Bottom Currents and Bottom Sediment Distribution in Massachusetts Bay

by Bradford Butman[1] and John Schlee[1]

with a section on

Suspended Matter in Massachusetts Bay September - October 1970

by Charles J. O'Hara[1] and Robert H. Meade[2]

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ABSTRACT

Massachusetts Bay is a coastal Bay 100 km long and 40 km wide located in the western Gulf of Maine. The Bay is open only to the Gulf to the east; the opening is partially blocked by a shallow bank. The bottom sediment distribution in the bay is complex; fine grained material is found in the deep basin, sand and gravel on the shallow bank, and mixtures of sand, gravel and finer sediments nearshore. Richardson current meters were moored 1 m from the bottom over a one-year period at several locations in the Bay to define the bottom currents and to determine the frequency of bottom sediment movement due to currents. The measurements suggest that the bottom sediments can be expected to move occasionally in certain areas. The maximum bottom current speeds were determined principally by the strong tidal currents in the basin.

In winter, the near bottom currents were dominated by wind stress associated with storms. Bottom currents in the shallow areas were generally in the direction of the wind while currents in the deep portion of the basin were often opposite to the direction of the wind. Sea-surface setup in the direction of the wind was observed, as well as variations in sea level attributed to changes in the adjacent Gulf of Maine. Adjustment of the bottom current to windstress required approximately 12 hours.

Total concentrations of suspended particulate matter, in general, were found to be higher in the near-shore and near-bottom waters and lower in the offshore

and near-surface waters. Near-bottom concentrations tended to increase as the grain size of the bottom sediments decreases. The greatest concentrations of suspended matter were observed in waters adjacent to Boston Harbor.

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PART I

Near Bottom Currents and the Sediment Distribution in Massachusetts Bay

A. Introduction

Massachusetts Bay and its southeast extension, Cape Cod Bay, are bounded on three sides by the Massachusetts coast and open to the Gulf of Maine on the northeast between Cape Cod and Cape Ann (Figure 1.1). The opening is partially blocked by Stellwagen Bank which rises to within 20 m of the surface. Stellwagen Basin, located in the center of Massachusetts Bay, has a maximum depth slightly in excess of 100 m, though most is about 80 m deep. Depth changes in Cape Cod Bay, Stellwagen Basin, and on Stellwagen Bank occur gently (grades of .1-.5%), except on the western side of Stellwagen Bank (grades of 6%). In contrast, the bottom along the western side of the Bay from Cape Ann to Plymouth (42°20'N 70°40'W) is hummocky and rough with depth changes of 5 m in .1 km (see C & GS chart No. 0808N-50 Cape Cod to Cape Ann).

The bottom sediments can be grouped into four categories by location (Schlee and others, 1973; Oldale and others, 1973; Tucholke and others, 1972). Nearshore, adjacent to the rocky coast from Cape Ann to Plymouth, the rough bottom is a patchwork of gravel, sand, mud and bedrock; adjacent to constructional features (outwash and moraines) from Plymouth around Cape Cod, however, the smooth bottom is covered by well sorted sand mixed with gravel. Offshore, Stellwagen Bank has a venner of well sorted sand, or sand and gravel, whereas Stellwagen Basin and the channels which enter the Bay are covered by clay, silt and sand (Fig. 1.2).

Figure 1. 1 Map of Cape Cod and Massachusetts Bays. Smoothed 40 and 80 m contours show major bathymetric features. (Boston Lightship, located off Boston Harbor is labeled BLS).

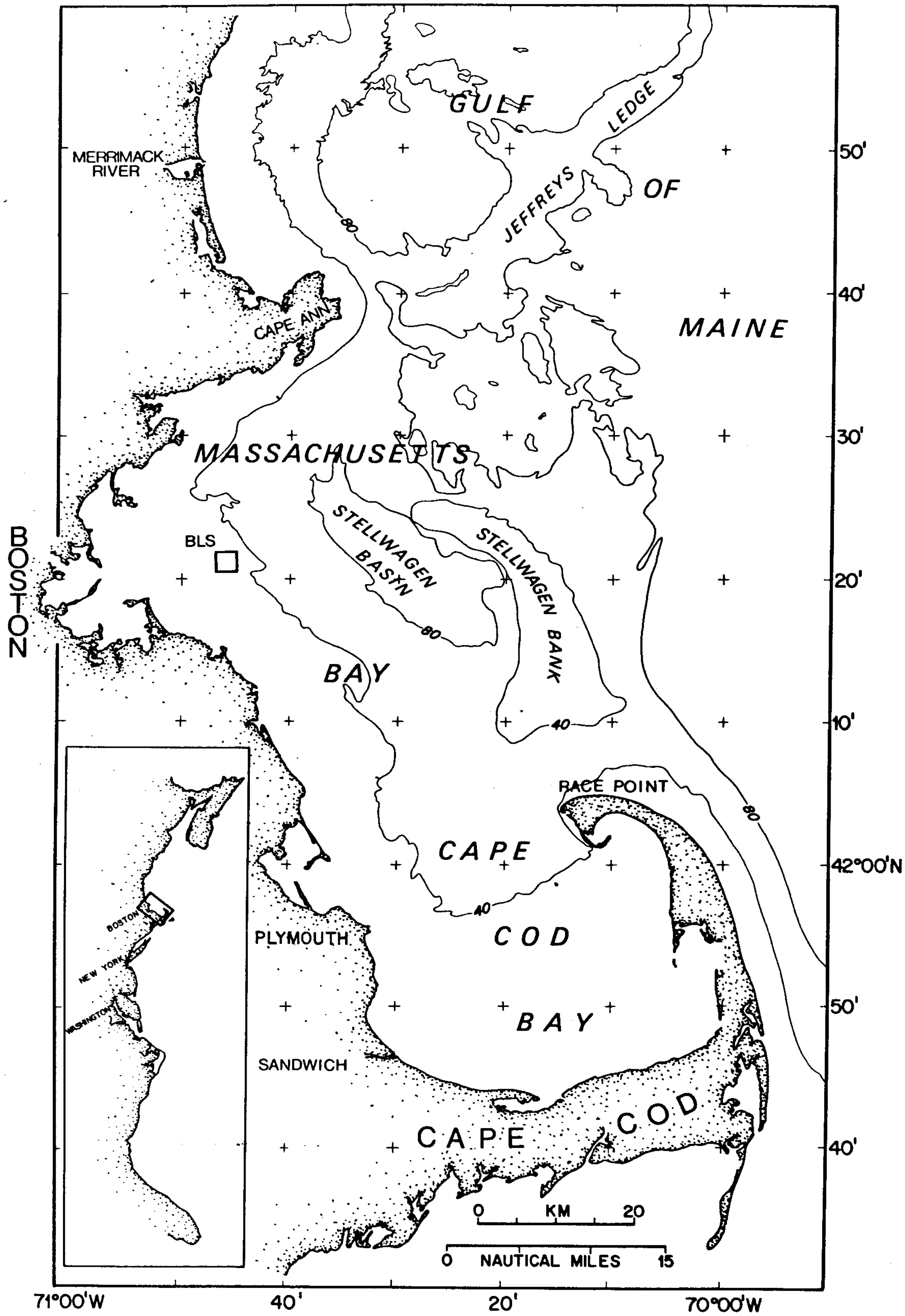

GULF
OF
MAINE
JEFFREYS LEDGE
MERRIMACK RIVER
CAPE ANN
MASSACHUSETTS
BAY
BOSTON
BLS
STELLWAGEN BASIN
STELLWAGEN BANK
RACE POINT
CAPE
COD
BAY
PLYMOUTH
SANDWICH
CAPE COD
80
40
0 KM 20
0 NAUTICAL MILES 15
50'
40'
30'
20'
10'
42°00'N
71°00'W
40'
20'
70°00'W
BOSTON
NEW YORK
WASHINGTON

Figure 1.1

Figure 1.2 Bottom sediment distribution (percent by weight) in Massachusetts and Cape Cod bays, after Schlee and others (1973).

(a) Percent sand (2.00 - .062 mm).

(b) Percent silt (.062 - .004 mm).

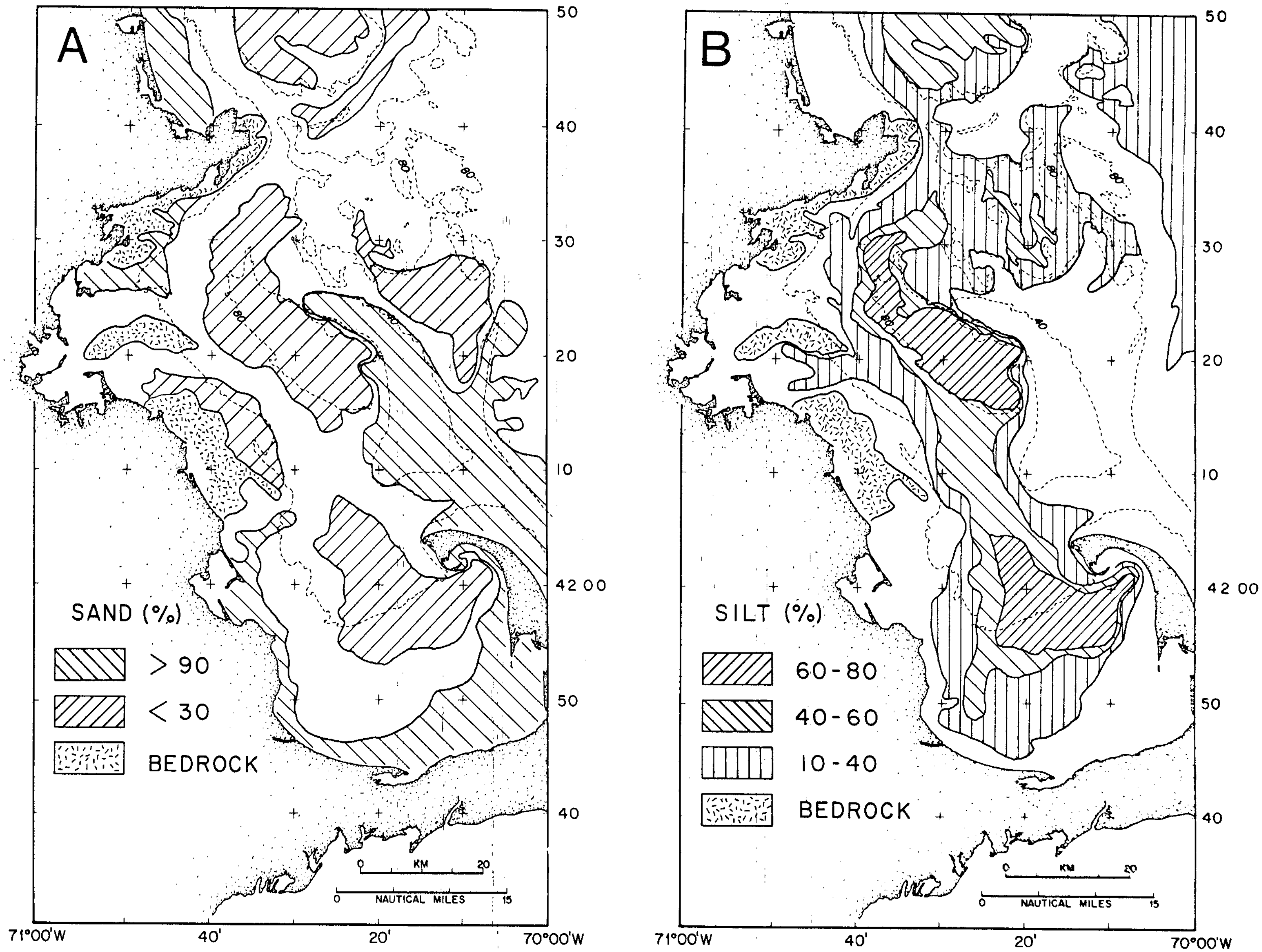

A
SAND (%)
> 90
< 30
BEDROCK
B
SILT (%)
60-80
40-60
10-40
BEDROCK
50
40
30
20
10
42 00
50
40
71°00'W
40'
20'
70°00'W
KM
NAUTICAL MILES

Figure 1.2

The glaciation of the New England coast and the subsequent rise of sea level formed the major bathymetric features and sediment deposits in Massachusetts Bay (Oldale and others, 1973; Tucholke and Hollister, 1973). The accumulation of fine sediments in the deep basin is attributed to the winnowing of mud from the topographic highs and from nearshore, and redeposition in the basins, most of the deposition occurring just after glacial retreat. The sedimentation rate has steadily decreased since then and currently is estimated to be 1 - 2 cm per thousand years (Tucholke and Hollister, 1973).

With such a complex sediment distribution and bottom topography, two questions arise (1) does movement of the bottom sediment occur in Massachusetts Bay under present conditions and if movement does occur, where and how frequently? (2) what is the pattern of bottom-water movement in the Bay that might redistribute sediment if eroded and what are the major factors which drive the bottom currents? To address these questions we have conducted a study of the bottom currents in Massachusetts Bay using moored current meters. In this paper, we first present a brief review of the bottom boundary layer and incipient sediment motion. We then investigate the movement of sediments by bottom currents at several locations in Massachusetts Bay. Finally, we describe the bottom flow pattern and sea level adjustment associated with winter storms, which were found to be a major forcing mechanism of net bottom flow.

B. The Bottom Boundary Layer and Incipient Sediment Motion

For this study of the adjustment of bottom sediments to current, an estimate of the stress required to erode the existing material and a method to determine the bottom stress from the field current observations are needed. (A review article by Wimbush and Munk (1971), work of Weatherly (1972), and a collection of articles edited by Swift, Duane and Pilkey (1972) were found useful references in the literature on the benthic boundary layer and processes of sediment transport.)

Field and laboratory studies have shown that the velocity profile in the bottom boundary layer is generally logarithmic, extending 1-4 m from the bottom (Sternberg, 1971, 1972; Miller and others, 1972; Weatherly, 1972). Thus

$$u(z) = \frac{u^*}{\kappa} \ln (z/z_0), \tag{1}$$

where

u = mean current speed (typically steady for periods on the order of 10 min.),

κ = VonKarman's constant = .4,

u^* = friction velocity = $(\tau/\rho)^{1/2}$,

τ = bottom stress dynes cm^{-2},

z_0 = roughness length,

z = height from bottom, $(z>z)$,

ρ = density, gm cm^{-3}.

The value of z_0 is found empirically to vary with flow characteristics. Specifically, the value of z_0 depends on the relative size of the laminar sublayer and the roughness elements (d) of the boundary. The depth of the laminar sublayer is

$$\delta_\ell \approx \frac{5\nu}{u^*} \qquad \nu = \text{kinematic viscosity, } cm^2 sec^{-1}. \tag{2}$$

For hydrodynamically smooth flow, the roughness elements are enclosed completely within the laminar sublayer, while for rough flow the layer is disrupted by the roughness elements. The conditions for smooth or rough flow are summarized in Table 1.1. For a smooth bottom, velocity measurements at a single height will give an estimate of u^*, but, for a rough bottom, an estimate of z_0 is also required. Alternatively, for measurements at a fixed height above the bottom (1) can be written as

$$u^{*2} = \rho\, C_D\, u^2 , \tag{3}$$

where C_D, the drag coefficient, is a property of the bottom roughness and is determined empirically. We use bottom photographs to estimate roughness (Z_0) and (1) to estimate stress.

