THE ROLE OF INTERNAL TIDES IN THE NUTRIENT ENRICHMENT OF MONTEREY CANYON

A Thesis Presented to the Graduate Faculty

of

California State University, Hayward

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Biological Sciences

By

Russell E. Shea

July 1980

ABSTRACT

Semi-diurnal internal tides in Monterey Canyon are shown to be partially responsible for macronutrient enrichment of surface waters in Monterey Bay. CTD time series at five stations in Monterey Canyon revealed the presence of semi-diurnal internal tides with heights between 50 m and 120 m. Spectrum analysis of thermistor data at the head of Monterey Canyon showed the dominant period of the temperature fluctuations to be twelve hours. Cross-spectrum analysis showed a seven-hour lag between predicted surface tide and observed bottom temperature. Thermistor data also demonstrated the presence of an internal tidal bore at the head of Monterey Canyon. Data and theory suggest that internal tidal bores may be breaking, either due to shear instability or direct overturning, thereby enriching the immediate area near the canyon head.

From distributions of temperature at both high and low predicted internal tides along a transect normal to, and north of, Monterey Canyon, a lens of 12 °C water 20 m thick was observed moving out of the canyon at high internal tide. This lens was then pinched off from the canyon water as the 12 °C isotherm descended below the canyon rim at low internal tide.

Distribution of dissolved reactive phosphate sampled along the same transect showed an increase in concentrations at 20 m and 30 m (bottom) at all stations, from low to high internal tide. Calculations of potential primary productivity enhancement from volume continuity and phosphate distribution indicate that a net tidal divergence of 50%, which was the estimated volume of the 12 °C lens, could account for as much as 31% of

the daily primary productivity in the northern part of Monterey Bay during non-upwelling periods.

This mechanism may be responsible for the nutrient enrichment of waters near similar submarine canyons around the world.

TABLE OF CONTENTS

ACNKOWLEDGEMENTS

This thesis would not have been possible without the help and support of many people. I would first like to thank Dr. William Broenkow, my research advisor, for his guidance and assistance in completing this research. It truly would not have been possible without his help. Sincere thanks go to Chris Pelletier, Jeff Nolten, Bob Petty, Jerry Kashiwada, Mark Carr and Mike Reilly for the long hours put in on a rolling deck doing CTD casts and filtering water. Also, a special thanks to Rosie Stelow for her patience and professionalism in typing this thesis. Finally, I would like to thank my wife, Beverly Stiles Shea, for her patience and encouragement throughout this study, and my parents for a lifetime of love and support.

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

This paper discusses the role of macronutrient enrichment by internal tides in Monterey Canyon, California. Wind-induced upwelling south of Monterey Bay probably has a greater overall effect on the productivity of the area during the spring and summer, but during non-upwelling periods, enrichment due to internal tides may play a significant role in the primary production of the bay.

Monterey Canyon is one of the world's largest submarine canyons, with dimensions comparable to those of the Grand Canyon of the Colorado River, (Shepard and Dill, 1966). Aligned southwest by northeast, it is centrally located in Monterey Bay with its head near Moss Landing, California (Figures 1 and 2). The canyon head is approximately 0.2 km wide and lies about 0.3 km from the mouth of Elkhorn Slough, while at the seaward edge of the bay, it is about 12 km wide and 1000 m deep. It is believed that this canyon strongly influences the circulation of waters in Monterey Bay (Broenkow and Smethie, 1978).

Wind-induced upwelling is a seasonal phenomenon which normally occurs along the central California coast from February to September. During that time, low temperatures, high salinities, and high nutrient concentrations characterize nearshore waters. This upwelling period is dominated by strong northwesterly winds (Reid, et al., 1958; Reid and Schwartzlose, 1962; Wickham, 1975). Satellite photographs show an upwelling locus 10 to 20 km south of Monterey Bay. Broenkow and Smethie (1978) have observed recently-upwelled tongues of water penetrating northward into the bay from this locus, and have found strong correlation between peaks in local northerly winds and upwelling episodes. They

FIGURE 1. Monterey Bay, California.

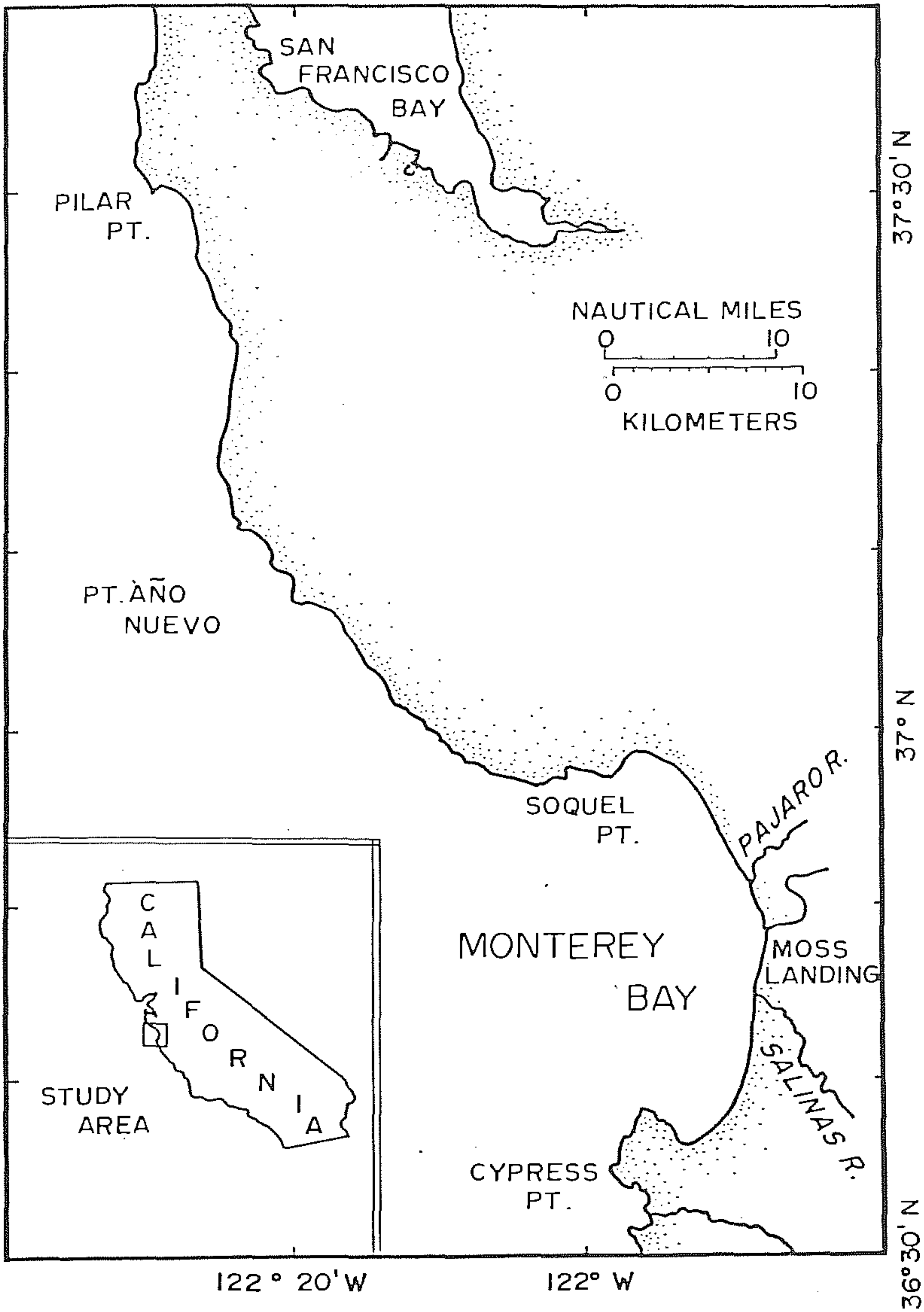
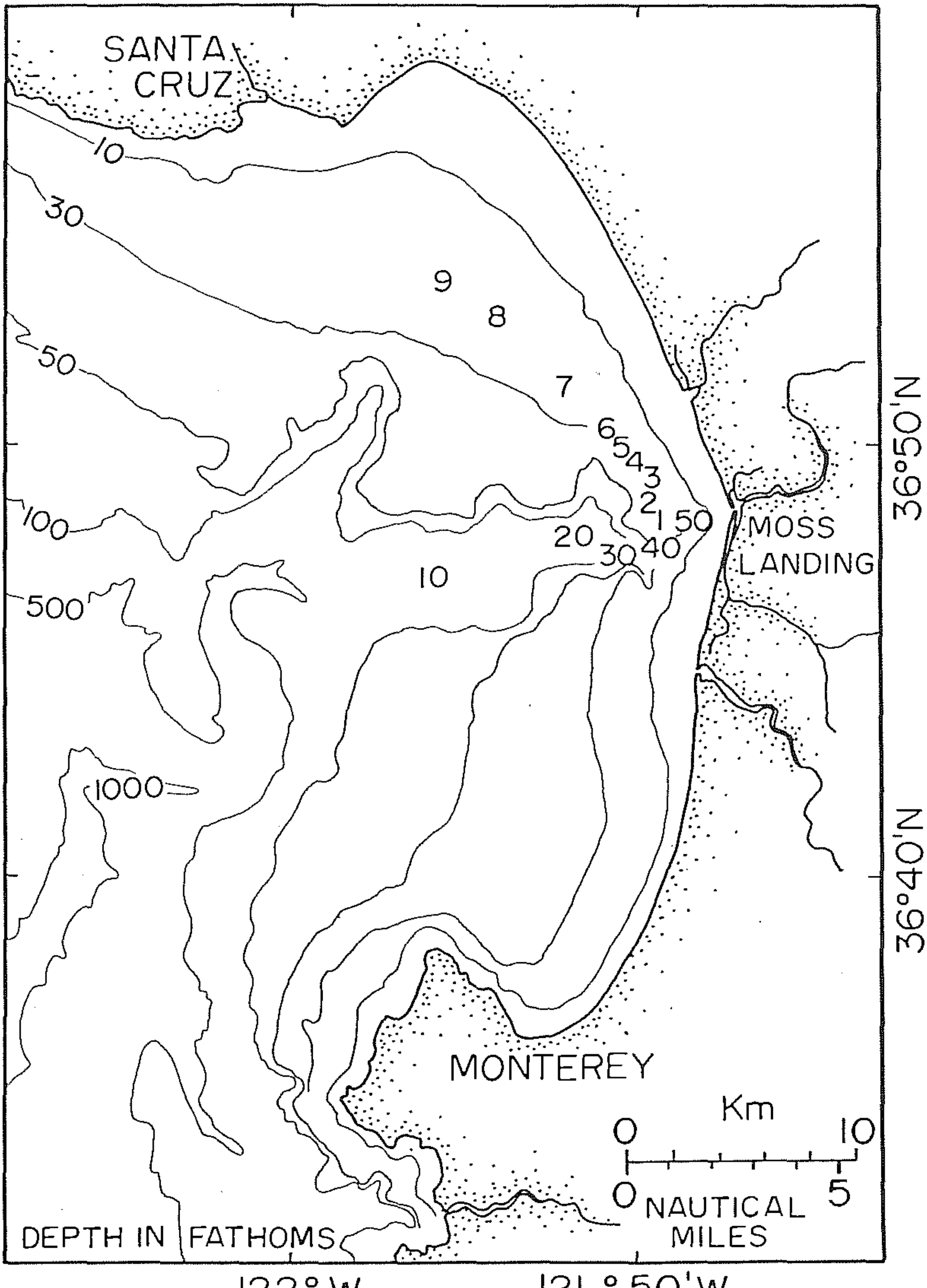

