Suspended particle and bacterial maxima in Peruvian coastal waters during a cold water anomaly

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(Received 28 January 1987; in revised form 12 October 1988; accepted 1 November 1988)

Abstract—Simultaneous optical, biological and chemical analyses of coastal waters off Peru were made during a period characterized by anomalously cold surface waters and weak wind-driven coastal upwelling. Particle size distributions and the microbial and chemical nature of the intermediate nepheloid layers provide strong evidence that bacterial growth, settling and offshore transport of particles are major processes controlling the particulate structure of the nearshore waters. The data also support previous suggestions that mid-depth maxima in suspended particles associated with nitrite maxima have a large bacterial component. Further, these results demonstrate the effectiveness of in situ optical methods for detection and quantification of the bacterial component of particle size distributions. While some features were similar to the particulate structures observed previously in Peruvian coastal waters, the data show the region to have significant temporal and spatial variability.

INTRODUCTION

Particle distributions in the coastal waters off Peru have received considerable attention during recent studies of coastal upwelling and El Niño phenomena (GARFIELD et al., 1979; PAK et al., 1980a; KULLENBERG, 1982, 1984). Optical analyses of irradiance attenuation (SPINRAD et al., 1979), beam attenuation (PAK et al., 1980a) and scatter (KULLENBERG, 1982, 1984) have shown that this area is characterized by zones of anomalously high concentrations of suspended particles within the water column.

Previous optical studies were performed ancillary to physical, biological or chemical studies of the region. Consequently, many provocative data sets have indicated that simultaneous analyses of the optical, physical and biochemical particle characteristics were needed to describe adequately the processes involved. KULLENBERG (1982) and PAK et al. (1980a) made light scatter and transmission profiles in the shelf, slope and offshore waters of Peru and described several intermediate nepheloid layers in the region. Offshore transport of shelf material has been suggested as a mechanism for the development of these turbid layers (PAK and ZANENVELD, 1978; PAK et al., 1980a,b).

KULLENBERG (1984) showed that profiles of light scatter at approximately 15°S agreed with results expected from previous studies of bacterial concentrations and that consider-
able variability in the particle structure should be expected. Reports of correlations between the intermediate particle maxima and biological indicators in Peru (Garfield et al., 1979) and the Northeast Tropical Pacific (Devol et al., 1976; Garfield et al., 1983; Lewitus and Broenkow, 1985) indicate that the roles that horizontal advection, microbial activity, setting and upwelling play in the development of intermediate particle maxima are not fully understood.

In stratified water masses, a primary fluorescence maximum due to phytoplankton biomass often occurs in the photic layer at the pycnocline/nitracline (e.g. Kiefer et al., 1976; Pingree et al., 1978; Cullen and Eppley, 1981; Holligan et al., 1984). However, much deeper secondary and tertiary fluorescence maxima have been observed in association with high nitrite and low oxygen concentrations (Anderson, 1982; Broenkow et al., 1983a; Lewitus and Broenkow, 1985). A significant positive correlation between total beam attenuation coefficient and in situ fluorescence suggests that particles are a major source of fluorescence (Broenkow et al., 1983a; Lewitus and Broenkow, 1985). Both phytoplankton and bacterial pigments could contribute to these deep particulate fluorescence maxima.

The mechanisms for particle production, transport and maintenance in the coastal waters off Peru are not well understood. The temporal and spatial variability of the region is unknown, which implies that any conclusions concerning the nature of the intermediate particulate maxima off Peru should be based on simultaneous measurements. The extent of the variability of the region is evident in the historic physical data taken off Peru (e.g. Huyer et al., 1979). The optical data also suggest a wide variability in the structure and extent of the intermediate nepheloid layers of the Peru coast. This is seen in the changes detected over several days in the transects of light scatter along the C-line (approximately 15°S) presented by Kulnenberg (1982). Similarly, Pak et al. (1980a) have implied significant meridional differences in the appearance of the intermediate nepheloid layers.

