Temporal Variability of Suspended Matter in Astoria Canyon

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Suspended matter in Astoria canyon was monitored by means of an in situ nephelometer and by means of light-scattering and particle concentration measurements performed aboard ship on water samples. Nephelometer profiles obtained along the axis of the canyon in February and April 1973 indicate that the canyon is divided into two distinct zones: a nearshore zone in which the suspensoid distribution undergoes large changes and an offshore zone in which the distribution varies to a much lesser degree. A 15-hour time series of light-scattering and particle concentration profiles at a depth of 1100 m in the canyon shows extensive and rapid changes in suspended matter concentration at several depths. The effect of nonsteady state distributions of suspended matter on calculations of the coefficient of eddy diffusivity is examined and shown to be an important consideration in a submarine canyon.

The extent to which observed distributions of suspended matter vary with time is important relative to their roles as indicators of abyssal circulation and sediment dispersal, and at the present time, information on the time variability of suspended particulates, especially in the deep ocean, is limited.

In estuaries and on the continental shelf a great deal of work has been done concerning the distribution and transport of sediments [*Swift et al.*, 1972]. However, observations of changing distributions of suspended matter, which are an integral part of the problem of sediment transport, have been rare. The response of suspended sediment to tidal effects has been studied by *Schubel* [1969, 1971], *Wasowski* [1974], and others. Over the continental shelf, *Rodolfo et al.* [1971] have observed the responses of suspended matter to a hurricane, and *Harlett* [1972], in a study of sediment transport on the shelf off Oregon, reported several time-series measurements of light transmission in depths of 100–200 m.

The data presented in this report resulted from our efforts to determine how the observed distributions of suspended particulates respond to the regimes of wind, surface and internal waves, and tides and currents in deep oceanic waters. Our initial efforts in this study were to determine the extent in time and space of changes in the concentration of suspended matter in the nearshore region and to extend these measurements offshore.

It was felt that Astoria canyon would be an advantageous site for this study for several reasons. It has been suggested often [*Moore*, 1969; *Lyall et al.*, 1971] that submarine canyons are sites of 'channelization' of sediment transport and perhaps of bottom water flow, and there have been numerous studies of bottom currents in submarine canyons [*Fenner et al.*, 1971; *Shepard and Marshall*, 1973; *Keller et al.*, 1973], all of which have shown that bottom currents of significant magnitude exist in canyons and that flow reversals are common. One would thus expect that conditions would be favorable for resuspension and advective and diffusive transport of particulates.

Astoria canyon is located off the mouth of the Columbia River, a source of large amounts of particulate matter [*Gross and Nelson*, 1966; *Pak et al.*, 1970; *Conomos and Gross*, 1972]. Also, storm activity and large waves are not uncommon, a fact well known to oceanographers and others in this area. All these factors seemed to indicate a high probability of measurable short-term changes in the distribution of suspended matter within the canyon. A general survey of the bathymetry and geology of the canyon has been done by *Carlson* [1967]. His studies of sedimentation in the canyon indicate that major erosional activity has ceased in the canyon as a result of the increasing distance of the canyon head from the shoreline. The canyon, at present, appears to be filling up.

EXPERIMENTAL METHODS

Several different techniques were used in our studies of suspended matter. On earlier cruises, water samples were collected in plastic National Institute of Oceanography bottles, and laboratory measurements were made of light scattering by using a Brice-Phoenix light-scattering photometer and of particle concentration and size distribution by using a Coulter counter. On later cruises, in situ profiles of light scattering were measured by using a nephelometer constructed by the optical oceanography group at Oregon State University. The instrument, which has been described in detail previously [*Plank et al.*, 1972], measures the intensity of light scattered at 45° at depths up to 10,000 meters and provides a deck readout of the light-scattering signal along with temperature and depth signals. A surface-actuated rosette sampler allows the collection of water samples at any depth.

In addition to the light-scattering and particle measurements, temperature and conductivity were determined with a Geodyne CTD.

