OCEANOGRAPHIC OBSERVATIONS OF THE SCRIPPS INSTITUTION IN 1939

BY

H. U. SVERDRUP AND THE STAFF

OF THE

SCRIPPS INSTITUTION OF OCEANOGRAPHY

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
1943

RECORDS OF OBSERVATIONS
SCRIPPS INSTITUTION OF OCEANOGRAPHY
EDITORS: H. U. SVERDRUP, R. H. FLEMING, L. H. MILLER, C. E. ZOBELL
Volume 1, No. 2, pp. 65–160, 4 figures in text, 20 charts
Transmitted June 6, 1941
Issued May 17, 1943
Price, $1.00

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY, CALIFORNIA

CAMBRIDGE UNIVERSITY PRESS
LONDON, ENGLAND

[Contributions from the Scripps Institution of Oceanography, New Series, No. 185]

MANUFACTURED IN THE UNITED STATES OF AMERICA

CONTENTS

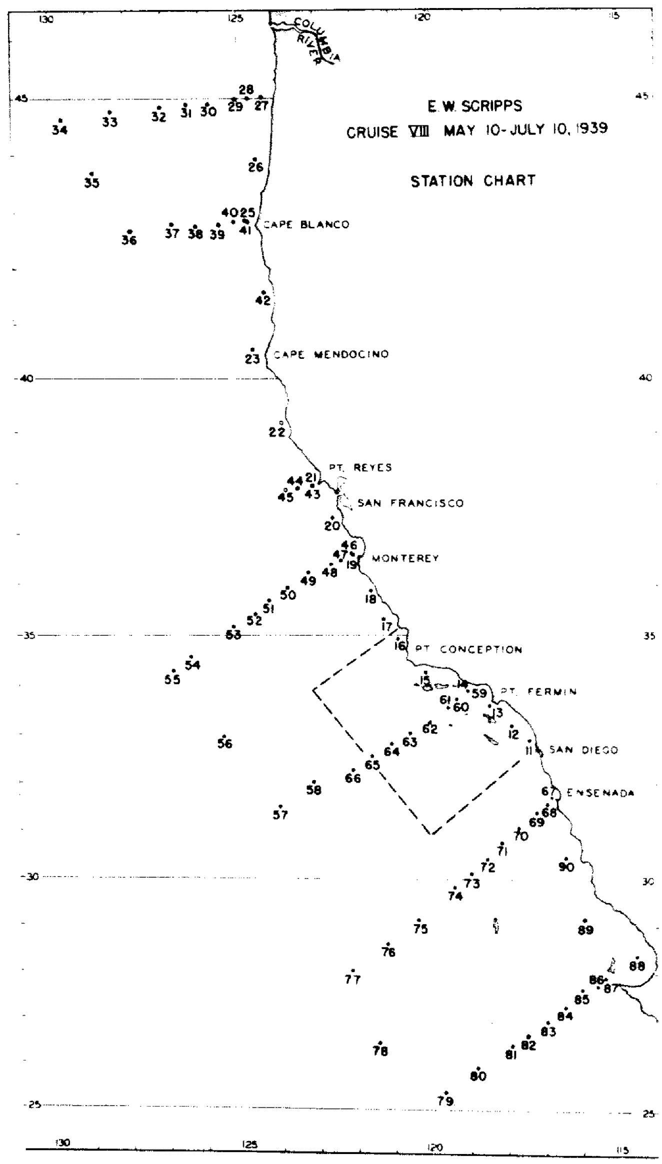


Chart 1.--Station chart, "E. W. Scripps" Cruise VIII.

OCEANOGRAPHIC OBSERVATIONS OF THE SCRIPPS INSTITUTION IN 1939

THE "E. W. SCRIPPS" CRUISES IN 1939

By

H. U. SVERDRUP and STAFF

In 1939 three cruises, numbered VII, VIII, and IX, were completed. On Cruise VII to the Gulf of California fifty-three hydrographic stations were occupied at which temperature observations were obtained at a number of depths, water samples were collected, hauls for phytoplankton and zoöplankton were made, and bottom samples were taken. In addition, about 2500 sonic soundings were obtained. Professor Loye H. Miller of the University of California at Los Angeles accompanied the "E. W. Scripps" on part of this cruise in order to study marine birds, and Harry Allen, graduate student in the geology department of the University of California at Los Angeles, took part in the whole cruise in order to collect molluscs.

Cruise VIII was undertaken in coöperation with the South Pacific investigations of the U.S. Fish and Wildlife Service for the purpose of studying the hydrographic conditions off the American west coast in late spring and early summer and the distribution of eggs and larvae of the California sardine. Members of the staff of the Scripps Institution conducted the standard hydrographic observations and made collections of phytoplankton and zoöplankton. Net hauls for sardine eggs and larvae were taken by members of the Fish and Wildlife Service. During the part of the cruise off Lower California numerous sonic soundings were made and bottom samples were collected. The extent of the cruise is shown on chart 1.

Cruise IX was made in the area off southern California in order to obtain samples of bottom sediments and to measure currents near the bottom.

The hydrographic observations from the Gulf of California, being the first deep-sea data from that region, are considered so important that both original and interpolated values are published. Table 1 contains values for temperature, salinity, oxygen, calcium, and the ratio Ca:Cl at the depths of observation as determined by means of wire-length and unprotected thermometers. The calcium content was determined in the laboratories of the Scripps Institution by E. G. Moberg, using the method of Kirk and Moberg (1933). Most of the values given represent the averages of at least two determinations. Tables 2, 3, and 4 present interpolated values of temperature, salinity, and oxygen at standard depths, table 5 gives the corresponding values of σ_t, and tables 6 and 7 give the anomalies of specific volume and the anomalies of dynamic depth at standard pressures. Most of the soundings which were taken in the Gulf are entered in table 10, and a description by Roger Revelle of the manner in which the data have been worked up is included in this report.

Table 12 gives the observations of plankton diatoms. The samples were obtained by means of the Allen closing bottle which has a capacity of five liters. The water sample brought up from the desired depth was filtered through a small net of number-25 bolting silk and collected in a glass bottle. All samples have been examined microscopically by W. E. Allen. The table gives the total number of diatoms per liter of water and the percentage of specimens in poor condition.

The principal hydrographic results from the cruise to the Gulf of California have been discussed by H. U. Sverdrup (1941) and will not be repeated here. Reference is also made to a paper by W. H. Munk (1941), which contains a theoretical examination of standing internal waves and assists the interpretation of conditions observed in the course of the cruise. Preliminary discussions of the bottom samples have been published by Roger Revelle (1939), and a bathymetric chart based on soundings and on interpretation of the hydrographic conditions will be published by the Geological Society of America.

The oceanographic observations on Cruise VIII off the American west coast between latitudes 25°N and 45°N are reported as interpolated values only and are given in table 8, which also contains computed values of σ_t and anomalies of specific volume and dynamic depth. In table 11 are listed the sonic soundings off the west coast of Lower California. The manner in which the tables have been prepared is explained in the contribution by Revelle. The number of diatoms per liter of water and the percentage of specimens in poor condition are listed in table 13.

A brief description of the oceanographic conditions encountered on Cruise VIII has been prepared by Richard B. Tibby and is included in the reports following.

Discussion of the bottom samples collected on Cruise IX will appear in publications of the Geological Society of America. Results of bacteriological studies made on these and on bottom samples from Cruise VIII have been presented by Sydney Rittenberg (1940). The current measurements taken on Cruise IX, together with those obtained on cruises in 1938, have been dealt with by Roger Revelle and F. P. Shepard in a paper to be submitted to the Geological Society of America. A number of the observations on currents are given in tables 14 and 15, and in one of the following reports Revelle and Shepard have described the methods of measurement.

We take great pleasure in acknowledging the whole-hearted coöperation of the crew of the "E. W. Scripps." The staff members and assistants of the Scripps Institution who took part in the cruises and the working up of the data were W. E. Allen, C. C. Davis, R. H. Fleming, M. W. Johnson, E. C. LaFond, John Lyman, E. G. Moberg, Roger Revelle, Sydney Rittenberg, E. P. Shepard, L. Simpson, H. U. Sverdrup, and R. B. Tibby.

PUBLISHED REPORTS BASED ON OCEANOGRAPHIC OBSERVATIONS ON THE "E. W. SCRIPPS" IN 1939

Munk, W. H.
1941. Internal waves in the Gulf of California. Jour. Mar. Res., IV, pp. 81-91, 1941.
Revelle, Roger
1939. Sediments of the Gulf of California. Geol. Soc. Amer., Abstract, G. S. A. Bull., 50:1929.
Rittenberg, Sydney
1940. Bacteriological analysis of some long cores of marine sediments. Jour. Mar. Res., III, 191-201.
Sverdrup, H. U.
1941. The Gulf of California. Preliminary discussion of the cruise of the "E. W. Scripps" in February and March, 1939. Sixth Pac. Sci. Cong., California, 1939, Proc., Vol. III.

OCEANOGRAPHIC OBSERVATIONS OF THE U. S. S. "BUSHNELL" IN 1939

By

H. U. SVERDRUP and STAFF

The Hydrographic Office of the U.S. Navy arranged in 1939 to have the U.S.S. "Bushnell" occupy a number of oceanographic stations between Panama and San Diego and between San Diego and the Hawaiian Islands. The reports from the former stations are of particular interest because observations were made at the same time the "E. W. Scripps" was completing the cruise in the Gulf of California. Observations of temperature and collection of water samples were made by the personnel on board the U.S.S. "Bushnell," but in order to obtain determinations of the oxygen content Mr. E. C. LaFond of the Scripps Institution staff joined the vessel in Panama and accompanied it to San Diego. The data from this part of the cruise not only facilitate the interpretation of conditions in the Gulf of California, but they also represent the first reliable deep-sea data for the region off the west coast of Mexico and Central America.

The work at the stations between San Diego and the Hawaiian Islands was successfully completed by the personnel on board the U.S.S. "Bushnell," and these data represent a valuable supplement to earlier information obtained by the "Carnegie" in 1928 and by the U.S.S. "Louisville" in 1936. The results of the oceanographic data from the U.S.S. "Bushnell" are given in table 9, which also includes values of the calcium content and the ratio Ca:Cl according to determinations made by E. G. Moberg in the laboratories of the Scripps Institution, using the method of Kirk and Moberg.

The coöperation of the Hydrographic Office in procuring these data is greatly appreciated.

OCEANOGRAPHIC RESULTS FROM THE "E. W. SCRIPPS" CRUISE VIII, MAY 10 TO JULY 10, 1939

By

RICHARD B. TIBBY

This report presents a summary of the oceanographic results of an extended cruise off the coasts of California and Mexico from May 10 to July 10, 1939. The cruise was undertaken by the Scripps Institution of Oceanography and the United States Bureau of Fisheries (now the Fish and Wildlife Service) in coöperation. The program originally planned comprised the occupation of seventy-four stations along eight station lines extending from 140 to 360 miles out from the coast at various points from just south of the Columbia River to Cedros Island, Lower California, of a number of stations close to the coast between the station lines, and of a few between the offshore endpoints of the lines. Because of adverse weather conditions, two lines of stations in the northern part of the area were omitted, but at all other stations water samples for temperature, salinity, and oxygen determinations, diatom samples, and plankton samples with vertical nets were taken, and, in addition, oblique net hauls were made at various levels by members of the Fish and Wildlife Service, whose primary interest was in the distribution of eggs and larvae of the California sardine.

The investigation was the first of its kind to be undertaken over such a large area off the west coast of the United States, and its purpose was twofold: (1) to provide observations on the physical and chemical characteristics of the region in question, and (2) to determine the limits of the region of maximum spawning of the sardine and to establish the relative importance of offshore and northern spawnings.

Chart 1 shows the stations occupied, and the area (within the broken lines) covered by the "Bluefin" in 1937 (Sverdrup and Fleming, 1941) and the "E. W. Scripps" in 1938 (Sverdrup and Staff, 1942).

The charts of dynamic topography (charts 2, 3, 4, and 5) must be looked upon with even more reservation than usual in interpreting data of these kinds, since both the time intervals and the space intervals between station lines were large. Station 27 at the extreme northeast corner was occupied on May 22, station 87 at the southeast corner not until July 8. It was not possible to draw contours over the many miles between the second and the third lines (reckoned from north to south) and the time interval between the first and the last stations in the southern part of the area, stations 46 and 87, was twenty-eight days, a length of time which introduced some uncertainty in the drawing of the contour lines. In twenty-eight days marked changes in the distribution of properties may take place in any given region and especially within the one under consideration where numerous eddies may rapidly develop or change position.