In February 1985, anomalously cold water and very high values of nitrite were detected in the waters off Peru during the NITROP-85 study of microbial nitrogen transformations (Codispoti et al., 1986). Studies of the regional physical oceanography, optics and microbiology were performed as part of this program. These new data address the physical and biological nature of the particulate maxima in this region and further define the range of variability in the structure of the Peruvian coastal intermediate nepheloid layers. In addition, simultaneous optical, biological and physical data are presented that provide new insight into the mechanisms that create and maintain these particle-rich strata.

METHODS

During the NITROP-85 experiment (2 February–3 March 1985) transects of stations were made at 10°S, approx. 15°S (the C-line of previous studies) and alongshore (approx. 100 km offshore) (Fig. 1). In addition, three 3-day stations were occupied at the indicated sites.

An EG&G Neil Brown Instrument Systems Mark III CTD (Conductivity–Temperature–Depth) in conjunction with a Sea Tech. Inc. 25 cm beam transmissometer (660 nm peak wavelength) and a General Oceanics bottle rosette were used for water profile analysis and sampling. A light scattering meter was used to measure the fixed-angle light
scatter in red (650 nm) and separately in green (530 nm) to a maximum depth of about 1000 m, and the volume scattering function over the angular interval 10°–160° at selected depths (Kullenberg, 1982). An in situ fluorometer measured Chl a fluorescence to a maximum depth of about 300 m (Hundaahl and Holck, 1980).

Particle concentrations and size distributions were measured on a Coulter ZM Particle
Size Analyzer (aperture diameter of 50 μm) equipped for analysing a range of equivalent spherical diameters of approx. 1.5–22 μm. Particle size analysis was typically performed on at least two depth samples from each station. The depths selected were usually the surface and intermediate nepheloid layers. In addition, occasional samples were taken from the clear waters both above and below the particle maxima.

Microbiological samples were collected in 30-l Niskin and Go-Flo™ bottles mounted on the CTD rosette. Samples for enumeration were preserved in 2% formalin (v/v final concentration) in dark glass bottles and stored in the dark until analysis. Total bacteria were counted in replicate subsamples (1–10 ml) by staining with acridine orange and observing with epifluorescence microscopy (Hobbe et al., 1977). Because at least 2 months had elapsed between sample collection and the counting of the last samples, an attempt was made to correct for loss of cells over time. Several samples were counted twice, some months apart, and the two sets of counts were used to derive an average loss equation of the form:

\[ N_t = N_0 e^{-2.35t}, \]

where \( N_0 \) is the original number of cells; \( N_t \) is the number of cells counted at time ‘\( t \)’ and \( t \) is the time elapsed as a fraction of a year. This equation was consistent with the observed loss of counts between 2 and 10 months. Cell concentrations, reported at the time of sample collection, have been corrected using the equation. The coefficient of variation among replicate counts averaged 11.7% (range 0.1–33.1%). Kendall’s nonparametric correlation analysis was used to evaluate the relationships between bacterial numbers and beam attenuation coefficient (discussed below).

Water samples also were collected in glass bottles and preserved in formalin (2% final concentration) for laboratory particle analysis with a Coulter EPICS V™ laser-based flow cytometer. Immediately before analysis samples were mixed thoroughly by vortexing and then filtered through 25 mm Nuclepore filters of 3 μm pore size. Forward-angle light scatter and ultraviolet-induced fluorescence emission were used as signals to identify particles. Ultraviolet excitation lines used were 357 and 361 nm, with emission detection between 418 and 530 nm. Control experiments were run with the same optical filter settings for the instrument sheath fluid and a sample which had been filtered through a 2 μm pore size Nuclepore filter on top of a Whatman GF/F glass-fiber filter. Forward angle light scattering was also determined on sheath fluid containing 2 μm non-fluorescing beads, which allowed the size range of the sample particles to be estimated.

