La mer 24: 11-20, 1986
Société franco-japonaise d'océanographie, Tokyo

Distribution of fragile particles in the sea determined by measurements by the Coulter Counter*

Masahiro KAJIHARA**

Abstract: In view of fragility of macroscopic aggregates the coefficient of variation (ratio of standard deviation to mean particle number) for disintegrated particles in samples subdivided from a water sampler was obtained. The coefficient was compared with the coefficient for glass powder samples. The ratio of the two coefficients was used to denote the fragility of particles.

Measurements were made on a variety of waters of 23 layers from the Bering Sea and Funka Bay, Hokkaido. Fragility had no relationship to temperature, salinity, or nutrients, but was correlated to the concentration of total volume of particles. The ratio of smaller to the total particle number that was clearly shown in the slope of hyperbolic distribution of particles played an important role in fragility. Fragility was high under oceanographic conditions that seemed to supply fine particles from the seabed as a resuspension. When the concentration of total volume of particles was small, it appeared that fragility was dominated by the composition of materials in aggregates. Comparison of the measured total volume of particles with the assumed volume of macroscopic aggregates suggested that most of particles in the sea is in a state of aggregation.

1. Introduction

Some particulate materials in the sea are formed into aggregates. These aggregates range in size from microscopic (RILEY, 1963, 1970) up to several millimeters (SUZUKI & KATO, 1953; ALLDREDGE, 1972, 1976; TRENT *et al.*, 1978; SHANKS & TRENT, 1979), and occasionally, enormous aggregates are observed (TSUJITA, 1952; JANNASCH, 1973; HAMNER *et al.*, 1975). They have been reported not only in surface layers but also in deep layers (DIETZ, 1959; COSTIN, 1970; MANHEIM *et al.*, 1970; SILVER & ALLDREDGE, 1981; ALLDREDGE & COX, 1982). Primarily because of their chemical compositions and their high sinking rates, the role of large aggregates in the sea as carriers for particulate and dissolved materials (ALLDREDGE, 1979; SHANKS & TRENT, 1979), as a food source (HAMNER *et al.*, 1975), and as a removal of materials by sedimentation (SHANKS & TRENT, 1980), has recently attracted special interest. However, with increasing size, these aggregates become too porous and fragile (KAJIHARA, 1971) to be collected intact by traditional shipboard methods. It is known that aggregates are partly disintegrated when trapped in a water sampler, although no information is available on the relationship between the *in situ* size of intact particles and the size of those trapped in the sampler. The size distribution of particles in sampled water is undoubtedly the result of a balance between two forces, the cohesive force of the aggregates and destructive forces such as pressure variations during the closing of a sampler. However, some of the broken particles in sampled water may still hold the state of aggregates due to the imbalance of the two forces. Since the concentration of aggregate particles is low, the distribution of aggregates in the sampler will not be uniform. In addition, if other unnatural forces such as shock during rinsing of the water sample from the water bottle, are applied, the aggregates will further disintegrate. To determine the amount of aggregates, I obtained the coefficient of variation (ratio of standard deviation to mean particle number) for replicate samples of suspended particles in samplers. The results are discussed with

* Received May 14, 1985
** Research Institute of North Pacific Fisheries, Faculty of Fisheries, Hokkaido University, Minato, Hakodate, Hokkaido, 041 Japan

respect to the occurrence of fragile particle and dissolved and particulate materials in the sea.

2. Methods

The number of particles counted by a Coulter Counter is not truly representative of the total number present because of coincident passage through an aperture and the subsequent concentration of particles in the water sample (SHELDON & PARSONS, 1967). If the particle is solid or does not disintegrate, however, the precision of reproducibility for the replicated measurements on the same sample, or measurements on some subdivided samples from a well-mixed water, show a definite count fraction that depends on the number of particles counted. If some fragile particles exist in the water sample, and if they are selectively trapped in some bottles of water that are subdivided from the initial sample, then the numbers and sizes of particles in each bottle will show, after their subsequent disintegration, different distributions depending on whether fragile particles are present or not in a given aliquot. The coefficient of variation (CV), or the measure of reproducibility of particle counts in subsamples, will be different from the CV for a sample in which the particles consist of evenly dispersed solids only. Thus, it may be possible to determine the existence of fragile particles in the sea by comparing the CV of suspended particles in seawater with that of solid particles used as a standard for count reliability. As solid particles, glass powder was made by crushing a piece of glass and removing larger particles by water-sieving in electrolyte (ISOTONE).

For obtaining the different concentration of suspended particles, a vertical profile of beam attenuation coefficient was measured and examined before water sampling, and then seawater was collected with a 7-*l* Van Dorn bottle. Seawater in the sampler was split into ten 300-m*l* polyethylene bottles. Before counting particles with the Coulter Counter (model TA-II), the bottles were shaken and allowed to stand just long enough to remove bubbles. Measurements were made from a 250-m*l* round beaker, with stirring until just before counting. Particle counts are affected by strong radiated noise, which is not eliminated by using a metal shield around the sample stand of the Coulter Counter. Miscounts also arise both from plugging of the aperture and from the forced displacement of mercury in a manometer due to rolling of the ship. In order to check for miscounts, attention was paid to the total counts and the required time for counting; three or more measurements for each subsample of the bottles were performed. All sets of counts at each station were completed within a few hours in the Bering Sea and within 10 hours at Funka Bay, Hokkaido, after collection of water samples.

