basal glide planes of practically all crystals have become orientated within 15 deg of the horizontal plane of the ice sheet; that is, principal crystallographic axes are all orientated within 15 deg of the vertical. This structure persisted to a depth of 1800 m.

Crystals between 1200 and 1800 m were appreciably smaller than crystals observed directly above and below this zone (Fig. 3) which also contained numerous cloudy bands (as thick as 2 cm) of very fine-grained ice that resembled shear layers. All fabric elements observed in this zone, together with the widespread occurrence of "strain shadows" in crystals, are entirely consistent with some process of shear deformation in this part of the ice sheet. "Smearing out" of entrapped air bubbles by such a process may possibly explain the decrease and ultimate disappearance of air bubbles at about 1200 m. The very rapid increase in size of crystals below 1800 m (crystal cross sections of 30 cm^2 or more are not uncommon) is probably attributable to annealing at elevated temperatures near the bottom of the ice sheet; practically identical structure occurs in ice from near the bottom of the Ross Ice Shelf (*14*).

Measurements of electrolytic conductivity of melted samples indicate very low levels of dissolved solids at all depths; conductivities varied between 1.7 and 3.1 μmho/cm, the 45 samples of dirt-free ice tested averaging 2.1 μmho/cm. No systematic changes in conductivity with depth (time) were detected.

ANTHONY J. GOW
HERBERT T. UEDA
DONALD E. GARFIELD

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755

References and Notes

1. By the U.S. Army Cold Regions Research and Engineering Laboratory. Earlier holes had reached 100-370 m: V. Schytt, "Glaciology II," in *Norwegian-British-Swedish Antarctic Expedition 1949-52* (Norsk Polarinstitutt, 1958), vol. 4; V. N. Bogoslovski, in *Publ. 47* (Intern. Union Geodesy Geophys. Symp., Chamonix, France, Sept. 1958), p. 287; R. W. Patenaude, E. W. Marshall, A. J. Gow, *Tech. Rep. 60* (U.S. Army Snow Ice Permafrost Res. Establ., 1959); R. H. Ragle, B. L. Hansen, A. J. Gow, R. W. Patenaude, *Tech. Rep. 70* (U.S. Army Snow Ice Permafrost Res. Establ., 1960).
2. H. Oeschger, B. Alder, C. C. Langway, *J. Glaciol.* **6**, 937 (1967).
3. Electrodrill; invented by Armais Arutunoff, Reda Pump Co., Bartlesville, Okla.
4. B. L. Hansen and C. C. Langway, *Antarctic J.* **1**, 207 (1966).
5. E. H. Ratcliffe, *Phil. Mag.* **7**, 1197 (1962).
6. R. M. Koerner, in *Amer. Geophys. Union Antarctic Res. Ser.* (1964), vol. 2, p. 219.
7. J. J. Anderson, *ibid.* (1967), vol. 6, p. 1.
8. G. A. Doumani and E. G. Ehlers, *Geol. Soc. Amer. Spec. Paper 68* (1962), p. 166; *Geol. Soc. Amer. Bull.* **73**, 877 (1962); G. A. Doumani, in *Proc. Scientific Comm. Antarctic Res. Symp. Antarctic Geol. Sept. 1963* (1964), p. 666.
9. A. J. Gow and R. Rowland, *J. Glaciol.* **5**, 843 (1966).
10. J. Nye, *ibid.* **4**, 785 (1963); H. Bader, *Spec. Rep. 58* (U.S. Army Cold Regions Res. Eng. Lab., 1962).
11. When compacted snow (firn) becomes impermeable it is said to have transformed into ice; transformation occurs at a density of about 0.83. The ice contains about 10 percent air by volume, which is retained in the form of discrete bubbles.
12. Ice densities were determined by hydrostatic weighing, with very pure isooctane (2-2-4 trimethyl pentane) used as the immersion liquid; they are accurate to within 0.0003.
13. C. C. Langway, in *Publ. 47* (Intern. Union Geodesy Geophys. Symp., Chamonix, France, Sept. 1958), p. 336; H. Bader, *Res. Rep. 141* (U.S. Army Cold Regions Res. Eng. Lab., 1965); A. J. Gow, *J. Glaciol.* **7**, 167 (1968).
14. A. J. Gow, in *Publ. 61* (Intern. Union Geodesy Geophys. Symp., Berkeley, Calif., Aug. 1963), p. 272.
15. Supported by NSF grants AG-105 and AG-106, and aided by Task Force 43, U.S. Navy. We thank B. L. Hansen, who directed the drilling project, for suggestions regarding the manuscript; and R. Doescher, W. Strange, D. Gianola, L. Strawn, L. Trenholm (all of the U.S. Army Cold Regions Research and Engineering Laboratory), and E. Parrish for assistance with the drilling.