In general, samples were taken at alternate stations to a depth of 500 meters, except inshore where the depth to the bottom was sometimes insufficient, and at the intervening stations to 1000 meters. At the offshore ends of the four southern station lines observations were made to 3500 meters and at the end of the northern line to 2500 meters. In preparing the charts of dynamic topography, the 1000-decibar surface was selected as a reference surface, and the necessary interpolations were made at the 500-meter stations. At some inshore stations where the depth to the bottom did not permit observations to 500 meters values were extrapolated wherever possible. The charts thus prepared agreed in all except minor details with those in which the 500-decibar surface was used as a reference level.

The surface topography (chart 2) shows several remarkable features. In the northern sections currents were poorly defined and of low velocity. It may be noted that the winds during the period in which these stations were occupied were light and variable in direction. In the region between Point Reyes and Monterey Bay conditions were complicated, partly because of the paucity of observations and partly because of the apparent presence of more or less isolated patches of cold, highly saline water, probably recently upwelled along the adjacent coast.

Farther to the south, off Point Conception, the narrow and relatively swift southerly current has previously been interpreted as the inshore boundary of the California Current and the steepness of the dynamic gradient across it as the consequence of rapid offshore movement of light surface water due to prevailing strong northwesterly winds. In 1937 and 1938 this boundary was first developed close inshore in the early spring soon after the beginning of the season of northwesterlies, becoming progressively sharper and moving offshore as the season advanced. It is obvious, however, that the water to the west of this boundary does not all flow to the south but that further offshore in the region off southern California a reversal in direction may take place. A suggestion of this northeasterly current, west and south of Point Conception, was found in 1937 and 1938 when one corner of a large eddy sometimes

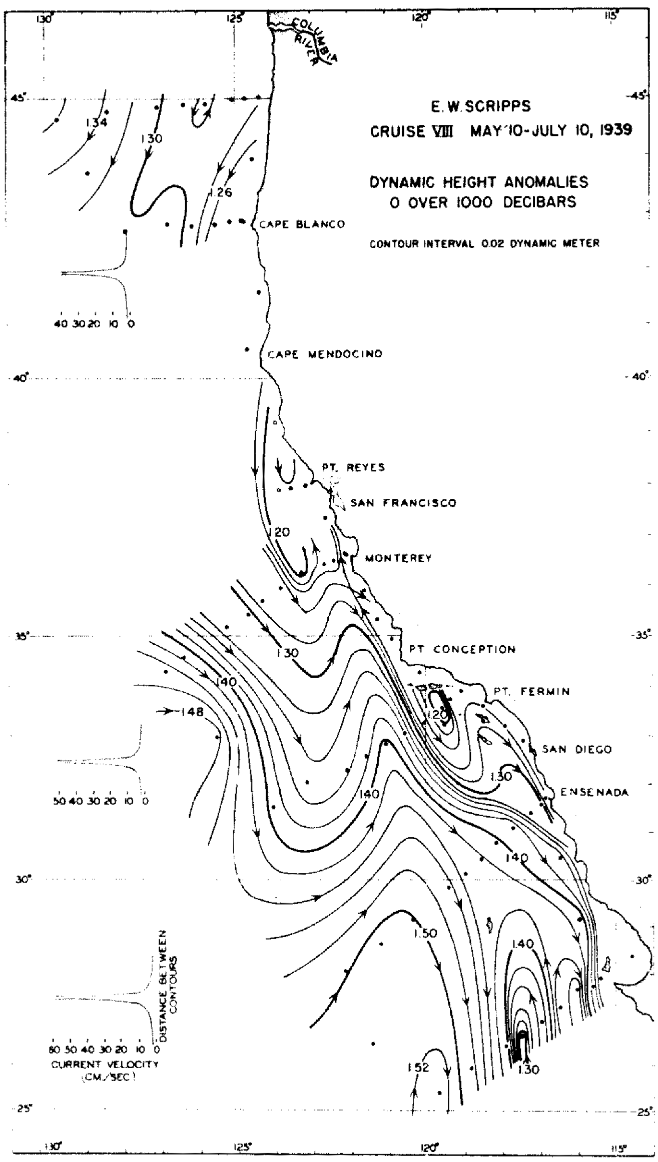


Chart 2.--Dynamic height anomalies of surface referred to 1000 decibars. Contour interval, 0.02 dyn. m. "E. W. Scripps" Cruise VIII.

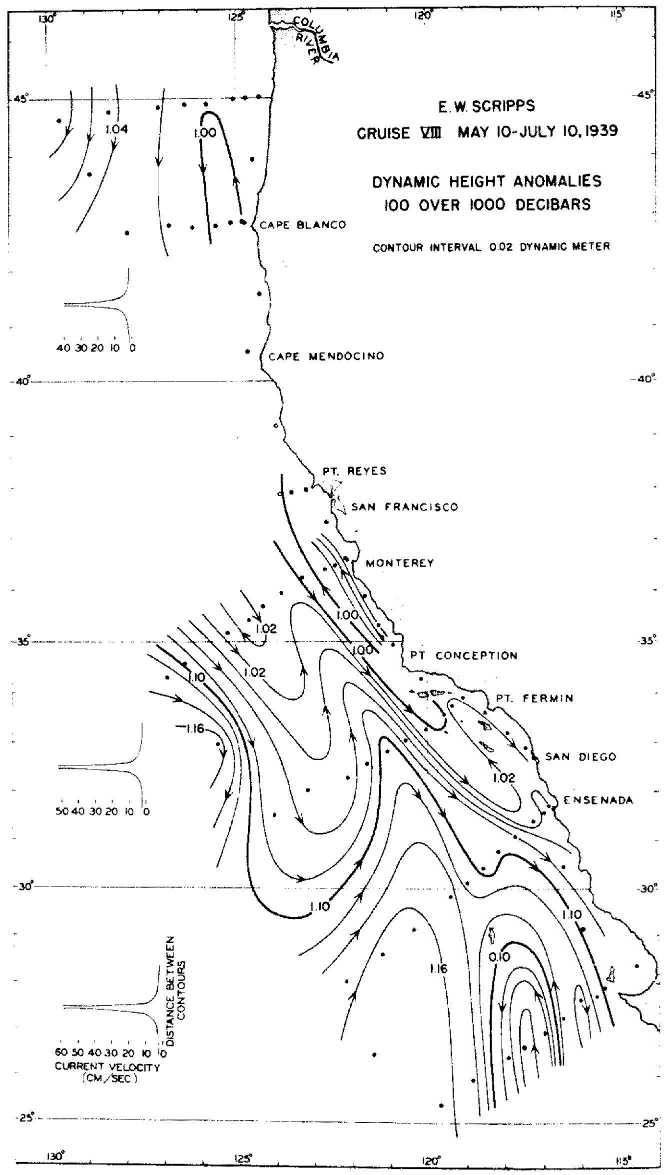


Chart 3.--Dynamic height anomalies of 100-decibar surface referred to 1000 decibars. Contour interval, 0.02 dyn. m. "E. W. Scripps" Cruise VIII.

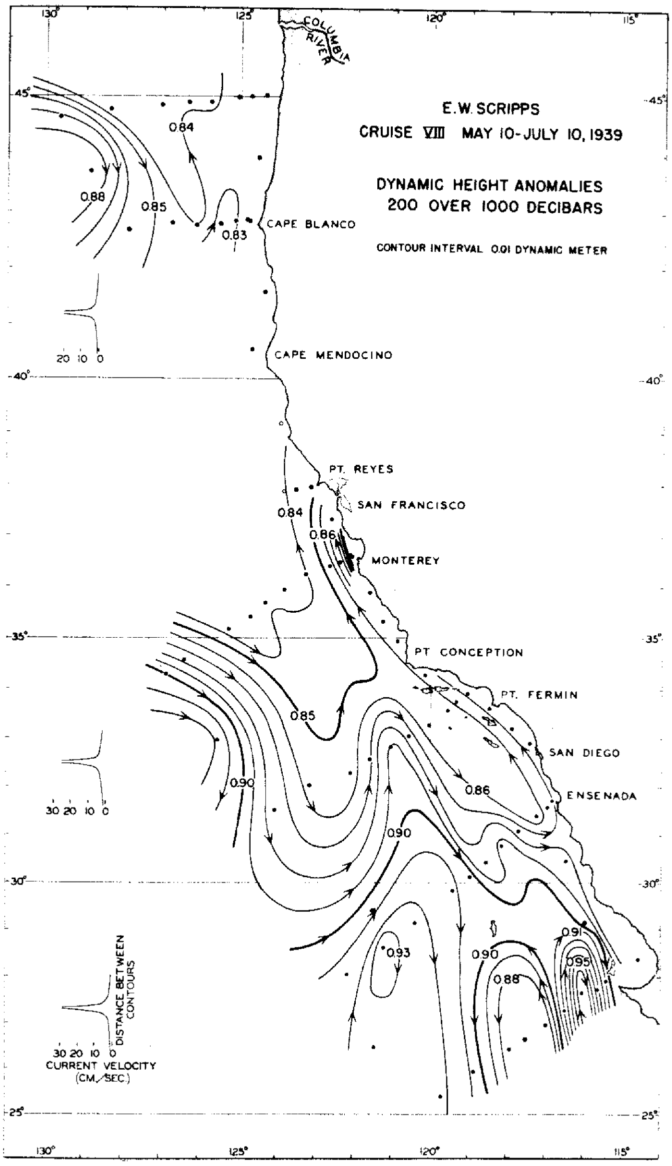
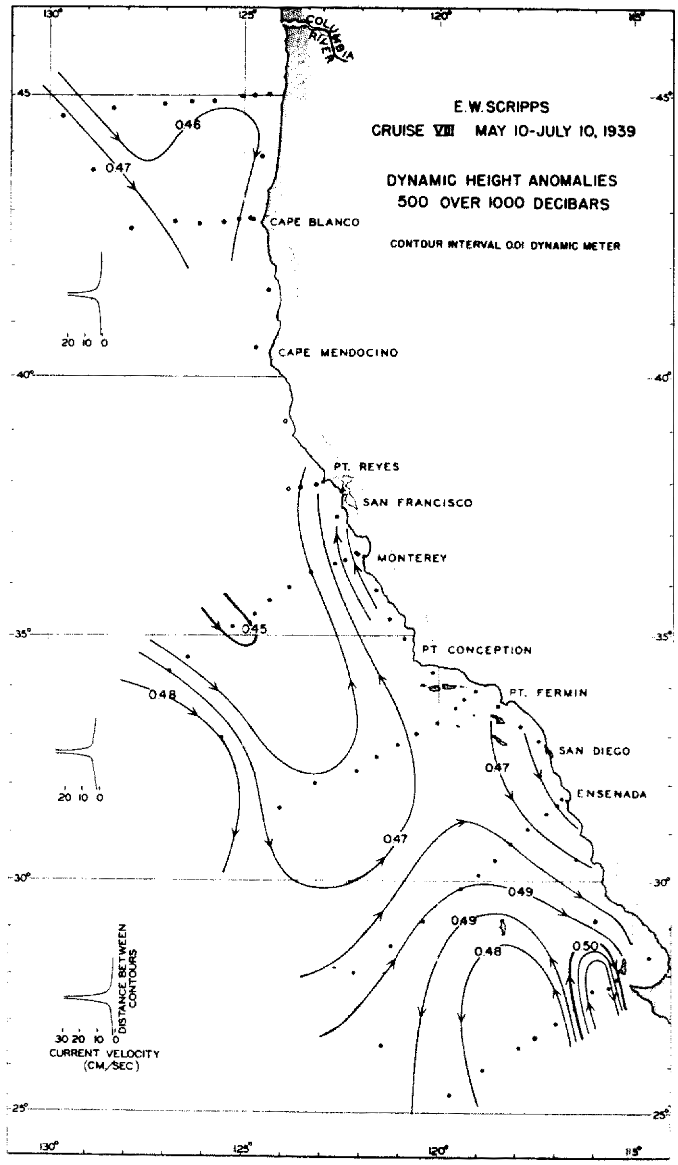


Chart 4.--Dynamic height anomalies of 200-decibar surface referred to 1000 decibars. Contour interval, 0.01 dyn. m. "E. W. Scripps" Cruise VIII.



CChart 5.--Dynamic height anomalies of 500-decibar surface referred to 1000 decibars. Contour interval, 0.01 dyn. m. "E. W. Scripps" Cruise VIII.

appeared at the outer stations of those surveys, but the magnitude of this eddy was not established. There are also certain indications that somewhat similar conditions prevail between the station lines leading out from Cape Blanco and from Monterey Bay where, unfortunately, no observations were taken.