Duplicate water samples (3.5 l) from each depth below the photic layer were filtered through 25 mm diameter Whatman GF/F glass-fiber filters at <125 mm Hg vacuum for chlorophyll and phaeophytin measurements. At some stations, water samples were also prefiltered through 15 cm diameter Nuclepore filters of 3 μm pore size and the particulate material in these filtrates was then collected on glass-fiber filters. Chlorophyll \( a \) and phaeophytin concentrations were determined on a Turner fluorometer by the method of Yentsch and Menzel (1963), using the acetone extraction techniques of Smith et al. (1981). Methods used in this experiment for obtaining nitrite data have been described by Codispoti et al. (1986) and Friederich et al. (1985).

RESULTS AND DISCUSSION

Beam transmission, nitrite and hydrography

The response of the beam attenuation coefficient, \( c \), as measured with a 25 cm pathlength transmissometer, \( c = -4 \ln T \) (Jerlov, 1976), where \( T \) is transmission
Correlation of beam attenuation coefficient and particle volume concentration (in parts per billion) for all samples.

(0 < T < 1.00) has been shown to be linear with particle concentration (PETERSON, 1978; SPINRAD and ZANEVELD, 1982; SPINRAD, 1986). Any variability in the correlation of c to suspended load is generally attributable to changes in the particulate size distribution or composition (i.e. refractive index distribution or shape distribution) (Fig. 2). The figure shows a correlation defined by two linear regimes. The significance of these two correlations will be discussed below.

The beam attenuation coefficients along the three sections (Fig. 3) were characterized by a near-surface particle maximum at 5–25 m; deeper (intermediate) particle maxima also were detected at many stations.
10° South line

At 10°S the offshore stations showed an intermediate particle maximum between approximately 200 and 300 m (defined by values of $c > 0.41 \text{ m}^{-1}$), significantly less than that of the surface maximum. Along this transect in 1985 nitrite and particle features were reasonably well correlated (Table 1), and the 200–300 m particle maximum was found to be associated with a high nitrite maximum (Codispoti et al., 1986 and Fig. 4a).
Fig. 4a, b.
Earlier studies (Pak et al., 1980a) had detected a possible relationship between particles and nitrite in the main secondary nitrite maximum (between 100 and 400 m and located south of approximately 10°S) but the observations were not made concurrently. The particle and nitrite maximum extending offshore from the shelf break at a depth of 200–350 m at 10°S (Fig. 4a) in 1985 was continuous and coincided with the depth, and horizontal structure of the particle maximum seen at 9°S by Pak et al. (1980a). However, beam attenuation coefficients in 1985 were in the range of 0.41–0.43 m$^{-1}$, vs the reported values of 0.45–0.60 m$^{-1}$ by Pak et al., for the 1977 data set. Also, while the 1985 particle maxima were associated with slightly higher densities, the density stratification was slightly stronger in 1977.

The low temperature of the coastal waters (e.g., <16° C) at the nearshore surface vs roughly 18°C in 1977 as reported by Huyer et al. (1979) is reflected in the high densities (Fig. 5a). However, as the figure shows, the isopycnals indicate no strong wind-driven upwelling in the region. The isonephs (constant turbidity, Fig. 3a) characteristic of the intermediate particle maximum at 200–300 m do not parallel the density structure.

<table>
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<th>Station</th>
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<th>Variable 2</th>
<th>Tau</th>
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<tr>
<td>I</td>
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<td>NO$_2$</td>
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<tr>
<td>II</td>
<td>c</td>
<td>NO$_2$</td>
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</tr>
<tr>
<td>III</td>
<td>c</td>
<td>NO$_2$</td>
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$c =$ beam attenuation coefficient (m$^{-1}$).
NO$_2 =$ nitrite concentration (µg-at. l$^{-1}$).
* $P < 0.05$. 

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**Fig. 4.** Sections of NO$_2$ for the three transects performed.