Empirical curves of the bottom velocity (Sundborg, 1956; Allen, 1965), or of the bottom stress (Inman, 1963; Bagnold, 1962) required to erode well-sorted sediment of a given grain diameter and density have been found to agree roughly with field measurements in a tidal channel (Sternberg, 1971; Miller and others, 1972). The bottom stress required for movement is a minimum for sand of size 0.1 to 1 mm diameter and is about 4 dynes cm^{-2} ($u* = 2$ cm sec^{-1}); larger stress is required to move coarser material ($u* = 8$ cm sec^{-1} for diameter >1 cm). For material in the silt and clay range, the stress required for incipient movement depends on the degree of consolidation and elapsed time since deposition (Postma, 1967; Southard, and others, 1971). The curves of Inman (1963) suggest that $u*$ of at least 4 cm sec^{-1} is required to erode consolidated silts and clays, but there is little experimental data to confirm this estimate. One exception is the laboratory study of Southard, and others (1971), where a $u*$ of 1.37 cm sec^{-1} was required to move a deep sea mud.

If the bottom boundary layer is sufficiently turbulent, deposition of fine-grained material will not occur. The Sundborg (1956) curve indicates that sediments less than .05 mm in diameter (silt) will not accumulate if the velocities are more than 1 cm sec^{-1}. McCave (1972), reports that deposition of fine-grained sediments will not occur for $u*$ in the range of .6 -.9 cm sec^{-1}.

TABLE 1.1

CONDITIONS FOR FLOW OVER SMOOTH AND ROUGH BOTTOM

Smooth Bottom	Rough Bottom
$d < \frac{4\nu}{u^*}$	$d > \frac{40\nu}{u^*}$
$z_o \sim \frac{.1\nu}{u^*}$	$z_o \sim d/30$
$u(z) = \frac{u^*}{\kappa} \ln \left(\frac{zu^*}{.1\nu}\right)$	$u(z) = \frac{u^*}{\kappa} \ln (z/z_o)$

d = characteristic roughness-element height

ν = kinematic viscosity

z = height from bottom

z_o = effective roughness

u^* = friction velocity

κ = VonKarman's constant

u = fluid speed

Several problems with the idealized stress calculation and the established threshold curves should be noted. First, the effects of cohesion, biological activity, bedform, and sorting on incipient sediment motion are not well understood. Rhoads and Young (1971) show intense biological reworking and resuspension of fine-grained bottom sediment in Cape Cod Bay. Thus, biological activity may be a significant factor affecting sediment movement in Massachusetts Bay. Also, shear stress determined from (1) may not be an accurate measure of the stress acting on a sediment particle since bedform roughness and grain size both determine stress (Smith, 1977). At best, the stress estimated from (1) in the rough bottom case will be an overestimate of the true stress acting on a sediment particle. We also have assumed the bottom flow to be steady; oscillatory currents, for example, due to waves, may significantly increase the bottom stress for a given speed measured at a fixed distance from the bottom. In the wave dominated case, stress estimates from (1) will be low (Madsen and Grant, 1976; Komar, 1976). Finally, detailed measurements of the logarithmic layers particularly those of Sternberg (1971) and Weatherly (1972), have shown considerable variability in estimates of Z_0 and C_D for a given location.

Despite these problems, the approximate bottom stress and corresponding speed required for incipient motion of material in the sand, silt, clay, and gravel range have been estimated from the logarithmic law (Table 1.2, (1)). The estimates in the sand and gravel range are probably fairly accurate while the estimates for finer material are somewhat uncertain, primarily because of uncertainty in the degree of consolidation and cohesion of the sediments and lack of laboratory and direct field erosion data. Although stress and velocity estimates in Table 1.2 should be viewed as approximate, they should provide a useful range of erosion velocities for this study.

TABLE 1.2

ESTIMATES OF BOTTOM STRESS REQUIRED FOR INCIPIENT SEDIMENT MOTION AND DEPOSITION.

	Required Friction Velocity (U*) (cm/sec)	Speed 100 cm from bottom[2] (cm/sec)		
		Smooth	Rough	
Incipient Motion[1]			(a)	(b)
Sand, recently deposited silt and clay	2	61	40	32
Consolidated silt and clay	4	129	80	64
Gravel (1 cm diameter)	8	272	160	128
Deposition[3]				
Silt and clay	.6 - .9	17-26	12-18	10-14

[1]Estimated from Inman (1949), reproduced in Miller and others (1972); Southard and others (1971), Postma (1967).

[2]Speeds estimated from Equation (1). For a rough bottom, two roughness heights were used: a) d = 1 cm, b) d = 5 cm (z = d/30). All estimates to nearest cm/sec. Due to the contribution of bed roughness to the measured stress, the predicted speeds are minimum speeds required for incipient motion. The calculations also assume steady flow (no wave component).

[3]Estimates from McCave (1972).

C. Field Program

1. Bottom Current Monitoring

Measurements of the near-bottom currents were made at several locations in Massachusetts Bay from May, 1971 through July, 1972 (Fig. 1.3). The station locations were selected in order to define the general bottom current pattern in Massachusetts and Cape Cod Bays, and also to assess the currents over various types of topography and bottom sediments. Stations A and F were placed to monitor flow in the two channels leading into Stellwagen Basin; Stations B and E were selected to monitor circulation on the coastal shelf. Station C was placed in Stellwagen Basin, and Station D was placed to monitor on Stellwagen Bank. Stations A, C and F are in areas of fine sediments, while B,D and E are in areas with coarser bottom material. A current meter was deployed throughout the study at the Boston Lightship to provide continuous measurements at one location. We hoped to obtain a one month, bottom current record each season at stations A-F. However, because of temporary loss of one current meter and other malfunctions, we did not attain this objective. The times, depths and locations of the successful measurements are listed in Appendix A. The sequence of current meter deployments is shown in Figure 1.4.

The current meters at Stations A-F were moored 1 m from the bottom. All floatation was within approximately 5 m of the bottom (Figure 1.5). Ground lines were used on either side of the main anchor to facilitate recovery of the instrument if the surface marker were lost, and a small acoustic beacon was attached to the meters to aid in locating the instrument. The meter at Boston Lightship was suspended approximately 8 m from the bottom. A Geodyne model 850 meter was deployed continuously

Figure 1.3 Locations of bottom current monitoring stations and bottom photographs. (Bathymetry after C & GS Chart 0808N-50).

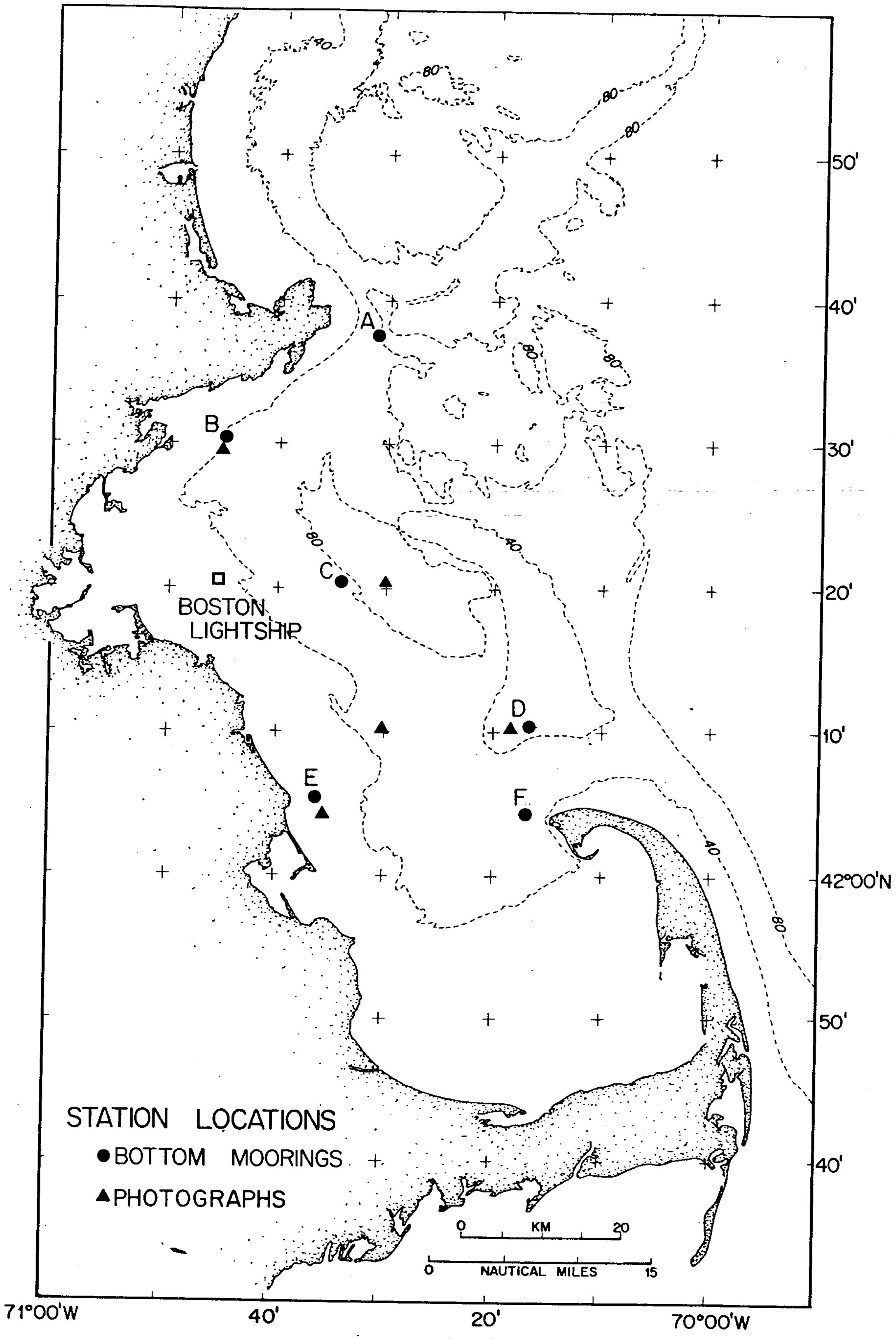

STATION LOCATIONS
BOTTOM MOORINGS
PHOTOGRAPHS
A
B
C
D
E
F
BOSTON LIGHTSHIP
80
40
0 KM 20
0 NAUTICAL MILES 15
50'
40'
30'
20'
10'
42°00'N
50'
40'
71°00'W
40'
20'
70°00'W

Figure 1.3

Figure 1.4 Schedule of current meter deployment in Massachusetts and Cape Cod bays. Records are numbered sequentially at each station and dashed lines indicate records with inaccurate sampling rate and time base. See Figure 1.3 for station locations. Several records with instrument malfunctions were split into two pieces to facilitate data processing. These are labeled as record/1, record/2, etc.

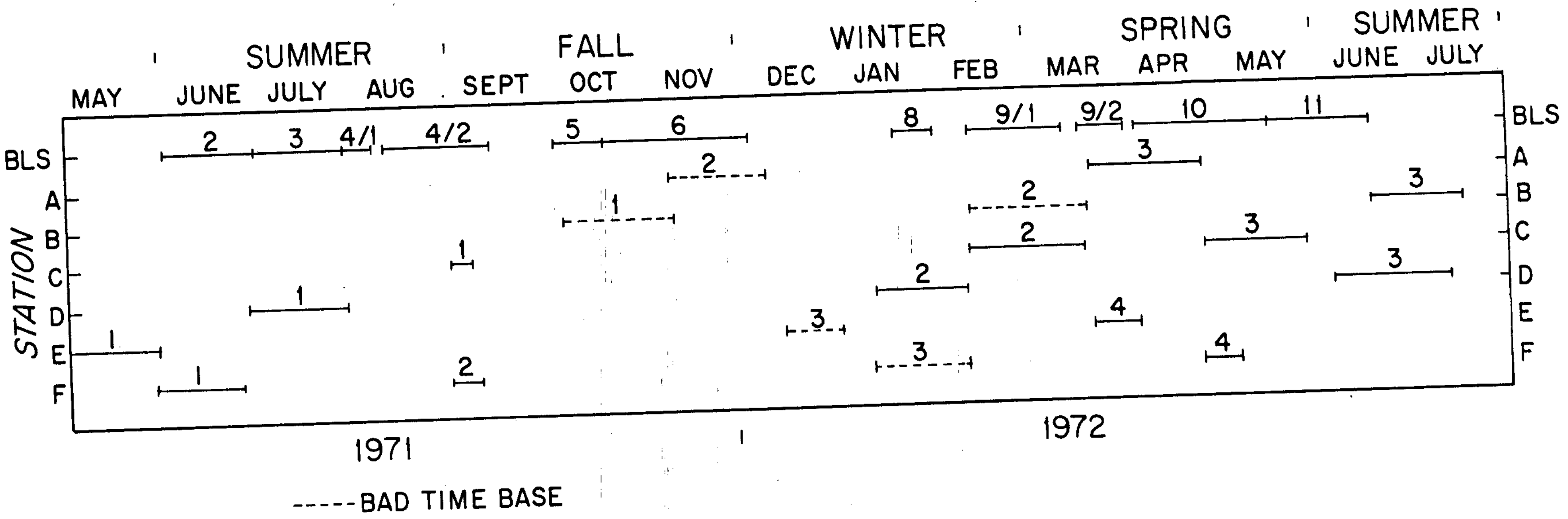

SUMMER
FALL
WINTER
SPRING
SUMMER
MAY
JUNE
JULY
AUG
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUNE
JULY
STATION
BLS
A
B
C
D
E
F
2
3
4/1
4/2
5
6
8
9/1
9/2
10
11
1971
1972
-----BAD TIME BASE

Figure 1.4

from the Boston Lightship, whereas two model 102 Richardson-type meters were rotated among the offshore stations. No current meters were permanently lost during the program, and approximately 60% of the instruments returned useable data. Instrument malfunctions occurred in the 102 current meters which record on film, and were due to film advance problems, malfunctions of the circuitry, and an inaccurate time base. The 850 current meter was extremely reliable.

2. Bottom Sediment Composition and Texture Near Current Meter Stations

Grain size analysis of the bottom sediment near the current meter stations (Table 1.3) was obtained from an earlier sediment survey (Schlee and others, 1973; Hathaway, 1971). Most of the samples are sandy silt or sand, except at Station E where a large amount of gravel is present. At the deeper Stations (A,C,F) the bottom composition is similar (44-49% sand, 32-39% silt, 16-19% clay). At Stations B and D, the bottom is sand or sand plus gravel.