The trough extending some distance to the south from Point Reyes and the concomitant reversal of current direction on its easterly side are conditioned primarily by the presence of a tongue of water of low temperature and high salinity. The northerly current southeast of the Santa Barbara Islands (below Point Conception) is related to a similar tongue of cold and saline water. It has previously been pointed out that this surface counter current has its greatest development during the winter months when it continues inshore up the coast for some distance above Point Conception; but with the onset of the northwesterly winds it becomes reduced or may even disappear. The character of the counter current during this cruise was typical of that found on the 1937 and 1938 cruises in the spring and early summer.

Two remarkably strong eddies were present in the southeast corner of the region, just west of Cedros Island. Between stations 81 and 82 a surface velocity of about 35 centimeters per second, or 0.7 knots, is indicated. At the surface the more westerly of the two eddies was the more pronounced, but at and below 200 meters the inner eddy was particularly well defined; even at 500 meters a difference of 0.03 dynamic meters existed over a distance of about 40 kilometers, giving a computed velocity of 1.1 centimeters per second, or 0.5 miles per day. This latter eddy is characterized by a very high temperature and salinity at 200 meters, namely, 10.36°, and 34.51 ‰ at station 85 as compared with 9.04° and 34.26 ‰ at station 82. The warm and saline water represents an intrusion of extreme "southern" water at that depth. At 100 meters the temperatures at stations 85 and 81 were, respectively, 11.79° and 10.07°.

At the 100-decibar surface (chart 3) the current pattern was essentially the same as that at the surface except for the presence of a well-defined northerly flow along the coast above Point Conception, called the California Coastal Subsurface Counter Current. This current is present also at the 200- and 500-decibar surfaces (charts 4 and 5), but begins farther south, about off Ensenada, Lower California.

The dynamic height anomalies at the 500-decibar surface were small but indicate a general correspondence in directions of the currents at this depth with those at higher levels.

There are several striking points of similarity between the pattern of circulation in this region and in that off the coast of South America (Gunther,1936). Within the Peru Current, Gunther found two wedges of warm water which penetrated to the south and were probably closely related to two large anticyclonic eddies. Even a cursory examination of the temperature charts given in the present report immediately suggests that similar tongues of warm water, penetrating to the north, were present off the California coast, and the dynamic topographies indicate that these warm tongues were associated with eddies similar to those of the Peru Current. It is interesting to note that these eddies have approximately the same dimensions in both regions. The same factors probably operate in both, the primary factor being upwelling along the coast due to the effects of the prevailing winds. The California Coastal Counter Current also has its counterpart in the Peru system. It must be noted, however, that the circulation there is, in general, much more intense than off California, and that it is associated with a greater contrast in types of water within a region of size comparable to that of the California Current.

The north-south distribution of temperature and salinity at the surface (charts 6, 11) shows clearly the effects of dilution by water of low salinity and low temperature from the northeastern Pacific and the influence of water of high salinity and high temperature from the south. The temperature varied from 12° in the north to 20° in the south, and the salinity from 32.8 ‰ to 34.2 ‰. The isolated lows in surface salinity between the two northernmost lines and close in to the coast are without doubt due to dilution by the Columbia River. The north-south difference is shown even at 500 meters by temperatures of 5° in the north and 6.5° in the south (chart 10). At that depth the difference in salinity is not pronounced, being only 0.3 ‰ (chart 15).

To the north of Point Conception temperatures down to a depth of about 200 meters (charts 6, 7, 8, 9) show a general decrease toward the coast which is due to upwelling. Below this depth and down to at least 500 meters (chart 10) the influence of the California Coastal Subsurface Counter Current, which transports warm water to the north along the coast, is shown by the slightly higher temperatures inshore along the entire coast. Inshore and south of Point Conception, on the other hand, the temperature is higher at all depths than farther offshore, and this difference is a consequence of the northward flow of the Coastal Counter Current which, at this season of the year, does not extend north of Point Conception.

Salinities at 200 meters (chart 14) generally increase toward the coast, and this feature is an effect of the Subsurface Counter Current.

At all depths the oxygen content is somewhat higher in the north and offshore than in the south and inshore.

Analysis of the temperature-salinity relationships and of the oxygen content shows that the Subsurface Coastal Counter Current is of relatively high temperature, high salinity, and low oxygen

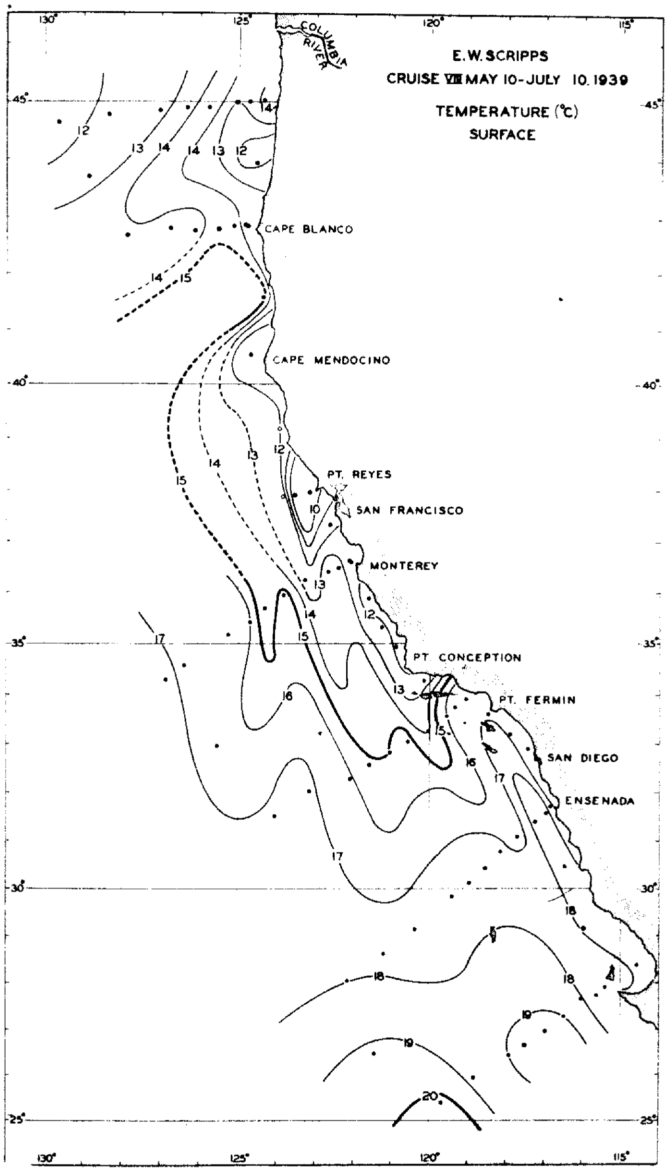


Chart 6.--Surface temperature. "E. W. Scripps" Cruise VIII.

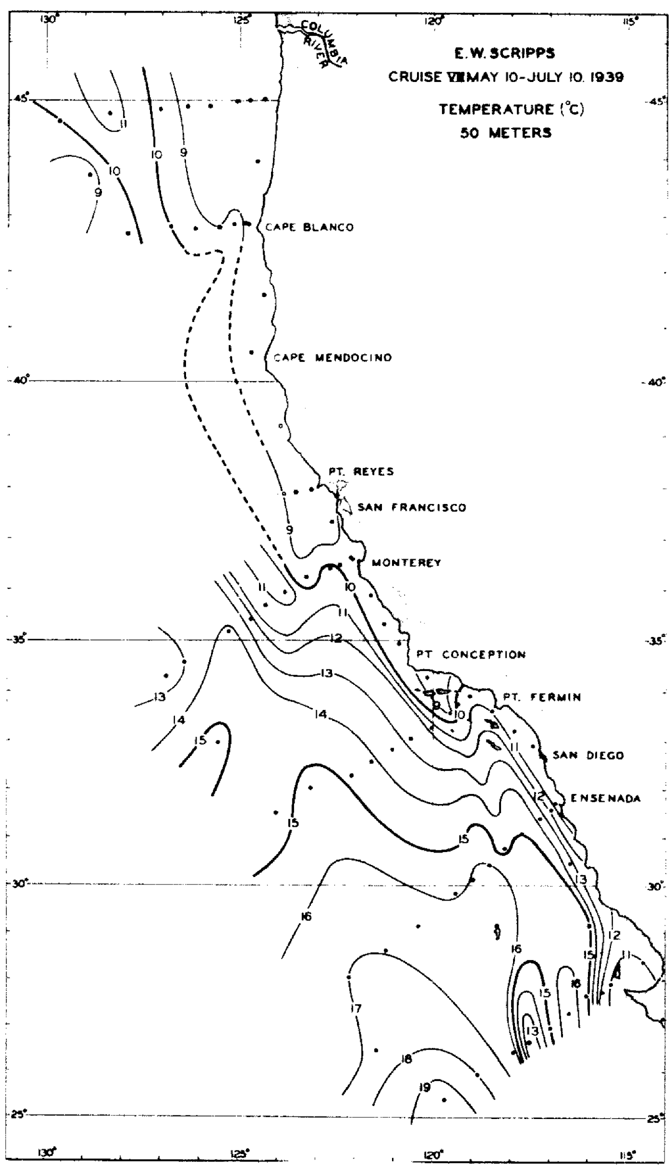


Chart 7.--Temperature at 50 meters. "E. W. Scripps" Cruise VIII.

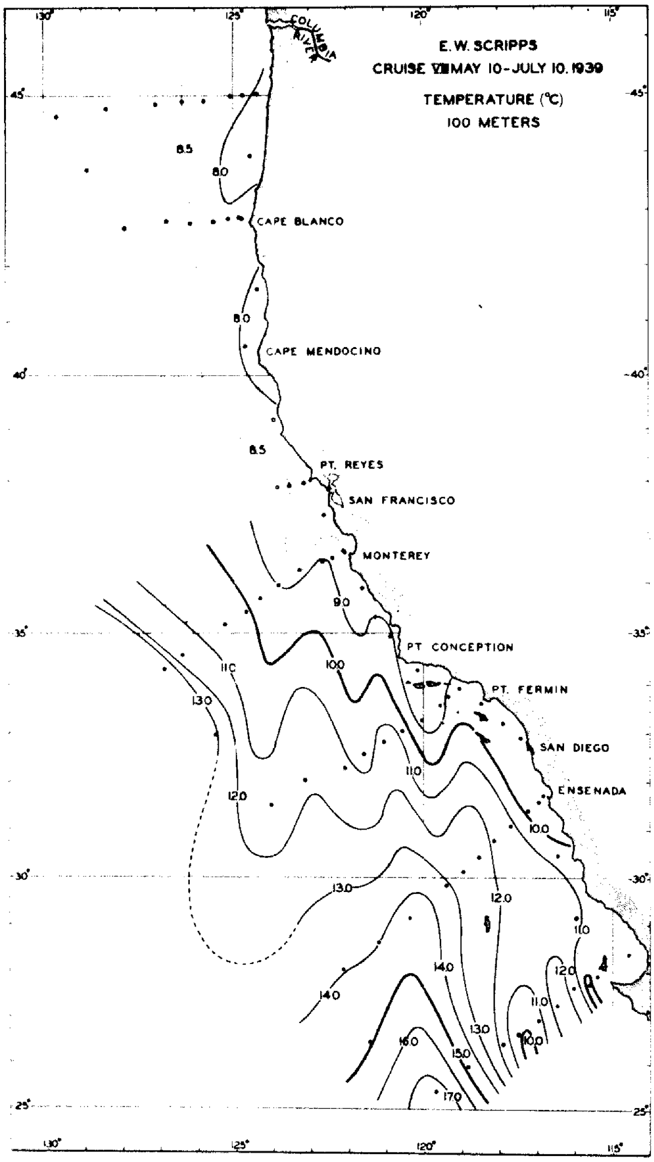


Chart 8.--Temperature at 100 meters. "E. W. Scripps" Cruise VIII.

