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A Study of the Optical Characteristics of the Suspended Particles in the Benthic Nepheloid Layer of the Scotian Rise

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Light transmission profiles have been used to study the optical properties of the suspended particles which are characteristic of the area of the Scotian Rise in the North Atlantic Ocean. This area is typified by very strong bottom currents and a highly variable bedform morphology. A good correlation ($r = 0.96$) has been found between the suspended volume and the light beam attenuation coefficient. This correlation is consistent with the fact that the cumulative slope of the hyperbolic particle size distribution is nearly constant throughout the region (slope = 3.1 ± 0.3). Numerical analysis of the optical data in conjunction with particle size analysis yields values of the index of refraction of the suspended particles of 1.20 ± 0.07 relative to water. The conclusion drawn from these results is that the Scotian Rise benthic zone is characterized by suspended particles of high relative index of refraction and size distributions which do not vary much with altitude above bottom or over periods of time of more than a year in spite of the extensive fluctuations in activity of the region.

INTRODUCTION

Optical characteristics of deep-sea suspended particulate matter have been studied as part of the High Energy Benthic Boundary Layer Experiment (HEBBLE) (Figure 1). HEBBLE is a multi-disciplinary, multi-institutional program developed in order to "... increase dramatically our understanding of the flow dynamics and geological effects of strong flows in the deep-ocean benthic boundary layer" [*Hollister et al.*, 1980]. The data presented in this work were collected primarily during cruise number 74, from September 7, 1979, to October 4, 1979, aboard the R/V *Knorr* from Woods Hole Oceanographic Institution. A large amount of data was collected over the whole HEBBLE region (nearly 50 CTD casts were made on this one cruise) and several zones of interest were surveyed. (The CTD is a conductivity-temperature-depth measuring instrument designed by Neil Brown instrument Systems. A light transmissometer designed at Oregon State University and a General Oceanics-Niskin bottle rosette sampler were used in conjunction with the CTD on each cast.) It was found that the region of highest activity lay at the deepest part of the continental rise, near the landward edge of the Sohm Abyssal Plain; it was in this zone that bottom photographs, current meters, transmissiometers, and sediment traps indicated the highest levels of near-bottom current activity [*Hollister et al.*, 1980; *Spinrad and Zaneveld,* 1982]. For this reason the work described herein will concentrate on the data obtained from the stations that were located in bottom depths between 4900 and 5000 m. This depth range also corresponds to the zone where fixed-location instruments (e.g., Bottom Ocean Monitor, Chandelier, and TRIFFID) were placed during this time. (The Bottom Ocean Monitor contained an OSU transmissometer, a Lamont nephelometer, and an Aanderaa current meter. Chandelier was a vertical array of current meters. TRIFFID contained bottom cameras, transmissometer, and sediment trap.)

Measurements of fine resolution (±10%) of suspended particulate matter concentration can be made with highly collimated beam transmissometers [*Tyler et al.*, 1974; *Bartz et al.*, 1978]. The use of optical measurements as an indicator of particle concentrations is a well accepted practice [e.g., *Kalle,* 1939; *Jerlov,* 1957; *Thorndike and Ewing,* 1967; *Eittreim et al.*, 1972; *Eitreim and Ewing,* 1972; *Biscaye and Eittreim,* 1974; *Gibbs,* 1974*a*, *b*, *c*; *Jerlov and Steemann-Nielsen,* 1974; *Kullenberg,* 1974; *Carder et al.*, 1974; *Pak,* 1974; *Pak and Zaneveld,* 1977].

METHODS

The attenuation coefficient is expressed as

$$c = c_w + a_p + b_p + a_y \tag{1}$$

[*Jerlov,* 1976] where c = beam attenuation coefficient defined as the internal attenuance of an infinitesimally thin layer of medium normal to the beam divided by the thickness of the layer (m^{-1}); a = the absorption coefficient; b = the scattering coefficient also $c = a + b$.