Bottom photographs (see Figure 1.2 for locations) were obtained from previous studies and clearly show the different sediment types. Near Station B, a thin layer of fine sediment overlies gravel and coarse sand (Figures 1.6 a,b) suggesting little active current erosion. The two photographs near Station B illustrate the patchiness of the bottom sediment distribution and the difficulty in estimating a meaningful roughness height in these areas with poor sorting. In the deep basin (Figure 1.6 c,d) the bottom is soft silt, sand and clay. Here the bottom is smoother than at Station B (roughness elements less than 1 cm), and again, there is little evidence for active erosion. In contrast, on Stellwagen Bank (station D, Figure 1.6 e) there is no apparent fine material and ripple marks suggest recent transport; the roughness height is about 5 cm. At Station E (Figure 1.6 f) the bottom is covered by coarse sand and active erosion is not apparent.

On the basis of the photographs, the bottom in the deep basin (Station C) is considered smooth, while at Stations B,D, and E the bottom is rough. No

Figure 1.5 Schematic diagram of mooring for near-bottom current measurements.

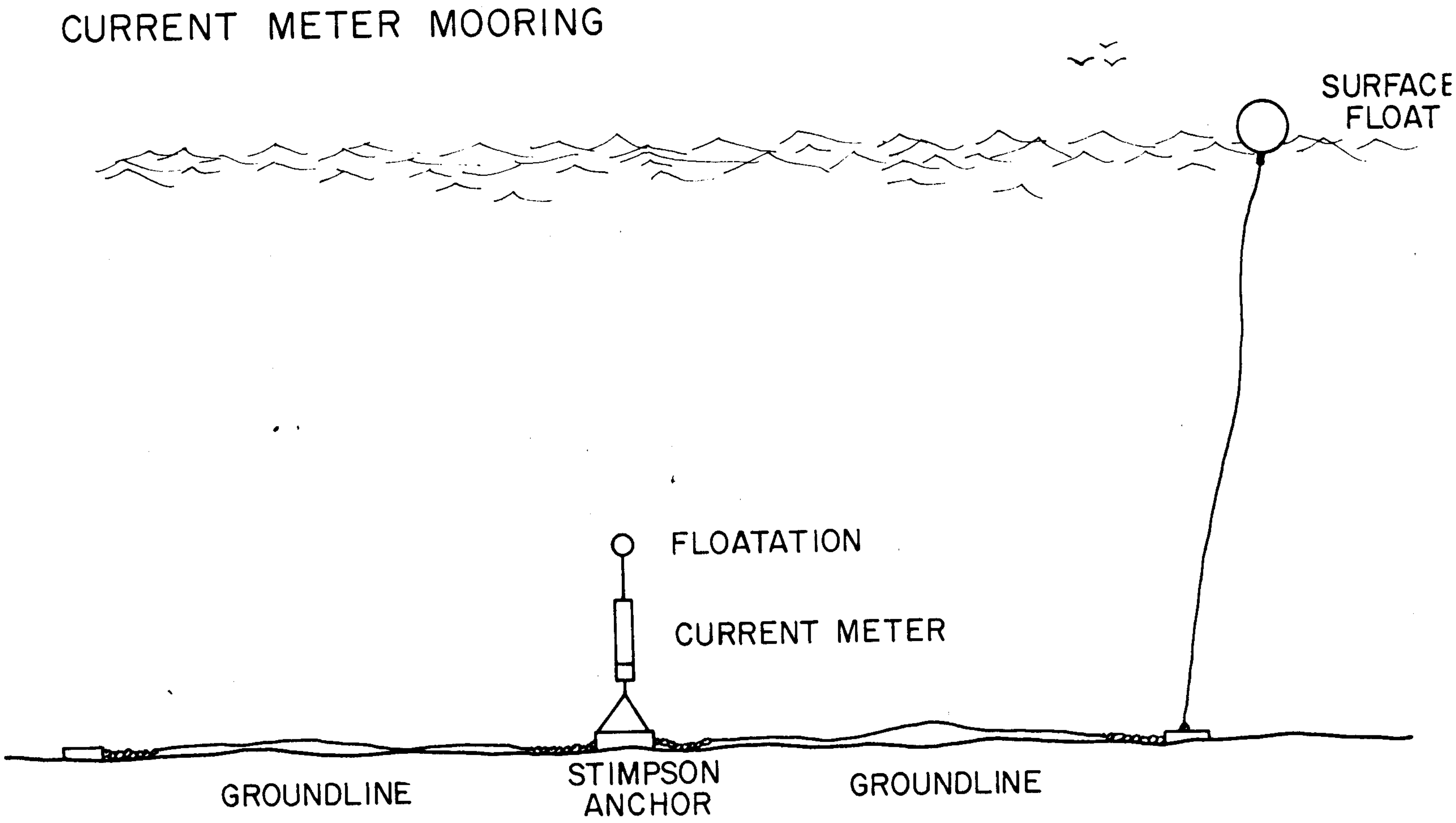

CURRENT METER MOORING
SURFACE FLOAT
FLOATATION
CURRENT METER
GROUNDLINE
STIMPSON ANCHOR
GROUNDLINE

Figure 1.5

TABLE 1.3

SEDIMENT ANALYSES NEAR CURRENT METER STATIONS

PERCENT BY WEIGHT

STATION	GRAVEL[1]	SAND[2]	SILT[3]	CLAY[4]
A	0	49	32	19
B	13	76	10	0
C	0	47	37	16
D	1	99	0	0
E	94	6	0	0
F	1	44	39	16

[1]Gravel > 2 mm.

[2]Sand 2.00 - .062 mm.

[3]Silt .062 - .004 mm.

[4]Clay < .004 mm.

bottom photographs were available at Stations A or F. However, the bottom sediments at these stations are similar to those at Station C suggesting that the bottom might be considered smooth.

D. Speed Statistics and Estimates of Bottom Sediment Movement

The stations may be grouped in three classes by the observed maximum and average speed (Table 1.4). The largest maximum and average speeds occurred at Stations D and F at the southern mouth of the Bay. Nearshore (Stations B and E), the maximum and average speeds were weaker, and at the deep Stations (A and C) the average speeds were similar to the nearshore stations, but the maximum speeds were somewhat less. The speed distribution in the basin was affected primarily by the strength of tidal currents and the water depth. At the mouth of the Bay, the higher speeds were probably due to tidal currents, reinforced by wind-generated currents and possibly by waves. In the deep basin and along the shallow border of the Bay, the tidal currents were substantially weaker, but maximum speeds were larger in the shallow regions probably because of wind and wave action.

At Station B, D, and F, the observed maximum speeds were above the estimated minimum critical erosion speeds (Table 1.2), assuming a rough bottom. None of the observed speeds were large enough to move sand for a smooth bottom. At stations A and C, the maximum speeds were substantially below critical erosion speeds for consolidated or unconsolidated silt and clay. At all stations during most of the measurement period, the current speed was substantially less than the critical erosion speed, and thus bottom movement of sediments, if it occurred at all, was infrequent. The average current at Stations D and F was sufficiently high to prevent deposition of fine material, while at the Stations A,B,C, deposition was possible 95% of the time. The data suggests that the maximum bottom current speeds occurred in the fall and winter months (Table 1.5).

Figure 1.6 Bottom photographs* in Massachusetts Bay showing bottom texture.

a) Station 1200 (near current meter station B)
42°29.8'N 70°44.7'W 43 m
Grab sample description: grey silty sand
Composition (%): gvl 13.4; sand 76.3; silt 10.4; clay 0.

b) Second photograph at station 1200.

c) Station 1202 (near current meter station C)
42°20.6'N 70°30.0'W 91 m
Grab sample description: grey clay
Composition (%): gvl 0; sand 4.7; silt 49.3; clay 43.0.

d) Station 1203
42°10.1'N 70°30.2'W 55 m
Grab sample description: 5 cm soft brown clay overlying stiff grey clay
Composition (%): gvl 0; sand 39.0; silt 49.5; clay 11.7.

e) Bottom photograph near station D. Rod in picture approximately 1 m long.

f) Bottom photograph near station R.

*Photographs at stations 1200-1203 from continental margin study (Hathaway, 1971). Others from Dr. D. Cooper, U.S. National Marine Fisheries Service, Woods Hole, Mass.

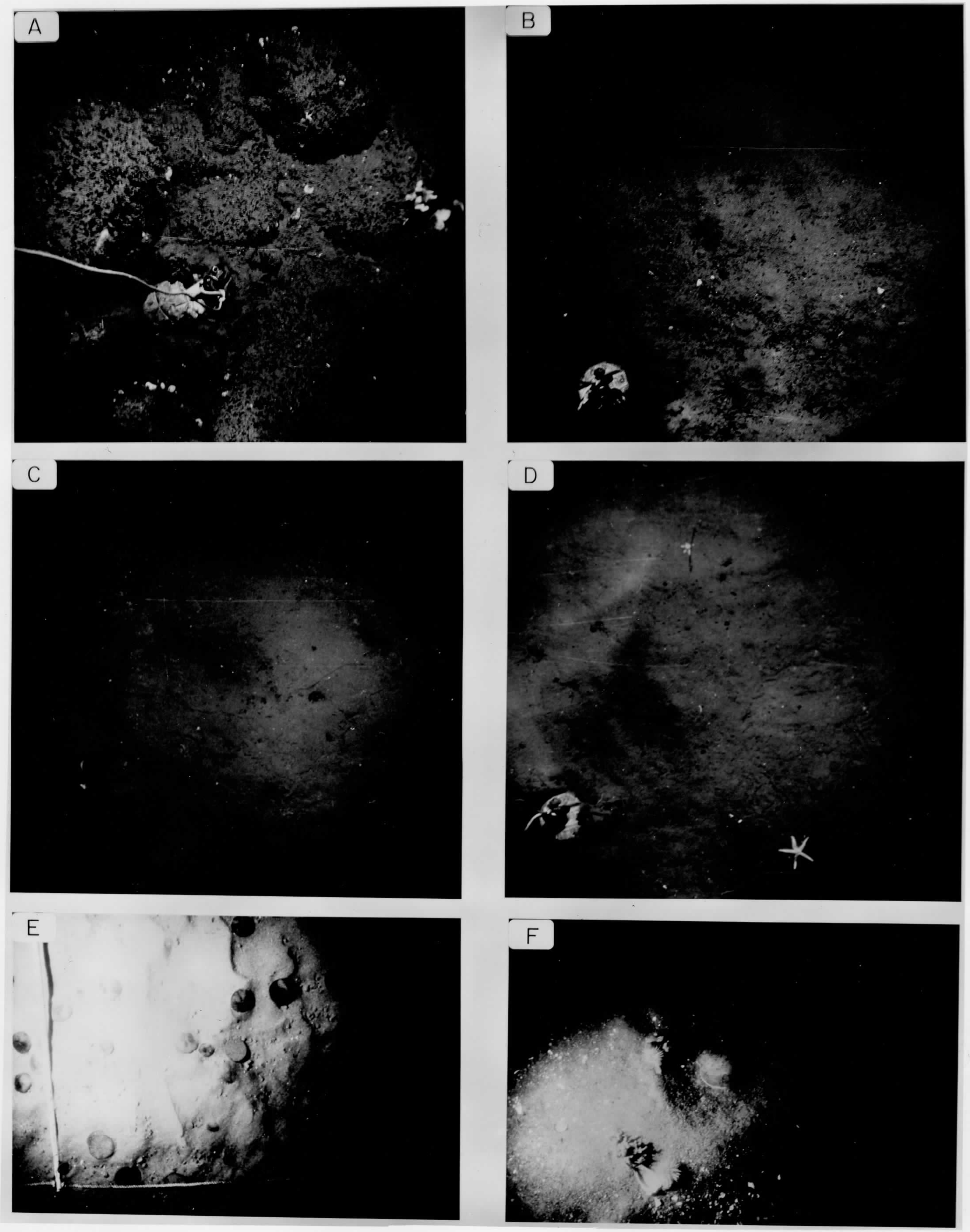

A
B
C
D
E
F

TABLE 1.4

RANGE OF SPEED STATISTICS FOR BOTTOM CURRENT RECORDS[1]

	A	B	C	D	E	F
Maximum Speed	24-34	25-43	26-29	32-47	29-37	35-47
Speed Exceeded 1% of Time	18	14	20	26-36	20-26	27-33
Speed Exceeded 5% of Time	12	10	12-13	23-29	17-21	24-28
Average Speed[2]	5.7	4.7	4.7-6.1	13.1-17.0	4.2-7.9	14.5-15.9
Stand. Dev.	3.2	3.8	3.0-3.5	5.2-8.1	4.2	5.5-7.7
No. Records, Time Base[3]	2,1	3,2	3	3	3,1	2
Days[4]	36	28	66	98	42	44
Semidiurnal Tide[5]						
Major	2.6	3.5	6.2	20.2	5.2	17.5
Minor	.1	2.6	1.2	-3.6	.4	2.2
Orientation	17	5	79	72	170	34

[1]Only records longer than 15 days included except for max. speed. Records not simultaneous, so not directly comparable. All numbers in cm sec^{-1}.

[2]Average speed and standard deviation for vector-averaged one-hour samples.

[3]Number of records included (first digit); number with time base error (2nd digit); only max. speeds tabulated for records with time base error.

[4]Total number of days excluding records with time base error.

[5]Computed from 15 day pieces; ellipse orientation with respect to north. Estimated error ±.5 cm sec^{-1} in speed, ±5° in direction. Positive minor axis indicates vector rotates counterclockwise, negative clockwise.

For most of the monitoring stations, the maximum one minute average current speed observed during each of the bottom current meter records is near the movement threshold of the competency curves of Sundborg (1956) (Fig. 1.7). Only at Station E do the values fall far below the competency curve, and this may be because most of the sample used to characterize the bottom sediments at Station E is gravel which is relict glacial material. This suggests that the existing sediment at each station is not often moved by the observed currents, and implies that the sediment distribution is in equilibrium with the present current regime. This conclusion is similar to that presented earlier, although the Sundborg curve is highly generalized, and does not take into account bottom roughness effects.

In summary, in the well sorted sand regions (Stations B and D), the data suggests occasional movement of bottom sediment due to currents if the bottom is assumed to be rough with roughness elements of at least 1 cm. For the silt-sand bottoms (Stations A,C) however, the data suggests that the observed maximum speeds were not strong enough to move the existing sediment. At Station F, where the bottom is also a sandy-silt, we cannot predict incipient motion without additional information on critical erosion stress of the sediment, and bottom roughness. For a consolidated bottom - hard packed clay material retrieved with the current meter anchor suggests the bottom is consolidated - movement will not occur. The distinction between a smooth and a rough bottom in this study is important because the maximum observed bottom current, assuming no waves, was not strong enough at any station to move sand on a smooth bottom. Shear stress was sufficiently low to allow deposition of fine material for a large fraction of the time at Stations A,B,C, and E but only for short periods at Stations D and F, primarily because of the large tidal currents at the mouth of the bay.

