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Physical, Chemical, and Biological Oceanography of the Entrance to the Gulf of California, Spring of 1960

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Physical, Chemical, and Biological Oceanography of the Entrance to the Gulf of California, Spring of 1960

By

RAYMOND C. GRIFFITHS

Contribution from the Scripps Institution of Oceanography,
University of California, San Diego, La Jolla, Cal.

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By

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ABSTRACT

The whole area at the entrance to the Gulf of California and off southwestern Lower California in the spring of 1960 was underlain by Intermediate Water (marked by a salinity minimum of about 34.5 p.p.t. at about 800 m.) and, above that, by Subtropical Subsurface Water (marked by a salinity maximum of 34.80 p.p.t. at about 200 m.). Above these waters were: to the northwest, California Current Surface Water (marked by a shallow salinity minimum of about 34.10 p.p.t. at about 100 m.); to the northeast, Gulf Surface Water (marked by high surface salinities that obscure the maximum of the Subtropical Subsurface Water); and, to the south, Subtropical Surface Water (marked by intermediate salinities and high temperatures).

The most important oceanographic feature of the area was a strong front between California Current and Gulf Surface Waters. At Cape San Lucas this front was roughly vertical, but to the south and west it became more sinuous and much weaker and was formed more and more by California and Subtropical Surface Waters. At the Cape the stronger flow of the California Current Water seemed to hold back the Gulf outflow at the surface, and to the south of the Cape it penetrated Gulf Surface Water at depths between 50 and 100 m., spreading horizontally or affecting in some way the entire Gulf entrance, often in a complicated manner. The vertical front at Cape San Lucas thus became a horizontal one offshore at depth. The frontal system was very clearly shown in the distributions of temperature and salinity in the upper 100 m., but only between 50 and 100 m. in the oxygen distribution.

The Subtropical Subsurface Water was in the extensive oxygen minimum of the eastern Pacific, and the oxygen content of the surface waters was affected by upwelling and probably by phytoplankton activity.

The second important feature of the area was upwelling. Distributions of temperature, salinity, and oxygen showed it to be strong off western Lower California and weaker off Cape Corrientes and other parts of the eastern side of the Gulf entrance. The water upwelled off Lower California was initially low in oxygen content, but this content increased as the water moved south. The distributions of temperature and, particularly, salinity showed this transport. The standing crop of zooplankton was generally highest in the areas in which upwelled water occurred.

INTRODUCTION

This paper describes the oceanography of the entrance to the Gulf of California and adjacent waters off western Lower California, observed in the spring of 1960. It is based on all the data of the May 1960 cruise (TO-60-1) of the STOR (Scripps Tuna Oceanography Research) Program, and some data of the April 1960 cruise (6004-B) of CalCOFI (California Cooperative Oceanic Fisheries Investigations). Data reports of these cruises, including particulars of methods, have been published by the Scripps Institution of Oceanography (1961, 1967).

Our interest in this area arises from the fact that tuna are known to migrate seasonally across it (Schaefer, Chatwin, and Broadhead, 1961). The purpose of the paper is to present and interpret observations about ocean

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conditions that are likely to be useful in studies of tuna ecology in the area.

In the spring of 1960 three kinds of surface water met in the entrance of the Gulf of California. If we assume that other years and other seasons are similar, the entrance is a complicated transition zone. It has not been extensively studied or described. Roden and Groves (1959) described the oceanography of the Gulf proper from CalCOFI data, but they had few data from the Gulf entrance. Reid, Roden, and Wyllie (1958) described the California Current system to the southern tip of Lower (Baja) California, using CalCOFI data. The amount of data decreases south of Magdalena Bay (24° 30' N.), and is scanty to the south of Cape San Lucas and Cape Falso at the southern tip of the peninsula. I have described one of the major oceanographic features of the region, the Cape San Lucas frontal system (Griffiths, 1963, 1965), partly from data of cruise TO-60-1 and partly from data of another cruise, TO-61-1 (April 1961). Wyrtki (1966) summarized the available information on the oceanography of the eastern Pacific; his paper on water masses (1967) defines water types reported here.

The area of cruise TO-60-1 is shown in figure 1, which also shows the area of the part of CalCOFI cruise 6004-B from which data were used.

The track of cruise TO-60-1 covers what may be considered as the entrance to the Gulf of California. Although cruise 6004-B was outside this area, it was a most useful source of contemporaneous data about one of the main kinds of water in the Gulf entrance. Such data were not available for the area south of the entrance.

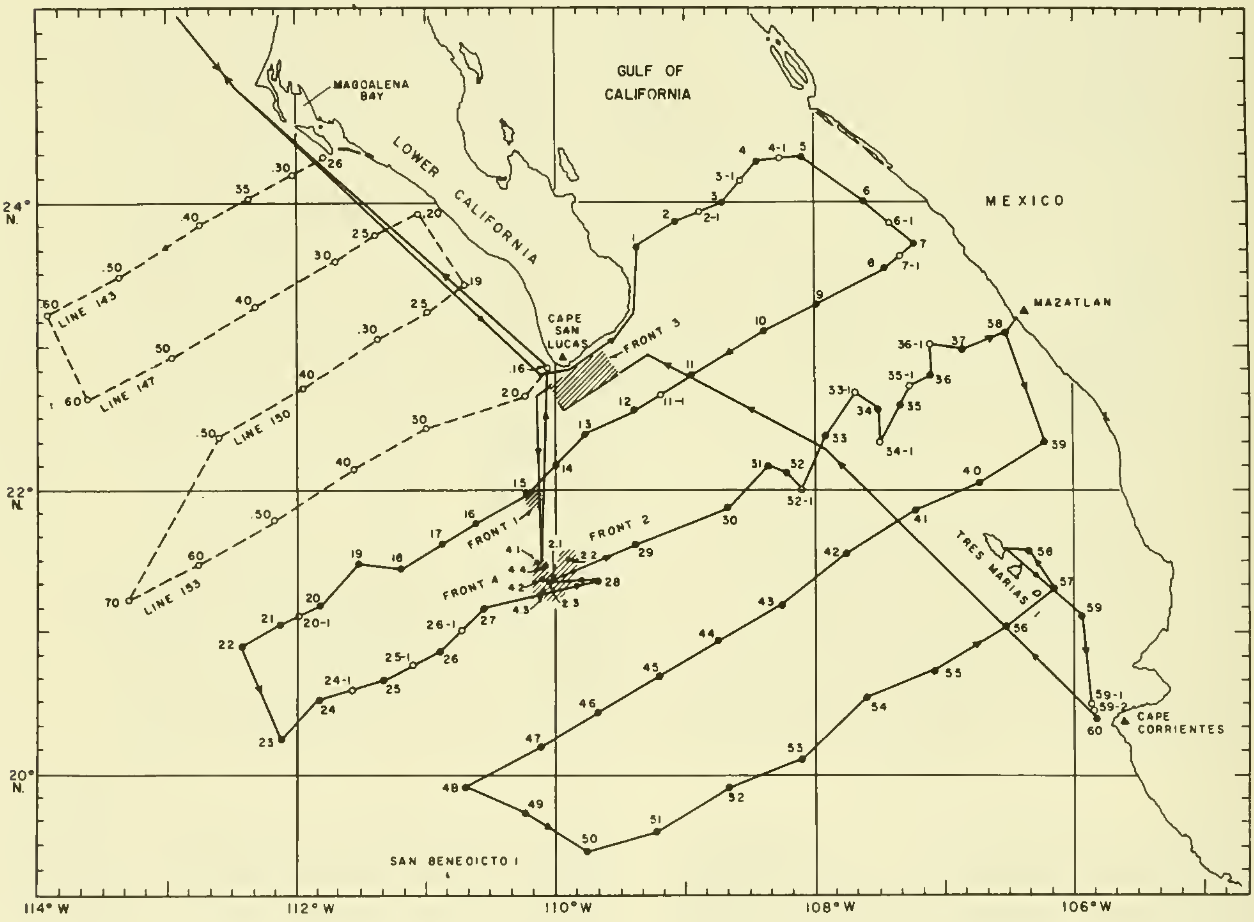

Figure 1.--Chart showing the track of STOR cruise TO-60-1, May 1960 (—●—, full hydrocasts or 10-m. bottle casts; —o—, between-station BT's) and part of the track of CalCOFI cruise 6004-B, April 1960 (--o--, full hydrocasts). Areas of front studies are shown by hatching and labeled as fronts (1, 2, 3, 4). Special stations at front 2 are shown as 2.1, 2.2, and 2.3. Special stations at front 4 are shown as 4.1, 4.2, 4.3, and 4.4.

THE KINDS OF WATER IN THE MOUTH OF THE GULF

Roden and Groves (1959) stated that the entrance to the Gulf of California has three kinds of water: Gulf Water, California Current Water, and Eastern Tropical (or equatorial) Pacific Water. They did not thoroughly define the three types. Wyrtki (1967) defined the water masses of the eastern Pacific in ways with which my results can be compared.

Figure 2 shows T-S-δ_T[2] curves for some of the CalCOFI (cruise 6004-B) stations on line 120, off Point San Eugenio (28° N., 115° W.), and on line 143, off Magdalena Bay (fig. 1). Figure 3 shows similar curves for stations farther south, on line 153 of the CalCOFI pattern and for TO-60-1 stations west of Cape San Lucas.

Figures 4 and 5 show T-S-δ_T curves for TO-60-1 stations in the southern and northeastern parts of the Gulf entrance.

Where there are data from depths greater than about 700 m. all these curves demonstrate the presence of the oceanwide Intermediate Water (Sverdrup, Johnson, and Fleming, 1942) in the shape of a salinity minimum for which Wyrtki (1967, fig. 4) suggested the following rough limits: T: 4.5 to 6.4° C.; S: 34.2 to 34.6 p.p.t. (parts per thousand).

Wyrtki (1967, fig. 4) defined the average T-S relationship of equatorial subsurface water and its immediate derivative, Subtropical Subsurface Water, by the line between the coordinates 6.8° C., 34.5 p.p.t. and 17.0° C., 35.2 p.p.t. All the T-S-δ_T curves except those from lines 120 and 143 (fig. 2), show a significant agreement with this line within the range of salinities observed. Since this water flows beneath water of lower salinity, except in the Gulf of California, it gives rise to a salinity maximum of about 34.80 p.p.t., which is obscured in the Gulf (see below). This maximum, for our data, comprises water of temperatures between about 10 and 13° C. and thermosteric anomalies between about 130 and 180 cl./ton. It is recognizable in the curves from lines 120 and 143 (fig. 2) in a similar density range, but at lower salinity.

Subtropical Surface Water is warm and of fairly high salinity ($>$34.5 p.p.t. in the North Pacific, according to Wyrtki, 1967). This water, probably together with some California Current Surface Water, supplies the Gulf of California, where its salinity is raised so much by evaporation ($>$35.0 p.p.t.) that the salinity maximum mentioned above is obscured (fig. 5). This high-salinity derivative, Gulf Surface Water, flows out of the Gulf and separates two kinds of water of lower salinity--California Current Surface Water to the north, and unmodified Subtropical Surface Water and Tropical Surface Water (Wyrtki, 1967) to the south (see Sund, 1961, for T-S curves; and Bennett, 1966, for surface salinity charts). Gulf Surface Water also flows northward off western Lower California late in the year (Bennett, 1963; Griffiths, 1965; Wyrtki, 1967). By mixing with the California Current Surface Water, which is also subjected to relatively high insolation and consequent salinity increase at the surface, at this latitude, the Gulf Surface Water helps to form salinities at the surface that are greater than those immediately below the surface where, consequently, a salinity minimum forms (compare figs. 2 and 3). This minimum marks the presence of California Current Surface Water, albeit in an ever more modified form with decreasing latitude. Below the minimum is a transition of the T-S-δ_T relationship to that of the Subtropical Subsurface Water.

From this discussion it is clear that the three kinds of water alluded to by Roden and Groves (1959) and by Griffiths (1965) are composite when their data are reviewed in relation to the terms set out by Wyrtki (1967). This is not to say that these authors were unaware of the composite nature of the water types they discussed.

Table 1 shows the composition of the three kinds of water; only depths above the 60 cl./ton density surface are considered, because few observations were made deeper than this. The ranges in thermosteric anomaly are approximate, and I attempted to take into account vertical transitions from one water type to another, as shown by the data.

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[2] δ_T is the thermosteric anomaly, defined by Montgomery and Wooster (1954), and measured in units of 10^{-5} centiliters/metric ton but given for convenience as cl./metric ton.

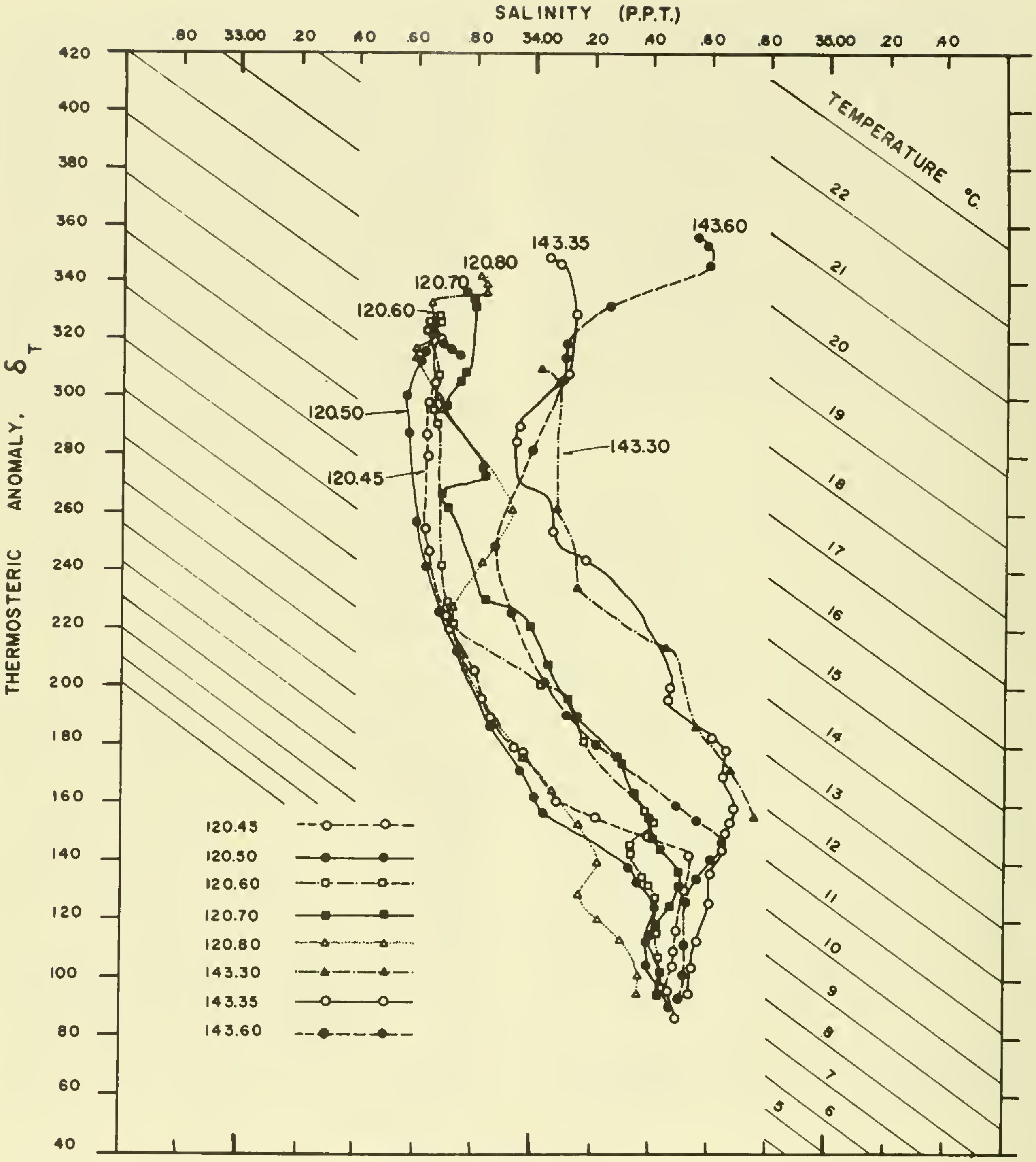

Figure 2.--T-S-δ_T curves from stations on CalCOFI lines 120 (off Point San Eugenio) and 143 (off Magdalena Bay) made on cruise 6004-B off western Lower California.

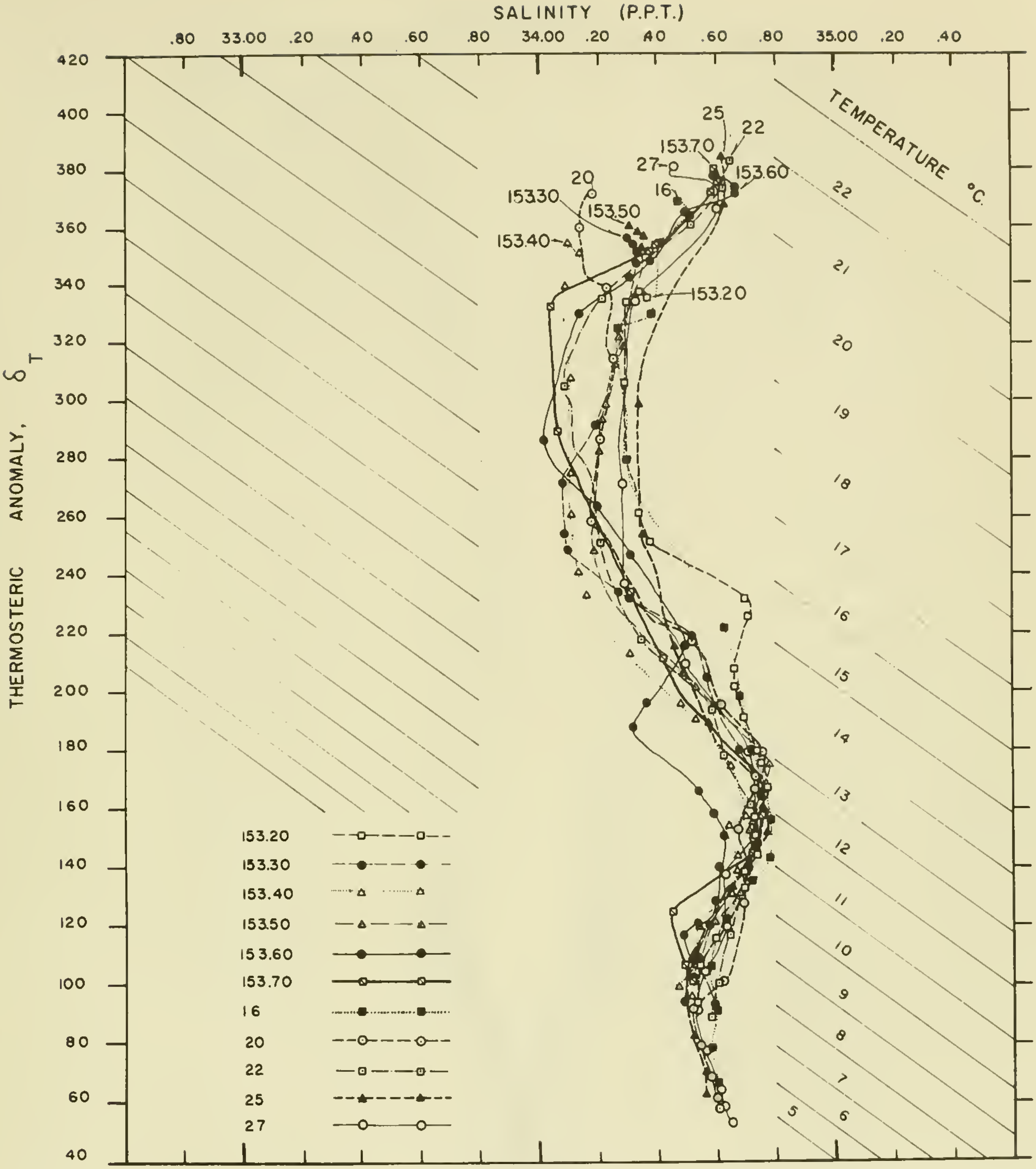

Figure 3.--T-S-δ_T curves from stations on CalCOFI line 153 (off Cape San Lucas) made on cruise 6004-B and five stations (16, 20, 22, 25, and 27) of cruise TO-60-1 in the northwest part of the entrance to the Gulf of California.

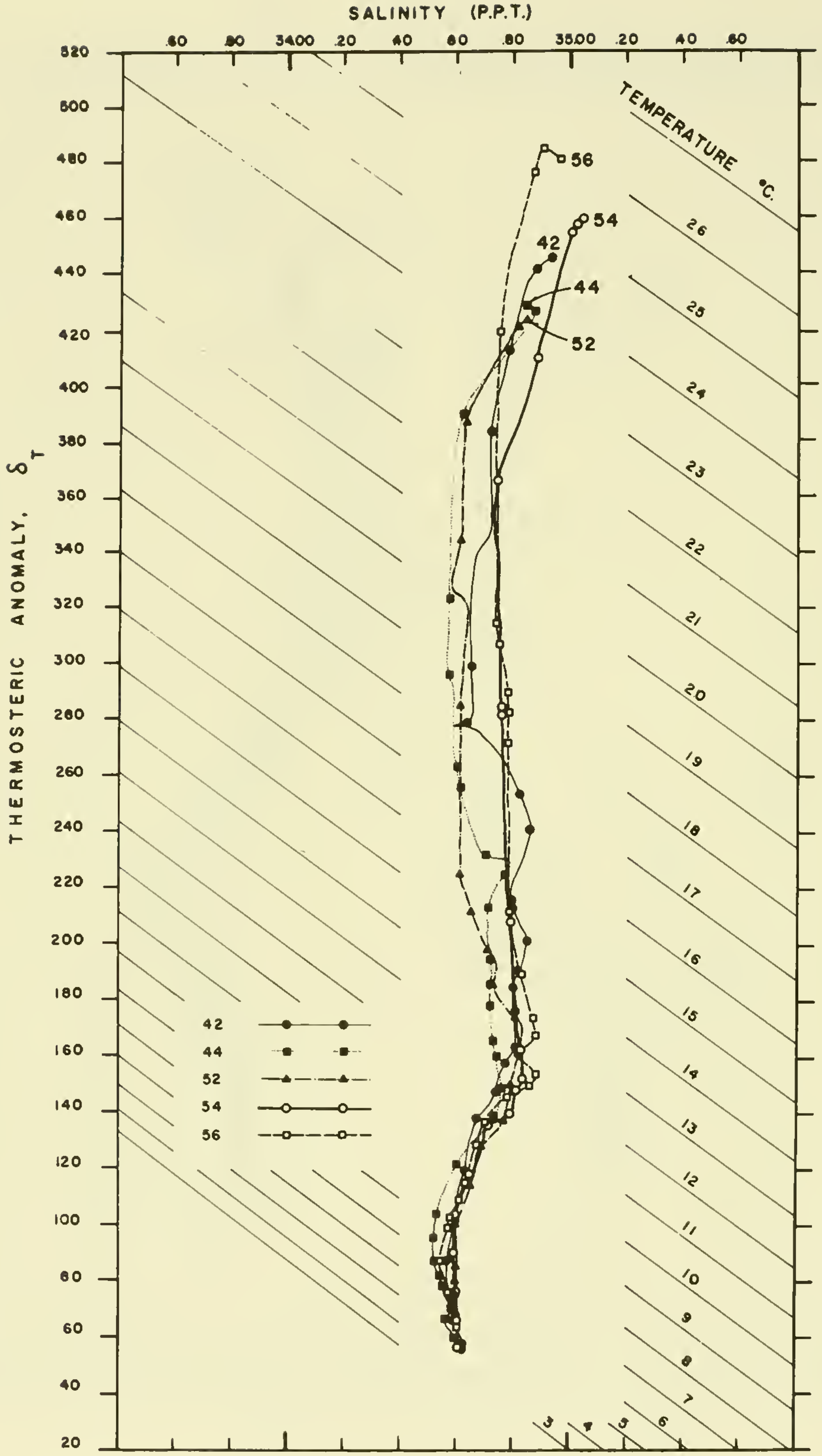

Figure 4.--T-S-δ_T curves from stations 42, 44, 52, 54, and 56 of cruise TO-60-1 in the southern part of the entrance to the Gulf of California.