DATA

Figure 1 shows the bathymetry of the Astoria canyon region and the location of the stations at which measurements were made. These stations ranged in depth from 500 m, 28 km (15 n. mi.) off the mouth of the Columbia River, to 1900 m, 106 km (57 n. mi.) off the coast. The shallowest station was located near the beginning of the canyon, where relief between the canyon floor and the nearby shelf was about 200 m. The deepest station was located near the point where the canyon reaches the Astoria fan and becomes a deep sea fan valley. The stations were intended to be located along the axis of the canyon, however, the strong surface currents in the area and the narrowness of the canyon floor (as little as 0.6 km) made it difficult to consistently achieve this aim. These difficulties account for the lack of correspondence in depths at stations of the same number on different cruises.

The data presented here were collected on three different cruises in 1972 and 1973. In November 1972 a 15-hour time series of light scattering and particle content was obtained in a

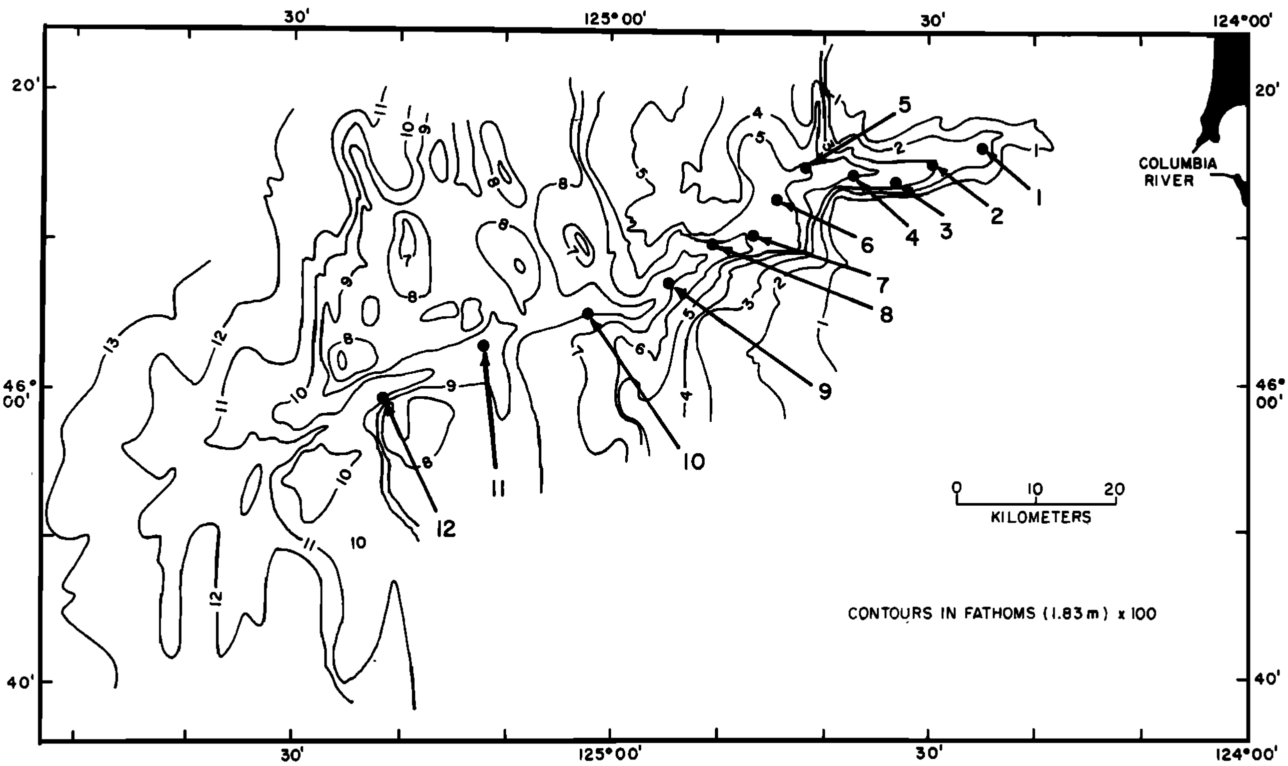

Fig. 1. Bathymetry and station locations in the vicinity of Astoria canyon after *Carlson* [1967].

depth of 1100 m on the canyon axis, and in February and April 1973 light-scattering profiles were obtained at a series of stations along the canyon axis. Figure 2 shows this series of light-scattering profiles. The relative geographic position of each profile is indicated by the point at which the profile comes closest to the bottom. The date and time each station was occupied are shown below the profiles so that the degree of nonsynopticity of the data can be evaluated. The profiles represent the relative magnitude of the logarithm of the value of the volume-scattering function β at 45° from the forward direction. Although the instrument calibration did not change from station to station, it was not calibrated in absolute values of $\beta(45)$, so that we can really only compare the shapes of the curves.

