Suspended Matter in Surface Waters of the Atlantic Continental Margin from Cape Cod to the Florida Keys

Abstract. *Appreciable amounts of suspended matter (> 1.0 milligram per liter) in surface waters are restricted to within a few kilometers of the Atlantic coast. Particles that escape estuaries or are discharged by rivers into the shelf region tend to travel longshoreward rather than seaward. Suspended matter farther offshore, chiefly amorphous organic particles, totals 0.1 milligram per liter or less. Soot, fly ash, processed cellulose, and other pollutants are widespread.*

We have studied the distribution and composition of suspended matter from about 600 stations covering a large part of the Atlantic continental margin of the United States. Samples were taken during coastal cruises of the Woods Hole Oceanographic Institution vessels *Asterias* (inshore) and *Gosnold* (offshore). Although the samples represent surface waters almost exclusively, they were obtained during a limited period (May and June of 1965) and hence give a nearly synoptic view of the area.

Our data, briefly reported earlier (*1*, *2*), show a rapid decrease with distance from shore of terrigenous influence on suspended matter in surface waters. Our seawardmost samples contain lower concentrations of total suspended matter than the 0.1 to 1 mg/liter range that has been reported for the Atlantic Ocean by many previous workers (*3*) (Table 1). Our results agree within analytical error with those of Krey and co-workers, Folger and Heezen, with the average of Jacobs and Ewing and with the maximum value of 0.050 mg/liter for inorganic detritus in the world oceans calculated by Kullenberg (*4*) from data collected by N. G. Jerlov. The large proportion of combustible organic matter that we found in surface waters outside the direct influence of rivers, estuaries, or nearshore sediments disagrees with some previous observations on the general proportions or total amounts of organic detritus in oceanic surface waters (*5*). The absolute values of organic matter, however, agree with those that others have found in Atlantic waters (*6*).

