Intermediate Nepheloid Layers Observed off Oregon and Washington

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Two distinct kinds of particle maxima (nepheloid layers) were observed off Oregon in November 1977 and off Washington in October 1978 by an in situ light transmissometer: one in the thermocline in the euphotic zone and the other at intermediate depth well below the thermocline. The thermocline nepheloid layer is associated with well-defined maxima of dissolved oxygen, chlorophyll-*a*, and phaeophytin, and these associations suggest that the nepheloid layer is primarily composed of phytoplankton under-going active photosynthesis. The intermediate nepheloid layer is found in connection with the bottom waters near the shelf break and shares some of the characteristic properties of the bottom water: high concentration of suspended particles, low concentrations of dissolved oxygen, chlorophyll-*a*, and phaeophytin. The particle size distributions in the intermediate nepheloid layer are different from those in the clear water above the nepheloid layer but similar to those in the bottom nepheloid layer. Two hypotheses for the generation of intermediate nepheloid layers, settling and horizontal advection, are examined, and the data support the latter hypothesis.

INTRODUCTION

Natural waters contain large numbers of suspended parti-cles. The distribution and characteristic properties of the sus-pended particulate matter (spm) are subject to the structure and changes in the oceanic environment. Particles are in-troduced into the ocean by streams and by the wind. They are also generated by in situ production through biochemical processes. What happens to the particles after they are in-troduced into the ocean is of considerable interest: they are transported by currents and gravitational settling; they may change their characteristic properties by dissolution, con-sumption by organisms and aggregation [*Zaneveld*, 1971; *Ler-man et al.*, 1974].

Tracing individual particles in the ocean is impractical, if not impossible, so particles contained in natural water sam-ples are studied collectively. One of the common approaches to studying particle transfer processes is to identify specific particle characteristics so that the particles can be related to known source(s). There are a number of particle properties which have been used for such purposes: organic/inorganic fraction, chemical composition, optical properties, particle size distributions (PSD), species identification of the biologi-cal fraction, etc.

Concentration of spm was traditionally determined by weighing particles collected on a 0.45-μm pore diameter mem-brane filter. Recently, optical instruments measuring either light scattering or beam attenuation have been applied suc-cessfully to the determination of concentration of spm in the ocean [*Drake*, 1974; *Peterson*, 1977]. Optical instruments are particularly useful in obtaining vertical profiles of spm in situ rather than at discrete points, and long-term measurements at a point are possible if the instruments are moored. From light transmission profiles, for example, we have learned the major sources of spm in the ocean; from temporal variations of light transmission profiles, we began to recognize some of the im-portant processes of particle transfer [*Pak and Zaneveld*, 1977, 1978].

Vertical distribution of suspended particulate matter in the

ocean generally reveals one or more layers of maximum par-ticle concentration. Regional differences are large near land and river plumes, and where biological productivity is high [*Jerlov,* 1953; *Beardsley et al.,* 1970; *Carder et al.,* 1971; *Mat-lack,* 1974]. A vertical particle maximum has been widely ob-served in seasonal thermoclines, usually in the upper part of the thermocline. The long-standing interpretation of such a spm maximum is based on a decreased particle settling rate in combination with a minimum in turbulent diffusion. Maxi-mum phytoplankton production is assumed to occur in the surface layer and to decrease with depth. The biologically produced particles are then thought to accumulate at some depth in the thermocline due to (1) downward increase in density of water (mainly from decrease in temperature), (2) reduction in particle size as a result of decomposition and dis-solution during settling, and (3) minimum turbulent mixing at the depth of the spm maximum. A downward increase of tur-bulent diffusion below the particle maximum is also required in order to form a maximum [*Riley et al.,* 1949; *Jerlov,* 1959; *Lerman et al.,* 1974].

Over the continental shelves and slopes off Oregon, Wash-ington, and Peru, intermediate nepheloid layers (INL) have been observed below the euphotic zone [*Pak and Zaneveld,* 1977, 1978; *Pak et al.,* 1980a]. Although its long-term varia-tion has not been confirmed, the INL off Oregon (in approxi-mately 420 m of water) was observed to be stable for the pe-riod of a week [*Pak and Zaneveld,* 1978]. Observations off Peru suggest that a well-defined INL persists over a period of months [*Pak et al.,* 1980a]. Since there is no major source of particles beneath the euphotic zone and above the bottom, presence of an INL at several hundred meters depth indicates spm in transit. There are two hypotheses for the origin of such layers: the settling hypothesis and the horizontal advection hypothesis. These hypotheses conflict with one another to a large degree. In this paper, we will examine the two hypothe-ses by means of vertical distributions of spm, particle size dis-tributions (PSD), dissolved oxygen, chlorophyll-*a*, phaeophytin, and hydrographic data. Particle transfer proc-esses are of major significance to biological, chemical, and geological processes. In addition, since an INL is often a well-defined and easily detectable phenomenon it may be a simple
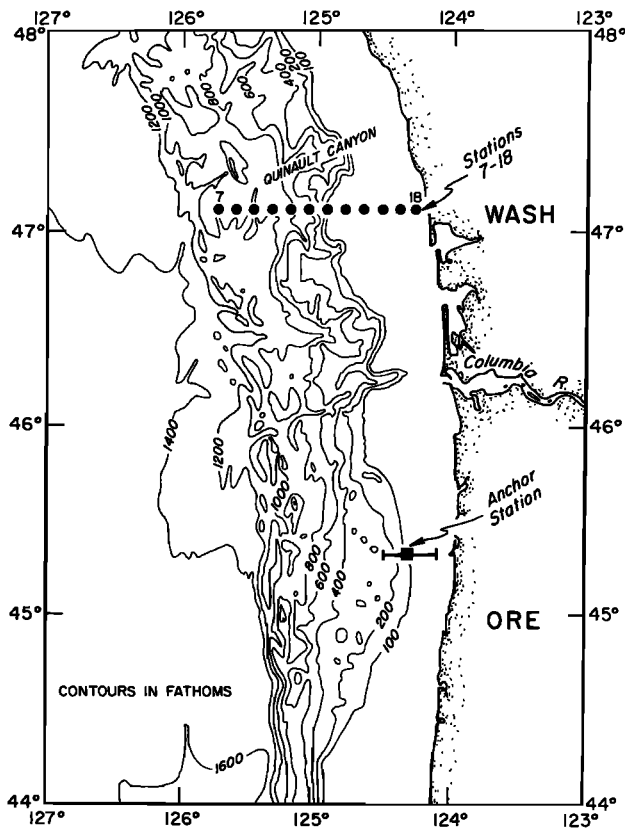
Fig. 1. Bathymetry and approximate locations of stations occupied during the TT135 cruise (near Quinault Canyon) and the W7711A cruise (off Oregon).

and useful indicator of particle transfer and of the dynamics of the water containing the INL.