SAN FRANCISCO BAY
PILAR PT.
37°30' N
NAUTICAL MILES
0 10
0 10
KILOMETERS
PT. AÑO NUEVO
37° N
SOQUEL PT.
PAJARO R.
MONTEREY BAY
MOSS LANDING
SALINAS R.
CALIFORNIA
STUDY AREA
CYPRESS PT.
36°30' N
122° 20' W
122° W

FIGURE 2. Monterey Bay station locations, August 1971 through November 1979.



SANTA CRUZ
10
30
50
100
500
1000
9
8
7
6
5
4
3
2
1
50
20
30
40
10
MOSS LANDING
36°50'N
36°40'N
MONTEREY
Km
0
10
0
5
NAUTICAL MILES
DEPTH IN FATHOMS
122° W
121 ° 50'W

believe that upwelling probably does not occur within Monterey Bay itself, because winds in the central part of the bay are predominantly onshore.

During non-upwelling months, water which was cooler and higher in macronutrients, such as nitrate and phosphate, was observed over Monterey Canyon, particularly near the head (Broenkow and Smethie, 1978). They discounted several mechanisms for these observations in favor of internal tidal mixing.

The idea of internal tidal mixing as an enriching mechanism is not new. Cooper (1947) postulated that internal waves in the English Channel impinging at right angles to the continental slope would run up the slope much as a surface wave runs up a shelving beach. As this cold, nutrient-rich, mid-water moved closer to the surface, vertical mixing due to wind waves and surface cooling (during the winter) would act to incorporate the mid-water into the surface layer, thereby enriching it. Cooper also suggested that submarine valleys or canyons might concentrate the energy of the internal waves into contracting cross-sections and greatly amplify the power of these internal waves to project deeper water into the surface layers.

The objectives of this study were to: (1) further characterize semi-diurnal internal tides in Monterey Canyon, since the only published evidence of internal tides in Monterey Bay was from one 25-hour time series (Broenkow and McKain, 1972); (2) demonstrate that these internal tides are capable of transporting cold, nutrient-rich waters to the surface; and (3) estimate the amount of enrichment due to internal tides in terms of the daily photosynthetic fixation rate.

METHODS

Data from Broenkow and McKain (1972) were redrawn in order to examine temperature distribution in relation to their internal tide observations. They obtained a 25-hour time series of temperature at stations 30 and 50, on 7 and 8 August 1971, by hydrocasts using 5-liter Niskin bottles (see Broenkow and McKain [1972] for details). CTD profiles were obtained at station 10 approximately every two hours for twenty hours, on 6 and 7 May 1976 (Figure 2). The same method was used again at stations 20 and 40 on 13 and 14 November 1978. These stations were sampled about every hour and a half over a 13-hour period. From 5 through 13 October 1979, a continuous record of bottom temperature was made from a thermistor placed at 25 m at the head of Monterey Canyon (Figure 3).

CTD profiles were also used to trace the hypothesized lateral movement of water out and over its flanks. This CTD section north of, and perpendicular to, the canyon axis along the 20-fathom contour line was made at both high and low predicted internal tide on 13 and 14 September 1979 (Table 1, Figure 2). High and low internal tides were predicted from the previous day's CTD time series results in the canyon.

CTO measurements were made with a Plessey 9040-9400 CTD system. Data acquisition was under the control of a Hewlett-Packard 9825A calculator and data were stored on magnetic tape cassettes (Broenkow, et al., 1977). All data were interpolated to 1 m intervals.

In order to investigate whether this mechanism enriches the area around the head of the Monterey Canyon, vertical profiles of dissolved reactive phosphate (PO_4^{3-}) were examined. On 8 and 9 November 1979, the

FIGURE 3. Thermistor location at Monterey Canyon head: 6 through 13 October 1979. Depth contours in meters.

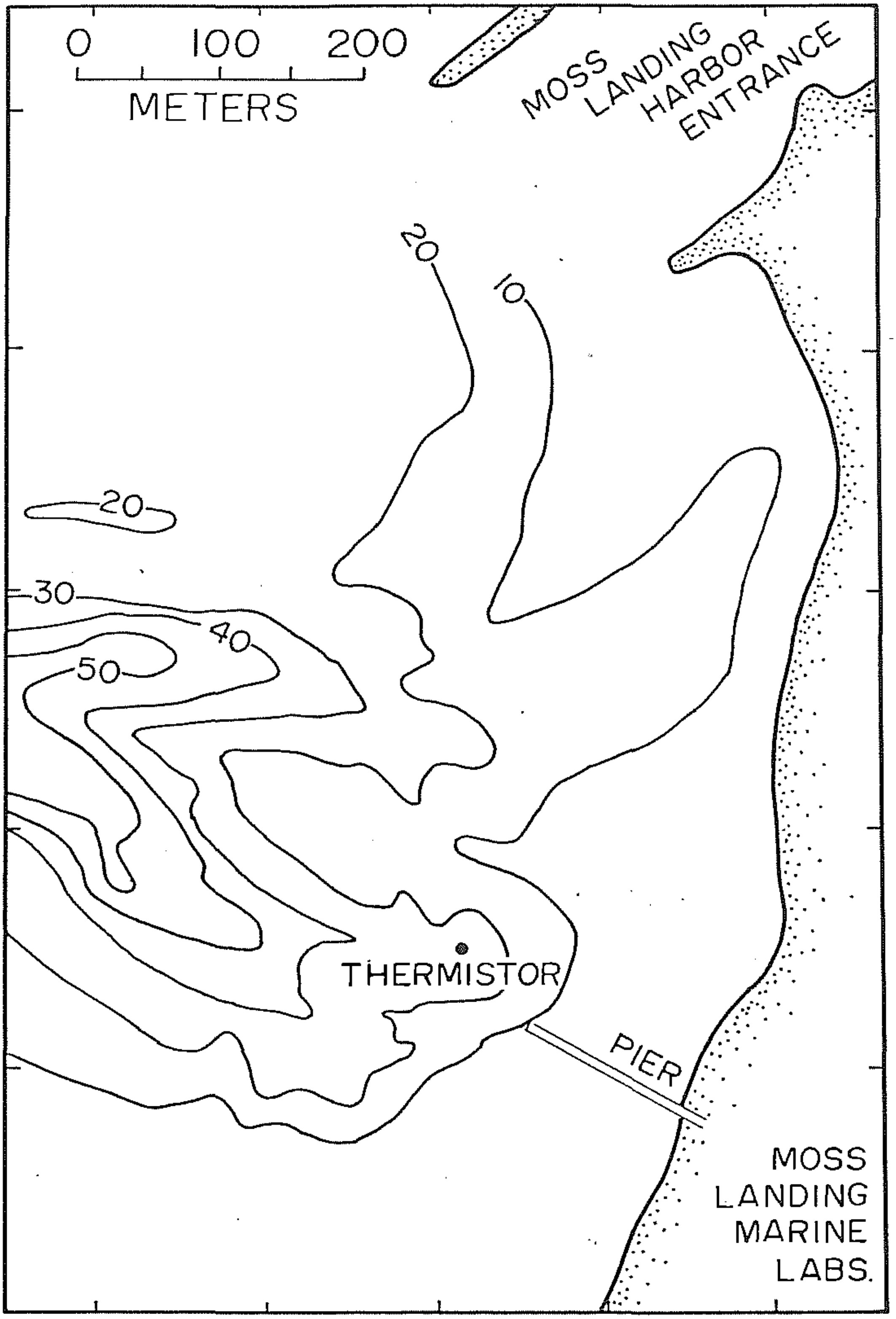

0
100
200
METERS
MOSS LANDING HARBOR ENTRANCE
20
10
20
30
40
50
THERMISTOR
PIER
MOSS
LANDING
MARINE
LABS.

