NOAA Technical Report ERL 382-OD 13

an Advection-Diffusion Model of the DOMES Turbidity Plumes

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an ADVECTION - DIFFUSION MODEL of the DOMES[1] TURBIDITY PLUMES

Wilmot N. Hess and Walter C. Hess[2]

The sediment dumped overboard from a manganese nodule mining ship in the Central Pacific Ocean will contain many small particles of diameter ~ 3 microns. These will not settle rapidly and will form a near-surface plume extending a long distance from the mining ship. A second plume will be formed near the bottom due to the disturbance by the mining device. This paper discusses the nature, extent and density of these two plumes. A physical model using advection of the sediment plus horizontal diffusion plus settling of the fines by Stokes Law is used to calculate several cases of plume behavior. Typical surface plume densities are less than 1 milligram/liter except quite near the mining ship. The benthic blanket produced by the bottom plume will typically have thicknesses of less than 100 micrograms/cm^2.

1. INTRODUCTION

In a year or two when mining of deep sea manganese nodules starts in the Pacific Ocean, hydraulic lift systems will carry not only nodules but also bottom water and resuspended fines to the surface of the ocean. The ship collecting the nodules will sort the material, hold the nodules, and dump overboard the bottom water and fines. Surface currents will carry this stream of fines away from the ship, producing a surface plume of resuspended sediments. A second plume of fines will be formed near the dredge head of the mining ship on the bottom of the ocean. Much of the sediment collected with the nodules from the bottom by the dredge head will be separated out and rejected back into the near bottom water before moving the nodules up the pipe. This plume will slowly settle out and blanket the benthos near the track of the dredge head.

The question to be addressed here is what will be the appearance of these plumes of fines from such a one-ship mining operation? In order to describe these plumes we must separate the particle motion into three components: (a) advection, which describes the mean motion of the plumes by some average horizontal current velocity; (b) settling, which describes the falling of the particles back to the bottom; and (c) diffusion, which describes the dispersal of material off the track of the mean motion.

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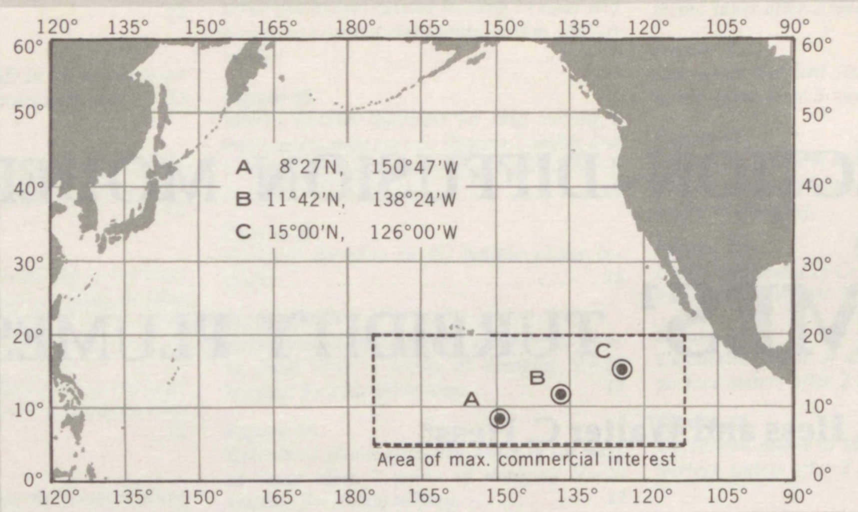


Figure 1. DOMES sites in the central Pacific.

2. OCEAN CURRENTS

First, in the case of advection, let us consider what is known about ocean currents in the DOMES area. The DOMES Project selected three sites for study as shown in Figure 1. Until very recently there were no direct current measurements in these areas. Geostrophic currents had been calculated based on STD measurements, but there are uncertainties in this procedure. When carrying out the geostrophic approximation one has to assume a level of no motion somewhere in the water column. For the tropical waters of the eastern Pacific, this is typically taken at 500 m and this may or not be a valid assumption. Using the geostrophic approximation, surface currents at Site C, which is about 15° N, are roughly 25 cm/sec to the west. At Site A, which is about 8°N, the currents are about 40 cm/sec to the east (Halpern, private communication). Site A is in the North Equatorial Countercurrent.

Recently, the first direct current measurements in this area were carried out by Dr. David Halpern (1976). Table 1 gives his preliminary values at Site C. We will make calculations of the turbidity plume using constant horizontal advection velocities of $V = 10$ km/day = 11.5 cm/sec, $V =$ 20 km/day = 23 cm/sec, and $V =$ 40 km/day = 46 cm/sec. We will also make calculations of the surface plume based on Halpern's daily average current vectors measured at Site C in September and October 1975 as shown in Figure 2. These currents are at 20-m depth and have been low-pass filtered to remove the high frequency components. They show the considerable variability of the currents.

Table 1. Average Current at Site C Observed During September and October 1975.

Depth	Total Velocity	Component E-W	Component N-S
20m	25cm/sec	17 (to W)	10 (to N)
50	20	11	6
100	15	6	2
200	12	+3	2
300	12	+5	0

There is very little data on near-bottom currents in the DOMES area (Amos et al., 1976). We will assume that the currents are in the range $1 < V < 5$ cm/sec (Halpern, private communication).

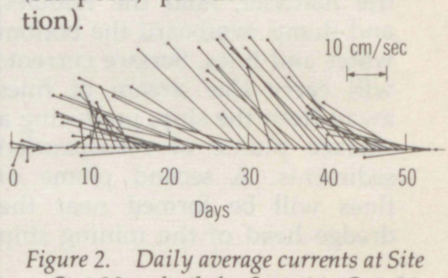


Figure 2. Daily average currents at Site C at 20 m depth for Sept. 1 to Oct. 26, 1975 (from Halpern) (low pass filtered).

3. VERTICAL MOTION

In considering vertical behavior of the plumes we must take into account the initial nature of the discharge, the settling to be expected from Stokes Law, the vertical mixing that will occur fairly rapidly in the wind-mixed layer of the ocean, and the considerably slower mixing below the near-surface mixed layer.

3.1 Initial Nature of the Discharge

We will assume that the discharge of fines takes place at the surface with trivially small initial velocity. The fines and bottom water may not stay at the surface because bottom water is denser than surface water and tends to sink. We will assume it mixes rapidly and does not sink any appreciable distance. We will also assume that the material, when initially pumped overboard from the ship, is so dilute that there is no turbidity current, and that the material is initially deposited in the surface layer of the ocean. This seems reasonable because when dumped overboard the material will be diluted at least ten to one with water and will be at very low velocity.

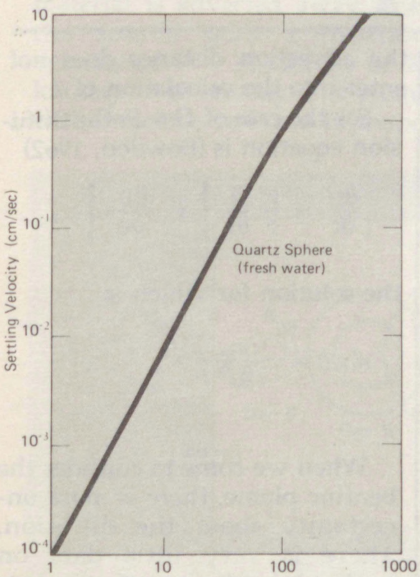


Figure 3. Settling velocities for small particles calculated using Stokes Law.

3.2 Expected Settling

A solid object placed in a fluid tends to settle under gravity by Stokes Law which states

$$\omega = \frac{1}{18}\left(\frac{\rho - 1}{\mu}\right) g d^2$$

where ω is the settling velocity given in cm/day, ρ is the particle's density, μ is the coefficient of molecular viscosity of the fluid, g is the acceleration of gravity, and d is the particle diameter in microns. Evaluating with accepted values of the coefficients, we can simplify this to $\omega = 7.85\ d^2$. We have assumed that we are dealing here with quartz spheroids in 35 parts per thousand salinity sea water at a temperature of 20°C. A graph of settling velocity is given in Figure 3.

A typical particle size in sediments in the nodule zone of the Pacific has been measured to be about 4 microns in diameter (Bishoff, private communication; Cooke, private communication). Using $d = 4$ microns, we find that ω, the settling velocity, is approximately 125 cm/sec. There are some oversimplifications made here: for example, we have considered the particles to have a density of 2.2 and it is probably less than this since the particles have odd shapes rather than spherical shapes. This would tend to make the settling velocity less than our estimate. Further, we have ignored flocculation. Particles naturally tend to gravitate together in water and as a result of this probably settle somewhat faster. Also, many particles in the plumes will not be broken down to their fundamental particle size but will be considerably larger and these will, of course, fall faster.

Our estimate of the settling velocity is quite small. In fact, it is so small that for part of the work we want to carry out we can completely ignore settling and only treat mixing. We will take a range of values of 100 tons/day to 1000 tons/day (DOMES, 1976) for the daily mass of sediment introduced into the plumes. This range of values will allow for some of the particles to settle out rapidly and still permit reasonable estimates for the plume density.

3.3 Vertical Mixing in the Wind-Mixed Layer

The mixed layer of the ocean in the region of Site C is typically 20 m deep (see data from Dr. Halpern in Table 2) and is an area of rapid mixing. Under conditions of fairly good winds, a mixing time, T, is about half an inertial period, T_θ, where the inertial

Table 2. Depth of Mixed Layer in the Site-C Region.

Cast	Latitude	Longitude	Mixed Layer Depth
2	18° N	126° W	40 m
5	17° N	126° W	30 m
9	16° N	126° W	20 m
18	15° N	126° W	25 m
24	14° N	126° W	20 m
28	13° N	126° W	15 m
32	12° N	126° W	10 m

Table 3. Values of Inertial Periods (T_θ) and Mixing (T).

Site	Latitude	T_θ	$T = T_{\theta/2}$
C	15° N	46 hrs.	23 hrs.
B	12° N	58 hrs.	29 hrs.
A	8° N	86 hrs.	43 hrs.

period is given by $T_\theta = 12/\sin\theta$ and θ is the latitude. Table 3 below gives inertial periods and mixing times. From this table we see that if the trade winds blow for a day or so we mix the water to a depth of 20 m. There will be periods when the winds are slack and this mixing does not occur; hence the material will tend to remain near the surface. For the purposes of our present calculations we will assume uniform mixing through the top 20 m of the water and a simple scaling of the numbers to give surface densities for the condition of no mixing. We will consider that even the first day's fines are mixing to 20 m even though they may tend to stay closer to the surface than this.

3.4 Vertical Mixing Below the Wind- Mixed Layer

Mixing through the thermocline is very slow. Vertical diffusion coefficients in this region, according to Dr. Claes Rooth of Miami, are in the range 0.1 to 1.0 cm²/sec. This mixing is so slow that we will completely ignore it for the time periods in which we are interested, a few weeks or even a few months. However, this clearly should be included in calculating behavior of the plume for years.