The subscripts w, p, and y refer to water, particles, and yellow matter (humic acids and dissolved organic substances), respectively (if no subscripts are used then the terms refer to total attenuation, scattering and absorption). Owing to the greatly reduced attenuation by dissolved matter in the long wavelengths, the transmission measurements made at 660 nm described in this paper will yield values of the beam attenuation coefficient of

$$c = c_w + a_p + b_p = c_w + c_p \tag{2}$$

The absolute value of c_w at 660 nm is not known but estimates range from roughly 0.25–0.50 m^{-1} [*Jerlov,* 1976; *Smith and Baker,* 1981] (the explanation for this lies in the extreme difficulty in obtaining an optically clean system and optically pure seawater). The beam transmissometer used in this experiment has been calibrated to yield a value of c_w of 0.40 m^{-1}. The relationship between the beam attenuation

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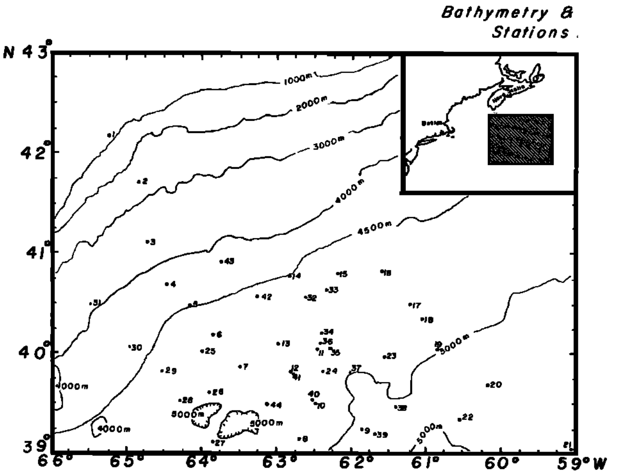

Fig. 1. Map of the study area showing bathymetry and station numbers.

coefficient and transmission, T, is

$$T = e^{-cr} \tag{3}$$

where T = the fraction of incident light transmitted and r = pathlength = 1 m in this case.

The beam attenuation coefficient and particle concentration are well correlated when size and refractive index distribution are constant or mutually compensating [*Peterson*, 1978]. Particle volume concentrations were measured by Coulter Counter at the same locations as transmission measurements. A strong correlation was found ($r = 0.96$; see Figure 2) and is given by

$$P = -265.1 + 569.5c \tag{4}$$

where P is in parts per billion volume concentration and c is in m^{-1} ($40 \text{ ppb} \le P \le 600 \text{ ppb}$).

Also shown in Figure 2 are the 95% confidence limits of the slope as well as the limit defined by 2 standard deviations from the predicted concentrations.

This relationship yields a value of $c = 0.47 \text{ m}^{-1}$ or $T = 63\%$ for particle-free water. This deviation of the attenuation coefficient for clear water from the calibration value of 0.40 m^{-1} is a consequence of the way in which the Coulter Counter data were acquired. Instrument limitations make it impossible to count accurately the smallest particle sizes. Consequently, depending on the experimental setup, the Coulter Counter can "miss" a certain percentage of the particle size distribution. In this way the water sample which the Coulter Counter may consider reasonably clear is one for which the transmissometer may detect small particle concentrations. This discrepancy also explains most of the scatter seen in Figure 2. Additional sources of scatter in the figure are variations in the optical characteristics of the particles and local inhomogeneities in the suspended particle concentrations.

A similar correlation was calculated by McCave for data collected in the same area a year and a half later. The regression equation he obtained was (I. N. McCave, personal communication, 1981)

$$P = -203.4 + 496.0c$$

$$r = 0.93$$

The agreement between this regression and the one used in this work is shown in Figure 2.

Zaneveld [1973] has shown that a linear correlation exists between suspended mass or volume concentration and an optical measurement, provided the nature of the particles (including particle size distribution) does not vary. The beam attenuation coefficient is dependent on the total cross-sectional area of the particles, and, consequently, any changes in the particle size distribution that might go undetected in measurement of volume concentration would be seen by the transmissometer. The opposite situation is also valid: The particle size distribution could change without a change in the overall cross-sectional area. However, in that case the volume concentration would change. Yet the previous discussion of the correlation betwen volume concentration and beam attenuation coefficient indicates a linear relationship between the two. The narrowness of the 95% confidence interval about the ordinate emphasizes the near-constancy of the ratio of the beam attenuation coefficient to the particle volume concentration. Changes in the slope of the particle size distribution over the range of volume concentrations observed would result in deviations from the slope of the curve shown in Figure 2. Calculations of c and PPB indicate that the slope of the curve shown in Figure 2 would exceed the 95% confidence limits if the slope of the particle size distribution were to increase by about 0.35. The result is that optical measurements indicate that variations in the slope of the particle size distribution in the zone under consideration are small. This conclusion is verified by the measurements made with a particle size analyzer; data for stations 12, 24 and 36 have been made available to these authors and are shown in Table 1 and Figure 3. The slopes indicated are the slopes of the cumulative size distribution given by

$$N_D \sim D^{-\gamma} \tag{5}$$

[*Bader*, 1970] where γ = cumulative slope, and N_D = number of particles with diameters greater than D per unit volume.