TABLE 1. Cruise dates, objectives and station locations in Monterey Bay.

Cruise Dates	Objectives	Stations
7- 8 Aug. 1971*	25-hour hydrocast time series	30, 50
6- 7 May 1976	20-hour CTD time series	10
13-14 Nov. 1978	13-hour CTD time series	20, 40
13-14 Sep. 1979	High and low internal tide CTD transects;	2, 6, 7, 8, 9, 30
	CTD time series	30, 50
5-13 Oct. 1979	Thermistor record	Canyon head
8- 9 Nov. 1979	High and low internal tide PO_4^{3-} transects;	1, 3, 6, 7, 9, 30
	CTD time series	30, 50

Station Positions

Station	N Latitude	W Longitude	Depth (m)
1	36° 48.2'	121° 49.2'	42
2	36° 48.7'	121° 49.4'	36
3	36° 49.2'	121° 49.4'	36
4	36° 49.7'	121° 49.7'	36
5	36° 50.0'	121° 50.2'	36
6	36° 50.3'	121° 50.7'	36
7	36° 51.8'	121° 52.5'	36
8	36° 53.3'	121° 54.1'	29
9	36° 54.4'	121° 56.5'	27
10	36° 47.0'	121° 56.1'	637
20	36° 47.8'	121° 51.7'	364
30	36° 47.4'	121° 50.0'	255
40	36° 47.8'	121° 49.2'	186
50	36° 48.1'	121° 48.2'	109

*Data from Broenkow and McKain, 1972.

vertical distribution of dissolved reactive phosphate was examined on a transect normal to, and north of, the canyon's axis following the 20-fathom contour line at times of both high and low predicted internal tide (Table 1).

Dissolved reactive phosphate was determined by the method of Murphy and Riley (1962) described in Strickland and Parsons (1972). This method uses ascorbic acid to reduce the phospho-molybdate complex. Precision of this analysis is about ± 0.03 µg-at/liter (2 SD). Aboard ship, samples were filtered through GF/F 0.7 um glass fiber filters and refrigerated. Upon return to shore, the samples were frozen and then analyzed within four weeks. Discrete water samples for phosphate determination were taken with 5-liter plastic Niskin sampling bottles.

RESULTS

Long period internal waves were detected at stations 50 and 30 on 7 and 8 August 1971 (Figures 4a and b). During the 25-hour time series, the 9 °C isotherm moved vertically by at least 53 m at station 50 and 68 m at station 30. The vertical displacement of the 10 °C isotherm was 74 m and 66 m, and the 11 °C isotherm did not exhibit such large oscillations, moving only 12 m and 9 m. At these two stations, the largest vertical displacement was 120 m by the 9.5 °C isotherm at station 30.

On 6 and 7 May 1976, a CTD time series at station 10 showed long period internal waves as demonstrated by the vertical movement of the 8.5 °C isotherm (Figure 5). This surface oscillated vertically by 49 m in 8.5 hours. It is important to note in Figure 5 that the main thermocline (between 9 °C and 11 °C) did not oscillate more than 15 m and the mixed layer depth was only 3 to 5 m.

At stations 40 and 20 on 13 and 14 November 1978, CTD profiles showed long period internal waves similar to those observed previously. During this 13-hour time series, the 9 °C isotherm moved vertically by at least 94 m at station 40 and 49 m at station 20; the 10 °C isotherm by at least 106 m and 62 m, respectively; and the 11 °C isotherm by 118 m at 75 m (Figures 6a and b). Note that waves of greater height were found at station 40, where the width and depth of the canyon are much less than at station 20 (Figure 2, Table 1). The largest long period waves in this last study were associated with the relatively deep thermocline, whereas previously, the largest internal tides were below the near-surface thermocline.

FIGURE 4a. Distribution of temperature (°C), station 50, 1 km west of Monterey Canyon head, 7 and 8 August 1971.

4b. Distribution of temperature (°C), station 30, 4 km west of Monterey Canyon head, 7 and 8 August 1971.

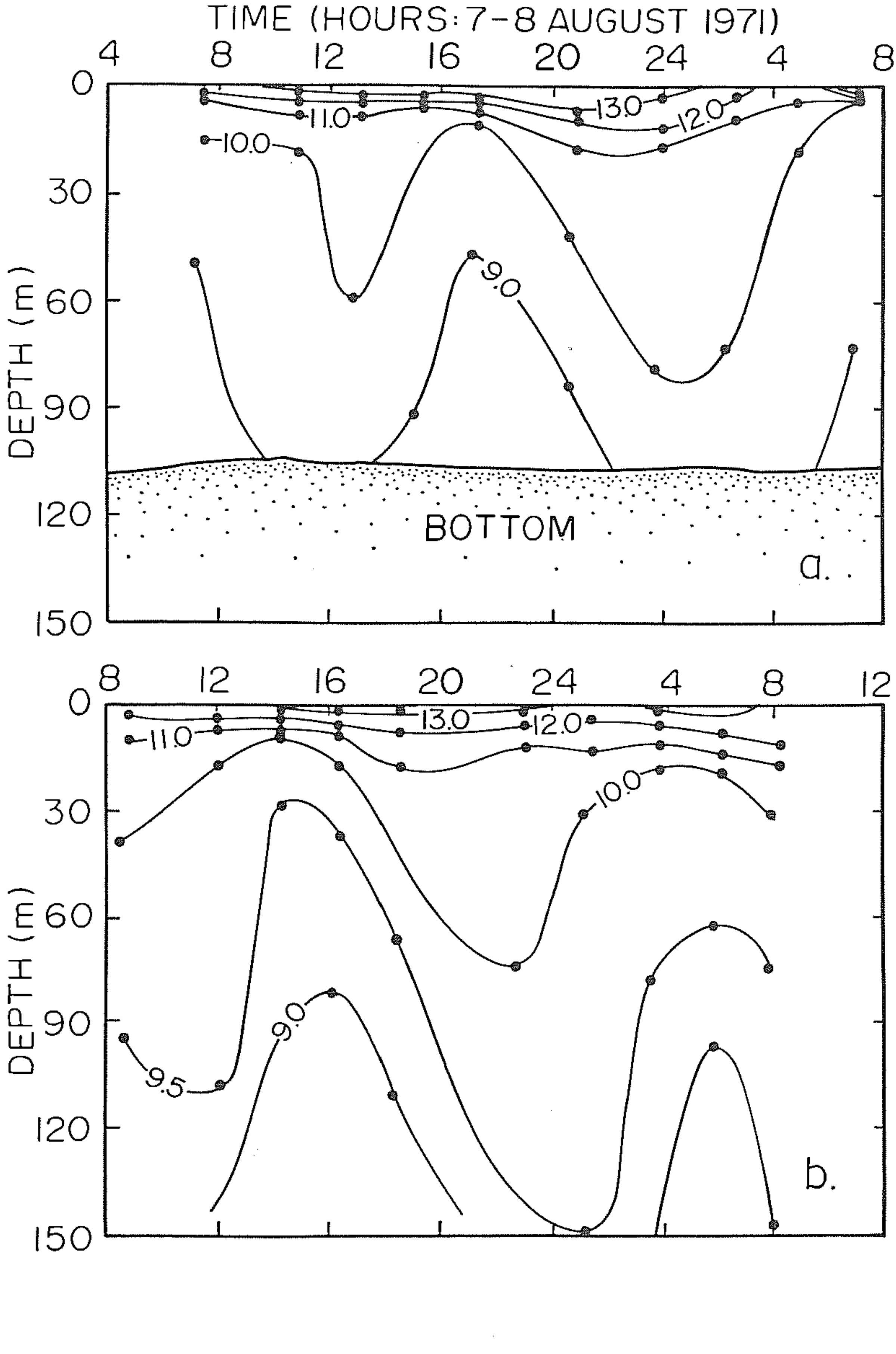

TIME (HOURS: 7-8 AUGUST 1971)
4
8
12
16
20
24
4
8
0
30
60
90
120
150
DEPTH (m)
13.0
12.0
11.0
10.0
9.0
BOTTOM
a.
8
12
16
20
24
4
8
12
0
30
60
90
120
150
DEPTH (m)
13.0
12.0
11.0
10.0
9.0
9.5
b.

FIGURE 5. Distribution of temperature (°C), station 10, 13 km west of Monterey Canyon head, 6 and 7 May 1976.