The aperture orifice used was 100 μm in diameter and water volume for the measurement sucked into the manometer of the instrument was 0.5 m*l*. The beam attenuation coefficient was measured by an *in situ* transmittance meter (Martek, model XMS), and nutrients and particulate organic materials were analysed by an Auto Analyzer (Technicon) and a CHN Analyzer (Hitachi), respectively.

3. Results

Standardization of the CV. Ten concentrations of glass powder in water (ISOTONE) were prepared, and thirty measurements were performed

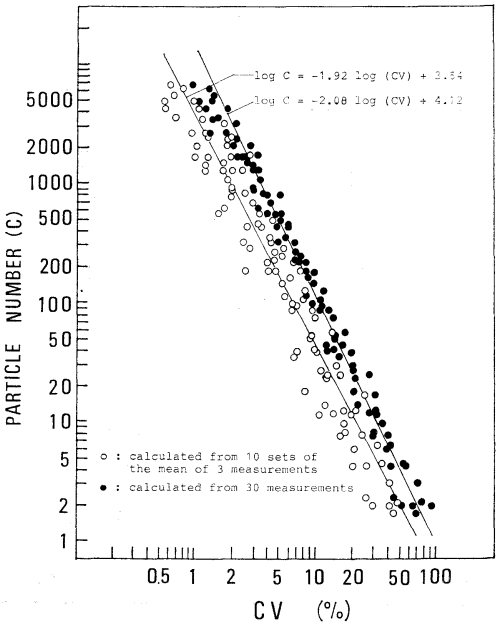

Fig. 1. Standardization of the coefficient of variation for glass powder, determined with the Coulter Counter (model TA-II).

for each concentration. The CV was then calculated for two cases, one by the raw measured values in each concentration, and the other by the same data but with ten sets of three measurements. The relationship between the CV and the mean particle number is shown in Fig. 1. The mean counts less than 1 and greater than 10^4 were omitted from the data. Total data points in each case were 110.

When using the mean of three measurements, the CV tended to be smaller than those obtained from n=30, as the fluctuations of particle number were diminished. Regression lines calculated from the least squares method were as follows:

$$\log C = -2.08 \log (\mathrm{CV}) + 4.12; \quad n=30, \quad (1)$$

$$\log C = -1.92 \log (\mathrm{CV}) + 3.54; \quad n=10, \quad (2)$$

where C and CV are the mean particle number and the coefficient of variation, respectively. Equation (1) was calculated from the raw measured values and equation (2) was from the ten sets of the mean of three measurements. The correlation coefficient for the former was 0.99 and that for the latter was 0.97. The experimental results almost agreed with the error relationship for sample counts theoretically predicted (FRIEDLANDER *et al.*, 1981). The regression line obtained by SHELDON and PARSONS (1967) was located between the two lines in Fig. 1. As the particle number increases over ten, their CV value becomes larger than the present result for n=10, and the larger the particle number becomes, the closer their line gets to the present one for n=30, which is caused by the high slope of their line.

Description of oceanographic conditions. The nature of suspended particles in seawater depends on the water mass characteristics. As is evident from the temperature-salinity diagram (Figs. 2a and 2b), the stations located in the Bering Sea and Funka Bay are influenced by a variety of water masses. Bering Sea station 79045 was situated in the region of the Alaskan Stream water, with the surface layer diluted by water from the coast. Station 79055 was occupied by coastal water of slightly low salinity, and the vertical profiles of both temperature and salinity show the presence of strong convection. Stations 79065, 79069 and 79075 were situated in the region of the Bering Sea source water (OHTANI, 1973; COACHMAN & CHARNELL, 1979).

The Funka Bay water is characterized by periodical inflowing of two major water masses,

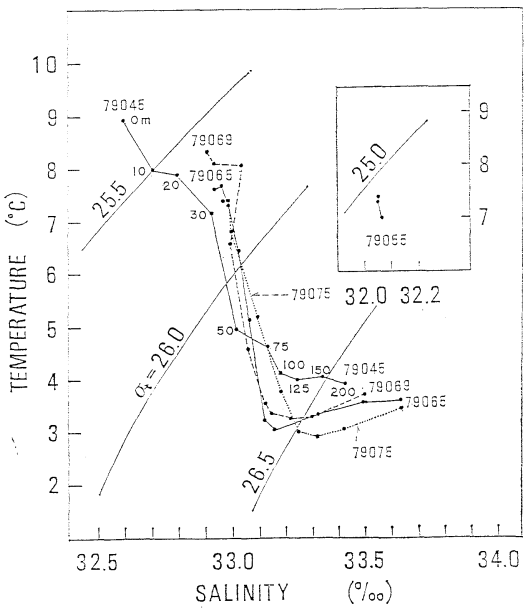

Fig. 2a. Temperature-salinity diagram for the upper 200 m layer in the Bering Sea.

