Journal of Marine Research, 43, 907–924, 1985

Dynamics of temperature and chlorophyll structures above a seamount: An oceanic experiment

by Amatzia Genin[1] and George W. Boehlert[2]

ABSTRACT

Three hydrographic surveys comprised of densely spaced XBT and CTD stations were conducted over Minami-kasuga Seamount, in the northwest Pacific (21°36′N, 143°38′E). A cold dome, similar to a Taylor column, was observed above the seamount top during the first survey. Uplifted isotherms penetrated to the lower euphotic zone and were associated with higher chlorophyll concentrations. Vertical displacement of uplifted isotherms decayed with elevation above the seamount, so that both temperature and chlorophyll anomalies were undetectable at depths less than 80 m. Relatively high chlorophyll concentrations in a layer from 80 m to 100 m depth formed a distinctive deep chlorophyll maximum (DCM) which was less well defined away from the seamount. Calculations based on the observed chlorophyll increase and on estimated phytoplankton growth rate suggested a minimal residence time of the cold dome on the order of several days. Zooplankton densities were also higher over the seamount top, both within and above the cold dome. No cold dome, chlorophyll increase, or high zooplankton biomass were detected above the seamount on the second and third surveys, carried out 2 and 17 days later, respectively. Mixing and deflections of isotherms occurred within a "boundary zone" around the seamount slope during the first and third surveys.

Our observations suggest that seamounts are a source of both biological and physical patchiness in the surrounding ocean as features developed above them are swept away. The importance of the seamount-generated "experiment" is discussed in relation to field studies of the DCM. Specifically, our observations suggest that a sharp chlorophyll maximum can be formed by enhanced *in situ* growth following a sub-surface upwelling event.

1. Introduction

Recent studies of the interactions between seamounts and ocean currents have provided considerable evidence for the occurrence of unique physical phenomena at these habitats. Local deflections of isotherms, usually in the form of uplifting, have been observed above several seamounts at different locations and depths (Meincke, 1971; Vastano and Warren, 1976; Fukasawa and Nagata, 1978; Owens and Hogg, 1980; Gould *et al.*, 1981; Roden and Taft, 1985). The Taylor column theory (Taylor,

---

[1] Scripps Institution of Oceanography, A-008, University of California, San Diego, La Jolla, California, 92093, U.S.A.

[2] National Marine Fisheries Service, Southwest Fisheries Center, Honolulu Laboratory, P. O. Box 3830, Honolulu, Hawaii, 96812, U.S.A.

1923; Hogg, 1973; Huppert, 1975; Huppert and Bryan, 1976) predicts the occurrence of such deflections as a result of the encounter between a current and a seamount in which water from below the summit depth flows above the topographic obstacle. Vortex lines above the seamount are compressed, and due to conservation of potential vorticity anticyclonic vorticity is induced. The resulting flow-field is a combination of the velocity induced by the anticyclonic vorticity and the free-stream velocity. Under certain conditions of current, stratification, and topography, a closed-streamlined anticyclonic vortex, or a Taylor column, comprised of relatively deep upwelled water, is expected to remain trapped above the seamount (Hogg, 1973; Huppert, 1975). A few field observations of Taylor columns have been reported (Owens and Hogg, 1980; Gould *et al.*, 1981; Eide, 1979), but no work so far has examined the biological consequences of this phenomenon.

Seamount-induced upwelling may affect local biological processes in the overlying waters, depending upon its vertical extent above the topography and the residence time of the upwelled waters within the trapped vortex. In oligotrophic oceans, phytoplankton production would increase if the uplifted isotherms penetrated into the euphotic zone, replenishing its depleted water with nutrients. Such local enrichment can proceed along the trophic chain as a function of the residence time of the upwelled water above the seamount. Entrapment on the order of a day(s) (i.e., comparable to a typical generation time of phytoplankton) would probably affect only the primary producers, and hence, a patch of relatively high chlorophyll concentrations would be associated with the physical structure. A longer residence time, on the order of several weeks, may locally affect the growth and abundance of zooplankton species. Lagrangian current observations made above the Emperor Seamounts (Cheney *et al.*, 1980) and the Corner Rise Seamounts (Richardson, 1980) suggested entrapment periods up to several weeks within seamount-generated anticyclonic eddies. Much longer periods (on the order of several months) were inferred from hydrographic and Eulerian current measurements above a deep seamount in the North Atlantic (Owens and Hogg, 1980). If local enrichment persists for long periods, and if it is a recurrent phenomenon, nektonic organisms may be attracted to or aggregated in these habitats, and demersal predatory species may proliferate there (Boehlert and Seki, 1984). It is well known that many seamounts are excellent fishing sites for both pelagic nekton, such as tuna, and several epibenthic species (Uda and Ishino, 1958; Hubbs, 1959; Herlinveaux, 1971; Hughes, 1981; Uchida and Tagami, 1984; Boehlert, in review).

The local modification of physical and biological conditions by a mid-oceanic seamount has a unique methodological importance. Experimental manipulations commonly performed in marine intertidal and subtidal research (see reviews by Connell, 1974; Dayton and Oliver, 1980) have significantly contributed to the understanding of key ecological processes. Unfortunately, such manipulations cannot be reasonably performed on scales large enough to be applicable to the open ocean. Warm- and cold-core rings have provided natural experiments in which isolated

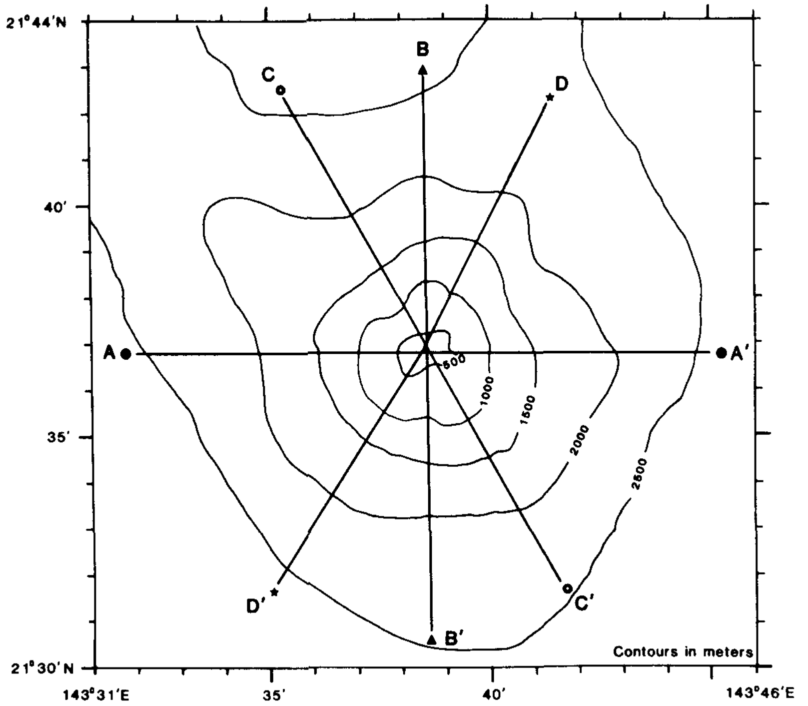

Figure 1. Bathymetry of Minami-kasuga Seamount and survey transect lines. The first two surveys were comprised of transect lines AA′ and BB′; the third survey was comprised of lines AA′, CC′, and DD′. A detailed bathymetric chart of the seamount has been published by Hussong and Fryer (1983).

pelagic populations have been studied (Backus *et al.*, 1981; Olson and Backus, 1985). Seamount-induced upwelling may provide similar "manipulations"; for example, changes of chlorophyll profiles induced by seamount-generated upwelling may help us understand processes related to the formation and maintenance of the deep chlorophyll maximum (DCM). In addition, relationships between different time scales and the trophic level of the associated biological response make the biological investigation useful for understanding temporal characteristics of the relevant physical processes. In this paper we describe the physical and biological dynamics in the waters overlying a seamount in the northwest Pacific, compare the observed features to criteria of the Taylor column theory, and discuss the implications of the results to several problems in biological oceanography.