METHODS AND OBSERVATIONS

Hydrographic and light transmission measurements were made in situ over the continental shelves and slopes off Oregon during November 6–13, 1977, and off Washington during

October 18–21, 1978 (Figure 1). During the November 1977 cruise on R/V *Wecoma* a CTD and a light transmissometer were used (both instruments were designed and built by the OSU optical oceanography group). Particle size distribution was determined by an in vitro electronic particle counter using water samples obtained by a Niskin rosette water sampler. Descriptions of these instruments and their operation and data reduction procedures are given by Zaneveld et al. [1978] and Bartz et al. [1978].

During the October 1978 cruise on the R/V *Thompson*, a light transmissometer [Bartz et al., 1978] and an oxygen sensor (Beckman high-pressure oxygen sensor) were rigged in a stainless steel cage which also housed a Neil Brown CTD and a Niskin rosette water sampler. Profiles of light transmission, oxygen, and CTD were determined simultaneously, primarily in a zonal section at 47°–07.0′N latitude (Figure 1).

A number of chemical and biological analyses also were performed on the water samples. The sampling depths were determined by means of on-line temperature and light transmission profiles. Some of the chlorophyll-a and phaeophytin concentration data are presented in this paper to corroborate arguments made based on the in situ light transmission and hydrographic data. Light is attenuated by spm and 'yellow matter' in the water in addition to water itself. Light transmission has been shown to be useful for the determination of the temporal and spatial distribution of spm concentration in the ocean because it can be measured in situ [Peterson, 1977; Bartz et al., 1978]. Thus we are able to infer spm distributions from light transmission data; the conversion of light transmission to spm concentration is particularly justified when the spatial distribution of spm is the main interest rather than absolute values of spm concentration. Chlorophyll-a is an indicator of live phytoplankton biomass, and phaeophytin is indicative of dead or moribund phytoplankton biomass [Lorenzen, 1965]. These plant pigments were determined according to the procedures described by Strickland and Parsons [1972].

Particle size distributions (PSD) were measured with a Nuclear Data pulse height analyser coupled to Coulter glassware
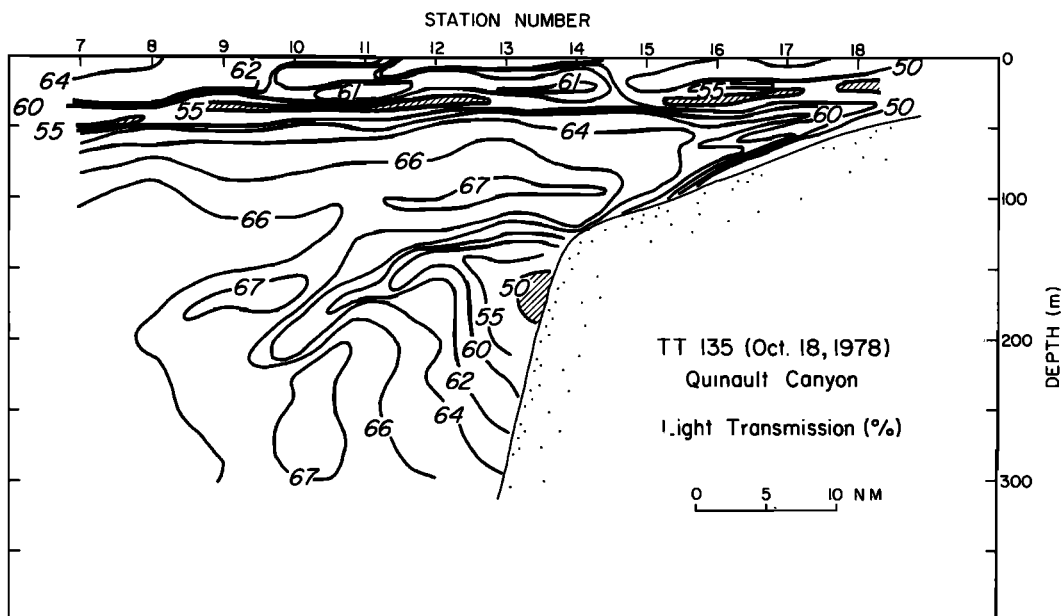

Fig. 2. Distribution of light transmission (in percent) in the zonal section near Quinault Canyon observed during the TT135 cruise (October 18, 1978).
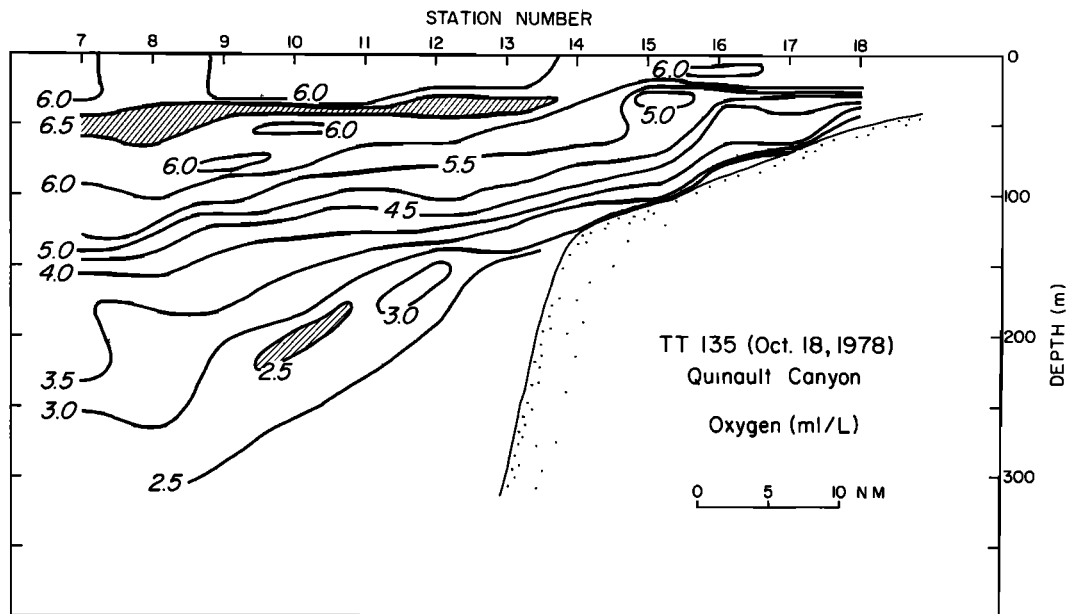
Fig. 3. Distribution of dissolved oxygen (ml/l) in the zonal section near Quinault Canyon observed during the TT135 cruise (October 18, 1978).

using 100 and 400 μm apertures. The effective size range measured was from 3.5 to 126.0 μm diameter. Each successive data window of the pulse height analyzer covers a particle volume of a half-power of 2 μm^3. For example, the first window covers particles with volumes between $16(2)^{1/2}$ and 32 μm^3, and the second window covers from 32 to $32(2)^{1/2}$ μm^3.

Volume concentrations (in ppm) were computed by multiplying the particle concentration in each window by the average of the delimiting volumes for that window. Assuming a hyperbolic distribution, this method of computing volume concentrations gives a value that is 0.5 to 2% too high over a reasonable range of PSD slopes.