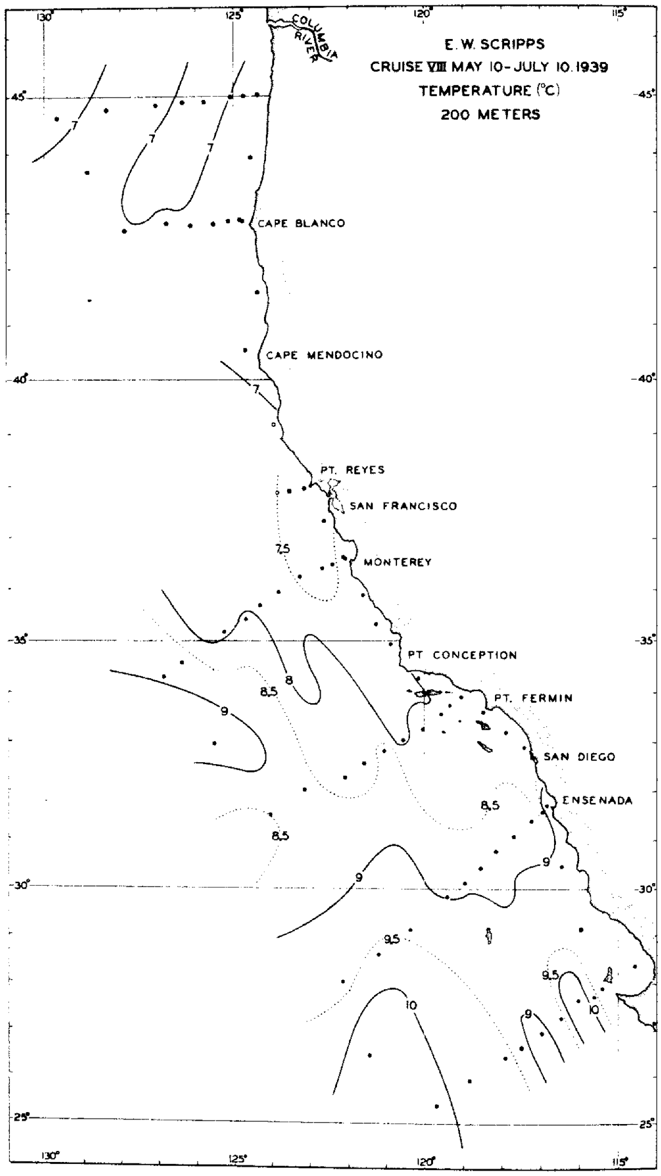


Chart 9.--Temperature at 200 meters. "E. W. Scripps" Cruise VIII.

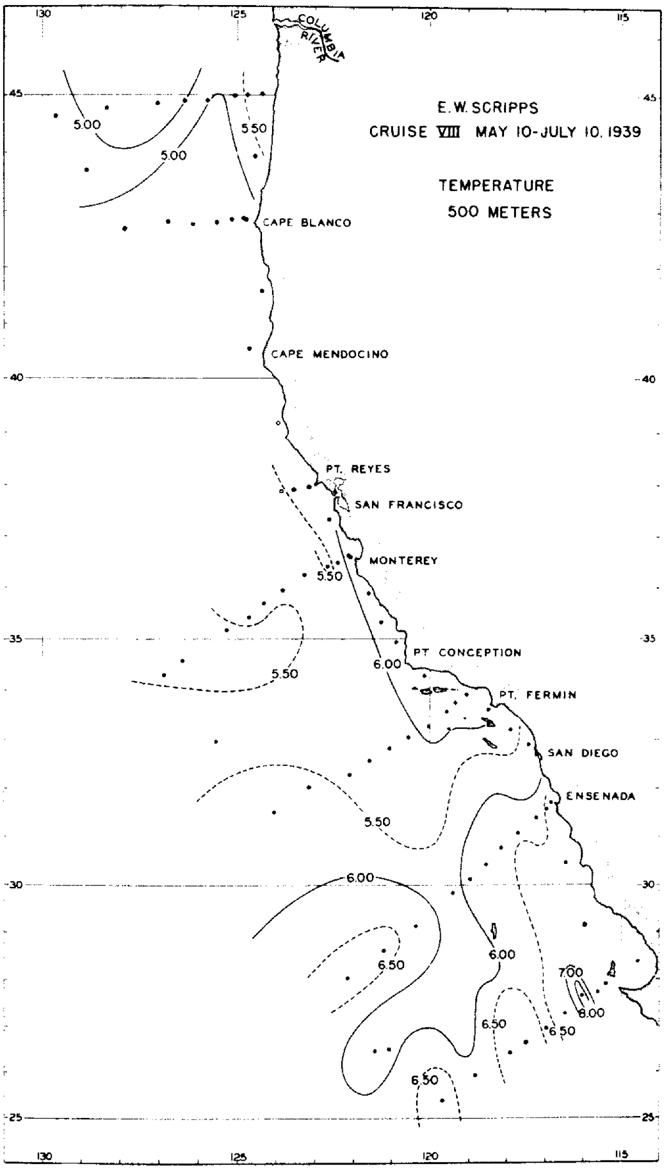


Chart 10.--Temperature at 500 meters. "E. W. Scripps" Cruise VIII.

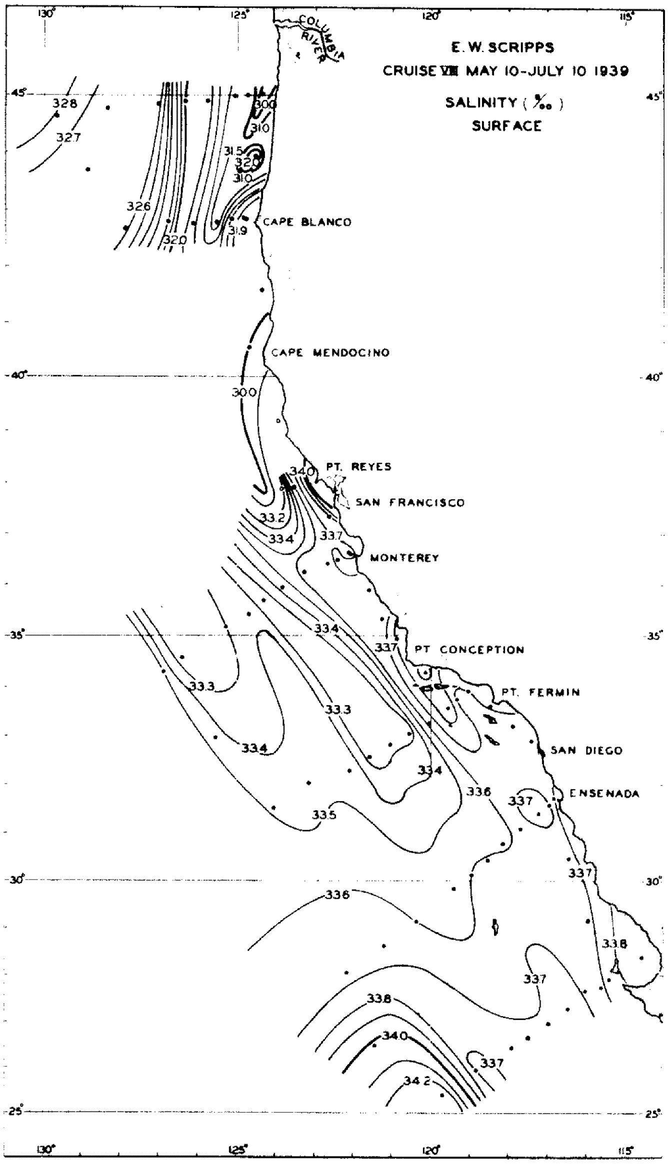


Chart 11.--Salinity at surface. "E. W. Scripps" Cruise VIII.

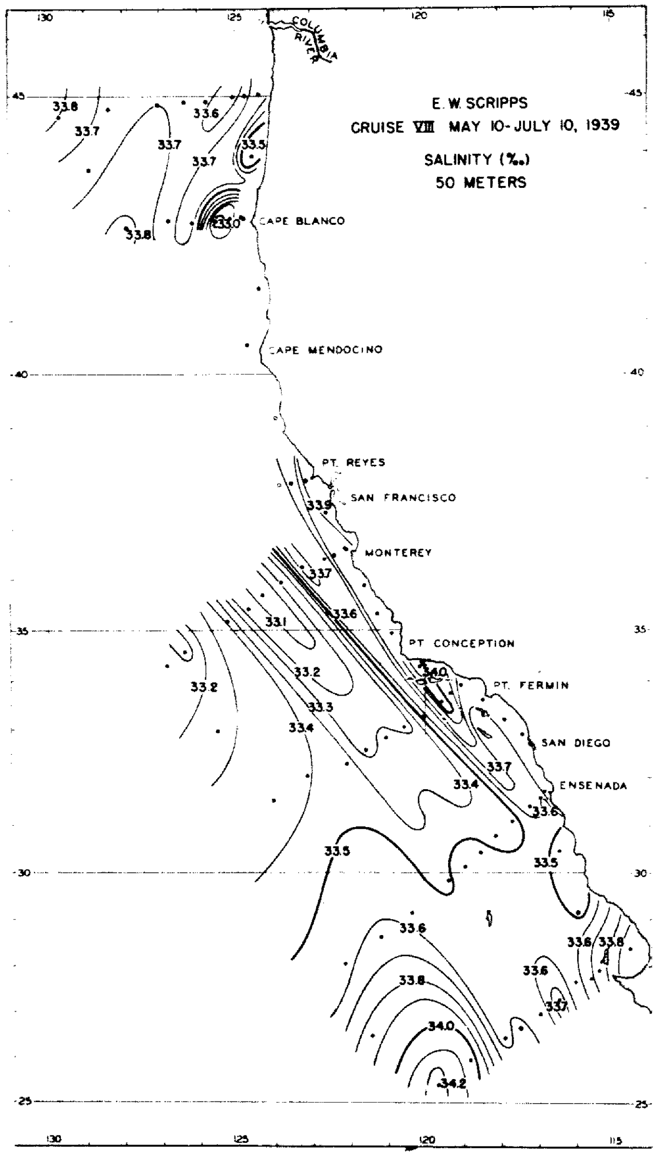


Chart 12.--Salinity at 50 meters. "E. W. Scripps" Cruise VIII.

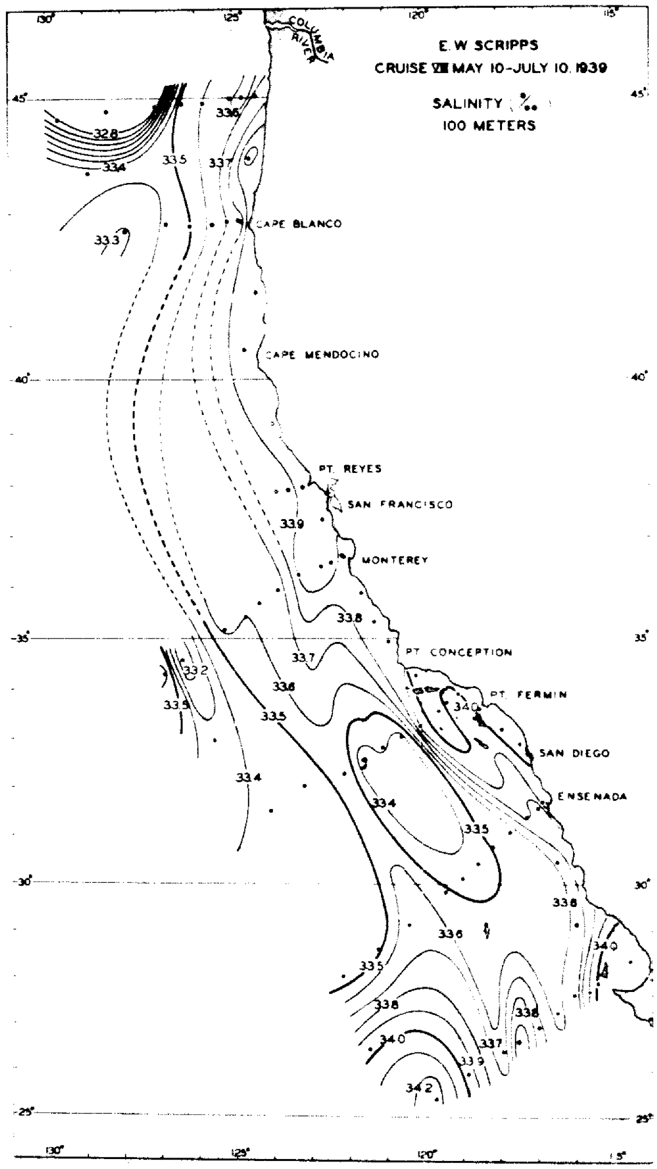


Chart 13.--Salinity at 100 meters. "E. W. Scripps" Cruise VIII.