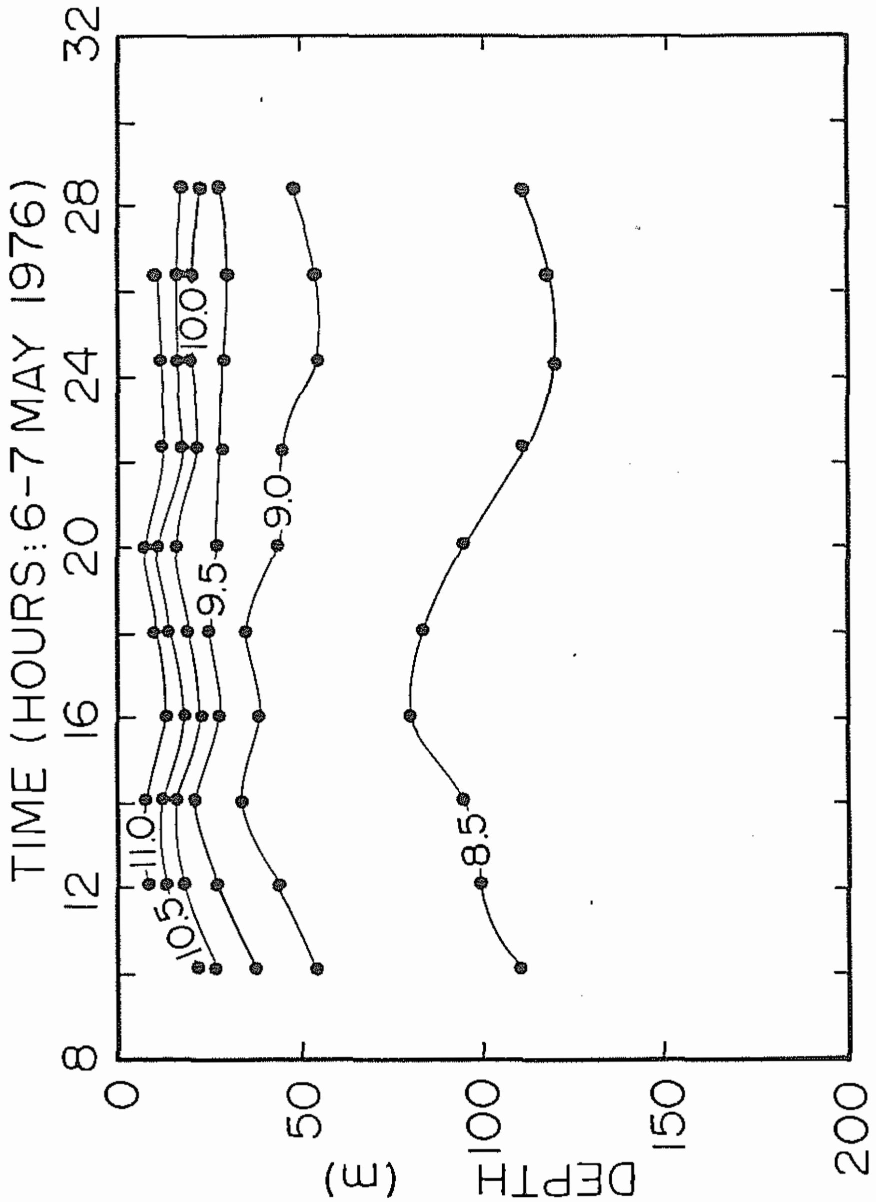
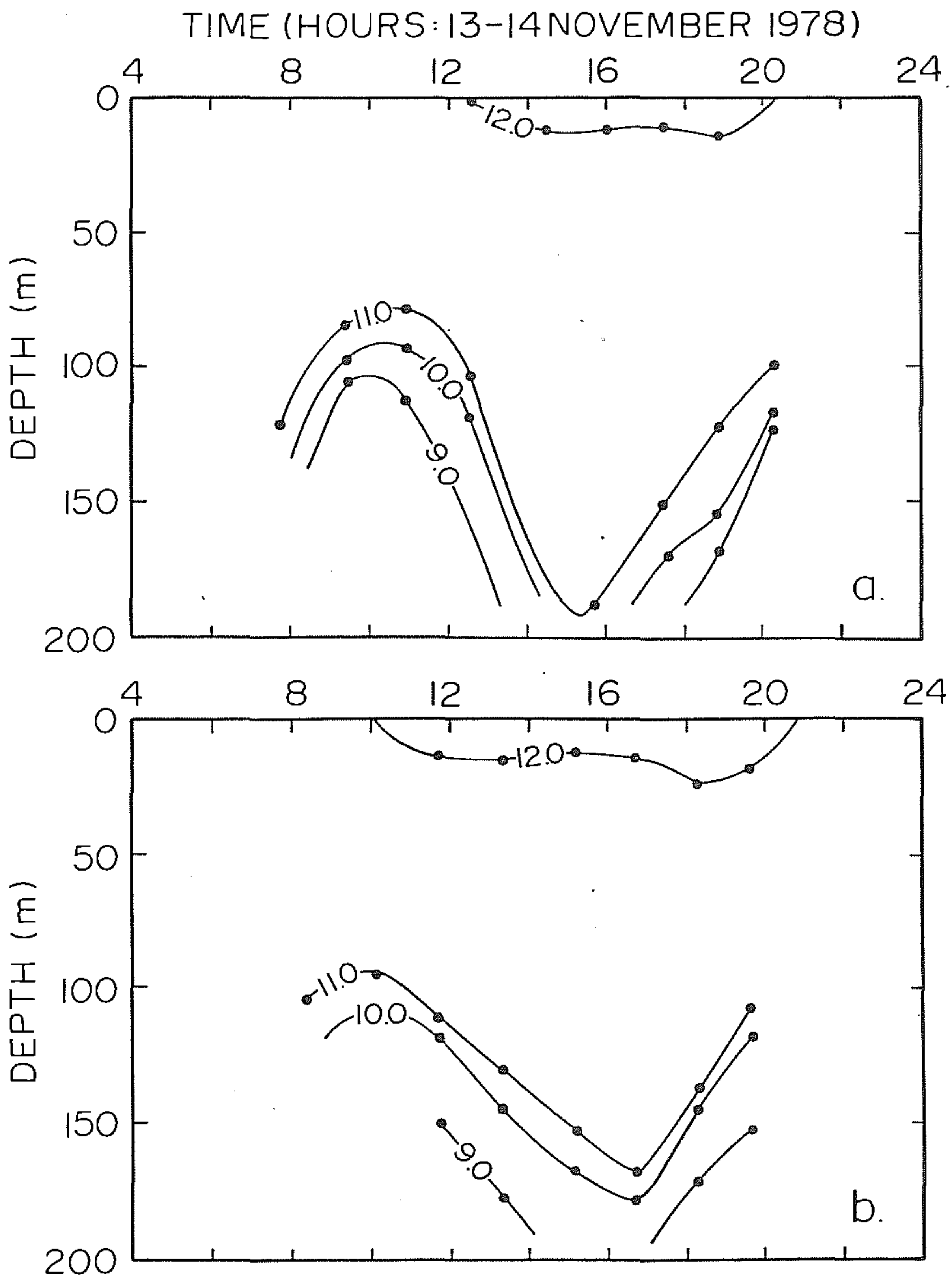

TIME (HOURS: 6-7 MAY 1976)
8
12
16
20
24
28
32
DEPTH (m)
0
50
100
150
200
11.0
10.5
10.0
9.5
9.0
8.5

FIGURE 6a. Distribution of temperature (°C), station 40, 3 km west of Monterey Canyon head, 13 and 14 November 1978.

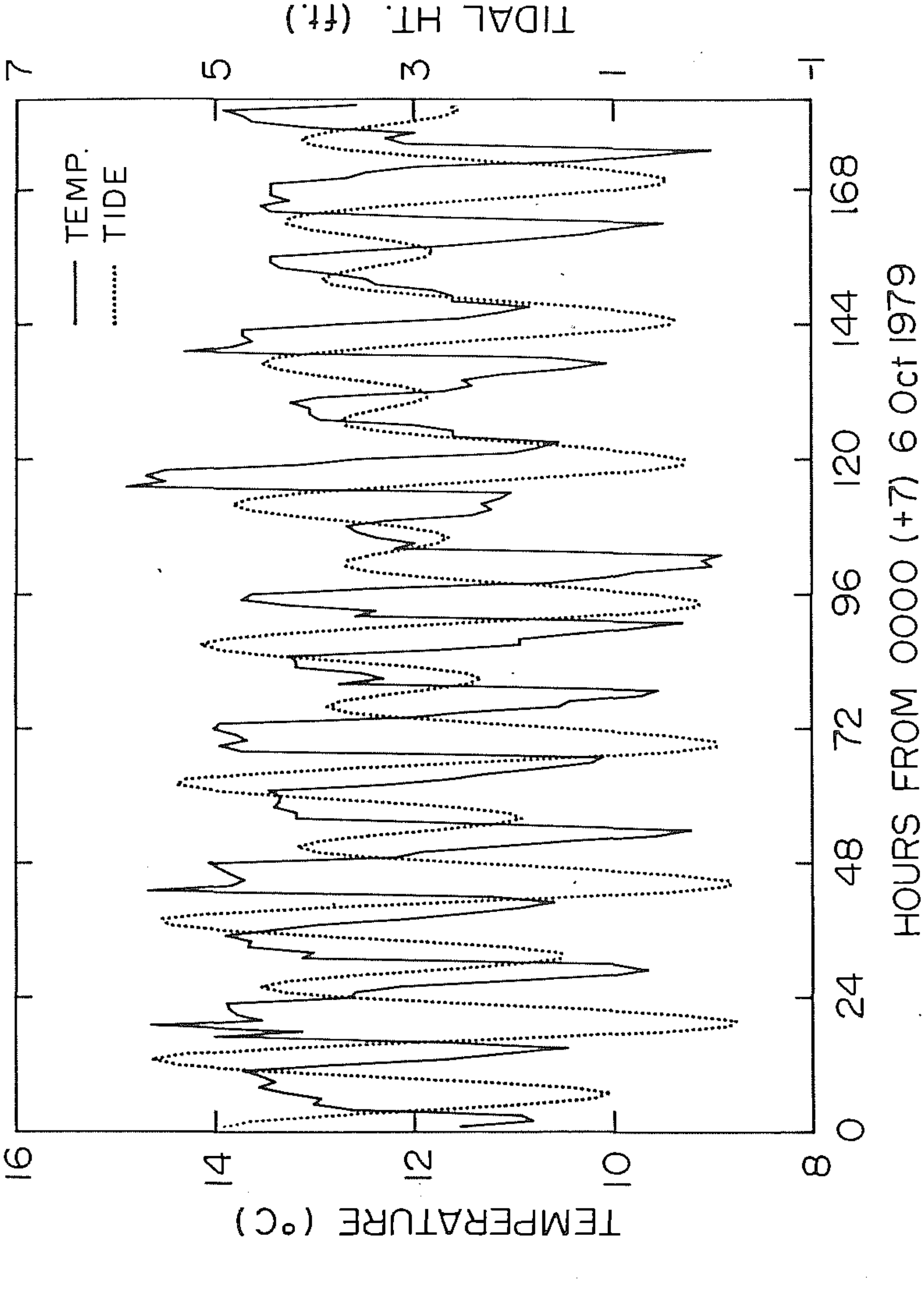
6b. Distribution of temperature (°C), station 20, 6.1 km west of Monterey Canyon head, 13 and 14 November 1978.