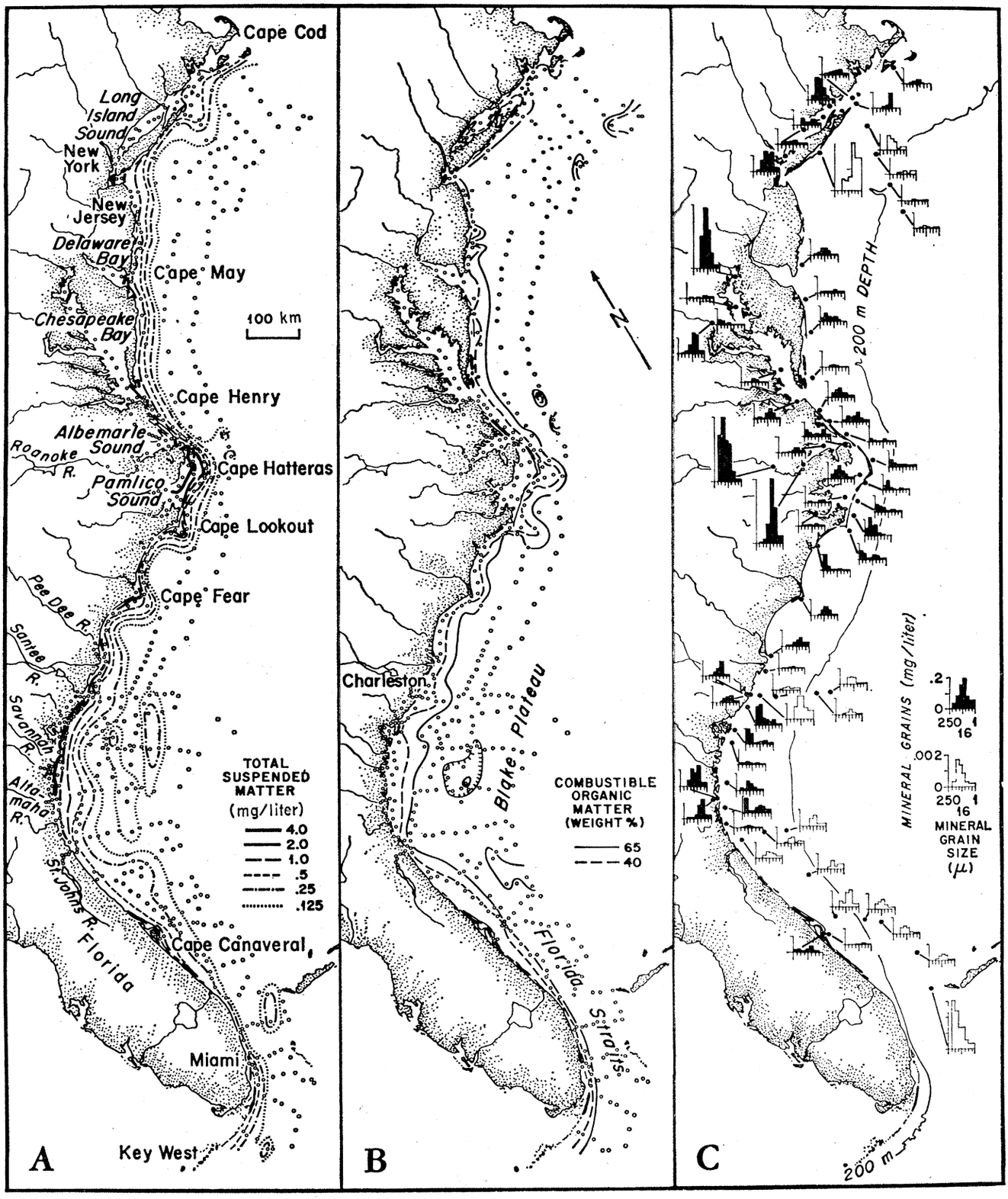
In our study, surface waters were collected by lowering buckets over the sides of the vessels and immediately filling one or two 1-liter sampling bottles. In inshore waters, salinity samples, Forel color, Secchi-disk, and temperature measurements were usually taken simultaneously. On offshore cruises, only water samples were taken; these were collected in clean polyethylene buckets on polypropylene rope lowered from the bow of the moving vessel and poured immediately into precleaned polyethylene sampling bottles. We were careful to check for and avoid soot and other sources of shipboard contamination, but the small water samples and the relative crudity of our sampling technique give doubtful accuracies at concentrations of total suspended matter less than 0.1 mg/liter.

The technique for obtaining and analyzing suspended matter is based on micropore filters, which have been used extensively in suspended-matter studies by Lisitsin and others (*7*). We filtered the water samples on board ship through preweighed Millipore R filters having nominal pore size of 0.45 μ and a diameter of 47 mm. A vacuum pump and a special stainless steel filter holder were used in this operation. The filters were then washed five times (with filter funnel removed) with filtered distilled water. Residual salt retained by the filters proved to be the most serious single source of error and was a potential source of erroneously large concentrations of suspended matter. Some filters, therefore, required further washing in the shore laboratory (*8*). All filters were stored in individual plastic petri dishes.

Table 1. Total suspended sediment concentrations in open Atlantic waters. Sources cited in (*3*). Nearshore studies, studies involving particle counts (*22*), or optical studies only (*23*) are not included here. "Membrane" filters refer to filters with pore size of 1 μ or less.