2. Study site

Minami-kasuga Seamount (21°36′N, 143°38′E, 260 m minimum depth; Fig. 1), is located in the Mariana Ridge about 180 km north-west of Farallon de Pajaros, the northernmost island on the ridge. Surveys carried out by Japanese vessels (Hokkaido

University, 1967, 1968, 1969—about 200 km east of the seamount; Japan Oceanographic Data Center 1977–1979,—about 550 km east of the seamount) exhibit warm and oligotrophic conditions; sea-surface temperatures are between 24° to 25°C, surface chlorophyll concentrations of about 0.1 mg m^{-3}, and integrated primary production values (^{14}C uptake) range from 0.1 to 0.5 gC m^{-2} day^{-1}. An euphotic zone of about 100 m to 130 m deep is characterized by nitrate and phosphate concentrations typically lower than 0.1 $\mu g/l$. The nutricline is usually deeper than 100 m. Additional characteristics of Minami-kasuga Seamount region, relevant to Taylor column theory, are described in Section 4.

3. Materials and methods

Three XBT/CTD surveys across the seamount were performed on 13, 15, and 30 March 1984. Each survey consisted of 2 (during the first two surveys) or 3 (during the third survey) 22 km-long transects, centered above the seamount top (Fig. 1). Each transect along line AA′ (Fig. 1) included a CTD station at each end, one to three CTD stations above the top, and XBT stations in between, so that the distance between adjacent temperature profiles was 2.5 km or less. All other transects were comprised of XBT stations, except line BB′ of the first survey, which included CTD's at its ends, and line CC′ of the third survey, which included CTD's at both its center and end stations. CTD Model 9041 (Plessey Environmental Systems, California) and XBT's Model T-4 (Sippican Corp., Massachusetts) were used throughout the cruise. Water samples were collected at all CTD stations with twelve 1.7 l Niskin bottles mounted on the CTD rosette. Chlorophyll *a* concentrations, retained on GF/C filters, were determined fluorometrically (Yentsch and Menzel, 1963; Holm-Hansen *et al.*, 1965), using a Turner model 111 fluorometer.

The depth channel of the CTD magnetic tape recorder malfunctioned during the first two surveys, and the analog chart records were therefore used to analyze the temperature profiles. The error of this procedure was estimated from data of the third survey, when the depth channel did function. Comparison of analog- to digital-recorded depths showed that the former values were greater by a mean (±SD) of 3.1 ± 3.3 m than the latter values. Chart-inferred depths of the first and second survey were corrected accordingly. Density during these surveys was calculated by matching tape-recorded salinity and temperature values with chart-recorded depths which corresponded to the same temperature values. Time series of temperature–salinity data taken at two stations in the region (21N, 137E; and 22N, 137E) from 1974 to 1977 (Japan Oceanographic Data Center, 1977–1979) demonstrated that temperatures between 10°C – 22°C are good indicators of salinity. Similar T-S relationships have also been reported for the general region (Fig. 8 in Emery and Dewar, 1982). Temperatures were therefore used throughout this work as the principal physical parameter, representing water density.

Zooplankton tows above the seamount and in the deep ("control") areas were made with an opening-closing 1 m^2 Tucker trawl with 0.333 mm mesh deployed as described by Boehlert *et al.* (1985). Five tows were carried out during the first survey, and three tows during the third survey. Samples were taken in two depth ranges, from 150 m to the bottom of the mixed layer and from there to the surface. If the bottom of the mixed layer was indistinct, tows were divided at 80 m; all division points were thereby in the depth range of 60 m to 85 m. All tows were performed at night in order to minimize the effects of avoidance and diurnal migration on our estimates of zooplankton biomass.

4. Results and discussion

a. First survey (March 13, 1984). Uplifted isotherms formed a sub-surface cold dome above the seamount top (Fig. 2a). The vertical displacement of the uplifted isotherms gradually decreased with elevation above the seamount, from a 50 m uplift of the 17°C isotherm close to the substratum, to a decay of the cold anomaly at a level of about 80 m depth (180 m above the seamount top). Different deflection trends of isotherms in the vicinity of the substratum around the seamount slope formed a "boundary zone" comprised of three distinctive layers: a layer of downward deflected isotherms from approximately 500 m to about 420 m deep; a relatively well-mixed "transition zone" (Fig. 2b) between the 14.5°C and 15°C isotherms, approximately 50 m above the previous layer; and an upwelling layer shallower than 340 m depth.

Several parameters of the physical structure can be used to compare our observations with theoretical criteria for the existence of a closed-streamline Taylor column. The model (Hogg, 1973; Huppert, 1975; Huppert and Bryan, 1976) considers a water column, of total depth H, in which bottom water (i.e., from depth H) is flowing over a seamount of height h. In our case, H would thereby be the depth of the base of the upwelling (340 m), and the relevant seamount height, h, would be the altitude of the seamount top above this base (80 m). The width of the observed cold dome at the depth of the seamount (approximately 5.5 km) was thereby considered as the typical horizontal scale (L). Vertical variation of stratification strength caused a gradual decrease of the buoyancy frequency, N, from $1.79 \times 10^{-3}\ s^{-1}$ in the upper thermocline to $1.13 \times 10^{-3}\ s^{-1}$ at the depth of the seamount top, with a mean of $1.35 \times 10^{-3}\ s^{-1}$ for the entire depth range of the cold dome (N values were calculated at the control station C5). Coriolis parameter at the seamount latitude is $5.34 \times 10^{-5}\ s^{-1}$, and the relevant Rossby number, R, was $U/29.4$ (where U is the upstream velocity in cm s^{-1}). A critical criterion for the existence of a closed-streamline Taylor column (Huppert, 1975; Owens and Hogg, 1980) is the value of the non-dimensional height h_o/R (where h_o is the scaled seamount height h/H). No closed-streamline occurs when the seamount height is too low (lower h_o) or the oncoming flow is too strong (higher R). The critical h_o/R value for Minami-kasuga Seamount is 1.4 (Fig. 3 of Huppert [1975], using the mean value of N). Hence, a Taylor column, similar to the observed cold dome would occur when R is smaller than 0.16, or when the upstream velocity is about 5 cm s^{-1} or less. Much lower velocities, however, would not have sufficient energy to lift the water