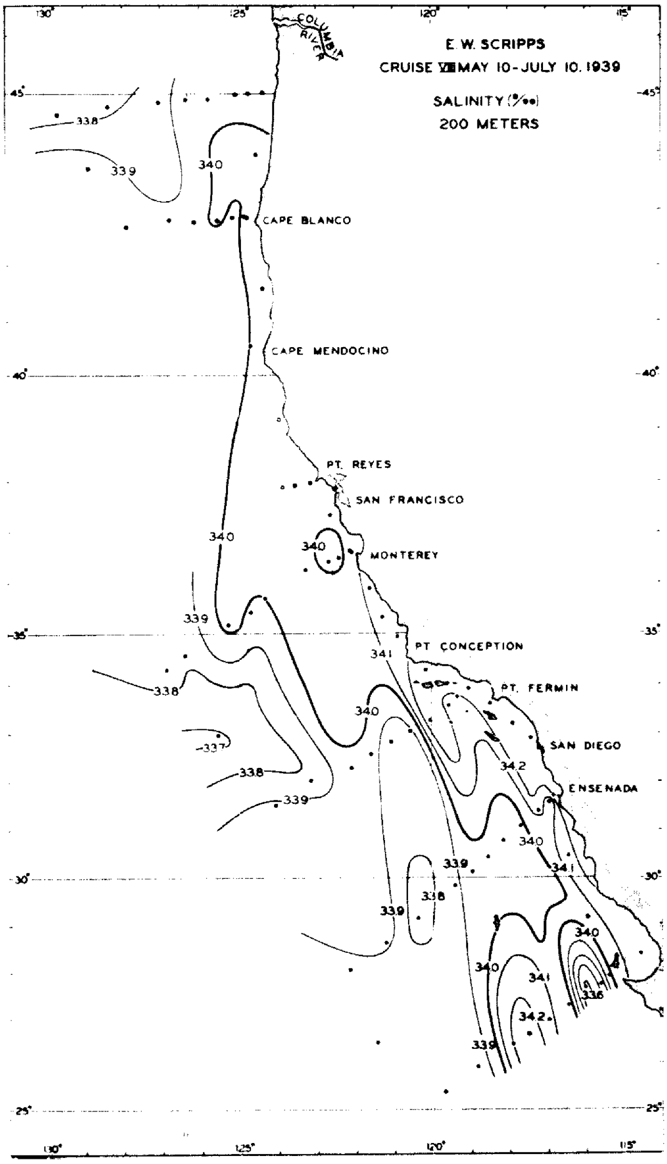


Chart 14.--Salinity at 200 meters. "E. W. Scripps" Cruise VIII.

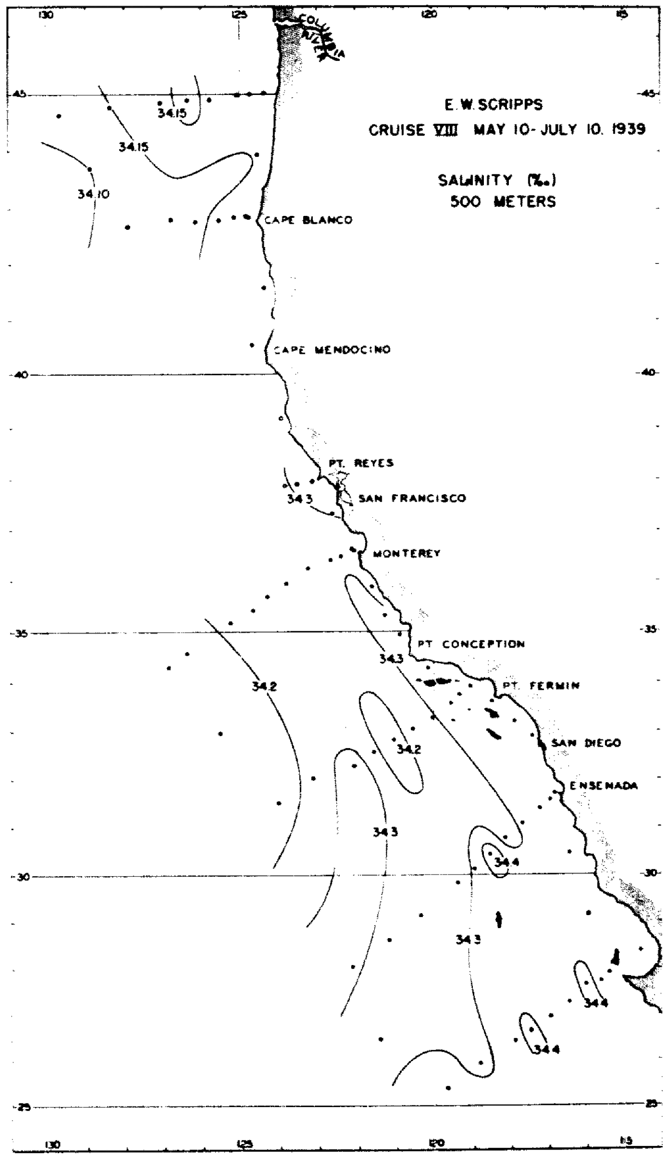


Chart 15.--Salinity at 500 meters. "E. W. Scripps" Cruise VIII.

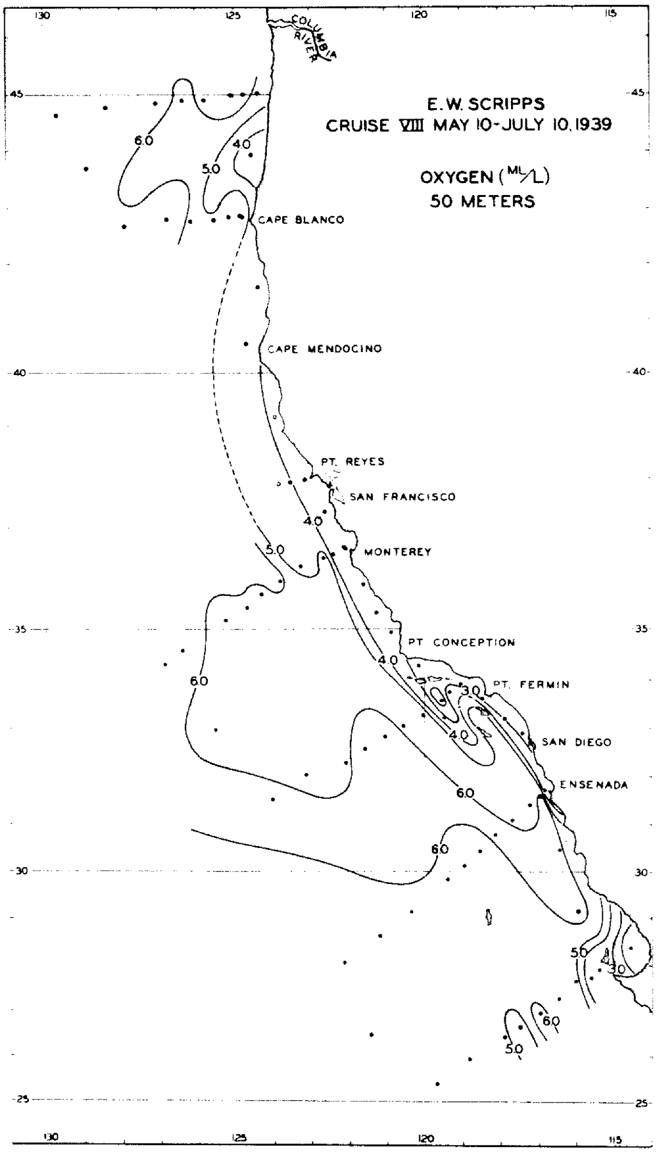


Chart 16.--Oxygen content at 50 meters. "E. W. Scripps" Cruise VIII.

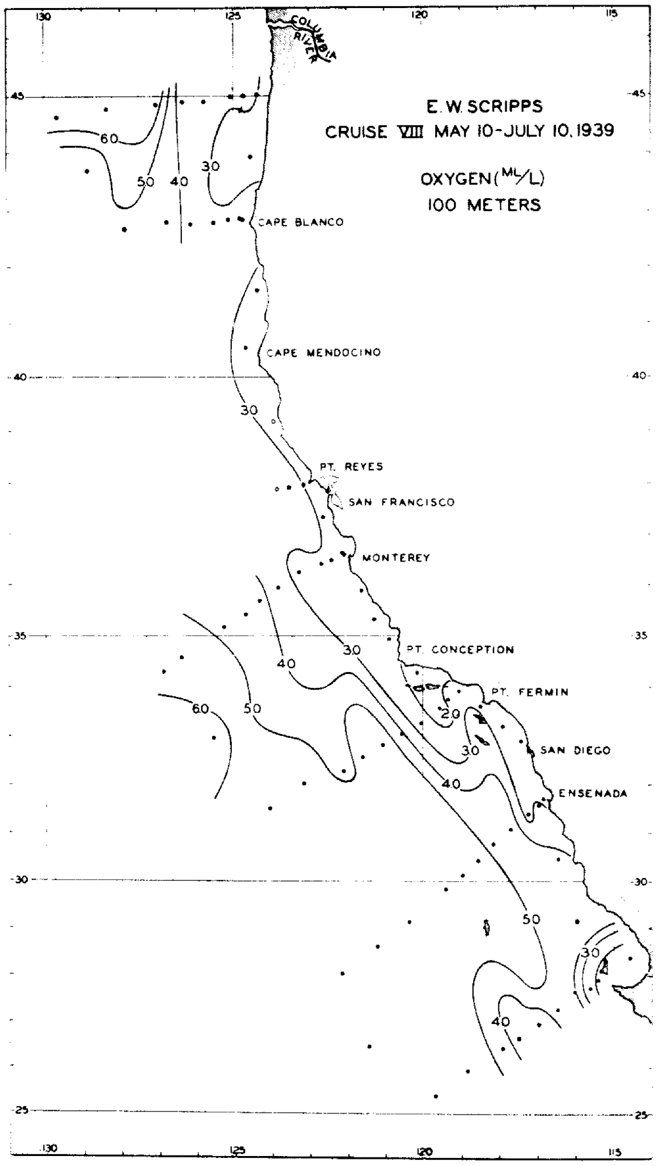


Chart 17.--Oxygen content at 100 meters. "E. W. Scripps" Cruise VIII.

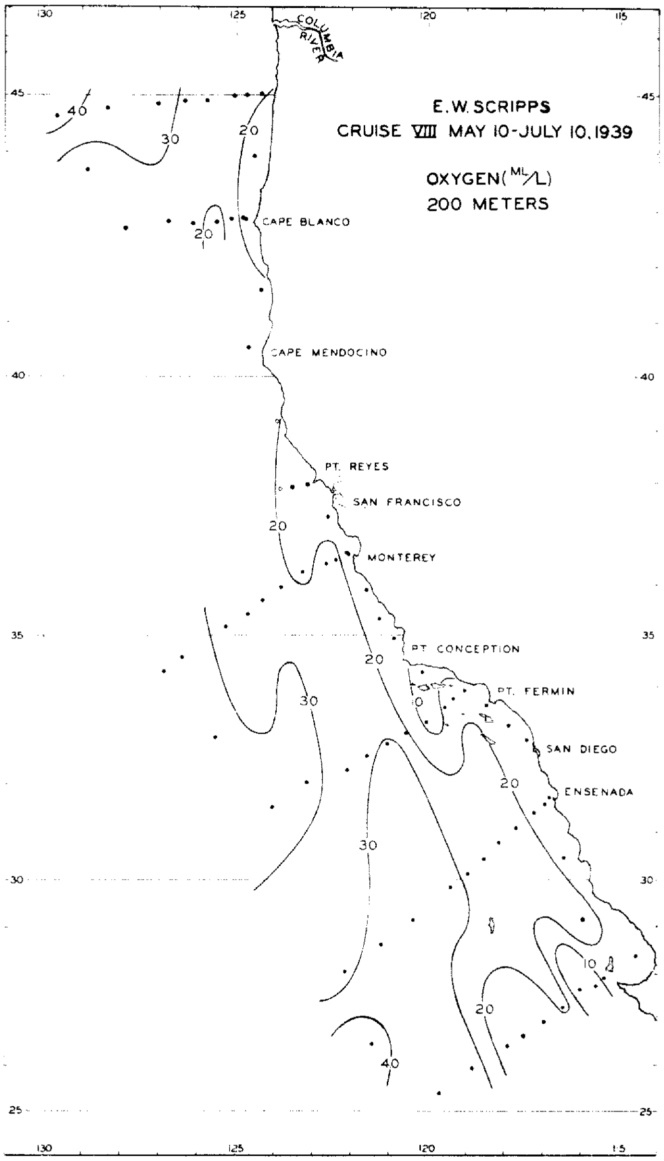


Chart 18.--Oxygen content at 200 meters. "E. W. Scripps" Cruise VIII.