TIME (HOURS: 13-14 NOVEMBER 1978)
4
8
12
16
20
24
0
50
100
150
200
DEPTH (m)
12.0
11.0
10.0
9.0
a.
4
8
12
16
20
24
0
50
100
150
200
DEPTH (m)
12.0
11.0
10.0
9.0
b.

From 5 through 13 October 1979, the thermistor record of bottom temperature at the head of Monterey Canyon resolved some of the higher frequency details associated with the predominantly semi-diurnal internal tides (Figure 7). Spectrum analysis of these temperature data and predicted surface tidal heights showed the dominant period to be twelve hours. Cross-spectrum analysis between bottom temperature and predicted surface tidal heights indicated that the 12- and 24-hour periods were most coherent, with the 12-hour period more so. Phase relationships from cross-spectrum analysis showed a phase lag of 208° (or seven hours) at the 12-hour period and 118° (or eight hours) at the 24-hour period. The maximum rate of temperature change was 3.8 °C increase in one hour. Maximum temperature change during one-half a tidal cycle was 5.4 °C.

On 13 and 14 September 1979, distribution of temperature was examined at both high and low predicted internal tide along a transect normal to, and north of, the Monterey Canyon axis (Figures 8a and b). During high internal tide, the thermocline at station 30 (in the canyon axis) was closer to the surface and more compressed relative to the situation found at low tide. During the time of high internal tide, the 11 °C isotherm at station 30 was observed at 33 m and extended north to station 2 just past the canyon rim. At the time of low internal tide, the 11 °C isotherm was observed at 73 m at station 30, but no 11 °C water was observed at any other station. The 12 °C isotherm was observed at 27 m during high internal tide at station 30 and extended northward 7.8 km to station 7. During the period of low internal tide, this water type was observed at 62 m at station 30, but was not seen at stations 2

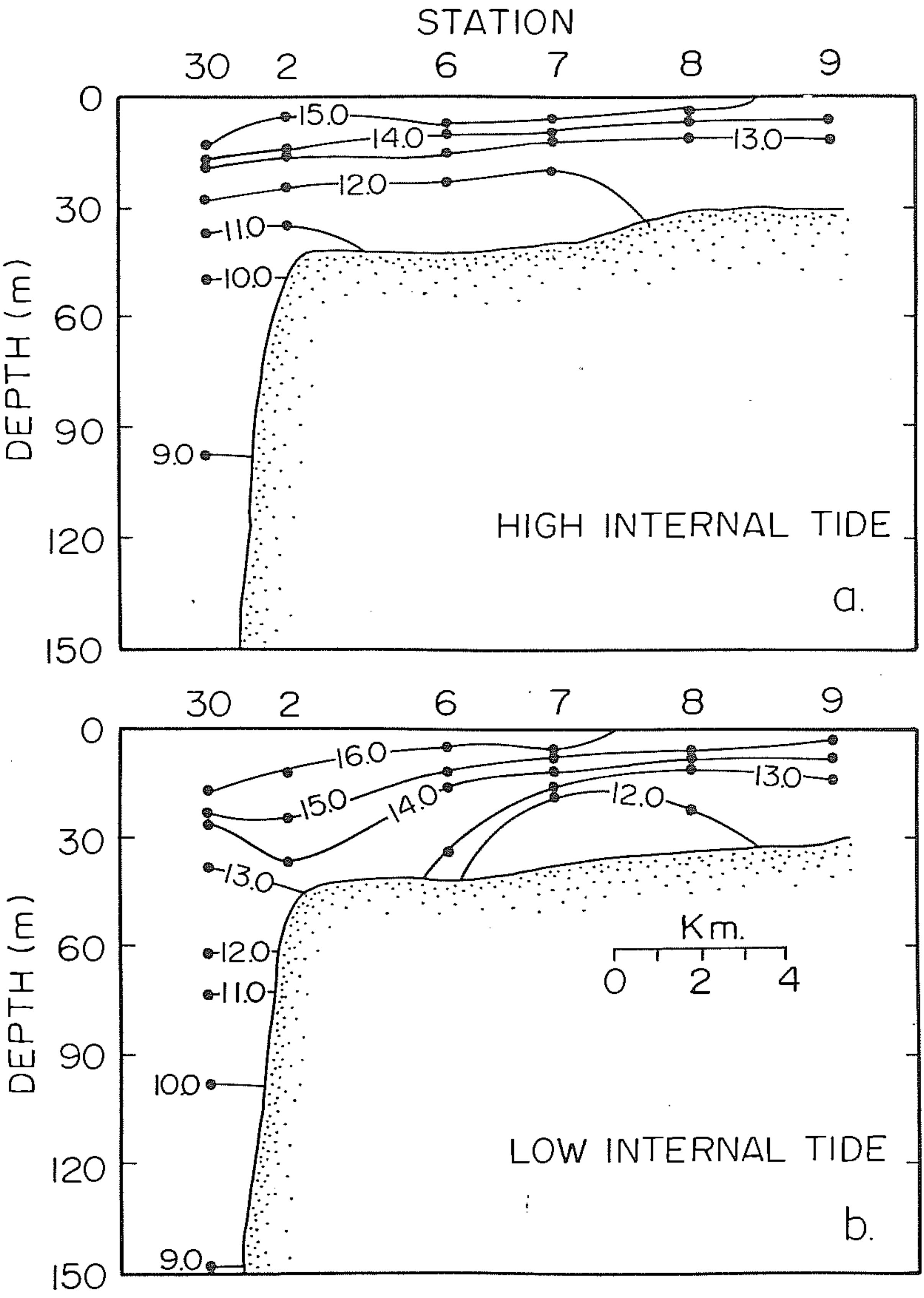
FIGURE 7. Bottom temperature and predicted surface tidal height at Monterey Canyon head, 6 through 13 October 1979. Digitizing interval was 60 minutes.



TEMP.
TIDE
HOURS FROM 0000 (+7) 6 Oct 1979
0
24
48
72
96
120
144
168
TEMPERATURE (°C)
8
10
12
14
16
TIDAL HT. (ft.)
-1
1
3
5
7

FIGURE 8a. Distribution of temperature (°C) at predicted high internal tide along a transect normal to, and north of, the Monterey Canyon axis, 13 and 14 September 1979.

8b. Distribution of temperature (°C) at predicted low internal tide along a transect normal to, and north of, the Monterey Canyon axis, 13 and 14 September 1979.


STATION
30
2
6
7
8
9
0
30
60
90
120
150
DEPTH (m)
15.0
14.0
13.0
12.0
11.0
10.0
9.0
HIGH INTERNAL TIDE
a.
30
2
6
7
8
9
0
30
60
90
120
150
DEPTH (m)
16.0
15.0
14.0
13.0
12.0
13.0
12.0
11.0
10.0
9.0
Km.
0
2
4
LOW INTERNAL TIDE
b.

or 6. This 12 °C water was, however, detected again at stations 7 and 8. At the time of high internal tide, the 13 °C isotherm was observed at 19 m at station 30, extending north to station 9, 14 km away from the canyon axis. During low internal tide, this water type was found at 37 m at station 30. It was not observed at station 2, but appeared again at station 6 and extended to station 9.

Change in bottom temperature at the same station, from high to low internal tide on 13 and 14 September 1979, at the stations mentioned above, was particularly interesting. The largest change in bottom temperature occurred at station 2, where the temperature increased 3.5 °C (Table 2). At station 6, 5.4 km from the canyon axis, the next largest temperature change (1.6 °C) was observed. At station 7, 7.8 km from the canyon axis, a change of 0.03 °C represented the smallest observed change.

On 8 and 9 November 1979, distribution of dissolved reactive phosphate (PO_4^{3-}) was examined at predicted high and low internal tide along a transect normal to, and north of, the Monterey Canyon axis. At station 30 at all depths, phosphate concentrations were observed to be higher during the period of high internal tide (Table 3). Phosphate concentrations were consistently higher at 30 m from stations 30 to 6 during the period of high internal tide, but not at stations 7 and 9. Mean PO_4^{3-} concentration between 5 m and 30 m showed consistently higher values during high internal tide at stations 30 through 6. At station 6, it is important to note the values of mean phosphate concentration: at low internal tide, it was lowest of all stations (0.59 µg-at/liter) and at high internal tide, it was the highest of all stations (0.99 ug-at/liter).