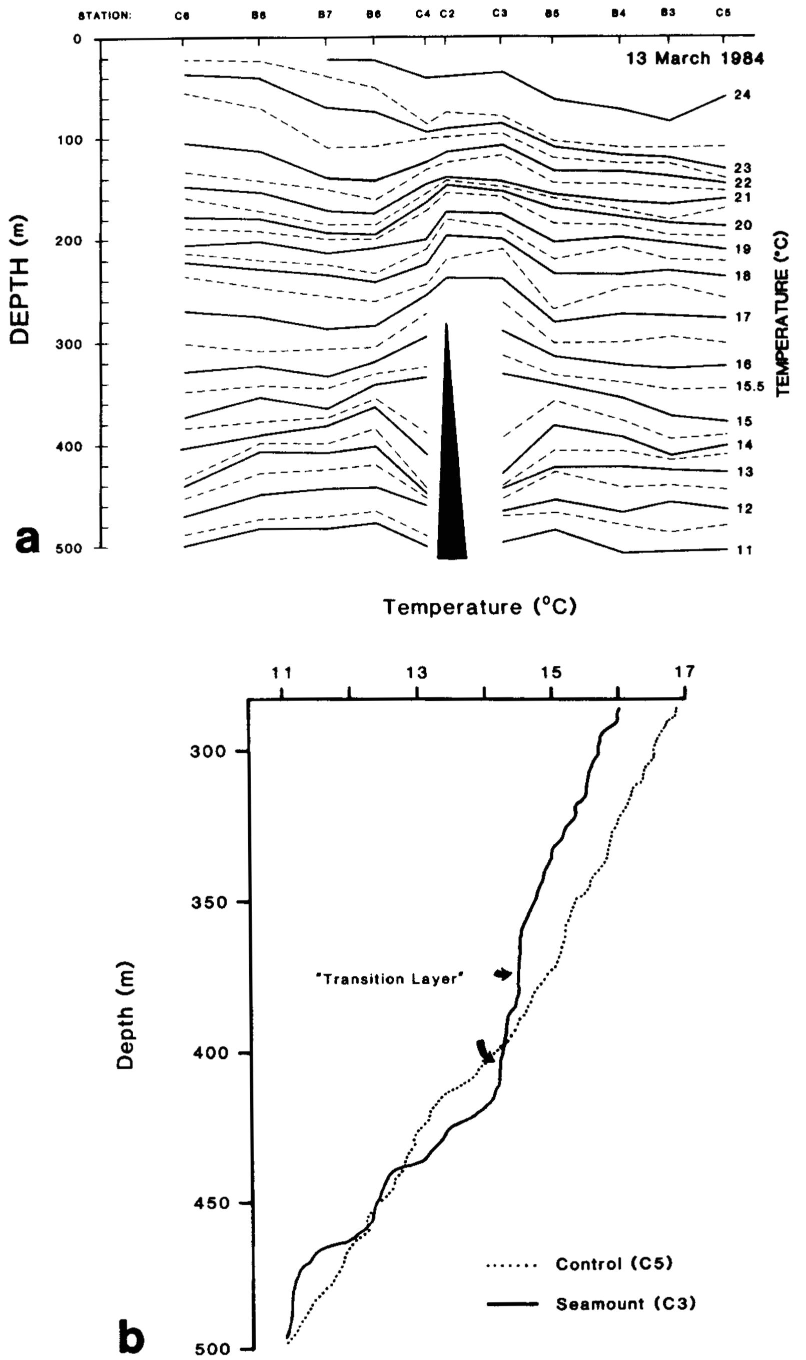

Figure 2. The first survey. (a) temperature structure along transect line AA′. Similar temperature structure at the deep area was observed along transect line BB′, which did not include CTD stations above the seamount top. Note that the vertical scale is 50 times greater than the horizontal scale. (b) expanded temperature profiles in the boundary zone close to the seamount (station C3) and at a station about 11 km to the east of the seamount (C5). The "transition" layer at C3 is comprised of two steplike structures, of which the upper one is isothermal and the lower one is characterized by a very gradual gradient. (c) chlorophyll *a* profiles above the seamount top (right) and in the control stations (left).

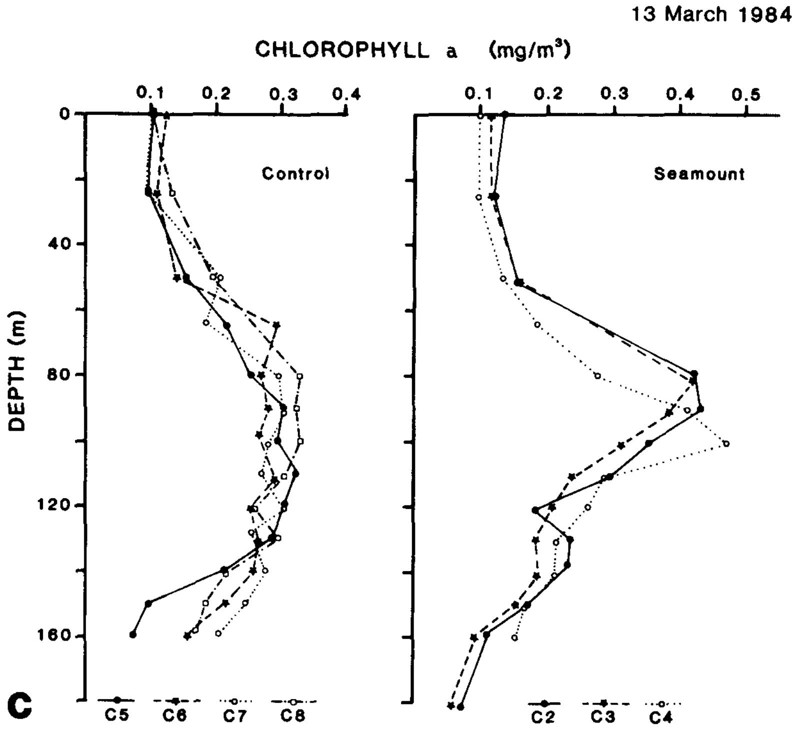

Figure 2. (Continued)

through a vertical displacement comparable to the height, *h*, of the seamount; Huppert and Bryan (1976) have found that in the case of strong stratification the amplitude of the disturbance in the vicinity of the topographic feature is dependent on the parameter Nh/U. Stronger stratification (higher N) would require higher upstream velocity to upwell water above a seamount top. For the stratification strength found at the depth of Minami-kasuga Seamount top and for the previously calculated critical velocity of 5 cm s^{-1}, the value of Nh/U is about 1.8, which is on the order of the critical value (Huppert and Bryan, 1976) required for water from 340 m to flow above the seamount top. An additional effect of stratification is to confine the vertical extent of the cold anomaly near the bottom. A decay of the seamount-induced deflections is expected at a height fL/N above the top (Huppert, 1975; Owens and Hogg, 1980); that is, for stronger stratification (greater N) the cold anomaly would decay closer to the bottom. The observed height of the cold dome above the seamount (approx. 180 m) is in good agreement with the theoretically-predicted range of 164 m (using N value of the upper thermocline) to 260 m (using N value at the level of the seamount top).