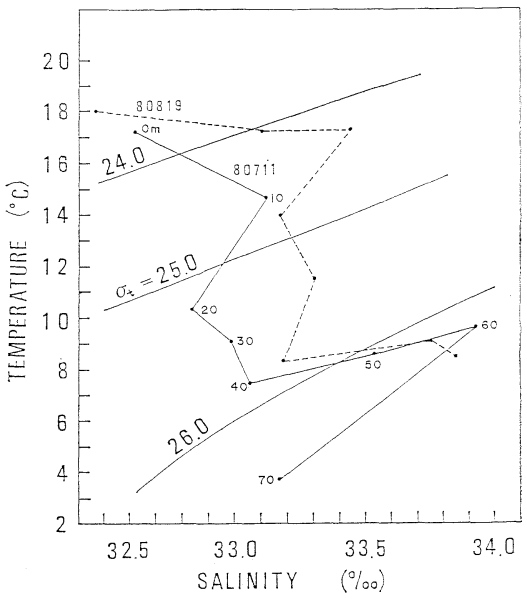

Fig. 2b. Same as Fig. 2a, except for Funka Bay, Hokkaido.

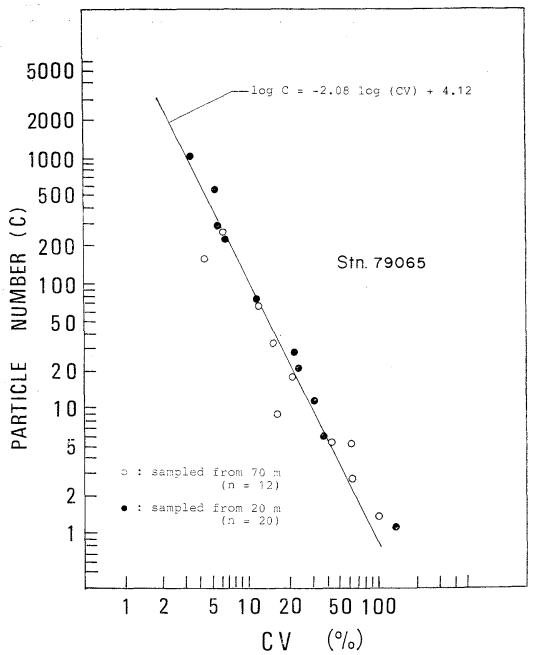

Fig. 3. Relation between the coefficient of variation and the particle number, obtained from replicate measurements for the water in one bottle.

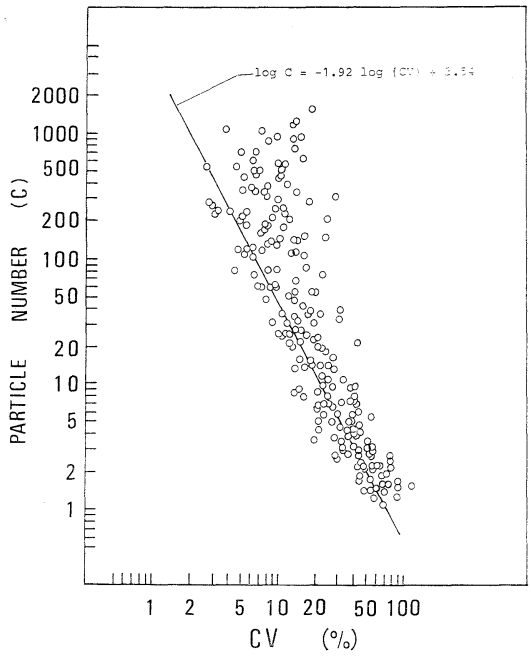

Fig. 4. Deviation of the coefficients of variation from the standard line (n=10) in the Bering Sea and Funka Bay.

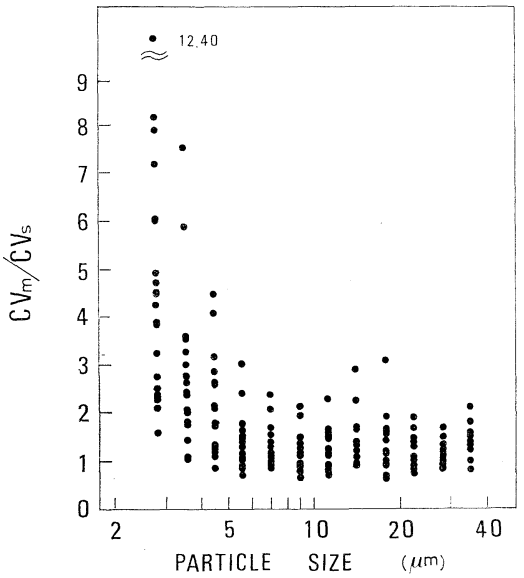

Fig. 5. Relationship between the particle size and the fragility of particles, calculated from the data for Fig. 4.

a cold and low saline water mass originating from the Oyashio, and the warm and saline Tsugaru warm water water mass from the Kuroshio. The waters that enter the bay are affected mostly by meteorological effects and runoff from land, while they are resident in the bay (OHTANI, 1979). The measurements were carried out during the inflowing season of Tsugaru warm water. At Stn. 80711, an intrusion of Tsugaru warm water appeared in a layer centered at 60 m depth, just above the resident Oyashio water near the sea bottom. At Stn. 80819, the inflowing Tsugaru warm water spread over the bottom layer under 50 m depth. The intrusion in the upper layer (temperature, 17.23°C, salinity, 33.45‰) was stronger than that in July (temperature, 14.62°C, salinity, 33.13‰). The contrast of water masses was seen in both the concentrations of nutrients and of particulate organic matters (Table 1).