Area	Depth	Dominant conc. range (mg/liter)	Source	Remarks
Mid-Atlantic Ridge about 52°N	Surface	0.32 (SiO_2)	Murray and Irvine (1891)	Single sample; paper filter
North Atlantic	Variable	0.05–1.0	Armstrong (1958)	Membrane filter
Cape Farewell to Flemish Cap	Variable	.02–.15	Krey *et al.* (1959)	Paper filter
Northern North Atlantic	Surface Deeper water	.5 (av.) .1 (av.)	Krey (1964)	1.8-μ filter
North and South Atlantic	Variable	.1–1.0	Klenova *et al.* (1962)	Membrane filter; higher conc. near bottom
North Atlantic	Variable	.3–3.0	Vikhrenko and Nikolaeva (1962)	Membrane filter
East of Blake Plateau	4030 m	2.5	Groot and Ewing (1963)	Single sample; continuous centrifuge
Eastern North and South Atlantic	Surface	.7 (av.) .1–.3	Gordeev (1963) Gordeev (1963)	Membrane filter Continuous centrifuge
Western North Atlantic	Surface	.2–1.0	Vikhrenko (1964)	Membrane filter
Central Gulf Stream	Surface Deeper water	.13 .06	Krey (1961)	Membrane filter
Tropical Atlantic	Surface Deeper water	.1–.2 .02–.08	Hagmeier (1964)	Membrane filter
Tropical Atlantic	Variable	.2–1.0	Klenova and Vikhrenko (1965)	Membrane filter
North Atlantic	Just below surface	.04–.14	Folger and Heezen (1968)	Membrane filter
Subtropical western North Atlantic	Variable	.001–.25 (mean 0.05)	Jacobs and Ewing (1969)	Continuous centrifuge
Western North Atlantic	Surface	$\leq$ .1	This report	Membrane filter

For original and subsequent weighings, the dried filters were allowed to equilibrate for several days in a room where temperature and humidity were controlled. They were then weighed, along with control filters, to the nearest 0.01 mg on a microbalance. A fresh 500-pc polonium source reduced electrostatic attraction. Approximately every tenth petri dish contained two filters that were carried through the operation as one (*9*). The lower filter receives virtually no suspended matter during filtration, and it provides a means of evaluating the losses and gains of weight that are due to seawater filtration, washing, humidity, absorption, or other influences. Systematic weight variations among the control filters of given batches were usually reproducible within about 0.05 mg, and



appropriate corrections were applied to the uncontrolled filters.

To determine the composition of the suspended matter, the reweighed filters were carefully halved. One half of each filter was ashed, after preliminary charring with alcohol, in a crucible made of 2.5-μ platinum foil. The ash was weighed on a Cahn electrobalance (microbalance). Hydrated substances other than organic matter (clay minerals, for example) constituted such a small proportion of the total suspended matter that they should not have significantly affected the weight loss on ignition. A part of the other half was rendered transparent with cedar oil (index of refraction, 1.51) and mounted on a glass petrographic slide for microscopic study. Sizes of the grains of mineral particles were measured, and their weights were estimated by special counting and conversion techniques described elsewhere (*2*). Mineral particles as small as 4 μ were recognizable by their birefringence under crossed polarizers. All weight estimates were converted to units of milligrams per liter of seawater for plotting in the diagrams shown here.

The main results gained from the analysis of the suspensates are shown in Fig. 1. Waters containing more than 1 mg/liter of suspended matter are generally restricted to river mouths, estuaries, and a narrow nearshore zone less than 10 km wide. Surface waters over the continental shelf and slope generally contained less than 0.125 mg/liter of total suspended matter, most of which (60 to 90 percent) consisted of combustible organic matter. Local increases in concentrations of terrigenous suspended matter were noted offshore from promontories such as capes Hatteras, Lookout, and Fear, from the discharge areas off the mouths of the Pee Dee, Santee-Cooper, Savannah, and Altamaha rivers, and off the mouth of Long Island Sound.

Although the combustible organic matter dominates the suspended particulates in the offshore waters, recognizable organisms or organic remains make up only a small part. The bulk is present as irregular organic aggregates and as particles of amorphous and optically isotropic (or faintly birefringent) material. The most commonly recognized organisms were dinoflagellates, diatoms, silicoflagellates, and radiolarians. Masses of coccolithophorids, together with diatoms, were concentrated in the Georgia-Florida-Bahama area in a belt a few tens of kilometers from shore. Soft-bodied algae were probably also abundant, but their recognition was hampered by their tendency to disintegrate when the filters were flushed with fresh water (*8*).