TABLE 2. Surface and near bottom temperature and associated change from high to low predicted internal tide along a transect normal to, and north of, the Monterey Canyon axis, 13 and 14 September 1979.

Station	Distance From Canyon Area (km)	High Tide	ΔT	Low Tide
		------Surface Temperature (°C)-------		
30	axis	15.86	0.93	16.79
2	1.7	15.72	1.03	16.75
6	5.4	15.68	0.69	16.37
7	7.8	15.51	0.87	16.38
8	10.9	15.19	0.65	15.84
9	14.1	14.49	1.03	15.52
		-------Bottom Temperature (°C)-------		
30	axis	8.49	0.52	9.01
2	1.7	10.08	3.54	13.62
6	5.4	11.13	1.60	12.73
7	7.8	11.00	0.03	11.03
8	10.9	12.16	-0.68	11.48
9	14.1	11.81	0.96	12.14

TABLE 3. Distribution of PO_4^{3-} (µg-at/liter) along a transect normal to, and north of, the Monterey Canyon axis at high and low predicted internal tide, 8 and 9 November 1979. Mean PO_4^{3-} concentration calculated between 5 and 30 m.

Low Internal Tide

	Station					
Z (m)	30	1	3	6	7	9
5	0.39	0.35	0.79	0.81	0.82	0.71
20	0.60	0.77	1.00	0.40	0.95	0.58
30	0.89	1.02	0.86	0.73	1.20	1.36
50	0.69					
100	1.43					
150	1.53					
Mean PO_4^{3-}	0.59	0.69	0.91	0.59	0.96	0.78

High Internal Tide

5	0.50	0.62	0.41	0.71	0.62	0.25
20	1.07	0.85	1.09	1.06	1.01	0.76
30	1.25	1.24	1.27	1.24	0.66	1.17
50	1.20					
100	1.57					
150	1.88					
Mean PO_4^{3-}	0.93	0.86	0.92	0.99	0.82	0.69

DISCUSSION

Semi-Diurnal Internal Tides in Monterey Canyon

The first objective of this study was to demonstrate the general occurrence of semi-diurnal internal tides in Monterey Canyon. Figures 4, 5 and 6 show temperature distributions from CTD time series of 25, 20 and 13 hours, respectively. From these data, it is difficult to determine the wave periodicity because the time series were short. It would be safe to conclude that the long period internal waves in the canyon axis were probably semi-diurnal internal tides.

The greatest internal tidal wave heights observed in Monterey Canyon ranged from 50 m to 120 m (Figs. 4, 5 and 6a). Heights in the lower part of the range are comparable to the 50 m heights of the semi-diurnal internal tide found at the continental slope off Norway (Keunecke, 1971, 1972). Similar results have been found by Reid (1956) and Carsola (1967) off the California coast. The greatest height observed in Monterey Canyon (120 m) is comparable to observations reported by Magaard and Krauss (1967) near the Iceland-Faeroe Ridge, where they observed semi-diurnal heights as great as 100 m. Although the heights reported in this study were greater than those reported for internal tides found in other locations (Halpern, 1971; Schott, 1971; Roberts, 1975), even larger waves have been observed. For instance, Bockel (1962) has observed heights up to 180 m in the Straits of Gibralter. For most semi-diurnal tides, however, Roberts (1975) reports that heights are usually between 4 and 20 m.

The large heights of semi-diurnal internal tides reported in this paper probably result from the topography of Monterey Canyon. Roberts (1975) concludes that near coasts, the height of the semi-diurnal internal tide is influenced by bottom topography. Keunecke (1971, 1972) found that the height is less than 10 m outside the shelf region on the continental slope off Norway, about 50 m at the slope and about 20 m on the shelf. Small amplitude wave theory predicts that long waves moving into shallow water should show an increase in height, while the period remains constant. This appears to be the case for semi-diurnal internal tides observed in Monterey Canyon, where the narrowing and shoaling of the canyon causes a focusing of wave energy and an increase in wave height.

Spectrum analysis of thermistor data at the Monterey Canyon head confirms that the waves had predominantly semi-diurnal periodicity. Cross-spectrum analysis of the thermistor data and predicted surface tidal heights indicated a phase lag of seven hours at the dominant twelve-hour period. Cairns and Lafond (1966) and Carsola (1967) both found the internal tide lagging the surface tide by three to six hours. The phase lag reported here is consistent with that reported by Broenkow and McKain (1972) in Monterey Canyon, where they found a phase lag of approximately 180°. Phase lag should not be expected to be constant for a given location, because it will vary depending on the strength and distribution of density stratification, circulation, and energy losses due to mixing (C.N.K. Mooers, pers. comm.).

When the amplitude of an internal wave is no longer small with respect to water depth as occurs at the Monterey Canyon head, the wave profile changes during its shoreward travel (Defant, 1961). Cairns'

(1967) data from Mission Beach, California showed that the internal wave became asymmetric as it entered shallow waters. The asymmetry became more pronounced with increasing wave height, and higher amplitude waves assumed the characteristics of internal tidal bores. An internal tidal bore is characterized by a very rapid increase in temperature at a fixed station and depth, in which the advancing water forms an abrupt front. Thermistor data from the Monterey Canyon head clearly indicated the presence of an internal tidal bore (Figure 7) by the rapid increase in temperature (3.8 °C/hour).

Breaking internal waves may be an important mechanism for oceanic mixing (Roberts, 1975). Cacchione (1970) investigated shoaling of both high- and low-frequency internal waves in a linearly stratified ocean. He found generally that low-frequency waves over a steep slope and high-frequency waves over a shallow slope will both develop considerable turbulence. The latter characterizes the situation observed in this study. Hall and Pao (1971) investigated mechanisms which cause internal waves to break. They considered long waves shoaling on a gradually sloping beach in a two-fluid system. In all cases observed, the breakdown of the primary shoaling wave train began with the formation of small ripples on the wave crest, which was probably due to shear instability. Then, if the amplitude of the wave was large, the wave could form a bore with the ripples becoming so large that there would be a horizontal detachment of the wave crest due to the shearing motion. They stress that this mechanism would be dominant for highly steepened waves, such as those observed in this study at the head of Monterey Canyon.

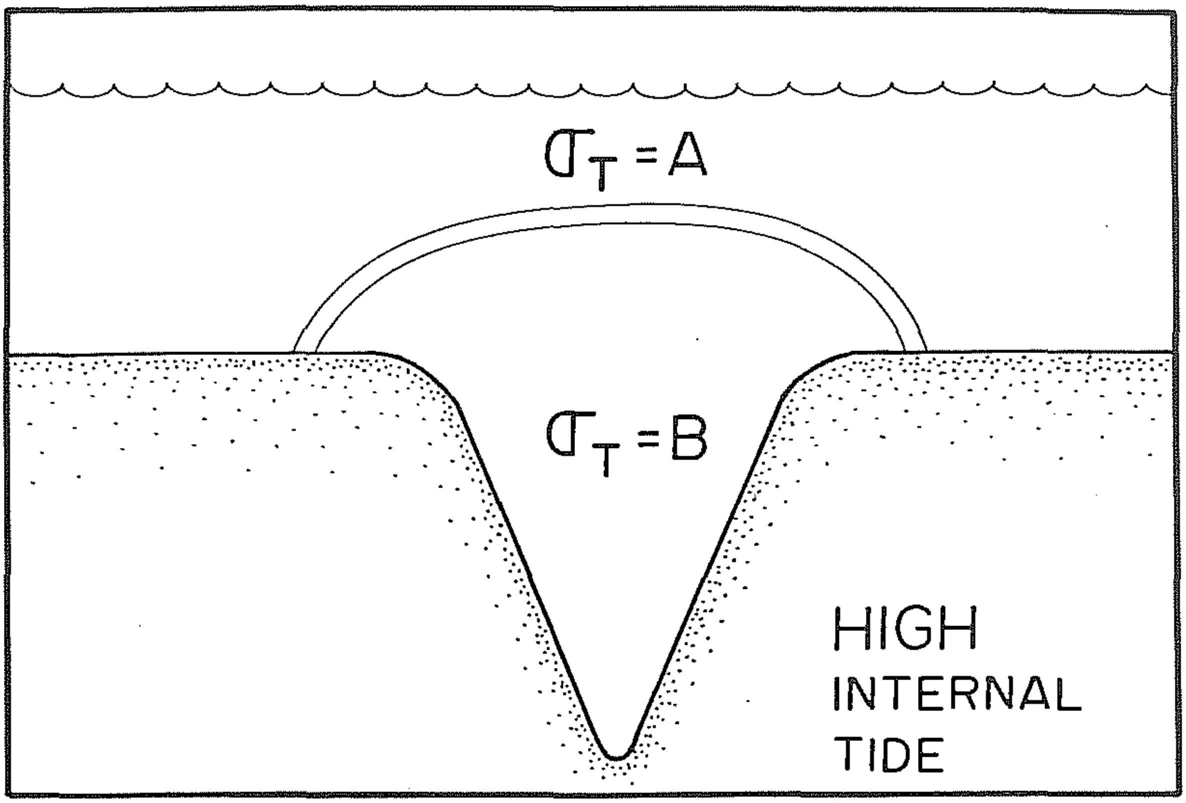
There is evidence to suggest that these shoaling internal waves at the Monterey Canyon head, or internal tidal bores, are mixing deeper water to the surface, either by shear instability or direct overturning of the waves. Percent oxygen saturation at a station at the Monterey Canyon head near the location of the thermistor used in the October 1979 study (Figure 3), showed consistently lower values at the surface than at another station 0.5 km seaward (Broenkow, 1980). During the twelve-month period, the difference was about 15%. However, from May through August, the station at the canyon head showed values on the order of 36% lower oxygen saturation. Cooler surface temperatures and lower percent oxygen saturation are indicative of recently upwelled water possibly caused by shear instability or overturning of internal waves. From these data, it appears that internal tidal wave breaking, as an enriching mechanism due to mixing, is active at the very head of Monterey Canyon.