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**Table 1.** Kendall's tau correlation analysis of optical and chemical data
Longshore section

The longshore section (Fig. 3b) was characterized by a nepheloid layer of varying thickness, centered at a depth of approx. 250 m and bounded above and below by relatively clear waters (except Stas 73 and 99). Stations 68–71 (approx. 9°–11°S) contained patches of relatively clear, particle-free water between 160 and 320 m. This

Fig. 5a, b.
section also showed no evidence of any meridional homogeneity in offshelf transport of suspended material into the intermediate particle maximum. The shoaling of the isopycnals in the 100–300 m depth range at Stas 65–66, 73–75 and 98–99 (Fig. 5b) suggests that physical forcing (e.g. in the form of onshore–offshore advection) may play a strong role in the isolation of nepheloid layers along this transect. In fact, geostrophic current calculation and preliminary satellite imagery suggest the existence of an onshore flow regime between 10°30'S and 11°45'S (near Sta. 73) separating the northern and southern portions of this section (G. E. Friederich, personal communication). The nitrite date for this section (Fig. 4b) demonstrate a meridional structure similar to the optics.

15° South line

Along the section at 15°S (the C-line offshore of San Juan) a horizontally continuous particle-rich layer (as defined by c >0.41 m⁻¹) was seen to a depth of 180 m at Sta. 117, shoaling to 150 m at Sta. 114 and 80 m at Sta. 113, then deepening to approx. 300 m depth at Stas 112 and 111. A similar shoaling of the pycnoclines was seen in Stas 113–117 (Fig. 5c), and the nitrite data in Fig. 4c also show a correlated structure in the 4 μg-at. l⁻¹ contour. This agreement of the beam attenuation coefficient and the NO₂ was seen dramatically in the profile for Sta. 115 (Fig. 6), where the particle maximum at 100 m coincided with the secondary nitrite maximum associated with low oxygen and a nitrate minimum. Even further inshore the deepened particle maximum to depths of 300 m at Stas 112 and 111 corresponded to nitrite maxima of as much as 12 μg-at. l⁻¹.

The 200–300 m layer some 30–50 km offshore of the shelf break along the C-line was seen by Kullenberg (1982) to be a region of localized increased light scatter in 1977. The same zone in 1985, in fact, was characterized by a bolus of anomalously clear water. Codispoti and Packard (1980) noted a reduction in nitrite or a nitrate deficit in this region in 1977. Similarly a region of lowered nitrite was measured in 1985 (Fig. 4c).
Hydrography alone did not support the structure of the regional turbidity (Fig. 5c). Sigma-\(\tau\) surfaces were typically shoaler than those reported from the C-line by PAK et al. (1980a) in 1977. Local turbidity maxima at Stas 117, 115, and 114 were primarily horizontal in extent and were located at depths characterized by relatively strong pycnoclines (i.e. higher stability). Similarly, local particle maxima adjacent to the shelf break (Stas 112, 111 and 109) had considerably larger vertical extent and appeared in waters that were much less stratified (possibly associated with poleward-flowing sub-surface water; G. E. FRIEDERICH, personal communication; SMITH, 1978). KULLENBERG (1982) has suggested the possibility of a front-like structure in the zone some 25 km from the shelf break along this line. The data sets of 1985 and 1977 both show similar front-like features in the isopycnals and the isonephs near Sta. 112. These features are presumably associated with a front between undercurrent waters and offshore waters.

While significant regional differences existed in the structure of the intermediate nepheloid layers in 1985, meaningful similarities were seen throughout the experimental area. The intermediate nepheloid layers varied in thickness from roughly 20 to 100 m and were characterized by beam attenuation coefficients between 0.39 and 0.43 m\(^{-1}\).