Figures 3 and 4 present the results of the time-series measurement of light scattering and particle content. These measurements were made between stations 7 and 8 as close to the axis of the canyon as possible in approximately 1100 m of water. During the time series of 6 nephelometer lowerings, which lasted from 0730 and 2230 on November 20, 1972, the ship drifted 3.9 km (2.1 n. mi.) in a westerly direction, which drift accounts for the increasing depth during the time on station. Figure 3 shows the profiles of $\beta(45)$ as determined by in vitro measurements with the Brice-Phoenix light-scattering photometer on water samples collected by hydrographic casts and also corresponding profiles of the total number of particles per milliliter greater than 2.2 μm as determined by Coulter counter measurements on the same samples.

In Figure 4 the values of particle count have been contoured to present a temporal cross section of suspended particulate variation. The cross section is also to some extent spatial because of the drift of the ship during the experiment.

DISCUSSION

The two sets of nephelometer profiles in Figure 2 are interesting in several respects. We can see that, especially for the stations nearer shore, there is a great deal of variation between the profiles taken in February and those taken in April. Some of the more pronounced differences include the light-scattering maximums at 200–350 m at stations 5, 6, and 7 in February that do not appear in April and the intense maximum at 100–200 m at stations 1, 3, 4, and 5 in April, which is present to some extent at stations 2 and 3 in February but is not nearly as well defined then. At the majority of the stations the intensity of light scattering increases as we approach the bottom, but the magnitude of the increase, as well as the depth range over which the increase takes place, varies a great deal. The most striking difference is at station 7 where in February there is a 350-m-thick layer of high-intensity scattering adjacent to the bottom but in April the layer is only about 50 m thick and the vertical gradient of light scattering is extremely high. These observed differences between the February and April distributions of light scattering are indications of the nonsteady state nature of the regimes of advective and diffusive energy which, along with particle settling and the strength of the various particle sources, determines the distribution of suspended matter.

It seems likely that the pronounced maximums at depths between 100 and 350 m, as noted above, are related to erosion and near-bottom transport on the shelf, which in this area extends offshore about 56 km (30 n. mi.) and lies at a depth of about 180 m near the shelf break. The light-scattering maximums at depths equal to or less than the surrounding shelf depth may represent sediment eroded nearby or further inshore at shallower depths and then transported into the axis of the canyon by offshore or longshore currents. The maximums at depths greater than the surrounding shelf depth may represent material similarly eroded and transported but of sufficient size to have settled somewhat and thus become trapped in the canyon.