27 May 1968

Turbidity Maximum of the Northern Chesapeake Bay

Abstract. *The turbidity maximum near the head of the Chesapeake Bay is produced primarily by the local resuspension of bottom sediments, and by the estuarine "sediment trap" which is formed in the upper reaches of the estuarine circulation regime by the net nontidal circulation.*

Zones of turbidity maximums in the upper reaches of a number of coastal plain estuaries throughout the world have been reported. These zones begin in the estuary where a vertical gradient of the salinity first appears and extend downstream for 20 to 40 km. They are characterized by tubidities and suspended sediment concentrations greater than those found either upstream in the source river or farther seaward in the estuary. Their formation has been attributed both to the flocculation (*1*) and to the deflocculation (*2*) of river-borne sediment, and to hydrodynamic processes (*3, 4*). Although there have been numerous reports of turbidity maximums, the turbid zone extending from the head of the Chesapeake Bay at Turkey Point seaward for about 32 km (nearly to Tolchester) (Fig. 1) is the first of such features to be comprehensively studied.

From 1 April 1966 through 31 March 1967 samples were collected fortnightly from several depths at each of the stations shown in Fig. 1 for determinations of the concentration of the total suspended solids, the concentration of combustible organic matter, the mineralogy, and the size distribution of the suspended particles (*5*). Supplementary samples were also collected at stations farther seaward in the estuary, and at a

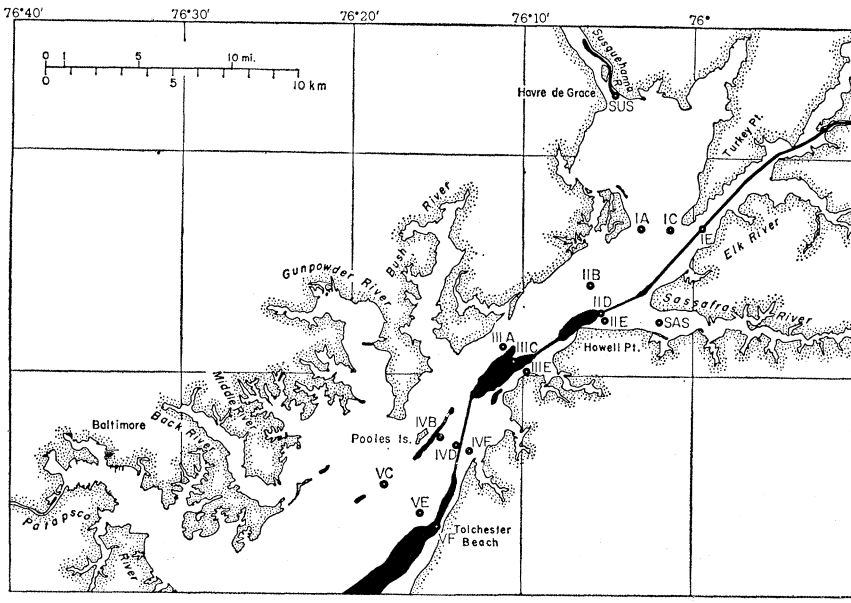

Fig. 1. Stations of the northern Chesapeake Bay. All areas deeper than 8 m are shown in black.