Slopes of PSD are computed by means of linear regression of the logarithms of the particle number concentration in windows versus the logarithm of the central diameter for each window. Assuming the hyperbolic distribution holds this is mathematically equivalent to determining the cumulative slope. This method was compared with the standard method of determining cumulative slope [Kitchen, 1978], and the mean difference was found to be negligible. The correlation coefficient was 0.96. The method used in this paper is much simpler from a computational standpoint.

RESULTS

SPM Maximum in Seasonal Thermoclines

The thermocline spm maximum (transmission minimum) is a relatively thin layer (about 20 m thick) over the shelf and extending offshore to the westernmost station (Figure 2). This layer is presumed to extend farther to the west. There is a slight but definite tendency of the spm maximum layer to become deeper away from the coast, which is probably due to the increased sunlight penetration as the surface water gets more transparent. An offshore increase in transparency in the surface water is evident in Figure 2. Another example can be found in Figure 7, where the light transmission in the surface layer is around 55%, clearly less than those further offshore shown in Figure 2. Distribution of dissolved oxygen (Figures 3 and 4) show a well-defined maximum corresponding to the thermocline spm maximum over the slope. Over the shelf the oxygen maximum is absent, and thus no oxygen maximum is corresponded to the spm maximum. Distributions of both spm and oxygen show patchiness, suggesting that more than a simple one-dimensional (vertical) process is involved. In addition, the spm maximum is characterized by maxima in offshore chlorophyll-a and phaeophytin (Figures 5 and 6). Depth resolution of the dissolved oxygen profiles is excellent because it is based on in situ oxygen measurements. The oxygen concentrations in the maximum are in excess of the values in the surface layer, and the concentrations in the surface layer exceed saturation levels. The supersaturated oxygen concentration extends to about 80-m depth in the region where the oxygen maximum was observed in the thermocline (stations 7–13 in Figures 2 and 3).

The most significant implication of the maxima in oxygen, chlorophyll-a, and phaeophytin observed concurrently with the spm maximum is that the spm maximum layer contains large amounts of phytoplankton which are producing oxygen photosynthetically.

Intermediate Nepheloid Layers

A layer of turbid water is equivalent to a nepheloid (cloudy) layer, and the nepheloid layer is called either intermediate nepheloid layer (INL) or bottom nepheloid layer (BNL) depending on its location. Descriptively, an INL may be called intermediate spm maximum or intermediate particle maximum. In this paper, however, we use thermocline spm maximum to identify the particular INL located at the thermocline.

Over the continental shelves and slopes off Oregon/Washington, light transmission profiles typically show an intermediate nepheloid layer well below the thermocline [Pak and Zaneveld, 1978]. This layer is in addition to the spm maximum at the seasonal thermocline, described in the previous section.

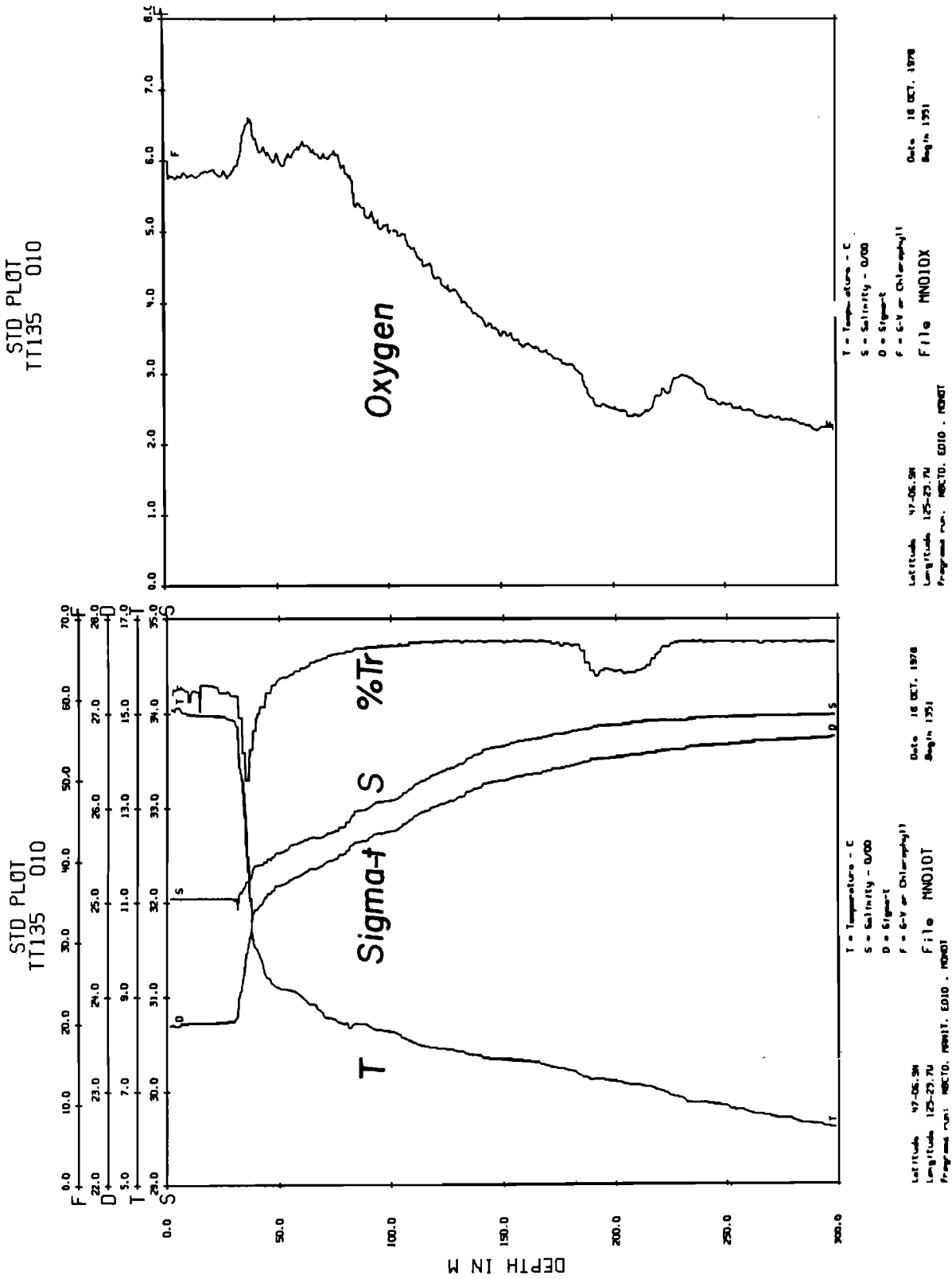*Intermediate nepheloid layers observed during November 1977.* During the R/V Wecoma cruise in November 1977,

Fig. 4. Profiles of T, S, σ_t, light transmission (% Tr), and dissolved oxygen over the continental slope (station 10 in Figures 1 and 2) observed during the TT135 cruise (October 18, 1979).

W7711A, the INL was observed over the continental shelf off Oregon in a zonal section (Figure 7) and at an anchor station located at mid-shelf in approximately 170 m of water (Figure 8). The INL over the shelf extended offshore a distance of about 15 km at an intermediate depth with its eastern end connected to the bottom nepheloid layer near station 9-8. At the anchor station, two separate INL's were observed most of the time.