TABLE 1. Cumulative Slope of the Hyperbolic Particle Size Distribution at Various Altitudes Above Bottom

Height Above Bottom, m	Cumulative Slope
Station 12	
4	3.1
4	3.0
57	3.1
134	3.0
240	3.4
673	3.2
Station 24	
4	3.1
4	3.0
55	3.0
182	3.3
290	3.1
434	3.1
572	3.0
727	3.0
Station 36	
4	3.3
4	3.2
127	3.3
157	3.2
196	3.2
277	3.2
360	3.0
510	2.9

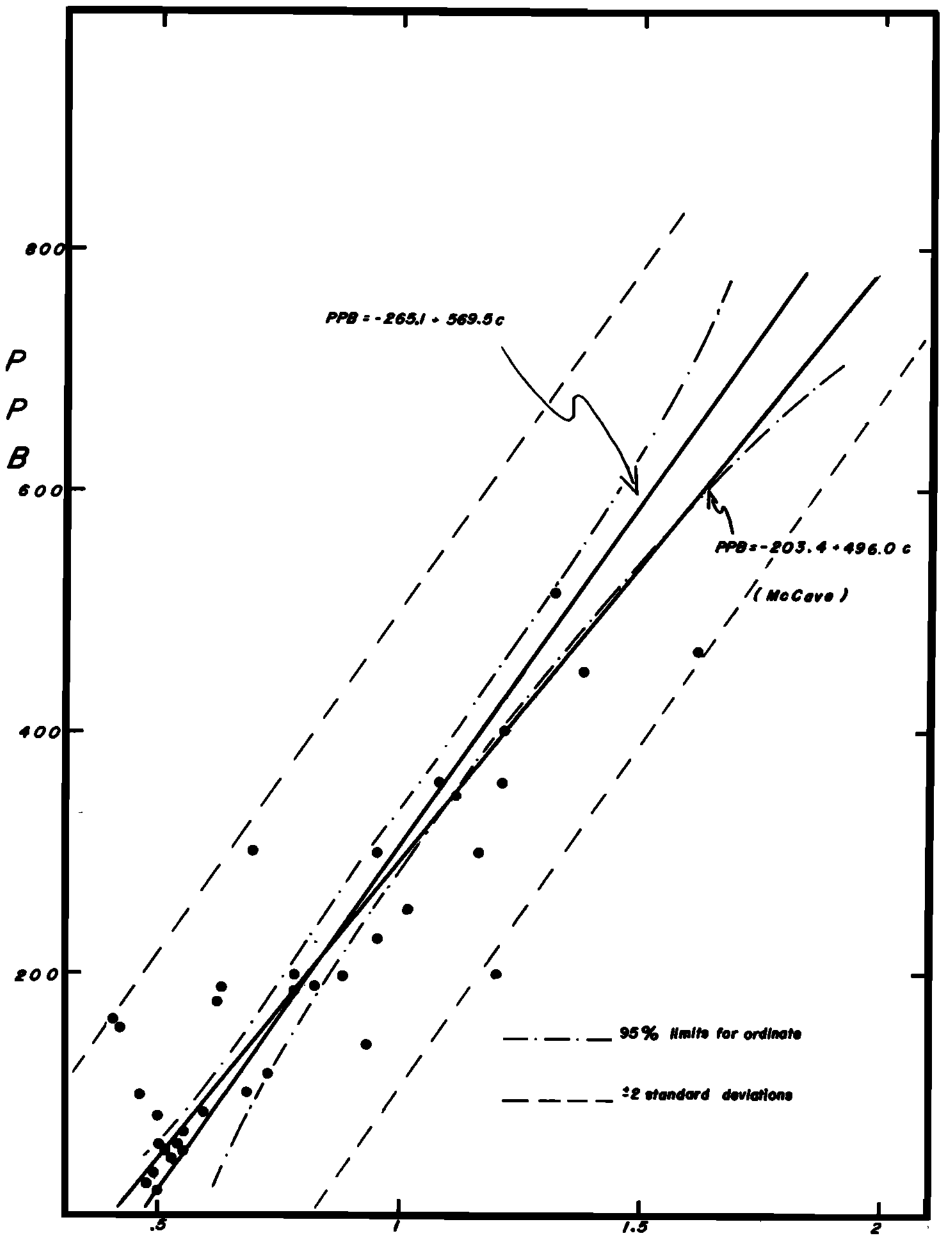

Fig. 2. Correlation of particle volume concentration (ppb = parts per billion) and beam attenuation coefficient.