4. HORIZONTAL DIFFUSION

We will combine all motions into the ocean (other than the average advection velocities) into a simple, uniform horizontal diffusion coefficient. We will consider then that the motion is uniform radial diffusion from a point source. The diffusion equation is

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left[Dr \frac{\partial n}{\partial r} \right]$$

If D can be considered to be a constant, this then becomes

$$D\frac{\partial^2 n}{\partial r^2} + \frac{D}{r}\frac{\partial n}{\partial r} = \frac{\partial n}{\partial t}$$

For this situation the solution of the diffusion equation is:

$$n(r,t) = \frac{n_0}{4\pi Dt}\exp\left(\frac{-r^2}{4Dt}\right)$$

where n is the density of material at radius r and time t, D is the horizontal diffusion coefficient, and n_0 is the initial amount of material introduced at the source.

The horizontal diffusion coefficients actually depend upon the scale of the motion. In this case we are talking about scales of tens to hundreds of kilometers. We will use 10^6 cm²/sec as a first approximation to a constant diffusion coefficient for surface diffusion.

Munk et al. (1949) suggested that one could use $D = P\ell$ for $10^3 < \ell < 10^8$ cm. Here ℓ is a distance giving the scale of the process. We will use $\ell = r$ where r is the distance from the midpoint of each day's dumped sediment. This sediment is advected from point to point (see Fig. 13) but we will consider for simplicity that the advection distance does not enter into the calculation of ℓ.

For the case of $D = Pr$ the diffusion equation is (Bowden, 1962)

$$\frac{\partial n}{\partial t} = \frac{P}{r}\frac{\partial}{\partial r}\left[r^2 \frac{\partial n}{\partial r} \right],$$

the solution for which is

$$n(r,t) = \frac{n_0}{2\pi P^2 t^2} e^{-r/Pt}.$$

When we come to consider the benthic plume, there is more uncertainty about the diffusion. There is very little data on horizontal diffusion of near bottom water in the central Pacific Ocean so we will have to estimate. The value of D should be lower than for surface waters because average currents are lower and also the scale we are considering is smaller. We will assume for the benthic plume that $D = 10^5$ cm²/sec (Halpern, private communication).

5. CALCULATION OF THE SURFACE PLUME

We will now calculate sediment densities in the surface plume, assuming that there is uniform mixing of fines through the 20-meter-deep mixed layer. The material will be advected away from the source with an average velocity V and diffused horizontally with a diffusion coefficient D. We will consider two cases using two different values of V and D. A third case will include settling out of heavy particles by gravity.

5.1 Case A. Using Uniform Velocity

We will assume that the material is advected away from the source with a constant velocity of V = 10 km/day or 20 km/day or 40 km/day. The plume will, therefore, be linear in shape. The plume densities should be reasonably correct even though the plume shape is oversimplified.

Csanady (1973) has treated this case analytically. He transformed the case of a stationary source to a moving point source to give:

$$n(x,y,t) = \frac{n_0}{4\pi Dt} \exp\left[-\frac{(x-vt)^2+y^2}{4Dt}\right]$$

This is the solution of the diffusion equation that has a convective term:

$$\frac{\partial n}{\partial t} + V\frac{\partial n}{\partial x} = -D\left[\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2}\right]$$

Extending this to a continuous source in a current maintained indefinitely, Csanady obtained the concentration field for $t \rightarrow \infty$ by integration:

$$n(x,y,t) = \int_0^\infty \frac{n_0 dt'}{4\pi D(t-t')} \exp\left\{-\frac{[x-v(t-t')]^2+y^2}{4D(t-t')}\right\}$$

This concentration distribution is independent of time as $t' \rightarrow \infty$.

We are interested in the nature of this concentration distribution for times shortly after the source has been turned on, so we cannot use the analytic form given above. We have taken a numerical approximation by using what Csanady calls a "puff model." We put a pulse of particles out from the source and let it advect and diffuse away from the source and then one day later we put out a second pulse from the source, and so on, as shown in Figure 4.

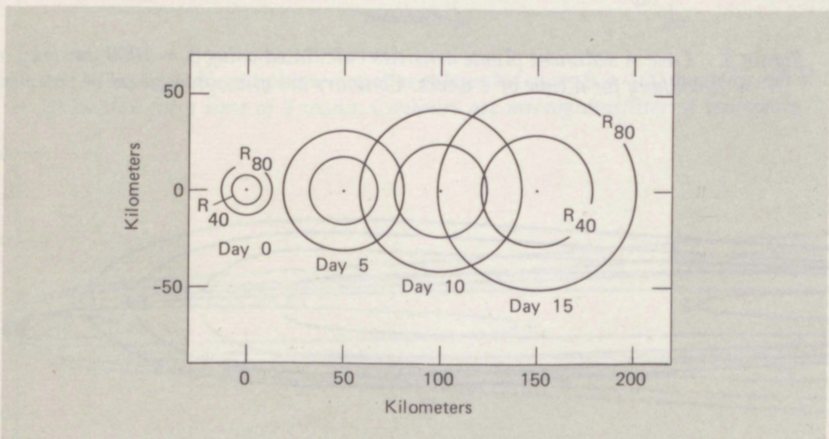


Figure 4. The puff model of advection-diffusion. V = 10 km/day; D = 3 × 10⁶ cm²/sec; R80 contains 80% of the particles; R40 contains 40% of the particles. A pulse of particles introduced each day moves away from the source and grows by diffusion with time.

We have numerically integrated for times of weeks or months and for sediment source strengths of 1000 tons/day or 100 tons/day (DOMES, 1976). The scheme is to calculate the puff size and density $p(x,y,t)$ for each day's source (see Fig. 4) and then sum the puffs for the several days the source is on to obtain

$$n(x,y,t) = \sum_{\text{puffs}} p(x,y,t).$$

The results of these calculations are given in Figures 5–11. After two months the plume reaches out several hundred kilometers but the sediment densities are quite low except very near the source. Near the source sediment densities can become larger than 0.1 mg/liter (see Fig. 12). One hundred kilometers downstream from the source the densities are less than 0.1 mg/liter, which represents reasonably clean water. Typically, the dense portion of the plume is less than 100 km wide at large distances downstream from the source. In the DOMES area the water in the mixed layer is quite clean. Typical inorganic particle concentrations are about 30 μg/liter. For comparison, sediment loads in the Columbia River plume in the ocean are given in Table 4 (Conomos, 1972).

5.2 Case B. Using Halpern's Measured Currents

In order to get a better idea about the appearance of a surface sediment plume, we used actual measured currents from Halpern (1976) as shown in Figure 2. With his daily averaged velocities and $D = 10^6$ cm^2/sec, we calculated the shape of the plume after 10 days, 20 days, and 30 days. We used the puff model and assumed the densities in the daily source puffs as shown in Figure 13. The results of these calculations are shown in Figures 14–19 for the indicated times. Again, we assumed mixing through the top 20 m. We repeated the plume calculations using the last half of the current data from Halpern. A comparison of Figures 14–16 and Figures 17–19 shows how variable the plume was.

We carried out one additional test to show the sensitivity of the calculations to the value of D. So far, Case B has been carried out using $D = 10^6$ cm^2/sec. Now we change D to 10^5 cm^2/sec and recalculate the plume distribution using Halpern currents for days 1 to 30. We start with the same initial size for the puff of particles put in each day because this initial size depends not on D but on ship motion, tides, and inertial oscillations. This initial size is chosen to

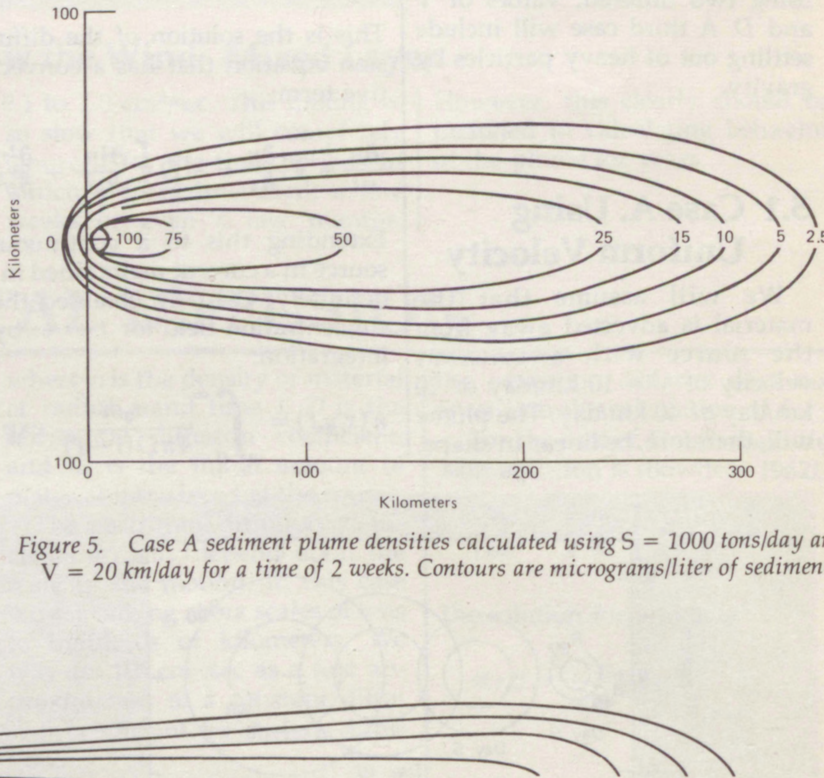


Figure 5. Case A sediment plume densities calculated using S = 1000 *tons/day and* V = 20 *km/day for a time of 2 weeks. Contours are micrograms/liter of sediments.*

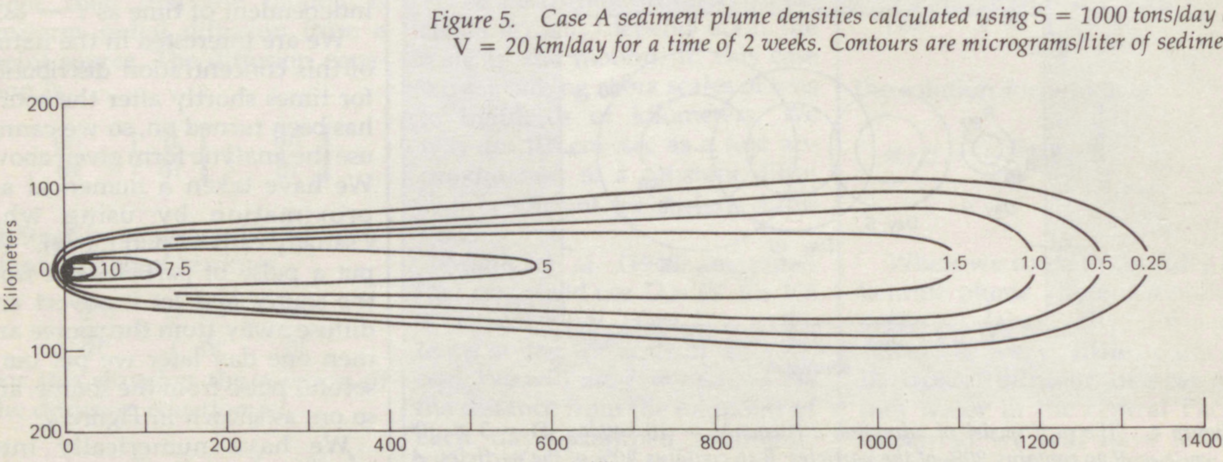


Figure 6. Case A sediment plume densities calculated using S = 1000 *tons/day and* V = 20 *km/day for a time of 2 months. Contours are micrograms/liter of sediments.*

Table 4. Sediment Density in the Columbia River Plume

Depth	13 km*	20 km*	25 km*	40 km*
Early Summer – High Discharge				
1 m	8 mg/ℓ	5 mg/ℓ	1.1 mg/ℓ	0.9 mg/ℓ
3 m	6	4	1.0	1.0
9 m	3	2	1.0	1.1
20 m	2	1.7	0.7	0.9
30 m	3	1.5	0.5	0.5
Late Summer – Low Discharge				
Depth	6 km*	10 km*	15 km*	22 km*
1 m	8.5 mg/ℓ	4.2 mg/ℓ	5.0 mg/ℓ	2.5 mg/ℓ
3 m	10.0	4.2	4.0	1.3
6 m	11.0	5.0	2.2	2.3
9 m	10.0	6.0	1.3	0.1
12 m	17.0	12.0	2.2	0.3

* distance offshore.