When the slope of the PSD is plotted against light attenuation (total particle concentration) for the entire cruise (W7711A), as in Figure 10, it is found that data from BNL's, INL's, surface water and clear water at intermediate depths lie in well-defined areas on the graph. The slopes of the PSD for the INL and the BNL are nearly linearly correlated with spm concentration (Figure 10). From the graph, the mid-depth clear waters and the surface mixed layers were clearly separated from the INL and BNL, but are located very close to each other (Figure 10). The slopes of PSD from the mid-depth clear water and surface mixed layer were widely scattered over narrow ranges of total particle concentration. The scatter may have been due partly to reduced precision caused by the low number of particle counts when the concentration is small.

In Figure 11 are illustrated the shapes of the PSD of two water samples with different total spm concentrations. It is clear that the concentrations of the large particles differed little in the two water samples, but the concentrations of the small particles differed a great deal. The water with large spm concentration can be characterized by a steep slope (Figure 11) which implies a large concentration of small particles without appreciable difference in large particles (relative to water with smaller total spm concentration).

We took water samples at five depths at a station 8 n. mi. offshore (Figure 12) in order to study vertical changes in PSD, particularly within the BNL. The PSD's of these five samples indicate that the slope of the PSD increases with increasing
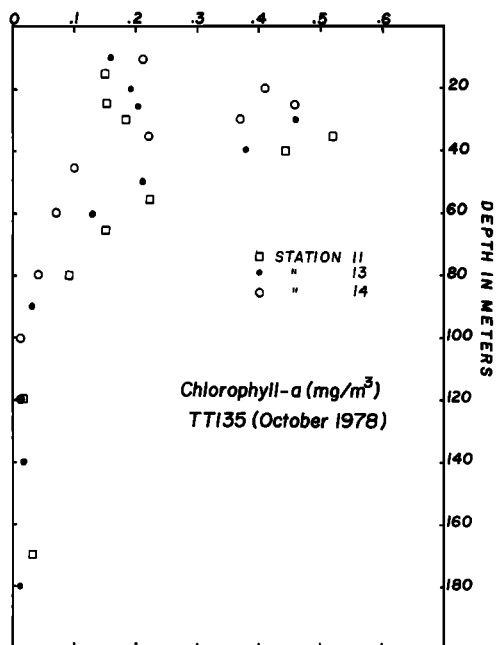

Fig. 6. Profiles of phaeophytin (mg/m^3) over the continental slope (stations 11, 13 and 14 in Figures 1 and 2) observed during the TT135 cruise (October 18, 1978).

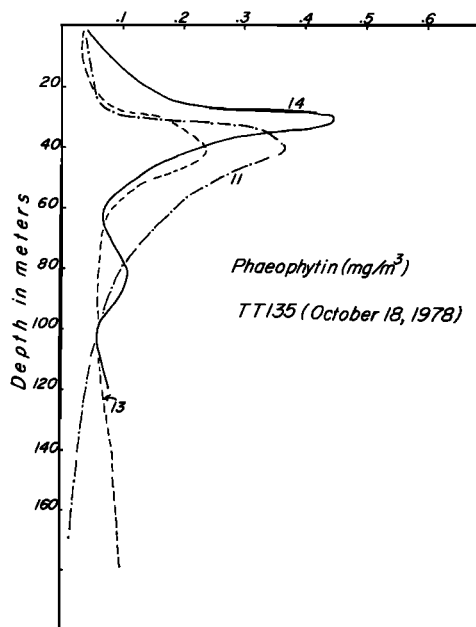spm concentration. Figure 13 is a plot of particle volume concentration against particle volumes. The volume concentrations of small particles clearly increase with depth.

Intermediate nepheloid layers observed during October 1978. A well-defined INL was observed at about 200-m depth during the R/V *Thompson* cruise in October 1978 over the continental slope off Washington near the Quinault Submarine Canyon (Figure 2). The INL extended from the shelf break at 150-m depth to 220-m depth, 20 nm further offshore. The layer was also characterized by a minimum in oxygen (Figure 4) and by low values of chlorophyll-*a* which prevailed at all depths below about 100 m (Figure 5). The phaeophytin concentration, on the other hand, showed a slight increase at the shoreside of the INL (stations 13 and 14 in Figure 6).

PSD measurement was made only for one sample in the INL, and its slope-concentration relation is consistent with the result from the W7711A cruise data (Figure 10).

Intermediate nepheloid layers and distributions of hydrographic data. The depths of spm maxima are usually observed to be parallel to isotherms. This trend has been verified by several observations over the past 5 years [*Pak and Zaneveld*, 1978; *Pak et al.*, 1980a]. The trend holds true when the isotherms are not horizontal. An example of a downward extending INL offshore is shown in Figure 2, and an upward extending INL is given by *Pak and Zaneveld* [1978]. In the two examples cited above, the layers were parallel to the local isotherms. Because salinity changes with depth are often small below the halocline, isotherms are usually also parallel to isopycnals.

A comparison of light transmission and temperature distributions (Figures 8 and 9) shows that the clear water at about 60-m depth is associated with relatively low temperatures, and the INL around 100-m depth is associated with relatively high temperatures. The clear water appears to be directly correlated with the minimum temperatures, while the INL lies just under, rather than at, the maximum temperature. *Huyer* [1974] described the existence of a subsurface layer of rela-

Fig. 5. Profiles of chlorophyll-*a* (mg/m^3) over the continental slope (stations 11, 13 and 14 in Figures 1 and 2) observed during the TT135 cruise (October 18, 1978).
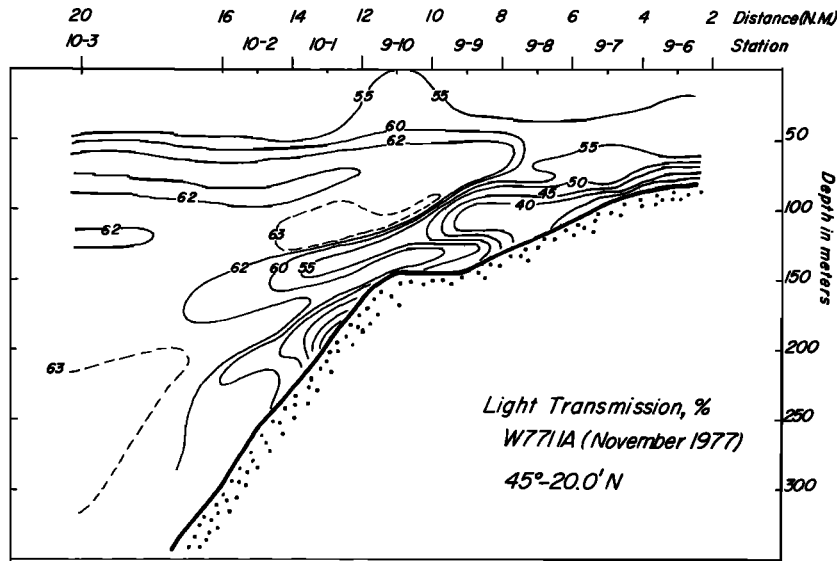
Fig. 7. Distribution of light transmission over the shelf off Oregon (Figure 1) observed during the W7711A cruise (November 9-10, 1977).

tively cold water in this region, and the layer was accounted for by advection of subarctic water by the coastal jet associated with the coastal upwelling regime. The low spm concentration in the cold water implies an offshore origin, while the low temperatures imply a northern source.