The most obvious feature of Table 1 and Figure 3 is the homogeneity of the particle size distributions in the HEBBLE area. The slope of the distributions never varied by more than 0.3 from a value of 3.1. These data represent measurements taken over the course of nearly two weeks in time and roughly 80 km separation in distance. At the bottom of the water column the mean slope for these three stations is 3.1 with a standard deviation of only 0.1. Additional Coulter Counter data indicate that this homogeneity is the general rule for HEBBLE suspended particle distributions (M. J. Richardson, personal communication, 1981).

The transmissometer data may also be used to study the nature of the particles. Specifically, an analysis may be made of the particulate index of refraction by applying the classical equations of light attenuation to the measurements made here.

For a single particle of diameter D, with a single-valued index of refraction, m_p, the effective area coefficient or efficiency factor, Q, is given by

$$Q = \frac{c_p}{\pi(D^2/4)} \tag{6}$$

where c_p = particulate beam attenuation coefficient.

For a given particle size distribution equation (6) may be written as

$$c_p = \sum_{i=i}^{n} N_i Q_i \frac{\pi D_i^2}{4} \tag{7}$$

N_i is the number of particles of diameter D_i per unit volume.

Most particle ensembles are not characterized by a single index of refraction but rather by a distribution of values over a range of indices [*Zaneveld et al.*, 1974; *Roach*, 1975].

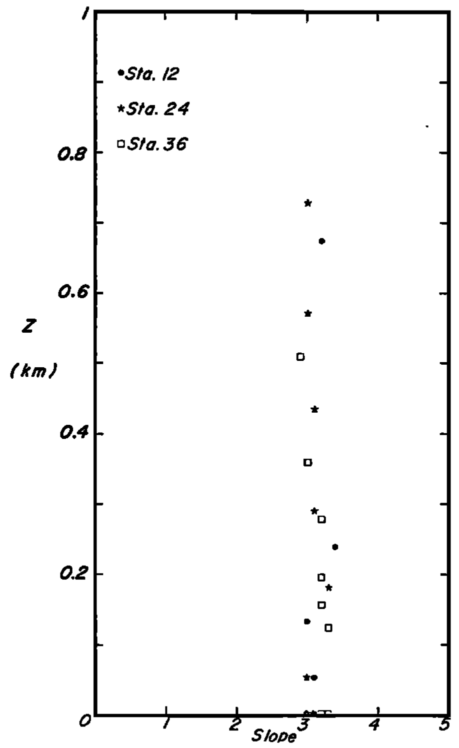

Fig. 3. Cumulative slope of the hyperbolic particle size distribution as a function of altitude above bottom (from data provided by M. J. Richardson).

By inserting the expression for Q [*Van de Hulst*, 1957] into equation (7) one obtains

$$c_p = \frac{\pi}{4}\Sigma N_i\left(2D_i^2 - \frac{4}{\alpha}D_i \sin \alpha D_i + \frac{4}{\alpha^2}(1 - \cos \alpha D_i)\right) \qquad (8)$$

where α is a function of wavelength and particulate index of refraction.

A numerical solution was obtained for indices of refraction varying from 1.02 to 1.20 relative to water (1.36 to 1.60 absolute) and using the Coulter Counter data. A similar single-component model for the determination of the index of refraction has been used by *Carder et al.* [1972] and *Carder et al.* [1974], however, the technique they have used was based on measurements of light scattering. For each of the three stations observed (12, 24, and 36) the best approximation of the particulate beam attenuation coefficient was obtained when high values of the index of refraction were used. Figure 4 shows the curves of refractive index versus particulate beam attenuation coefficient obtained from equation (8) for specific water samples taken at each of the three stations. The actual value of the particulate beam attenuation coefficient, c_p, as obtained from the transmissometer is shown (i.e., $c_p = c - c_w$). The consequent index of refraction is then obtained from the intersection of the measured value of c_p with the curve. Having little or no defined variation with altitude above bottom the relative index of refraction was found to have an approximate range of 1.15–1.20 for all three stations. This variation allows for the accuracy in the estimate of the beam attenuation coefficient of pure water. (No direct in vitro analyses of the index of refraction of HEBBLE sediments have yet been performed.) This result is consistent with the adoption of a value of 1.15–1.20 for the relative refractive index of inorganic materials as denoted by *Jerlov* [1976]. *Rothe and Tucholke* [1981] have shown that the principal mineral components found in the sedimentary formations of the western North Atlantic are aluminosilicates and calcite (relative index of refraction 1.17–1.20). Consequently, if a range of values is sought for the absolute index of refraction of particles in the HEBBLE region it would be between 1.55 and 1.60.