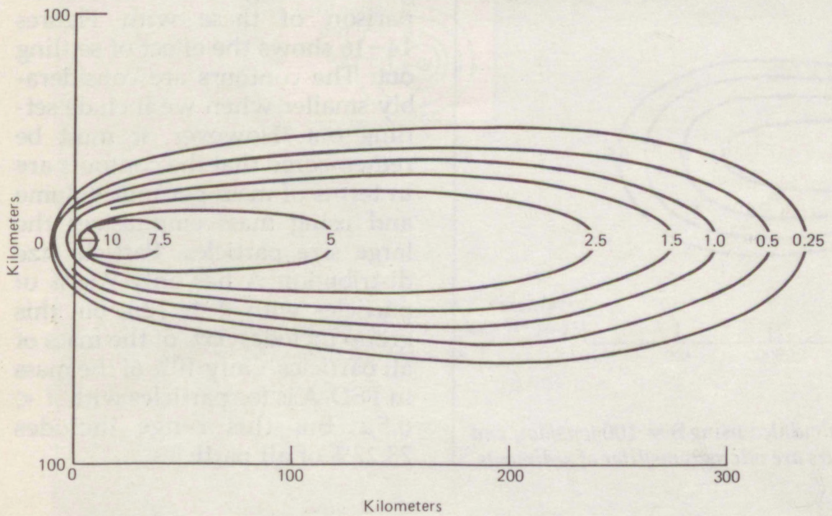


Figure 7. Case A sediment plume densities calculated using S = 100 *tons/day and* V = 20 *km/day for a time of 2 weeks. Contours are micrograms/liter of sediments.*

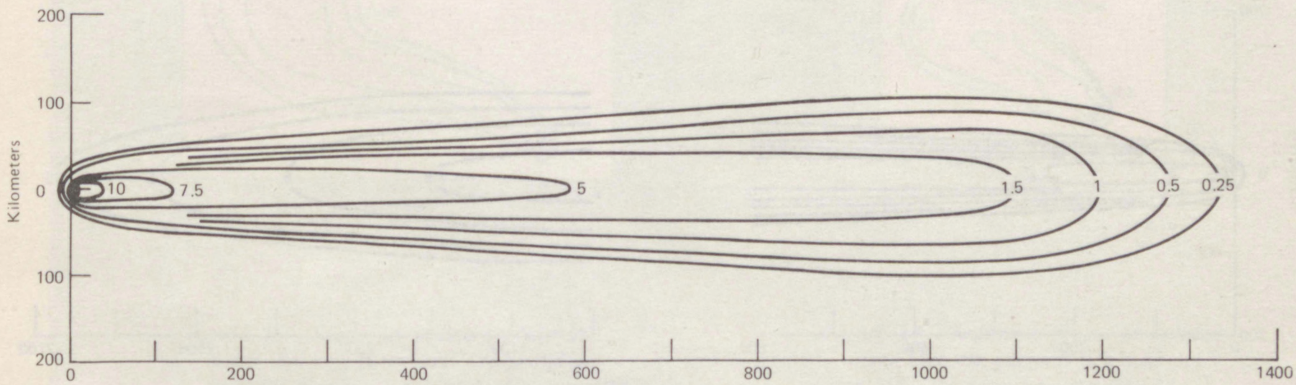


Figure 8. Case A sediment plume densities calculated using S = 100 *tons/day and* V = 20 *km/day for a time of 2 months. Contours are micrograms/liter of sediments.*

put 80% of the particles within a radius of 7.5 km. The results are shown in Figure 20. The plume using $D = 10^5$ is considerably narrower and has values almost a power of ten lower. Both results are to be expected.

5.3 Case C. Using Halpern's Currents with Settling Out

We now consider the third case for the surface plume in which we have vertical motion of the particles. We can estimate how much the surface sediment plume is reduced by treating the settling out of heavier particles. We have constructed two values of particle size distribution (PSD), A and B (Figs. 21 and 22). We assume here that the PSD is the one given in Figure 21. This is an estimate from the mining companies and has half of the number of particles finer than 4μ. We assume continuous mixing of the sediment

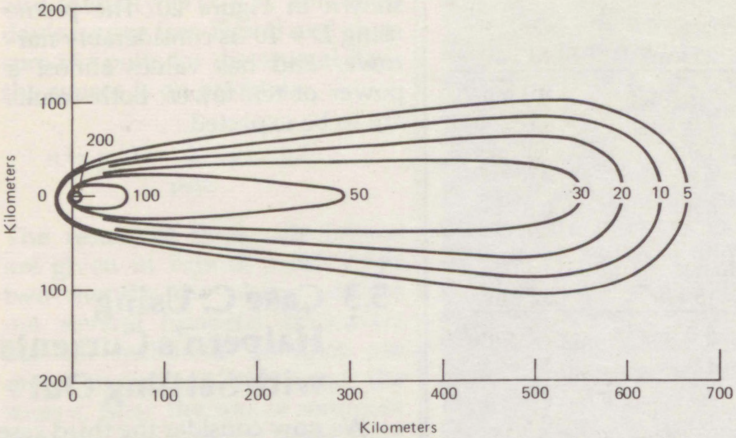


Figure 9. Case A sediment plume densities calculated using S = *1000 tons/day and* V = *10 km/day for a time of 2 months. Contours are micrograms/liter of sediments.*

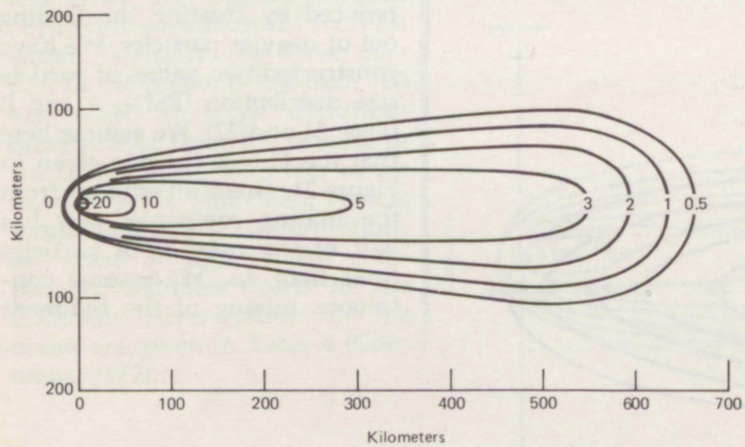


Figure 10. Case A sediment plume densities calculated using S = *100 tons/day and* V = *10 km/day for a time of 2 months. Contours are micrograms/liter of sediments.*

through the 20-m mixed layer depth. Then the fraction of group-i particles that settle through the thermocline per day will be

$$f_i = \frac{\omega_i}{2000 \text{ cm}} \quad ,$$

where ω_i = settling velocity in cm/day. We can obtain the PSD for each day from

$$n_i(t = m + 1) = (1 - f_i)\, n_i(t = m) \, .$$

Now if we take the diminished puffs from each day's plume source and add them together

$$(n = \sum_i n_i)$$

we have the diminished plumes given in Figures 23-25. Comparison of these with Figures 14–16 shows the effect of settling out. The contours are considerably smaller when we include settling out. However, it must be remembered that the contours are in terms of mass per unit volume and using mass emphasizes the large size particles. Particle size distribution A has only 7.66% of particles with $d > 12\mu$, but this group includes 55% of the mass of all particles. Only 10% of the mass in PSD-A is for particles with $d < 6.5\mu$, but this range includes 73.27% of all particles.

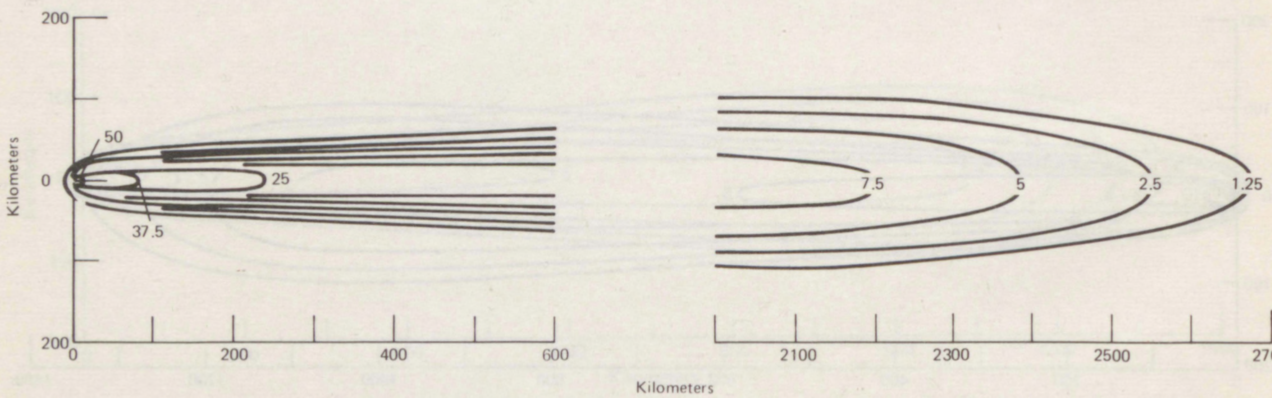


Figure 11. Case A sediment plume densities calculated using S = *1000 tons/day and* V = *40 km/day for a time of 2 months. Contours are micrograms/liter of sediments.*

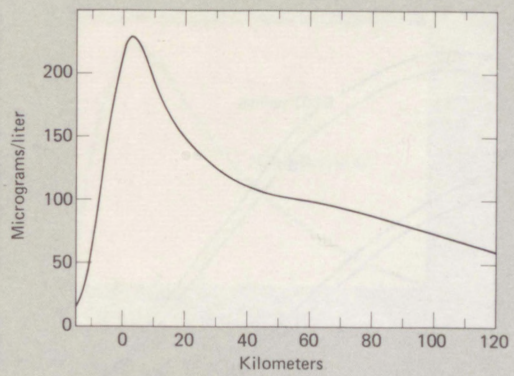


Figure 12. Case A sediment plume density along the center line of the turbidity plume. V = 10 km/day and S = 1000 tons/day.

