westward and upward. East of 125°W, within 500 km from the coast, geostrophic flow patterns show an onshore transport of water within the wide frontal zone. There is a lack of convergence that probably explains the weak horizontal gradients of temperature and salinity in the frontal zone nearshore. The water carried onshore 200 km from the coast is a mixture of northern and southern water.
Flow Northward along the West Coast of the U. S.

Interpretation of Tongues Originating in the Frontal Zone

The distribution of salinity on isentropic surfaces (Figures 20 through 23) exhibits tongue-like distributions. These tongues originate from the weak portion of the frontal zone east of 125°W, and the water in the region is a mixture of northern and southern water.

The flow patterns in Figures 24 and 25 exhibit intermittent flow northward adjacent to the coast. This flow was discussed in the section describing geostrophic flow on isentropic surfaces. The tongues of high salinity extending northward along the west coast of the U. S. are manifestations of this flow. This interpretation is utilized to estimate subsurface poleward transport adjacent to the coast.

Estimation of Subsurface Northward Transport Adjacent to the Coast

Let us return to the equation on page 70 that states that a non-varying concentration of a conservative property in an incompressible fluid requires a balance between turbulent mixing and advection. In order to reduce the equation into a tractable form, we make the following assumptions. The vertical mixing term, $A_v \nabla^2 S$ is
negligible when compared to \( A_H \nabla^2 S \) in the tongue-like distributions. This is a good assumption since the vertical salinity gradient, \( S_z \), is almost constant in the depths in which we are interested.

We further assume that \( \nabla^2 S \) along the direction of flow is smaller than \( \nabla^2 S \) in the direction perpendicular to flow and that vertical velocities are negligible. If we orient the \( x \)-axis perpendicular to the axis of a tongue and the \( y \)-axis in the direction along the axis, the equation on page 70 reduces to

\[
A_H S_{xx} - \rho \nu S_y = 0,
\]

This is equivalent to assuming that the tongue-like distributions of salinity on isentropic surfaces are maintained by a balance of advection along the axes and lateral mixing perpendicular to the axes.

A solution to the above equation is given by Defant (1961) as

\[
S = S_o + \Delta S_o e^{-ay} \cos \left( \frac{\pi}{2l} x \right),
\]

where \( S_o \) is the salinity of water outside a tongue, \( l \) is one-half the width of the tongue, \( \Delta S_o \) is the difference between \( S_o \) and the maximum (or minimum in the opposite case) salinity at the origin of the tongue, \( y \) is the distance along the tongue with \( y = 0 \) at the tongue's origin, and \( a = \pi A_H / 4l^2 \rho \nu \). All other terms are as previously specified. For a tongue adjacent to the
coast, \( \lambda \) is effectively the distance from the coast to the axis. Given a series of tongues along the coast, we know the distance, \( y \), measured from the origin of the tongue-like distributions to a particular isohaline (S) in the series, and we know \( S_o \), the salinity outside the tongues. With \( \Delta S = S - S_o \) and \( x = 0 \) at the axis of the tongue, our equation reduces to

\[
\Delta S = \Delta S_o e^{-ay}.
\]

The coefficient, \( a \), may be written \( K/v \) where \( K \) is constant for any one tongue if we assume a constant value of \( A_H = 10^6 \) gm/cm/sec, as before. Thus at a particular isohaline in a series of tongues, we can solve for \( v \), or

\[
v = -K\sqrt{\frac{\Delta S}{\Delta S_o}}.
\]

This equation has been evaluated for three locations along the west coast: off northern Baja California, off Point Conception and off northern California. The velocity, \( v \), is assumed to be the mean velocity across the entire width of the tongue. This velocity, when multiplied by the width of the tongue and by one meter, gives the estimated transport over a one-meter depth that would produce the tongue-like distribution in salinity. The results are presented in Figures 31 through 33. Each point in the figures gives the transport in \( 10^9 \) cm\(^3\)/sec over a one-meter depth at each isentropic surface.
Figure 31. Northward transport as a function of depth off northern Baja California. Numbers adjacent to data points identify isentropic surfaces on which transport was measured.
Figure 32. Northward transport as a function of depth off Point Conception. Numbers adjacent to data points identify isentropic surfaces on which transport was measured.
Figure 33. Northward transport as a function of depth off northern California. Numbers adjacent to data points identify isentropic surfaces on which transport was measured.
considered. The points are connected by a smooth curve, and the total transport is estimated by integrating each curve over its depth range.

Figure 31 presents the vertical profile of northward transport off northern Baja California. The transport is about 0.6 sverdrup, most of which occurs between 200 and 250 meters. No transport northward is shown above 130 meters or below 570 meters, the depths of the 200- and 100-c1/t surfaces, respectively, since the tongues of salinity on these surfaces were negligible.

Figure 32 shows the vertical profile of northward transport off Point Conception. The transport is roughly 5 times that off northern Baja California, or 3.1 sverdrups. The high values occur over a depth range between 300 and 800 meters. The transport is shown as zero at 1000 meters, but this is uncertain. The 70-c1/t surface is the deepest considered and shows a sharp decrease in transport from the surface of 80 c1/t. The highest transport occurs at about 750 meters on the 80-c1/t surface.

Figure 33 shows the vertical profile of northward transport off northern California. The profile is roughly the same shape as the one off Point Conception, but the magnitude of the transport has diminished by a factor of over one-half to only 1.4 sverdrup.
Discussion

The results of Figures 31, 32 and 33 have a limited objective. They show that, assuming that all the tongues of salinity have been produced by similar processes, the northward transport along the coast is distributed differently north and south of the front. While the absolute values of transport may not be accurate (for example, they depend linearly on the assumption of a single value for $A_H$), the ratios of the transports between one section and another are meaningful.