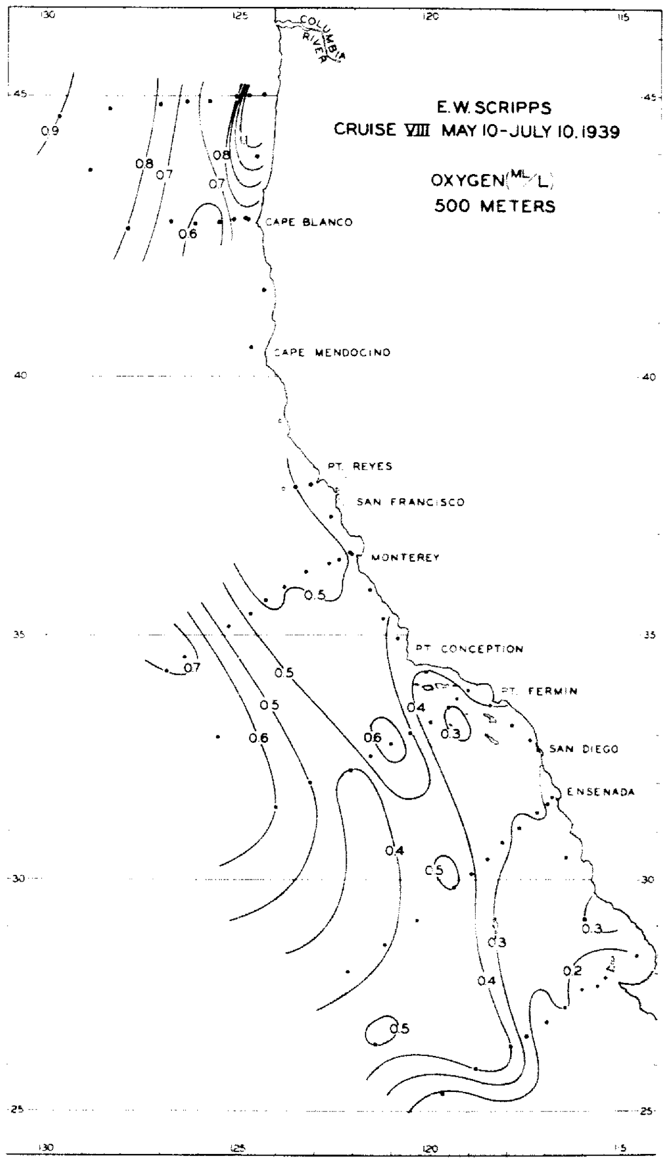


Chart 19.--Oxygen content at 500 meters. "E. W. Scripps" Cruise VIII.

content, indicating its responsibility for the transport to the north of a certain amount of "southern" water, or water typical of more southerly latitudes. It is also apparent that over the entire region there is a regular progressive change from north to south in the characteristics of the water.

In figure 1 are entered the temperature-salinity relationships of selected stations from just south of the Aleutian Islands ("Carnegie" station 124, 52° 19' N, 162° 02' W) to the equatorial region ("Bushnell" station 299, 9° 02' N, 86° 50' W), including several of those from the present survey (VIII 37 - VIII 85) and one station occupied by the "Catalyst" (C4843-12819, 48° 43' N, 128° 19' W). The series of T-S curves show in a remarkable fashion the transition in types of water from north to south along the west coast of North America. As reference points B, E, I, and C have been entered corresponding respectively to North Pacific deep water (1.5°, 34.7 ‰), equatorial intermediate water (5.0°, 34.55 ‰), North Pacific intermediate water (6.0°, 33.9 ‰) and California intermediate water (10.0°, 34.0 ‰) as defined by Fleming, Moberg, and Revelle (1937).

The T-S curves from stations off the west coast of North America show that those waters, to a distance from shore of perhaps 400 miles, are mixtures of two types of water which have been called (Sverdrup, Johnson, and Fleming, 1942) the Subarctic North Pacific Water and the Equatorial Pacific Water. The former is found over the entire North Pacific above latitude 45° north approximately, and the latter over the equatorial region of the Pacific Ocean.

In order to investigate the process of mixing, we have established characteristic T-S curves for Subarctic and Equatorial water (fig. 2) in which the curve for northern water (S-A) is that of the "Carnegie" station 124 and the curve for southern water (Eq.) is an average curve from the Equatorial Pacific region, which closely approximates that of "Bushnell" station 299. Assuming that mixing takes place along surfaces of equal density (σ_t) a graph can be constructed as in figure 2 from which, for water with a given temperature and salinity, the percentage of Subarctic or Equatorial water may be obtained.

The results of such an analysis for percentage of Equatorial water at a depth of 200 meters are given in chart 20. Highest percentages are found at stations 81 (61 per cent), 82 (61 per cent), 85 (70 per cent) and 62 (61 per cent). The effect of the California Coastal Counter Current in transporting water of southern origin to the north is clearly shown by the consistently higher percentages inshore which extend up the coast at least as far as Cape Mendocino. The isolated patch west of Point Conception which contained greater than 45 per cent Equatorial water corresponds in its location to that of the large offshore eddy. The high values inshore and south of Point Conception follow rather closely the limits of the large submarine bay off southern California.

Computation of volume-transport across the Monterey line between stations 49 and 55 gave a value of 4.2×10^6 cubic meters per second to the south above 1000 meters. The actual net transport to the south between the coast and station 55 is probably somewhat less than this value since a large part of the Coastal Counter Current runs north inside of station 49. Station 46 was not used in this computation because it appeared to be somewhat anomalous. Between 500 and 1000 meters a net transport to the north of 0.10×16^6 cubic meters per second is indicated.

Across the Point Dume line (stations 59 to 57) the volume transport over the 500-decibar surface was 1.8×10^6 cubic meters per second. The agreement between this and the foregoing value for the volume transport is fairly good, considering the fact that only part of the water (see chart of dynamic topography, 0/1000 decibars, chart 2) which passes through the Monterey line also crosses the Point Dume line.

REFERENCES

Fleming, R. H., E. G. Moberg, R. R. D. Revelle.
1937. The water masses of the North Pacific. Assoc. Oceanog. Phys., Proc.-Verb., No. 2, pp. 106-107.

Gunther, E. R.
1936. A report on oceanographical investigations in the Peru Coastal Current. Discovery Repts., XIII:107-276.

Sverdrup, H. U., and R. H. Fleming.
1941. The waters off the coast of southern California, March to July, 1937. Scripps Inst. Oceanog., Tech. Bull., vol. 4, no. 10, pp. 261-378.

Sverdrup, H. U., M. W. Johnson, and R. H. Fleming.
The Oceans: Their physics, chemistry, and general biology, Prentice-Hall; New York. 1942

Sverdrup, H. U., and Staff.
1942. Oceanographic observations on the "E. W. Scripps" cruises of 1938. Records of Observations, Scripps Inst. Oceanog., vol. 1, no. 1, pp. 1-63.

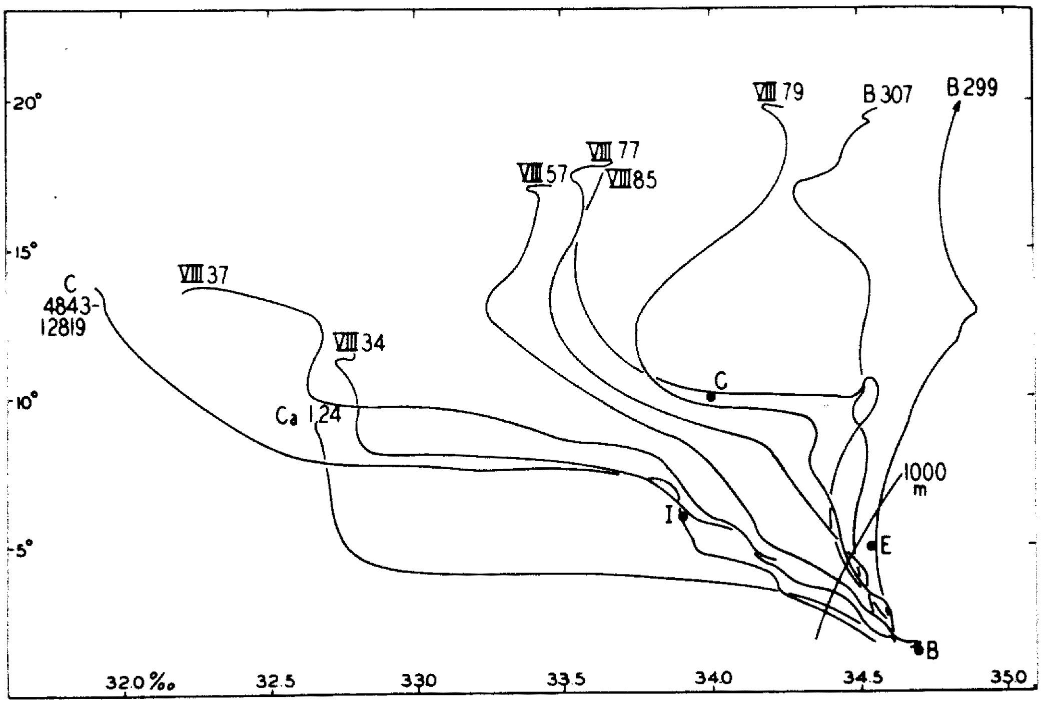


Figure 1.--Temperature-salinity curves for stations off the west coast of North America from the Aleutian Islands to Central America.

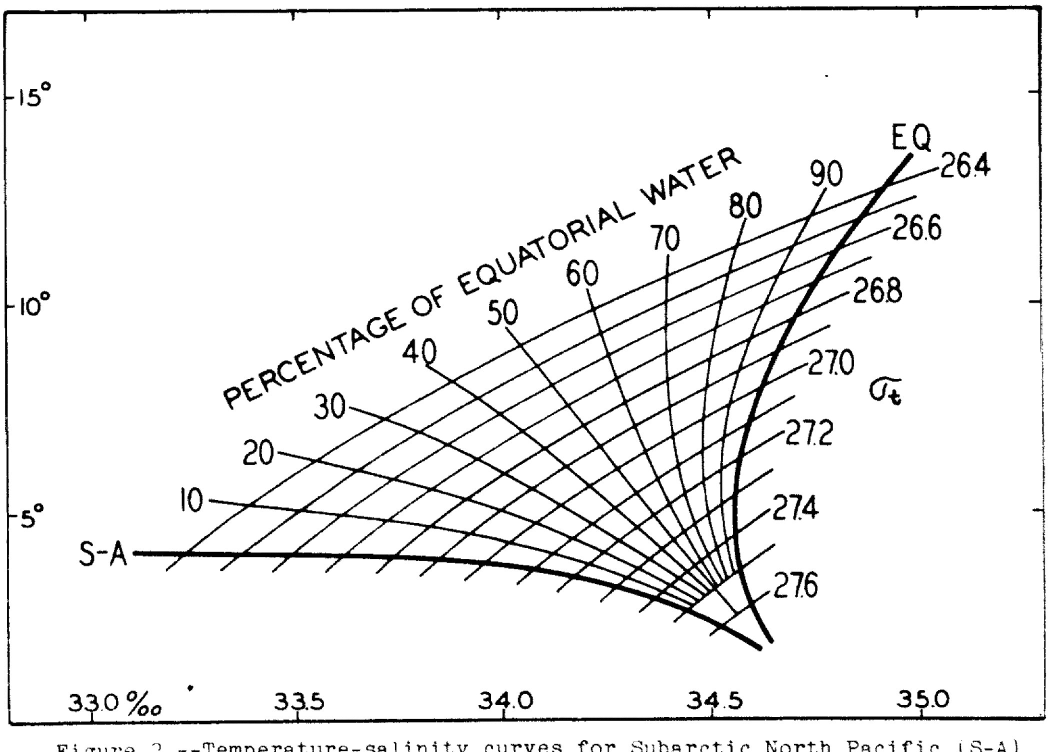


Figure 2.--Temperature-salinity curves for Subarctic North Pacific (S-A) and Equatorial Pacific (Eq.) water masses. T-S curves are shown for various percentages of equatorial water, assuming mixing only along surfaces of equal σ_t.