Three chlorophyll profiles, taken within the cold dome, showed a distinctive maximum between 80 and 100 m depth; the chlorophyll maximum layer at the four control stations was comparatively diffuse (Fig. 2c). The causal relationships between

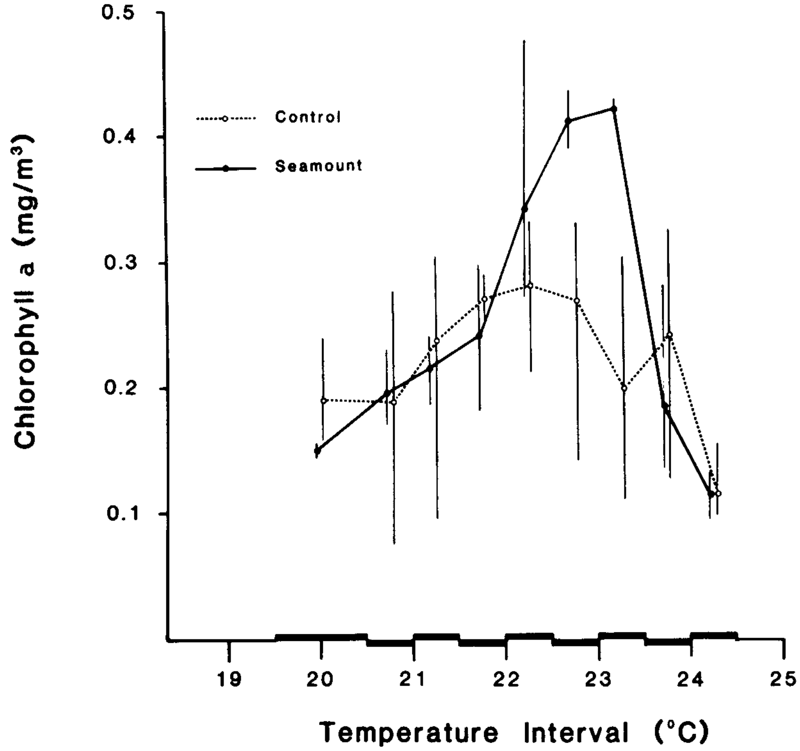

Figure 3. Chlorophyll—temperature diagram of the first survey. The mean (circle) and range (vertical bar) of the chlorophyll concentrations in each temperature interval (horizontal bar on the abscissa) are plotted for the seamount stations (solid line) and control stations (dashed line).

the localized upwelling and the biological response are corroborated by the confinement of the chlorophyll increase to depths below 80 m, the uppermost edge of the cold dome. The chlorophyll concentrations at shallower depths varied little throughout the area, both above the seamount and at the control stations. "Hardness" values (maximum chlorophyll concentration divided by the mean, Dandonneau, [1979]), which reflect the sharpness of chlorophyll profiles, were significantly higher ($p < 0.05$, Mann-Whitney U-test) in the seamount stations (mean [±SD] = 2.08 ± 0.16) than in the control stations (1.49 ± 0.13). This reflected a mean increase of 50% in chlorophyll concentrations in the 80 to 100 m depth interval.

Temperature versus chlorophyll diagrams (Fig. 3) revealed that the chlorophyll increase was confined to waters between 22°C to 23.5°C, where concentration increases for a given water temperature ranged from 21% to 112% with a mean of 62%. The chlorophyll increase, however, did not significantly affect the integrated chlorophyll values in the upper 160 m (the means [±SD] for the control and seamount stations were 35.88 ± 2.4 and 36.45 ± 1.5 mg Chl a m^{-2}, respectively; $p > 0.1$, t-test).

This similarity in the integrated values was apparently due to high variability of the concentrations at depths below the DCM and to the confinement of the chlorophyll increase to a rather narrow layer.

Estimates of the time necessary for the formation of the observed chlorophyll maximum at the seamount stations can be used to calculate a minimum residence time of the hypothesized Taylor column. Although the chlorophyll:biomass ratio in phytoplankton is by no means constant (see review by Cullen, 1982), several studies have shown that the increase of chlorophyll in grazer-free incubation experiments is an adequate variable for estimating phytoplankton growth, giving similar values to those obtained by other techniques (Thomas, 1970; Redalje and Laws, 1981; Furnas, 1982; Bienfang and Takahashi, 1983; Laws *et al.*, 1984). Estimates of phytoplankton growth rates in oligotrophic waters, however, vary considerably among different investigators and techniques (see reviews by Goldman *et al.*, 1979; Eppley, 1981), and efforts have recently been made to resolve this important controversy (Eppley, 1982). Growth rates found in two related multi-method experiments, carried out in the oligotrophic Hawaiian coastal waters were 0.29 doubling per day (station TT-157 of Welschmeyer and Lorenzen, 1985) and in the range of 0.95 to 2.88 doubling per day (Laws *et al.*, 1984). The latitude, hydrographic conditions, integrated primary production, and nutrient and chlorophyll profiles in those waters (Bienfang and Szyper, 1981) are similar to these found in the vicinity of Minami-kasuga Seamount. Applying these estimates of growth rate to the observed 50% to 60% increase of chlorophyll gives values of about 2.25 days (using the estimate of Welschmeyer and Lorenzen) or a range of 0.25 to 0.75 days (using the estimates of Laws *et al.*). These are most likely underestimated values since the unknown mortality rate due to zooplankton grazing (Jackson, 1980; Welschmeyer and Lorenzen, 1985) has not been included in our calculations. A lack of chlorophyll increase during the period between the occupation of the three seamount stations (C2 at 12:30, C3 at 14:15, and C4 at 17:30, Fig. 2c) further supports the assumption that the net growth rate within the cold dome was slower than those estimated by Laws *et al.* (1984). A crude estimate of the minimal time which had passed between the onset of upwelling above the seamount and our survey would therefore be on the order of days.

Zooplankton samples in this survey, although not duplicated, suggest a larger biomass over the seamount than at the control stations (Table 1). This observation is inconsistent with the possibility that the observed chlorophyll increase above the seamount was the result of reduced zooplankton grazing there. In contrast to the chlorophyll signal, zooplankton volumes were higher both within the cold dome and above it, and therefore might have been unrelated to the physical structure found above the top. Over Hancock Seamount (29°48′N, 179°04′E) where the summit depth is also 260 m, consistent decreases in larval fish densities were observed compared to a control station, even in 0–25 m tows (Boehlert, unpublished data).

An alternative explanation of our observations which cannot be refuted by the

Table 1. Zooplankton displacement volume (ml/1000 m^3) in the upper 150 m above the seamount top and in the control stations, during the first and third surveys. Approximate depth intervals of the strata are 150–80 m, and 80–0 m, for the deep and the shallow strata, respectively.