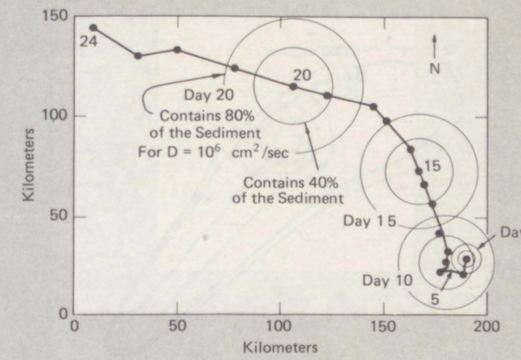


Figure 13. Advection and diffusion of sediments placed in water at DOMES Site C on Aug. 29, 1975, using puff model (Fig. 4).

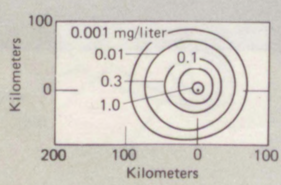


Figure 14. Sediment plume calculated using Halpern currents (Case B) and S = 1000 tons/day for days 1–10.

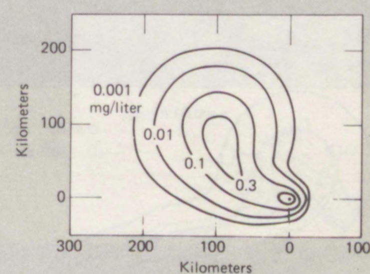


Figure 15. Sediment plume calculated using Halpern currents (Case B) and S = 1000 tons/day for days 1–20.

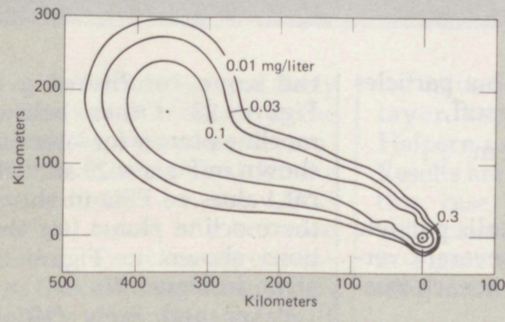


Figure 16. Sediment plume calculated using Halpern currents (Case B) and S = 1000 tons/day for days 1–30.

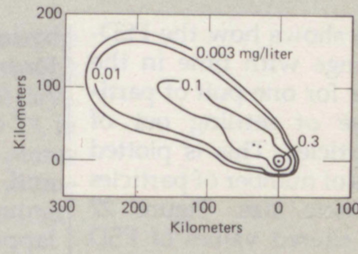


Figure 17. Sediment plume calculated using Halpern currents (Case B) and S = 1000 tons/day for days 24–34.

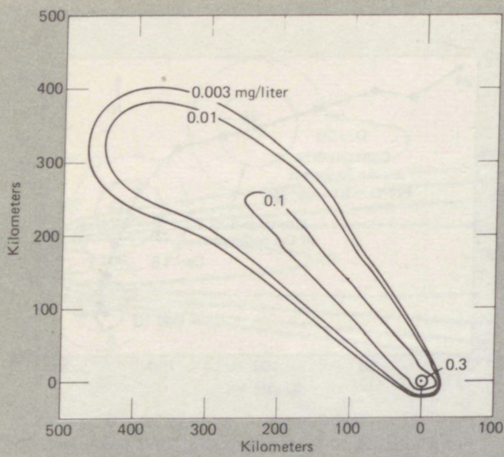


Figure 18. Sediment plume calculated using Halpern currents (Case B) and S *= 1000 tons/day for days 24–44.*

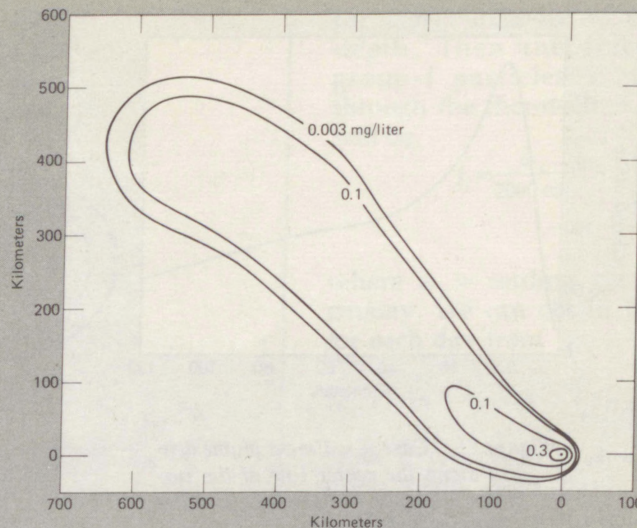


Figure 19. Sediment plume calculated using Halpern currents (Case B) and S *= 1000 tons/day for days 24–54.*

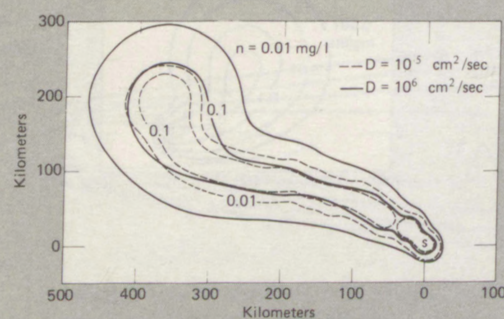


Figure 20. A comparison of sediment plumes for D *=* 10^5 *cm²/sec and* D *=* 10^6 *cm²/sec, calculated using Halpern currents for days 1–30, and* S *= 1000 tons/day.*

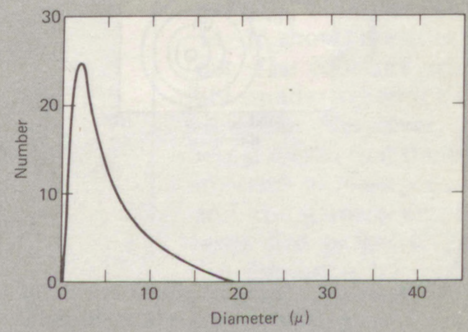


Figure 21. Assumed particle size distribution (A) having 50% of particles with d $> 4\ \mu$. Vertical scale is relative number of particles.

Figure 26 shows how the PSD-A will change with time in the mixed layer for one puff of particles because of settling out of heavier particles. This is plotted on the basis of number of particles versus particle size. Figure 27 shows the altered values of PSD for the points A, B, and C in Figure 25. Figure 27 has been plotted in terms of mass of particles (in each size group of Table 5) versus particle size.

We also have calculated the approximate sediment density expected just under the thermocline by taking the settled out particles for one day for each puff,

$$s_i = f_i p_i \text{ gm/cm}^3 \ ,$$

and summing for all particle groups and for the several overlapping puffs present at each location,

$$s(x,y,t) = \sum_{\text{puffs}} \sum_i s_i(t,x,y) \ .$$

The values for this below-thermocline sediment plume density $s(x,y)$ are shown in Figure 28 for the same conditions given in Figure 23. Other below-thermocline plumes for later times are shown in Figures 29 and 30. Typical values of PSD in this below-thermocline plume (for the locations shown in Figure 30) are given in Figure 31.

Baker and Feely (1976) have measured the PSD of particles in the upper water column in the DOMES area by filtering water samples and then using a scanning electron microscope. The PSD-C measured this way is shown in Figure 32 and is also

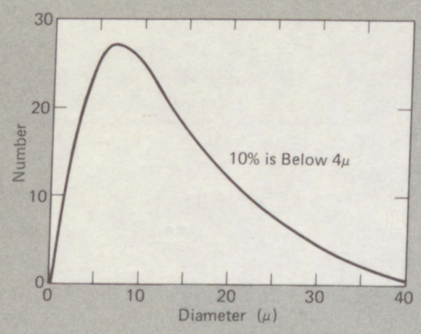


Figure 22. Assumed particle size distribution (B) having 90% of particles with d $> 4\,\mu$. Vertical scale is relative number of particles.

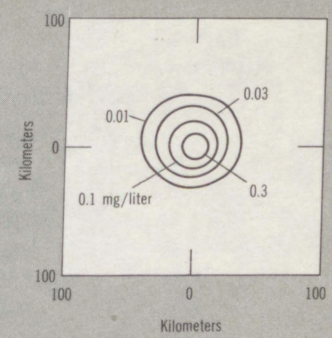


Figure 23. Case C. Diminished surface sediment plume allowing the heavy particles to settle out. PSD-A and Halpern currents for days 1–10 are used. S = *1000 tons/day.*

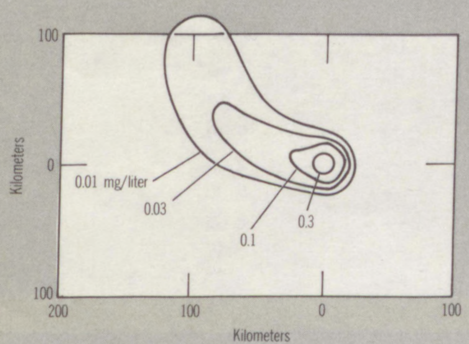


Figure 24. Case C. Diminished surface sediment plume allowing the heavy particles to settle out. PSD-A and Halpern currents for days 1–20 are used. S = *1000 tons/day.*

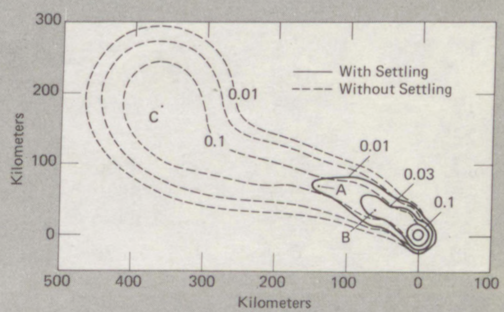


Figure 25. Case C. Diminished surface sediment plume allowing the heavy particles to settle out. Halpern currents for days 1–30 and PSD-A are used. Shown for comparison are the contours for no settling out from Figure 16.

given in Table 5. Baker and Feely state, "The size distribution in the water column compares favorably with that determined for the bottom sediment by the USGS preliminary report of a box core from Site C. The close agreement suggests that mining debris, when completely disaggregated, will have a PSD very similar to the naturally occurring suspended particle matter." However, recent data from Sallenger (private communication) of the USGS would seem to say that PSD-A may be nearer to actuality. Using PSD-C we have recalculated the surface layer sediment plume using Halpern's currents for 1–30 days. Results are shown in Figure 33. In this case, the sediment plume quite closely resembles the plume in Figure 16, which had no settling out included.

Table 5. Settling Velocities and Times for Different Size Particles, and Particle Size Distributions(PSD) Used in the Calculations.