Mineral grains, which included quartz, feldspar, micas, clay minerals, and carbonates, represented only a small proportion of the suspended matter in surface waters during the sampling period [Table 2; see also (*2*)]. The largest proportions of mineral grains (10 to 25 percent of the total suspended matter) were found in the longshore zone where river effluents were mixed with grains from littoral sources. Farther seaward, mineral grains coarser than 4 μ constitute less than 3 percent of the suspended matter. A typical sample of suspended matter from the outer continental shelf and slope is shown in Fig. 2A, which is dominated by the opalescent outline of a *Ceratium* (dinoflagellate) between crossed polarizing lenses; the darkness of most of the remaining area of the photograph indicates a lack of birefringent mineral particles. Mineral grains finer than 4 μ cannot be readily distinguished from birefringent organic particles, but maximum weight estimates from particle counts indicate that they probably do not form a significant portion of the total suspended matter. In rivers and estuaries landward of the longshore zone, mineral grains typically accounted for 2 to 10 percent of the total suspended matter in surface waters (Fig. 2, B and C).

Pollutants were particularly evident in the New York Bight (the shelf area bordered by Long Island and New Jersey) and the Straits of Florida. Characteristic of pollutants from the New York Bight are the opaque aggregates of soot and fly ash shown in Fig. 2D. Other artifacts, previously used to trace the mixture of river waters into the offshore region (*10*), are round iron-oxide aggregates that apparently form when iron-rich effluents are discharged into coastal waters; similar red-brown particles have been noted in Baltimore Harbor (*11*) and as far seaward as the Sargasso Sea (*12*) (some iron aggregates may be natural particles such as those

Table 2. Selected values of suspended matter, Atlantic coastal waters.

Location and description	Total wt. (mg/liter)	Percent organic	Recognizable mineral grains (mg/liter)	Recognizable mineral grains (%)	Modal sizes of mineral grains (μ)
Surface waters					
Roanoke River near Plymouth, N.C.	29.1	33	0.86	3.0	8–16
Albemarle Sound (center)	5.1	24	.095	1.9	4–8
Pamlico Sound, south of Swanquarter	3.3	28	.068	2.1	4–8
Nearshore shelf off Hatteras Inlet	1.4	41	.13	9	62–125* 4–8†
Charleston Harbor	5.5	31	.19	3.5	4–8
Nearshore shelf off Helena Is., S.C.	2.4	24	.21	8.7	125–250* 4–8†
Offshore shelf southeast of Charleston	0.40	58	.0009	0.2	8–16
Blake Plateau off Charleston	.05	90	.0015	3	16–32
Subsurface waters					
Blake Plateau, 31°48′N, 79°15′W *Alvin* dive 203, July 1967, 175 m	0.15	50			
Blake Plateau, 31°48′N, 79°12′W *Alvin* dive 201, July 1967, 518 m current 2 to 5 cm/sec ‡	1.7	76			
Blake Plateau, 31°18′N, 78°53′W *Alvin* dive 200, July 1967, 543 m current approximately 50 cm/sec ‡	1.8	75			
Blake Plateau, 31°18′N, 78°53′W *Alvin* dive 200, July 1967, 548 m current approximately 50 cm/sec ‡	2.2	83			

* Principal mode of bimodal distribution. † Secondary mode of bimodal distribution. ‡ About 20 cm off bottom.

Fig. 1. Composition and grain size of suspended sediments in surface waters along the Atlantic continental margin, May and June 1965. (A) Total suspended matter. In the area off New Jersey, obvious pollutants such as soot and fly ash were subtracted, wherever possible, from the total concentrations portrayed. (B) Combustible organic matter. (C) Grain-size distribution of recognizable minerals; note the hallow histograms represent concentrations that are 100 times smaller than those represented by solid histograms.

Table 3. Suspended matter and other properties of water on opposite sides (within about 100 m) of prominent color boundaries.