CONCLUSIONS

The area of the high Energy Benthic Boundary Layer Experiment is one in which the optical characteristics of the suspended particles are nearly constant, despite the highly variable nature of the currents and bottom bedforms. The

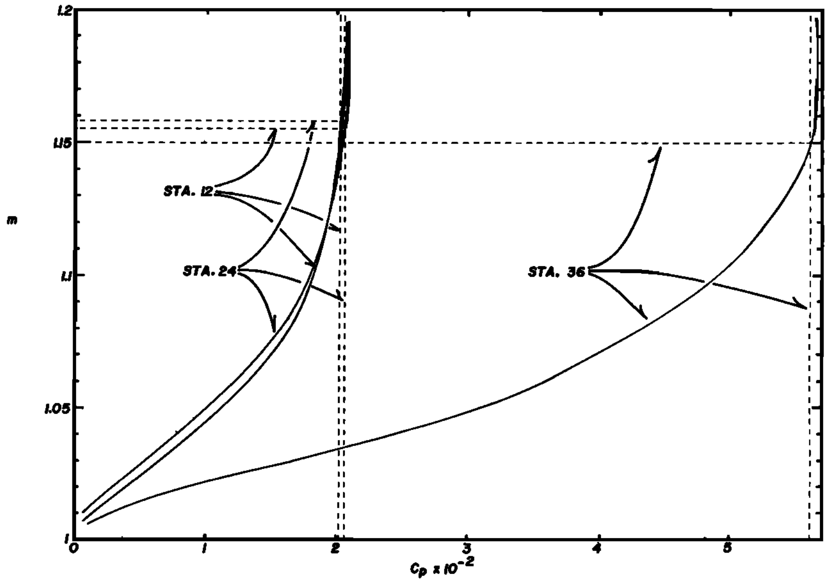

Fig. 4. The curves of solution of equation (8) where m is the particulate relative index of refraction and c_p is the particulate beam attenuation coefficient for water samples at stations 12, 24, and 36. The intersection of c_p for a given sample with its curve indicates the relative refractive index of the particles in that sample.

correlation between particle concentration and beam attenuation coefficient was found to vary little over a period of more than one year (with a standard deviation of 65 ppb for a given value of c). This result is consistent with the fact that the cumulative slope of the particle size distribution was nearly constant at 3.1 (±0.3). Further analysis of transmission data and particle size data yielded a minimum error when a particulate index of refraction relative to water of 1.20 ± 0.07 was used. This corresponds to an absolute index of refraction of 1.60 ± 0.09 which compares to 1.55–1.65 for marine clays [*Carder et al.*, 1974]. The particle size data and index of refraction calculations were also nearly constant over distances of tens of kilometers.

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REFERENCES

Bader, H., The hyperbolic distribution of particle sizes, *J. Geophys. Res., 75,* 2823–2830, 1970.

Bartz, R., J. R. V. Zaneveld, and H. Pak, A transmissometer for profiling and moored observations in water, *Soc. Photo Opt. Instr. Eng., 160,* 102–108, 1978.

Biscaye, P. E., and S. L. Eittreim, Variations in the benthic boundary layer phenomena: Nepheloid layers in the North American Basis, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 1974.

Carder, K. L., R. D. Tomlinson, and G. F. Beardsley, Jr., A technique for the estimation of indices of refraction of marine phytoplankters, *Limnol. Oceanogr., 17,* 833–839, 1972.

Carder, K. L., P. R. Betzer, and D. W. Eggiman, Physical, chemical and optical measures of suspended particle concentrations: Their intercomparisons and applications to the West African Shelf, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 1974.

Eittreim, S., and M. Ewing, Suspended particulate matter in the deep waters of the North American Basin, in *Studies in Physical Oceanography,* vol. 2, edited by A. L. Gordon, Gordon and Breach, New York, 1972.