Particle Size Range (μ)	Particle Av. Diameter (μ)	ω (cm/day)	T_{20} (days)	PSD-A (%)	PSD-B (%)	PSD-C (%)
1	0.5	1.96	1020	6.84	0.42	12
2	1.5	17.7	113	15.85	2.08	28
3	2.5	49.0	40.8	15.75	3.32	34
4	3.5	96	20.8	11.60	4.16	16
5	4.5	159	12.6	9.56	5.00	5
6	5.5	238	8.40	7.52	5.48	3
7	6.5	332	6.04	6.15	5.68	2
8	7.5	441	4.54	5.50	5.68	—
9	8.5	566	3.54	4.10	5.51	—
10	9.5	710	2.82	3.56	5.31	—
11	10.5	865	2.32	3.14	5.05	—
12	11.5	1040	1.92	2.60	4.51	—
13	12.5	1230	1.62	1.92	4.37	—
14	13.5	1430	1.40	1.64	4.07	—
15	14.5	1650	1.22	1.37	3.84	—
16	15.5	1880	1.06	1.09	3.52	—
17	16.5	2140	0.94	0.82	3.28	—
18	17.5	2400	0.84	0.55	3.00	—
19	18.5	2680	0.75	0.27	2.80	—
20	19.5	2980	0.67	—	2.60	—
25	22.5	3980	0.50	—	10.00	—
30	27.5	5940	0.338	—	6.02	—
35	32.5	8300	0.241	—	3.12	—
40	37.5	11020	0.181	—	1.25	—

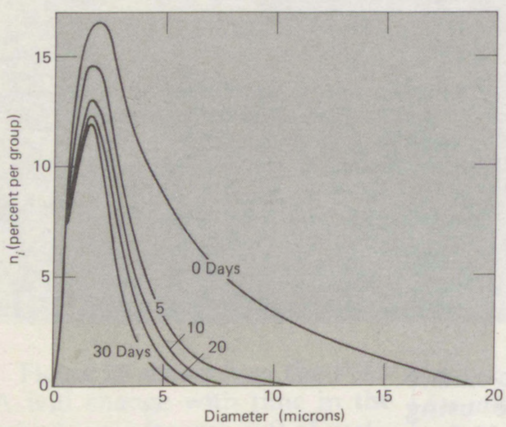


Figure 26. Change, with time, of PSD-A in the mixed layer due to settling out of heavy particles.

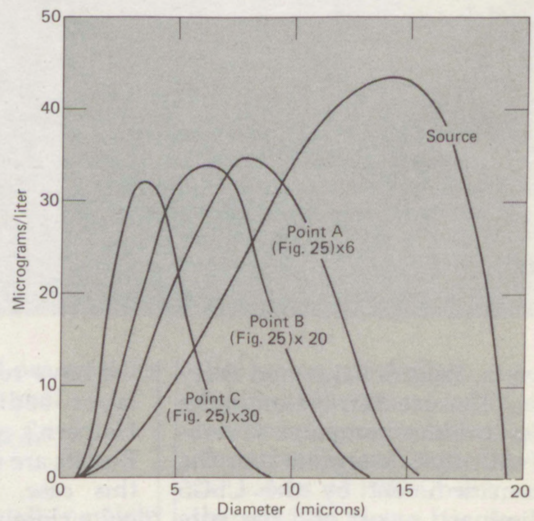


Figure 27. Change, with time, of PSD-A in the mixed layer due to settling out of heavier particles. This is calculated for the positions shown on Figure 25.

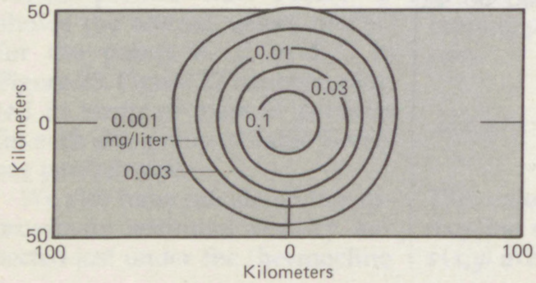


Figure 28. Case C. Sediment plume below the mixed layer due to settling out of heavier particles for days 1–10. Halpern currents and PSD-A are used. S = *1000 tons/day.*

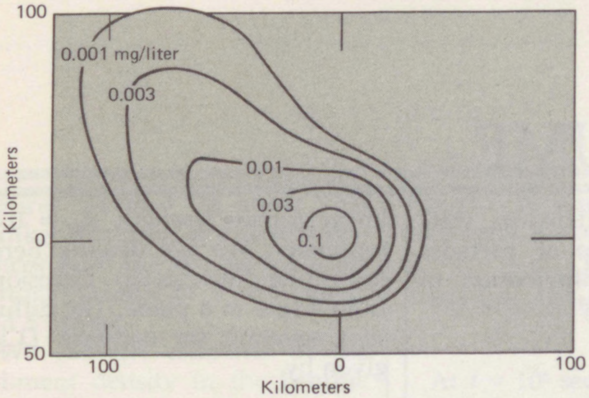


Figure 29. Case C. Sediment plume below the mixed layer due to settling out of heavier particles for days 1–20. Halpern currents and PSD-A are used. S = *1000 tons/day.*

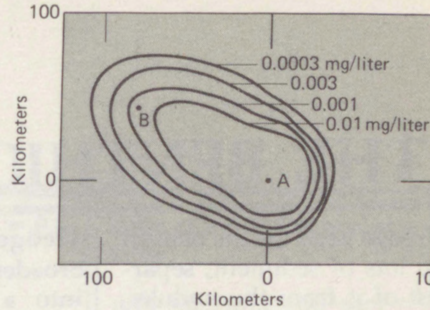


Figure 30. Case C. Sediment plume below the mixed layer due to settling out of heavier particles for days 1–30. Halpern currents and PSD-A are used. S = *1000 tons/day.*

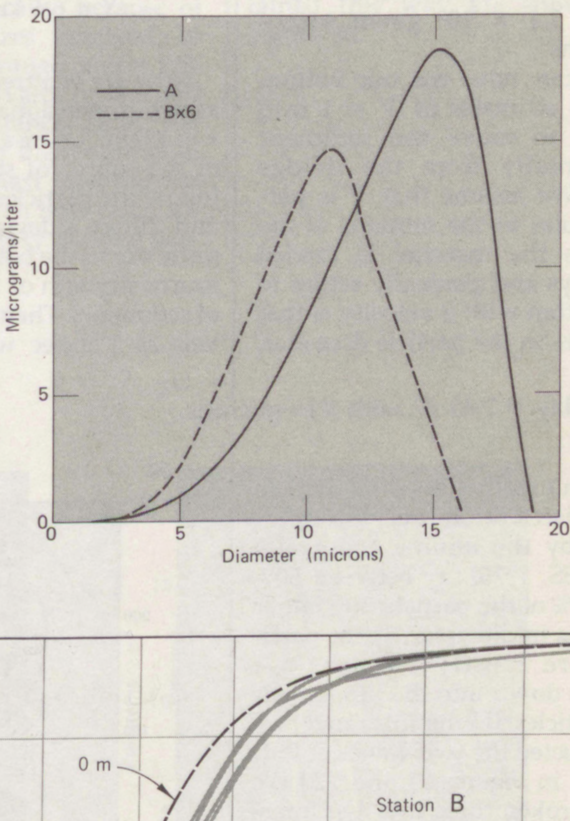


Figure 31. Typical PSD for the below-thermocline plume at locations indicated in Figure 25.

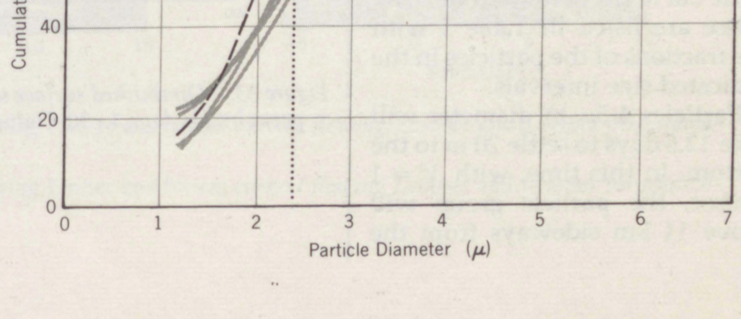


Figure 32. Particle size cumulative curves at station B for depths 0 m, 56 m, 173 m, 298 m, and 800 m. The dotted line indicates the median diameter.

6. THE BENTHIC PLUME

The dredge head on the bottom picks up lots of sediment, separates most of it from the nodules, and drops the sediment about 20 m above the bottom. The dredge puts out sediments of from 14,000 to 120,000 tons/day (DOMES, 1976). The mining ship moves at roughly 1 m/sec so we have a line source of sediment released by the dredge head equivalent to 1.6×10^5 to 1.4×10^6 gm/m source strengths.

We can now use our bottom current estimates of $V = 1$ to 5 cm/sec to move the sediment horizontally from the dredge track. We assume that V is perpendicular to the motions of the ship so the material is carried sideways and gradually settles to the bottom with a velocity ω that depends on the particle diameter:

$$\omega \text{ cm/day} = 7.85\, d^2 \text{ with } d \text{ in microns.}$$

We don't really know the particle size distribution but estimates made by the mining companies (DOMES, 1976) say between 50% and 90% of the particles are larger than 4μ in diameter. These particles are mostly clumps, not broken down into the fundamental particles. (Using this range, we constructed the two values of PSD shown in Figures 21 and 22.) We have broken these into $1\text{-}\mu$ intervals and calculated the settling velocities ω and the times T_{20} to settle out to the bottom from 20 m. These are listed in Table 5 with the fractions of the particles in the indicated size intervals.

Particles $4\text{-}5\mu$ in diameter will take 12.6 days to settle 20 m to the bottom. In this time, with $V = 1$ cm/sec, the particle group will move 11 km sideways from the dredge track. Diffusion will broaden this group of particles into a Gaussian distribution of half-width given by

$$\frac{X^2}{4DT_{20}} = 1$$

or, in this instance,

$$X = 6.6 \text{ km.}$$

Now we can treat this problem as two-dimensional motion in the x−z plane. Using a 1-meter length of the source of strength, n_0, we follow the particles as they advect and diffuse sideways and slowly settle out to the bottom. We take a source strength of 35,000 tons/day of sediments. Then, if the ship travels at 1 m/sec we will have a linear source strength $n_0 = 0.4$ ton/meter. We are dealing here with one-dimensional diffusion from a line in a plane. The diffusion equation for constant D is given by

$$\frac{\partial n}{\partial t} = D\,\frac{\partial^2 n}{\partial X^2}\,,$$

and the solution is

$$n(X,t) = \frac{n_0}{\sqrt{4\pi Dt}}\,e^{-X^2/4Dt}\,.$$

We will allow each particle group to settle for a time, T_{20}, calculate the shape of the diffusion pattern for each particle group, and then sum them. This gives the thickness of the blanket of fines that is deposited on the bottom near the dredge head.