E. Wind Driven Near Bottom Currents in Winter

Rapid changes in the direction and magnitude of bottom flow occurred in winter on time scales of 1-5 days (Figure 1.8), with many of the changes associated with strong winds. A similar correlation between low frequency currents and wind stress on the continental shelf and Great Lakes has been noted by Beardsley

TABLE 1.5

MAXIMUM SPEEDS BY SEASON (cm/sec)

STATION	WINTER	SPRING	SUMMER	FALL
A		24		34
B	43		25	26
C	29	26		27
D	47		32,40	
E	37	29,37		
F	42	41	35	47

Figure 1.7 Maximum one minute average speed observed at current meter stations A-F and Sundborg (1956) competency curves (reproduced in Miller and others, 1972). Note logarithmic velocity scale.

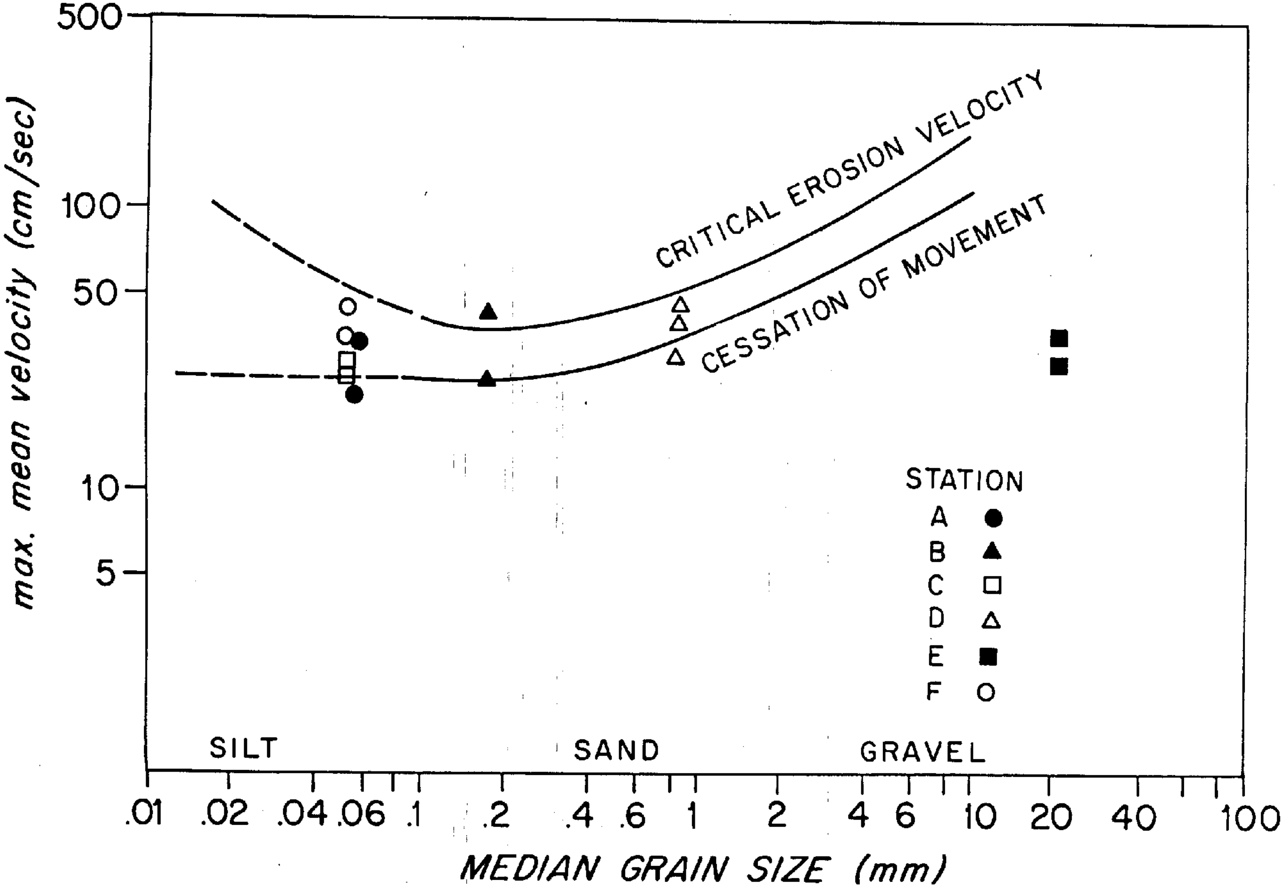

500
100
50
10
5
max. mean velocity (cm/sec)
CRITICAL EROSION VELOCITY
CESSATION OF MOVEMENT
STATION
A
B
C
D
E
F
SILT
SAND
GRAVEL
.01 .02 .04 .06 .1 .2 .4 .6 1 2 4 6 10 20 40 100
MEDIAN GRAIN SIZE (mm)

Figure 1.7

and Butman (1974), Csanady (1973a,b) and Blanton (1974). Theoretical and numerical studies of flow in closed basins such as the Great Lakes (Rao and Murty, 1970; Bennett, 1974; Csanady, 1973a) suggest that topographic variations in a long lake produce a "two gyre" flow pattern in response to wind stress parallel to the major axis; flow is in the direction of the wind in shallow areas and opposite to the wind in the deep regions, the return flow being driven by a surface pressure gradient or setup. The depth distribution and the semienclosed geometry of Massachusetts Bay suggests that a similar flow pattern may be driven by strong winds. Such a flow pattern could be important in eroding the fine bottom sediments from the nearshore areas and bank, and redistributing them to the deep basin. In this section we investigate the low frequency response of the bottom currents and sea level in Massachusetts Bay to

winter storms, using coastal sea level observations and the bottom current measurements made during December - February, 1972.

1. Sea Level Response to Wind

Because Massachusetts Bay is a semi-enclosed basin opening on the east to the Gulf of Maine, sea level will reflect changes in the level of the Gulf at the mouth of the Bay, as well as local changes due to wind stress. For winds parallel to the major axis of the basin (150°-330°T, Figure 1.9) a setup of the sea surface in the direction of the wind (Figure 1.10a,b) was observed. A northwest-southeast wind stress of 1 dyne cm^{-2} (using a drag coefficient of 1.1×10^{-3}) resulted in a change in elevation between Boston and Sandwich of approximately 5 cm, with the setup occurring almost immediately.

The basin response to a wind blowing across the minor axis of the Bay (60°-240°T, Figure 1.10) was more complicated than a simple setup in the direction of the wind. A wind blowing to the northeast resulted in a large drop in sea level at Boston and Sandwich (about 50 cm for a 1 dyne cm^{-2} wind), while

Figure 1.8 Progressive vector diagram of current at Station D in January and February, 1972. Two major departures from the net drift on Jan. 25-26, and Feb. 3-6 are associated with winter storms.

a) Progressive vector diagram from hourly data.

b) Daily average current and wind stress.

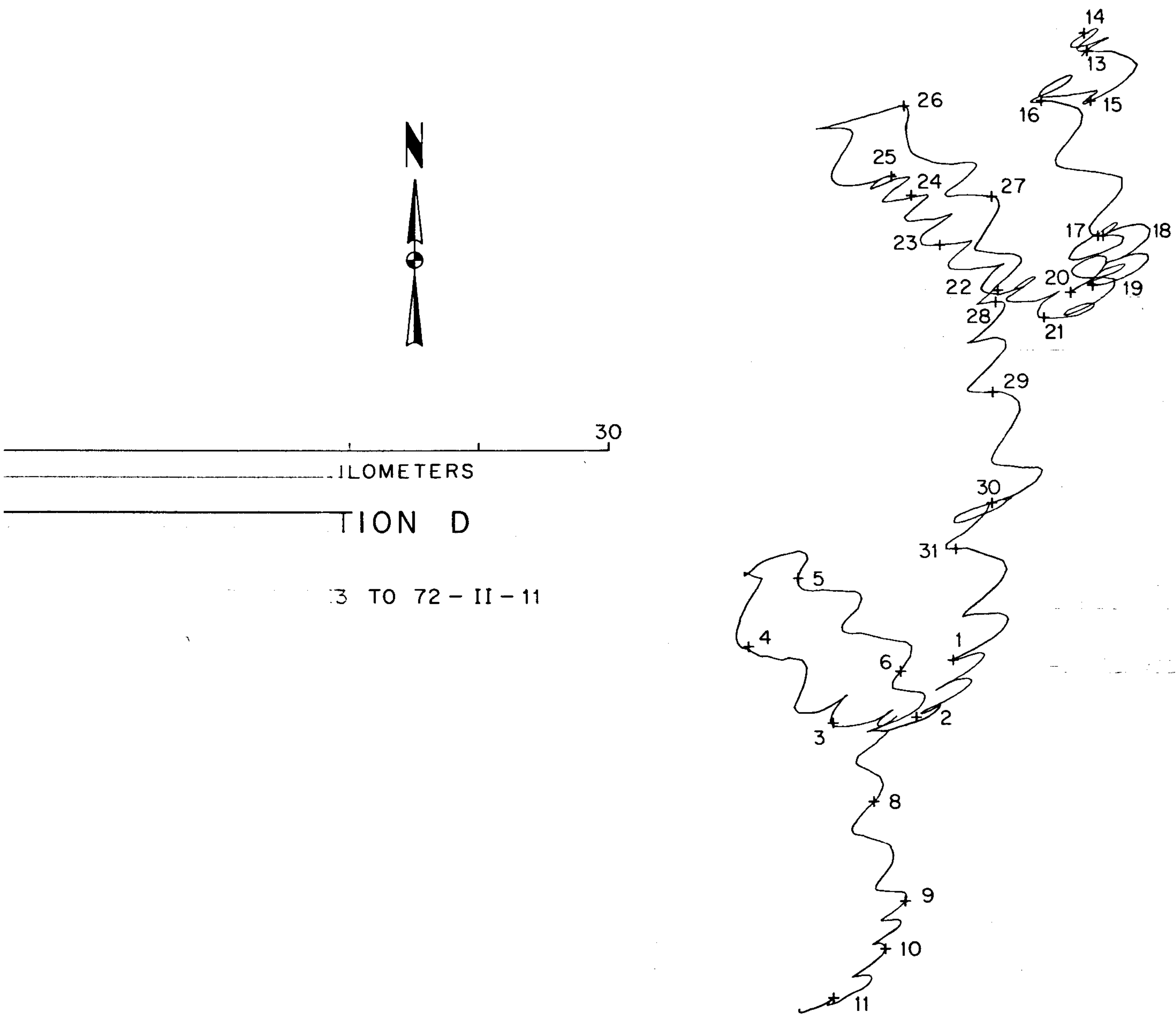
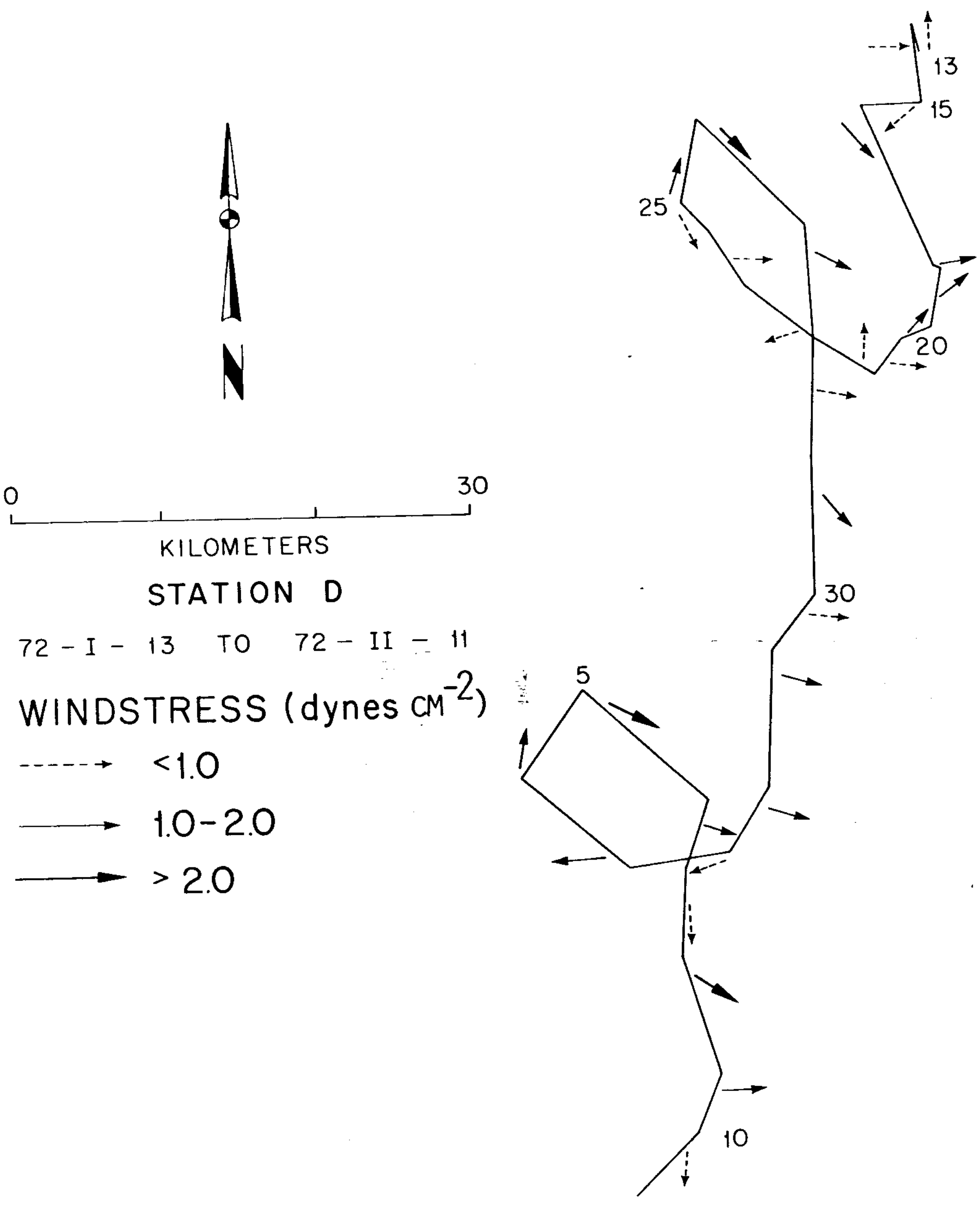

N
30
ILOMETERS
TION D
3 TO 72 - II - 11
14
13
15
16
26
25
24
27
23
17
18
20
19
22
28
21
29
30
31
5
4
1
6
2
3
8
9
10
11

Figure 1.8a



N
0
30
KILOMETERS
STATION D
72 - I - 13 TO 72 - II - 11
WINDSTRESS (dynes CM^{-2})
<1.0
1.0-2.0
> 2.0
13
15
25
20
30
5
10