Location	Date (May 1965)	Azimuth of boundary (deg)	Forel color (percent yellow)	Suspended matter (mg/liter)		Chloride (parts per thousand)	Temperature (°C)
				Total	Ash		
Pamlico Sound (south end), N.C.	14	110	85 (north side)	11.2	8.1	8.1	22.2
			65 (south side)	3.1	1.7	7.8	22.4
St. Catherines Sound, Ga.	23	90	80 (north side)	8.8	6.4	15.3	
			55 (south side)	4.5	3.0	15.3	
Sapelo Sound, Ga.	23	90	90 (north side)	13.0	9.8	14.5	
			80 (south side)	9.8	6.6	14.5	
St. Johns River, Fla. (4 km off mouth)	25	100–110	60 (north side)	2.8	1.7	17.9	26.2
			35 (south side)	0.8	0.3	18.7	26.0

formed in marshes and bog waters). Another pollutant, in the form of strongly birefringent fibrous material (Fig. 2, E and F), is especially abundant near port areas and in the Straits of Florida. These fibers do not resemble any of the planktonic and terrestrial plant residues that we examined; they appear to be a form of processed cellulose. When compared with rope shreds and various commercial cellulose products, their closest resemblance is to toilet paper (Fig. 2G). Miami cannot be the source of the fibers shown in Fig. 2, E and F, not so much because its sewage is treated to settle solids (Miami Beach discharges untreated sewage) but because material from the metropolitan Miami area would tend to be swept northward by the Gulf Stream before it could reach the eastern part of the Straits of Florida. Havana is a possible source, since it discharges 50–100,000 gallons of raw sewage per day into a coastal current that joins the Gulf Stream (*13*). A more likely source, however, is refuse from ships in the densely traveled shipping lane through the Straits of Florida to and from New Orleans and other ports on the Gulf of Mexico.