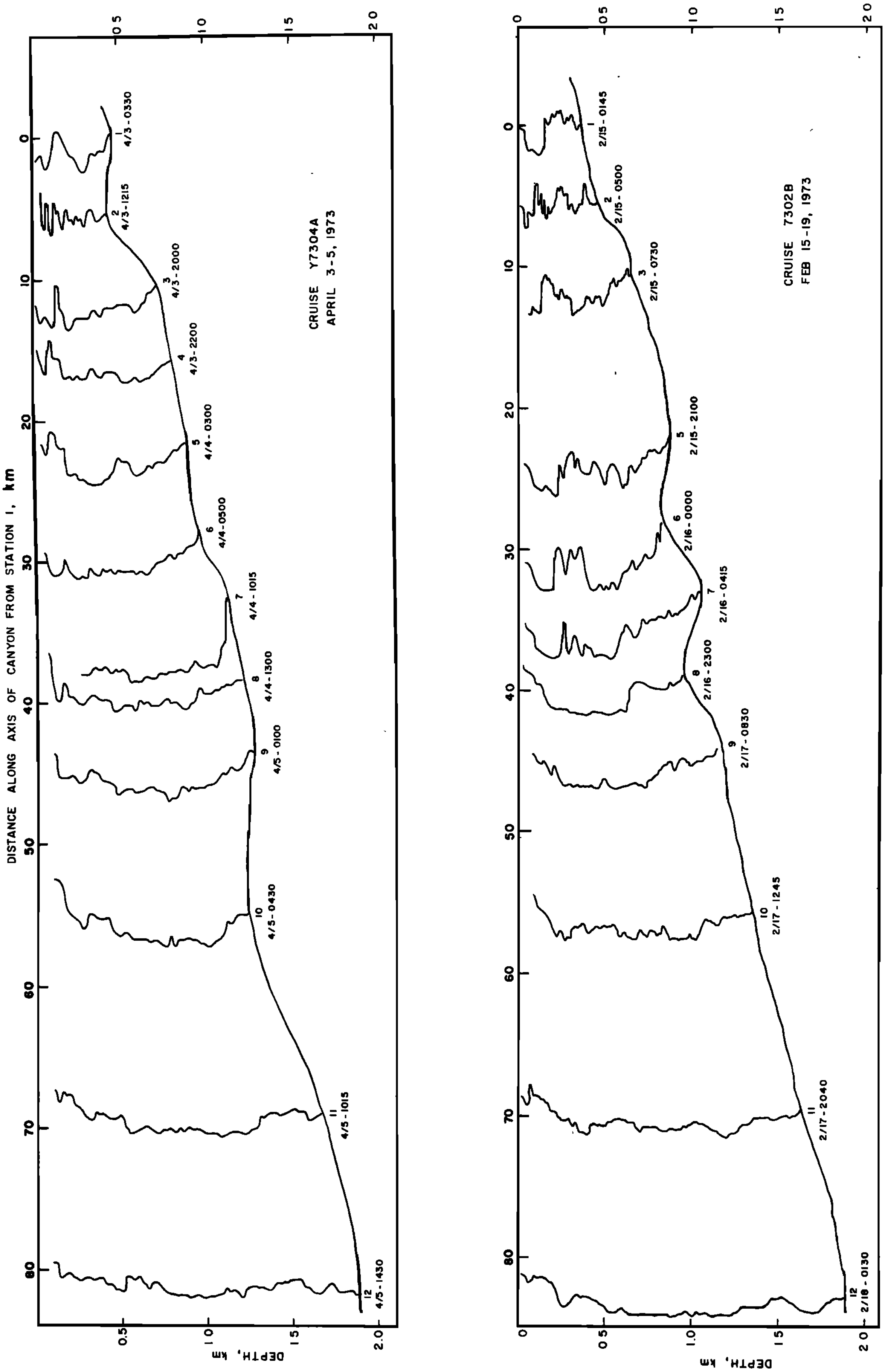

Fig. 2. Profiles of light scattering along the axis of Astoria canyon in February 1973 (bottom) and April 1973 (top). The location of the stations are indicated by the point at which the profile comes closest to the bottom. Values of light scattering represent the relative magnitude of the logarithm of the volume-scattering function $\beta(45)$.