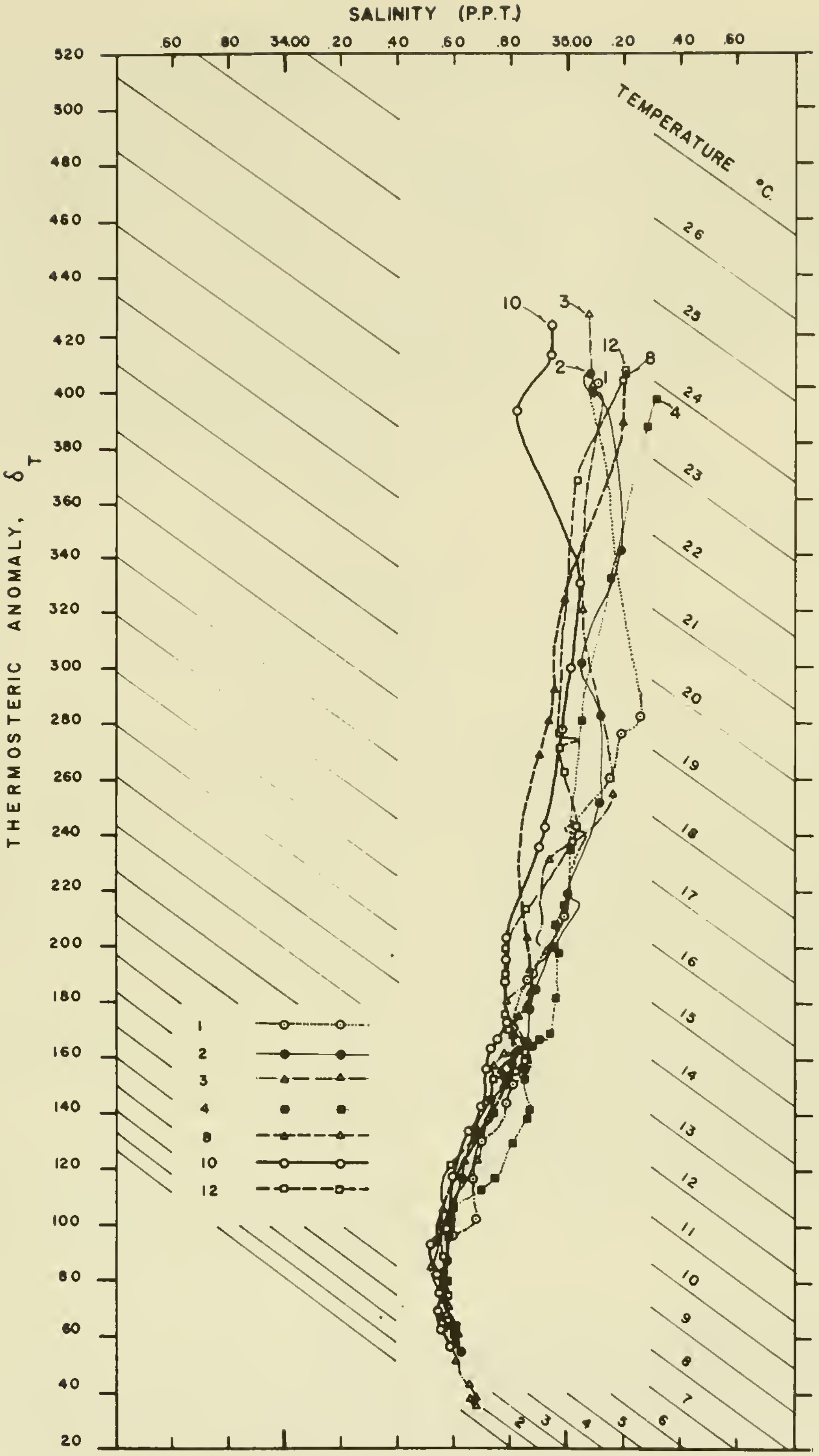

Figure 5.--T-S- δ_T curves from stations 1, 2, 3, 4, 8, 10 and 12 of cruise TO-60-1 in the northeastern part of the entrance to the Gulf of California.

Table 1.--Composition of water masses named by Roden and Groves (1959) and illustrated by figures in this paper, in terms of water masses recognized by Wyrtki (1967)

Water masses according to Roden and Groves		Water masses according to Wyrtki	
Name	See figures in this paper	Name	Range in thermosteric anomaly (cl./ton)
California Current Water.........	2, 3	California Current Surface Water	220 to 380
		Subtropical Subsurface Water modified at higher latitudes by mixing with less Saline water above	130 to 180
		Intermediate Water, likewise modified	60 to 120
Gulf of California Water.........	5	Gulf Surface Water	260 to 420
		Subtropical Subsurface Water	130 to 180
		Intermediate Water	60 to 120
Eastern Tropical (or Equatorial). Pacific Water	4	Subtropical Surface Water	260 to 480
		Subtropical Subsurface Water	130 to 180
		Intermediate Water	60 to 120

VERTICAL DISTRIBUTION OF PROPERTIES

The station lines shown in figure 1 are approximately normal to the coastline and, on the average, to the flow of water. The vertical distribution of four principal properties are considered first--temperature, salinity, thermosteric anomaly (a function of density), and dissolved oxygen. The distribution of temperature, thermosteric anomaly, and dissolved oxygen are qualitatively similar; the distribution of salinity is more or less unlike them and, for my purpose, much more informative. As a general rule, however, low temperatures are associated with low salinities and high salinities with high temperatures, in the upper layers. The relative depths of Nansen bottles are indicated by black dots in all figures depicting vertical profiles.

Temperature

Figures 6, 7, 8, and 9 show the respective temperature profiles of lines 143, 147, 150, and 153 of CalCOFI cruise 6004-B (fig. 1). These profiles share one general property: the thermocline in each is about 100 m. deep at the offshore stations (station 60 at left side of figure 5) and slopes steadily upwards, breaking the surface somewhere near the coast (at right side of figures); this intersection with the surface indicates upwelling, about which more is said later. Also discussed later is the oxygen minimum shown on all temperature and salinity profiles (except line 143, for which the oxygen data were erroneous); this minimum is a property of Subtropical Pacific Subsurface Water, though its lower boundary may be in Intermediate Water.

Figure 10 shows the temperature profile across the mouth of the Gulf proper (stations 1 to 5). Here the thermocline is much stronger and shallower, and there is no indication of upwelling.

The shallow thermocline in the Gulf appears to be superimposed on the deeper thermocline typical off western Lower California, according to the profile between stations 7 and 22 (fig. 11). The main frontal system (Griffiths, 1963, 1965) shows up between stations 12 and 14. Dotted isotherm contours in figure 11 show a feature between stations 12 and 14 that was found by BT (bathythermograph) but not by the hydrocast pattern; all profiles were drawn from bottle cast data only. The cool water at stations 15 and 20 was evidently upwelled farther north; this phenomenon is discussed later under horizontal distributions.

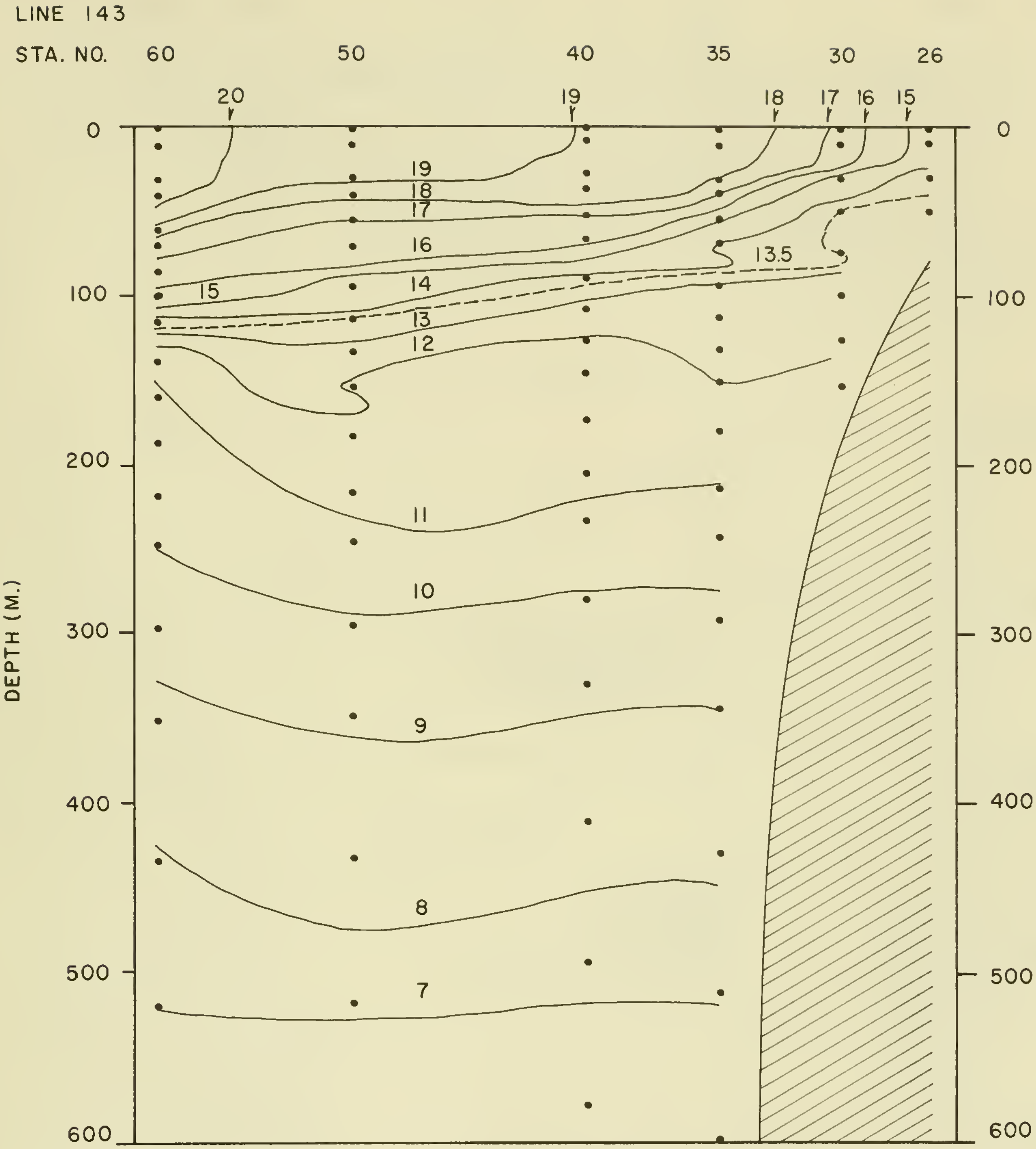

Figure 6.--Vertical temperature profile along line 143 of CalCOFI cruise 6004-B. The contour interval, here and on other temperature profiles is 1° C.; the 13.5° C. isotherm is contoured (by a dashed line) because it has an inversion. Nansen bottle depths are shown in this and subsequent vertical profiles by black dots.

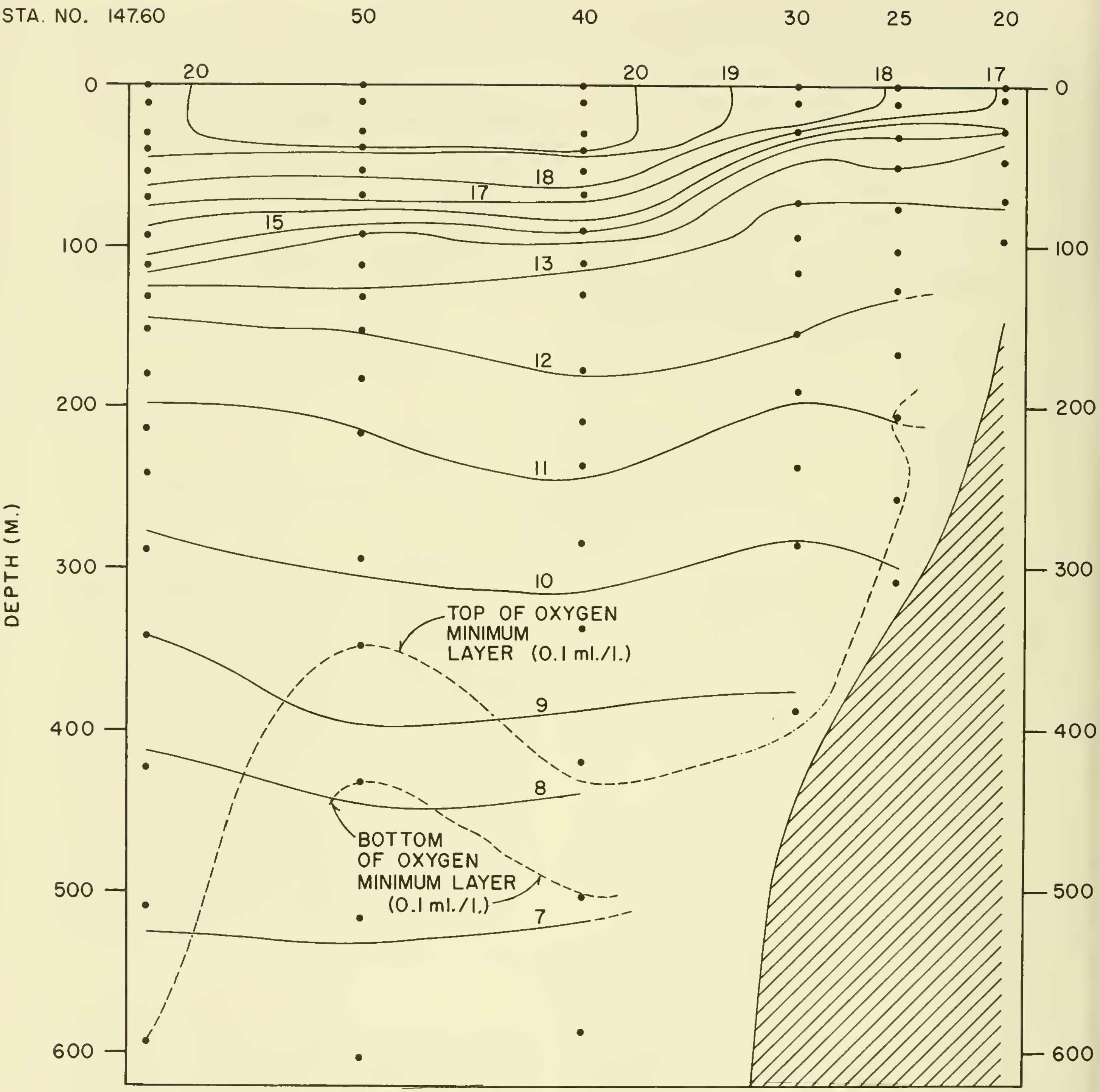

Figure 7.--Vertical temperature profile along line 147 of CalCOFI cruise 6004-B. The upper and lower boundaries of the subtropical Pacific oxygen minimum (taken as 0.1 ml./l.) are shown by dashed contours in this and the remaining vertical profiles of temperature, salinity, and dissolved oxygen.

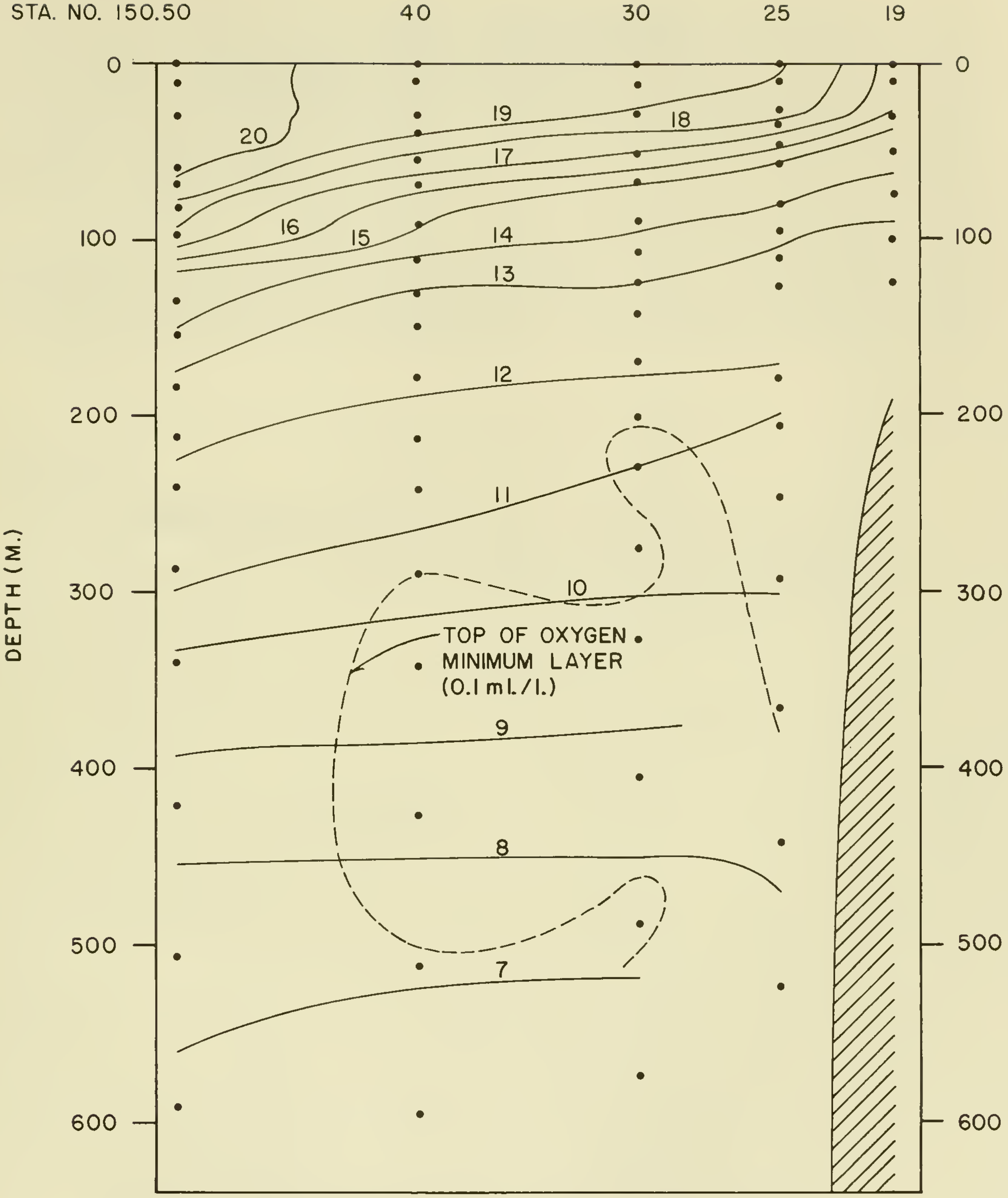

Figure 8.--Vertical temperature profile along line 150 of CalCOFI cruise 6004-B.

The well-defined temperature structure seen between stations 7 and 22 persists, though with rather less intense gradients, between stations 23 and 37 (fig. 12). The strong, shallow thermocline on the eastern side is still superimposed on the deeper one that extends to the west beyond the frontal system between stations 29 and 31; remains of the cool water found at station 15 persist at station 29.

The structure and relationship of the thermoclines mentioned above are modified between stations 40 and 48 (fig. 13.). Compared with the profile to the north (fig. 12), the thermocline is shallower in the west (station 48) and weaker in the east (station 40). The frontal system is not present (see horizontal distributions later).

The thermocline is shallower still, farther south, between stations 50 and 56 (fig. 14), but has recovered some of its strength on the eastern side between stations 54 and 56. These data, however, show no marked upwelling in the area of Cape Corrientes at the time of the cruise, although it is generally believed to occur thereabouts (Roden and Groves, 1959).

The foregoing discussion has been largely concerned with the thermocline; it is therefore appropriate to include here the horizontal distribution of thermocline depths (fig. 15). At stations where two thermoclines were evident, only the stronger was used in the figure.

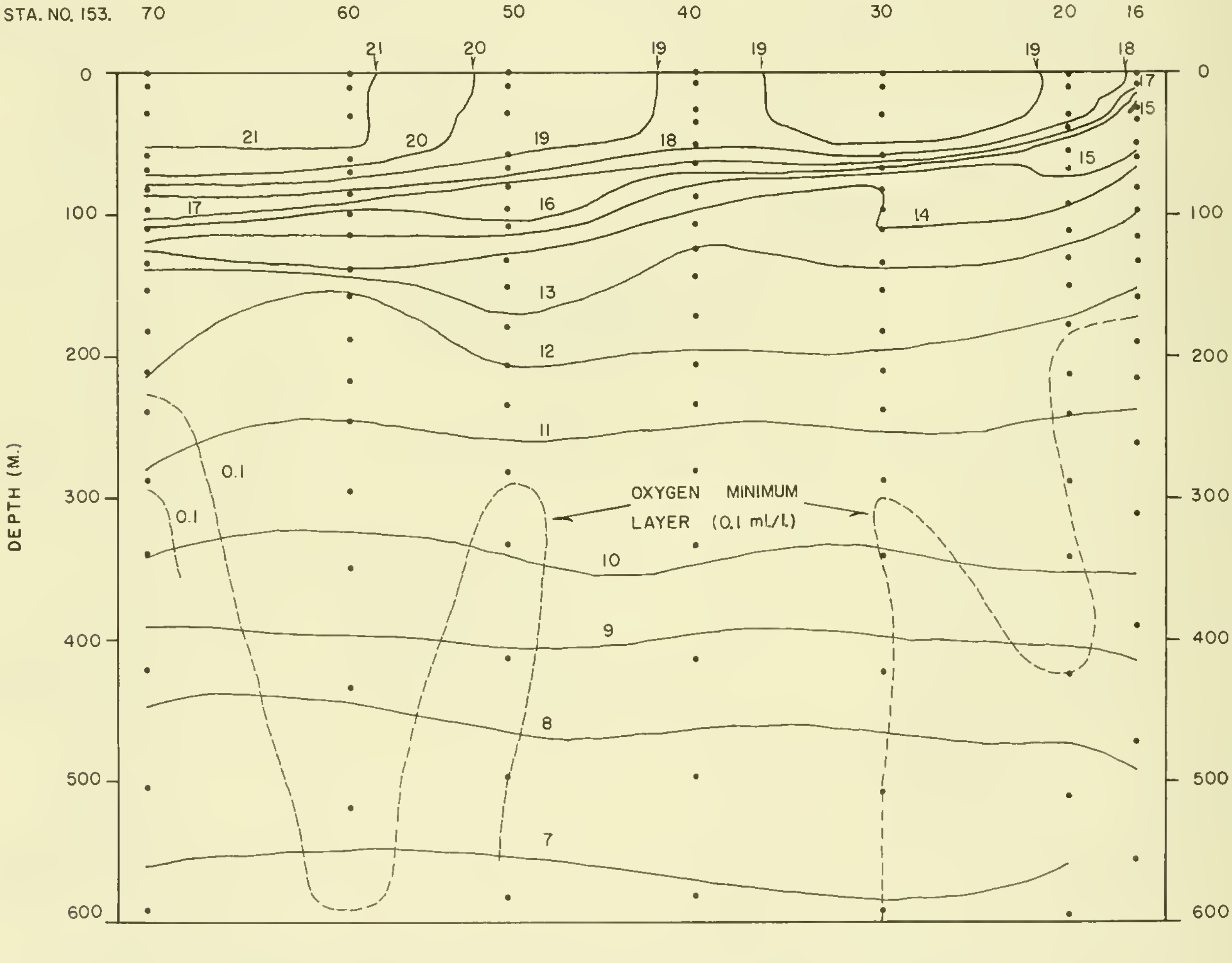

Figure 9.--Vertical temperature profile along line 153 of CalCOFI cruise 6004-B.