Field observations. The CV resulting from the replicate measurements for the same subsample from one bottle, sampled from 20 m (n=20) and 70 m (n=12) depths at Stn. 79065, was in fair agreement with the relation in the case of n=30 for glass powder (Fig. 3). This means that the accuracy of the CV in a well-stirred

sample was within the mechanical error of the instrument. However, the relation between the particle number and the CV obtained from data for ten subsamples divided from one Van Dorn bottle gave a quite different tendency in the result; *i.e.*, the CV tended to deviate more with increasing particle number (Fig. 4). This figure shows all the data from the Bering Sea and Funka Bay, and the regression line inserted in the figure is for the case of n=10. Each particle number is the mean of three measurements.

To estimate the deviation for the CV for n=10 in each size, the ratio of the measured CV (CV_m) to the CV obtained with glass powder (CV_s) was plotted (Fig. 5). On the whole, the deviation of ratios was greater in the smaller size range, showing that fragile aggregates were trapped selectively in some subsamples and subsequently broken into smaller particles, causing the CV to increase. As an indicator of the fragility of particles, the CV_m/CV_s in the range of 2.52–3.17 μm (the smallest size range in the present measurement, mean diameter 2.82 μm), is given in Table 1.

Although there were wide variations in temperature, salinity and nutrient concentrations in the waters, fragility showed no direct relationship to them. However, fragility tended to increase with the total volume of particles 2.52–40.3 μm (V_1) in size, which were calculated from the sum of particle volume in each size. In this case, the correlation coefficient r was 0.49. Similarly, correlation was weak ($r=0.17$) between fragility and the beam attenuation coefficient α, and also weak ($r=0.26$) between fragility and the particulate organic carbon POC. The factors V_1, α and POC are all properties of particulate matter suspended in the sea, but α is a value defined as the sum of the absorption coefficient and the total scattering coefficient of both water and particles suspended in the water (JERLOV, 1976), whereas POC is only the

Table 1. Dissolved and particulated organic matters, beam attenuation coefficient α, mean volume of particles between sizes 2.52 μm and 40.3 μm in seawater per 0.5 ml, and fragility CV_m/CV_s at 2.82 μm.

Station	Date	Depth (m)	Temp. (°C)	Sal.	NO_2^- (μm)	NO_3^- (μm)	PO_4^- (μm)	C (μgC/l)	N (μgN/l)	α (m^{-1})	V_1 ($\times 10^3 \mu m^3$)	CV_m/CV_s
79045	July 12, '79	10	7.95	32.71	0.17	7.1	0.74	196	35	1.26	619.6	5.95
(55°48′N, 168°54′W)		20	7.86	32.80	0.26	9.8	0.94	494	58	0.61	183.1	3.26
		40						427	52	0.23	122.7	4.55
79055	July 15, '79	10	7.32	32.05	0.05	0.2	0.56	755	53	0.53	125.4	7.18
(59°00′N, 168°00′W)		20	7.02	32.06	0.03	0.3	0.50	712	44	0.55	156.6	4.85
		30	6.97	32.02	0.06	0.2	0.61	626	49	0.56	211.7	5.99
79065	July 20, '79	20	7.40	32.98	0.30	18.4	1.63	292	44	0.46	203.3	2.23
(57°00′N, 177°02W′)		30	6.39	33.02	0.17	14.7	1.44	447	55	0.32	176.4	3.82
		70						198	35	0.16	47.9	7.88
79069	July 22, '79	10	7.71	32.96	0.18	13.6	1.14	195	34	0.45	171.9	2.73
(58°00′N, 179°00′W)		30	6.39	33.02	0.27	15.9	1.36	146	22	0.39	137.4	2.15
		100	3.05	33.16	0.08	21.9	1.79	118	24	0.12	36.5	5.44
79075	July 30, '79	10	7.27	32.99	0.18	15.4	1.42	202	42	0.36	82.6	2.34
(52°59′N, 179°01′W)		30	6.76	33.00	0.18	12.0	1.42	190	42	0.32	84.3	2.45
		50	5.13	33.10	0.26	18.8	1.59	133	24	0.32	79.2	3.83
80711	July 11, '80	30	9.09	32.99	0.09	1.4		300	62	0.29	503.7	12.40
(42°06′N, 140°56′W)		50	8.48	32.54	0.33	2.0		301	72	0.27	102.6	1.59
		65	8.50	33.85	0.44	4.2		207	55	0.62	131.7	3.91
		75	5.20	33.40	0.71	10.8		337	84	1.20	184.3	8.16
80819	Aug. 19, '80	0	18.0	32.47	0.03	0.9		174	38	0.30	66.2	2.38
(42°06′N, 140°56′W)		30	13.93	33.18	0.03	0.5		219	45	0.31	49.2	4.57
		50	8.23	33.19	0.19	1.1		184	44	0.27	51.7	2.33
		70	8.17	33.86	0.54	9.9		181	39	1.02	59.0	4.25

concentration of organic carbon in particulate matter. Thus, the correlations might become weak especially in α and POC, depending upon the water mass.