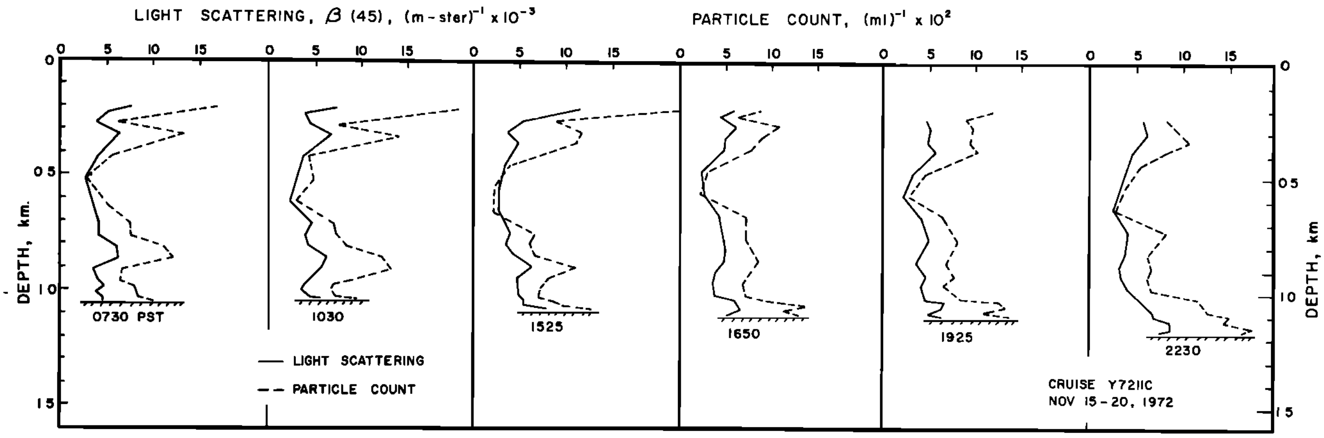

Fig. 3. Profiles of the volume-scattering function $\beta(45)$ in $(m\ sr)^{-1} \times 10^{-3}$ and the number of particles per milliliter larger than 2.2 μm at the time-series station in Astoria canyon.

The variations in the shape of the light-scattering profile at station 7 are undoubtedly a result of the changing nature of the fields of diffusive and advective energy within the canyon. The near-bottom thick layer of high-intensity light scattering present in the February profile may be a result of high-energy vertical diffusion in the lower part of the water column. On the other hand, the thin layer with a large vertical gradient at this same location may indicate bottom currents of sufficient velocity to erode sediments but vertical diffusion that is insufficient to transport the material upward.

Along with the February to April variations in the profiles at stations 1 through 8, another striking thing we notice about these data is the lack of temporal variation in overall shape between the profiles taken at stations 9–12. Although there are small-scale differences, light scattering appears to have changed very little between February and April and, in