		Station				
	Stratum	Top	East	West	South	North
First Survey	Deep	73.8	40.0	49.3	43.6	42.2
	Shallow	88.5	56.2	61.9	48.9	59.2
Third Survey	Deep	29.8	43.0	33.9		
	Shallow	48.6	110.6	50.7		

present data is that the observed cold dome and the associated chlorophyll enrichment may simply be an oceanic "patch" which by chance was located above the seamount during our survey. Patchiness of different spatial scales in the ocean is a well documented phenomenon (e.g. Steele, 1977, and references therein), though its intensity in the oligotrophic central North Pacific is relatively low (McGowan and Walker, 1979). An adequate test of this alternative explanation against the Taylor column hypothesis would require deployment of an extensive array of current/temperature/fluorescence meters above and around the seamount. On the other hand, the location of the dome just above the seamount is consistent with other observations where seamount-generated upwelling was observed (Meincke, 1971; Vastano and Warren, 1976; Fukasawa and Nagata, 1978; Owens and Hogg, 1980; Gould *et al.*, 1981; Roden and Taft, 1985). Furthermore, the alternative explanation is weakened by the fact that no "patch" of a comparable spatial scale (several km) was found in any of the deep-water portions of the transects performed during our three surveys. These portions, nearly 100 km in total length, can be considered as a sample of the background patchiness. The ambient fluctuations of the 17°C to 20°C isotherms, for example, were almost an order of magnitude lower than their vertical displacement over the seamount (see below). The most important support, however, for explaining our observations in terms of the Taylor column theory is the agreement between the observed characteristics of the cold dome and the predictions and criteria of the theory, particularly its vertical decay and extent above the top.

b. Second survey (March 15, 1984). Neither cold dome nor chlorophyll increases were detectable along the transects of this survey (Fig. 4). The depths of the 17°C to 23°C isotherms and the chlorophyll profiles (mean [±SD] "Hardness" = 1.71 ± 0.36) were similar to those at the control stations of the first survey ($p > 0.1$ Mann-Whitney U-test, for the "Hardness" values). Quasihorizontal isotherms also characterized the benthic boundary zone around the seamount slope. A possible cause for this remark-

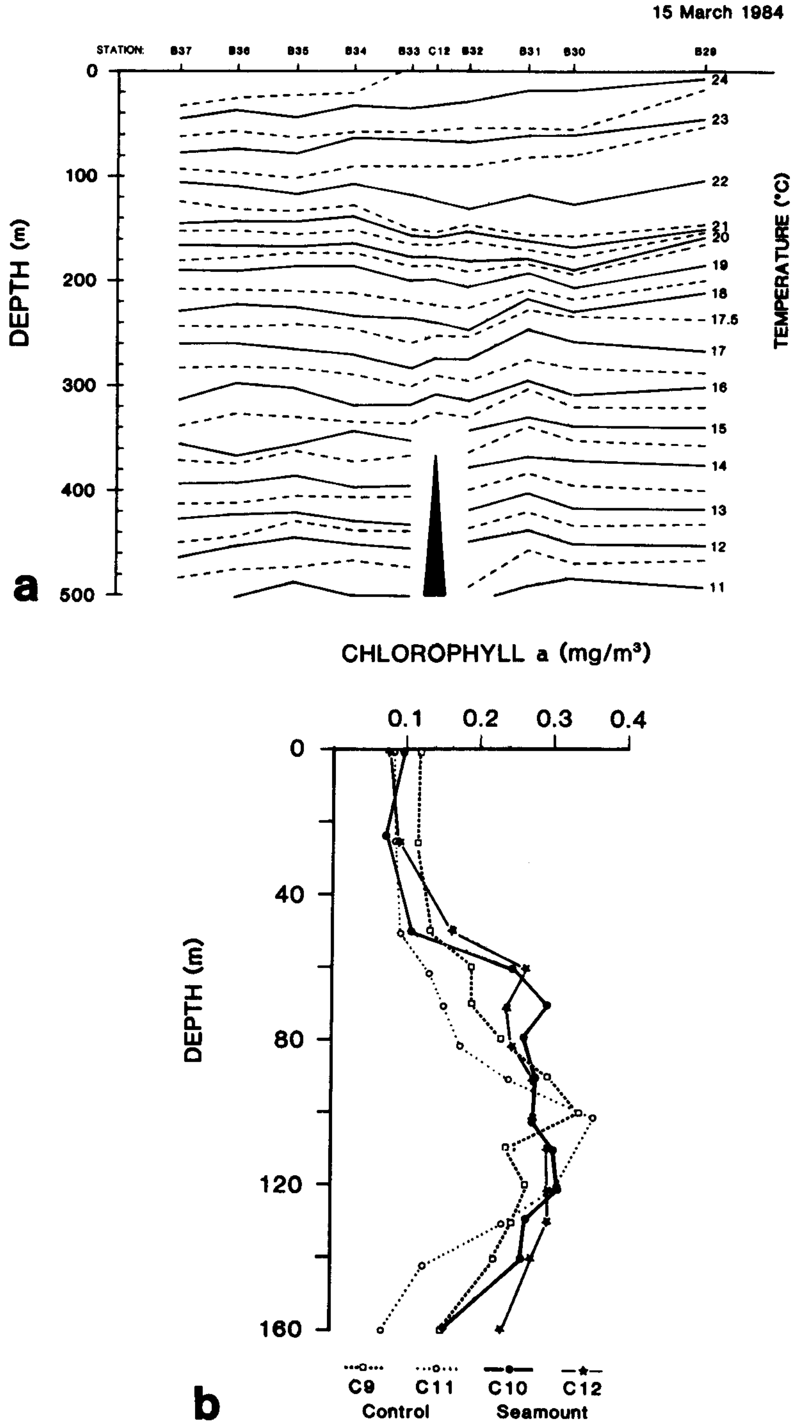

Figure 4. The second survey. (a) temperature structure along transect line BB′. A similar pattern was found along line AA′. (b) chlorophyll *a* profiles above the seamount top (solid lines) and in the control stations (dashed lines).

able difference between the two surveys is a change in the on-coming current velocity. An increase of the upstream velocity to about 20 cm s^{-1}, for example, which is a speed well within the range found at mid-ocean measurements at similar depths (e.g., record #7041 of Schmitz *et al.,* 1982—in the western North Pacific south of the Kuroshio Current [28N, 152E]) would result in $h_o/R = 0.33$, much lower than Huppert's (1975) critical value. Surface currents during this survey were apparently much stronger than during the first survey: in spite of decreased wind speed (by approximately a factor of 3), the speed of the ship's drift during CTD operations of the second survey was about 3 times faster than during the first survey (means [±SD] were 33.4 ± 13.7 and 12.9 ± 8.6 cm s^{-1}, respectively, subject to the unrecorded variability inherent in the ship's drift measurements). Similarly, Owens and Hogg (1980) have found that a persistent Taylor column was undetectable above a seamount during a period when the largest sustained current speed was recorded. However, different conditions of complex flow might also be responsible for the absence of the cold dome during our second survey. The previously existing cold dome was probably swept downstream, away from the seamount top, since it was not encountered in the two orthogonal transects. Several observations of abundant sub-surface small-scale eddies in the mid-ocean have been attributed to the existence of seamounts upstream (Vastano and Warren, 1976; Royer, 1978).

c. Third survey (March 30, 1984). Quasihorizontal isotherms characterized the waters shallower than the seamount top through the entire survey area (Fig. 5a). Sharp deflections of isotherms in the boundary zone around the slope, however, were clearly visible. An uplifting trend, much weaker than in the first survey, was found in the upper part of the slope (represented by the 15.5°C isotherm), and downward deflected isotherms in the lower part. Unlike the first survey, the deflections were not symmetrical around the seamount: the downwelling trend was shallower and more pronounced on the west slope. The "transition" layer on the west slope, between the 15°C and 15.5°C isotherms, was approximately 140 m shallower than that on the east slope (between 10.5°C and 11°C). The weak uplifting of the 15.5°C and 16°C isotherms, just above the seamount, was indistinguishable from the ambient isotherm fluctuations. Consequently, no local upwelling occurred and no chlorophyll enrichment was found above the seamount top (Fig. 5b).