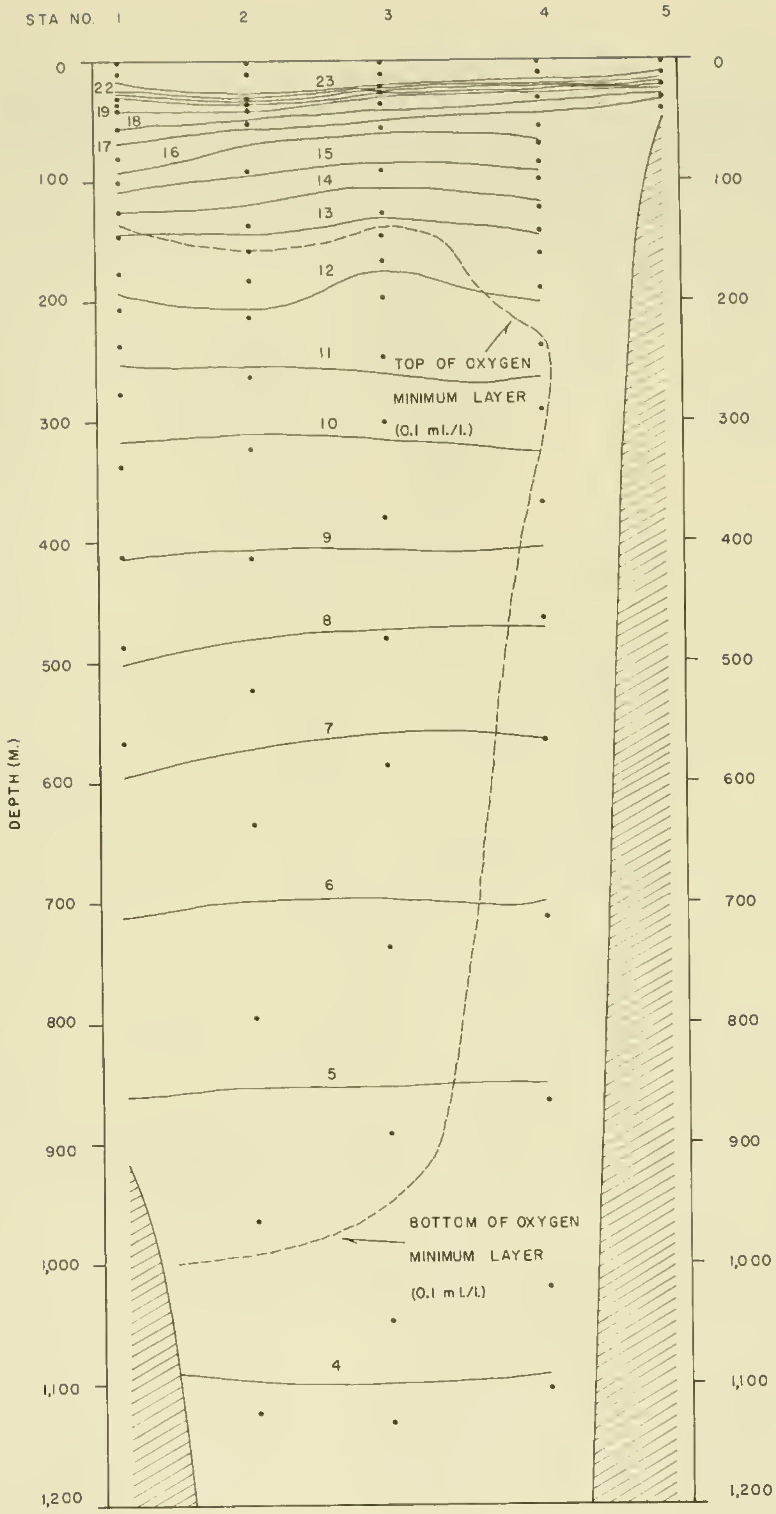

Figure 10.--Vertical temperature profile along the line of stations, 1 to 5, inside the mouth of the Gulf of California on cruise TO-60-1.

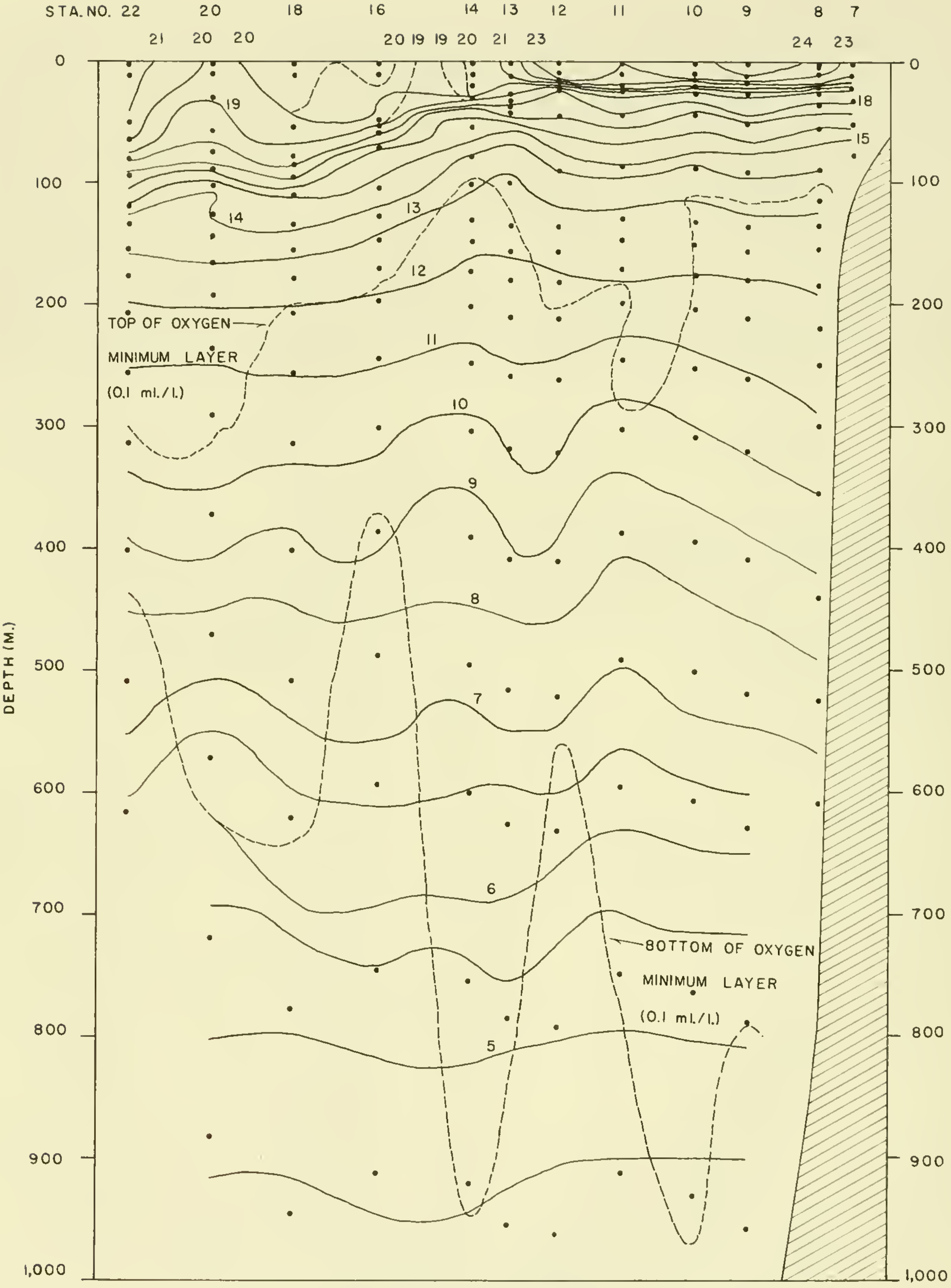

Figure 11.--Vertical temperature profile along the line of stations, 7 to 22, on cruise TO-60-1. The dashed isotherms (19° and 20° C.) were detected by between-station bathythermograph observations.

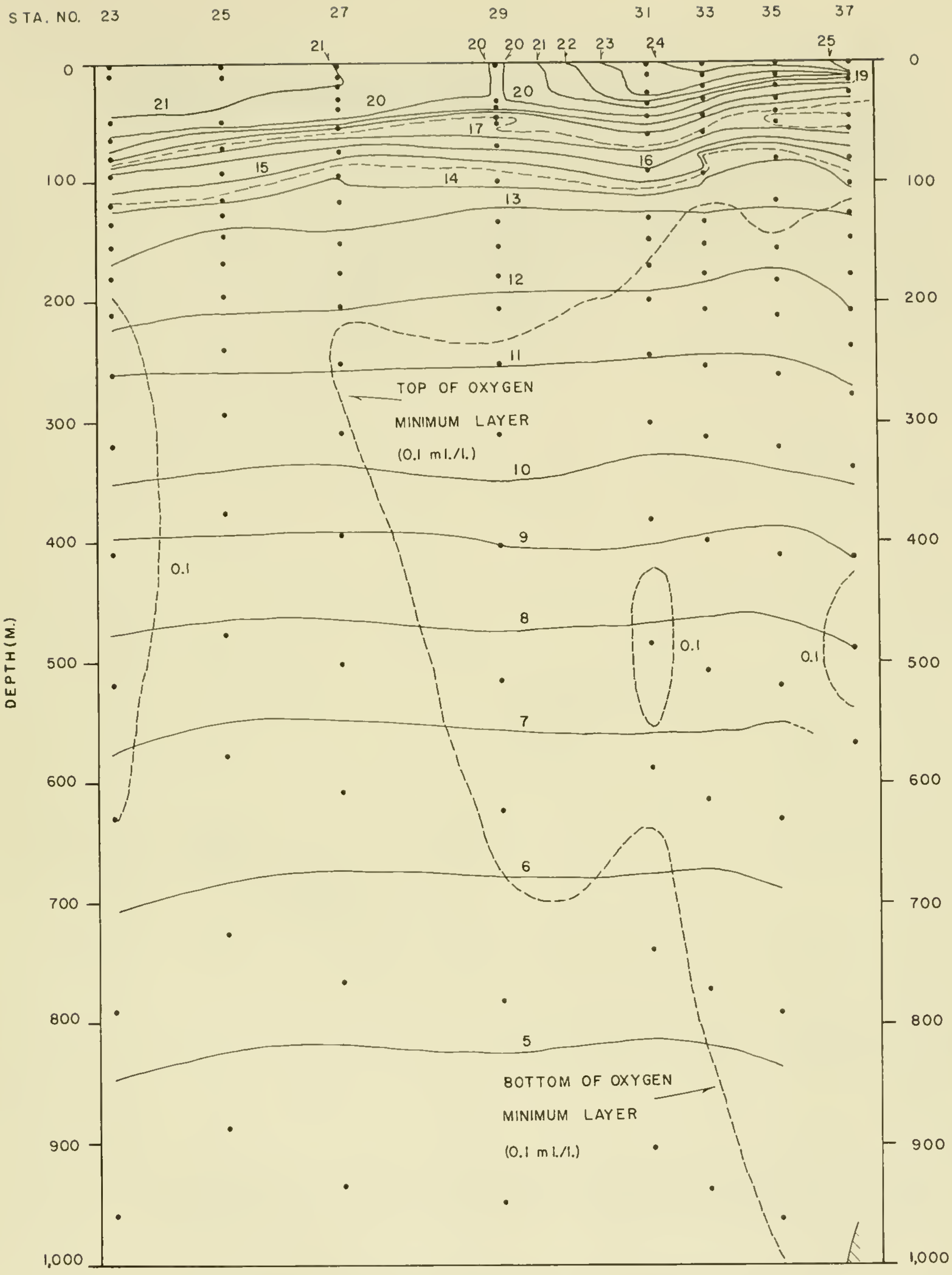

Figure 12.--Vertical temperature profile along the line of stations, 23 to 37, on cruise TO-60-1. The dashed contours are of the 14.5° and 17.5° C. isotherms in which inversions were found.

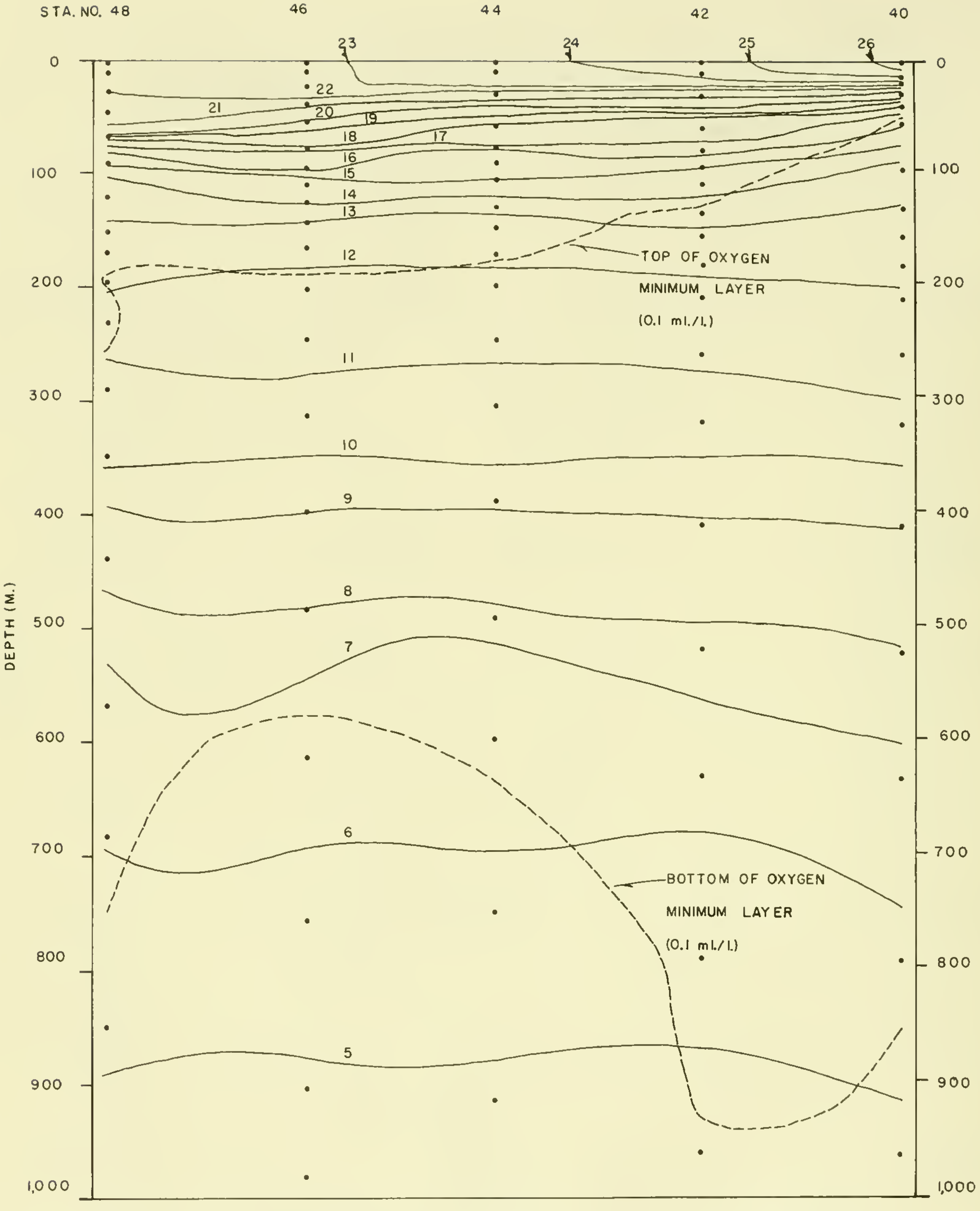

Figure 13.--Vertical temperature profile of the line of stations, 40 to 48, on cruise TO-60-1.

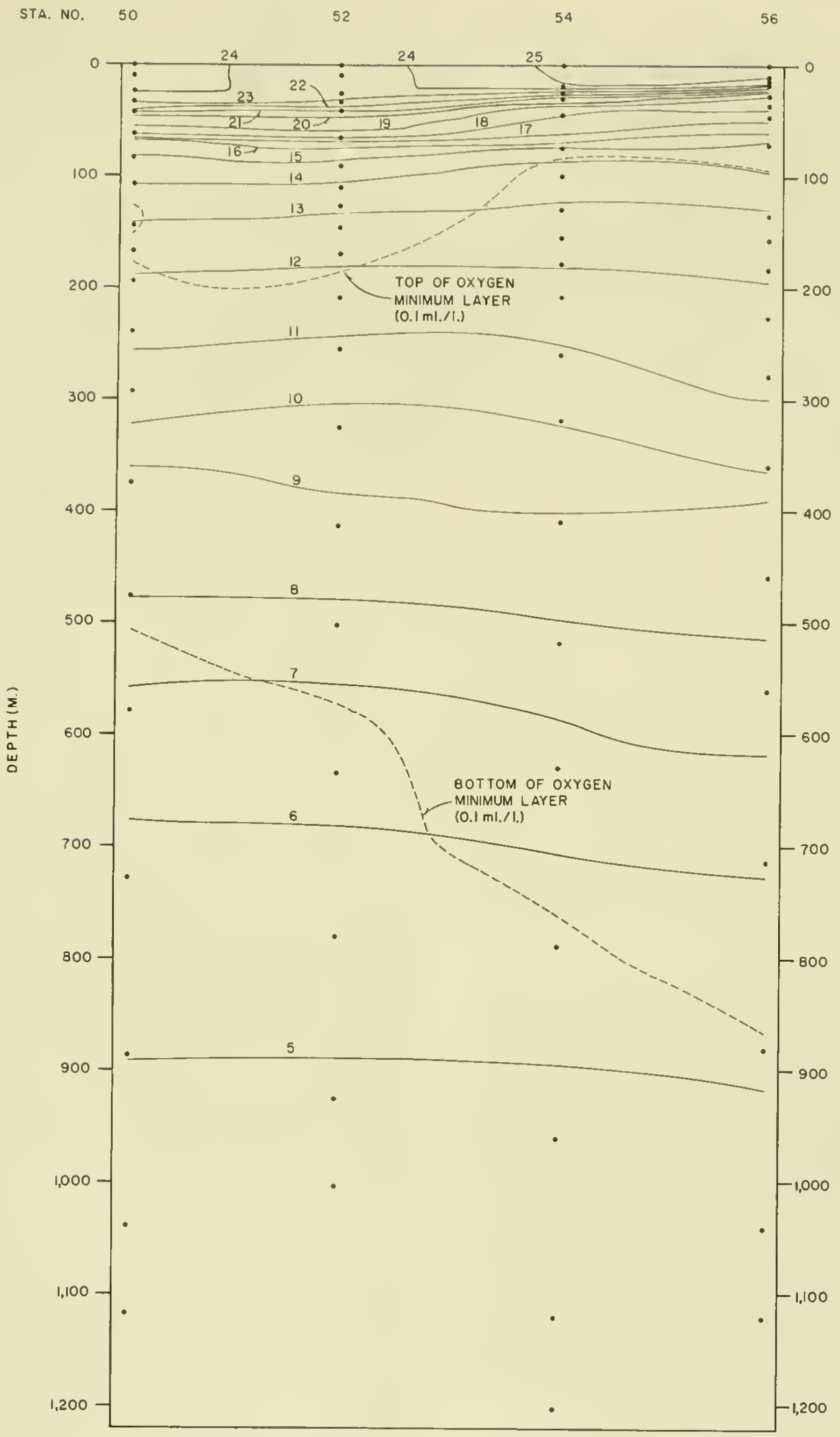

Figure 14.--Vertical temperature profile of the line of stations, 50 to 56, on cruise TO-60-1.

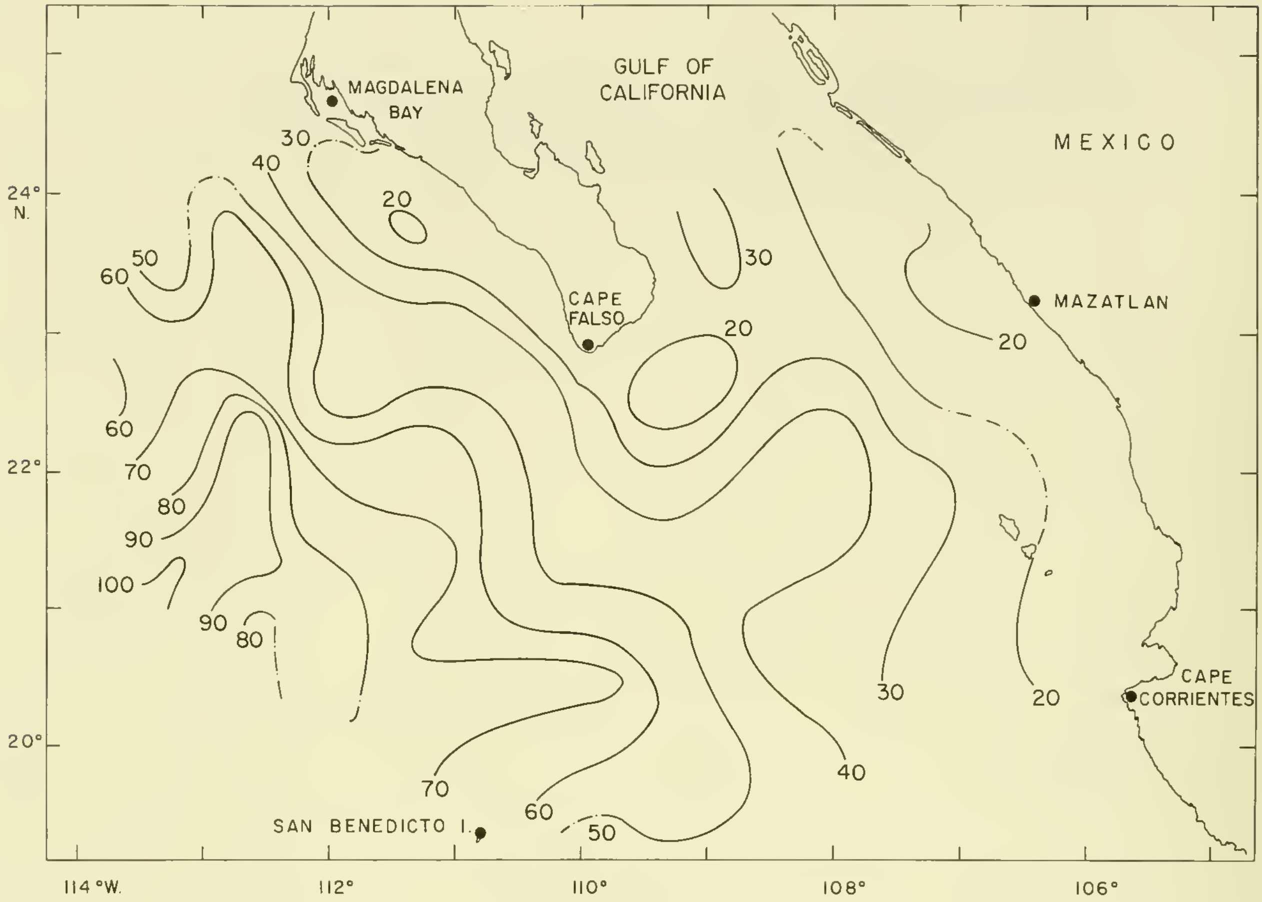

Figure 15.--Thermocline topography in the entrance to the Gulf of California and off western Lower California during cruises TO-60-1 and 6004-B, respectively. The contour interval is 10 m.

Salinity

Figures 16, 17, 18, and 19 show the profiles for station lines 143, 147, 150, and 153, respectively, off western lower California. In all of them the surface salinity generally increases westwards. The salinity minimum, typical of California Current Surface Water is present; it tends to increase in salinity with decreasing latitudes and agrees in depth with the thermocline (figs. 6, 7, 8, and 9). The maximum that marks Subtropical Subsurface Water (now being modified at these latitudes) is represented by nodes of water of about 34.70 p.p.t., the extent of which increases with decreasing latitude. The deep minimum of Intermediate Water is not fully revealed in these profiles. Upwelling tends to produce relatively high inshore salinities and a slight surface minimum offshore.

A further unusual feature is the subsidiary salinity minimum at 150 m. at station 153.60. This apparent parcel of water shows on the corresponding temperature profile (fig. 9) as a dome in the 12° C. isotherm and on the corresponding oxygen profile (fig. 26); it probably originated in the California Current Surface Water. The high salinity at 50 m. at station 153.16 is undoubtedly due to an intrusion of Gulf Surface Water. As is seen here and later, the isohalines, 34.70 and 34.80 p.p.t., of this Gulf Surface Water often join with the same isohalines of the salinity maximum of the Subtropical Subsurface Water, and traverse a wide range of density surfaces in so doing. The profile along line 153 also shows less upwelling inshore than do the profiles to the north.