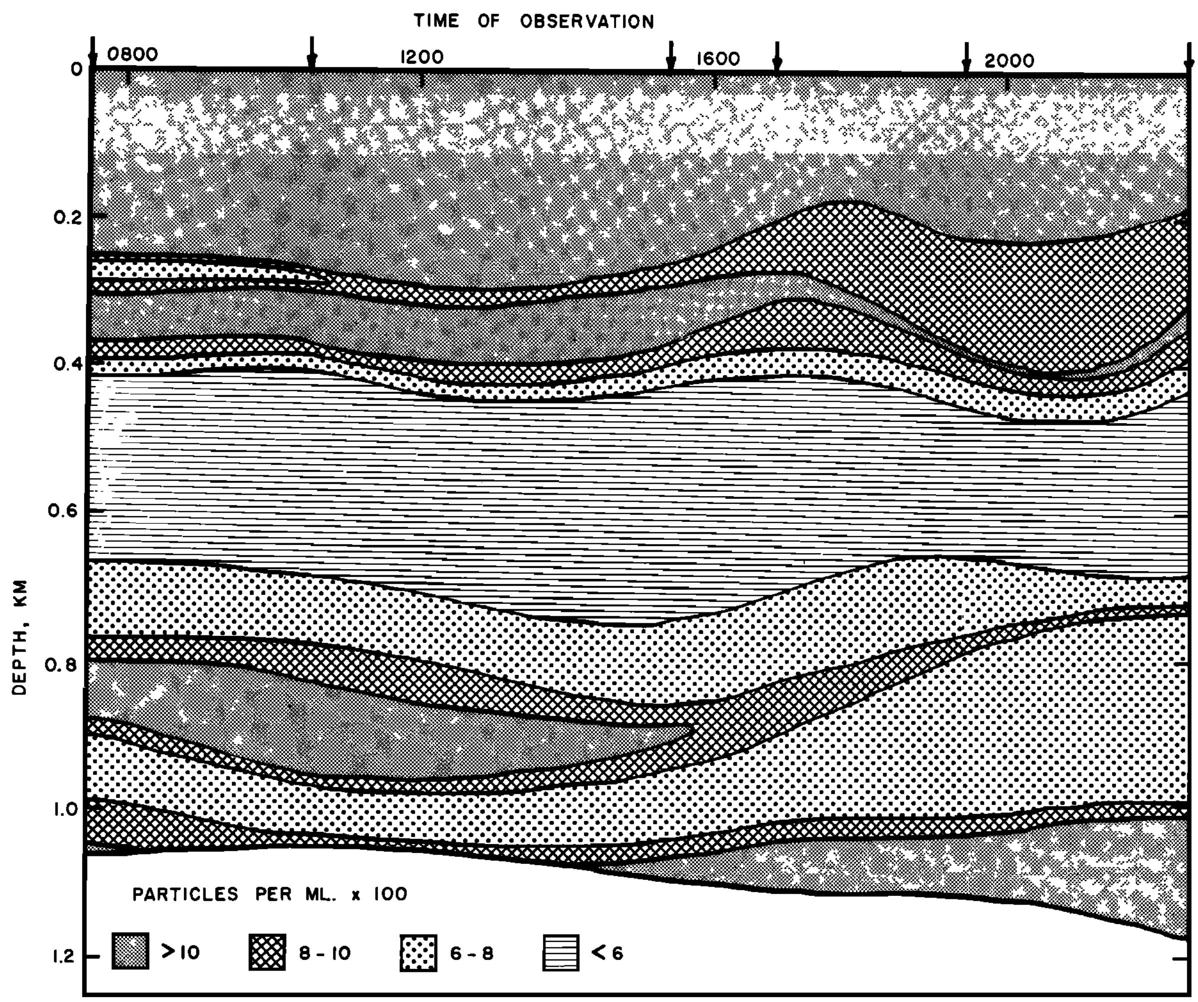

Fig. 4. Contours of particle count data from Figure 3 during time-series measurement in Astoria canyon. Arrows indicate times of nephelometer lowerings.

general, it seems that the increase in light scattering near the bottom seems less marked than in the stations closer to shore. As a result, it appears reasonable to divide the canyon into two distinct regions that reflect the observed light-scattering distribution and the probable regimes of advection and mixing.

Zone 1 (between stations 1 and 9). This is a zone of high temporal variability in the processes of advection and diffusion leading to large spatial and temporal gradients in suspended matter. Bottom erosion and near-bottom turbulent transport are likely. Flow is probably channelized to a large extent.

Zone 2 (beyond station 9). This is a 'quieter' zone where properties are more stable. Erosion of bottom sediments is less likely in this zone, although there is still some variability in the suspensoids resulting from nonsteady state advection and horizontal and vertical mixing.

By examining the bathymetry of the canyon we can find a possible explanation for this division. Shoreward of station 9, bathymetric profiles across the canyon show a deep (up to 500 m) canyon with steep sides. Water motions here would be restricted laterally and the likelihood of strong horizontal currents and vertical mixing greater. Beyond station 9 the shape of the canyon changes. The height of the canyon walls is less (<300 m) and the slope of the walls more gradual. The effect is to allow more lateral spreading, which may reduce the velocity of axial currents and decrease the intensity of vertical gradients within the canyon. The characteristics of the suspended sediment distribution in zone 1 are also undoubtedly related to the nearness of sediment sources (Columbia River, surf zone) and the greater intensity of surface wave effects.

We can get some idea of the magnitude and rapidity of the changes in the distribution of suspended matter by examining the results of the time-series measurements of light scattering and particle count in Figures 3 and 4. During a time period of 15 hours the measurements of both of these properties increased by a factor of about 1.9 near the bottom, and it can be seen that a turbid layer about 300 m in thickness adjacent to the bottom has appeared in this short time. Also an intermediate maximum at 800–900 m depth has completely disappeared, and a maximum at 300–400 m depth has diminished greatly in intensity.

Previous investigators have indicated relationships between suspended matter and canyon bottom currents or meteorological conditions [*Rodolfo et al.*, 1971; *Shepard and Marshall*, 1973]. Shipboard records of wind and sea state show that there was a fairly rapid rise in wind speed (from 5 to 10 m/s in about 18 hours) and in wave height (from about 1.3 to 2.7 m) about 60 hours prior to the beginning of the time series. These strong winds blew for about 36 hours and then decreased to less than 2.5 m/s. At the time the measurements were taken the wind was again in the process of increasing to above 10 m/s. It is possible that the increase in suspended matter adjacent to the bottom is the result of sediment erosion in shallow water and subsequent transportation by advection to the site of the measurements. If we assume that the increase in light scattering near the bottom is due to sediment eroded in the surf zone by the rapid increase in wind and wave height and then carried down the canyon by a bottom current, we can estimate the speed of this current at about 25 cm/s (56 km in 60 hours). We might compare this to the net transport figures for bottom currents in canyons off southern California and Baja California reported by *Shepard and Marshall* [1973] that ranged from 0 to 123 m/h with an average of only 67 m/h or about 1.8 cm/s. It seems unlikely therefore that our observed rise in particle concentration near the bottom is the direct result of the meteorological conditions observed during the cruise. It is possible, of course, that we could be observing the results of some previous storm, however, considering the lack of spatial coherence in the canyon bottom currents observed by *Shepard and Marshall* [1973] and the time variability we have observed in suspensoid distributions, it is probably unrealistic to think of 'patches' of sediment traveling down the length of a canyon, and we should rather think of a continuous process of erosion, mixing, advection, redeposition, etc. What we see then at a depth of 1000 m (35 n. mi.) off the coast may be poorly correlated with recent meteorological events.