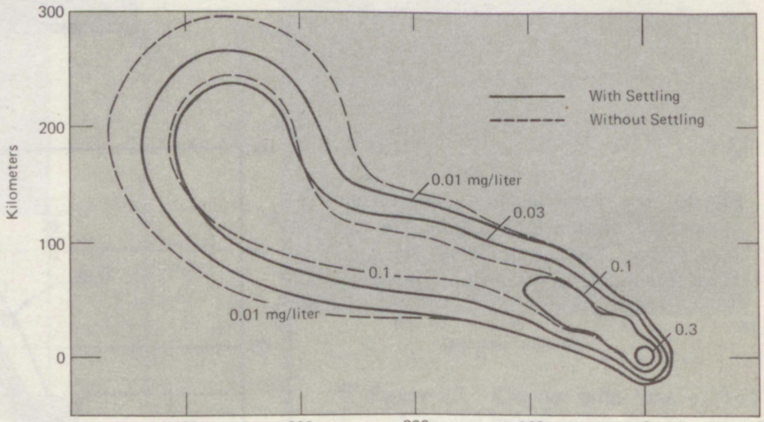


Figure 33. Diminished surface sediment plume (Case C) including settling of heavy particles for days 1−30. Halpern currents and PSD-C are used.

Figures 34 and 35 show this blanket thickness at different distances from the dredge track for bottom currents of $V = 1$ cm/sec and 5 cm/sec.

We can get estimates of the sediment density in the benthic plume before the sediment settles back onto the bottom. The particles settle toward the bottom from the 20-meter level of the source with the velocity ω shown in Table 5. Particles of different sizes are sorted vertically by this process. At a time of 10^5 sec, the particles will have moved 1 km sideways from the dredge track (using $V = 1$ cm/sec). The particles also diffuse horizontally to give the horizontal distribution

$$n(x,t) = \frac{n_0}{\sqrt{4\pi Dt}} \exp\left(-\frac{X^2}{4Dt}\right)$$

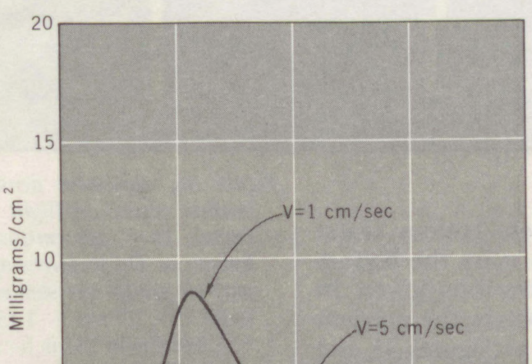
For $D = 10^5$ cm^2/sec and $n_0 = 0.4$ ton/meter we obtain

$$n(1 \text{ km}, 10^5 \text{ sec}) = 113 \text{ gm/m}^2.$$

At $t = 10^5$ sec, particles of $d > 16\mu$ will have settled to the bottom. Particles of diameter $8\mu < d < 9\mu$ will have settled a depth of $\bar{z} = 6.55$ m. We assume they spread out vertically, because of the range of sizes involved, to cover a vertical range of $H = 1.56$ m around $\bar{z}$. This value of H is half the vertical distance from the center of the next higher group of particles to the next lower group of particles. We can now calculate the sediment density of these particles at $z \sim 6.5$ m and at $x = 1$ km to be

$$n_i(z = 6.5 \text{ m}, t = 10^5 \text{ sec}) = \frac{(113)(0.0566)}{1.56} = 4.08 \text{ gm/m}^3$$

where 0.0566 is the mass fraction of particles of $8\mu < d < 9\mu$. Values of the plume density obtained this way are shown in Figure 36.



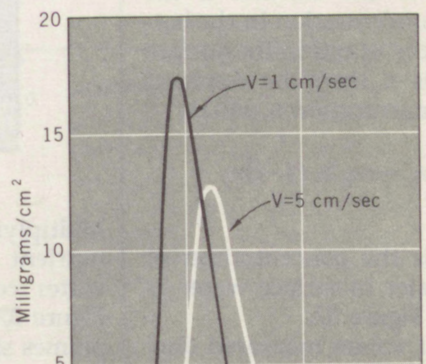


Figure 34. Benthic blanket thickness for ship moving 1 m/sec and bottom current flowing 1 cm/sec and 5 cm/sec perpendicular to ship motion. PSD-A is used.

Figure 35. Benthic blanket thickness for ship moving 1 m/sec and bottom current flowing 1 cm/sec and 5 cm/sec perpendicular to ship motion. PSD-B is used.

7. BOTTOM WATER PLUME

From 10,000 to 40,000 m^3/day of bottom water will be brought up the pipe from the bottom by the mining ship and released into the surface water (DOMES, 1976). This water will probably be colder and denser than surface water even though it has been frictionally heated rising through the pipe. This bottom water might settle out at some intermediate depth where it would be neutrally buoyant but more probably it would mix promptly and become part of the surface waters of the ocean. Assuming it spread uniformly through the 20-m layer, we can calculate directly what the plume of bottom water looks like. Using sources of 10,000 m^3/day and 100,000 m^3/day, $D = 10^6$ cm^2/sec, and constant advection velocity V, we have found the bottom water plumes shown in Figures 37–40. Typical bottom water concentrations are a few ppm.

The bottom water carries nutrients to the surface. If the nutrient concentration in the bottom water is n_b and in the surface water it is n_s then the resultant surface concentration n_r will be

$$n_r = cn_b + (1-c)n_s$$

where c is the concentration of bottom water in surface water as shown in Figure 37.

Nutrient values measured during the DOMES project and representative of all sites are (Anderson, private communication)

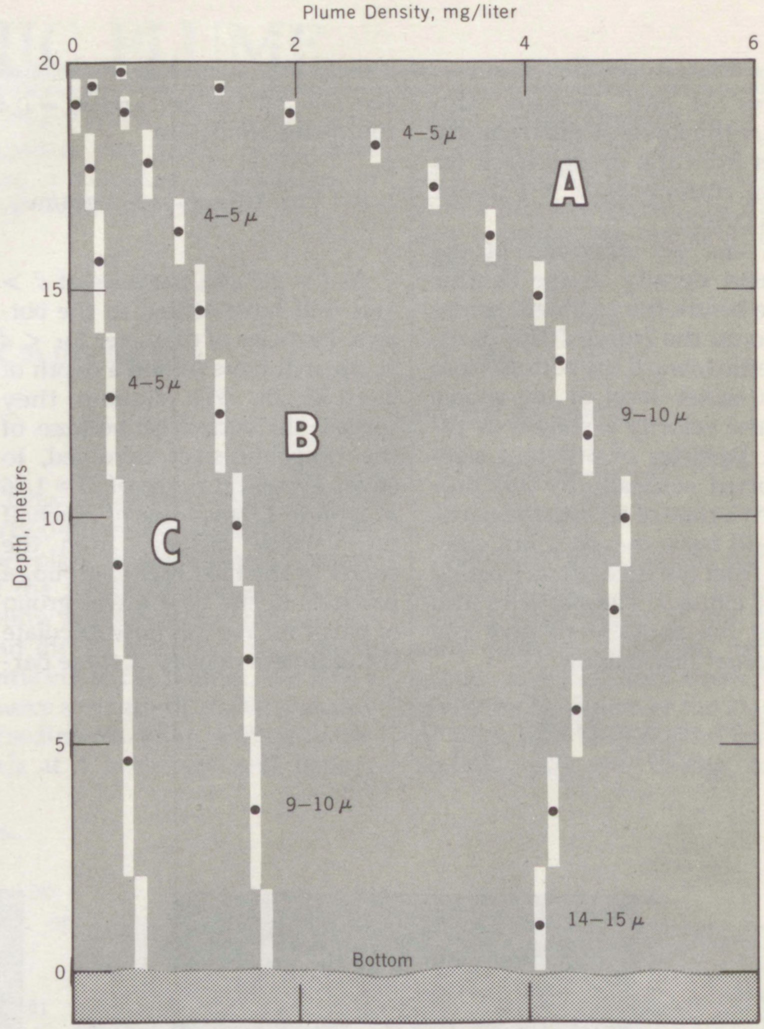


Figure 36. Sediment densities in the benthic plume in-flight for V = 1 cm/sec, D = 10^5 cm²/sec, n_0 = 0.4 ton/meter. The locations of the various particle groups are shown. Curve (A) is for t = 10^5 sec ~ 1.15 days and x = 1 km; Curve (B) is for t = 2 × 10^5 sec ~ 2.3 days and x = 2 km; Curve (C) is for t = 4 × 10^5 sec ~ 4.6 days and x = 4 km.

Multiplying these bottom water nutrient values n_b by the bottom water concentrations given in Figure 37, we obtain the nutrient plumes shown in Figures 41 and 42. Except in regions where the nitrates in the mixed layer are essentially zero, the added nutrients shown in Figures 41 and 42 represent a small addition to the preexisting nitrates and silicates in the surface waters given above.

	Nitrate	Silicate
Upper mixed layer (n_s)	0–0.5 μmols/liter	1–4 μmols/liter
Bottom water (n_b)	35–36 μmols/liter	137–138 μmols/liter

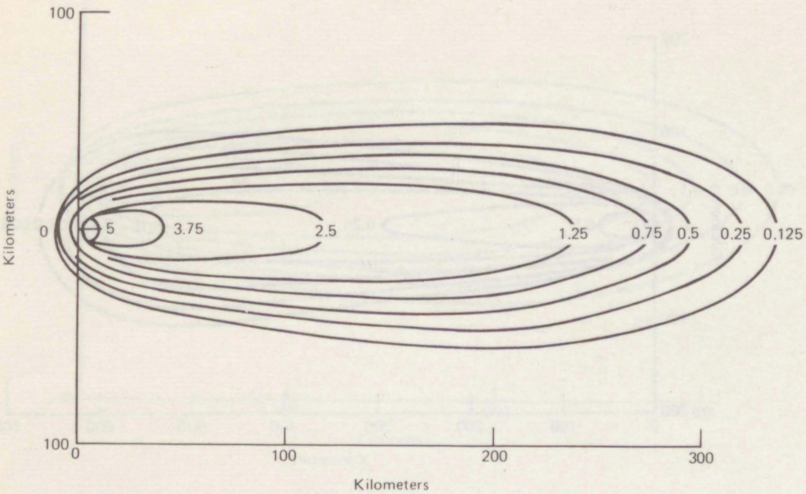


Figure 37. Calculated plume of bottom water in the mixed layer after 2 weeks of dredging (in ppm). V = 20 *km/day;* S = *100,000 m³/day.*