Eittreim, S., A. L. Gordon, M. Ewing, E. M. Thorndike, and P. Bruchhausen, The nepheloid layer and observed bottom currents in the Indian-Pacific Antarctic Sea, in *Studies in Physical Oceanography,* vol. 2, edited by A. L. Gordon, Gordon and Breach, New York, 1972.

Gibbs, R. J. (ed.), *Suspended Solids in Water,* Plenum, New York, 1974*a*.

Gibbs, R. J., The suspended material of the Amazon Shelf and tropical Atlantic Ocean, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 1974*b*.

Gibbs, R. J., Principles of studying suspended materials in water, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 320 pp., 1974*c*.

Hollister, C. D., A. R. M. Nowell, and J. D. Smith, Third annual report, High Energy Benthic Boundary Layer Experiment, *Rep. 80-32,* Oceanographic Inst., Woods Hole, Mass., 1980.

Jerlov, N. G., A transparency-meter for ocean water, *Tellus, 9,* 229–233, 1957.

Jerlov, N. G., *Marine Optics,* Elsevier, New York, 1976.

Jerlov, N. G., and E. Steeman-Nielsen, *Optical Aspects of Oceanography,* Academic, New York, 1974.

Kalle, K., Teilfahrt der deutsche noratlantische Expedition "Meteor 5," Die chemischen Arbeiten auf der "Meteor"—Fahrt, Januar bis Mai, 1938, *Ann. Hydrog. Meteorol., Suppl. Pap.,* 23–30, 1939.

Kullenberg, G., The distribution of particulate matter in a Northwest African coastal upwelling area, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 1974.

Pak, H., Distribution of suspended particles in the Equatorial Pacific Ocean, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 1974.

Pak, H., and J. R. V. Zaneveld, Bottom nepheloid and bottom mixed layers observed on the continental shelf off Oregon, *J. Geophys. Res., 82,* 3921–3931, 1977.

Peterson, R. L., A study of suspended particulate matter: Arctic Ocean and Northern Oregon Continental Shelf, Ph.D. Thesis, Oregon State Univ., Corvallis, 1978.

Roach, D. M., The determination of refractive index distributions for oceanic particles, Ph.D. Thesis, Oregon State Univ., Corvallis, 1975.

Rothe, P., and B. E. Tucholke, Mineralogy of sedimentary formations in the Western North Atlantic Ocean: Preliminary results, *Geol. Rundschau, 70,* 327–343, 1981.

Smith, R. C., and K. Baker, Optical properties of the clearest natural waters, *Appl. Opt., 20,* 177–184, 1981.

Spinrad, R. W., and J. R. V. Zaneveld, An analysis of the optical features of the near-bottom and bottom nepheloid layers in the area of the Scotian Rise, *J. Geophys. Res., 87,* 9553–9561, 1982.

Thorndike, E. M., and M. Ewing, Photographic nephelometers for the deep sea, in *Deep-Sea Photography, Johns Hopkins Univ. Oceanogr. Stud.,* vol. 3, Johns Hopkins University Press, Baltimore, Md., 1967.

Tyler, J. E., R. W. Austin, and T. J. Petzold, Beam transmissometers for oceanographic measurements, in *Suspended Solids in Water,* edited by R. J. Gibbs, Plenum, New York, 1974.

Van de Hulst, H. C., *Light Scattering by Small Particles,* John Wiley, New York, 1957.

Zaneveld, J. R. V., Variation of optical sea parameters with depth, in *Lecture Series on Optics of the Sea,* number 61, pp. 2.3-1–2.3-22, Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, Nevillyi sur Seine, France, 1973.

Zaneveld, J. R. V., D. M. Roach, and H. Pak, The determination of the index of refraction distribution of oceanic particulates, *J. Geophys. Res., 79,* 4091–4095, 1974.

Zaneveld, J. R. V., D. M. Roach, and H. Pak, The determination of the index of refraction distribution of oceanic particulates, *J. Geophys. Res., 79,* 4091–4095, 1974.

Zaneveld, J. R. V., J. C. Kitchen, R. Bartz, D. Menzies, S. Moore, R. W. Spinrad, and H. Pak, Optical, hydrographic, and chemical observations in the Monterey Bay area during May and September, 1977, *Ref. 78-13,* Oregon State Univ., School of Oceanogr., Corvallis, 1978.

Zaneveld, J. R. V., R. W. Spinrad, and D. W. Menzies, Optical and hydrographic observations in the Congo River and Angola Basin during May, 1978, *Ref. 79-3,* Oregon State Univ., School of Oceanogr., Corvallis, 1979.

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