On the other hand, all the chlorophyll profiles of this survey showed a pronounced chlorophyll maximum. "Hardness" values (mean [±SD] = 2.45 ± 0.24) were significantly higher than those in all previous profiles ($p < 0.01$, Mann-Whitney). An overall regional shoaling of the 17°C to 22°C isotherms, relative to their depths during the second survey and the control stations of the first one, might have been related to the formation of the strong DCM at all stations. Temperature—chlorophyll relationships showed that the main chlorophyll increase (relative to other surveys) occurred in the 21°C to 22°C range, i.e., about one degree cooler than the increase above the

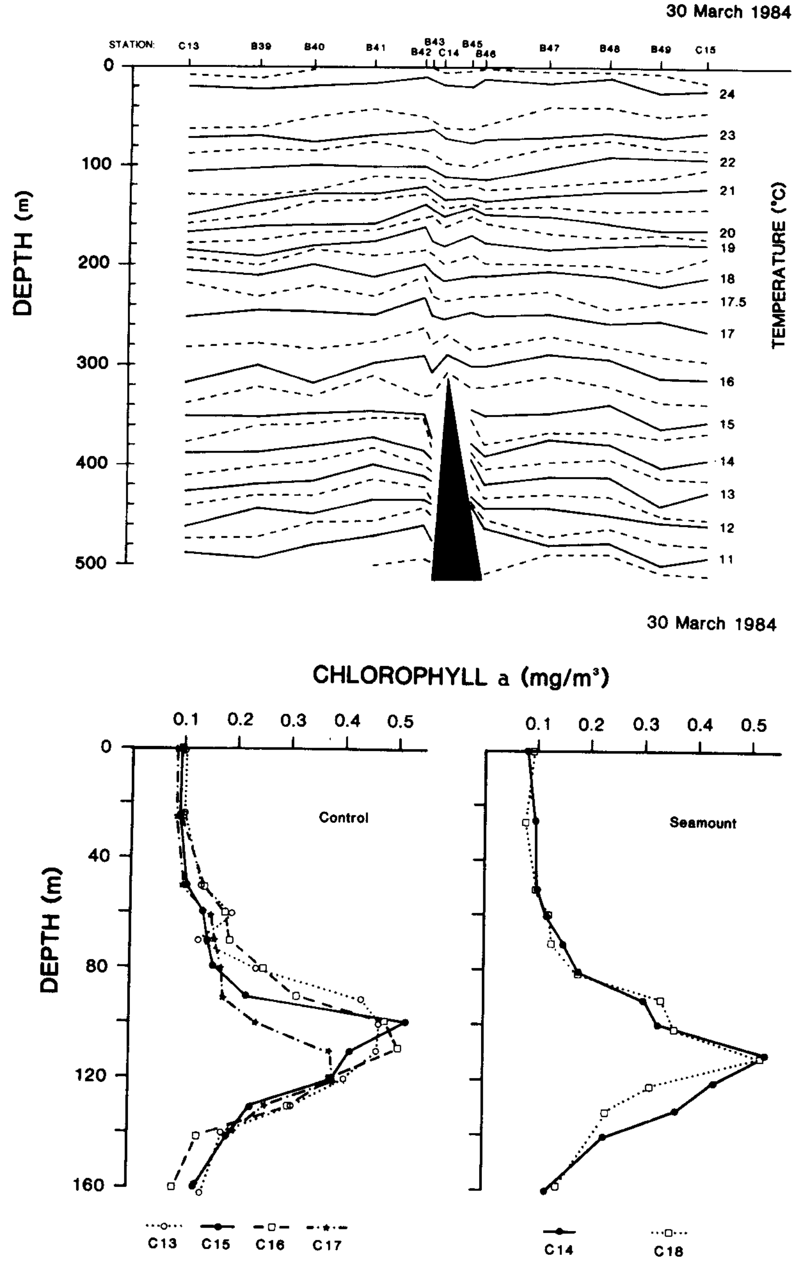

Figure 5. The third survey. (a) temperature structure along transect line AA′. Similar patterns were found along lines CC′ and DD′. (b) chlorophyll profiles above the seamount top (right) and in the control stations (left).

seamount during the first survey. We have no explanation for the cause of this regional change of the temperature structure over an area of at least 500 km^2. Zooplankton volumes in the two strata of the seamount tow were about half the quantities caught at this station during the first survey and were similar to the volumes at the control stations of both the first and third surveys (except a relatively high value at one of the control stations, Table 1).

d. The benthic boundary zone. Steplike structures along temperature profiles ("finestructures"), similar to the transition layer around the seamount slope (Fig. 2b), have been observed by Wunsch (1972) in the vicinity of Bermuda Island. The amount of finestructure increased as the island was approached, with notable asymmetry of finestructure strength around the island. Armi (1978) has found a similar multiple-step structure downstream of Corner Rise Seamount. Vertical mixing within a turbulent benthic-boundary layer has been suggested as the cause of this finestructure (Wunsch, 1972; Armi and Millard, 1976). In the presence of sloping bottom, however, reflection and breaking of internal waves can also produce mixing, finestructure, and isotherm deflections (Wunsch, 1969; Cacchione and Wunsch, 1974; Hogg *et al.*, 1978; Eriksen, 1982). Unfortunately, no current data are available to critically evaluate the actual processes which were responsible for the observed isotherm pattern within the benthic boundary zone of Minami-kasuga Seamount. This is the first field documentation of different deflection trends of isotherms in the vicinity of the bottom; more observational and theoretical work is required for a better understanding of this phenomenon. The exploration of both sediment thickness (Roberts *et al.*, 1974) and the distribution of benthic organisms on seamounts may contribute to such studies, as both variables are probably affected by such episodic events and integrate them over long periods.

e. Changes of the DCM. The seamount-induced "natural experiment" and the associated change of the chlorophyll profiles are relevant to studies of the DCM. Specifically, our observations are consistent with the hypothesis that enhanced growth of phytoplankton in the lower euphotic zone, due to nutrient replenishing from below, would contribute to the formation and maintenance of the DCM (Anderson, 1969; Venrick *et al.*, 1973; Herbland and Voituriez, 1979). Hypotheses relating the DCM to differential passive sinking of cells through irradiance and nutrient gradients (Steele and Yentsch, 1960; Bienfang, 1980), cannot explain the chlorophyll increase above the seamount since the slow sinking rate of cells (about 1 m/day or less, Bienfang, 1980) would require very long entrapment times to form this increase. Similarly, increase of the chlorophyll:carbon ratio of phytoplankton in the cold dome (Steele, 1964; Kiefer *et al.*, 1976; Bienfang *et al.*, 1983) cannot explain the observed strong DCM since increase of this ratio is expected to occur when the organisms are downwelled to a lower light regime, rather than when upwelling occurs as in the present study. The formation of sharp DCM by an increase of chlorophyll concentrations in that layer, rather than by a decrease in adjacent layers, and the higher zooplankton abundance found within the cold dome (Table 1) are inconsistent with the possibility that zooplankton grazing was responsible for the development of the sharp DCM (Longhurst, 1976, Jamart *et al.*, 1977).