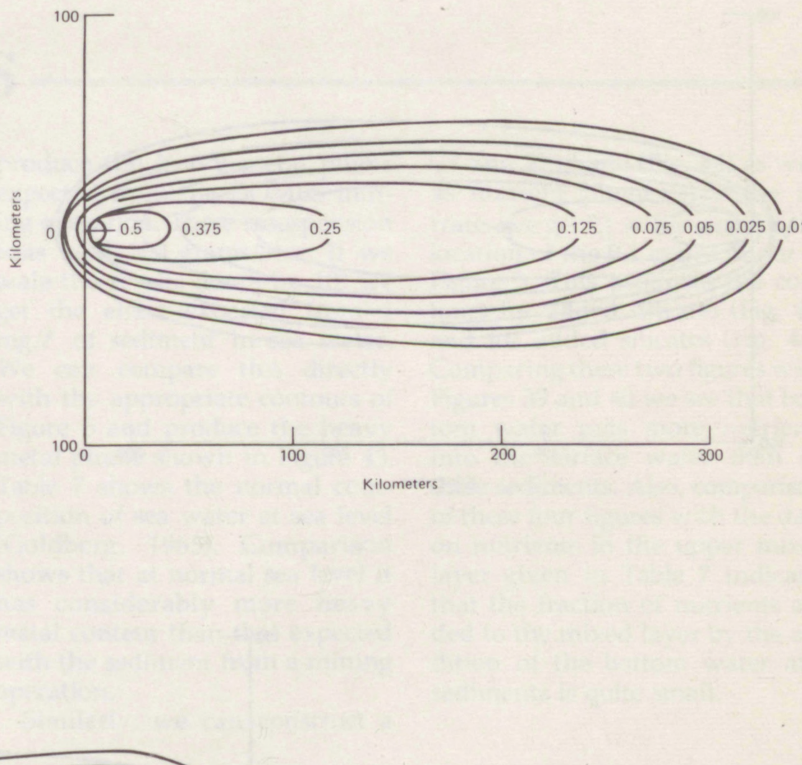


Figure 38. Calculated plume of bottom water in the mixed layer after 2 weeks of dredging (in ppm). V = 20 *km/day;* S = *10,000 m³/day.*

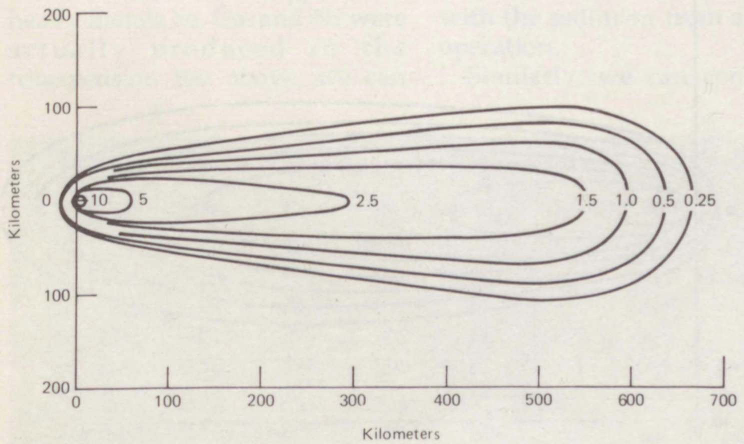


Figure 39. Calculated plume of bottom water in the mixed layer after 2 months of dredging (in ppm). V = 10 *km/day;* S = *100,000 m³/day.*

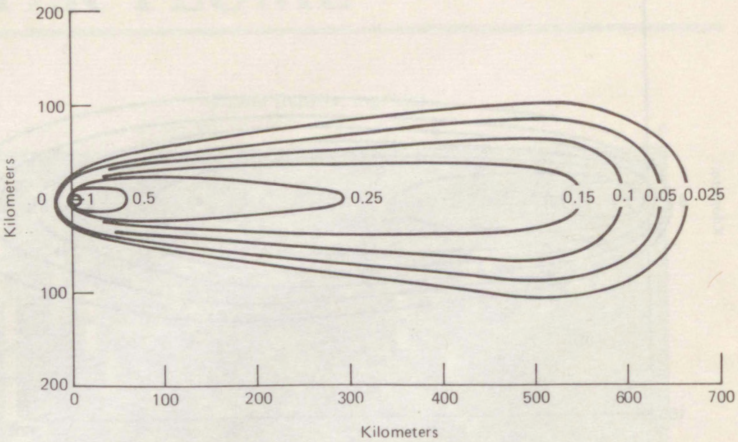


Figure 40. Calculated plume of bottom water in the mixed layer after 2 months of dredging (in ppm). V = 10 *km/day;* S = 10,000 *m³/day.*

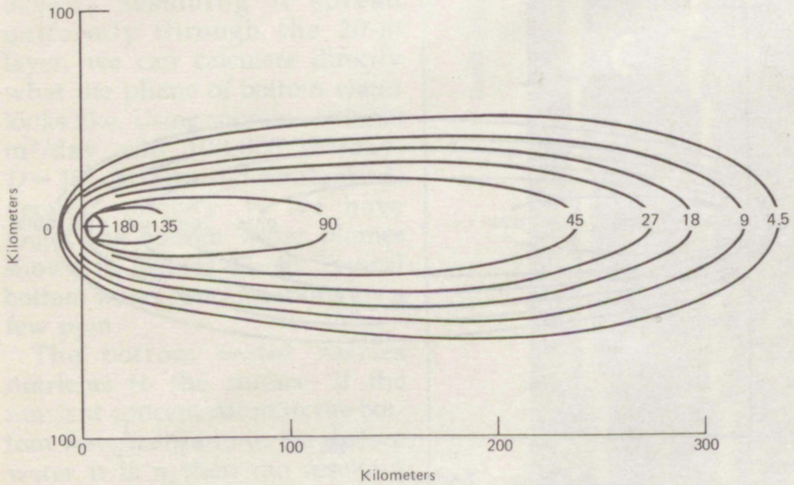


Figure 41. Calculated plume of nitrates added to the mixed layer after 2 weeks of dredging. Nitrates are introduced by bottom water of 100,000 m³/day. V = 20 *km/day. Contours are in micro-micro mol/liter.*

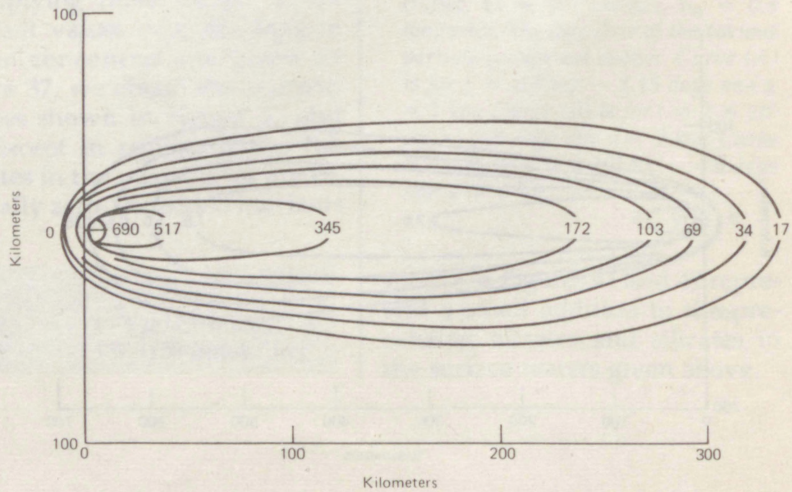


Figure 42. Calculated plume of silicates added to the mixed layer after 2 weeks of dredging. Silicates are introduced by bottom water of 100,000 m³/day. V = 20 *km/day. Contours are in micro-micro mol/liter.*

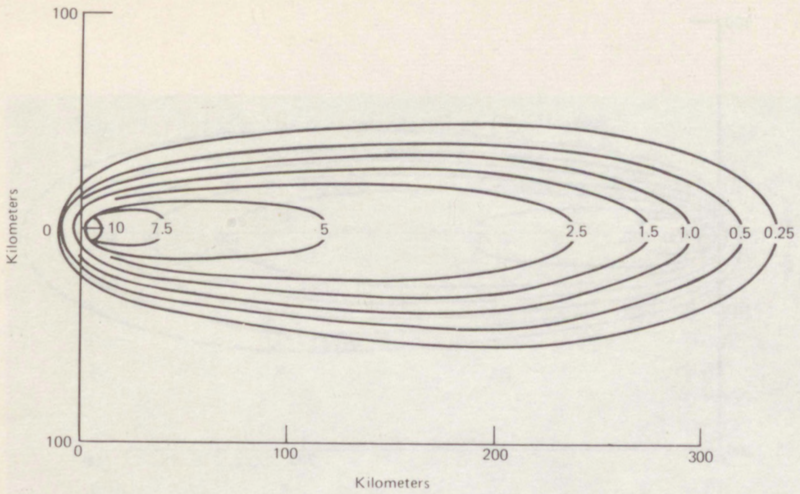


Figure 43. Calculated plume of heavy metals Mn, Fe, Cu, and Ni introduced into surface waters after 2 weeks of dredging. Contours are parts per 10^{15} parts of water. V = 20 km/day; S = 1000 tons/day. This plume is an upper limit to the expected heavy metals released from the sediments.

8. MATERIAL RELEASED from the SEDIMENTS

Recently Bishoff (private communication) placed sediment samples from the bottom in the DOMES area into clean sea water to find out what proportion of metals, nutrients, and other materials are released from the sediments. He placed 10 grams of sediments in 0.1 liter of sea water and agitated it for 11 days. Table 6 shows the material released from the sediment into the sea water. For most samples the heavy metals Fe, Cu, and Ni levels were obviously below the limit of detectability (about 20 ppb).

If we assume that 10 ppb of the heavy metals Fe, Cu, and Ni were actually produced in the resuspension test above, we can produce the heavy metal plume expected from the DOMES mining operation. These resuspension tests used 100 grams/liter. If we scale the results down by 10^5 we get the effect expected from 1 mg/ℓ of sediment in sea water. We can compare this directly with the appropriate contours of Figure 5 and produce the heavy metal plume shown in Figure 43. Table 7 shows the normal composition of sea water at sea level (Goldberg, 1963). Comparison shows that at normal sea level it has considerably more heavy metal content than that expected with the sediment from a mining operation.

Similarly, we can construct a Ca and K plume (Fig. 44) as well as nutrient plumes. For the nitrates we get 21×10^{-6} μm/ℓ at the location of the 0.1 mg/ℓ contour of Figure 5. This produces the contours for added nitrates (Fig. 45) and for added silicates (Fig. 46). Comparing these two figures with Figures 39 and 40 we see that bottom water puts more nutrients into the surface water than do these sediments. Also, comparison of these four figures with the data on nutrients in the upper mixed layer given in Table 7 indicates that the fraction of nutrients added to the mixed layer by the addition of the bottom water and sediments is quite small.

Table 6. Results of Resuspension Experiments.