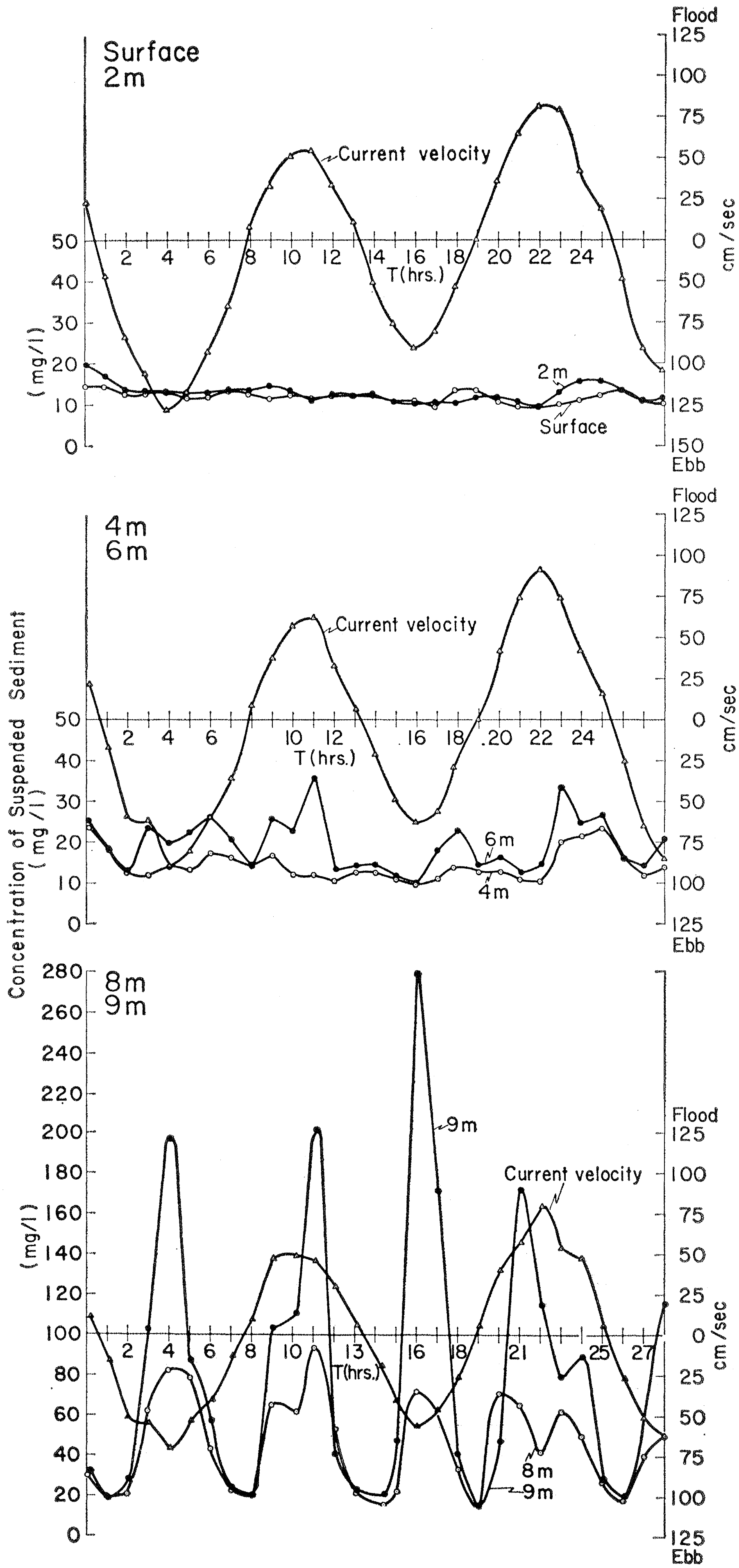

Fig. 2 (left). Variations of current velocity (cm/sec) and suspended sediment concentration (mg/liter) at station IIIC (Fig. 1) (9.5 m) over two tidal cycles. Based on hourly measurements at six depths.

number of anchor stations at which hourly measurements of current velocity, suspended sediment concentration, temperature, and salinity were made over two or more tidal cycles. Extensive size analyses of both river and bay samples by a photomicrographic method and by a sedimentation technique failed to produce any evidence of either the flocculation or the deflocculation of river-borne sediment (*5*).