5. Conclusions

Our observations suggest the existence of a highly dynamic system above the seamount. Intermittent upward deflection of isotherms can result in the formation of cold domes, similar to a Taylor column. These domes may penetrate into the euphotic zone and affect phytoplankton abundance in the overlying water. Seamounts are thereby a source of both physical and biological patchiness in the surrounding ocean, as features generated above them are swept away. Thus, relatively more finestructure in temperature profiles (Armi, 1978), higher variability (or patchiness) of chlorophyll profiles, and relatively high abundance of eddies (Vastano and Warren, 1976; Huppert and Bryan, 1976; Royer, 1978) are expected to be found downstream of seamounts. Biological effects in the euphotic layer, however, are less likely to be induced by deeper seamounts and by unsteady impinging currents.

Isotherm deflections within the benthic boundary zone also occur intermittently, even when no distinctive upwelling is generated above the seamount. These events are probably related to additional physical processes such as boundary layer mixing (Armi, 1978) or internal wave interactions with sloping bottom (Cacchione and Wunsch, 1974; Eriksen, 1982).

Our observations cannot explain the high abundance of fish over seamounts as the involved entrapment time was apparently too short for the enrichment to proceed to higher trophic levels. Nevertheless, it is possible that these events may also occur either frequently for short periods or for longer durations, thereby influencing higher trophic levels. Biological studies of interactions between a steady current such as the Kuroshio and the Emperor Seamounts, where the upwelling apparently reaches the surface (Roden and Taft, 1985) and long entrapment periods have been observed (Cheney *et al.*, 1980), are therefore highly desirable.

Acknowledgments. We are most grateful to Captain Larry Keister and the crew of the NOAA vessel *Townsend Cromwell.* Support to A. Genin from the Graduate Department, SIO, and from the UCSD Chancellor Associates Funds is gratefully acknowledged. We also thank Patricia Fryer, Hawaii Institute of Geophysics, for bathymetric data on Minami-kasuga Seamount, and Y. Dandonneau, ORSTOM, New Caledonia, for supplying Japanese data reports. R. W. Owen, O. Holm-Hansen, A. Neori, and J. Napp kindly offered their equipment for our use and helped with calibration of the fluorometer. R. Cowen, L. Armi, W. Balch, P. Dayton, R. Eppley, L. Haury, T. Klinger, M. Mullin, J. Napp, R. W. Owen, and an anonymous reviewer provided many useful comments on the manuscript. Special thanks are due to D. Genin for assistance with data analysis and preparations of the manuscript.

REFERENCES

Anderson, G. C. 1969. Subsurface chlorophyll maximum in the northeast Pacific Ocean. Limnol. Oceanogr., *14,* 386–391.

Armi, L. 1978. Some evidence for boundary mixing in the deep ocean. J. Geophys. Res., *83,* 1971–1979.

Armi, L. and R. C. Millard, Jr. 1976. The bottom boundary layer of the deep ocean. J. Geophys. Res., *81,* 4983–4990.

Backus, R. H., G. R. Flierl, D. R. Kester, D. B. Olson, P. L. Richardson, A. C. Vastano, P. H. Wiebe and J. H. Wormuth. 1981. Gulf Stream cold-core rings: their physics, chemistry, and biology. Science, *212,* 1091–1100.

Bienfang, P. K. 1980. Phytoplankton sinking rates in oligotrophic waters off Hawaii, USA. Mar. Biol., *61,* 69–77.

Bienfang, P. K. and J. P. Szyper. 1981. Phytoplankton dynamics in the subtropical Pacific Ocean off Hawaii. Deep-Sea Res., *28,* 981–1000.

Bienfang, P. K., J. P. Szyper and E. Laws. 1983. Sinking rate and pigment responses to light-limitation of a marine diatom: implications to dynamics of chlorophyll maximum layers. Oceanol. Acta, *6,* 55–62.

Bienfang, P. K. and M. Takahashi. 1983. Ultraplankton growth rates in a subtropical ecosystem. Mar. Biol., *76,* 213–218.

Boehlert, G. W. In review. Seamount resources: hypotheses and future research directions, *in* The Environment and Resources of Seamounts in the North Pacific, R. N. Uchida and S. Hayasi, eds., NOAA Tech. Report, NMFS.

Boehlert, G. W., D. M. Gadomski and B. C. Mundy. 1985. Vertical distribution of ichthyoplankton off the Oregon coast in spring and summer months. Fish. Bull., U.S., *83,* (in press).

Boehlert, G. W. and M. P. Seki. 1984. Enhanced micronekton abundance over mid-Pacific seamounts. EOS, Trans. Am. Geophys. Union, *65,* 928. [Abstract].

Cacchione, D. and C. Wunsch. 1974. Experimental study of internal waves over a slope. J. Fluid Mech., *66,* 223–239.

Cheney, R. E., P. L. Richardson and K. Nagasaka. 1980. Tracking a Kuroshio cold ring with a free-drifting surface buoy. Deep-Sea Res., *27,* 641–654.

Connell, J. H. 1974. Ecology: field experiments in marine ecology, *in* Experimental Marine Biology, Academic Press, New York, 21–54.

Cullen, J. J. 1982. The deep chlorophyll maximum: comparing vertical profiles of chlorophyll *a.* Can. J. Fish. Aquat. Sci., *39,* 791–803.

Dandonneau, Y. 1979. Concentrations en chlorophylle dans le Pacifique tropical sud-ouest: comparaison avec d'autres aires oceaniques tropicales. Oceanol. Acta, *2,* 133–142.

Dayton, P. K. and J. S. Oliver. 1980. An evaluation of experimental analyses of population and community patterns in benthic marine environments, *in* Marine Benthic Dynamics, K. R. Tenore and B. C. Coull, eds., University of South Carolina Press, Columbia, 93–120.

Eide, L. I. 1979. Evidence of a topographically trapped vortex on the Norwegian continental shelf. Deep-Sea Res., *26,* 601–621.

Emery, W. J. and J. S. Dewar. 1982. Mean temperature-salinity, salinity-depth and temperature-depth curves for the North Atlantic and North Pacific. Prog. Oceanogr., *11,* 219–305.

Eppley, R. W. 1981. Relations between nutrient assimilation and growth in phytoplankton with a brief review of estimates of growth rate in the ocean. Can. Bull. Fish. Aquat. Sci., *210,* 251–263.

——1982. The PRPOOS program: a study of plankton rate processes in oligotrophic oceans. EOS, Trans. Am. Geophys. Union, *163,* 522.

Eriksen, C. C. 1982. Observations of internal wave reflection off sloping bottoms. J. Geophys. Res., *87,* 525–538.

Fukasawa, M. and Y. Nagata. 1978. Detailed oceanic structure in the vicinity of the shoal Kokusho-sone. J. Oceanogr. Soc. Japan, *34,* 41–49.

Furnas, M. J. 1982. Growth rates of summer nanoplankton (<10 μm) populations in lower Narragansett Bay, Rhode Island, USA. Mar. Biol., *70,* 105–115.

Goldman, J. C., J. J. McCarthy and D. G. Peavey. 1979. Growth rate influence on the chemical composition of phytoplankton in oceanic waters. Nature, *279,* 210–215.

Gould, W. J., R. Hendry and H. E. Huppert. 1981. An abyssal topographic experiment. Deep-Sea Res., *28,* 409–440.