Depth Interval	Mg (ppm)	Ca (ppm)	K (ppm)	SiO_2 (ppm)	Fe (ppb)	Mn (ppb)	Cu (ppb)	Ni (ppb)	NO_3 (μm/ℓ)	NO_2 (μm/ℓ)	PO_4 (μm/ℓ)	NH_3 (μm/ℓ)
2–4 cm	1203	392	404	15	<5	<7	<5	<10	23	0.9	1.7	2.2
10–12cm	1194	399	403	14	<5	<5	<5	<10	15	0.9	1.3	2.8
18–20 cm	1225	395	404	13	<5	<5	<5	<10	18	0.7	1.2	2.2
26–28 cm	1228	391	434	12	<5	<5	<5	<10	26	0.6	2.2	3.5
30–32 cm	1230	397	405	13	400	100	<5	<10	23	0.7	1.4	2.8
Average	1216	395	410	13	80	20	<5	< 10	21	0.7	1.6	2.7

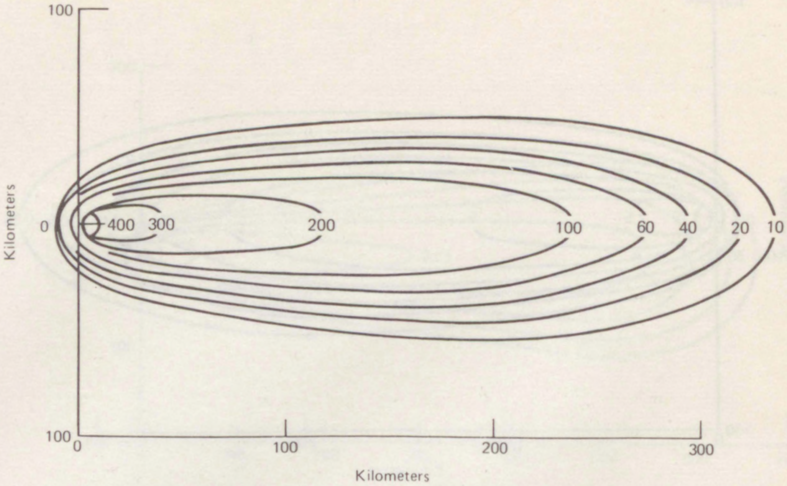


Figure 44. Calculated plume of Ca and K introduced into surface waters after 2 weeks of dredging. V = 20 km/day; S = 1000 tons/day. Contours are in parts per trillion.

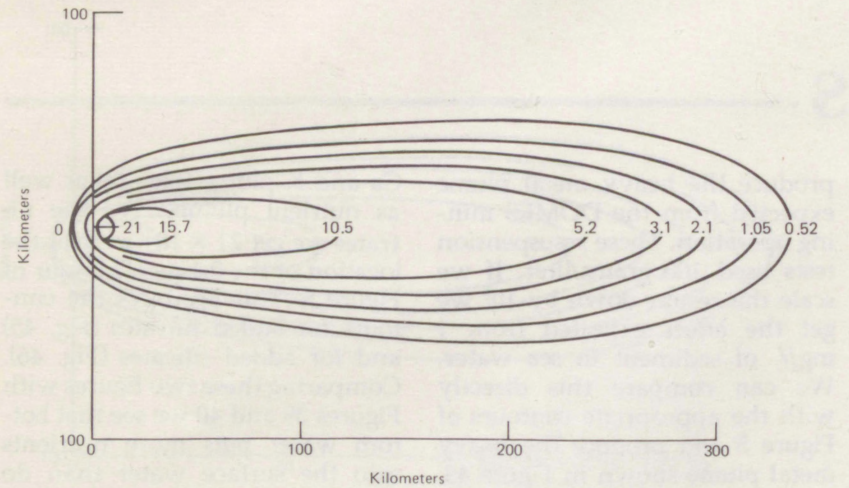


Figure 45. Calculated plume of nitrates added to surface waters after 2 weeks of dredging. These nitrates are the maximum expected to be released from 1000 tons/day of sediments introduced into the surface waters. V = 20 km/day; S = 1000 tons/day. Contours are in micro-micro mol/liter.

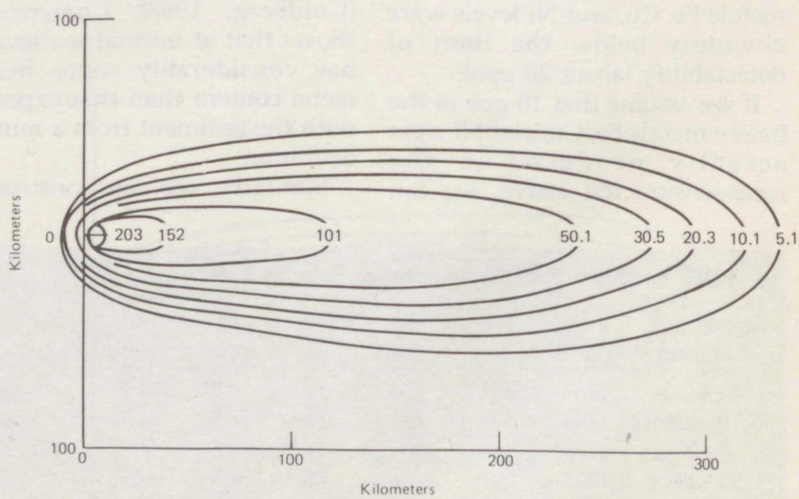


Figure 46. Calculated plume of silicates introduced into surface waters after 2 weeks of dredging. These silicates are the maximum expected to be released from 1000 tons/day of sediments introduced into the surface waters. V = 20 km/day; S = 1000 tons/day. Contours are in micro-micro mol/liter.

Table 7. Geochemical Parameters of Sea Water.

Element	Abundance (mg/ℓ)	Element	Abundance (mg/ℓ)	Element	Abundance (mg/ℓ)
H	108,000	Ti	0.001	Cd	0.00011
He	0.000005	V	0.002	In	<0.02
Li	0.17	Cr	0.00005	Sn	0.003
Be	0.0000006	Mn	0.002	Sb	0.0005
B	4.6	Fe	0.01	I	0.06
C	28	Co	0.0005	Xe	0.0001
N	0.5	Ni	0.002	Cs	0.0005
O	857,000	Cu	0.003	Ba	0.03
F	1.3	Zn	0.01	La	0.0003
Ne	0.0001	Ga	0.00003	Ce	0.0004
Na	10,500	Ge	0.00007	W	0.0001
Mg	1,350	As	0.003	Au	0.000004
Al	0.01	Se	0.004	Hg	0.00003
Si	3	Br	65	Tl	<0.00001
P	0.07	Kr	0.0003	Pb	0.00003
S	885	Rb	0.12	Bi	0.00002
Cl	19,000	Sr	8	Rn	0.6×10^{-15}
A	0.6	Y	0.0003	Ra	1.0×10^{-10}
K	380	Nb	0.00001	Th	0.00005
Ca	400	Mo	0.01	Pa	2.0×10^{-9}
Sc	0.00004	Ag	0.0003	U	0.003

9. REFERENCES

Amos, A. F., Roels, O. A., and Paul, A. Z. (1976), Environmental baseline conditions in a manganese-nodule province in April-May 1975, Proc. 8th Ann. Offshore Technology Conf., OTC Paper No. 2456 (Houston, Tex.).

Anderson, George, University of Washington, Seattle, Wash., private communication.

Baker, E. T., and Feely, R. A. (1976), DOMES Preliminary Report, Suspended Matter Program, Pacific Marine Environmental Laboratory, Seattle, Wash.

Bishoff, J., U. S. Geological Survey, Menlo Park, Calif., private communication.

Bowden, K. F. (1962), Turbulence, in *The Sea,* M. N. Hill, Ed., 1, 820, (Interscience).

Conomos, T. J. (1972), Processes affecting suspended particulate matter in the Columbia River effluent system, in *Columbia River Estuary and Adjacent Ocean Waters,* A. T. Pruter and D. L. Alverson, Eds. (Univ. of Washington Press).

Cooke, R. W., International Nickel Corp., Bellevue, Wash., private communication.

Csanady, G. T. (1973), *Turbulent Diffusion in the Environment,* (D. Reidel).

DOMES (1976), Mining Industry Meeting, February 24, 1976, Minutes. Office of the Director, NOAA/ERL, Boulder, Colo.

Goldberg, E. D. (1963), The oceans as a chemical system, in *The Sea,* M. N. Hill, Ed., 2, 3-25 (Interscience).

Halpern, David, Pacific Marine Environmental Laboratory, Seattle, Wash., private communication.

Halpern, David (1976), Upper ocean circulation studies in the eastern tropical Pacific during September and October 1975, Proc. 8th Ann. Offshore Technology Conf., OTC Paper No. 2457 (Houston, Tex.).

Munk, W. H., Ewing, G. C., and Revelle, R. R. (1949), Diffusion in Bikini Lagoon, *Trans. Am. Geophys. Union.* **30**, 59.

Sallenger, A., U. S. Geological Survey, Menlo Park, Calif., private communication.

Environmental Research LABORATORIES

The mission of the Environmental Research Laboratories (ERL) is to conduct an integrated program of fundamental research, related technology development, and services to improve understanding and prediction of the geophysical environment comprising the oceans and inland waters, the lower and upper atmosphere, the space environment, and the Earth. The following participate in the ERL missions:

MESA *Marine EcoSystems Analysis Program.* Plans, directs, and coordinates the regional projects of NOAA and other federal agencies to assess the effect of ocean dumping, municipal and industrial waste discharge, deep ocean mining, and similar activities on marine ecosystems.

OCSEA *Outer Continental Shelf Environmental Assessment Program.* Plans, directs, and coordinates research of federal, state, and private institutions to assess the primary environmental impact of developing petroleum and other energy resources along the outer continental shelf of the United States.

WM *Weather Modification Program Office.* Plans, directs, and coordinates research within ERL relating to precipitation enhancement and mitigation of severe storms. Its National Hurricane and Experimental Meteorology Laboratory (NHEML) studies hurricane and tropical cumulus systems to experiment with methods for their beneficial modification and to develop techniques for better forecasting of tropical weather. The Research Facilities Center (RFC) maintains and operates aircraft and aircraft instrumentation for research programs of ERL and other government agencies.

AOML *Atlantic Oceanographic and Meteorological Laboratories.* Studies the physical, chemical, and geological characteristics and processes of the ocean waters, the sea floor, and the atmosphere above the ocean.

PMEL *Pacific Marine Environmental Laboratory.* Monitors and predicts the physical and biological effects of man's activities on Pacific Coast estuarine, coastal, deep-ocean, and near-shore marine environments.

GLERL *Great Lakes Environmental Research Laboratory.* Studies hydrology, waves, currents, lake levels, biological and chemical processes, and lake-air interaction in the Great Lakes and their watersheds; forecasts lake ice conditions.

GFDL *Geophysical Fluid Dynamics Laboratory.* Studies the dynamics of geophysical fluid systems (the atmosphere, the hydrosphere, and the cryosphere) through theoretical analysis and numerical simulation using powerful, high-speed digital computers.

APCL *Atmospheric Physics and Chemistry Laboratory.* Studies cloud and precipitation physics, chemical and particulate composition of the atmosphere, atmospheric electricity, and atmospheric heat transfer, with focus on developing methods of beneficial weather modification.

NSSL *National Severe Storms Laboratory.* Studies severe-storm circulation and dynamics, and develops techniques to detect and predict tornadoes, thunderstorms, and squall lines.

WPL *Wave Propagation Laboratory.* Studies the propagation of sound waves and electromagnetic waves at millimeter, infrared, and optical frequencies to develop new methods for remote measuring of the geophysical environment.

ARL *Air Resources Laboratories.* Studies the diffusion, transport, and dissipation of atmospheric pollutants; develops methods of predicting and controlling atmospheric pollution; monitors the global physical environment to detect climatic change.

AL *Aeronomy Laboratory.* Studies the physical and chemical processes of the stratosphere, ionosphere, and exosphere of the Earth and other planets, and their effect on high-altitude meteorological phenomena.

SEL *Space Environment Laboratory.* Studies solar-terrestrial physics (interplanetary, magnetospheric, and ionospheric); develops techniques for forecasting solar disturbances; provides real-time monitoring and forecasting of the space environment.

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