There are rather striking differences between Figure 31 and Figure 32. Northward flow off Baja California is relatively small and shallow, compared with flow off Point Conception. The results suggest that a significant input of water is made at depths below 400 m in between northern Baja California and Point Conception. All indications are that this input comes from the weakened frontal zone of mixed northern and southern waters where we have already shown that there may be shoreward transport of roughly 2.6 sverdrups. The transports determined lend an air of confidence since if we add the transport onshore from the frontal zone (2.6 sverdrups) to the northward transport off Baja California (0.6 sverdrup), the result comes to 3.2 sverdrups. The calculated input from the frontal zone occurs between the depths of 300 and 1000 meters.
A shortcoming of such a model is that most of the transport off Baja California occurs on the 150-cl/t surface, while the input from the frontal zone occurs on deeper surfaces. It is conceivable that the flow off Baja California has been "transferred" to a lower level by the time it reaches Point Conception. This could be accomplished by sufficient mixing of the 150-cl/t water with, for example, the 100-cl/t water in the southern California area so that the resulting mixture is at some intermediate specific volume. But this process could not possibly account for the large transport on the 80-cl/t surface off Point Conception.

It is possible, of course, that the flow off northern Baja California simply turns offshore and never reaches the frontal zone off southern California. Geostrophic flow on the 150-cl/t surface indicates that the northward flow adjacent to the coast is a cyclonic eddy; this flow turns offshore at about 29°N. The suggestions offered in the preceding paragraph appears more feasible.

An interesting question is raised concerning the reason that the transport off northern California is only one-half that off Point Conception (compare Figures 32 and 33). Presumably, the water is transported offshore between the two regions. This may explain the tongues of high salinity extending offshore in a northwesterly direction (see Figures 20 through 22). The study by Sverdrup and Fleming (1941) of lateral mixing of subsurface water adjacent to the
coast led them to conclude that some of the salt transported northward was lost offshore.

For the sake of balancing the transports that have been calculated, let us decrease the input from the frontal zone from 2.6 sverdrups to 2.5 sverdrups. Using the above transport estimates, we can draw a schematic diagram of the poleward subsurface circulation. The diagram is shown by Figure 34. The northwestward branching flow off the central California coast is simply the difference in flow between Point Conception and northern California (Figures 32 and 33). The transport that is lost offshore could have possibly "leaked" offshore in eddies from the main poleward flow. Sverdrup and Fleming (1941) probably had this mechanism in mind when they concluded that some of the salt transported northward was lost offshore by lateral mixing.
Figure 34. Schematic diagram of subsurface poleward transport between depths of 200 and 1000 meters. Transports are in sverdrups. Stippled area defines the front.
SUMMARY AND CONCLUSIONS

It has been shown that there is a subsurface frontal zone offshore from the southern California area separating two water masses. We have called these water masses southern and northern water. The front is well defined west of 125°W, and the flow perpendicular to it is convergent. The front lies at depths between 400 and 1200 meters. East of 125°W, the front weakens abruptly in a region that contains a mixture of southern and northern water. Evidence suggests that subsurface currents in this region carry the mixture toward the southern California coast where it then flows northward between depths of 200 and 1000 meters. The water adjacent to the coast at Point Conception is mostly a mixture of southern and northern waters. There is shallower northward flow along Baja California, but the transport here is significantly smaller than the northward flow along the west coast of the U. S.

The front offshore (beyond 1000 km from the coast) is beneath the zone of the subtropical convergence in the eastern North Pacific. This surface convergence has a seasonal north-south migration of about 1000 km because the subtropical high pressure cell responsible for the convergence has this magnitude of seasonal movement according to Malkus (1962). In other words, the convergence occurs over a broad region rather than along a line as schematically shown.
by Dietrich and Kalle (1957). They, among others, have proposed a sinking of water at the subtropical convergences. This motion does not, apparently, affect the depths where the frontal zone is found. Furthermore, there is no evidence of a convergence on the surface in this region of the Northeast Pacific (there is no strong gradient of properties). It is therefore concluded that the front below the surface is caused by processes not directly related to those on the surface overhead.

The southern and northern water masses are not exactly the same as those described by Sverdrup and Fleming (1941). The T-S correlation of two sets of water masses are illustrated in Figure 4. Sverdrup and Fleming (1941) speculated that the source of the southern water was to the southwest. A superficial study made by the author of both northern and southern water between the Equatorial Pacific and the subtropical North Pacific reveals these two water masses at least as far west as 180° longitude. The data are not spaced closely enough to determine if they are separated by a sharp frontal zone. The areas of their formation must remain conjecture.

Finally, this thesis hopefully contributes to a better understanding of the poleward flow of subsurface water adjacent to the west coast of North America. This flow will probably not be verified by direct measurements in the near future because of limitations on the capabilities of current-measuring instruments. The evidence
that the Baja California subsurface countercurrent is weaker than that off Point Conception is in agreement with the research of Reid (1963) who concluded from his measurements that the northward subsurface flow off Baja California is weaker and narrower than the flow north of Point Conception. The flow northward off Point Conception and off northern California appears to be continuous below 200 meters and perhaps continues below 1000 meters although the distribution of properties does not show indications of flow below 1000 meters. The lack of gradients below this level makes an answer to this question of flow below 1000 meters purely speculative.
BIBLIOGRAPHY


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