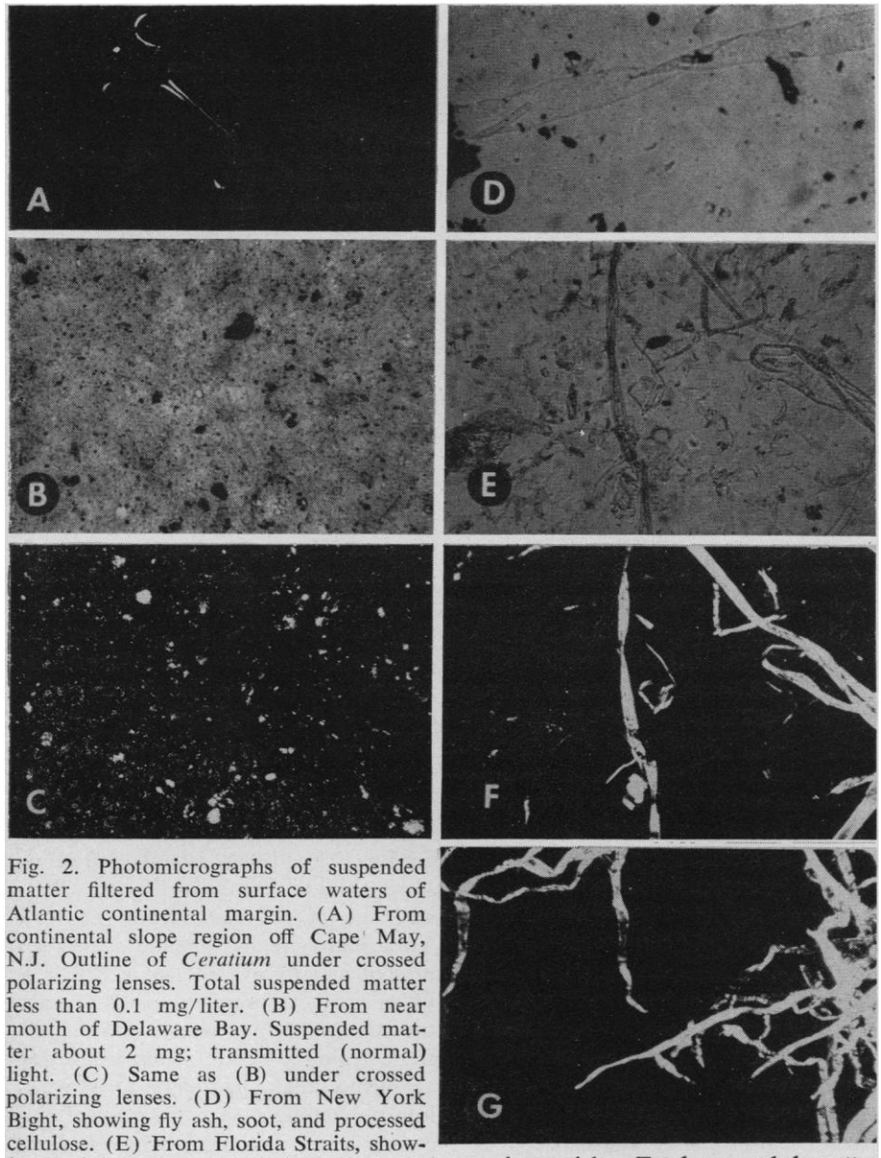


Fig. 2. Photomicrographs of suspended matter filtered from surface waters of Atlantic continental margin. (A) From continental slope region off Cape May, N.J. Outline of *Ceratium* under crossed polarizing lenses. Total suspended matter less than 0.1 mg/liter. (B) From near mouth of Delaware Bay. Suspended matter about 2 mg; transmitted (normal) light. (C) Same as (B) under crossed polarizing lenses. (D) From New York Bight, showing fly ash, soot, and processed cellulose. (E) From Florida Straits, showing mainly processed cellulose fibers and organic particles. Total suspended matter about 0.3 mg/liter. Transmitted (normal) light. (F) Same as (E) under crossed polarizers. (G) Laboratory preparation of macerated toilet paper, same magnification as in (E) and (F) and crossed polarizers. For scale, width of cellulose fibers is about 25 μ. All photos except (D) are same magnification.

Our studies provided an opportunity to evaluate the relations between concentrations of suspended matter and some simple measures of the transparency and color of water. Previous workers have shown that the relation between light transmissibility, as measured by the depth to which a 30-cm white (Secchi) disk is visible, and the concentration of suspended matter is described by a hyperbolic curve (*14*). Expressed in terms of weight, this relation is given by

$$D = kd\rho/w$$

where D is Secchi-disk visibility; d, mean diameter of particles; ρ, density of particles; w, weight of suspended matter; and k, a constant. The equation indicates an inverse log-linear relation between the weight of suspended matter and depth of the Secchi disk, provided the mean (effective) diameter and density of the suspended particles remain constant. The plot in Fig. 3 is strongly linear, despite considerable variability in distribution of the sizes of grains and in the amounts and propor-

tion of organic and inorganic matter. The coincidence of high organic and low organic samples on the plot suggests that the mean sizes of the low-density combustible organic particles are proportionately greater than those of the mineral grains or the noncombustible biogenic particles. If the relation in Fig. 3 is applied to the contours of Secchi-disk depth reported off southern California (*15*), the 1 mg/liter contour would occur, as it does on the Atlantic shelf, within 10 km of shore.

We observed a poorer relation between Forel color (blueness of the water) and the weight concentration of particulates. On a rough basis, however, we found that water containing 1 mg/liter or more of total suspended matter appeared greenish and that it became increasingly yellowish brown or reddish brown as concentrations of suspended matter increased. Clear blue colors, which are associated with the Gulf Stream along the Florida coast and which are also found near the southeast coast of North Carolina, appear to be associated with maximum concentrations of suspended matter of a few tenths of a milligram per liter. Transitions in color of the water, which are particularly striking when seen from the air, offer a potential method for estimating the suspended matter in surface waters over large areas, provided that one calibrates intermittently with actual measurements of concentrations of suspended matter (*16*). Sharp transitions in color of the water were observed within and off the mouths of estuaries of Florida, Georgia, and the Carolinas. While salinity and temperature showed little significant difference across the boundaries, the differences in the reflective properties were invariably marked by sharp changes in total suspended matter (Table 3).