Along the line of stations 1 to 5 (fig. 20), in the innermost part of the Gulf entrance, the salinity merely increases with depth to the deep minimum of the Intermediate Water at roughly 800 m. The profile between stations 7 and 22 (fig. 21) depicts a complicated salinity distribution. Although one cannot be dogmatic in ascribing various parts of the profile to various water types, the deep salinity minimum (400-1,000 m.) and the salinity maximum, now represented partly by isohalines of 34.80 p.p.t., remain as definite structures ascribable to Intermediate Water and Subtropical Subsurface Water, respectively. There is also the connection between

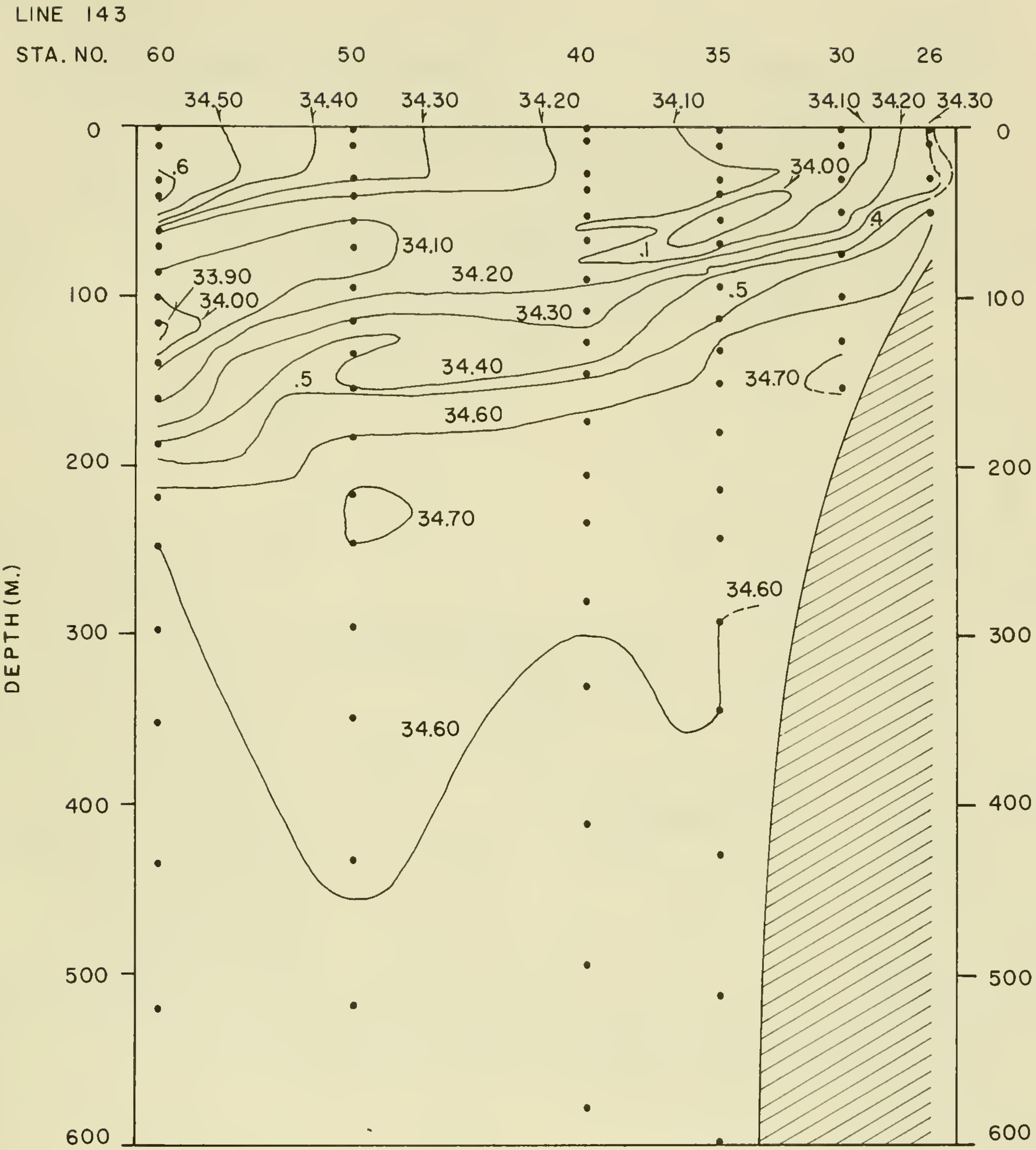

Figure 16.--Vertical salinity profile along line 143 of CalCOFI cruise 6004-B. The contour interval here and in the other vertical salinity profiles is 0.10 p.p.t.

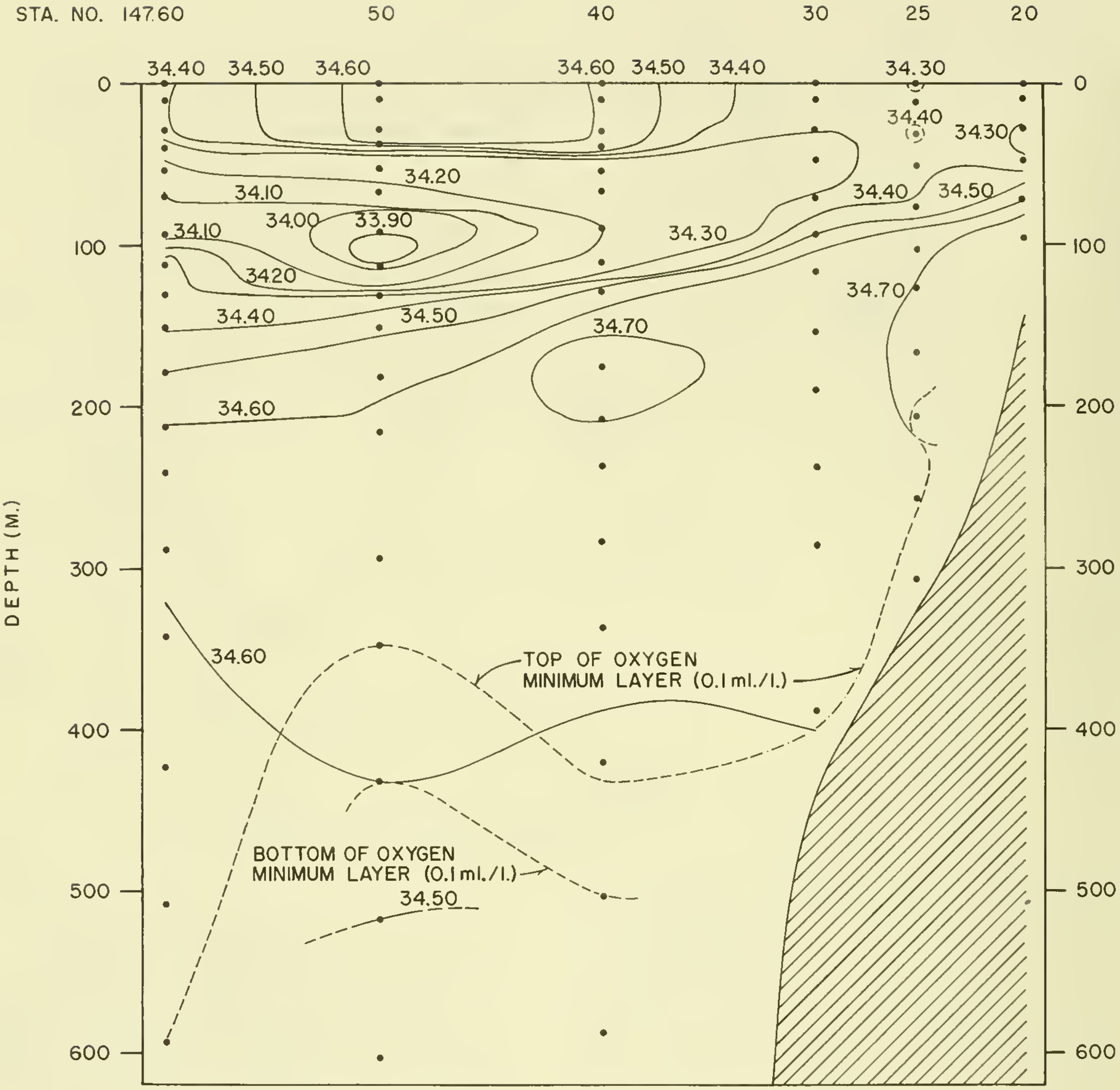

Figure 17.--Vertical salinity profile along line 147 of the CalCOFI cruise 6004-B.

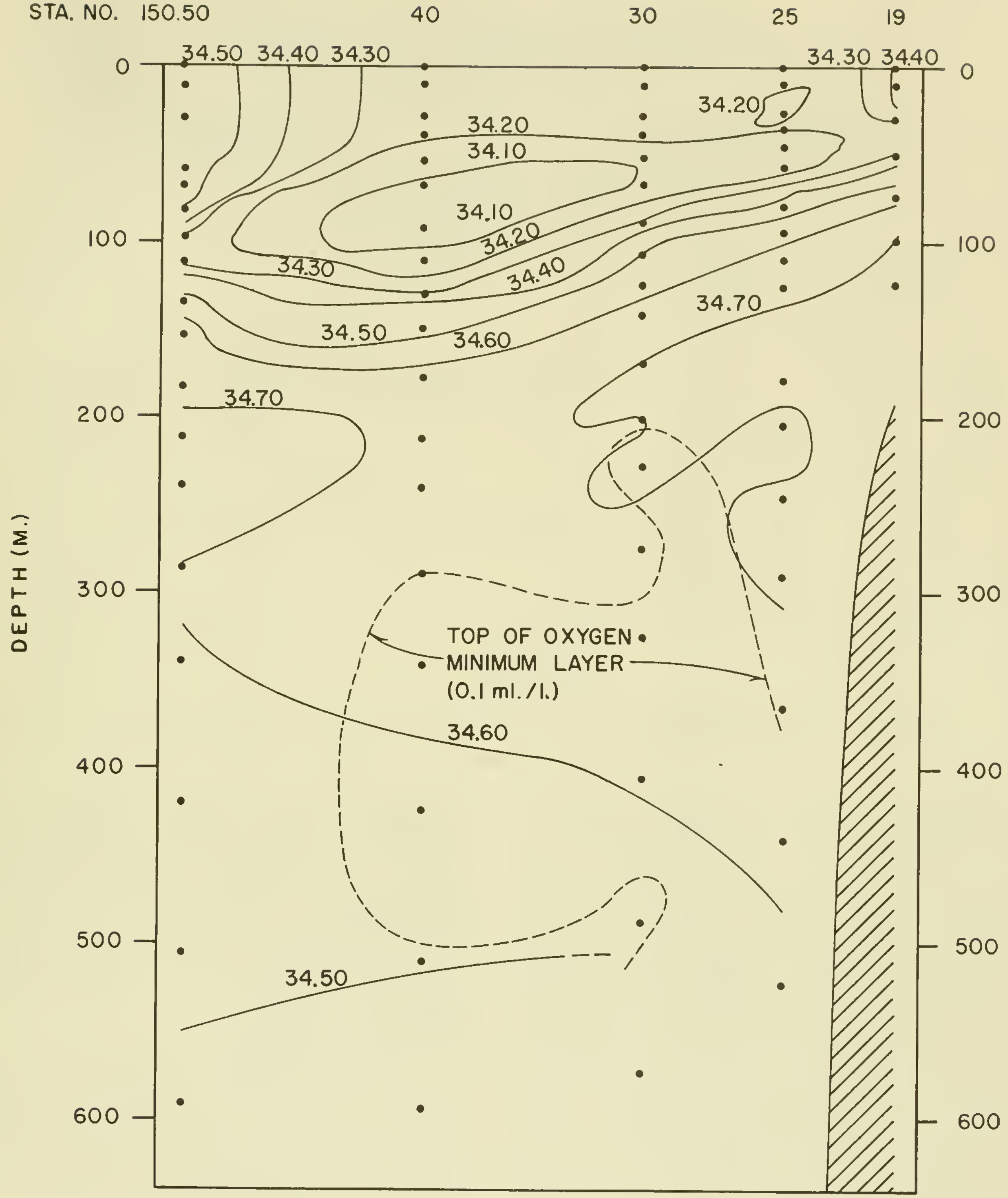

Figure 18.--Vertical salinity profile along line 150 of CalCOFI cruise 6004-B.

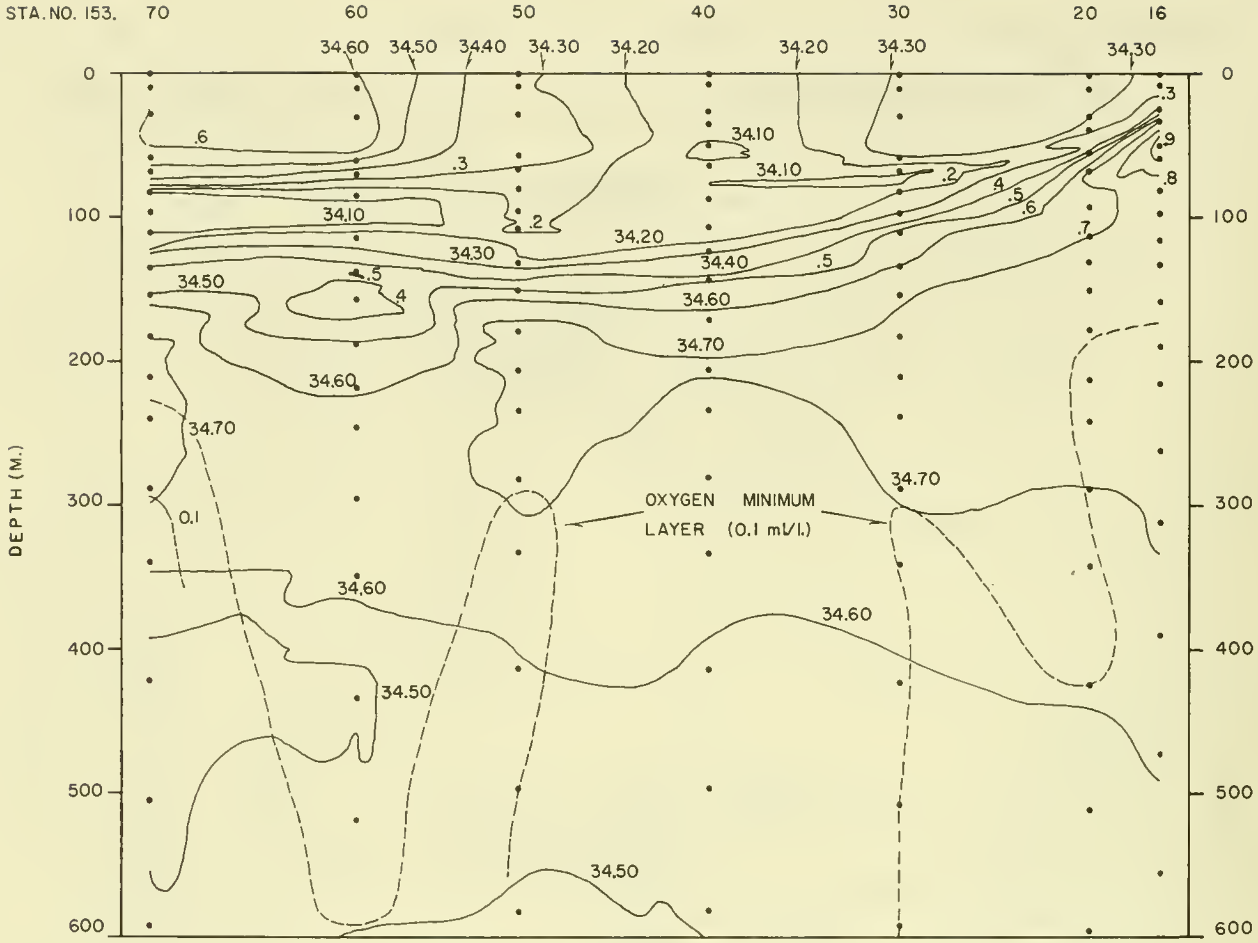

Figure 19.--Vertical salinity profile along the line 153 of CalCOFI cruise 6004-B.

the maximum and the surface water by way of the isohalines of 34.80 p.p.t. (stations 7, 8, and 9), which was mentioned above.

The thermal front between stations 12 and 14 corresponds to a salinity front which is strong between stations 12 and 14 and continues weaker between stations 14 and 16. The upwelled water present at stations 15 and 20 is represented by vertical isohalines corresponding to steeply sloped isotherms (fig. 11). The origin of the salinity node of about 34.70 p.p.t., approximately 100 m. deep at station 18, must be very different from that of the surrounding water. Salinity profiles to the north or immediately to the south lack water of such high salinity at this depth. Because salinity decreases rapidly from the center of the node to the ambient water, one may suppose that mixing is occurring and that the salinity of the node may have been higher than 34.70 p.p.t. Owing to its association with isanosteres[3] (260-320 cl./ton) that pass through the high-salinity Gulf Surface Water, I tentatively suggest that the node represents Gulf Surface Water. The node has a somewhat lower oxygen content than water to the west. The high-salinity water issuing from the Gulf near Cape San Lucas (mentioned above in reference to the profile for line 153) is associated with isanosteres around 240 cl./ton and seems a less likely cause of the node at station 18. The nearest other water of salinity ≥ 34.70 p.p.t. is in the salinity maximum (δ_T 130-180 cl./ton), which is an even less likely source.

The node of low-salinity water at station 16 is clearly due to California Current Surface Water. Likewise, nodes of high-salinity water at stations 12 and 10 are clearly due to Gulf Surface Water. The nodes of low-salinity water at station 11 ($S \leq 34.60$ p.p.t. at 40 m.) and at station 9 ($S \leq 34.50$ p.p.t., also at 40 m.) are probably due to California Current Surface Water, especially at station 9; this water influences the surface salinity at station 10 (see fig. 5). The node at station 9 corresponds to a depression in the oxygen isopleths, suggesting the presence of water of relatively higher oxygen content. The same is true to a

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[3] Lines of equal density.

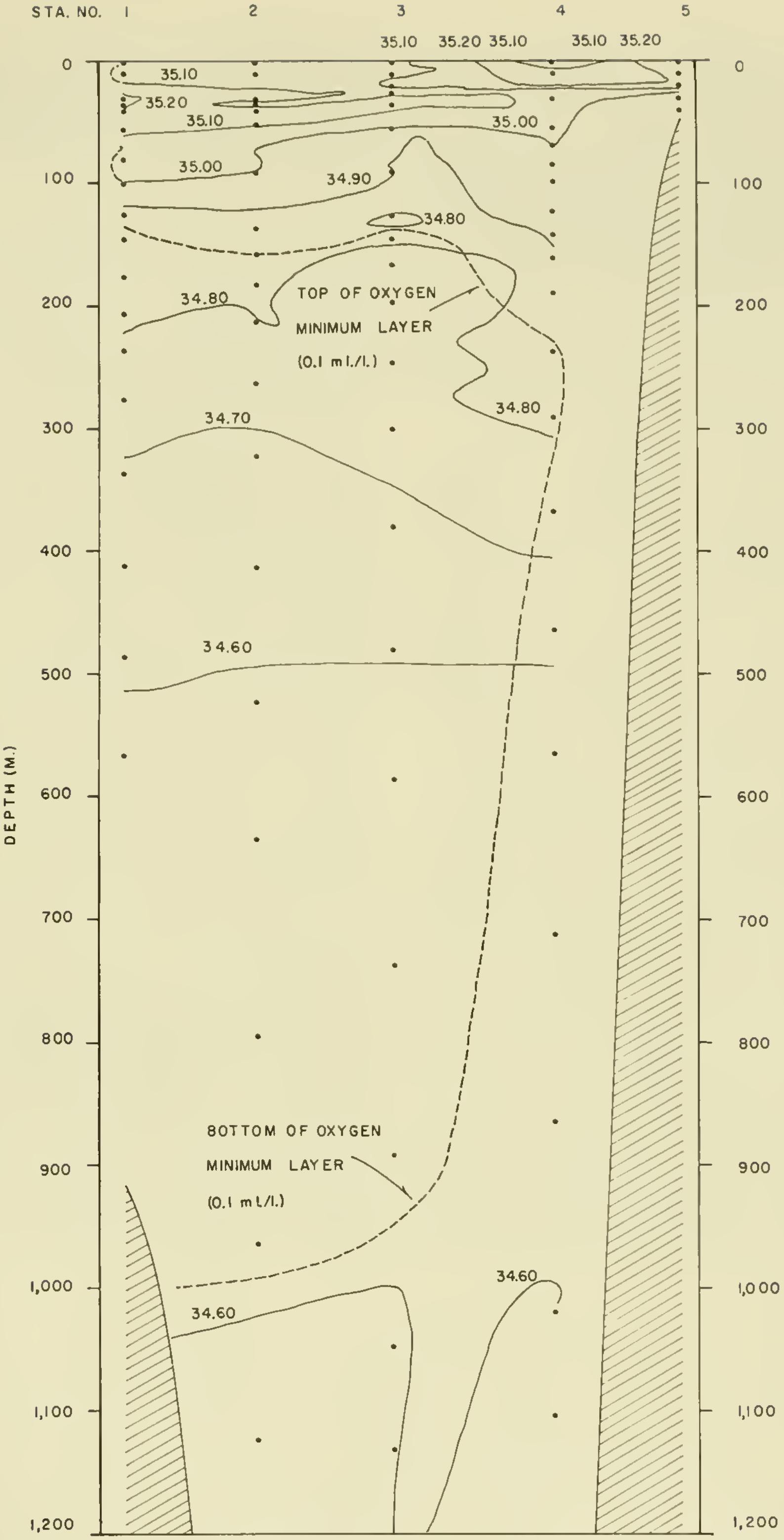

Figure 20.--Vertical salinity profile along the line of stations, 1 to 5, on cruise TO-60-1.

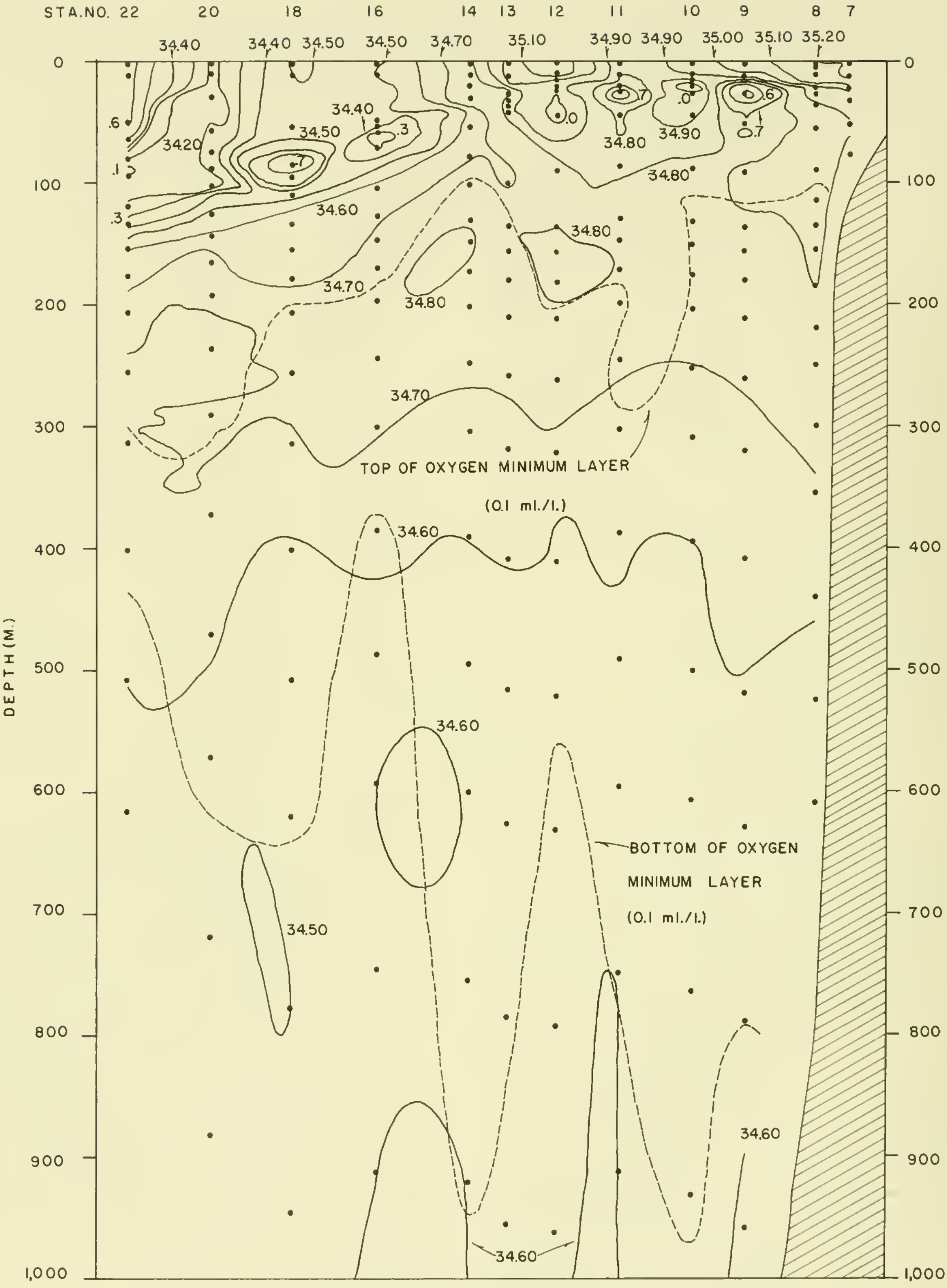

Figure 2i.--Vertical salinity profile along the line of stations, 7 to 22, on cruise TO-60-1.

lesser degree at station 11; in contrast the oxygen isopleths are raised at stations 10 and 12 where there are high-salinity nodes. These relationships are discussed further under oxygen distribution.