Figure 1.8b

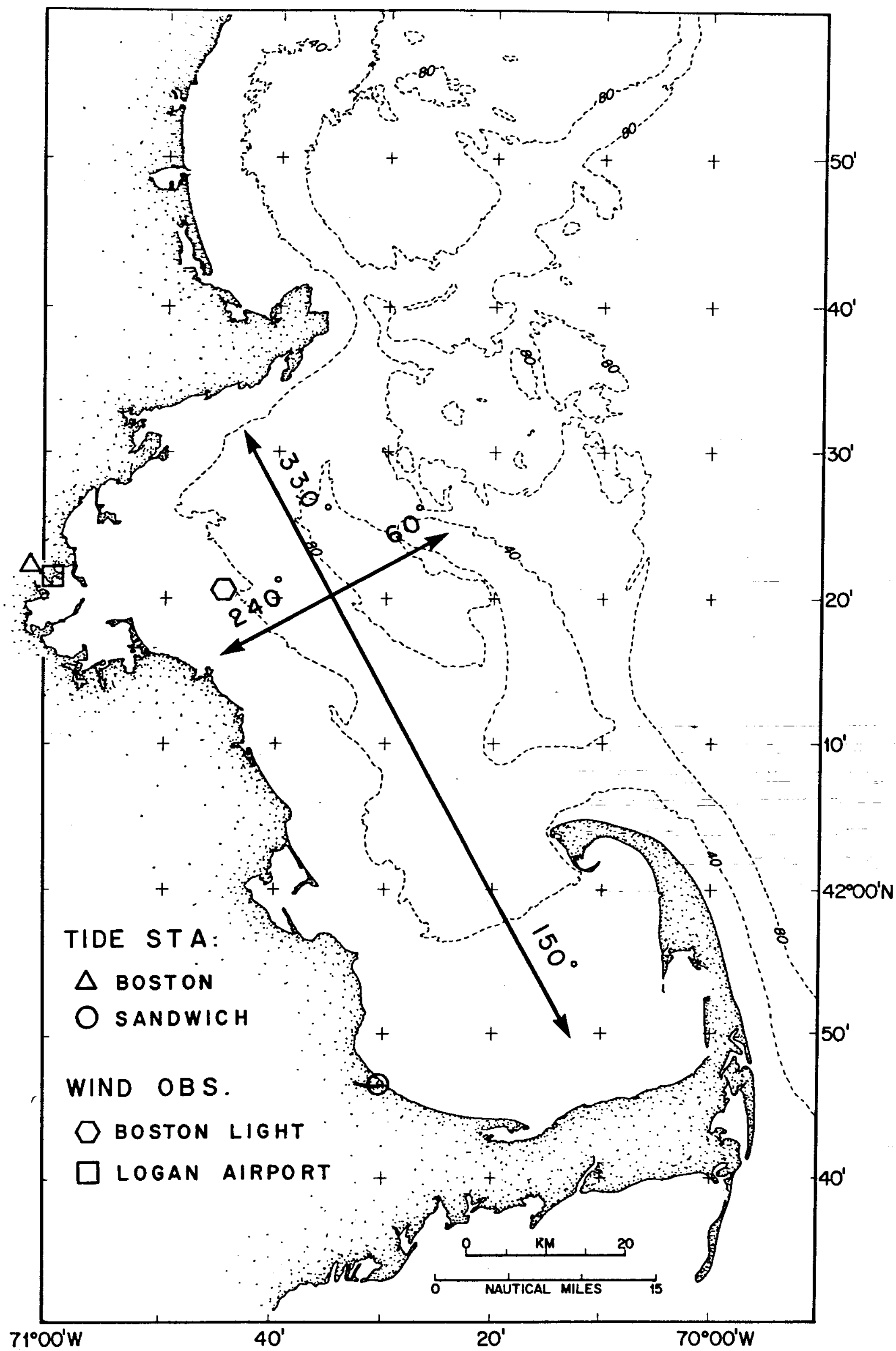
a wind blowing to the southwest caused a rise. Although no sea level observations were made in the outer part of the Bay, it is unreasonable to expect a large setup (an order of magnitude larger than the setup for winds along the long axis) to occur across the short axis of the Bay. The large observed change in sea level in response to northeast-southwest winds probably reflects a change in the level of the Gulf of Maine to which sea level in Massachusetts Bay adjusts. Superimposed on this change may have been a small setup in the direction of the wind with slope similar to that observed along the long axis. The response time to northeast-southwest winds for sea level at Boston and Sandwich was approximately 6-12 hours (Figure 1.10a,b) and was significantly longer than the setup time observed for northwest- southeast winds; this difference in setup time also suggests that sea level in the Gulf of Maine, a larger system than Massachusetts Bay is responsible for the large sea level changes in Massachusetts Bay. The change in sea level is in agreement with Csanady's (1974) model of the barotropic response of the Gulf of Maine to wind.

2. Bottom Current and Sea Level Response to Strong Wind Events

a. January 25 - 27, 1972 (Figure 1.10a,b; 1.11)

During the morning of January 25 winds at Boston were from the south, became more westerly during the day, and were strongly (3-5 dynes cm^{-2}) from the northwest on January 26 and 27. On January 25 the bottom current at Station D closely followed the rotation of the wind stress from north to east to southeast. On January 26 and 27, the flow was consistently to the southeast, approximately parallel to the coastline in the western Gulf of Maine. At the Boston Lightship, the flow was generally southeast parallel to the coast in the direction of the wind. During the 26th and 27th, with nearly constant northwest wind, the current at Boston Lightship rotated slightly to the west and gradually decreased. The flow pattern was established in response to the northwest wind on January 26 within 6 to 12 hours and did not change significantly throughout the day.

Figure 1.9 Map of Massachusetts and Cape Cod Bays showing location of tide and meteorological stations, and major and minor axes.



TIDE STA:
BOSTON
SANDWICH
WIND OBS.
BOSTON LIGHT
LOGAN AIRPORT
330°
60
240°
150°
50'
40'
30'
20'
10'
42°00'N
50'
40'
71°00'W
40'
20'
70°00'W
0 KM 20
0 NAUTICAL MILES 15

Figure 1.9

Figure 1.10 a,b Low frequency response of sea level in Massachusetts Bay to wind, Jan.-Feb., 1972.

Top: Difference in sea level between Sandwich and Boston and component of wind stress (dynes cm^{-2}) parallel to major axis of the Bay (330°-150°T, figure 1.9).

Bottom: Deviation of sea level at Boston from mean and component of wind stress parallel to minor axis of the Bay, and across the open side (60°-240°T). Deviation from mean level is corrected for the inverse barometer effect using atmospheric pressure measured at Logan Airport.

Notes:

1. All hourly series have been filtered with a Gaussian filter (1/2 power at 56 hr., see Appendix B).

2. Note difference in sea level scale between top and bottom figures; upper scale expanded five times.

3. Wind stress is computed from Logan wind data using a constant drag coefficient of 1.1×10^{-3}. The wind stress would be approximately a factor of two higher for wind observations from the Boston Lightship. The drag coefficient may vary by as much as a factor of two - three over the period (Csanady, 1972, Parker, 1974) as the stability of the air-water interface changes.

4. Sea level difference between Sandwich and Boston has not been corrected for atmospheric pressure differences. Parker (1974) indicates that the difference is less than 3 mb, and usually less than .5 mb, at least in summer.

5. Wind at Logan and Boston Lightship shown for the period Feb. 18-22 where the two observations differed significantly (Logan, solid line; Lightship, dotted line).

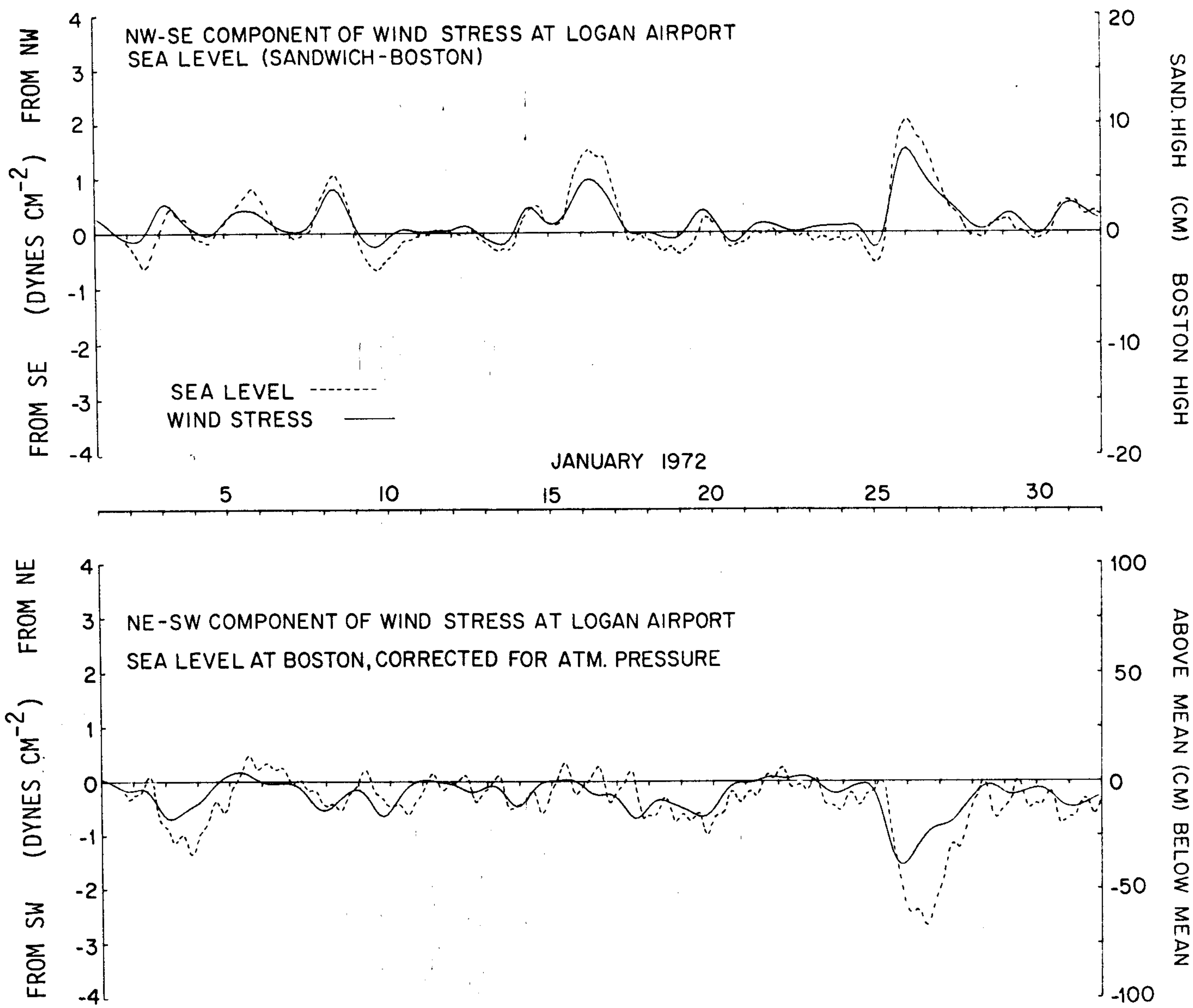

NW-SE COMPONENT OF WIND STRESS AT LOGAN AIRPORT
SEA LEVEL (SANDWICH-BOSTON)
FROM SE (DYNES CM^{-2}) FROM NW
SAND. HIGH (CM) BOSTON HIGH
SEA LEVEL
WIND STRESS
JANUARY 1972
5
10
15
20
25
30
NE-SW COMPONENT OF WIND STRESS AT LOGAN AIRPORT
SEA LEVEL AT BOSTON, CORRECTED FOR ATM. PRESSURE
FROM SW (DYNES CM^{-2}) FROM NE
ABOVE MEAN (CM) BELOW MEAN

Figure 1.10a

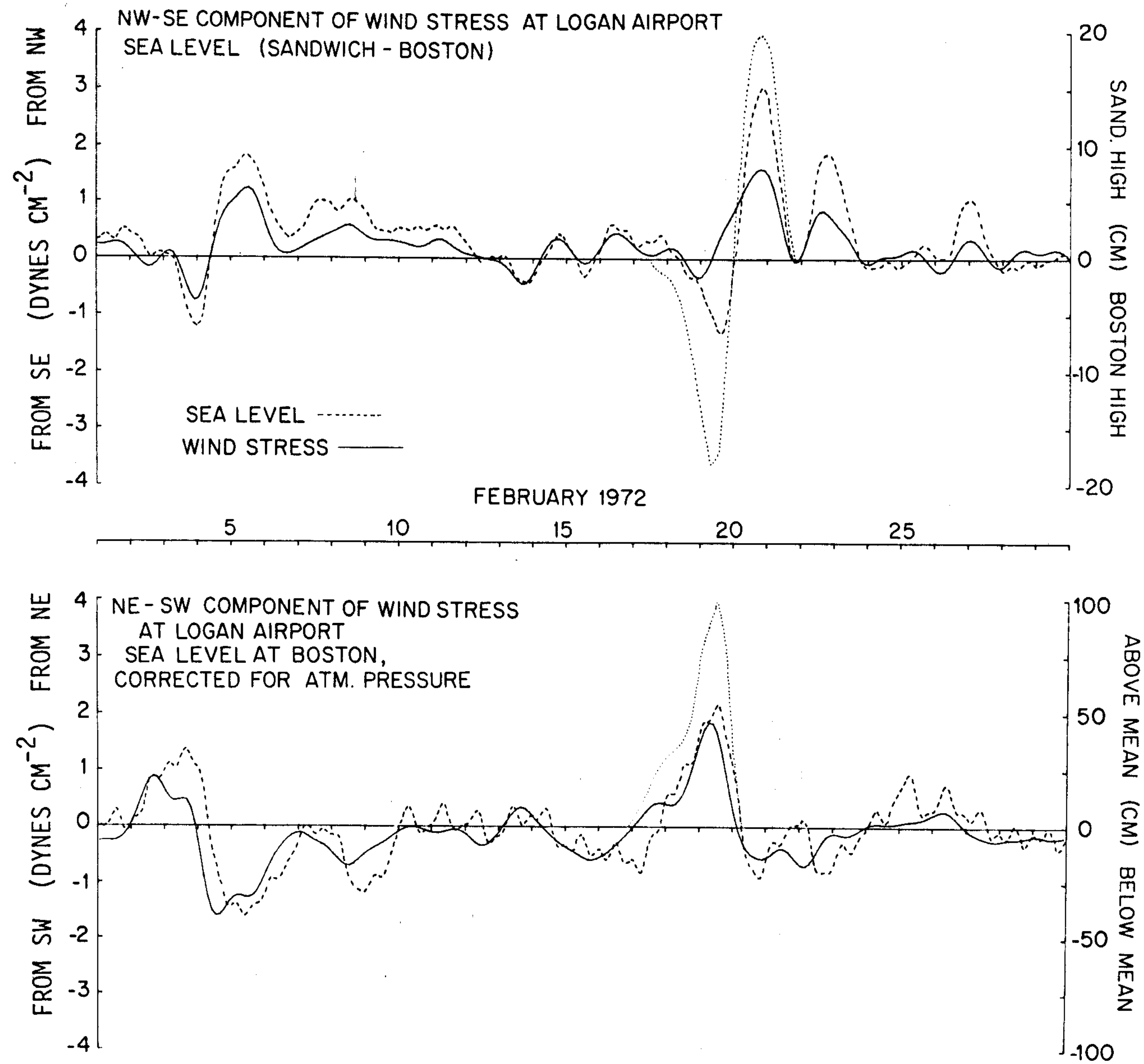

NW-SE COMPONENT OF WIND STRESS AT LOGAN AIRPORT
SEA LEVEL (SANDWICH - BOSTON)
FROM SE (DYNES CM^-2) FROM NW
SAND. HIGH (CM) BOSTON HIGH
SEA LEVEL
WIND STRESS
FEBRUARY 1972
5
10
15
20
25
NE - SW COMPONENT OF WIND STRESS
AT LOGAN AIRPORT
SEA LEVEL AT BOSTON,
CORRECTED FOR ATM. PRESSURE
FROM SW (DYNES CM^-2) FROM NE
ABOVE MEAN (CM) BELOW MEAN

Figure 1.10b

Figure 1.11 Windstress (shown in lower lefthand corner of each figure) at Boston Lightship (drag coefficient = 1.1×10^{-3}) and near-bottom current at three stations in Massachusetts Bay January 25-27, 1972. Current records have been filtered with a Gaussian filter (1/2 power at 33 hours, see Appendix B) to remove tidal oscillations. Values of current and wind stress shown every six hours. Current meter located 1 m from the bottom at Station D and F, 10 m from the bottom at the Boston Lightship. Measure length of windstress and current vector to center of arrowhead.