**Particle size distributions**

The size range of particles detected by the transmissometer includes the range of naturally occurring marine bacteria with cell diameters of less than 1 \(\mu\)m. Therefore, an unknown portion of the transmissometry signal is due to bacterial cells. Particle size spectra obtained by Coulter counting of samples from the particle maximum were characterized by the presence of many small particles. With the aperture size used in this study, however, particles below the size of 1.5 \(\mu\)m diameter could not be detected. Therefore Coulter counting did not detect free-living bacteria. The polydisperse distributions of marine particles as detected with the coulter counter may be described by a hyperbolic (Junge) curve of concentration where the cumulative number of particles, \(N\), larger than a nominal diameter, \(D\), is given by \(N = AD^{-S}\) (BADER, 1970) where \(A\) is a constant and \(S\) is the cumulative slope of the particle size distribution. The value of \(S\)
serves as a good water mass tracer (KITCHEN et al., 1978) and indicates changes in the relative concentrations of large and small particles. Generally, an increased value of the slope indicates an increased proportion of smaller (1.5–3 μm for the Coulter counter) particles in the population. While there was a general trend toward increased slope with depth, surface waters had a wide range in slopes from 3.0 to 4.5 (Fig. 7). The shallow high magnitude nitrite maximum was characterized by slopes between 3.0 and 4.0. An obvious “local” minimum in slope occurred at the depth of the intermediate particle maximum (approx. 200 m). Further examination of the data showed that the particle maxima at these depths had reduced concentrations of particles in the 1.5–3 μm size range. Concentrations of the larger particles were not increased, thus indicating the presence of particles undetected with Coulter counting but still measured by the transmissometer. This was supported by the variability of the particle size distribution as a function of the turbidity of the water (Fig. 8). The clearest (generally the deepest) and the most turbid (surface) waters had the highest slopes and, consequently, the

![Figure 7](image1.png)

**Fig. 7.** Cumulative slope of the particle size distribution vs depth for all samples.

![Figure 8](image2.png)

**Fig. 8.** Cumulative slope of the particle size distribution vs the beam attenuation coefficient for all samples.
greatest relative proportions of small (1.5–3 μm) particles. The intermediate nepheloid layers (both the subsurface and deep) were both defined by the lowest values of the slope, again suggesting a relative decrease in the proportion of the 1.5–3 μm particles in these two zones of increased nitrite. That is, analysis of the Coulter counter data implied constant particle concentrations from the region defined by transmissometry as a particle concentration maximum. Thus, the increased particle concentrations detected by transmissometry may have been due to the presence of particles that were not detected by the Coulter counter. These particles could have been larger than 22 μm or smaller than 1.5 μm, the limits of the Coulter counter detection.

**Bacterial abundances**

Vertical profiles of total bacterial abundances were compared to profiles of beam attenuation at three of the 3-day stations (Fig. 9). Samples from the photic zone were included only at Sta. I and highest concentrations of bacterial cells were found in this layer. Below the photic zone, bacterial numbers decreased sharply (Sta. I). This decrease coincided roughly with the decrease in dissolved oxygen, and defined the upper gradient of the oxygen minimum zone (which also coincided with the base of the photic zone). At Stas I and II a subsurface maximum in bacterial numbers was observed at about 260 m. The maximum at Sta. I was supported by surrounding data points while the maximum at Sta. II appeared to be a one-point maximum. At Sta. III the subsurface maximum was much shallower and broader; maxima at all three stations were coincident with the main secondary nitrite maximum.

The highest correlations of bacterial abundances and beam attenuation coefficients were found at Stas I and III (Table 2). Although both variables exhibited structure at Sta. II, and subsurface maxima were evident from the plots (Fig. 9b), no significant correlation was found at this station. At Stas I and II the bacterial abundance maximum was narrow and the sampling interval may have been too large to accurately define the shape of the distribution.

The bacterial abundances indicate the presence of approximately one million bacteria per milliliter in the particle maximum region. We suggest that the bacteria were the source of the increased turbidity, and that the bacterial cells made a significant contribution to the total transmissometry signal (e.g. brief calculations of the dependence of light scatter on particle size demonstrate that $10^6$ ml⁻¹ 1 μm cells attenuate approximately the same amount of light as $10^4$ 10 μm cells ml⁻¹ or $2.5 \times 10^3$ 20 μm cells ml⁻¹).