In the next profile south, stations 23 through 37 (fig. 22), the complications have largely disappeared. The deep-salinity minimum and the maximum above it are present, the maximum again represented by isohalines of 34.80 p.p.t. This value of the salinity maximum is found over much of the eastern tropical Pacific (Wyrtki, 1967; Bennett, 1963). The node of water of salinity about 34.80 p.p.t. at 100 m. between stations 29 and 31 is probably not part of the maximum because it is associated with isanosteres near 240 cl./ton rather than 130 to 180 cl./ton. Presumably this particular node is more correctly associated with the maximum due to Gulf Surface Water, at about 50 m. between stations 35 and 37. Such a maximum was found off Cape San Lucas at the eastern end of line 153 (fig. 19), also about the 240 cl./ton isanostere. The high surface salinities due to Gulf Surface Water, with which the isohalines of the salinity maximum usually connect in the Gulf mouth, are associated with isanosteres between 360 and 460 cl./ton. The relatively high surface salinities at the western end of the profile persist and the shallow salinity minimum of the California Current Surface Water is definite, although now somewhat thinner. This minimum extends its influence to the coast off Mazatlan, more or less following the thermocline and appearing to penetrate the high-salinity Gulf Water in the upper 100 m.; hence there is saltier water above and below the California Water. There is some possibility that the low-salinity water (about 34.50 p.p.t.) at about 20 m. at the easternmost end of this profile (station 37) was caused by river runoff in the region around Mazatlan. Roden and Groves (1959) suggested this possibility; however, the rainy season is in late summer and autumn. The extension of the low-salinity water from the west corresponds to one of relatively high oxygen content.

Farther south, between stations 40 and 48, the high salinity of the Gulf Surface Water is evident on the eastern side and extends its influence to the west, especially at the surface (fig. 23). The shallow minimum of the California Current Surface Water is much more restricted in this profile than in the previous one, but it still extends, much attenuated, almost to the coast on the eastern side. The maximum of the Subtropical Water is, as before, marked by the 34.80 p.p.t. isohaline which also circumscribes some Gulf Surface Water, in a layer at about 80 m. between stations 40 and 44; this maximum underlies the low-salinity extension from the west.

The southernmost profile (fig. 24) is like the one just to the north, but the shallow minimum is more restricted to the western side, though again it still extends its effects to the coast. In all these salinity profiles the shallow minimum, originating in California Current Surface Water, appears to compete with high-salinity Gulf Surface Water for density surfaces along which to spread, because this high-salinity water is found above and below the lower salinity water. The salinity minimum can be most liberally proscribed by the 34.60 p.p.t. isohaline, because no water in the upper 100 m. off western Lower California has a salinity exceeding 34.60 p.p.t. (except as noted at station 153.16), and no water in the immediate vicinity to the south or east has a salinity in the upper 100 m. of less than 34.60 p.p.t. (except for the possibility of river runoff already noted).

Along the southernmost line the salinity maximum is described entirely by water of ≥ 34.80 p.p.t. In this profile as well as in the others, the top of the oxygen minimum (dashed contour) is associated with the salinity maximum. Between stations 50 and 56 the deep salinity minimum is still present and is of nearly uniform salinity (≤ 34.60 p.p.t.); this agrees broadly with descriptions of this feature given by Bennett (1963) and Wyrtki (1967).

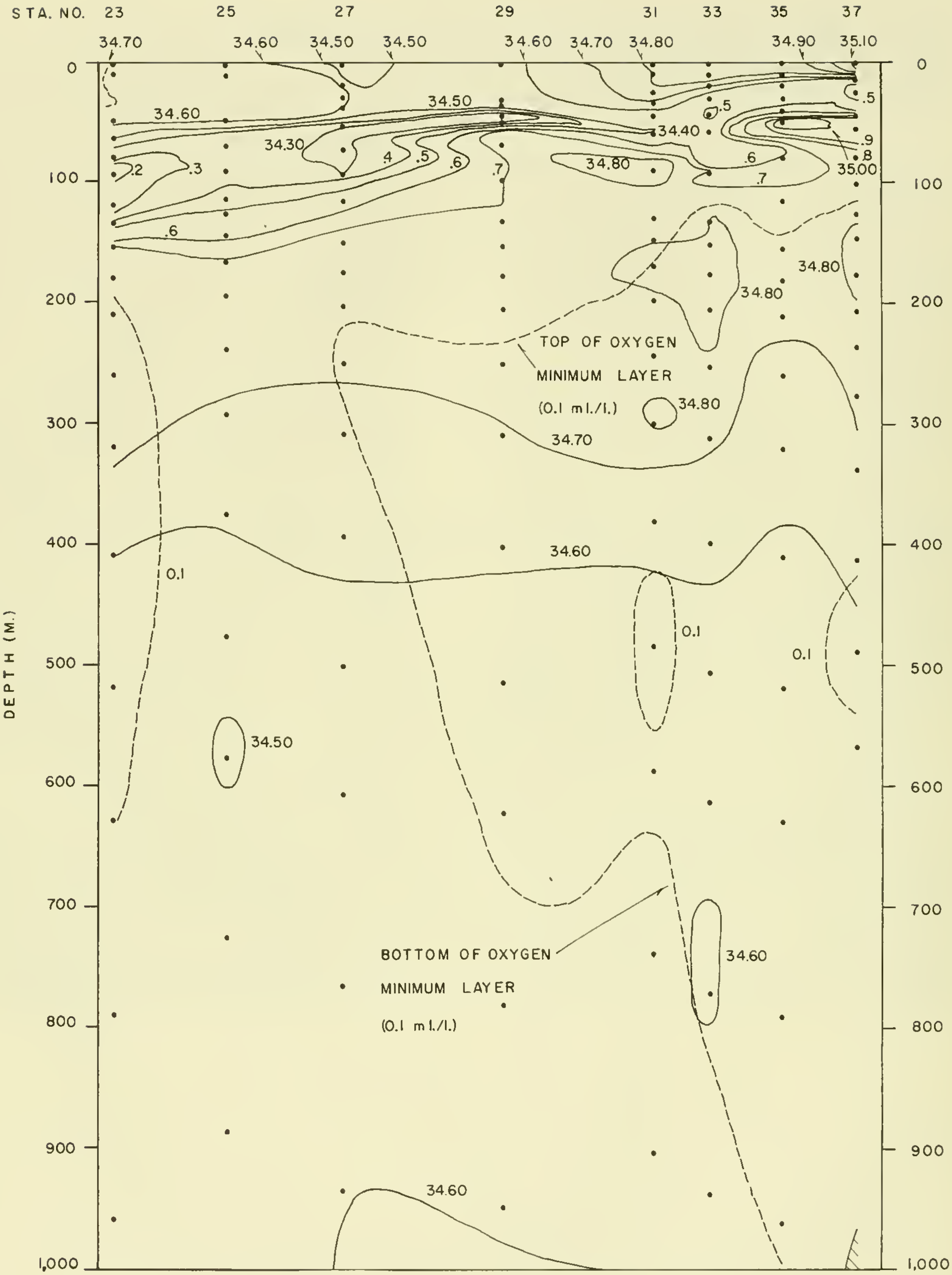

Figure 22.--Vertical salinity profile along the line of stations, 23 to 37, on cruise TO-60-1.

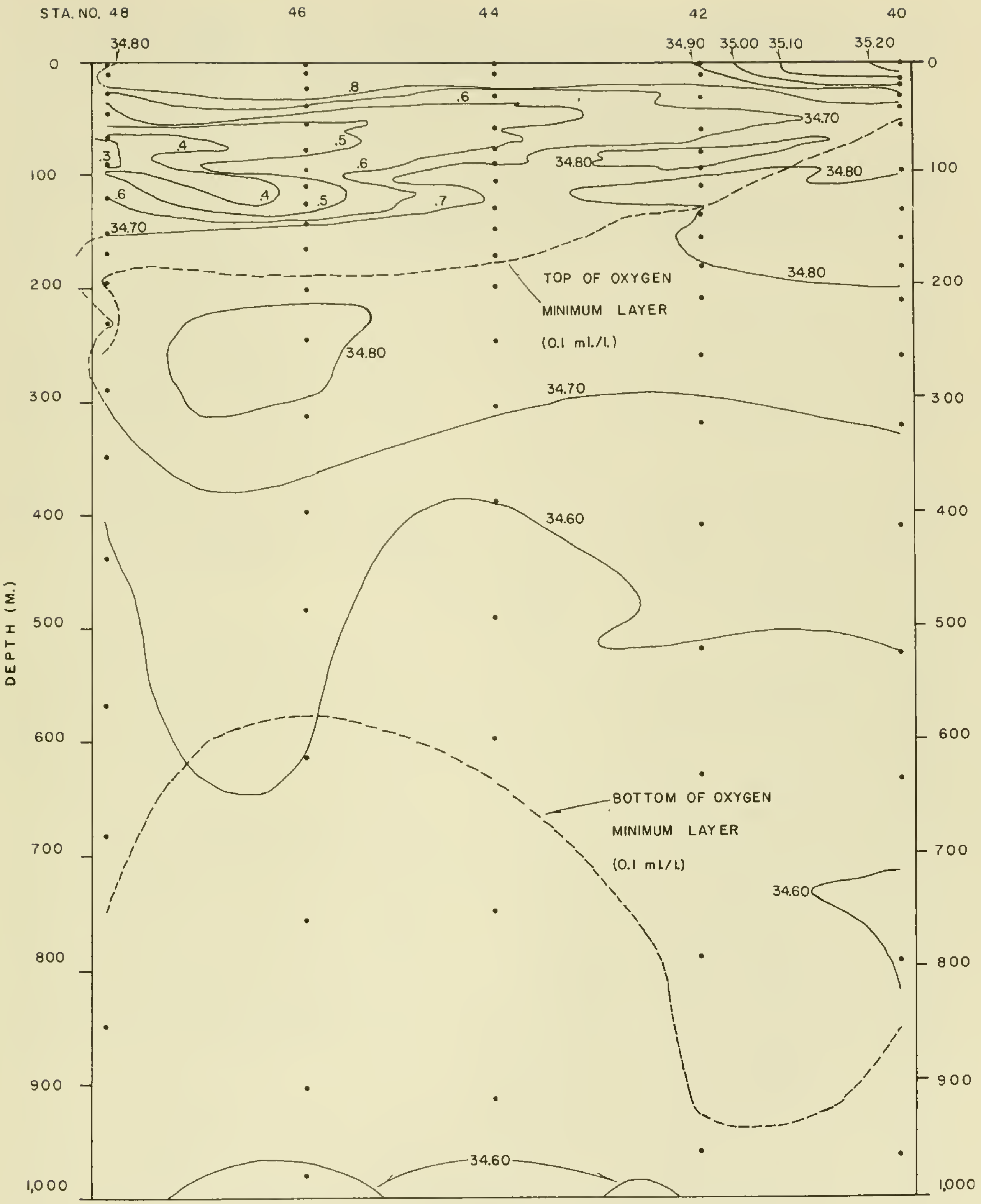

Figure 23.--Vertical salinity profile along the line of stations, 40 to 48, on cruise TO-60-1.

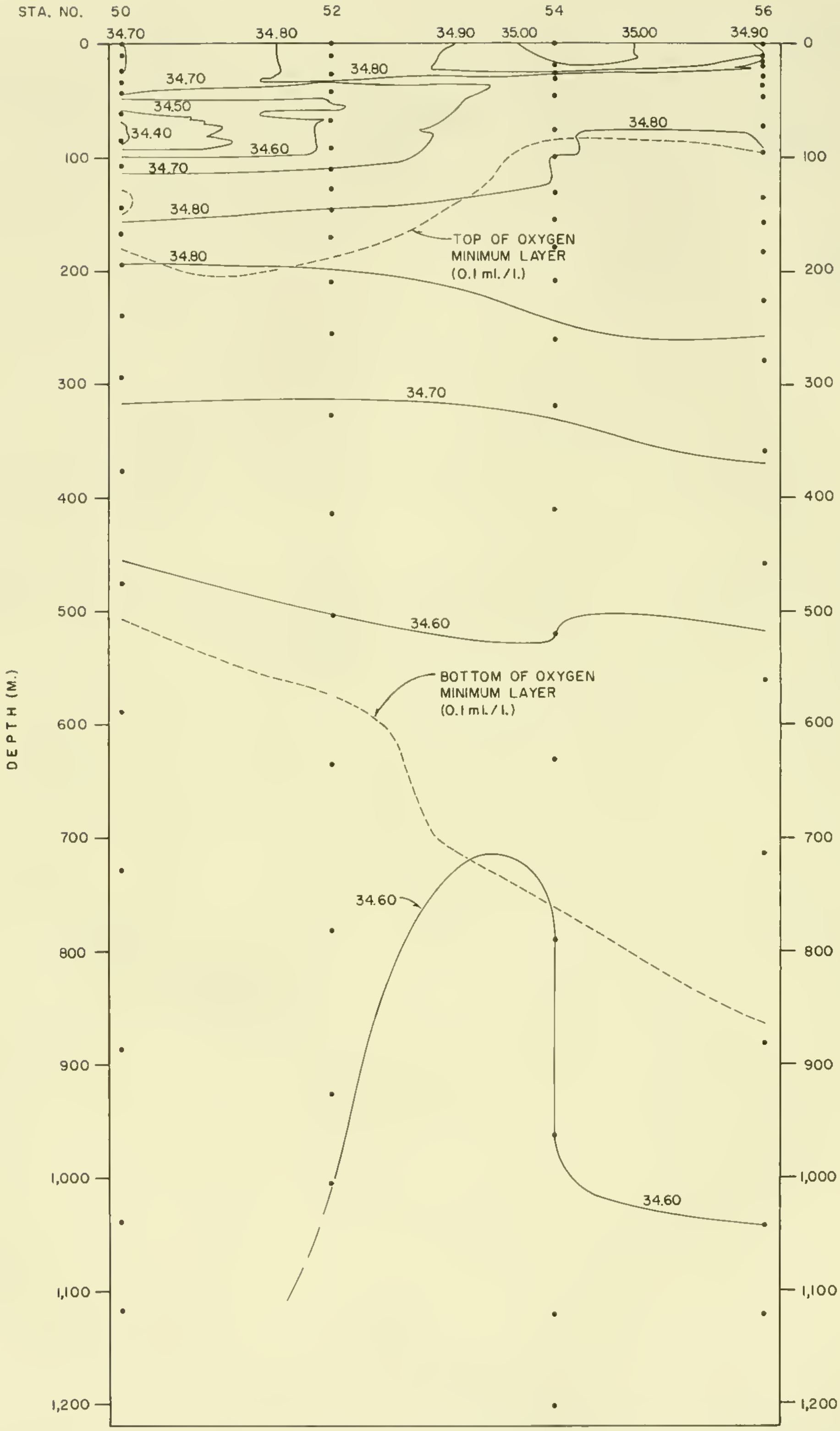

Figure 24.--Vertical salinity profile along the line of stations, 50 to 56, on cruise TO-60-1.

Thermosteric anomaly, δ_T

In terms of features the profiles of δ_T strongly resemble those of temperature. Off western Lower California the pycnocline is at 100 m. offshore and breaks the surface inshore; it may be somewhat stronger near Cape Falso. In the Gulf the pycnocline is strong and shallow, with surface values from 400 to 420 cl./ton. Figure 25 shows the distribution of the anomaly between stations 7 and 22. As in the temperature and salinity distributions a front exists between stations 12 and 14. The undulations in the subsurface density layers east of station 13 correspond very clearly to the various different salinity nodes there. On lines farther south the values at the surface tend to increase, as they do for temperature, and the structures in the density distribution continue to resemble closely those in the temperature distribution. The isanosteric surfaces chiefly associated with the gross features of the salinity distribution have already been mentioned: 60 to 120 cl./ton--deep salinity minimum; 130 to 180 cl./ton--deep salinity maximum; 260 to 320 cl./ton--shallow salinity minimum; 220 to 260 and 360 to 460 cl./ton--high Gulf salinities below and above the shallow salinity minimum.

Dissolved oxygen

So far I have assumed that the methods of data collection on the two cruises (6004-B and TO-60-1) with respect to the measurement of a property were the same. If any difference exists, it is likely to be most evident in the determination of oxygen, less so in that of salinity, and least in that of temperature.

In view of its lower temperature and salinity at the surface, one might expect the oxygen content of the California Current Surface Water to be higher than that of the warmer, saltier waters to the south and east. That this is not so may be partially due to the possible differences in method mentioned, but a more obvious explanation is that the upwelled water off Lower California has a low oxygen content and has spread toward the south and southwest. It would normally come, eventually, into equilibrium with the atmosphere, but at the time it was measured it was only 80 to 90 percent saturated over a large area.

Measurements of oxygen along line 143 were erroneous. In the profiles along lines 147, 150, and 153 (fig. 26) the chief feature is the "oxycline" that slopes upward and strengthens from west to east, like the thermocline but slightly deeper, especially to the west. The oxygen minimum, shown previously on the corresponding temperature and salinity profiles, is measured by the 0.1 ml./l. isopleth and is restricted, but is less attenuated with decreasing northern latitude. The node of oxygen concentration of 1.0 ml./l. at about 150 m. at station 153.60 corresponds to one of lowered salinity (see fig. 19).

Across the Gulf (stations 1 to 5) a strong, shallow stratification of oxygen is also present, somewhat deeper, and less marked, than the thermocline. Oxygen content is relatively high--about 115 percent of saturation--in the thermocline, at about 30 m., from station 2 to 3; local phytoplankton activity may be the cause.

The profile between stations 7 to 22 (fig. 27) also shows a strong oxygen gradient comparable to and slightly deeper than the corresponding thermocline. The front between stations 12 and 14 is not obvious from the oxygen distribution, but the depth of the "oxycline" changes relatively sharply at about station 14. The oxygen minimum is attenuated to the west, i.e., toward the California Current Water.

The point was made earlier that the oxygen contours had a wavelike form between stations 12 and 7 in the upper 100 m., that suggested a correlation with the observed salinity distribution (fig. 21). The nodes of water of relatively low salinity (California Current Surface Water) correlate fairly well with water of relatively high oxygen (depressed isopleths), whereas the nodes of high salinity (Gulf Surface Water) correlate with elevated oxygen isopleths (diminished oxygen content). It is not certain to what extent these correlations are meaningful because, according to the data, California water at the surface had generally lower values of dissolved oxygen than the Gulf and Subtropical Pacific Surface Water. The most likely cause of this lower oxygen content was the upwelling of low-oxygen water off western Lower California. At depths below the thermocline, however, the oxygen content of the California water generally exceeds that of waters to the south and east--as shown, for example, by the reduced oxygen minimum north of Cape San Lucas.

In the Gulf entrance the water at the surface is somewhat oversaturated. Thus along profiles 7 to 22 and line 153, the lower surface oxygen values are to the west. In the profile along line 23 to 37 and in the two profiles farther to the south, the situation is reversed; the oxygen content of water to the west, identifiable from its salinity as having been derived from California Current Surface Water, has a higher oxygen content than the Subtropical and Gulf waters to the east. It seems as though the low-oxygen, upwelled water from Lower California increased its oxygen content as it spread southward at the surface, perhaps by biological activity.

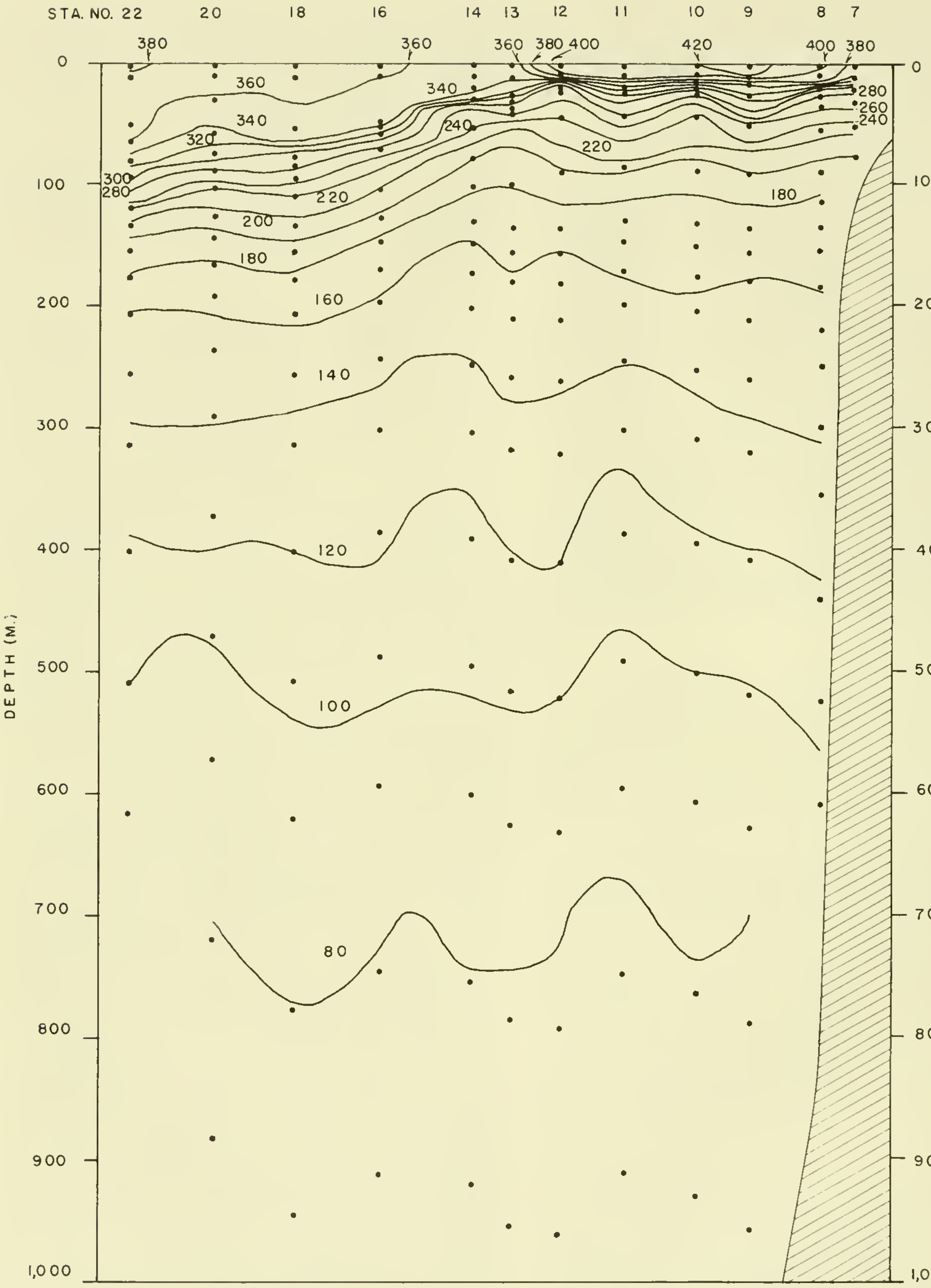

Figure 25.--Vertical profile of thermosteric anomaly along the line of stations, 7 to 22, on cruise TO-60-1. The contour interval is 20 cl./metric ton.