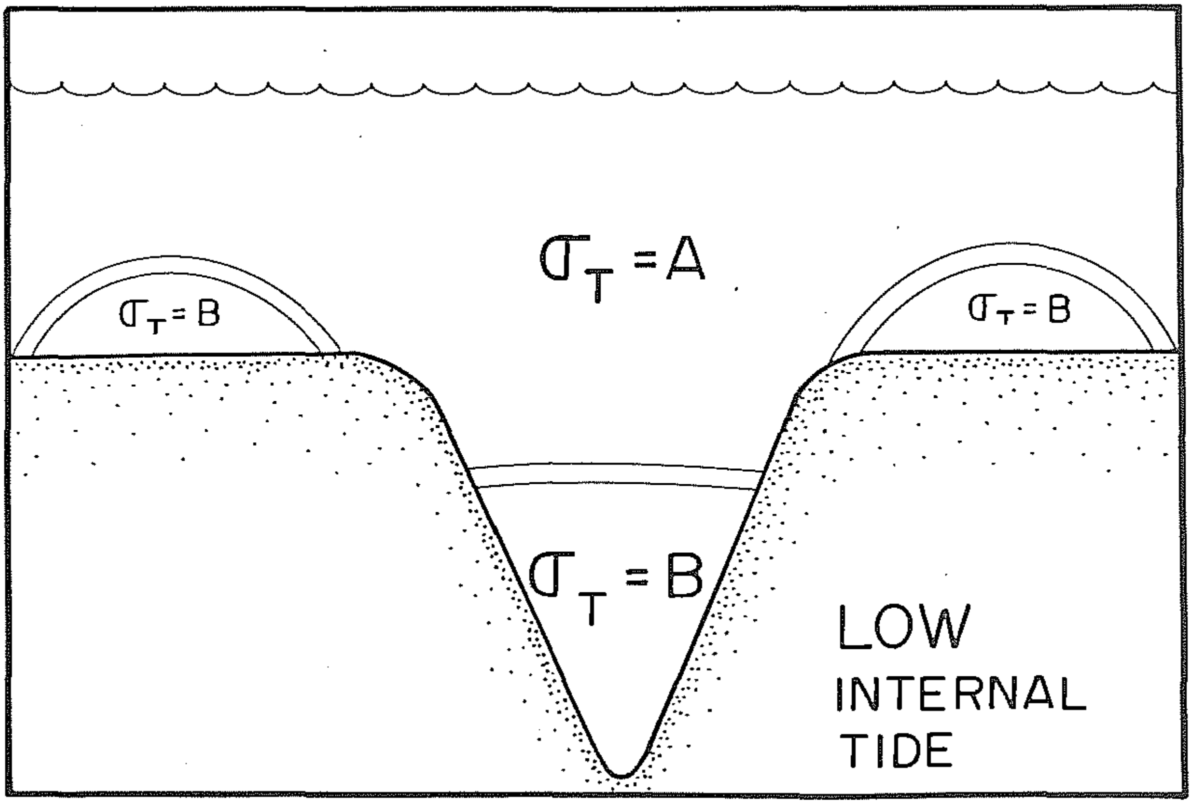
Internal Tidally Induced Density Flow

The second objective of this paper is to show that semi-diurnal internal tides in Monterey Canyon are capable of moving cold, nutrient-rich deep water to the surface. Observations of temperature distribution seaward of the canyon head and over the canyon flanks suggest that a second enriching mechanism, due to internal tides, is at work. This mechanism may be termed internal tidally induced density flow.

It is hypothesized that this mechanism works in the following manner (Figure 9). In its simplest form, a two-layer ocean is assumed.

FIGURE 9. Conceptual model of internal tidally-induced density flow.


σ_T = A
σ_T = B
HIGH
INTERNAL
TIDE


σ_T = A
σ_T = B
σ_T = B
σ_T = B
LOW
INTERNAL
TIDE

The main thermocline, or isotherms below the main thermocline, migrate vertically, due to the passage of large amplitude, semi-diurnal internal tides. As the thermocline (or isotherm) migrates above the canyon rim, denser water from below the thermocline moves laterally out of the canyon and over the shelf. When the thermocline is displaced below the canyon rim on the falling tide, this dense water type that has moved out of the canyon at high internal tide now begins to move back into the canyon. However, some of this water at the outer edge is left behind, due to mixing, surface heating and inertia.

Volume convergence (on the falling tide) and divergence (on the rising tide) and associated shelf break current speeds were calculated through consideration of volume continuity of 11 °C water at stations 20 and 40 during a tidal cycle on 13 and 14 November 1978 (Figure 6). It was estimated that a volume convergence of 520 x 10^6 m^3/6 hours would be pumped alternately into and out of the canyon. This would require horizontal velocities over the canyon rim of between 2 and 4 cm/sec. Associated up- and down-canyon velocities would be on the order of 4 to 8 cm/sec. Computed up- and down-canyon velocities agree well with current meter observations in Monterey Canyon of mean velocities of about 10 cm/sec (Dooley, 1968; Njus, 1968; Caster, 1969; Gatje and Pizinger, 1975). Data from Broenkow and McKain (1972) indicate that average lateral velocities across the edge of the canyon of about 13 cm/sec would account for an estimated volume convergence of 240 x 10^6 m^3/8 hours. These calculations are sensitive to canyon bathymetry and could account for the differences between the calculated volume convergences, since station positions and internal tidal characteristics were different for the two studies.

The shelf area north and south of the canyon that should be affected by this pumping action was also calculated. It was estimated that for a 10-m lens, an area of approximately 52 km^2 near the head of Monterey Canyon should be affected, and for a 20-m lens, an area of about 26 km^2. The area of effect for a 10-m lens was calculated to be 24 km^2 for data from Broenkow and McKain (1972). It should be noted that stations from Broenkow and McKain (1972) were in an area of the canyon that was considerably shallower and narrower than the area where the more recent data were obtained. This would account for the smaller volume convergence and area of effect calculated for the data from Broenkow and McKain (1972).

Data presented in this paper from transects normal to the canyon axis in the northern bight of Monterey Bay support calculations from volume continuity concerning the area of shelf affected by this mechanism. Temperature profiles from 13 and 14 September 1979 (Figure 8) at the time of low internal tide showed that the thickness of the lens was actually about 20 m. This figure clearly shows a lens of 12 °C water that has been pinched off of canyon water from time of high internal tide. From continuity, it was calculated that the edge of the affected area north of the canyon for a 20-m lens should be around station 6. Data showed that 12 °C water moved to station 7 during time of high internal tide, but was not found at stations 2 or 6 at time of low internal tide, a time when the 12 °C isotherm had been displaced below the canyon rim. There was, however, a lens of 12 °C water left at stations 7 and 8, but not at station 9. The change in bottom temperature from high to low internal tide also indicated that stations 2, 6 and 7 were critical with respect to this mechanism (Table 2): the greatest temperature change occurred at station 2, the next largest at station 6, and the smallest at station 7. This area between stations 2 and 7 appears to be at the edge of the observed effect; i.e., the 12 °C lens of water (Figure 8b), which is in good agreement with the calculated area of effect from volume continuity reported in this paper.

Macronutrient Enrichment

The final objective of this paper is to estimate the amount of enrichment in Monterey Bay attributable to the hypothesized mechanism of internal tidally induced density flow. To make these calculations, it was necessary to examine macronutrient distributions, specifically, dissolved reactive phosphate (PO_4^{3-}) in the canyon and at the critical areas mentioned previously (stations 2, 6 and 7).

Armstrong and Lafond (1966) demonstrated that nutrient ion concentrations rise and fall corresponding exactly to the passage of 5 m high, ten-minute period internal waves. Data presented in Table 3 are consistent with these observations. Phosphate concentrations increased at all depths at time of high internal tide at station 30. The mean phosphate concentration between 5 and 30 m at station 30 showed an increase of 36% from time of low internal tide to high internal tide.

The hypothesized mechanism presented in this paper predicts that nutrient concentrations should increase in at least the lower parts of the water column at stations normal to the canyon axis at time of internal tide. Increases in bottom concentrations should be larger at stations closer to the canyon axis because deeper water that is richer in macronutrients may flow a short distance out of the canyon by internal tides and as water moving out of the canyon and across the flanks moves further away from the axis and into shallower water, it tends to mix into the upper part of the water column due to mixing diurnal heating.

Data presented in Table 3 support predictions of nutrient distributions from the hypothesized mechanism. Increases in PO_4^{3-} concentration were observed from time of low internal tide to high internal tide at stations 30 through 6 at 20 and 30 m. The mean phosphate concentration between 5 and 30 m increased in a similar manner. It is important to note that the largest increase in the mean PO_4^{3-} concentration occurred at station 6, where a 40% increase was observed. This represented a 0.4 µg-at/liter increase of phosphate in approximately six hours. Stations 7 and 9 showed lower bottom concentrations at time of high internal tide, opposite what the model predicts. This indicates that station 6 is the edge of the immediate effect of deep canyon water moving out over the flanks (note 12 °C water in Figure 8a). As this water type is pinched off (Figure 8b), it should move northward away from the canyon, as flow in Monterey Bay is predominantly northward throughout the year (Broenkow and Smethie, 1978). This northward moving lens of water, isolated from canyon water, would account for higher phosphate concentrations at stations 7 and 9 on the falling tide.