While no attempts were made to quantify the degree of attachment or association between particles and bacterial cells in this study, microscopy showed that the great majority of cells were single cells, not associated with particles. We did not make direct measurements of bacterial growth or production rates. However, we suggest that the sharp maxima in distributions that we observed must be maintained by dynamic processes, either in situ growth of the cells, horizontal advection of layers rich in bacteria and particles, or a combination of both processes. Within the particle maximum, cell concentrations that are 10 times higher than those of surrounding clear layers cannot be maintained against diffusion in the absence of some kind of an in situ production term.

**Pigments**

Continuous in situ fluorometry profiles and extracted particulate chlorophyll and phaeophytin and bacterial counts implied a significant biological contribution to the
Fig. 9. Profiles of bacterial cell counts and beam attenuation coefficients at 3-day stations: (a) Sta. 1; (b) Sta. II; (c) Sta. III.
Table 2. Kendall’s tau correlation analysis of bacterial data

<table>
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<th>Station</th>
<th>Variable 1</th>
<th>Variable 2</th>
<th>Tau</th>
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<tr>
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</tr>
<tr>
<td>II</td>
<td>$\Sigma$</td>
<td>c</td>
<td>0.295*</td>
</tr>
<tr>
<td>III</td>
<td>$\Sigma$</td>
<td>NO$_2$</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>$\Sigma$</td>
<td>NO$_2$</td>
<td>0.908†</td>
</tr>
</tbody>
</table>

$\Sigma$ = bacterial abundance (cells per liter $\times 10^6$).
c = beam attenuation coefficient (m$^{-1}$).
NO$_2$ = nitrite concentration (µg-at. l$^{-1}$).
* $P < 0.05$, † $P < 0.01$.

particle load (Figs 10 and 11). Phytoplankton pigments extracted from particulate material at oxygen-deficient depths, ranged from <0.01 to 0.50 µg Chl a l$^{-1}$ and from 0.02 to 4.06 µg phaeophytin l$^{-1}$. The average of these chlorophyll values was one to two orders of magnitude lower than the average value observed in the photic layer. Phaeophytin concentrations were consistently more than three times higher than chloro-

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Fig. 10. Depth profiles of physical, chemical and biological parameters at Sta. II occupied between 13 and 16 February 1985. Continuous profiles of the beam attenuation coefficient (c) and in situ fluorescence (F) are shown in graph (A). Chlorophyll a (Chl), phaeophytin (Phaeo) and nitrite (NO$_2$) concentrations were determined from bottle samples at discrete depths (graph B).
phyll concentrations at oxygen-deficient depths (Fig. 10b). The major portion of the pigments was found in >3 μm particles, and no apparent difference with increasing depth was observed in the distribution of pigments between >3 and <3 μm fractions. Ratios of pigment concentrations in the total sample to that in a <3 μm fraction were 4.3 ± 2.6 for chlorophyll and 4.0 ± 1.6 for phaeophytin. At the stations at 7° and 9°S (Stas II and I, respectively), deep nitrite maxima were observed between 225 and 275 m. These maxima were associated but not coincident with maxima in the beam attenuation coefficient, phytoplankton pigment concentrations and bacterial numbers. There was good correlation between beam attenuation and the pigments for the water samples (> 100 m) taken at Stas I and II (Fig. 11). BLASCO et al. (1979) had previously reported a maximum in particulate phaeophytin, but not chlorophyll, in oxygen-deficient Peruvian waters.