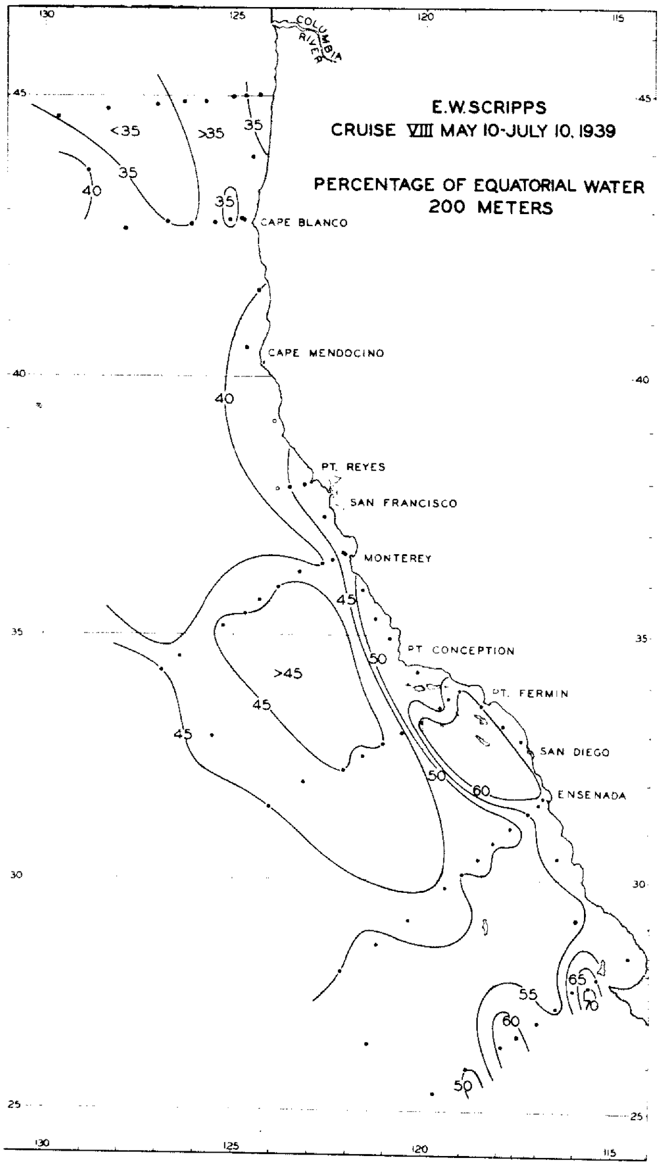


Chart 20.--Percentage of Equatorial water present at 200 meters. "E. W. Scripps" Cruise VIII.

SOUNDINGS IN THE GULF OF CALIFORNIA AND OFF THE WEST COAST OF LOWER CALIFORNIA IN 1939

By

ROGER REVELLE

The soundings dealt with here were taken on Cruises VII and VIII of the "E. W. Scripps." In the Gulf of California (table 10) the sounding lines mainly follow cross sections the locations of which were determined by the hydrographic program, but between these cross sections lines were run parallel to the coast line with minor detours for sounding purposes only (fig. 3). The Ballenas Channel was crossed and recrossed in an attempt to locate the maximum depth of the Ballenas Trench and the sill depth between the trench and the outer part of the Gulf.

It was planned to make soundings at intervals of one mile except where steep slopes were encountered along which soundings should be spaced more closely. This plan could not be entirely followed because the party on board the vessel was so small that occasionally no person could be detailed for the work, for which reason there exist a few gaps with intervals up to six miles between soundings. Where soundings were closely spaced, tabulations have been made only for distances of one-half mile, because the position of soundings could not be determined with sufficient accuracy to warrant communication of all values. However, for positions when profiles for geological purposes were being constructed, all soundings have been included.

The soundings were obtained by means of the Submarine Signal Company 710 Fathometer. Where the depth to the bottom was less than 250 fathoms, the flashing-light method was employed, and in water deeper than 1200-1400 fathoms, the sound method was generally used. In moderately deep water a combination method was employed of emitting the strong signal and receiving the echo by means of the flashing-light. This method necessitated a correction of 10 fathoms to the reading. The accuracy of the soundings in shallow water by the flashing-light method is about one fathom, whereas the probable error of soundings in water deeper than 1400 fathoms is not more than ± 10 fathoms. This accuracy could be improved by stopping the main engine during the short time needed for obtaining a sounding, but this was done only a few times in the course of the cruise in the Gulf. The accuracy obtained by the combination method which was employed at moderate depths is intermediate between the two which have been described.

The readings of the fathometer are based on a sound velocity of 800 fathoms per second. The uncorrected readings are published in the table, but curves 1 and 2 in figure 4 give the correction factors by means of which the readings in the Gulf and in the Ballenas Trench must be multiplied in order to find the depths corresponding

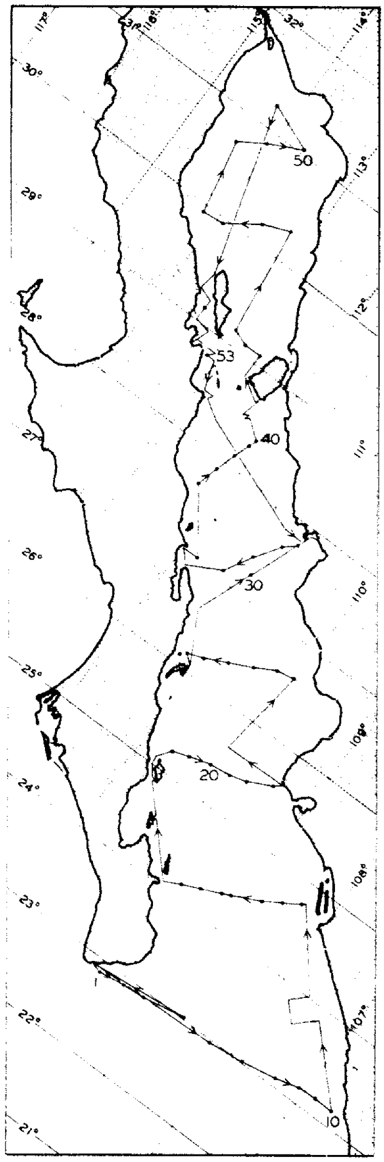


Figure 3.--Sounding lines in the Gulf of California in 1939. "E. W. Scripps" Cruise VII.

to the true velocity of sound. No slope corrections were applied owing to uncertainty with respect to the exact positions at which soundings were made. In areas where such corrections are important, the positions must be known with extreme accuracy in order to lead to improved presentation of the submarine topography.

The location of the soundings was determined by means of astronomical fixes or by bearings on terrestrial objects and sextant angles between such objects, and by means of dead reckoning between fixes. The accuracy of the positions determined by fixes is probably not more than ± 1 mile regardless of whether they were obtained astronomically or by piloting, because the available charts of the Gulf are not very exact.

In order to determine the position of soundings at locations between fixes the following procedure was adopted. Enlarged charts of the Gulf were prepared on scales of 5 miles to an inch or of 2 1/2 miles to an inch. On these charts the fixes were plotted, the true distances between fixes were read off and compared to the distances according to readings of the ship's log. The locations of the soundings were spaced along the line between fixes by computing the ratio between the true distances and the distances by the log, and by multiplying the log distances from the first fix by this ratio. In following this procedure it was occasionally found that the ratio jumped from a low value to a high value or vice versa. This occurred particularly if hydrographic stations had been occupied and can probably be ascribed to the drift of the vessel when hove to at stations. Some knowledge of the drift at stations could be obtained from the station record and adjustments could be made which brought subsequent ratios into better agreement with each other. Where sounding lines crossed, the procedure could be checked and was found to give fairly satisfactory results. The accuracy of the positions determined in this manner is not greater, in general, than ± 2 miles, but because of the pioneer-

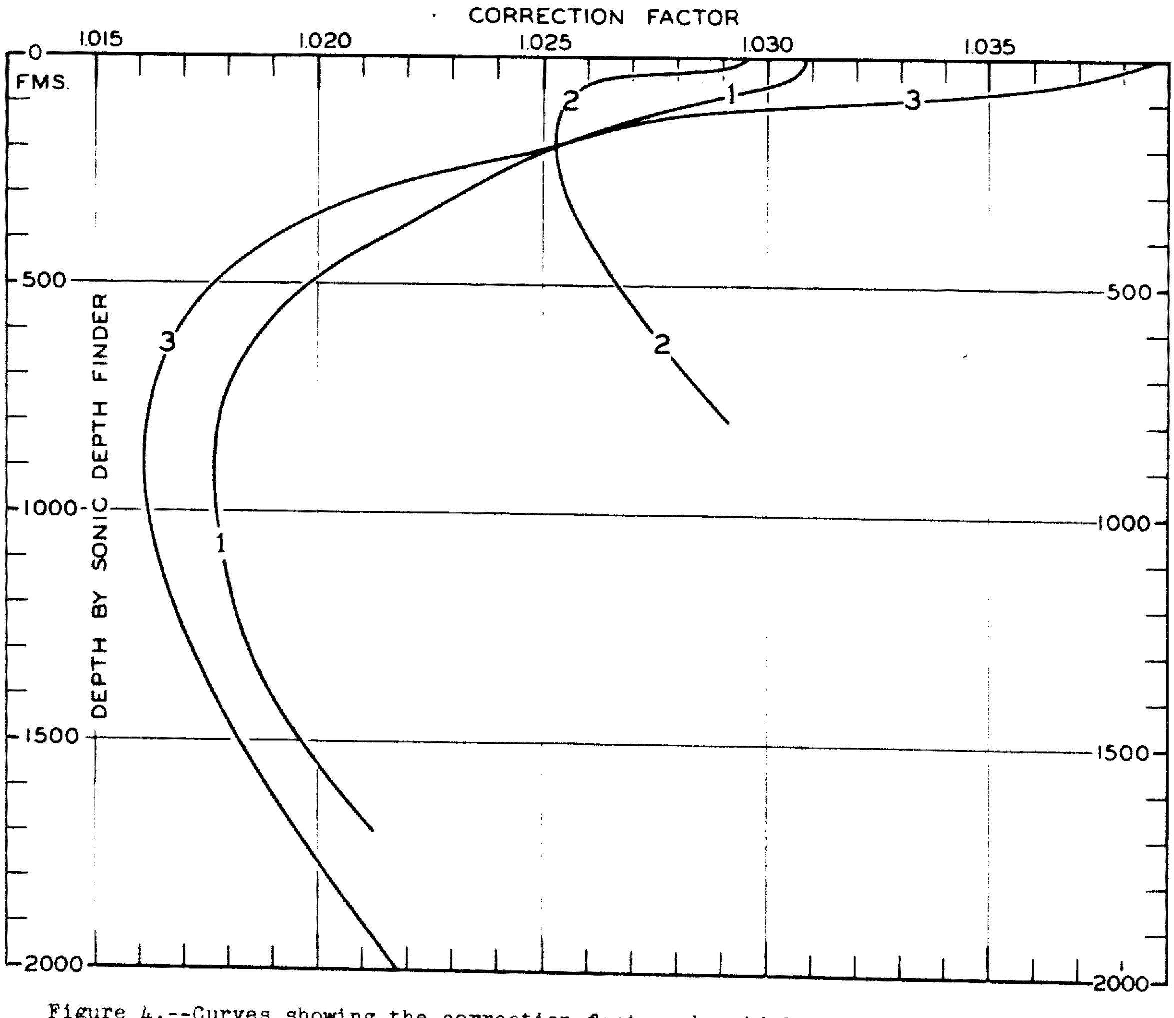


Figure 4.--Curves showing the correction factors by which the depths by sonic depth-finder must be multiplied in order to obtain the true depth. Curve 1 applies to the Gulf of California except Ballenas Trench, for which the corrections should be taken from curve 2. Curve 3 gives the corrections to be applied to soundings off the west coast of Lower California.

ing nature of the work errors up to 2 miles are not considered serious.

The soundings shown in table 10 give a fair idea of the depths along cross sections of the Gulf, but these cross sections are spaced at too great distances to give even a partially complete picture of the bottom topography. Information on this topography, particularly on the existence of depressions in the outer part of the Gulf, can be amplified by the results of the hydrographic observations (Revelle, G. S. A. Bull., 50:1929 [1939]).

The soundings off the west coast of Lower California are given in table 11. These are located along two lines running southwest at right angles to the coast and one connecting line running southeast and parallel to the coast at a distance of about 300 miles from the coast (chart 1). Soundings were taken less frequently than in the Gulf. The methods employed were similar except that in deep water the engine was always stopped when soundings were being taken, and these records should therefore be more accurate than the corresponding ones in the Gulf. The locations were determined by means of noon fixes and dead reckoning. The fixes were plotted on Hydrographic Office plotting sheets and the location of the soundings was determined by the same procedure followed when dealing with the soundings in the Gulf. The tabulated soundings are also based on a sound velocity of 800 fathoms per second but the curve marked 3 in figure 4 shows the factors by means of which the soundings should be multiplied in order to obtain the depth corresponding to the true sound velocity.