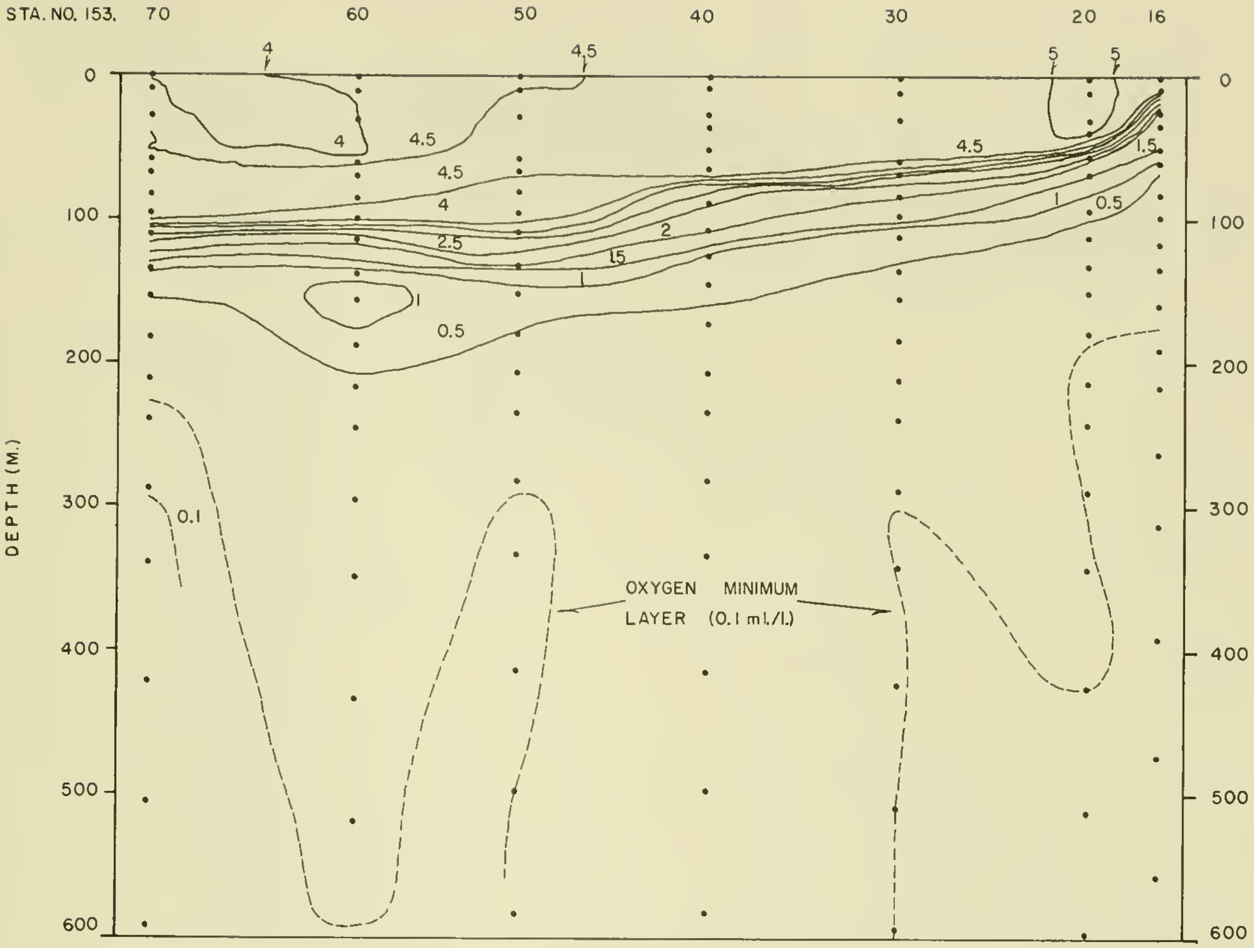

Figure 26.--Vertical profile of dissolved oxygen along line 153 of CalCOFI cruise 6004-B. The contour interval here and in the other vertical profiles of dissolved oxygen is 0.5 ml./l.

Figure 28, the oxygen profile between stations 40 and 48, illustrates a feature of the oxygen distribution that can be seen also, to a lesser degree, in profiles immediately to the north and south. The corresponding salinity distribution shows a well-developed tongue of low-salinity water (California Current minimum), below the surface but mostly above 120 m., spreading from the west and attenuating to the east. An oxygen maximum seems to overlie this salinity minimum, though there is some overlap in places. One cannot be sure that a causal relation exists between the two features, but it seems possible.

Inorganic phosphorus

This property was measured on most hydrocasts on TO-60-1, although not on 6004-B. The replicates were frequently more disparate than is desirable, as shown in the data list (Scripps Institution of Oceanography, 1967). Also, the profiles are generally featureless except for a strong gradient like that in the oxygen distribution and at a similar depth--at the bottom of the thermocline. For these reasons no profiles are reproduced. More is said in the section on the horizontal distribution of this property.

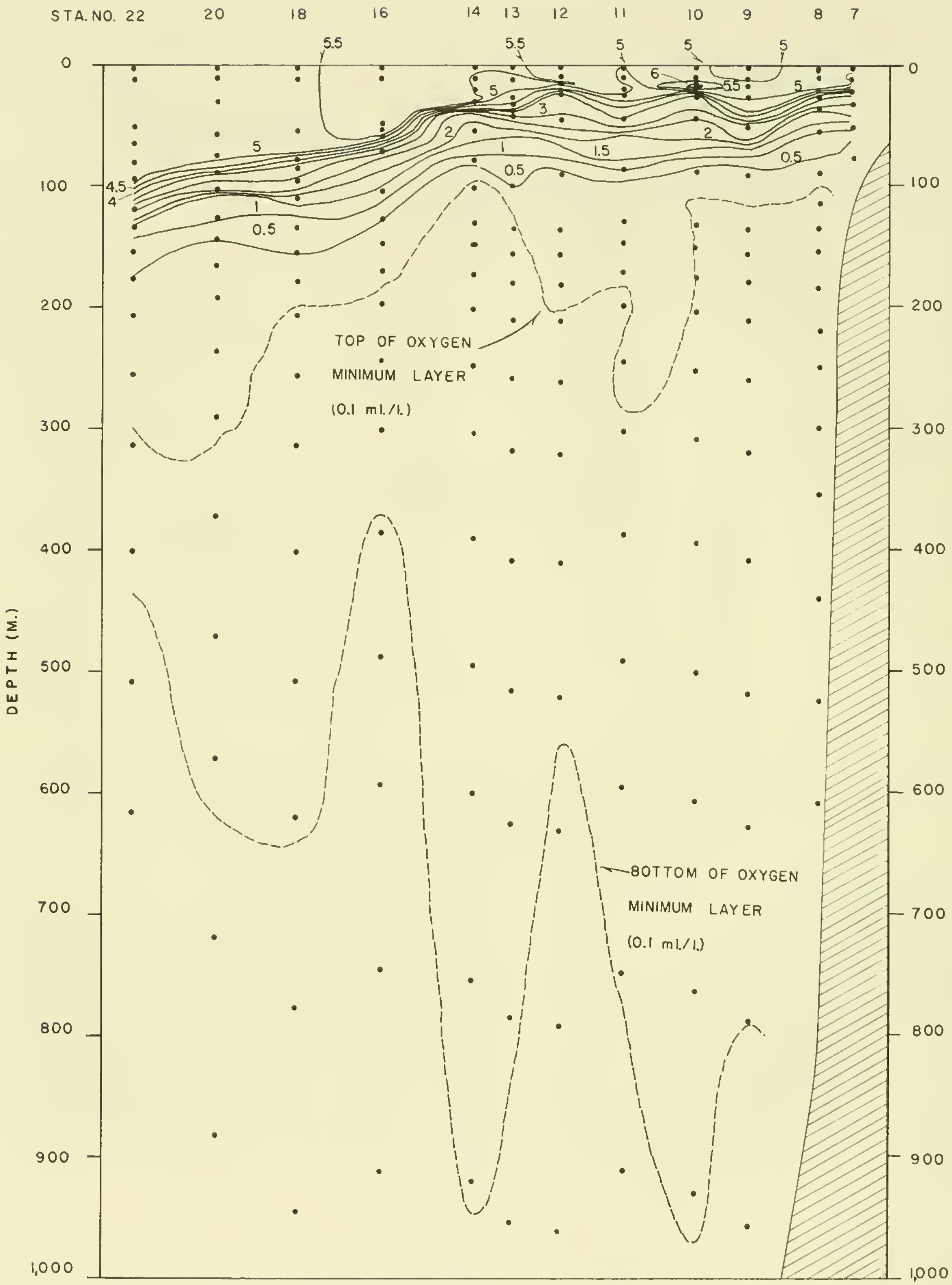

Figure 27.--Vertical profile of dissolved oxygen along the line of stations, 7 to 22, on cruise TO-60-1.

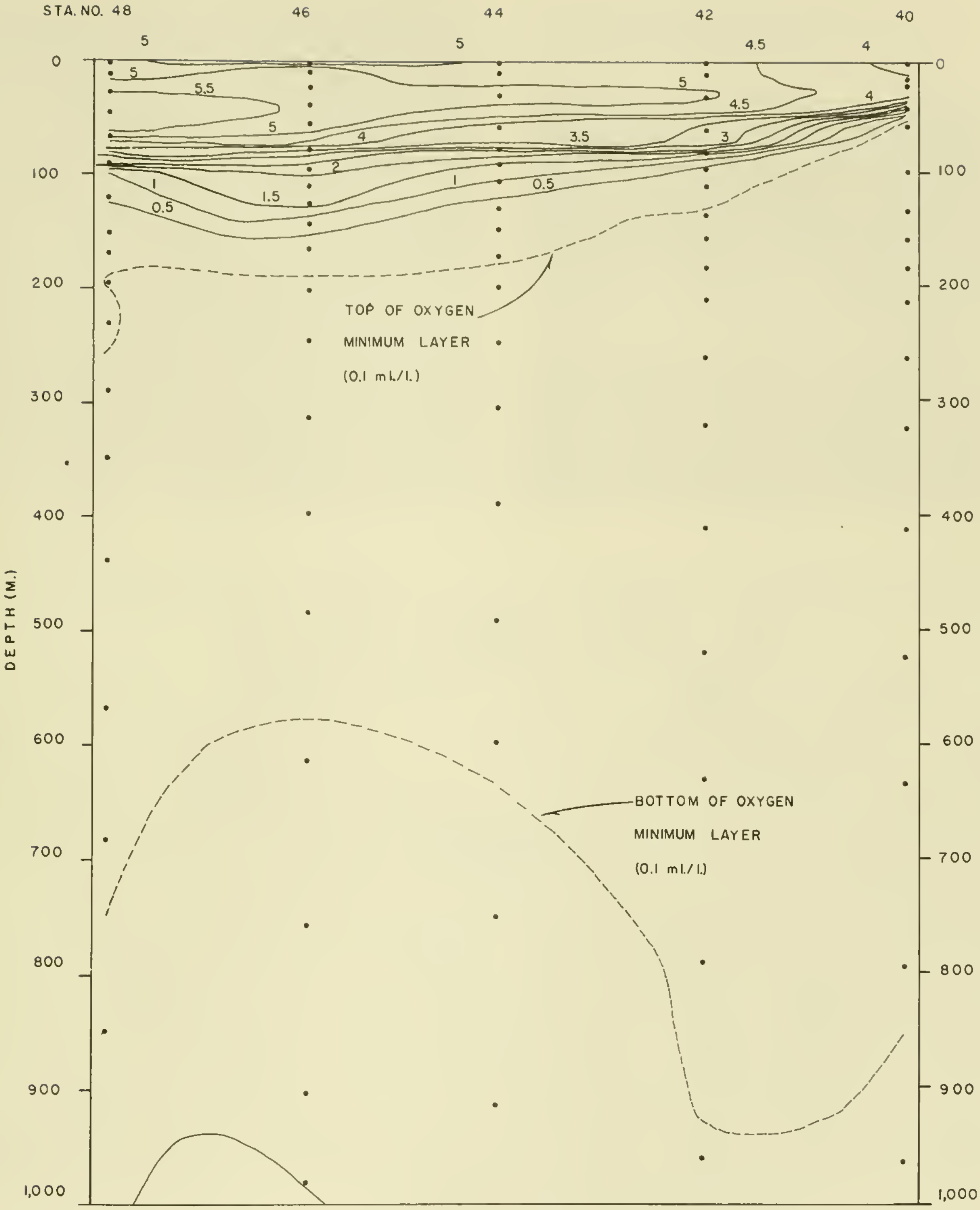

Figure 28.--Vertical profile of dissolved oxygen along the line of stations, 40 to 48, on cruise TO-60-1

HORIZONTAL DISTRIBUTION OF PROPERTIES

For several properties the horizontal distributions are similar over a considerable range of depth (e.g. upper 100 m.); consequently, only those that illustrate certain features are shown and discussed. The properties dealt with are: temperature, salinity, thermosteric anomaly, dynamic height anomaly, surface current, dissolved oxygen, inorganic phosphorus, chlorophyll a, zooplankton, and micronekton.

Temperature

As with most of the other properties, the distribution of temperature is more variable above a depth of 100 m. than below. Figure 29 shows the temperature distribution at 10 m. The general form of this distribution, though not necessarily the same isotherms, is practically the same from the surface to a depth of at least 30 m. Off western Lower California upwelling is apparent. The upwelled water appears to have spread southward, as suggested earlier. The isotherms of 19° and 20° C., in particular, extend far south from Cape Falso to form a sharp frontal system between California water and Gulf water. This frontal system turns westward at about 100 nautical miles (185 km.) south of the Cape and becomes weaker. In the upper 30 m. there is some evidence of an intrusion of warm water (see 24° C. isotherm) into the Gulf, to the east of the frontal system. Near Cape Corrientes there is evidence of a thermal anticline. This anticline is not evident from the surface data but is conspicuous at 10 m. and is indicated in the thermocline topography in figure 15. The vertical profile between stations 50 and 56 (fig. 14) did not provide any convincing indication of it. There is an indication of slight upwelling just north of Mazatlan (23° C. isotherm).

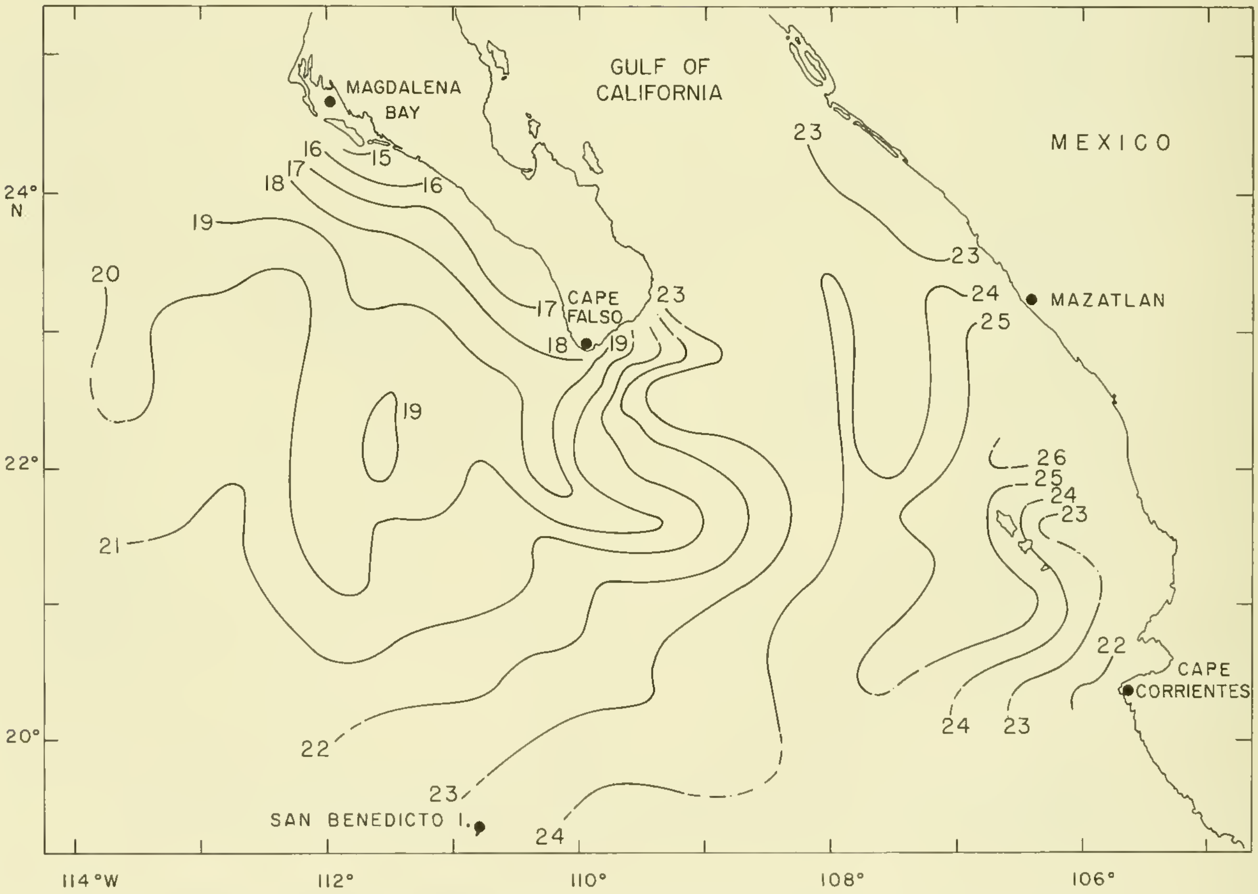

Figure 29.--Horizontal temperature distribution at 10-m. depth for part of CalCOFI cruise 6004-B and for cruise TO-60-1. The contour interval here and in the next figure is 1° C.

The first noticeable change in the temperature distribution occurs at about 50 m. (fig. 30). At this depth, upwelling is still prominent off western Lower California, as is the southward extension of this water (note 16° to 20° C. isotherms). The frontal system, however, has largely disappeared. Weak upwelling off the east coast of the entrance to the Gulf is still evident. The intrusion of the 18° and 19° C. isotherms northward to the Gulf suggests the way California Current water may have arrived at station 9, which had a node of relatively low-salinity water between about 30 and 50 m. deep.

The data (Scripps Institution of Oceanography, 1967) show that the form of the distribution at 50 m. is not much changed at 100 m. Upwelling off Lower California and the Mexican mainland is no longer detectable, but the strong gradient roughly parallel to the coast of Lower California is still present, though farther offshore. The possible advection from the southwest, mentioned above, seems to be still present. The same is true at 150 m., though no other feature noted above persists at that depth.

Salinity

Figure 31 depicts the salinity distributions at the 10-m. depth. The most important feature is, again, the frontal system between the Gulf water and upwelled California Current water. This upwelled water is identified by low salinities comparable to those in the subsurface minimum. It extends far south from the coast to stations 15 and 28, and westward to station 20. Farther west is an apparent intrusion of water of higher salinity (≥ 34.60 p.p.t.) from the south; this advection accounts for the high salinities at the surface at station 143.60 (fig. 16) and can be ascribed to Subtropical Surface Water, rather than Central Pacific water which I formerly suggested as a possibility (Griffiths, 1965). The frontal system has two parts: one between Gulf Surface Water and California Current Surface

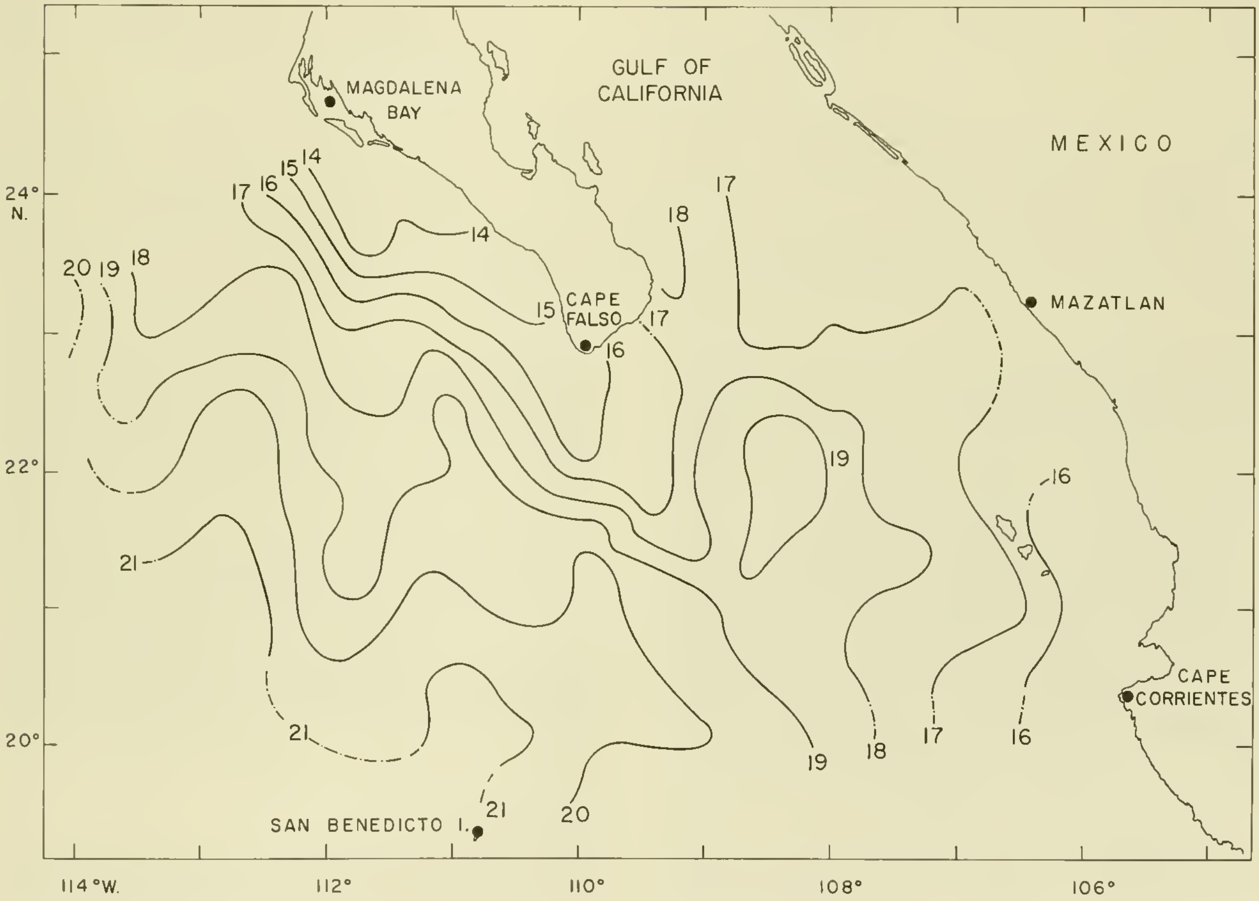

Figure 30.--Horizontal temperature distribution at 50 m.-depth for part of CalCOFI cruise 6004-B and for cruise TO-60-1.

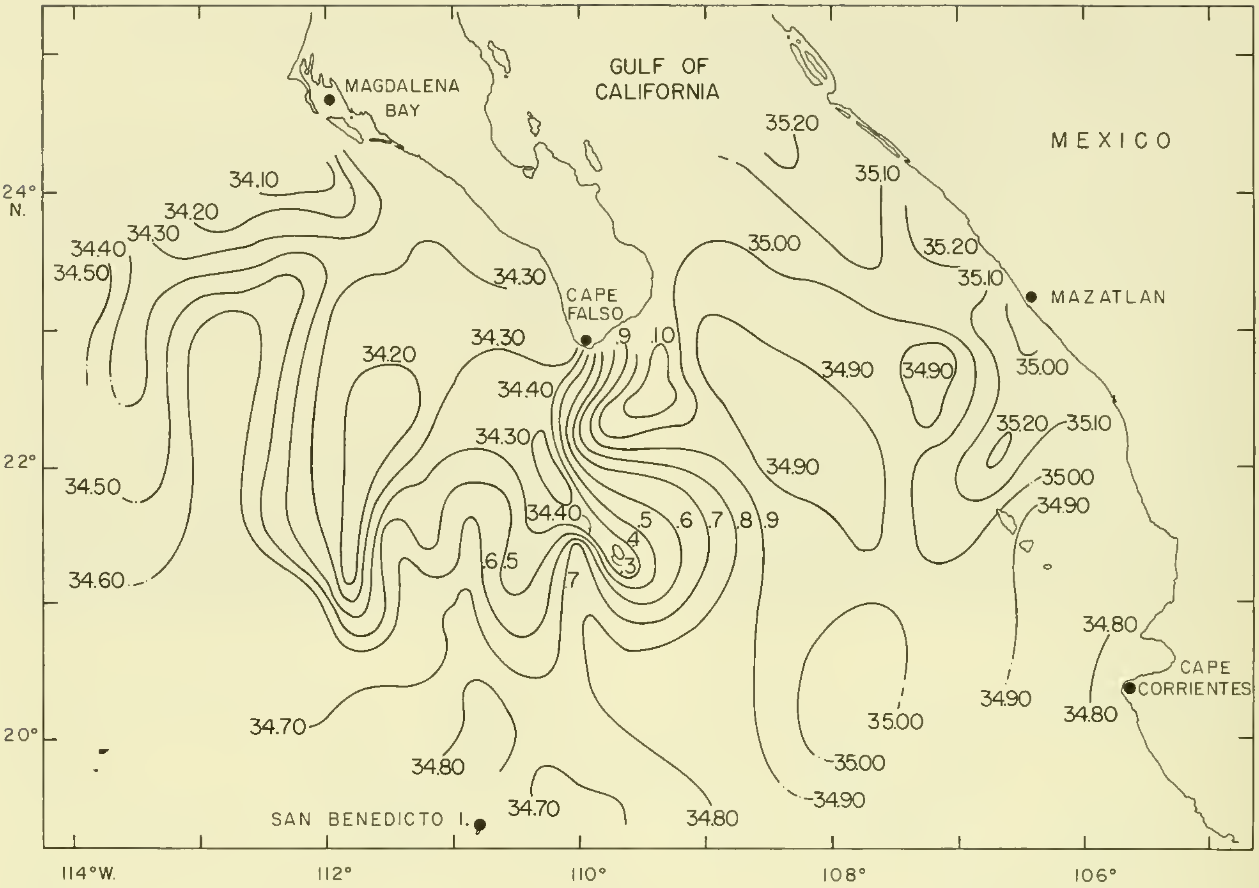

Figure 31.--Horizontal salinity distribution at 10-m. depth for part of CalCOFI cruise 6004-B and for cruise TO-60-1. The contour interval here and in the next figure is 0.10 p.p.t.