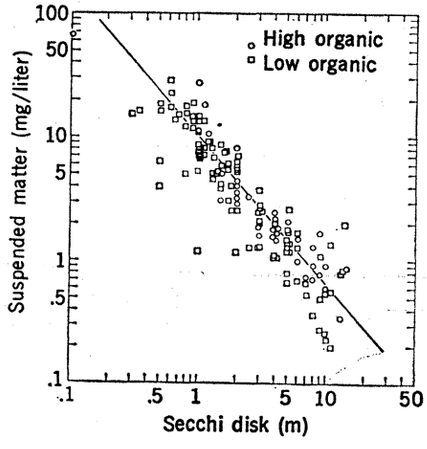


Fig. 3. Relation between suspended concentration (total) and Secchi-disk depth in inshore waters of Atlantic continental margin. Boundary between high and low organic samples taken at 50 percent combustible organic matter.

A principal aim of our study was insight into the dispersion of suspended sediment seaward from the continent. Our data showed that suspended matter moved mainly alongshore rather than directly seaward from the mouths of rivers and estuaries and that most of the mineral grains in suspension were derived from nearby sources. Some of the evidence for these conclusions is demonstrated in data collected in and near Charleston Harbor. The diverted Santee River, despite the large reservoirs that trap part of its sediment, discharges a substantial amount of suspended matter through the Cooper River and into the sea via Charleston Harbor. The concentrations shown in Fig. 1A suggest that material from Charleston Harbor moves southward. The modal size class of the mineral grains (4 to 8 μ) can be traced out of the harbor and, in diminishing concentrations, southwestward along the coast where it mixes with larger proportions of sands that are derived directly from local longshore areas (Fig. 1C). Seaward of Charleston Harbor the concentrations of suspended matter diminish rapidly within a short distance of shore, and distribution of the sizes of the mineral particles shows little relation to that found inshore.

Another aspect of the seaward movement of suspended matter is shown in the relations between concentration of suspended matter and chlorinity in five estuaries southwest of Cape Hatteras. Figure 4 shows that the relation between the two variables is fairly simple. Rather more complex relations prevail near the heads of the estuaries where river sediment first enters the tidal and brackish waters (*17*), but in the more seaward parts of the estuaries (where most of the samples in Fig. 4 come from) the gradual and linear decrease in the concentration of suspended matter with increasing chloride indicates that suspended matter decreases seaward mainly by simple dilution with seawater.

Although no subsurface samples were taken during our main period of effort in May and June 1965, we were able to sample and observe the material in suspension near the bottom during later cruises in 1966 and 1967. Samples were taken in two submarine canyons on the seaward edge of Georges Bank (southeast of Cape Cod; not shown in Fig. 1) with an inverted Van Dorn sampler that was triggered at a present distance (usually 0.5 to 1.5 m) above the bottom, and by means of special samplers from the deep submersible *Alvin* (*18*). Suspended matter in the head of Corsair Canyon and at a depth of 1500 m in Oceanographer Canyon amounted to less than 0.5 mg/liter, most of which was organic. Bottom currents at the time of sampling in Oceanographer Canyon were less than 10 cm/sec.