JAN 25, 1972

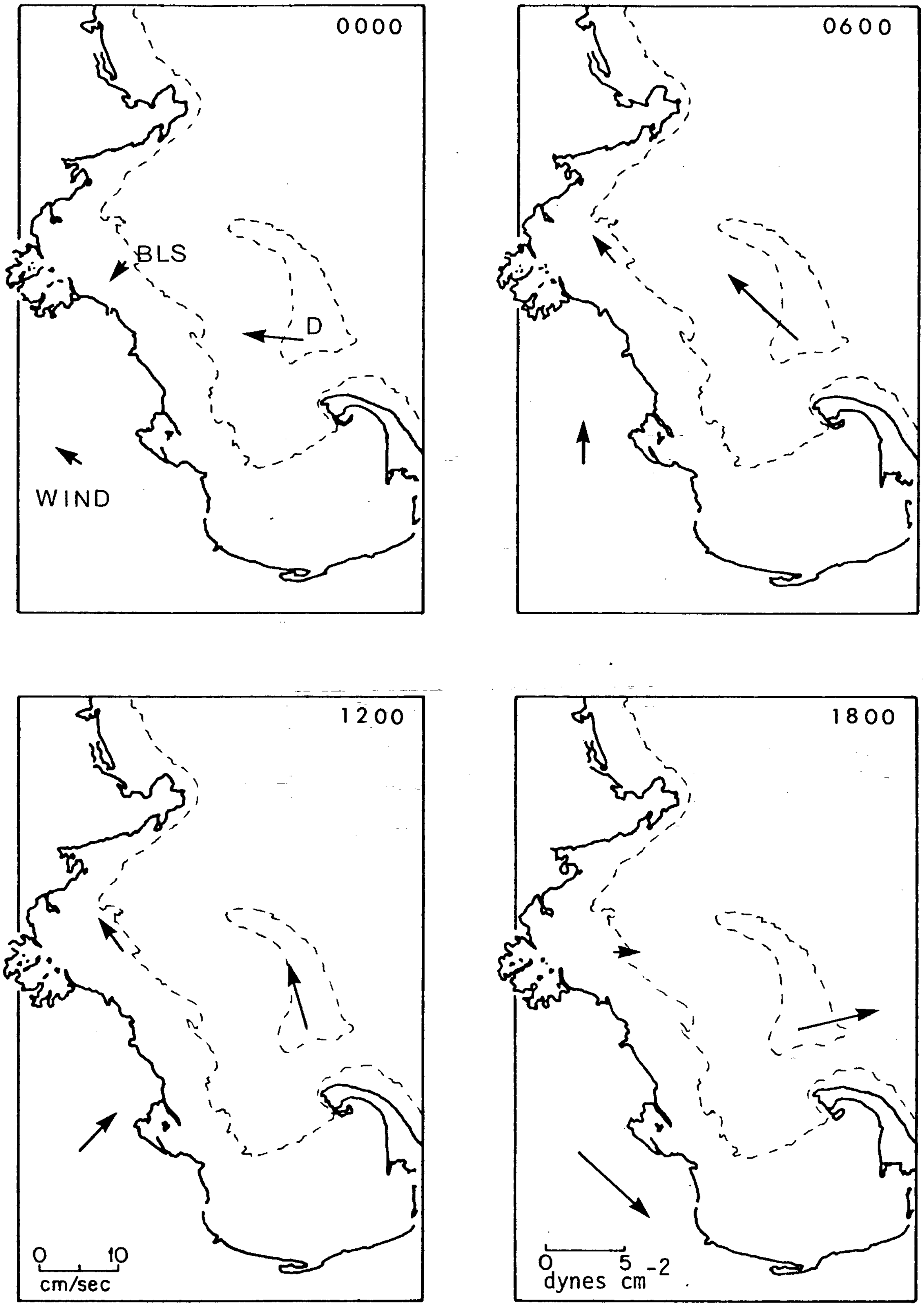


Figure 1.11

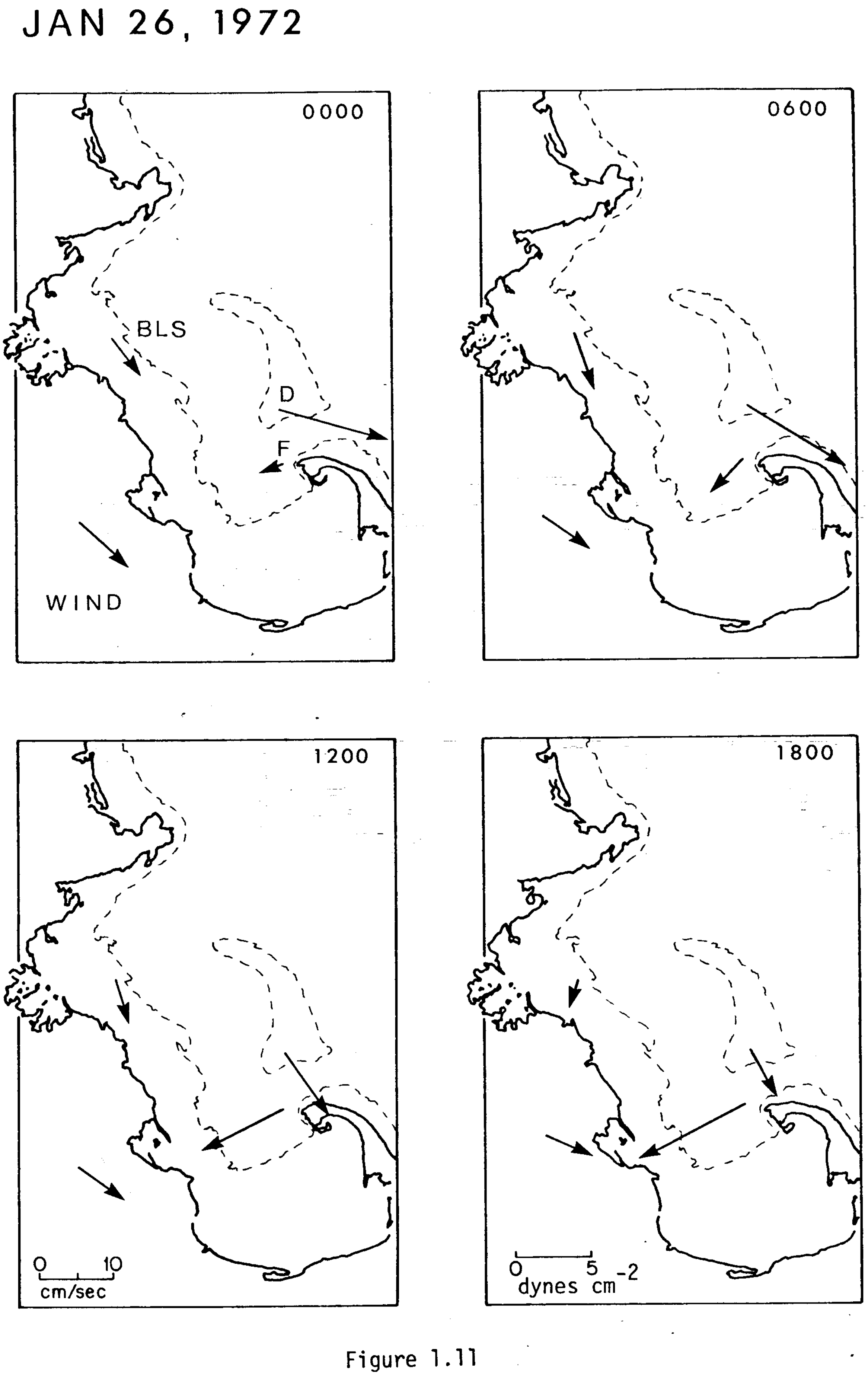

JAN 26, 1972
0000
BLS
D
F
WIND
0600
1200
0 10
cm/sec
1800
0 5
dynes cm-2

Figure 1.11

JAN 27, 1972

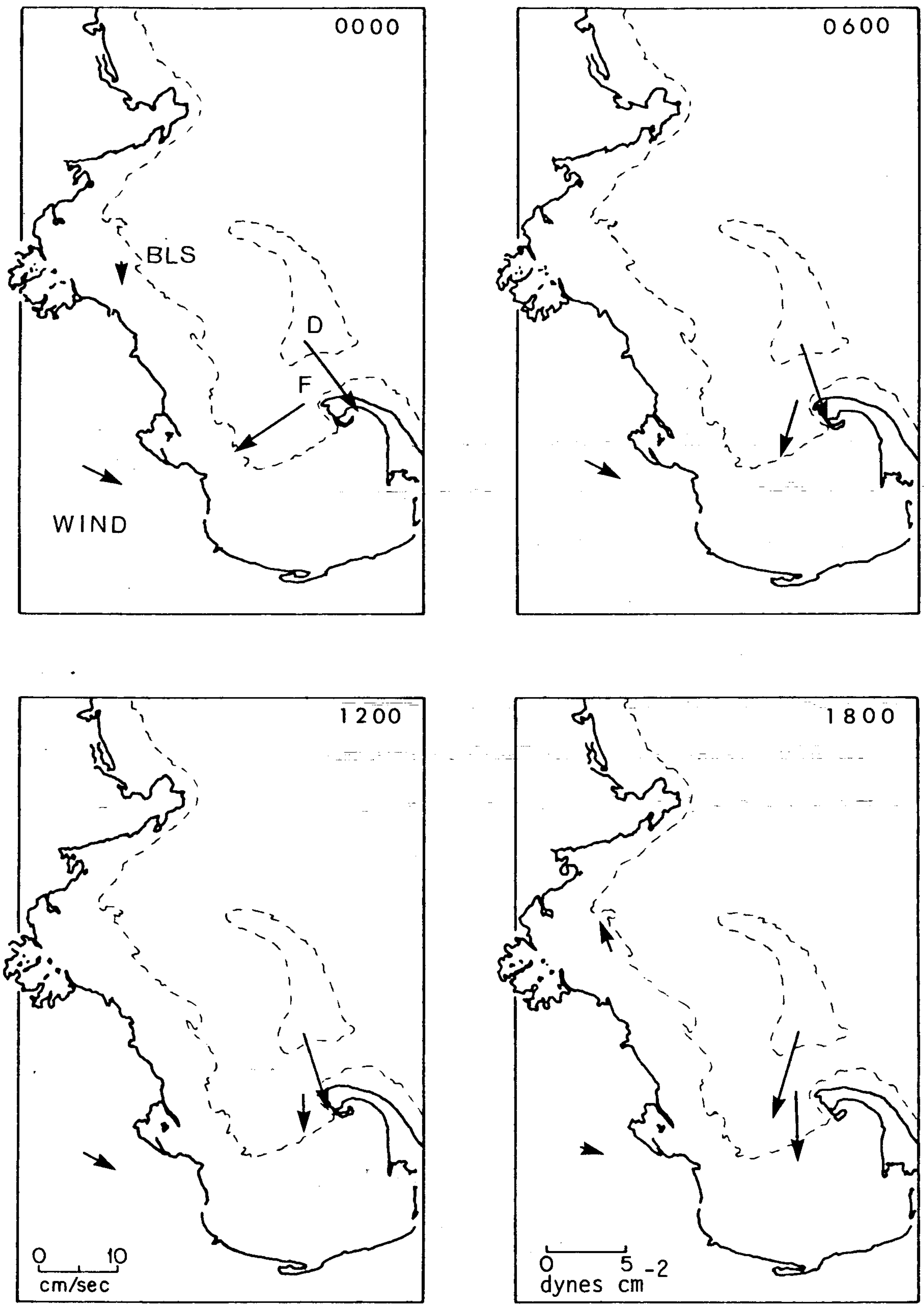


Figure 1.11

The sea level difference between Sandwich and Boston (Figure 1.10a) shows a slight setup on the 24th and early on the 25th in response to the southerly wind. The strong northwest wind on January 26-27 produced a larger setup, with the sea level at Sandwich higher than at Boston by approximately 10 cm. As the wind changed from blowing to the north to blowing to the south, the absolute level at Boston dropped 65 cm; the outflow is clearly seen at Station D at 1800 hr on January 25. The inflow on January 27 is somewhat more gradual and is not obvious from the current record at Station D.

b. February 2 - 5, 1972 (Figure 1.10, 1.12)

Winds over Massachusetts Bay were light on the morning of February 2, gradually became easterly in the afternoon and continued from the east on February 3, then changed to westerly on February 4. On February 5, the winds were from the northwest throughout the day. The bottom current at Station D on February 2 was to the west (into the Bay) as sea level at both Boston and Sandwich rose. The flow, at least early on February 2, did not appear to be driven by local winds. We suggest that the flow at Stations D and F was driven by a rise in sea level at the western end of the Gulf of Maine; wind over most of the Gulf on the morning of February 2 was to the southwest but was only to the southwest at Boston in the afternoon. The flow at Station D became parallel to the western coast of the Gulf on February 3 as the rise in sea level at Boston diminished. The flow at Station F late on February 3 and early on February 4 was in the direction of the pressure gradient caused by the slight setup of the bay to the north. On February 4 the wind changed from southeast to south to southwest to northwest. The bottom flow at Station D closely followed the rotating wind; sea level in the Bay fell below mean level when the bottom flow at Station D was to the east. The current at Station F rotated from south to north as the wind shifted. The strong northwest wind

Figure 1.12 Windstress (shown in lower left hand corner of each figure) at Boston Lightship (drag coefficient = 1.1×10^{-3}) and near-bottom currents at two stations in Massachusetts Bay February 2-5, 1972. Current records filtered with a Gaussian filter (1/2 power 33 hours, see Appendix B) and plotted every six hours. Current meters located 1 m from the bottom. Measure length of current and windstress vector to center of arrowhead.