The concentrations of suspended sediment were determined by shipboard filtration through 0.8-μ APD metal filters (*5, 6*). Apart from the period of high spring runoff, the mean concentration of suspended sediment in the mouth of the Susquehanna River—the source of more than 97 percent of the freshwater and fluvial sediment introduced into this segment of the bay —was 5 mg/liter with an average deviation of less than 2 mg/liter. During the spring freshet in late February and March, the suspended sediment concentration exceeded 140 mg/liter for a few days, and in a period of less than 2 months, the Susquehanna discharged into the the Chesapeake Bay more than 70 percent of its total sediment discharge of 0.6×10^9 kg from 1 April 1966 through 31 March 1967 (*7*). Nearly 70 percent of the sediment discharged during the freshet was deposited within the zone of the turbidity maximum. This sediment is all silt and clay-sized material; the coarser particles are trapped upstream in the reservoirs.

The concentrations of suspended sediment within the upper bay were greater than 7 mg/liter throughout the year and exceeded those in the mouth of the Susquehanna except for 1 to 2 weeks during the spring freshet. Throughout the year the seaward boundary of the turbidity maximum was marked by a steep longitudinal gradient of the concentration of suspended sediment. This boundary was located between cross sections IV and V (Fig. 1) except during the period of high runoff, when it was much farther downstream.

Except for the spring freshet and short periods of very rough seas, the concentration of suspended sediment was relatively constant in the upper layer of the turbid zone at stations deeper than about 4 m. In the lower layer and throughout the water column at shallower stations, resuspension and deposition produced large fluctuations (as much as 20-fold) of the suspended sediment concentration within a few hours or less. The average mean concentration of suspended sediment in the upper layer (the spring freshet excluded) over the entire zone of the turbidity maximum, was 14 mg/liter with a mean deviation of less than 4 mg/liter.

The spring period of high runoff then was one of fluvial domination of the upper bay's suspended sediment population and was characterized by a close link between the suspended sediment population and the principal "ultimate" source of sediment—the Susquehanna River. At all other times of the year, however, the concentrations of suspended sediment were higher within the upper bay than in the mouth of the Susquehanna, and this link was missing. A gradual purging out of the sediment-laden freshet water cannot explain the higher concentrations which persisted throughout the year since the renewal time is only of the order of a few weeks. The explanation for the higher concentrations lies in the continual resuspension of bottom sediments, and in the "sediment trap" produced by the net nontidal estuarine circulation which entraps much of the sediment—both resuspended and newly introduced—within this segment of the bay.

Throughout the year, sediment is resuspended from the bottom both by tidal scour and by wind waves. Since the area is shallow (mean depth, 4.8 m) resuspension by wind waves is an important factor during periods of rough seas. Resuspension by tidal scour is important at all times of the year and accounts for most of the resuspended material.

An example of the effectiveness of tidal currents as an agent of resuspension is shown in Fig. 2. For 38 hours in July 1967 hourly measurements of current velocity and the concentration of suspended sediment were made at the surface, and at depths of 2, 4, 6, 8, and 9 m just to the west of station IIIC in 9.5 m of water (Fig. 1). In the upper 4 m, the fluctuations of the sediment were relatively small. At 6 m, the concentration of suspended sediment ranged from 10 to 36 mg/liter, but the concentration of suspended sediment and the current velocity or the phase of the tide were not closely related. At 8 and 9 m, there were large fluctuations in the concentration of suspended sediment, and there was obviously a strong relation to current velocity and the phase of the tide at which the samples were collected. Maximum concentrations occurred near maximum ebb and flood velocities, and minimum concentrations shortly after slack water. At 8 m, the concentration of suspended sediment ranged from 14 to 93 mg/liter, and at 9 m, the range was from 15 to 280 mg/liter—nearly a 19-fold range.