DISCUSSION

We have presented data which demonstrate the presence of spm maxima at several depths, and have also presented characteristic properties of the spm. Based on these observations, we now proceed to examine two hypotheses for the origin of such spm maxima.

The Settling Hypothesis

The settling hypothesis is based on downward transport of spm from the surface layer to the depth of the INL by gravitational settling. Stokes settling was examined extensively by Lerman et al. [1974], including effects of particle shapes, eddy diffusion, and the dissolution of particles. According to Lerman et al. [1974], an INL is formed as a result of changes in settling velocity, through the following processes: (1) due to increase in viscosity with depth and decrease in particle size by particle dissolution, settling velocity decreases resulting in increase in particle concentration with depth; and (2) at greater depths, particle concentration is reduced both in number and mass by dissolution of particles and rapid settling as a result of aggregation. A particle maximum requires an increase in particle concentration with depth, but it also requires fewer particles below the particle maximum. Thus an INL formed by particle settling alone requires accumulation of particles above and elimination of particles below the maximum.

Direct verification of the settling hypothesis seems difficult partly because (1) settling velocities are generally small, (2) vertical changes in settling velocity are small, (3) dissolution and aggregation are difficult to observe, and (4) the water column is usually moving at least 3 orders of magnitude faster horizontally than the prevailing settling velocity. Furthermore, trajectories of settling particles may be complicated by

vertical currents and vertical shear from variations in horizontal currents.

Settling. Stokes settling velocity w is expressed by

$$w = \frac{2}{9} r^2 \frac{g(\rho_s - \rho)}{\eta}$$

where ρ_s and ρ are the densities of the particle and water, respectively, η is molecular viscosity, r is the radius of the settling particle, and g is acceleration due to gravity. Within the normal range of water densities of the ocean, the maximum effect of water density on Stokes settling velocities is found to
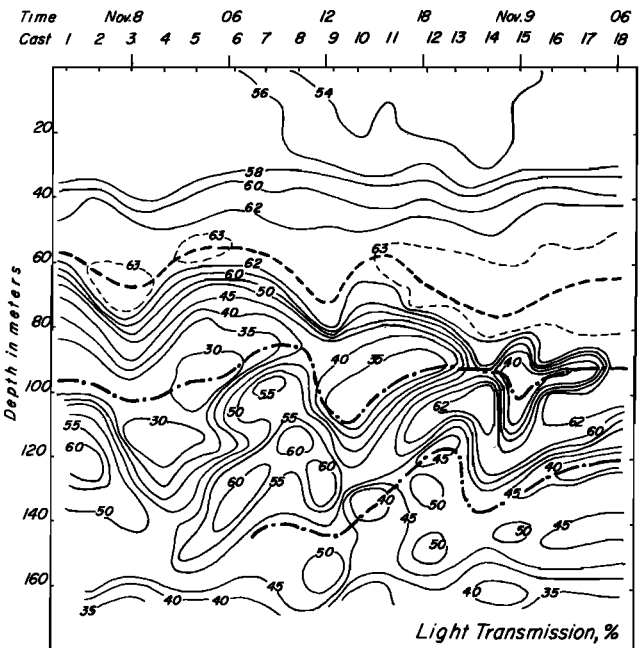

Fig. 8. Vertical distribution of light transmission (in percent) observed during the W7711A cruise at the anchor station approximately 10 n. mi. offshore (Figure 1). The clear water of over 63% transmission is denoted by a broken curve, and the intermediate nepheloid layers are denoted by dash-dot curves.

be approximately 0.5%, which is negligibly small. The viscosity of water increases, however, by 36% from 15° to 0°C, and Stokes settling decreases with increasing viscosity.

As shown above, changes in water properties could reduce Stokes settling by as much as, but no more than, 36%; hence particle concentration could increase by no more than 36% because of reduced settling. A large vertical gradient in water density has, nevertheless, often been considered to trap settling particles, particularly at a sharply developed thermocline [*Jerlov*, 1959; *Carder et al.*, 1971; *Lerman et al.*, 1974]. Changes in settling velocities at the thermocline are usually insufficient to fully account for the large spm maxima often observed there. Our data indicate that intermediate particle maxima often entail an increase of 300 to 1000% in particle volume compared to the water above the peak.

Particle settling has long been thought to be the dominant downward particle transfer process in the ocean. Based on Stokes settling velocities calculated from observed particle sizes and reasonable estimates of the other parameters in Stokes settling, *McCave* [1975] concluded that particles in aggregation, though rare, constitute most of the vertical flux. The other, much smaller, particles settle so slowly that their distribution is controlled by horizontal currents. Observed vertical distributions of spm, especially distributions that appear stable, are considered to consist of the slowly settling particles which are labelled 'background material' by *McCave* [1975]. The rapidly sinking particles, whether in aggregation or not, cannot be an important source to the INL because their residence at any one level will be short unless their settling velocity somehow changes abruptly to near zero. Thus when we consider settling as an important process of INL formation, the settling particles have to be the slowly settling background material.

Temperature of water decreases with depth; therefore the Stokes settling decreases with depth accordingly. In spite of smaller settling velocities in deep water, an INL is rarely ob-
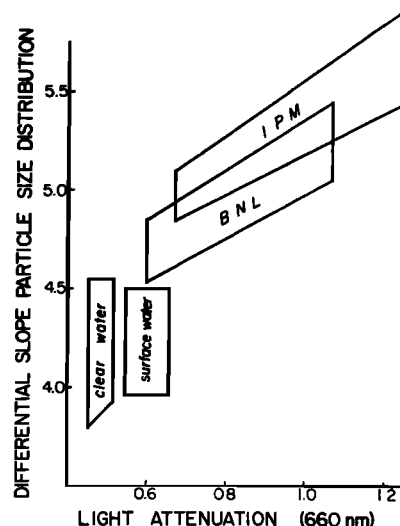
Fig. 10. Differential slope of particle size distribution plotted against light attenuation (660 n. mi.).

served in deep waters of the open ocean. Unless particles are eliminated from the water column by dissolution filter-feeders or aggregation and subsequent fast settling, more INLs would be expected in deep waters. Contrary results are found in observations.

Off the northern Peru coast (approximately 4°S latitude), a well-defined spm maximum was observed at approximately 400-m depth, and this maximum extended over 600 km offshore to the west from the coastal region [*Pak et al.*, 1980a]. At the same depth, sharp vertical temperature and density gradients were also observed. The layer is well below the euphotic zone. This INL is one rare example of an INL found at maximum temperature and density gradients well below the seasonal thermocline.