CURRENT MEASUREMENTS OFF THE CALIFORNIA COAST IN 1938 AND 1939

By

ROGER REVELLE and FRANCIS P. SHEPARD

In 1938 and 1939 a preliminary investigation was made of the character of the currents near the sea bottom in the region of complicated topography off the California coast. The investigation had a twofold purpose: (1) to determine the effect on bottom-current motion of such topographic irregularities as submarine canyons and basins, with a view to ascertaining whether currents capable of eroding the ocean bed could exist in these features; and (2) to gain information concerning the effect of friction on bottom currents.

In the course of this work numerous scattered measurements were made in a variety of environments, and also in a number of instances observations at a given locality were continued for extended periods. Only the latter are included in tables 14 and 15, but both the short- and the long-period observations are discussed in a forthcoming paper by Revelle and Shepard.[1] Because of different instruments and methods employed, the measurements can be separated into two groups according to the year of observation, and the form of the tables giving the results for 1938 differs in several respects from that used for the 1939 observations.

Four long series of measurements were taken in the first year, all from vessels anchored over a submarine canyon. The "E. W. Scripps" was employed in a 13-hour series obtained at the head of Monterey Canyon in September. Of two series carried out in La Jolla Canyon, offshore from the Scripps Institution, one was made in July, from the 38-foot sloop "Bjorn," and a 30-hour record, at a considerably greater depth and distance from shore, was obtained in October from a rowboat anchored bow and stern over the canyon. In a series taken at Newport Canyon in October, the motor launch of the Kerckhoff Marine Laboratory was employed.

A single Ekman current meter was used in all four of these series, and alternate measurements were made near the surface, at a depth approximately halfway to the bottom, and within 4 meters of the canyon floor. In an attempt to establish the vertical velocity distribution, the bottom measurements were taken alternately at heights of 2 and 4 meters, but these values are combined in the tables and the later treatment. For the first part of the La Jolla canyon series in October, the current meter was mounted in a tripod, and velocities were measured within a meter of the sea floor. In this series the current meter was supplemented at the surface by the use of a drift bottle attached to a light line.

The current meter was calibrated by suspending it from a traveling boom which could be moved along the Scripps Institution pier in such a manner that the instrument was carried through the water beneath. The number of turns of the propeller obtained when the instrument was moved through a certain distance at various speeds was then determined. The relationship between velocity, $\underline{V}$, in centimeters per second and number of turns per minute, $\underline{N}$, is given by the following equation:

$$\underline{V} = 2.0 + 0.4\,\underline{N}$$

That is, below a velocity of 2 cm/sec., no record is given by the meter. Uncertainty exists with respect to velocities only slightly greater than this figure.

The Ekman meter is so constructed that after a certain number of revolutions a shot is dropped onto a slotted compass needle, which deposits it in one of thirty-six compartments, depending on the direction. It is ordinarily found that, if there are a sufficient number of revolutions during a measuring interval of several minutes or more, shots will be found distributed in several compartments, often widely separated. Usually it is possible to find an average direction. This has been done in the measurements given herein by the simple process of taking an arithmetic mean. It might be supposed that the actual mean velocity in the average direction indicated by the compass in any measuring interval would be less than that obtained from the total number of revolutions, or in other words, that a considerable part of the motion was transverse to the mean direction. This is allowed for by some investigators, who in calculating the velocity during any interval, multiply the speed obtained from the number of revolutions by the cosine of the average angular deviation from the mean direction. However, if the behavior of the current meter when suspended in the air under the action of the wind is observed, it will be seen that, because of inertia of the instrument and friction on the bearings suspending it, the propeller slows down and often stops when, as frequently happens, the meter is deflected from the mean wind direction by a slight eddying motion. Consequently part of the mean velocity is not re-

[1] R. Revelle and F. P. Shepard, "Currents of the California Sea Floor," to be submitted to Bull. Geol. Soc. Amer.

corded, and this probably at least compensates for the inclusion of the transverse components which result from our method of averaging directions.

In the tables, the number of balls found in each compass compartment have been recorded directly, but the average values have been corrected for the magnetic variations of the earth. When measurements are taken near the surface from a steel ship, a further correction must be applied for the deviation induced by the vessel. However, this was not necessary in the measurements obtained by us, since the observation vessels were all wooden.

It was of some interest to determine the effect of the canyon topography on the speeds in various directions. Because of the stability of the stratification a motion below the rim of a canyon transverse to the axis would be strongly inhibited by the difficulty of vertical motion. Consequently the velocity components have not been calculated for a north-south or east-west direction, as is customary; instead, there are given velocity components parallel and transverse to the longitudinal axis of the canyon.

Because of the rapidly fluctuating nature of the observed currents, the instrument was not left down for more than short intervals. Ideally, an instrument giving a continuous record of instantaneous velocities would be required, and the Ekman meter, which gives only the average current existing during the interval of observation, is far from fulfilling this requirement. This ideal is nevertheless approached, as the interval of observation is shortened, especially if the depth to the bottom is shoal enough to allow observations to be repeated without much time intervening.

In all the series taken in canyons spring tides prevailed. At Newport and at La Jolla Canyon in July, the total time of observation was too short to enable the calculation of the possible tidal currents, but in the second La Jolla series and at Monterey such a computation was possible. It was found that at the surface at La Jolla a semidiurnal tidal current was predominant. At the lower depths, however, the comparatively small current of tidal period can best be accounted for as due to an internal wave motion. Similarly in Monterey Canyon the chief periodic currents seem to accompany an internal wave.

For the most part the maximum observed velocities near the bottom were as great or greater than those obtained near the surface, but the currents at the bottom were found to be constantly shifting in both speed and direction. In general the principal component of motion was up- or down-canyon, and the water oscillated back and forth in very irregular periods. The observed irregular movements are probably due to the piling up of water against topographic obstructions and the consequent building up of slopes of the sea surface or of surfaces of equal density.

The series of observations obtained in 1939 were somewhat different from those of the previous year. All measurements were taken within one meter of the ocean bed and no attempt was made to observe currents at higher levels.

Because of the rise and fall of waves and the rolling of the observing vessel a delicate instrument like a current meter cannot be suspended directly from the hydrographic cable very close to the sea floor. This difficulty was overcome by the use of a tripod resting on the bottom. From this device three current meters of the Ekman type were suspended on a brass rod at heights of 20, 48, and 84 centimeters. While the instruments were being lowered, the rod connecting the three meters was held in such a position that it engaged a lock on the propeller of each meter. When the bottom was reached, a spring at the top of the rod pulled it down and the propellers were released. The lifting of the tripod after the measurements were made pulled the rod back to the original position, thus stopping the propellers. Since the instrument was attached to the hydrographic cable, the drifting of the vessel, which was frequently not anchored, caused an occasional pull on the tripod even though the wire was paid out as fast as drift occurred. This would have tended to pull up the rod and cause a temporary cessation of the record if the spring holding the rod down had not been sufficiently strong. On the other hand, when a momentary surge occurred at such a rate that the tripod actually skipped or dragged over the bottom, a false reading would have been obtained unless the rod had been pulled up and the propellers locked. It was therefore necessary to adjust very carefully the strength of the spring holding down the rod to which were locked the propellers.

Although its use is limited to the observation of bottom currents, the instrument described has several advantages. Not only does it make possible the measurement of currents very close to the sea floor, but it also affords simultaneous readings at three different heights, thus giving data on the vertical gradient of velocity and the character of turbulent friction near the ocean bed. Furthermore, it was found possible to use the device successfully without anchoring the vessel, even in waters of some depth. The deepest observations made by us were in Santa Cruz Basin at 2000 meters. No difficulties were encountered, and it may be predicted that measurements at much greater depths are possible.

Previous current measurements made in the deep sea by suspending a meter from the hydrographic cable of an anchored vessel have been subject to some uncertainty because of the possible fictitious results caused by the swinging of the vessel on its anchor. No such difficulty, however, is encountered with the tripod, which is independent of the ship's motion. That the current meters have not recorded a dragging motion of the tripod through the water is shown by the marked difference in velocity usually found at the three levels of observation. If the observed currents had been fictitious, caused by a motion of the tripod instead of the water, no effect of bottom friction would have been evident, and all three meters would have given the same reading. The device has the further advantage of requiring no messengers to start or stop it. Messengers sometimes fail to operate, and in deep water, where the time of arrival of the messenger cannot be accurately predicted or determined by the cessation of vibration on the wire, the use of messengers results in uncertainty regarding the elapsed time. Details of the instrument were ingeniously worked out by Carl Johnson, mechanic at the Scripps Institution of Oceanography.

As with the single Ekman instrument, the three meters of the tripod were calibrated by suspending the apparatus in the water from a wire attached to a traveling boom on the Scripps Institution pier. The boom was moved a measured distance along the pier at various speeds, and the number of turns given by the three instruments was recorded. By keeping the meters attached to the tripod during the calibrations any interference effect caused by the framework was presumably included in the constants of the calibration equations. These were as follows:

Top meter:	$V = 1 + 0.39\,N$
Middle meter:	$V = 1 + 0.34\,N$
Bottom meter:	$V = 1 + 0.33\,N$

As before, V represents velocity in centimeters per second, and N is the number of turns of the propellers per minute.

In August 1939, on Cruise IX of the "E. W. Scripps," six series of bottom-current measurements were made with the tripod at various localities off the southern California coast. These included two offshore banks, ranging in depth from 190 to 300 meters, two inshore deep areas--one of which is a basin--at depths of 780 to 910 meters, and two points on the inner continental shelf with depths 11 to 40 meters. The lengths of the observation periods varied from 10 to 38 hours, but in the longest period a gap of several hours occurred in the record. Intervals of measurement ranged from 1 to 15 minutes, and were usually about 10 minutes. Over two hundred observations were made simultaneously with each of the three meters, or about six hundred in all. During the last series, on Santa Barbara Bank, the lowest propeller was lost, and for the remainder of the observation period measurements were carried out at only the two upper levels.

Because of the small vertical distance between the meters, it was thought that the average velocity direction would be approximately the same at the three levels. Accordingly, a compass was placed only in the middle meter, and the compass readings and mean true direction given in the tables thus apply strictly only to the currents at a height of 48 centimeters above the bottom. The north and east components of the measured velocities are given for both the top and middle levels, however, on the assumption that the directions were similar at all levels.

It will be noted from the tables that throughout the periods of observation there was little wind and that the sea was relatively calm. During the two shelf series the vessel was anchored at the bow with the main anchor ordinarily used. On Santa Barbara Bank the dredging cable and a grapnel were employed to anchor amidships, but the operation was not entirely successful, since appreciable dragging occurred. In the other three series, the vessel was not anchored and there was appreciable drift. This was especially noticeable on Thirtymile Bank, where the tripod several times became caught on the rough bottom while being hauled in, owing to the large amount of cable which had to be paid out to keep the apparatus from dragging.

Spring tides occurred at the time of the series on Santa Barbara Bank and on the shelf off Santa Monica. Harmonic calculations show that a moderately strong semidiurnal tidal current existed at these localities at this time. On the other hand, the series on the shelf off La Jolla and on Thirtymile Bank coincide with a period of neap tides, and the corresponding currents appear to be very small. No harmonic computation was possible for the two deep series, since the velocities over considerable periods at the middle level were too small to cause any shot to drop into the compass. In addition, one of these series was not long enough to allow a semidiurnal harmonic computation. Comparison with the tidal currents obtained near the surface in the observations of 1938, emphasizes the relatively small magnitude of the bottom tidal currents, even during periods of high spring tides. This is undoubtedly due to the effect of bottom friction.

The character of the frictional effect is strikingly shown in the average velocities obtained during each series at the three different levels. In all instances the average velocity decreased toward the bottom, but the magnitude of the decrease varied widely, apparently depending on the roughness of the bottom surface. On the relatively smooth shelf, at Santa Monica and La Jolla, the average velocities at 48 and 20 cm. were 83 and 55 per cent, respectively, of the velocity at 84 cm., whereas on the rough Thirtymile Bank the velocities at the two lower levels were only 70 and 43 per cent of the velocity at the top level.

At all localities investigated, the average velocities were very small, ranging from 2.6 cm/sec. for the two deep series in San Diego trough and Santa Monica Basin, to 6.4 cm/sec. on Thirtymile Bank and Santa Barbara Bank. The maximum velocities, likewise, were not as great as those obtained on the Santa Monica shelf and Thirtymile Bank respectively.