There is a "natural background" of suspended sediment which increases with depth and whose intensity at any depth is relatively constant over time scales of at least two tidal cycles (Fig. 2) (*8*). The background which increases from about 15 mg/liter at the surface to about 20 mg/liter at a depth of 9 m consists of very fine-grained suspended particles whose settling times are long compared to the mixing time. The volume-weighted mean velocity of settlement of the background particles is only about 10^{-3} cm sec^{-1}, which corresponds to a Stokes' diameter of approximately 3 μ (*5*). Particles of this diameter would settle a distance of less than 1 m in still water in more than two tidal periods. The spatial and temporal variability of the mean size of the background particles is small (*5*). This natural background is due in part directly to runoff, and in part to the internal sediment sources—resuspension, primary production, and shore erosion.

Below about 4 m, superimposed upon this natural background are semitidal fluctuations of the suspended sediment concentration which increase in magnitude near the bottom—the sediment source. These large fluctuations are produced by tidal "scour and fill." Large particles are resuspended with increasing ebb and flood velocities during each half-tidal period, and settle out when the current begins to wane. Settling times based on the data of Fig. 2 indicate Stokes' diameters of 8 to 12 μ for these particles which agrees well with our measured sizes (*5*). In depths less than about 4 m, the semitidal fluctuations are present throughout the water column.

Much of the sediment is trapped within this segment of the bay by the net nontidal estuarine circulation pattern (*5*). In estuarine circulation the less dense fresh river water flows downstream (seaward) in the upper layer while the denser saltier seawater flows upstream in the lower layer (*9*). This circulation leads to the formation of an effective "sediment trap" (*3*) in the transition zone of the upper reaches of the estuary where the net nontidal upstream flow of the lower layer dissipates until finally the net flow is downstream at all depths. Particles that settle out of the seaward-flowing upper layer into the lower layer are carried back upstream by its net nontidal upstream flow; sediment then accumulates, and a so-called "turbidity maximum" forms near the head of the bay. Many of these particles are transported back into the upper layer by vertical mixing, and the whole process is repeated many times. Within the turbid zone of the bay, the tidal mixing is intense enough to overcome the vertical stratification and to produce a nearly homogeneous water column twice during each tidal cycle. At the seaward end of the turbidity maximum, however, vertical mixing is inhibited, and the water column remains stratified over much longer time scales.

In the turbid zone of the upper Chesapeake Bay there are thus both a "source" of suspended sediment in the continual resuspension of the fluvial sediment deposited during the spring freshet, and a mechanism for entrapping much of that sediment within this segment of the bay—a mechanism absent from other segments of the bay proper.

J. R. SCHUBEL

Chesapeake Bay Institute,
Johns Hopkins University,
Baltimore, Maryland 21218

References and Notes

1. H. Lüneburg, *Arch. Deut. Seewarte* **59**, 1 (1939); A. T. Ippen, in *Estuary and Coastline Hydrodynamics*, A. T. Ippen, Ed. (McGraw-Hill, New York, 1966), pp. 648–672.
2. B. Nelson, in *Intern. Oceanogr. Congr. 1st preprints* (AAAS, Washington, D.C., 1959), pp. 640-641.
3. H. Postma and K. Kalle, *Deut. Hydrogr. Z.* **8**, 137 (1955).
4. L. Glangeaud, *Bull. Soc. Geol. Fr.* **8**, 599 (1938).
5. J. R. Schubel, *Chesapeake Bay Inst. Johns Hopkins Univ. Tech. Rep.* **35**, Ref. No. 68-2 (1968).
6. ———, *Southeast. Geol.* **8**, 85 (1967).
7. ———, *Chesapeake Sci.*, in press.
8. Other observations indicate that it is very uniform over much longer times.
9. D. W. Pritchard, *J. Mar. Res.* **11**, 106 (1952).
10. I thank A. Okubo, H. H. Carter, D. W. Pritchard for suggestions. Supported by the Department of Chesapeake Bay Affairs, State of Maryland and the Bureau of Commercial Fisheries, Fish and Wildlife Service, Department of the Interior through Public Law 88-309 funds, subproject 3-30-R. Contribution 123 from the Chesapeake Bay Institute, Johns Hopkins University.

18 July 1968