Types of spm inferred from oxygen, chlorophyll-a and phaeophytin distributions. The spm distributions determined by a transmissometer do not indicate anything about the nature of the particles. This information has to be obtained by other means. Particles in the oceans are generally classified as belonging to one of two types: terrigenous and biogenous. Terrigenous particles are brought into the ocean by winds and river plumes. Most biogenous particles are produced in the upper part of the ocean where solar radiation penetrates. Detrital materials derived from phytoplankton and zooplankton are also present in the ocean. Thus the spm maximum, for example, may contain particles of terrigenous and detrital origins in addition to living phytoplankton cells. Living phytoplankton, however, are the only kind of particle that can produce oxygen. An oxygen maximum in excess of saturation can result only from the photosynthetic process.

The presence of the spm maximum concurrent with the oxygen maximum (Figure 4) points out that the spm maximum contains a large population of oxygen-producing particles, and these phytoplankton cells are most likely produced at the depth of the oxygen maximum. The oxygen maximum therefore indicates that the spm peak mainly consists of locally produced phytoplankton and is not produced by an accumulation of settling phytoplankton generated in the surface water above the spm maximum.

The maximum phytoplankton production at the upper part of the thermocline is probably due to an optimum photosynthesis condition. Solar irradiance decreases nearly ex-
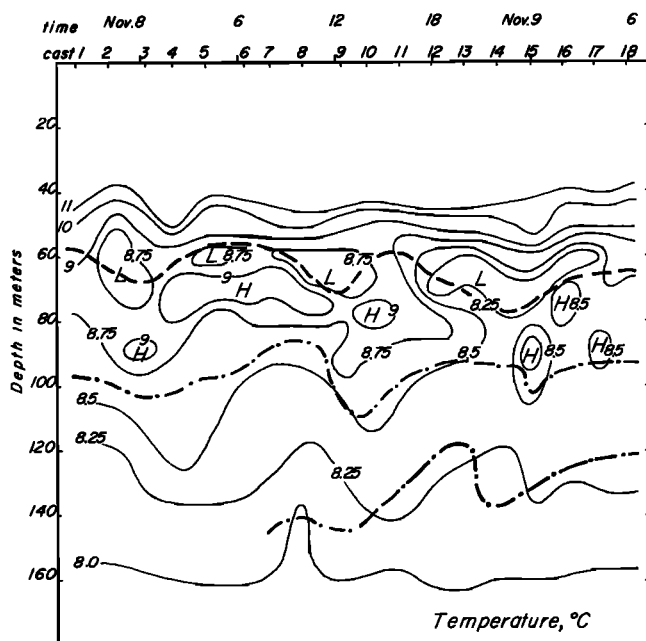
Fig. 9. Vertical distribution of temperature (°C) observed during the W7711A cruise at the anchor station approximately 10 n. mi. offshore (Figure 1). The axes of the clear water (broken curve) and intermediate nepheloid layers (dash-dot curves) in Figure 8 are added.
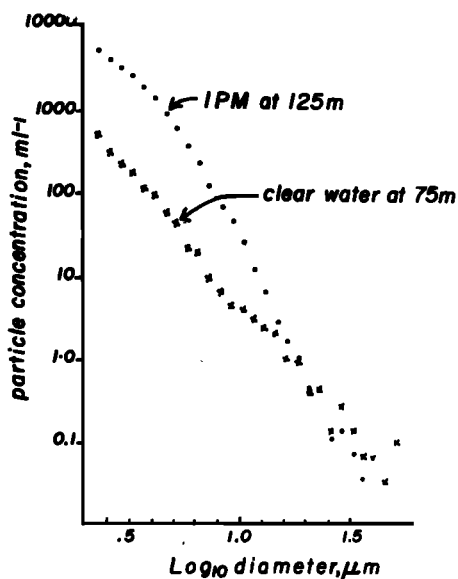
Fig. 11. Particle size distribution determined by a Coulter counter during the W7711A cruise at a station 10 n. mi. offshore on the 45°-20.0'N latitude.

ponentially with depth, but the nutrient concentration generally increases with depth from very low values in the surface water. Consequently, an optimum condition for photosynthesis usually exists at some distance below the sea surface, but still within the photic zone. The depths of the chlorophyll-*a* maximum (Figure 5) and phaeophytin maximum (Figure 6) also correspond to the spm and oxygen maxima, corroborating that the maximum photosynthetic production occurs in the spm maximum layer.

The vertically homogenous surface layer, indicated in all the parameters (Figure 4) including spm and dissolved oxygen, is obviously a result of mixing. Since the concentrations of spm and oxygen at their thermocline maxima are larger than those in the mixed layer above them, the maxima could not have been formed by the mixing process in the surface layer. Furthermore, the spm maximum is located in the thermocline where vertical mixing is limited.

Biochemical changes might change settling velocities of phytoplankton in the surface layer and contribute to the accumulation of phytoplankton at the thermocline. Those biochemical changes that might lead to retardation of settling phytoplankton are likely to be in the nature of degradation, and degradation of phytoplankton will consume rather than produce oxygen. Thus based on the oxygen maximum at the spm maximum, phytoplankton in the spm maximum layer are more likely to be living cells rather than dead cells; accordingly, they are more likely to be produced locally rather than be accumulated by settling from the surface layer.

Evidence is thus convincing that the thermocline spm maximum is a result of in situ phytoplankton production due to the optimum photosynthetic conditions present at the upper part of the thermocline. The settling hypothesis is therefore not corroborated by our observations of the thermocline spm layer.

The INL observed during October 1978 is not new in its shape, size, and location relative to the bottom topography [*Pak and Zanveld*, 1978] but its association with low oxygen concentration is newly observed. The distribution of oxygen in the section (Figure 3) shows that low oxygen concentration

is found in the deep water and in the bottom waters over the shelf and slope. Thus we can consider these low oxygen waters as possible sources of the oxygen minimum layer; that is, advection of the low oxygen water from the sources might have resulted in the observed oxygen minimum layer. We must not, however, neglect oxygen loss due to biochemical processes in the organic particulate matter in suspension. We do not have data to verify how much organic matter was present in the INL. Earlier data taken over the shelf off Oregon using an ozone method [*Pak et al.*, 1980*b*] indicated that both the BNL and INL contained relatively small amounts of organic matter. Under this circumstance, advection of low oxygen water may be the primary contribution to the formation of the oxygen minimum layer, and the local reduction of oxygen by suspended organic particles only a minor contribution.

Observed PSD. PSD slope is expected to be a relatively stable property of spm since it can be changed only by addition and subtraction of particles or by changes in particle sizes over a limited range of the size spectrum. The increase or decrease in particle size may come from particle disintegration or aggregation within a given water sample. The slopes of PSD in the surface water are approximately the same as those of the clear water below the surface water (Figure 10), indicating that the PSD did not change appreciably even if the particles had to settle through the surface layer and the clean water. Furthermore, the concentration of large-sized particles varies little from the INL to the clear water above it (Figure 11). The large population of small-sized particles in the INL therefore suggests addition of small-sized particles rather than internal shifts of particles sizes. If settling particles are to generate an INL with the observed characteristic PSD, the settling particles must reduce their size as soon as they reach the INL, not before, in order to maintain a constant concentration of large-sized particles. The decrease in settling velocity as a function of depth must correspond to the increase in spm concentration as a function of depth.