Water, extending sinuously southwards from Cape San Lucas for about 100 nautical miles (185 km.); the other part continuing westward out to sea and formed between California Current Surface Water and Subtropical Pacific Surface Water. This second part is much weaker than the first; front studies have been most successful at the first part.

There are indications of eddy formation; the Gulf Surface Water seems to be contained at the Cape by the California Current Surface Water which turns eastward in a large loop well south of the Cape. Between the large loop of low-salinity water and the high-salinity water to the east is a relatively large area of water of intermediate salinity, marked by two nodes about 34.90 p.p.t. Presumably this is mixed water.

This distribution, seen at the 10-m. depth, is essentially unchanged in form, at least down to 75 m. At 50 m. (fig. 32), low-salinity water south of Cape San Lucas has spread out and appears to have intruded into the Gulf as was mentioned earlier. At 150 m. most of the Gulf entrance and the area inshore along western Lower California is occupied by water of salinities between 34.75 and 34.85 p.p.t.; i.e., by the salinity maximum of the Subtropical Subsurface Water. The salinity increases immediately in the Gulf proper. No indication of upwelling appears off western Lower California, except perhaps at Magdalena Bay, and a strong gradient exists between the saline water inshore and the low-salinity water offshore, running roughly north-south. This low-salinity water is at the bottom of the salinity minimum of the California Current Water.

Thermosteric anomaly, δ_T

The δ_T and temperature distributions have a similar form. Figure 33 shows the distribution

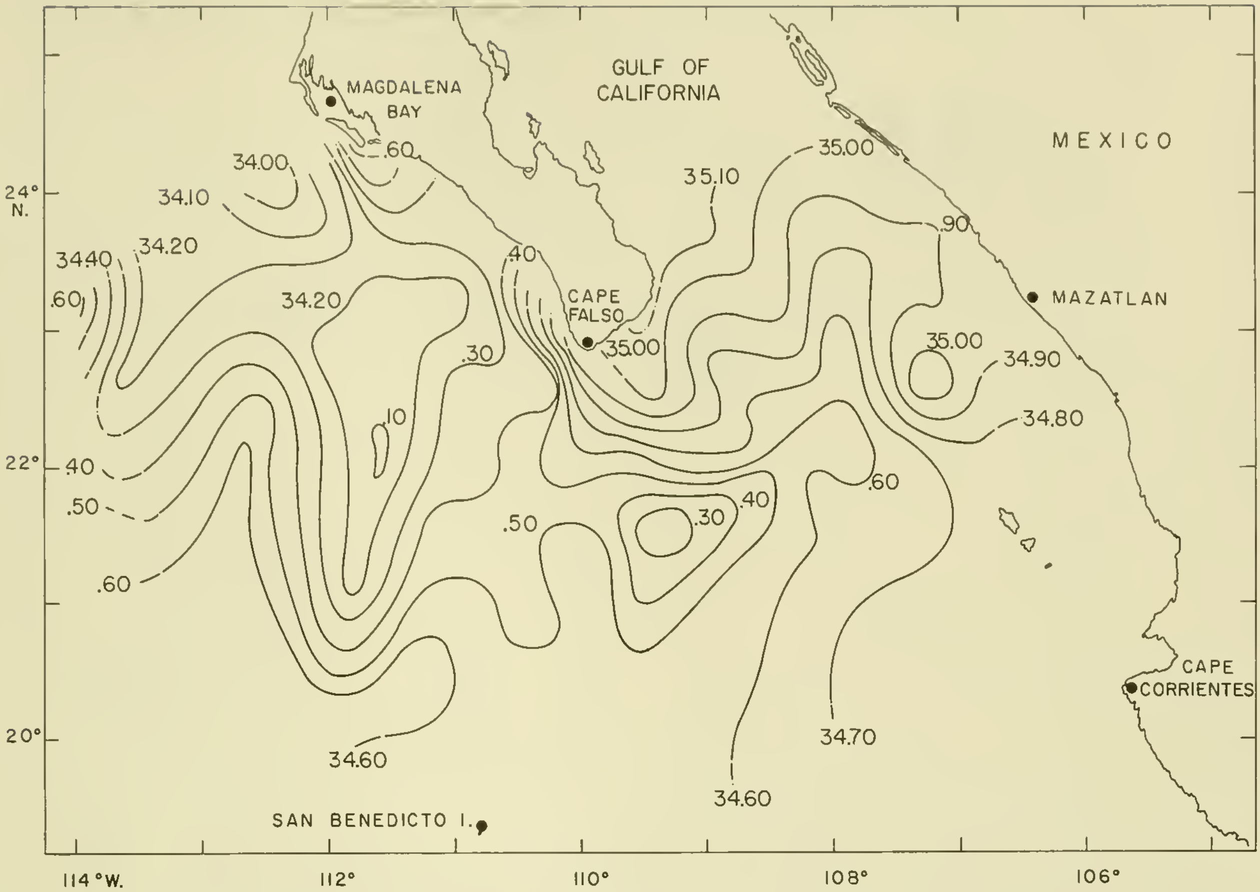

Figure 32.--Horizontal salinity distribution at 50-m. depth for part of CalCOFI cruise 6004-B and for cruise TO-60-1.

of the thermosteric anomaly at the sea surface. Strong upwelling off Lower California and weak upwelling just north of Mazatlan are evident. The anomaly increases toward Cape Corrientes and the Tres Marias Islands, as does the temperature. A few meters below the surface, however, the anomaly decreases rapidly, as does the temperature (fig. 29). These facts support the view of Roden and Groves (1959) that some upwelling occurs in this area.

Dynamic height anomaly, ΔD: geostrophic flow

Although geostrophic flow can be computed for vertical sections (Montgomery and Stroup, 1962), our data made this approach unsatisfactory; vertical profiles seemed to abound in currents flowing in opposite directions, alternately, along any given profile. Undoubtedly this situation was largely due to the slow, meandering currents present. Thus it seemed more sensible to present only horizontal distributions of dynamic height anomalies and associated patterns of geostrophic flow.

Because most casts on cruise 6004-B went only to a depth of about 600 m. and most of those on TO-60-1 went to about 1,100 m., two kinds of distribution are given below: the dynamic height anomalies over the 1,000-decibar surface (dotted lines) and over the 500-decibar surface (solid lines, covering a greater area). Figure 34 provides a graph from which one may read approximate velocities in cm./sec. or knots (1° of latitude equals 60 nautical miles or about 110 km.).

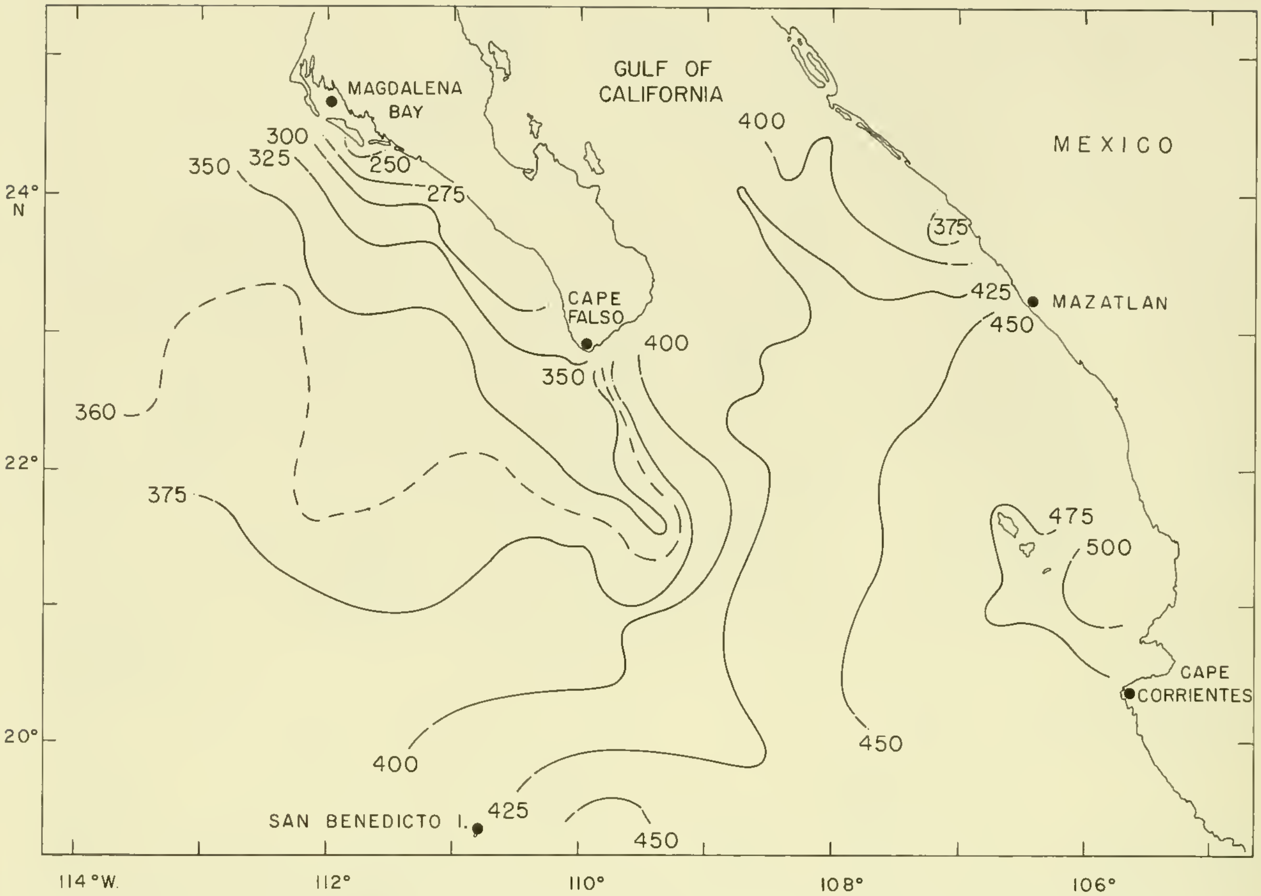

Figure 33.--Horizontal distribution of thermosteric anomaly at the sea surface for part of CalCOFI cruise 6004-B and for cruise TO-60-1. The contour interval is 25 cl./metric ton.

Figure 35 shows the distributions of the anomaly at the sea surface; arrows indicate the direction of geostrophic flow. The frontal system and the California Current water entering the Gulf entrance show clearly (regardless of whether the 500- or the 1,000-decibar reference surface is used). As might be expected from the temperature distribution, flow in the upwelling region off western Lower California is southward, because the temperature decreases toward the coast.

This picture is essentially unchanged in the upper 100 m., though the flow in general, and in the frontal system in particular, is somewhat weaker. At 125 m. there is a more definite indication of a flow into the Gulf in the southeastern part (fig. 36; note smaller contour interval). In contrast, the flow off Lower California has become less directed and weaker.

The most persistent feature is the distribution immediately about Cape San Lucas. The isopleths seem to run parallel to the coast of the peninsula. This characteristic is found at least to 200 m. Probably the outflow from the Gulf is contained at the Cape by the winds which blow mainly from the northwest in the spring and in much of the rest of the year, except in autumn (Meteorological Office, London, 1956). I found in front studies (Griffiths, 1965) that the mountainous land acts as a windbreak which probably prevents the removal of water by wind action from the lee of the Cape. Thus the frontal system tends to be preserved better near the Cape than it is out to sea.

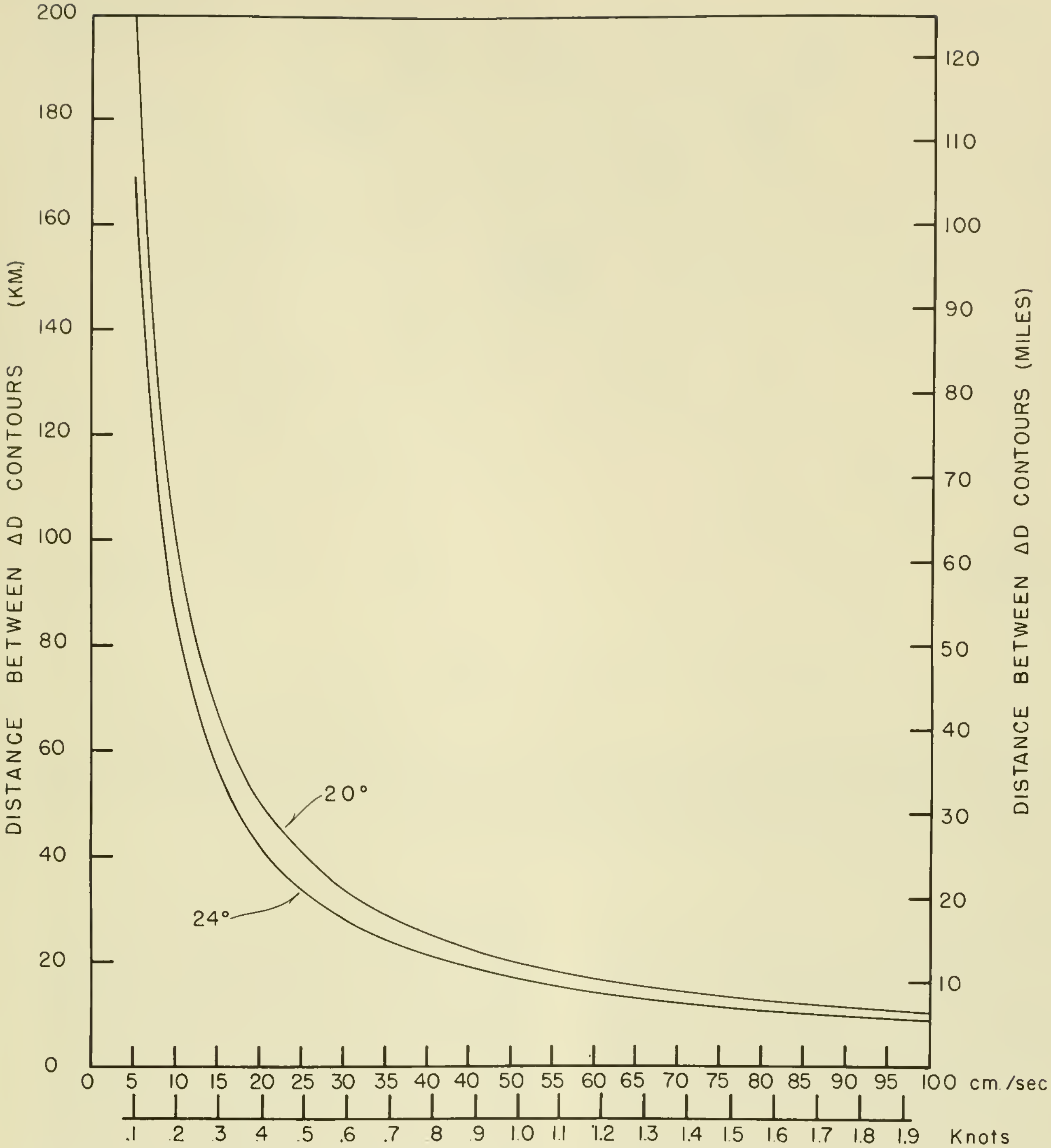

Figure 34.--A graph showing the relation between the distance between contours of the dynamic height anomaly, D, and current speed for two latitudes in the area under study.

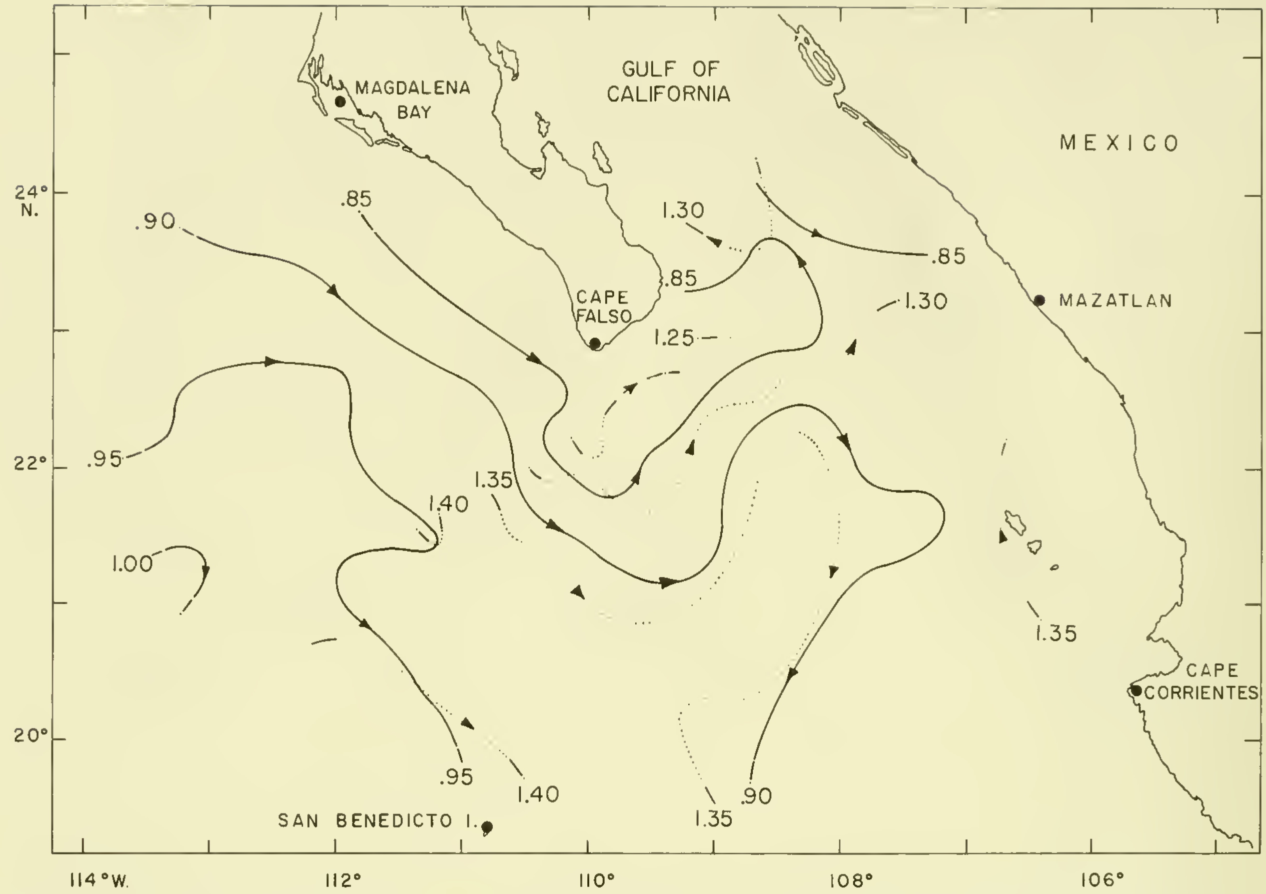

Figure 35.--Horizontal distribution of the dynamic height anomaly at the sea surface over the 500-decibar surface (solid lines) for part of CalCOFI cruise 6004-B and for cruise TO-60-1, and over the 1,000-decibar surface (broken lines) for cruise TO-60-1 only. Arrowheads show direction of flow; the speed of flow in this and the next figure can be judged by using the graph in figure 34. The contour interval is 0.05 dynamic meter.

Surface currents

As noted by Reid (1958), GEK (Geomagneto-ElectroKinetograph) measurements are instantaneous and may depart from average conditions because of tidal effects. It is not surprising therefore that the results of GEK measurements show only an indifferent agreement with geostrophic flow. Figure 37 shows the surface currents measured by GEK on TO-60-1. The currents are represented vectorially; velocities in centimeters per second are given next to each arrow. The four closely grouped measurements south of Cape Falso were made at Front 1 near station 15 (Griffiths, 1965).

Dissolved oxygen

The horizontal distribution of dissolved oxygen at the sea surface (fig. 38) differs markedly from the distributions of other properties so far mentioned. No frontal system is obvious. The water off western Lower California is all undersaturated (80 - 90 percent), presumably owing to recent upwelling as indicated by the isopleths. In contrast, water around stations 12 to 16 is oversaturated ($\geq$ 110 percent), as is the water south and west of the Tres Marias Islands. This oversaturation indicates prolonged contact with the atmosphere or considerable agitation at the sea surface. The water around Mazatlan

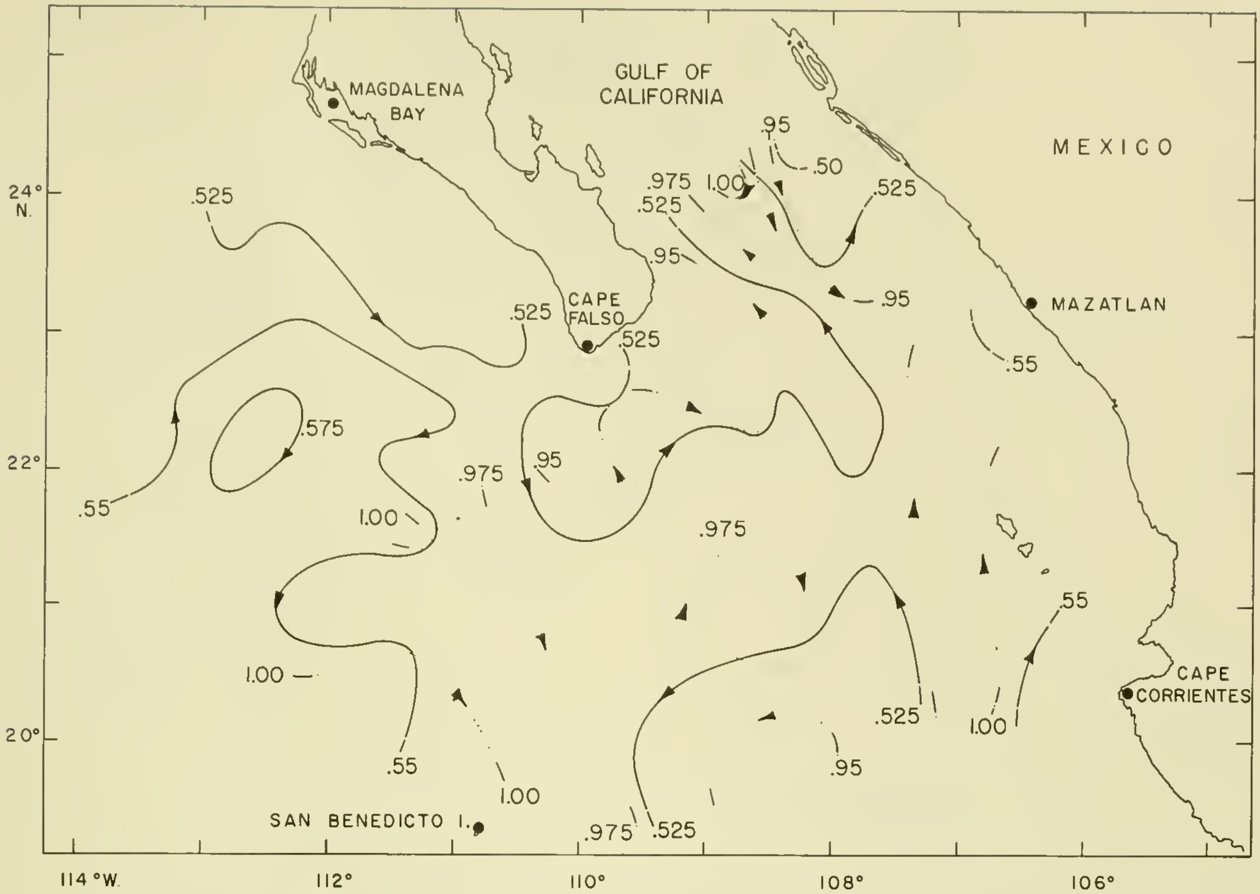

Figure 36.--Horizontal distribution of the dynamic height anomaly at 125 m. over the 500- and 1,000-decibar surfaces, as in figure 35. The contour interval is 0.025 dynamic meter.

is somewhat below 100 percent saturation and probably was upwelled recently. Extending out of the Gulf and turning westward, is a tongue of generally undersaturated water (80 - 100 percent). Agreement seems to be good between this tongue and one of high surface zooplankton volumes, but I do not think the data allow us to assert a causal relationship.