At Sta. II, depth profiles of continuous in situ fluorescence and extracted phytoplankton pigments (Fig. 10) indicated that the progressive increase in fluorescence from 100 to 225 m could not be solely attributed to Chl a or phaeophytin. While only Chl a has a fluorescent emission at 685 nm, the wavelength bands for excitation and emission could have detected a fraction of the fluorescence emission from other compounds at oxygen-deficient depths, where chlorophyll concentrations are low. Other fluorescent sources that have been considered include: chlorophyll degradation products, phycobiliproteins, bacteriochlorophylls and cytochromes (ANDERSON, 1982; BROENKOW et al., 1983a,b; LEWITUS and BROENKOW, 1985). Denitrifying bacteria have not previously been considered as a source of fluorescence in the particle layer at the core of the nitrite maximum, even though a peak in bacterial numbers occurs at these depths (Fig. 9). During a previous cruise to the Cariaco Trench, we had isolated denitrifying bacteria, which excreted a yellow fluorescent pigment with an absorption maximum at 340 nm. Cells demonstrated a fluorescence emission at 450 nm after excitation at 350 nm. Using flow cytometry with ultraviolet excitation lines at 357 and 361 nm and emission detection between 418 and 530 nm, we examined a <3 μm filtrate of a preserved sample from the core of the particle/nitrite maximum at Peru Sta. II. Analysis showed a population of autofluorescent particles, with similar characteristics to those of a denitrifying bacterial clone isolated from Cariaco Trench (Fig. 12). Control experiments with phytoplankton cultures demonstrated that chlorophyll fluorescence was not
detected and while phycoerythrin fluorescence of $<\!1\mu$m cyanobacteria could be detected with these instrument settings, the 240 m sample did not contain significant numbers of cyanobacteria (this was ascertained using a different laser line for the optimal detection of phycoerythrin). These data give the first indication that denitrifiers may be responsible for some portion of the observed \textit{in situ} fluorescence in oxygen-deficient waters. Further characterization of the composition of these particles is, however, needed since aromatic compounds in detrital particles could also contribute to fluorescence emission after ultraviolet excitation (\textsc{Duursma}, 1974).

Fig. 12. Flow cytometry analysis of $<\!3\mu$m particles in a preserved sample from 240 m at Sta. II and a culture of a denitrifying bacterium isolated from the Cariaco Trench. The sample was excited by ultraviolet laser lines 357 and 361 nm and fluorescence emission was detected between 418 and 530 nm. The histogram shows the distribution of particles (filled area is contour for 25 particles detected, hatched area is 10 particles, stippled area is 5 particles) as a function of fluorescence emission intensity and relative size (forward-angle light scatter). The arrow indicates where 2 \textmu m beads were detected.
CONCLUSIONS

Optical, physical, biological and chemical studies were performed simultaneously in Peruvian coastal waters to study the structure, processes of formation, and maintenance of intermediate particle maxima in this region. Forcing functions must include microbiological activity, particle setting, dissolution and advection.

Particle maxima in the coastal waters off Peru vary significantly in their temporal and spatial extent and intensity. The data taken during this experiment show the structure of the particle maxima during a cold water event. Northern stations (at 10°S) show many similarities to the optical features detected previously. Further south the Peruvian coastal waters are quite variable in particle structure in different years. The longshore data show dramatically that physical processes may play an important role in the vertical distribution of particles, yet there is a meridionally discontinuous transport of shelf material offshore.

We present the first in situ data of abundance of bacterial cells measured in conjunction with light transmission and particle characterization. We suggest that bacterial biomass contributes directly to the optical signal and that inorganic materials and organic detritus, derived from lateral transport and sinking (since generally surface values of the beam attenuation were higher where the chlorophyll levels were higher) probably constitute the remainder of the particle signal. In the absence of direct measurements of bacterial growth rates, we can only speculate that the subsurface bacterial maxima are maintained by in situ growth and horizontal advection, and that interactions between the bacteria and other particles form the basis of a dynamic subsurface microbial population. Future studies must focus on the processes supporting the establishment of the offshore bacteria/particle interactions and the obvious relationship such processes must have with coastal benthic processes.

Acknowledgements—This work was performed as part of NSF Grant No. OCE 83-16611 (also HG: OCE 83-16607 and BBW:OCE 83-16608). The comments and advice of Gernot Friederich, Ted Packard, Fred Lipschultz and Zhenglang Xu are greatly appreciated. The authors are grateful for the assistance provided by Andy Smith, K. A. Kilpatrick, Jeff Brown, Jane Kogelschatz and the Captain and crew of the R.V. Wecoma.

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