Lal and Lerman [1975] studied the changes in the particle size spectrum when particles undergo dissolution while settling. They considered dissolution at a constant rate and independent of particle size and water depth. Relative to a reference depth below the sea surface, dissolving particles are shown to generate domes or peaks at the small end of the size spectrum (size range of 1-10 μm), and location of the peak moves toward the large size with an increase in depth. Such a feature is a consequence of dissolution in proportion to the surface-to-volume ratio of particles. Dissolution is more effective in small-sized particles since a small particle has a higher surface-to-volume ratio than a large particle. Our observation of PSD's below the surface layer, however, show no indications of domes, both in and out of the INL.

Boundaries of INL's are often sharply defined (Figure 14). Such sharp boundaries are not likely to be the result of large differences in settling velocities. Similarly, bottom boundaries of INL's are sometimes defined as sharply as the upper boundary (Figure 14), and it is equally difficult to imagine that elimination of particles by dissolution and rapid settling by particle aggregation can result in such a sharp boundary.

Viscosity is strongly controlled by temperature, yet nepheloid layers are not often found at greater water depths beneath the euphotic zone, even in regions with a sharp temperature gradient or in the region of minimum temperature in the water column. As mentioned earlier, an exceptional case was observed off northern Peru where a neph-
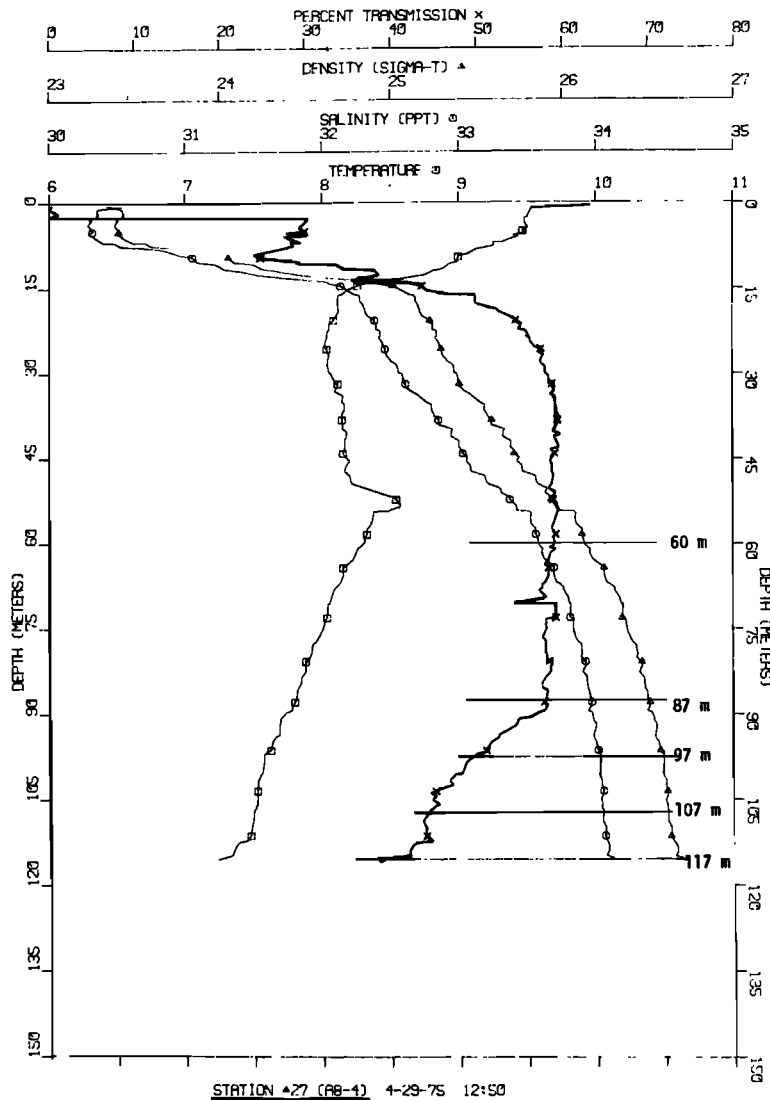
Fig. 12. Profiles of T, S, σ_t and light transmission (in percent) observed during the W7504 cruise at a station 8 n. mi. offshore on the 45°-10.0'N latitude. Depths of water samples for particle size analyses are denoted by horizontal lines.

eloid layer was found at a maximum temperature gradient at 400-m depth. Turbulence associated with internal waves at the temperature gradient may disturb the continental slopes [*Cachione and Wunch*, 1974], and particles may spread offshore in the layer. In this case, the particle transfer is a horizontal process, not a settling process.

Temporal variations of spm distribution. Time series of light transmission and temperature profiles were taken simultaneously during the W7711A cruise at an anchor station 10 n. mi. off the coast at 45°-20'N latitude. Observations were made for 36 hours at intervals of 2 hours. The data from the anchor station show the typical light transmission distribution of shelf water (Figure 8). The INL shows vertical displacements of up to 25 m in a few hours, and changes of the thickness of the INL centered around 100-m depth from 10 to 70 m. The temporal variations shown in Figure 8 (i.e., changes in thickness, depth, and spm concentration in the INL), are considerably larger than what Stokes settling by small particles can account for. The temporal variations clearly suggest that processes other than Stokes settling prevail.

Horizontal Advection Hypothesis

Observations at the thermocline spm maximum clearly suggest that the thermocline spm maximum is the result of a local maximum in photosynthetic production of phytoplankton. Deep INL's are obviously produced by other processes since they are not in the euphotic zone.

The distributions of spm concentration, PSD, oxygen, and hydrographic data at about 125-m depth off the Oregon coast (Figure 7) cannot be accounted for by the settling hypothesis. We now use the same evidence to examine an alternative hypothesis, the horizontal advection hypothesis.

Generation of an INL by horizontal advection of BNL's. There are two prominent sources of spm in the ocean, one in the surface layer and the other in the BNL. The possibility of generating an INL by drawing spm from the surface layer via the settling process has already been discussed. Alternatively, an INL may be generated by drawing particles from a BNL, the other prominent spm source in the ocean. In this case, the primary mode of particle transport will be hori-
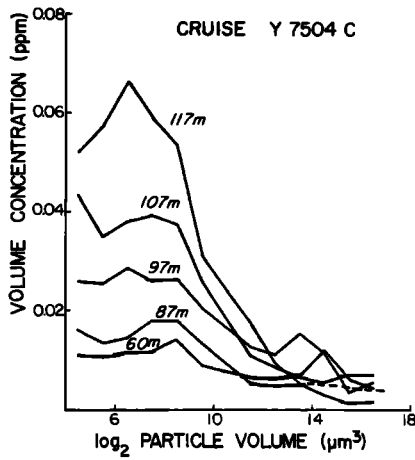
Fig. 13. Particle concentration by volume at five depths shown in Figure 12.

zontal advection rather than vertical settling. This process will be more effective in areas where the bottom is sloped. BNL's are nearly ubiquitous, although their intensity and thickness may vary substantially in time and space (Figures 7 and 8).