Distributions of finer particles. Since the aperture orifice used was 100 μm in diameter, and counts smaller than 2.52 μm particles were omitted, the particle sizes presented here were confined to those from 2.52 μm to 40.3 μm. However, particles of size less than 2.52 μm are most abundant in seawater, and therefore may contain information about the size composition of fragile particles.

It is known that the size distribution of suspended particles in seawater follows a hyperbolic distribution,

$$\tilde{N}=kX^{-m}, \qquad (3)$$

where $\tilde{N}$ is the cumulative number of particles larger than a given size X, and k and m are constants (BADER, 1970). This relationship also fitted the present data, including disintegrated particles. In this case, $\tilde{N}$ was taken as the cumulative particle number of the mean of ten sets of subsamples; the distributions were then plotted on log-log plots (Fig. 6). The patterns were convex in most cases; however, that at Stn. 79055 located in a region of strong convection, and that near the sea bottom in Funka Bay (Stns. 80711 and 80819), appeared concave. In a few cases, the two segments did not cross each other, if examined in detail, although they were nearly one straight line. MCCAVE (1975) discussed the hyperbolic distribution of particles offered by Sheldon, and noted that in shallow layers above 200 m, the distributions consisted of two or more segments, while below 200 m most of them fitted one straight line. The patterns MCCAVE discussed were convex in shallow layers. Concave patterns were seen in data collected around the Galapagos Island (CARDER *et al.*, 1971).

Table 2 shows a summary of slopes m in each segment and their applicable sizes. Although the slopes of the lines ranged widely from 1.12 to 6.30, most slopes were within the range 2.0–4.0. Steep slopes in the larger sizes may be spurious due to small particle number. For the hyperbolic distribution of particle number, the

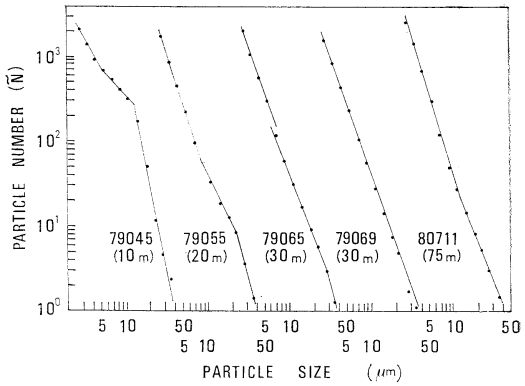

Fig. 6. Selective size distributions of the cumulative particle number. The numbers in parentheses indicate the depth of sample at the station.

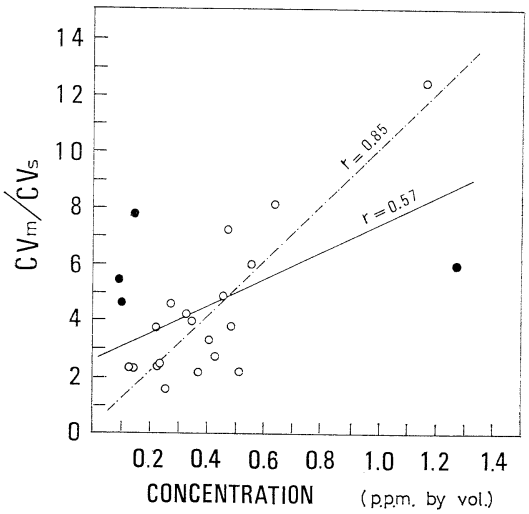

Fig. 7. The fragility of particles as a function of the concentration of total volume of particles (p.p.m. by vol.). Solid line was calculated from all data, and dot-dash line from data excluding solid circles.

volume of particles (assumed spherical) (V) contained between sizes X_0 and X is (BRUN-COTTAN, 1971),

$$V=-\frac{\pi km}{6(m-3)}\left[X^{-m+3}\right]_{X_0}^{X} \quad \text{for } m\neq 3, \qquad (4)$$

$$V=-\frac{\pi k}{2}\left[\log X\right]_{X_0}^{X} \quad \text{for } m=3. \qquad (5)$$

Thus, if the slope m obtained in the small size range holds in the range of smaller particles,

Table 2. Slopes of straight line segments m_i and their applicable size ranges in hyperbolic distributions, cumulative number of particles $\tilde{N}$ at a size of 2.82 μm, and mean volumes of particles V_2 between sizes 1 μm and 2.82 μm, calculated from samples of 0.5 ml volumes.