Immediately below the surface, off Lower California, the oxygen distribution shows the upwelling very strongly, especially at Cape Falso. Off Cape Corrientes, too, is a strong gradient to low dissolved oxygen values near the coast, extending northward beyond Mazatlan. The low-oxygen tongue extending from the Gulf becomes a high-oxygen tongue at 20 m.; it was suggested earlier that this change was due to local phytoplankton activity near the thermocline.

At 50 m. (fig. 39), upwelling off Lower California and between Cape Corrientes and Mazatlan is evident. At this depth more than at others, there is some sort of frontal system like the one shown by the temperature and salinity distributions.

At 100 m. most of the southeastern part of the area is occupied by water with an oxygen content of about 0.5 ml./l., from just above the subtropical minimum. At greater depths the oxygen minimum covers the Gulf entrance as well as the area off western Lower California. The strong gradient running roughly

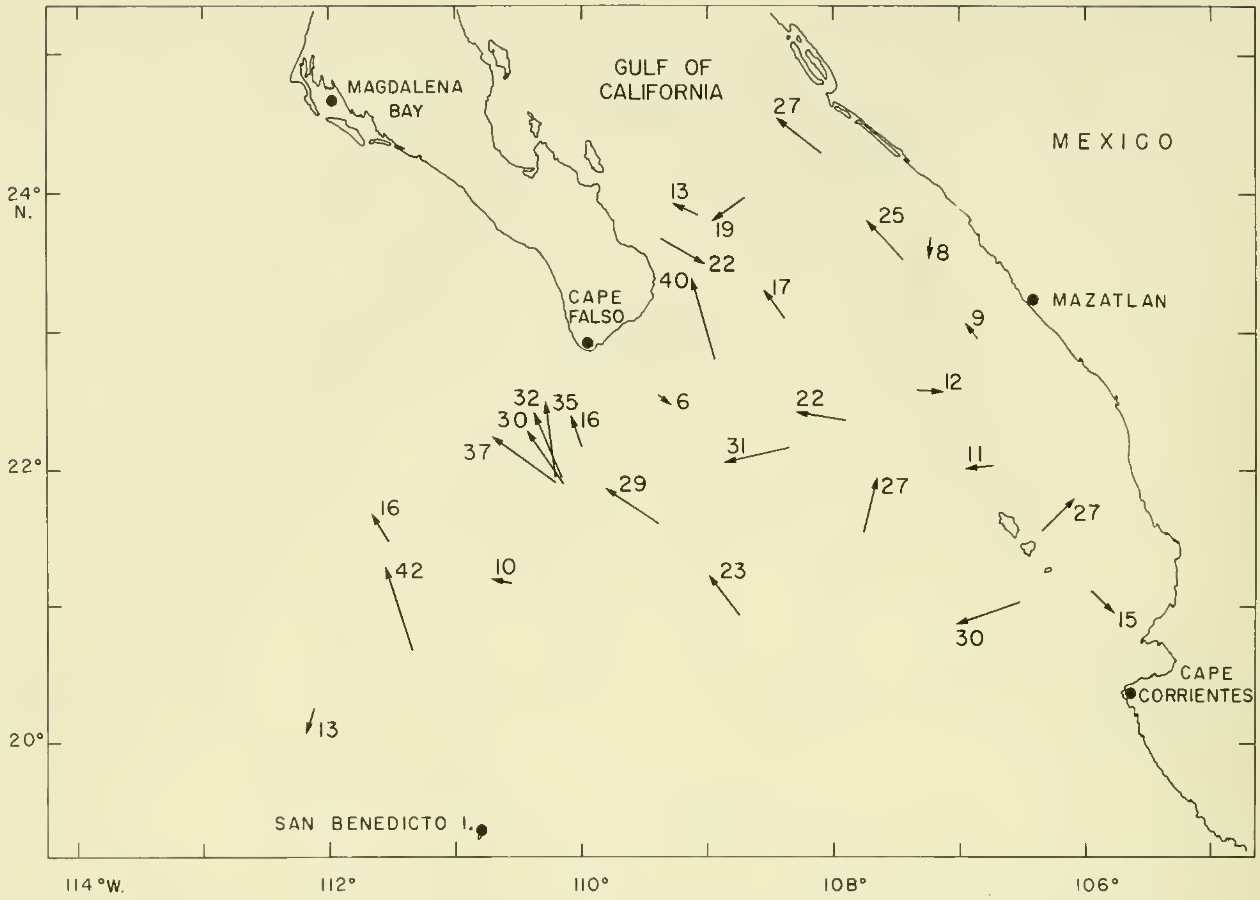

Figure 37.--The surface currents determined by GEK measurements made on cruise TO-60-1. The arrows are vectorial and the figures give velocities in cm./sec.

parallel to the coast off Lower California persists, though it is less strong than it was at 50 m.

Inorganic phosphorus

The distribution of surface inorganic phosphorus, not illustrated here, shows highest concentrations (between 0.70 and 1.00 μg.-at./l.) south of Cape Falso, and west from the mainland coast north and south of Mazatlan, although not west of Cape Corrientes. Lowest concentrations ($<$0.40 μg.-at./l.) are in the extreme western and southwestern parts of the station grid.

Chlorophyll a

The chart of standing crop of chlorophyll a in the 0- to 100-m. water layer, which is not given here, shows some resemblance to the chart of surface inorganic phosphorus. Concentrations over 20 mg./m.^{2} occur to the south of the peninsula of Lower California (highest values, $>$70 mg./m.^{2}, closest to the coast) and west of the mainland coast between Mazatlan and Cape Corrientes (again with the highest values, $>$ 30 mg./m.^{2} in this case, inshore). Data are lacking from north of Mazatlan.

Measurements of primary productivity were too few to permit any definite statements. The highest values (integrations over the upper 40 m.) were in the south (stations 54, 58, and 60) where oxygen saturation was also high. Values were intermediate at stations on the next line north (46 and 42), and lowest at stations still farther north (7, 25, and 31)--although station 20, at the end of a tongue of upwelled water from Lower California, had a high value. Data for chlorophyll a and primary productivity have been listed else-

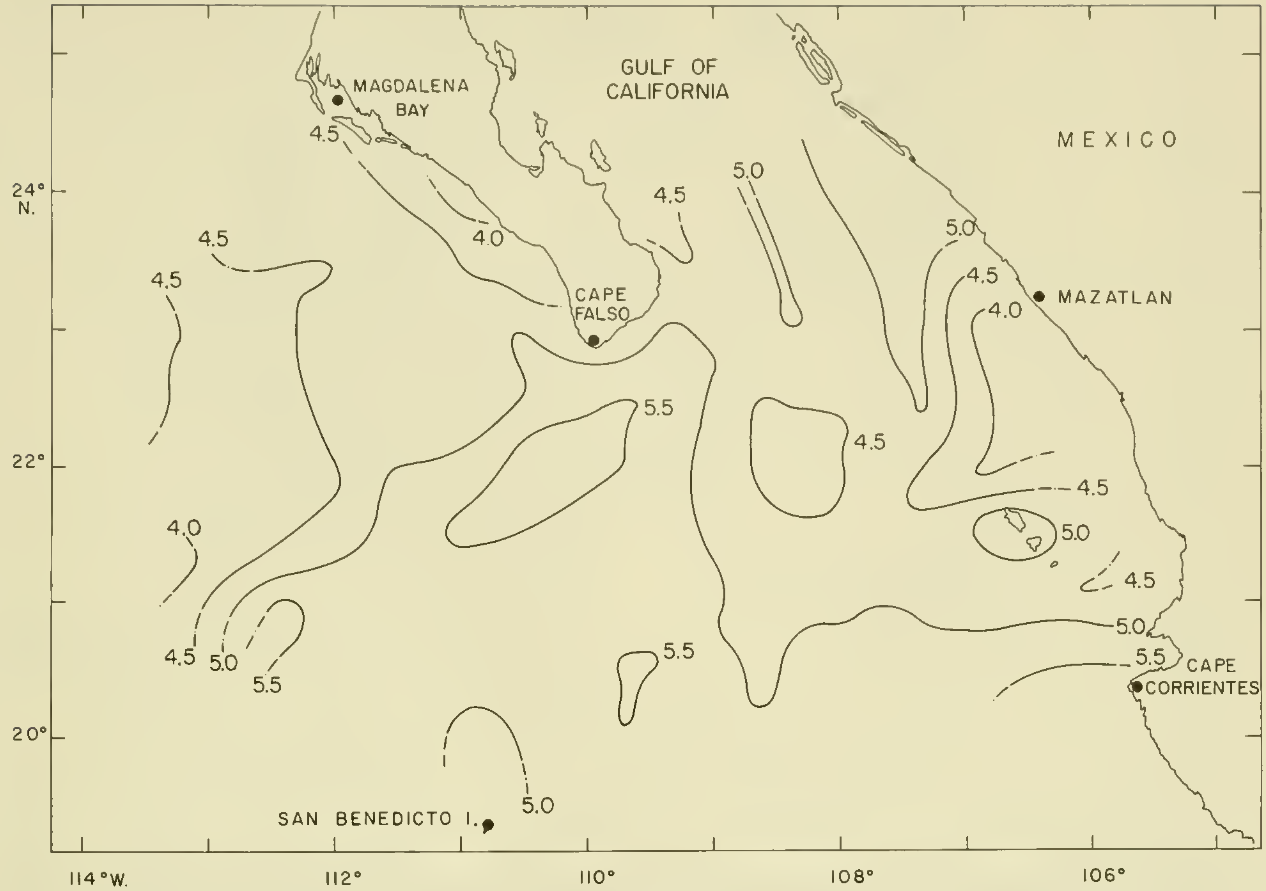

Figure 38.--Horizontal distribution of dissolved oxygen at the sea surface on part of CalCOFI cruise 6004-B and on cruise TO-60-1. The contour interval is 0.5 ml./l., here and in the next figure.

where (Scripps Institution of Oceanography, 1967).

Zooplankton and micronekton

The standing crop of zooplankton was the only biological property which was routinely measured on both cruises TO-60-1 and 6004-B. The same net (described by King and Demond, 1953) was used in oblique hauls at similar hauling speeds on both cruises, and displacement volumes of catches from both cruises were standardized in milliliters per 1,000 m.^{3} of water strained. The data for TO-60-1 (Scripps Institution of Oceanography, 1967) and for 6004-B[4] give such standardized volumes for both total zooplankton and small organisms; the following observations refer to the small organisms, which were less than 5 cm. in greatest dimension or less than 5 ml. in volume.

The depths sampled by the oblique hauls differed on the two cruises; the range was about 0 to 300 m. on TO-60-1 and about 0 to 140 m. on 6004-B. A regression given by Blackburn (1966) was used to estimate standardized volumes in the 0 to 300-m. layer from the standardized volumes measured in the 0 to 140-m. layer on 6004-B, to make the two sets of data as closely comparable as possible; they were then combined to construct figure 40. Contouring was done without regard to time of day, the effect of which is probably small on volumes from the 0-300 m. water layer.

The areas with highest zooplankton volumes broadly correspond to the areas of upwelling or shoal thermocline which were recognized in previous sections--namely south from the parts of the coast near Magdalena Bay and Cape Falso, west from the part of the coast

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[4] Unpublished data. Bureau of Commercial Fisheries, Fishery-Oceanography Center, La Jolla, Cal. 92037.

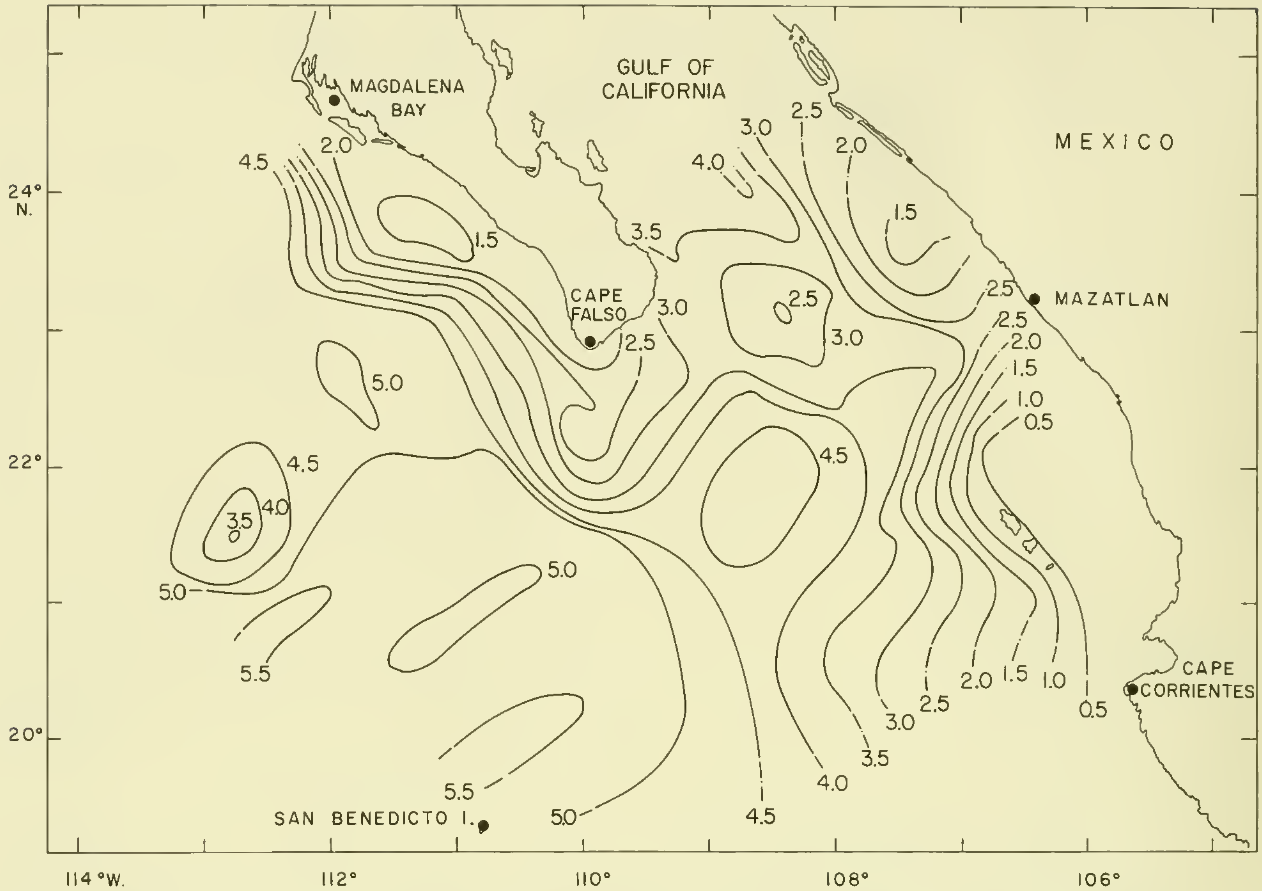

Figure 39.--Horizontal distribution of dissolved oxygen at 50-m. depth on part of CalCOFI cruise 6004-B and on TO-60-1.

north of Mazatlan, and west from Cape Corrientes. The 100 ml./1,000 m.^{3} contour of zooplankton in figure 40 and the 17° C. isotherm at 50 m. in figure 30 correspond rather well. As mentioned above, the area off Cape Falso was moderately rich in both inorganic phosphorus and chlorophyll, and the areas north of Mazatlan and west of Cape Corrientes were fairly rich in one or the other of these properties.

Standardized volumes of zooplankton from night surface hauls (5 m. deep), made on cruise TO-60-1 only, show a different distribution (not illustrated here). Volumes over 300 ml./1,000 m.^{3} occur in two areas--one running southwesterly from an area about halfway between Cape Falso and Mazatlan, and the other west of Cape Corrientes. The latter area agrees and the former area does not agree with the distribution of highest volumes from the oblique hauls (fig. 40).

The micronekton (Blackburn and Associates, 1962) was sampled from the upper 90 m. (approximately) at 14 night stations on cruise TO-60-1 only. The highest concentration (137 ml./1,000 m.^{3}) was at station 59, inshore of Tres Marias Islands, and the next highest (30 ml./1,000 m.^{3}) at station 37, off Mazatlan. Other values ranged from 1 to 13 ml./1,000 m.^{3} Blackburn (1966) discussed the relations between the following standing crops from the same or adjacent stations on cruise TO-60-1 and other cruises in the eastern tropical Pacific: micronekton at 0 to 90 m. (fish and cephalopods combined), zooplankton at 0 to 300 m. (total small organisms and copepods only), and chlorophyll a at 0 to 100 m. Crops of zooplankton and micronekton tended to be higher for the same amount of chlorophyll a on TO-60-1 than on other cruises.

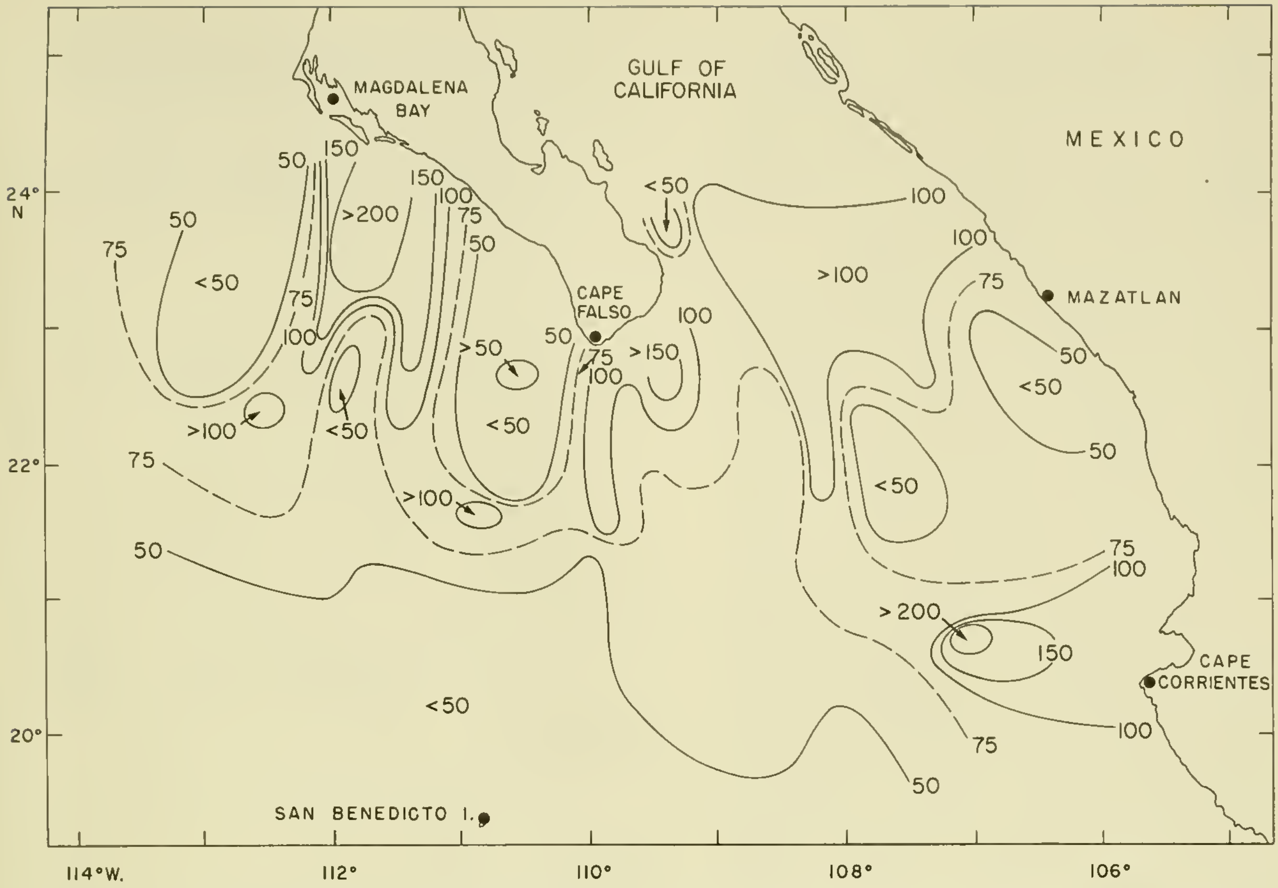

Figure 40.--Horizontal distribution of the standing crop of zooplankton as standardized volume (milliliters per 1,000 m.^{3} of water strained) from oblique hauls to about 300-m. depth. The contour interval between full lines is 50 ml./1,000 m.^{3}; the 75 ml./1,000 m.^{3} contour has been added as a dashed line. For further explanation see text.

DISCUSSION

The data of cruise TO-60-1 show that the Cape San Lucas frontal system is horizontal as well as vertical. The system is usually thought of as a sharp boundary, at or near Cape San Lucas, between California Current Water and Gulf or Subtropical Water. Apparently, the frontal system, in spring, is comparatively vertical only close to Cape San Lucas. Farther away the low-salinity California Current Surface Water spreads extensively, at depths between about 50 and 100 m., well into the high-salinity Gulf and Subtropical Surface Waters. Thus the frontal system becomes horizontal and has an upper and a lower boundary. These boundaries, especially the upper one, are about as strong as the vertical one at the Cape, where horizontal spreading is restricted. At the leading edge of the intrusion of California Current Water the boundary is weakest, mainly because mixing is occurring along roughly horizontal density surfaces. Although the horizontal density gradient is greatest at the Cape, the actual density difference at a given depth between the warm, saline water and the cool, low-salinity water is not particularly great.

The facts revealed by cruise TO-60-1 show, nevertheless, that rapid mixing between California Current and Gulf Water is impeded. Presumably the geography of the area helps to account for this impediment. The Lower California peninsula separates the flow of California Current Water and the outflow from the Gulf. The transport off the western coast of the peninsula is much greater than that from the Gulf, and for most of the year the prevailing winds favor the southward flow of the California Current, whereas the transport from the Gulf is more passive. The smallness of the Gulf outflow explains why the frontal system weakens rapidly out to sea from Cape San Lucas.

If the system is chiefly maintained by relative transports of California Current, Gulf of California, and Subtropical Surface Waters, its most probable position could be determined perhaps by simply studying these water masses throughout the year, after taking into account the geography of the Gulf entrance.

A review of the CalCOFI data indicates that observations of the Cape San Lucas front, as a particular object of study, are scant (Griffiths, 1965). These data do indicate, however, that the frontal system might be found at almost any time of the year, though it is best developed in spring and summer. It might also be found far from the Cape; sometimes inside the Gulf, though rarely far inside; and sometimes as far north as Magdalena Bay, particularly late in the year when warm, salty water is known to move northward inshore (Reid, Roden, and Wyllie, 1958). It might sometimes be absent. The CalCOFI and our data show that this area is likely to be oceanographically complicated at any time. It would therefore be desirable to continue the study of this area to elucidate seasonal changes. Apart from seasonal changes, the various features of the oceanography of this area should be studied in more detail. In particular it would be helpful to determine whether each kind of water contributing to the area has a distinctive biological regime associated with it, so that changes in these regimes might be related to oceanographic events.

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