The horizontal advection hypothesis has been suggested by the present authors [*Pak and Zaneveld*, 1978; *Pak et al.*, 1980a] on the basis of (1) a distinct tongue-shaped pattern of an INL extending horizontally from a BNL over the outer continental shelves off Oregon and Peru; (2) the presence of an INL along a narrow range of water densities; and (3) the association of the INL with maxima in nitrite and particulate protein and minima in oxygen and nitrate.

In addition to the above, the PSD data presented in this paper indicate that the PSD's in the INL are similar to those in the BNL, but dissimilar to those in the clear water above and below the INL. The similarity in PSD between the INL and the BNL suggests that the two are related. The relationship requires horizontal advection from the BNL into the INL. A BNL over a sloped bottom can be considered as a source from which particles can be spread horizontally to generate an INL. Since the spm in the BNL has the same PSD characteristics as the INL, the spm need not undergo any radical change in moving laterally from the BNL to the INL.

Both the upper and lower boundaries of the spreading turbid water (INL) can be sharp or diffuse, depending only on the mixing conditions of the INL, rather than on the dissolution behavior of the particles. It is only required that the
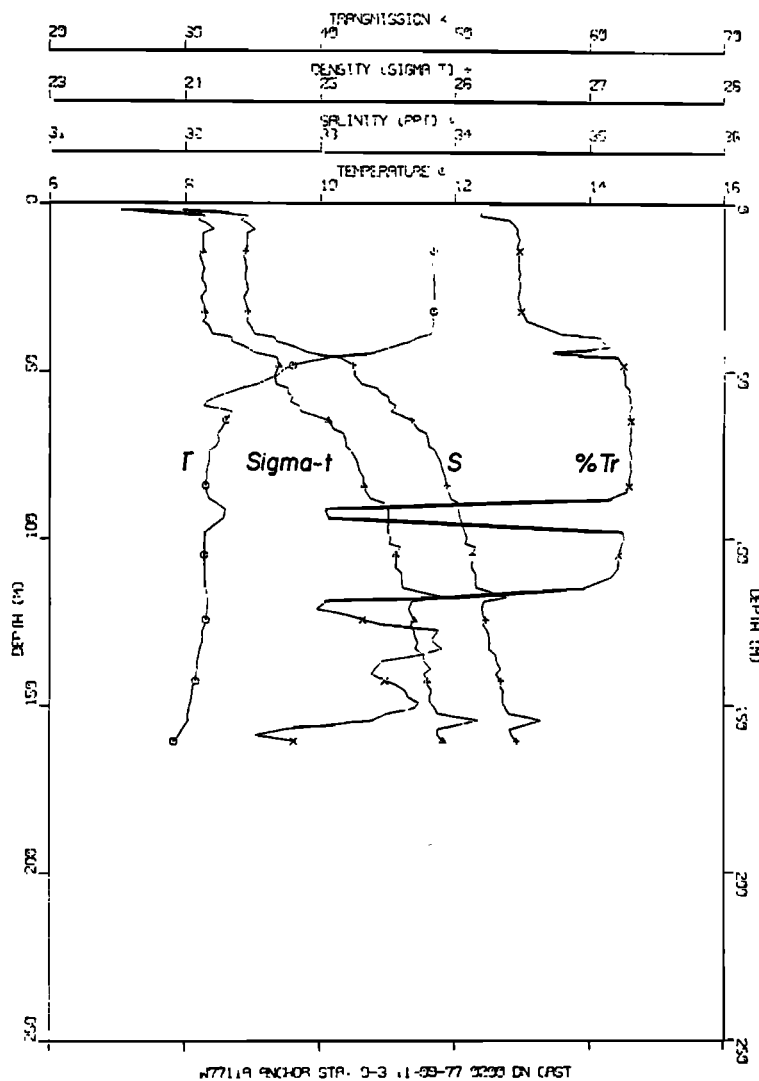

Fig. 14. Profiles of T, S, σ_t, and light transmission observed during the W7711A cruise at a station 10 n. mi. offshore on the 45°-20.0'N latitude.

particles be nearly neutrally buoyant, settling very slowly. The predominance of small particles, indicated by large slopes in PSD, assures that those particles meet this requirement.

An spm maximum, as shown in this paper, can be associated with either an oxygen maximum or minimum. The distribution of oxygen in the zonal section shown in Figure 3 suggests that the source of the low oxygen water (or oxygen sink) for the oxygen minimum layer near 200 m is in the bottom water over the shelf. Thus the process of the INL formation suggested above and in earlier papers [Pak and Zaneveld, 1978; Pak et al., 1980a] is also consistent with the formation of the oxygen minimum layer. The oxygen minimum layer presented in Figure 3 is a smaller-scale feature than that off Peru. It is not possible to ascertain from the data whether the spm maximum produces the oxygen minimum or whether they are advected jointly from the shelf. It is certain, however, that INL's such as those observed off Oregon, Washington, and Peru cannot be generated locally and must be the result of horizontal advection.

Other Remarks

It is noteworthy that similar INL's have been observed over widely separate areas (off the coasts of Peru, Oregon, and Washington) and over a span of several years. Observations off Peru have not been repeated, but repeated measurements were made off Oregon and Washington. The common features of these INL's suggest that these layers might be generated by common processes. All the observations made so far happened to be in the vicinity of the eastern boundaries of the Pacific, in connection with continental shelves and slopes, and approximately at depths of shelf edges. We would speculate that one or more physical processes together with the common topographic features may be important in generation of the observed INL's. We can think of several examples of such processes: coastal upwelling, eastern boundary currents, and interaction between internal waves and bottom topography. These topics are suggested for future studies.

The linear relationship between spm concentration and PSD slope (Figure 10) is remarkable. The BNL's and INL's have similar properties, but they are different from the surface layer and clear water at mid-depth. During the W7711A cruise (when the data for Figure 10 were taken), the seas were very rough, so that the bottom water might have been associated with unusually high turbulence. The unusually well-developed INL's observed during this cruise seem to substantiate the higher-energy conditions.

CONCLUSIONS

Significant vertical transport of particulate matter occurs only for larger particle sizes. Small suspended particles have settling velocities that are many orders of magnitude smaller than horizontal advection and their distribution is thus determined by processes other than vertical settling.

Vertical profiles of beam transmission, oxygen, and hydrographic parameters presented here demonstrate that the thermocline spm maximum is due to in situ phytoplankton generation. The upper part of the thermocline has sufficient light from above, a sufficient supply of nutrients from below to provide optimum photosynthetic conditions. Vertical mixing is also a minimum in the upper part of the thermocline, permitting large residence times for phytoplankton.

The intermediate nepheloid layers below the thermocline

are shown to be a result of offshore quasi-horizontal transport of bottom nepheloid material away from the shelf edge. A diagram mapping the slope of the particle size distribution and the beam attenuation coefficient clearly showed the relationship of INL and BNL materials. The increase in suspended volume in the INL and BNL relative to adjacent waters is due to small particles. An oxygen minimum coincident with the INL as well as hydrographic data corroborate the horizontal advection hypothesis for the generation of intermediate particle maxima.

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