Station	Depth (m)	m_1	Range (μm)	m_2	Range (μm)	m_3	Range (μm)	$\tilde{N}$	V_2 ($\times 10^3 \mu m^3$)
79045	10	1.62	<5.2	1.12	5.2-11.8	4.55	>11.8	1974.5	16.9
	20	2.13	<11.9	3.88	11.9-17.7	6.30	>17.7	1216.8	17.5
	40	2.57	<6.4	2.12	>6.4			614.7	13.5
79055	10	3.66	<8.2	2.34	8.2-23.3	4.78	>23.3	2026.7	119.5
	20	3.05	<9.1	2.01	9.1-23.5	4.03	>23.5	1777.7	60.6
	30	2.91	<8.2	2.26	8.2-22.0	4.08	>22.0	1895.3	56.9
79065	20	2.57	*	2.70	*	4.40	>19.1	2264.6	49.6
	30	2.84	*	2.61	*	3.55	>27.9	2083.9	58.7
	70	2.96	<14.1	4.88	>14.1			569.3	17.9
79069	10	2.84	<28.5	4.10	>28.5			1794.2	50.5
	30	2.88						1531.4	44.7
	100	2.91						377.1	11.3
79075	10	3.04	<18.2	4.13	>18.2			971.8	32.8
	30	3.02	<16.1	3.92	>16.1			1080.5	35.8
	50	2.87	<15.8	3.97	>15.8			956.1	27.7
80711	30	2.47	<14.4	2.86	>14.4			3762.6	75.1
	50	2.82	<14.5	2.37	>14.5			801.8	22.1
	65	3.10	<8.4	2.09	>8.4			1124.1	40.1
	75	3.49	<12.8	2.10	>12.8			2651.4	134.2
80819	0	2.55	<4.1	1.76	4.1-10.2	3.75	>10.2	511.8	11.0
	30	2.49	<19.6	3.30	>19.6			331.8	6.8
	50	2.67	<19.0	3.44	>19.0			549.5	13.2
	70	3.91	<9.1	2.94	6.1-15.5	3.66	>15.5	1482.0	109.2

* Two segments do not cross each other.

the volume of particles ranging from 1 μm to 2.82 μm (V_2) could be calculated as in Table 2, where 2.82 μm is the geometric mean diameter for the size range 2.52-3.17 μm. Although the correlation coefficients between fragility and V_1 and V_2 were 0.49 and 0.45, respectively, the correlation coefficient between fragility and (V_1 +V_2) or between fragility and the concentration of total volume of particles ranging from 1 μm to 40·3 μm was 0.57 (Fig. 7).

4. Discussion

According to direct observations of macroscopic aggregates of marine snow by SCUBA diving, concentrations were 1.9-27.7 l^{-1} (longest dimension >0.5 mm) (TRENT *et al.*, 1978). 0-3.2 l^{-1}, 0-8 l^{-1} (longest dimension >3 mm) (ALLDREDGE, 1979), 0.7-14.0 l^{-1} (longest dimension >1 mm) (SHANKS & TRENT, 1980) and 0.1-1.1 l^{-1} (longest dimension >3 mm) (ALLDREDGE & COX, 1982). Thus, it is recommended to sample marine snow by the 7-l Van Dorn bottle. Marine snow is not the only fragile class of particles suspended in seawater; colony-forming phytoplankton, fragile cells and skeletal materials also might be disrupted by the Coulter Counter technique, and thus become a source of smaller particles, although these planktonic particles are undoubtedly one of the main components of marine snow. An increase of smaller particles in seawater is of no necessity for increasing in fragility in the smaller size ranges. Fragility increases only when particles in the sampler in low concentrations are broken apart by stirring prior to measurements by the Coulter Counter, and are disrupted unevenly among the ten subsample bottles.

In the present measurements, the fragility

CV_m/CV_s of 2.52–3.17 μm ranged from 2.15 to 12.40 (Table 1). The average particle counts of ten subsamples per 0.5 ml in each case were 716 and 1528, respectively, *i.e.*, CV_s at these counts were 2.27 and 1.53, as is evident from Eq. (2), and CV_m were 4.48 and 19.00. This means that there are significant differences in the standard deviations of particle numbers among the 250-ml subsamples, which are 9.35×10^3 and 133.5×10^3 in the size range between 2.52 μm and 3.17 μm. If the calculation of standard deviations is extended to the full range of 2.52–40.3 μm, these differences become 23.4×10^3 and 247.9×10^3. Although a major assumption remains that fragile planktonic particles, much more abundant than fragile aggregates, are divided into ten subsamples with even dispersion, macroscopic aggregates and/or their broken pieces at water sampling might contribute as a main cause for the large variation of fragility.