Measurements of temperature and salinity made coincident with measurements of light scattering and particle count gave no indication of the changes taking place below the surface layers.

Several authors have used observed profiles of light scattering or particle concentration to compute coefficients of vertical eddy diffusivity [*Ichiye*, 1966; *Eittreim and Ewing*, 1972; *Ichiye et al.*, 1972], and it has been necessary because of a lack of data on temporal variability to assume steady state in these cases. Given the time series we have observed we can attempt to determine the effect of the time-dependent nature of the observed distributions. Since in this case we lack data on the horizontal distribution of suspended matter and the velocity field, we shall assume that only vertical processes are at work. If we disregard the effects of horizontal advection and diffusion, we will obtain an upper limit on the magnitude of vertical eddy diffusivity. We may then use as the diffusion equation

$$\frac{\partial}{\partial z}\left[A_z\frac{\partial P}{\partial z}\right] - \frac{\partial}{\partial z}[wP] = \frac{\partial P}{\partial t}$$

where P is the concentration of a property. In this case we use light-scattering values that are assumed to be proportional to the concentration of suspended matter. There is some experimental justification for this assumption [*Beardsley et al.*, 1970]. In this case, w will refer only to the settling velocity of the particles; we assume vertical advection, which is included in this term to be negligible. Also, since w varies with particle size and density, we will choose a single settling velocity for a particle of average size and representative density. The effect of the use of the complete particle size distribution in solutions to the diffusion equation has been considered by *Zaneveld* [1972], and it seems likely that the use of a single average particle size is adequate for our purposes here.

In order to determine the effect of the time-dependent nature of the particle distribution we first assume steady state. The diffusion equation then becomes

$$W/A_z = 1/P\ \partial P/\partial z$$

In order to calculate A_z we assume a settling velocity of 1.8×10^{-3} cm/s, which is given by *Gibbs et al.* [1971] as the settling velocity for a particle of diameter 5 μm and specific gravity 2.65. We obtain values for $\partial P/\partial z$ and P by assuming that A_z and w are constant over a layer 50 m thick. We choose the profile taken at 1525 PST as being representative in shape, and we determine P at 25 m above the bottom. We then use $\Delta P/\Delta z$ for this layer as $\partial P/\partial z$. Note that the units of P cancel. Using values thus determined from the profile at 1525 PST, we obtain $A_z = 17$ cm²/s.

If we do not assume steady state but we do assume that A_z

and w are constant, the diffusion equation becomes

$$A_z \frac{\partial^2 P}{\partial z^2} - w \frac{\partial P}{\partial z} = \frac{\partial P}{\partial t}$$

Here $\partial P/\partial t$ is determined by plotting values of $\beta(45)$ at 25 m off the bottom versus t for the entire time series and measuring the slope of the tangent to this curve at 1525 PST. Then $\partial P/\partial z$ and $\partial^2 P/\partial z^2$ are again measured from the 1525 profile for the layer 50 m above the bottom, and w is again assumed to be 1.8×10^{-3} cm/s. In the nonsteady state case then, $A_z = 500$ cm^2/s, and we can see that in this case an error of more than one order of magnitude would have been incurred by an assumption of steady state.

Our evidence of the time-dependent nature of the distribution of suspended sediment indicates that assumptions of steady state for the purpose of inferring deep-ocean circulation are unrealistic in the type of environment we have investigated. Our work indicates a need for similar studies in other deep-ocean environments that have often been assumed to be in steady state.

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