For calculations of enrichment due to internal tidally induced density flow, the difference in mean phosphate concentration at station 6 was used. Station 6 was chosen because it showed the largest difference from low to high internal tide, and all indications suggest that this area was the edge of the immediate effect. Enrichment was calculated for the northern part of Monterey Bay only (area approximately 400 km^2). For a 0.4 ug-at/liter increase in mean phosphate concentration from low to high internal tide (Table 3), it was calculated that this could account for 0.6 g-C/m^2/day if there were a net divergence of 100% of the volume involved (520 x 10^6 m^3/6 hours). If there were a net divergence of only 50%, then this mechanism could account for about 0.3 g-C/m^2/day. Estimates of the volume of water under the 12 °C lens (Figure 8b) indicate that this volume could have been as great as 50% of the water moving across the north rim. In fact, this mechanism may not act as an oscillating pump at all, but may be more of a one-way pumping mechanism laterally out of the canyon. If a net divergence of 50% is accurate, then 0.3 g-C/m^2/day enrichment would account for approximately 31% of the daily primary productivity in the northern part of Monterey Bay during non-upwelling periods (Malone, 1971). This is a large portion of the production to attribute to internal tidally induced density flow. The true percentage is probably less. Still, during times when wind-induced upwelling is not active, such as the Oceanic Period, this mechanism could contribute significantly to the primary production of Monterey Bay. During more productive times of the year, such as upwelling, this mechanism would probably contribute less, possibly as little as 7 to 13% of the daily primary productivity (Malone, 1971).

Although Monterey Canyon is the only location to date where this mechanism of internal tidally induced density flow has been observed, it is likely that this mechanism is active in most submarine canyons around the world. The extent of enrichment will vary, depending on their size, location and bathymetry, as well as local hydrographic conditions at different times of the year.

SUMMARY AND CONCLUSIONS

The general presence of semi-diurnal internal tides in Monterey Canyon was demonstrated. Heights of these internal tides were greater than most reported for other locations, ranging from 50 to 120 m. The large wave heights reported here are probably a function of Monterey Canyon bathymetry, where the narrowing and shoaling of the canyon causes a focusing of wave energy and an increase in wave height.

Thermistor data from the Monterey Canyon head revealed the presence of an internal tidal bore. Theory and evidence suggest that these shoaling internal waves, or tidal bores, are mixing deeper water to the surface, either by shear instability or direct overturning of the waves. This is considered to be a small-scale effect, enriching the area only in the immediate vicinity of the canyon head.

Spectrum analysis of the thermistor data showed the dominant period of the temperature spectrum to be twelve hours, conclusive evidence of semi-diurnal internal tides.

Cross-spectrum analysis between thermistor data and predicted surface tidal heights indicated a phase lag of seven hours at the dominant twelve-hour period. The surface tide may not always so correlate with internal tides and thus may not be useful to predict the internal tide because phase lag will vary depending on stratification, circulation and energy losses due to mixing.

The hypothesized mechanism of internal tidally induced density flow was observed in Monterey Canyon. The calculated area of effect (26 km^2 for the observed 20 m lens of 12 °C water) from volume continuity was in good agreement with observations of temperature and dissolved reactive phosphate distributions in the northern part of Monterey Bay.

From volume continuity and phosphate distributions, the amount of enrichment due to internal tidally induced density flow was estimated at 0.3 g-C/m^2/day for a 50% net divergence. A 50% net divergence approximated the volume of water contained within the observed 12 °C lens. This calculated amount of enhancement could account for as much as 31% of the daily primary productivity in Monterey Bay during the Oceanic Period (Malone, 1971). The true percentage is probably less, due to error in the estimation of the 12 °C lens volume. Still, during periods of low productivity, such as the Oceanic Period, this mechanism could contribute significantly to the primary productivity of Monterey Bay.

Finally, though local bathymetry and hydrography will vary the effects of this mechanism, it is suggested that internal tidally induced flow is probably active in most submarine canyons around the world and will produce significant local nutrient enrichment and attendant biological effects.

REFERENCES

Armstrong, F.A.J. and E.C. LaFond. 1966. Chemical nutrient concentrations and their relationship to internal waves and turbidity off southern California. Limnol. Oceanogr. 11:538-547.

Bockel, M. 1962. Travaux oceanographiques de l' "Origny" a Gibralter. Campagne Internationale 15 Mai - 15 Juin 1961. 1. Partie: Hydrologie dans le detroit. Cah. Oceanogr. 14:325-329.

Broenkow, W.W. 1980. Kaiser Refractories receiving water monitoring year-end report, March 1979 to February 1980. Moss Landing Marine Laboratories, Moss Landing, CA. 39 pp.

Broenkow, W.W. and S. McKain. 1972. Tidal oscillations at the head of Monterey Submarine Canyon and their relation to oceanographic sampling and circulation of water in Monterey Bay. Moss Landing Marine Labs. Tech. Publ. 72-5. Moss Landing, Calif. 42 pp.

Broenkow, W.W., W. Abrahams and R. McInnis. 1977. A CTD acquisition system for coastal oceanographic applications. 4th STD/Ocean Systems Conf. Proceed. 4:37-44.

Broenkow, W.W. and W.M. Smethie. 1978. Surface circulation and replacement of water in Monterey Bay. Estuar. Coast. Mar. Sci. 6:583-603.

Cacchione, D.A. 1970. Experimental study of internal gravity waves over a slope. MIT and Woods Hole Oceanogr. Inst. Rept. 70-6. 226 pp.

Cairns, J.L. 1967. Asymmetry of internal tidal waves in shallow coastal waters. J. Geophys. Red. 72:3563-3575.

Cairns, J.L. and E.C. LaFond. 1966. Periodic motions of the seasonal thermocline along the southern California coast. J. Geophys. Res. 71:3903-3915.

Carsola, A.J. 1967. Temperature fluctuations in the waters adjacent to San Clemente Island, California. Lockheed Oceanics Div. Rept. 20474. San Diego, Calif. 15 pp.

Caster, W.A. 1969. Near-bottom currents in Monterey Submarine Canyon and on the adjacent shelf. M.S. Thesis. U.S. Naval Postgraduate School. Monterey, Calif. 199 pp.

Cooper, L.H.N. 1947. Internal waves and upwelling of oceanic water from mid-depths on to a continental shelf. Nature 159:579-580.

Defant, A. 1961. Physical Oceanography, Vol. 2. Pergamon Press, N.Y. 729 pp.

Dooley, J.J. 1968. An investigation of near-bottom currents in the Monterey Submarine Canyon. M.S. Thesis, U.S. Naval Postgraduate School. Monterey, Calif. 55 pp.

Gatje, P.H. and D.D. Pizinger. 1965. Bottom current measurements in the head of Monterey Submarine Canyon. M.S. Thesis, U.S. Naval Postgraduate School. Monterey, Calif. 61 pp.

Hall, M.J. and Y.-H. Pao. 1971. Internal wave breaking in a two-fluid system. Boeing Sci. Res. Lab. Doc. D1-82-1076. Seattle, Wash. 141 pp.

Halpern, D. 1971. Semi-diurnal internal tides in Massachusetts Bay. J. Geophys. Res. 76:6573-6584.

Keunecke, K.-H. 1971. Interne gazeiten am kontinentalabhang wahrend des Expedition Norwegische See 1969. Forachung. der Bundeswehr fur Wasserschall- and Geophysik. FWG Bericht 1971-7. Keil, Germany. 7 pp.

Keunecke, K.-H. 1972. On the observation of internal tides at the continental slope of Norway. EOS Trans. Amer. Geophys. Un. 53: 396 (abstract).

Magaard, L. and W. Krauss. 1967. Internal waves at Diamond Stations during the International Iceland-Faroe Ridge Expedition, May-June 1960. Rapports et Proces-Verbaux, Intern. Council Expl. Sea (Copenhagen). 157:173-183.

Malone, T.C. 1971. The relative importance of nannoplankton and net plankton as primary producers in the California Current system. Fish. Bull. 69:799-820.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31-36.

Njus, I.J. 1968. An investigation of the environmental factors affecting the near-bottom currents in Monterey Submarine Canyon. M.S. Thesis, U.S. Naval Postgraduate School. Monterey, Calif. 68 pp.

Reid, J.L. 1956. Observations of internal tides in October 1950. Trans. Amer. Geophys. Un. 37:278-286.

Reid, J.L., G.I. Roden and J.G. Wyllie. 1958. Studies of the California Current system. Calif. Coop. Oceanic Fish. Invest. Rept. 1 July 1956 to Jan. 1958, pp. 27-56.

Reid, J.L. and R.A. Schwartzlose. 1962. Direct measurement of the Davidson Current off Central California. J. Geophys. Res. 67: 72-76.

Roberts, J. 1975. Internal Gravity Waves in the Ocean. Marcel Dekker, Inc., N.Y. 274 pp.

Schott, F. 1971. On horizontal coherence and internal wave propagation in the North Sea. Deep-Sea Res. 18:291-307.

Shepard, F.P. and R.F. Dill. 1966. Submarine Canyons and other Sea Valleys. Rand McNally, Chicago. 381 pp.

Strickland, J.D.H. and T.R. Parsons. 1972. A practical handbook of seawater analysis. Fish. Res. Bd. Can. Bull. 167. 311 pp.

Wickham, J.B. 1975. Observations of the California Countercurrent. J. Mar. Res. 33:325-340.