Fragility increases in proportion to the volume of particles contained in seawater. Thus, aggregates are apt to be formed when there are high concentrations of particulate materials; however, the correlation was not as good as expected. This may be due to the fact that fragility is affected not only by the concentration of particulate materials, but also by the nature of the aggregates themselves. Fragility was high in samples at Stn. 79055 and near the seabed in Funka Bay, where the distribution patterns were concave. The pattern signifies that the ratio of the number of smaller particles to total particle number in these samples was high, compared to the ratio in the distribution patterns of convex or one straight line relationships. In view of the oceanographic conditions in the region sampled, some of the smaller particles were possibly transported from the seabed as a result of resuspension. When macroscopic aggregates settle on the seabed, they will be broken by bottom shear stress and by collision with moving particles on the seabed. The particles thus produced are small both in size and weight and are therefore easily transported upward by turbulent diffusion. Some resuspended particles will aggregate onto other aggregates or will aggregate among themselves. In either case, the smaller particles transported from the seabed play an important role in the resulting high fragility. At Stn. 79045 in the Alaskan Stream water region, the fragility at 10 m depth was high, but the increase in values was not as high as expected from the concentration of total volume of particles. At this depth, the slope m_1 was extremely low, which meant that the ratio of the number of smaller particles to the total particle number was very low. I cannot explain exactly why such a low slope occurred, but it appeared to relate to weather conditions. Several days before the present measurements, there were strong winds. Under such weather conditions, rough seas tend to produce organic aggregates due to bubbe dissolution (JOHNSON, 1976), which may adhere to and thus consume smaller particles. If there was an imbalance between removal of smaller particles due to consumption and the supply of them at surface layers, a low slope would be formed. The amount of fragility also might be affected by the concentration of smaller particles in the opposite case.

Fragility was comparatively high at 70 m depth at Stn. 79065, at 100 m depth at Stn. 79069, and at 30 m depth at Stn. 80819, despite the low concentration of total particle volume. These zones of high fragility might be caused by the selective trapping of fragile particles into a limited number of subsamples, or they might relate to higher ratios of POC and PON to the total volume of particles (V_1+V_2). Specifically, fragility might be changed by the composition of materials in the aggregates. Mucous materials produced by zooplankton provide a particularly suitable nucleus for the gradual accumulation of small particles (ALLDREDGE, 1979). If the data from Stns. 79045 (10 m), 79065 (70 m), 79069 (100 m) and 80819 (30 m) different from the other data were excluded from the calculations, the correlation coefficient between fragility and the concentration of total volume of particles increases to 0.85 (Fig. 7).

The total valume of particles ranging from 1 μm to 40.3 μm in size, calculated both from results of the Coulter Counter measurements and with the assumption of hyperbolic distribution was $47.8–636.5 \times 10^3$ μm^3 (mean 200.5×10^3 μm^3) per 0.5 ml of seawater, *i.e.*, $9.56–127 \times 10^7$ μm^3 l^{-1} (mean 4.01×10^8 μm^3 l^{-1}). On the other hand,

if there were macroscopic aggregates of marine snow with 3 mm in diameter having 99 % porosity, the volume of solid portion would be $1.4\times 10^8\ \mu m^3$. Consequently, if the total volume of particles is the result of the disintegration of marine snow, its concentration would be 0.7-9.1 l^{-1} (mean 2.9 l^{-1}). Since suspended particles in the sea do not consist only of marine snow, the above calculations overestimate marine snow abundance, whereas, particles larger than 40.3 μm in size were out of the range of my measurements, the above calculations understimate it. Although the technique for estimation of the concentration of marine snow as discussed here is certainly rough, the result agrees well with *in situ* observation described earlier. I thus suggest that most of the particulate matter suspended in the sea is in the form of aggregates. This is supported by measurements by TRENT *et al.* (1978) showing a high ratio of the pigment concentration in aggregates to that in the surrounding seawater.

It is believed that high fragility results from the existence of large aggregates in seawater taken by water samplers. The presence of low fragility, however, does not always imply the reverse situation, because fragility does not increase if the aggregates are broken into a large number of fine particles and are evenly dispersed in the sampler. Consequently, fragility is not an indicator for the concentration of macroscopic aggregates themselves. It is true, however, that the fragility provides information about the existence of aggregates, probably of macroscopic size.

This work was supported by a grant No. 503032 from the Ministry of Education, Culture and Science, Japan. This is Contribution Number 166 from the Research Institute of North Pacific Fisheries, Hokkaido University.

References

ALLDREDGE, A. L. (1972): Abandoned larvacean houses: A unique food source in the pelagic environment. Science, **177**, 885-887.

ALLDREDGE, A.L. (1976): Discarded appendicularian houses as source of food, surface habitats, and particulate organic matter in planktonic environments. Limnol. Oceanogr., **21**, 14-23.

ALLDREDGE, A.L. (1979): The chemical composition of macroscopic aggregates in two neritic seas. Limnol. Oceanogr., **24**, 855-866.

ALLDREDGE, A. L. and J. L. COX. (1982): Primary productivity and chemical composition of marine snow in surface waters of the Southern California Bight. J. Mar. Res., **40**, 517-527.

BADER, H. (1970): The hyperbolic distribution of particle sizes. J. Geophys. Res., **75**, 2822-2830.