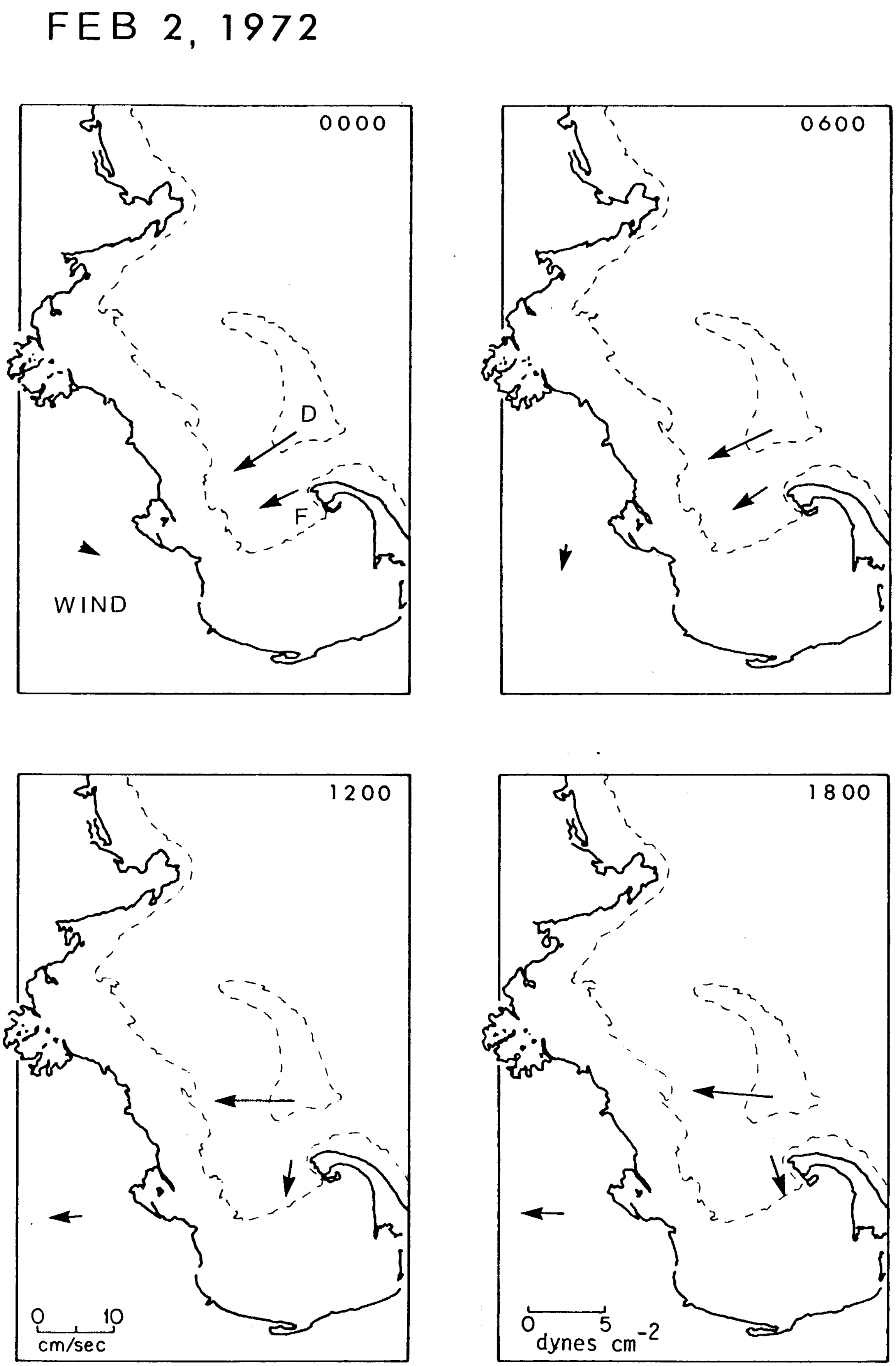


Figure 1.12

FEB 3, 1972

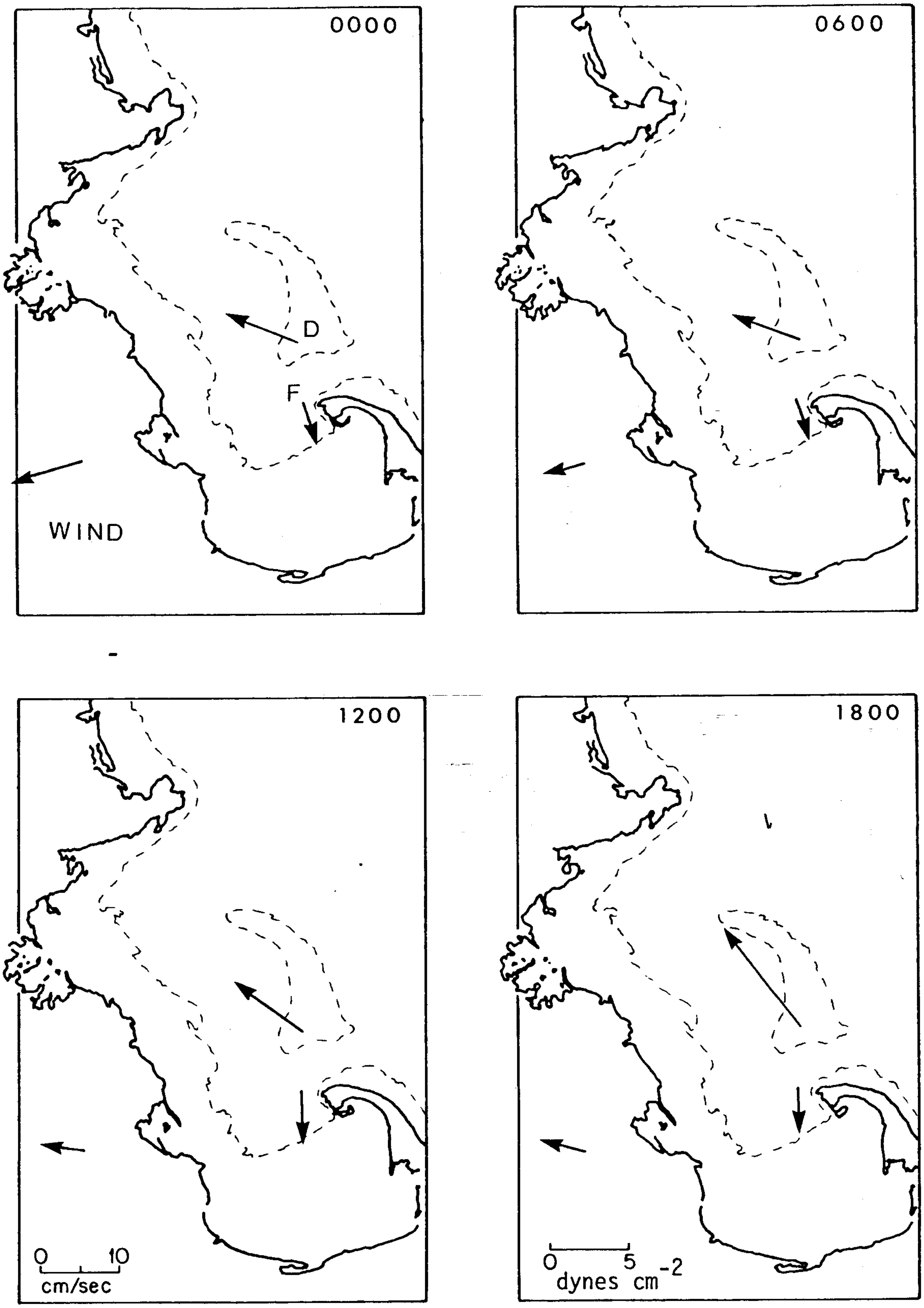


Figure 1.12

FEB 4, 1972

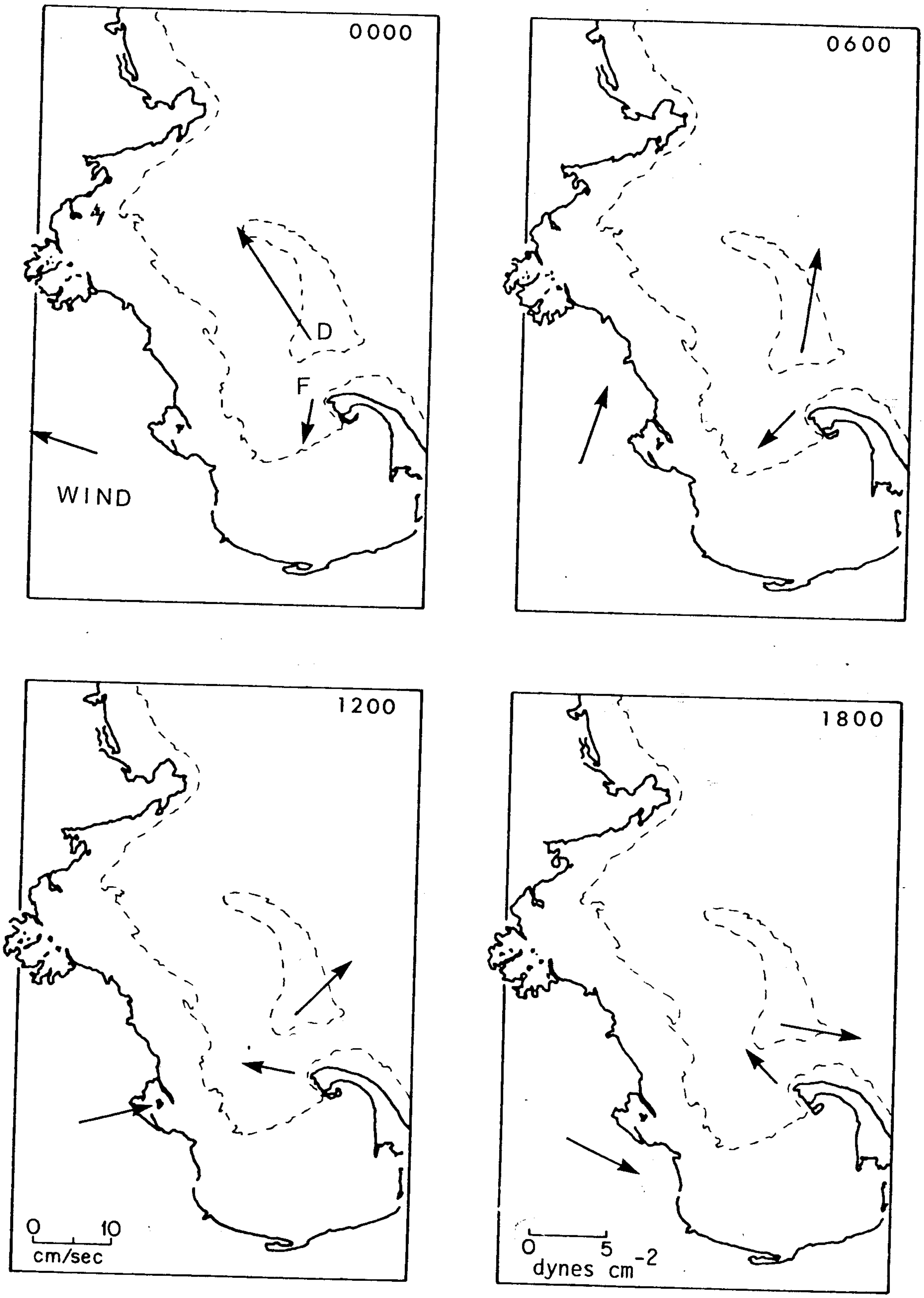


Figure 1.12

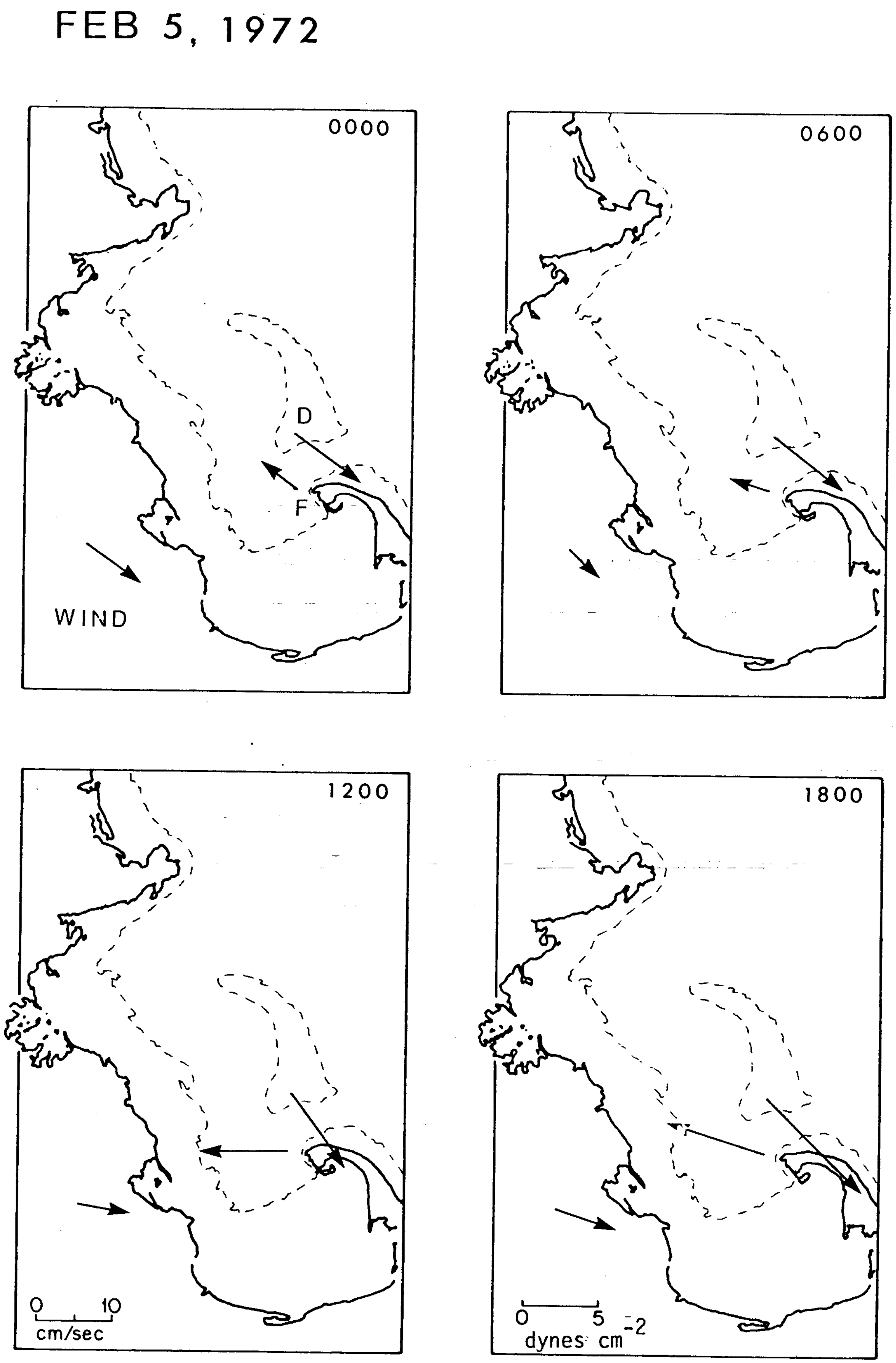


Figure 1.12

continued on February 5 with little change in the bottom flow pattern.

c. February 18 - 21, 1972 (Figure 1.10, 1.13)

On February 18, winds over Massachusetts Bay and the Gulf of Maine were from the east and southeast. Flow at Station B and at the Boston Lightship was southerly parallel to shore, while flow at Station C in the deep central basin was to the east and opposite to the direction of the wind. The windstress increased from the southeast during the morning of February 19, and in response the velocities at all stations increased, although the flow pattern basically remained unchanged. Late on February 19 and early on February 20 the wind rotated from southeast to northwest. Flow at Station C remained to the south for the first twelve hours of the northwest wind, but it then gradually rotated to the northwest after sea level at Boston reached equilibruim. Flow at Station B was to the northwest at midday on February 20 and became northeasterly on February 21. The flow pattern at 0600 on February 21 strongly suggests a double-gyre flow pattern, with the northwest flow at Station C feeding both shore parallel flows at Station B and at the Boston Lightship.