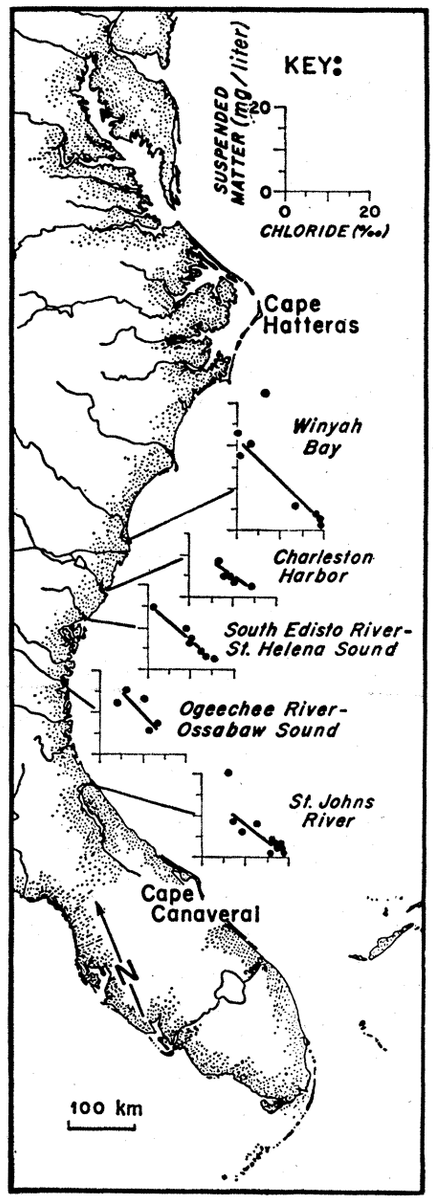


Fig. 4. Relations between suspended matter and chloride in surface waters of small river-estuary systems along the southeastern Atlantic coast.

Another group of samples was taken by *Alvin* on the Blake Plateau (Table 2). Two of the samples (dive 200) were taken near the axis of the Gulf Stream where the water current was about 50 cm/sec. In contrast, water farther up the column contained less than a tenth of the total suspensate noted in the bottom water. From the viewing ports of *Alvin* we observed soft gelatinous or flocculent particles, sometimes as large as 1 cm in diameter, that characterized the upper 200 m of water, both over the Blake Plateau and in slope waters off Cape Hatteras. The sizes of these particles increased downward, reached a maximum at depths of 20 to 100 m, and then diminished rapidly to an approximately constant size at deeper levels. Similar phenomena have been observed near Japan (*19*).

What is the significance of our results in the context of the long-term movement of sediment on the continental margin? Because 1965 was an exceptionally dry year in the North Atlantic states, our studies north of Cape Hatteras probably reflect minimum contributions of riverborne detritus. In the South Atlantic states, however, 1965 was wetter than average, and we may have sampled concentrations of suspended matter that were a little larger than normal for May and June. On the basis of this, we conclude that the transport of suspended detritus via surface waters across the continental shelf to the regions of the continental slope is minimum during normal or near-normal conditions. Abnormal events such as storms and floods, on the other hand, have a strong but quantitatively unknown effect on the transport of detritus in coastal water. For example, surface water 20 km off Cape Canaveral (Cape Kennedy) contained 7 mg/liter of suspended matter 2 days after Hurricane Betsy traversed the area in September 1965. One month earlier, surface water in the same area contained only 0.25 mg/liter. Similar increases in the concentration of suspended matter following storms have been observed in the Bering Sea (*20*). Evidence on the movement of bottom sediments on the continental shelf and in estuaries of the Atlantic seaboard indicates that the dominant direction of bottom movement is landward rather than seaward (*21*). If sediment transport by storms is limited to the present shelf regions, from which the sediment is subsequently moved inland by bottom currents, we conclude from the information now available that the continent is presently contributing litle detritus to the continental slope and deeper regions of the Atlantic Ocean.

FRANK T. MANHEIM
ROBERT H. MEADE
U.S. Geological Survey,
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts 02543
GERARD C. BOND
Department of Geology,
Williams College,
Williamstown, Massachusetts 01267

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Chemical Composition of the Lunar Surface in Sinus Medii

Abstract. *More precise and comprehensive analytical results for lunar material in Sinus Medii have been derived from the alpha-scattering experiment on Surveyor VI. The amounts of the principal constituents at this mare are approximately the same as those of constituents at Mare Tranquillitatis. The sodium contents of both maria are lower than those of terrestrial basalts. The titanium content at Sinus Medii is lower than that at Mare Tranquillitatis; this suggests important differences in detailed chemical composition at different mare areas on the moon.*

The alpha-scattering experiment on three of the Surveyor soft landings on the moon made possible the first direct chemical analyses of lunar surface material. Preliminary results of these anal-