Herbland, A. and B. Voituriez. 1979. Hydrological structure analysis for estimating the primary production in the tropical Atlantic Ocean. J. Mar. Res., *37,* 87–101.

Herlinveaux, R. H. 1971. Oceanographic features of and biological observations at Bowie Seamount, 14–15 August, 1969. Fish. Res. Board Can., Tech. Rep., *273.*

Hogg, N. G. 1973. On the stratified Taylor column. J. Fluid Mech., *58,* 517–537.

Hogg, N. G., E. J. Katz and T. B. Sanford. 1978. Eddies, islands, and mixing. J. Geophys. Res., *83,* 2921–2938.

Hokkaido University. 1967. Data record of oceanographic observations and exploratory fishing. The Faculty of Fisheries, Hokkaido University, *11,* 1–119.

—— 1968. Data record of oceanographic observations and exploratory fishing. The Faculty of Fisheries, Hokkaido University, *12,* 29–113.

—— 1969. Data record of oceanographic observations and exploratory fishing. The Faculty of Fisheries, Hokkaido University, *13,* 231–308.

Holm-Hansen, O., C. J. Lorenzen, R. W. Holmes and J. D. H. Strickland. 1965. Fluorometric determination of chlorophyll. J. Cons. Perm. Int. Explor. Mer, *30,* 3–15.

Hubbs, C. L. 1959. Initial discoveries on fish faunas on seamounts and offshore banks in the eastern Pacific. Pac. Sci., *13,* 311–316.

Hughes, S. E. 1981. Initial U.S. exploration of nine Gulf of Alaska seamounts and their associated fish and shellfish resources. Mar. Fish. Rev., *43,* 26–33.

Huppert, H. E. 1975. Some remarks on the initiation of internal Taylor columns. J. Fluid Mech., *67,* 397–412.

Huppert, H. E. and K. Bryan. 1976. Topographically generated eddies. Deep-Sea Res., *23,* 655–679.

Hussong, D. M. and P. Fryer. 1983. Back-arc seamounts and the SeaMARC II seafloor mapping system. EOS, Trans. Am. Geophys. Union, *64,* 627–632.

Jackson, G. A. 1980. Phytoplankton growth and zooplankton grazing in oligotrophic oceans. Nature, *284,* 439–441.

Jamart, B. M., D. F. Winter, K. Banse, G. C. Anderson and R. K. Lam. 1977. A theoretical study of phytoplankton growth and nutrient distribution in the Pacific Ocean off the northwestern U.S. coast. Deep-Sea Res., *24,* 753–773.

Japan Oceanographic Data Center. 1977–1979. Data Report of CSK. Hydrographic Department, Maritime Safety Agency, Tokyo, *385, 395, 406, 415, 424, 430, 439.*

Kiefer, D. A., R. J. Olson and O. Holm-Hansen. 1976. Another look at the nitrite and chlorophyll maxima in the central North Pacific. Deep-Sea Res., *23,* 1199–1208.

Laws, E. A., D. G. Redalje, L. W. Haas, P. K. Bienfang, R. W. Eppley, W. G. Harrison, D. M. Karl and J. Marra. 1984. High phytoplankton growth and production rates in oligotrophic Hawaiian coastal waters. Limnol. Oceanogr., *29,* 1161–1169.

Longhurst, A. R. 1976. Interactions between zooplankton and phytoplankton profiles in the eastern tropical Pacific Ocean. Deep-Sea Res., *23,* 729–754.

McGowan, J. A. and P. W. Walker. 1979. Structure in the copepod community of the North Pacific central gyre. Ecol. Monogr., *49,* 195–226.

Meincke, J. 1971. Observation of an anticyclonic vortex trapped above a seamount. J. Geophys. Res., *76,* 7432–7440.

Olson, D. B. and R. H. Backus. 1985. The concentrating of organisms at fronts: a cold-water fish and a warm-core Gulf Stream ring. J. Mar. Res., *43,* 113–137.

Owens, W. B. and N. G. Hogg. 1980. Oceanic observations of stratified Taylor columns near a bump. Deep-Sea Res., *27,* 1029–1045.

Redalje, D. G. and E. A. Laws. 1981. A new method for estimating phytoplankton growth rates and carbon biomass. Mar. Biol., *62,* 73–79.

Richardson, P. L. 1980. Anticyclonic eddies generated near the Corner Rise seamounts. J. Mar. Res., *38,* 673–686.

Roberts, D. G., N. G. Hogg, D. G. Bishop and C. G. Flewellen. 1974. Sediment distribution around moated seamounts in the Rockall Trough. Deep-Sea Res., *21,* 175–184.

Roden, G. I. and B. A. Taft. 1985. Effect of the Emperor Seamounts on the mesoscale thermohaline structure during the summer of 1982. J. Geophys. Res., *90,* 839–855.

Royer, T. C. 1978. Ocean eddies generated by seamounts in the North Pacific. Science, *199,* 1063–1064.

Schmitz, W. J., Jr., P. P. Niiler, R. L. Bernstein and W. R. Holland. 1982. Recent long-term moored instrument observations in the western North Pacific. J. Geophys. Res., *87,* 9425–9440.

Steele, J. H. 1964. A study of production in the Gulf of Mexico. J. Mar. Res., *22,* 211–222.

—— 1977. (Ed.) Spatial Pattern in Plankton Communities. Plenum, New York, 470 pp.

Steele, J. H. and C. S. Yentsch. 1960. The vertical distribution of chlorophyll. J. Mar. Biol. Assoc. U. K., *39,* 217–226.

Taylor, G. I. 1923. Experiments on the motion of solid bodies in rotating fluids. Roy. Soc. Lond. Proc., *104A,* 213–218.

Thomas, W. H. 1970. Effect of ammonium and nitrate concentration on chlorophyll increases in natural tropical Pacific phytoplankton populations. Limnol. Oceanogr., *15,* 386–394.

Uchida, R. N. and D. T. Tagami. 1984. Groundfish fisheries and research in the vicinity of seamounts in the North Pacific Ocean. Mar. Fish. Rev., *46*(2), 1–17.

Uda, M. and M. Ishino. 1958. Enrichment pattern resulting from eddy systems in relation to fishing grounds. J. Tokyo Univ. Fish., *44,* 105–119.

Vastano, A. C. and B. A. Warren. 1976. Perturbations to the Gulf Stream by Atlantis II Seamount. Deep-Sea Res., *23,* 681–694.

Venrick, E. L., J. A. McGowan and A. W. Mantyla. 1973. Deep maxima of photosynthetic chlorophyll in the Pacific Ocean. Fish. Bull., U.S., *71,* 41–52.

Welschmeyer, N. A. and C. J. Lorenzen. 1985. Chlorophyll budgets: zooplankton grazing and phytoplankton growth in a temperate fjord and the central Pacific gyres. Limnol. Oceanogr., *30,* 1–21.

Wunsch, C. 1969. Progressive internal waves on slopes. J. Fluid Mech., *35,* 131–144.

—— 1972. Temperature microstructure on the Bermuda slope with application to the mean flow. Tellus, *24,* 350–367.

Yentsch, C. S. and D. W. Menzel. 1963. A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence. Deep-Sea Res., *10,* 221–231.

Received: *3 June, 1985;* revised: *7 August, 1985.*