BRUN-COTTAN, J.C. (1971): Etude de la granulométrie des particules marines. Mesures effectuées avec compteur Coulter. Cah. Océanogr., **23**, 193-205.

CARDER, K.L., G.F. BEARDSLEY, JR., and H. PAK. (1971): Particle size distributions in the eastern equatorial Pacific. J. Geophys. Res., **76**, 5070-5077.

COACHMAN, L.K. and R.L. CHARNELL. (1979): On lateral water mass interaction—A case study, Bristol Bay, Alaska. J. Phys. Oceanogr., **9**, 278-297.

COSTIN, J.M. (1970): Visual observations of suspended-particle distribution at three sites in the Caribbean Sea. J. Geophys. Res., **75**, 4144-4155.

DIETZ, R.S. (1959): 1100-meter dive in the bathyscaph Trieste. Limnol. Oceanogr., **4**, 94-101.

FRIEDLANDER, G., J.W. KENNEDY, E.S. MACIAS, and J.M. MILLER. (1981): Nuclear and Radiochemistry. 3rd ed. JOHN WILEY & Sons.

HAMNER, W.H., L.P. MADIN, A.L. ALLDREDGE, R.W. GILMER, and P.P. HAMNER. (1975): Underwater observations of gelatinous zooplankton: Sampling problems, feeding biology, and behavior. Limnol. Oceanogr., **20**, 907-917.

JANNASCH, H.W. (1973): Bacterial content of particulate matter in offshore surface waters. Limnol. Oceanogr., **18**, 340-342.

JERLOV, N.G. (1976): Marine Optics. Elsevier.

JOHNSON, B.D. (1976): Nonliving organic particles formation from bubble dissolution. Limnol. Oceanogr., **21**, 444-446.

KAJIHARA, M. (1971): Settling velocity and porocity of large suspended particle. J. Oceanogr. Soc. Jpn., **27**, 158-162.

MCCAVE, I.N. (1975): Vertical flux of particles in the ocean. Deep-Sea Res., **22**, 491-502.

MANHEIM, F. T., R. H. MEADE and G. C. BOND. (1970): Suspended matter in surface waters of the Atlantic continental margin from Cape Cod to the Florida Keys. Science, **167**, 371-376.

OHTANI, K. (1973): Oceanographic structure in the Bering Sea. Mem. Fac. Fish. Hokkaido Univ., **21**, 65-106.

OHTANI, K. (1979): Renewal of the water in Funka Bay. (In Japanese). Bull. Coast. Oceanogr., **17**, 50-59.

RILEY, G.A. (1963): Organic aggregates in seawater

and dynamics of their formation and utilization. Limnol. Oceanogr., **8**, 372-381.

RILEY, G.A. (1970): Particulate organic matter in sea water. Adv. Mar. Biol., **8**, 1-118.

SHANKS, A. L. and J. D. TRENT. (1979): Marine snow: microscale nutrient patches. Limnol. Oceanogr., **24**, 850-854.

SHANKS, A. L. and J. D. TRENT. (1980): Marine snow: sinking rates and potential role in vertical flux. Deep-Sea Res., **27A**, 137-143.

SHELDON, R. W. and T. R. PARSONS. (1967): A practical manual on the use of the Coulter Counter in marine science. Coulter Electronics Sales Company.

SILVER, M.W. and A.L. ALLDREDGE. (1981): Bathypelagic marine snow: deep-sea algal and detrital community. J. Mar. Res., **39**, 501-530.

SUZUKI, S. and K. KATO (1953): Studies on suspended materials marine snow in the sea: Part 1. Source of marine snow. Bull. Fac. Fish. Hokkaido Univ., **4**, 131-137.

TRENT, J. D., A. L. SHANKS and M. W. SILVER. (1978): In situ and laboratory measurements on macroscopic aggregates in Monterey Bay, California. Limnol. Oceanogr., **23**, 626-635.

TSUJITA, T. (1952): A preliminary study on naturally occurring suspended organic matter in waters adjacent to Japan. (In Japanese). J. Oceanogr. Soc. Jpn., **8**, 113-126.

コールターカウンターの測定から求めた壊れ易い粒子の分布

梶　原　昌　弘

要旨: 大型の凝集粒子が壊れ易いことに注目し，採水器から分水した試水中の，崩壊した粒子による変動係数（標準偏差/粒子数平均）を求めた。この値をガラス粒子の変動係数と比較した。この比を粒子の壊れ易さ（fragility）を表わすのに用いた。

測定はベーリング海，噴火湾の異なる23試水について行なった。fragility は水温，塩分，栄養塩とは相関がなかったが，粒子の全体積濃度とは相関がみられた。双曲線分布の勾配として示される全粒子数に対する微小粒子の割合は，fragility に重要なかかわり合いを持っていた。海底から微小粒子が，再懸濁によって供給されていると考えられる海洋条件のもとでは，fragility は高かった。粒子の全体積濃度が低い時には，fragility は凝集粒子の物質組成に影響されていた。測定された粒子の全体積を，大型の凝集粒子を仮定した体積と比較してみると，海中のかなりの粒子が凝集状態にあると考えられた。