3. Bottom Wind Driven Circulation Pattern

Although the spatial coverage of the currents during any one storm was sparse, a qualitative composite picture of the bottom flow pattern can be developed from measurements made at different times but under similar wind conditions (Figure 1.14). Nearshore, flow is parallel to the coast. Bottom flow on Stellwagen Basin for a northwest or southeast wind is nearly opposite to the wind direction. The observed northwesterly flow at the Boston Lightship with a northwest wind suggests that it may be a continuation of flow from Stellwagen Basin, and that it feeds the northeast flow at Station B, or the southerly flow at Station E. Similarly, the southerly flow at Boston Lightship associated with a southeast wind may feed the easterly flow in the central portion of the basin and

Figure 1.13 Wind (shown in lower left hand corner of each figure) and near-bottom current at three locations in Massachusetts Bay February 18-21, 1972. Current records filtered with a Gaussian filter (1/2 power at 33 hours, Appendix B) and plotted every six hours. Flow at Station B is shown only occasionally because of a failure in the timing circuitry of the current meter. Measurements at Stations B and C, 1 m from the bottom; measurements at Boston Lightship, 10 m from the bottom. Windstress at both Boston Lightship (solid line) and Logan Airport (dashed line) is shown for Feb. 19, when direction of the two observations differed significantly. Scale for Logan stress is 0-2.5 dynes cm^{-2}. Measure length of current and windstress vector to center of arrowhead.

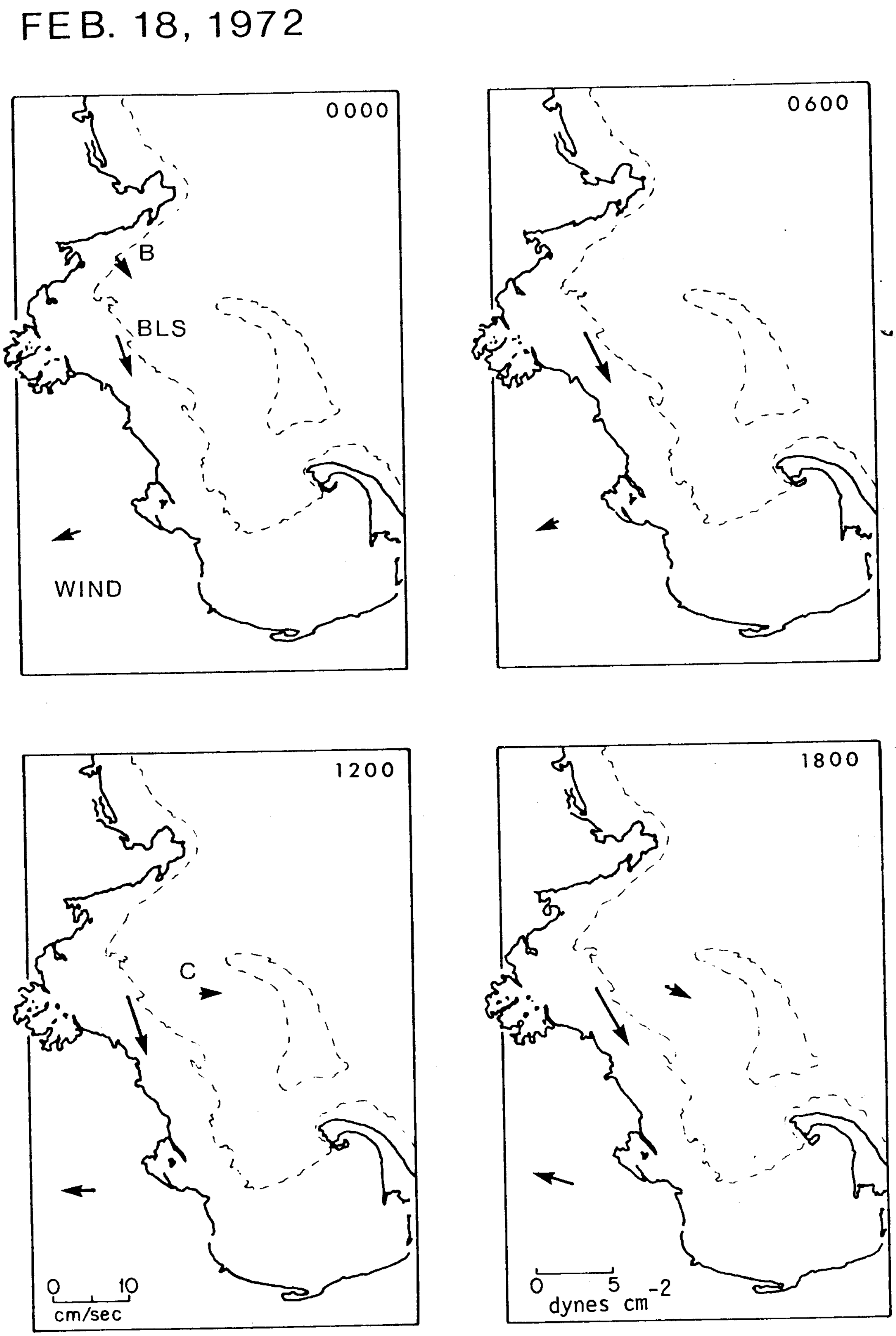

FEB. 18, 1972
0000
B
BLS
WIND
0600
1200
C
0 10
cm/sec
1800
0 5
dynes cm^-2

Figure 1.13

FEB. 19, 1972

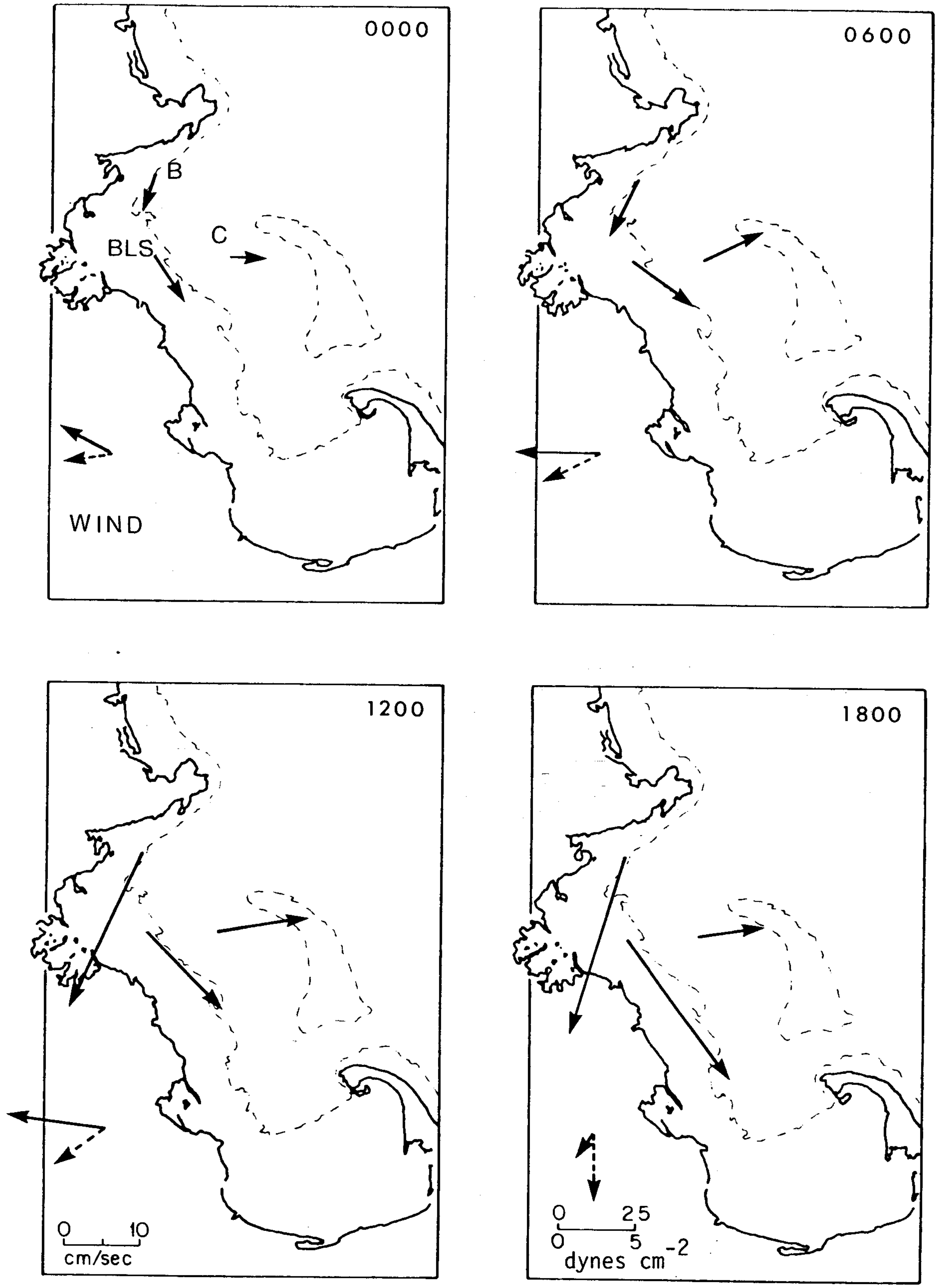


Figure 1.13

FEB. 20, 1972

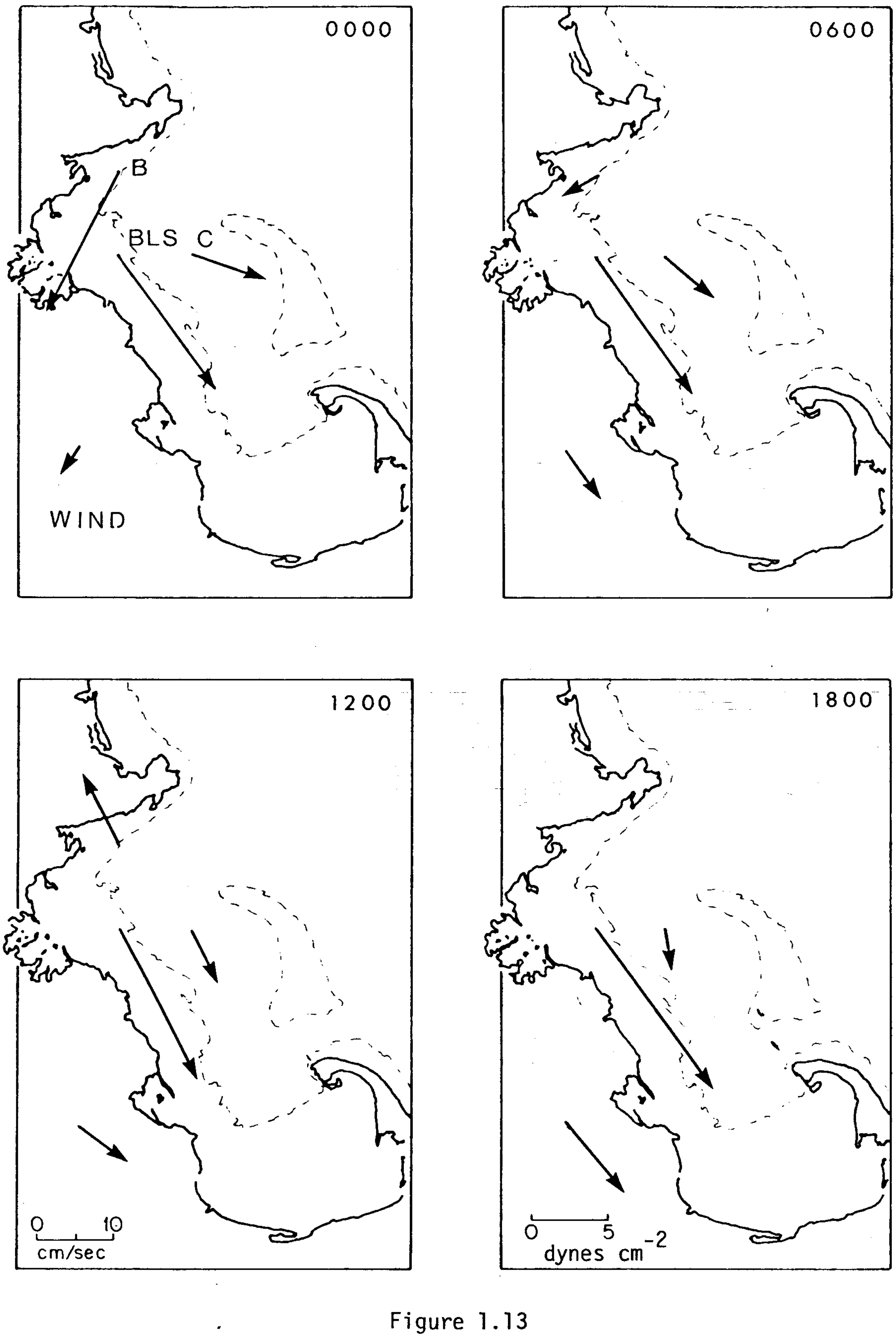


Figure 1.13

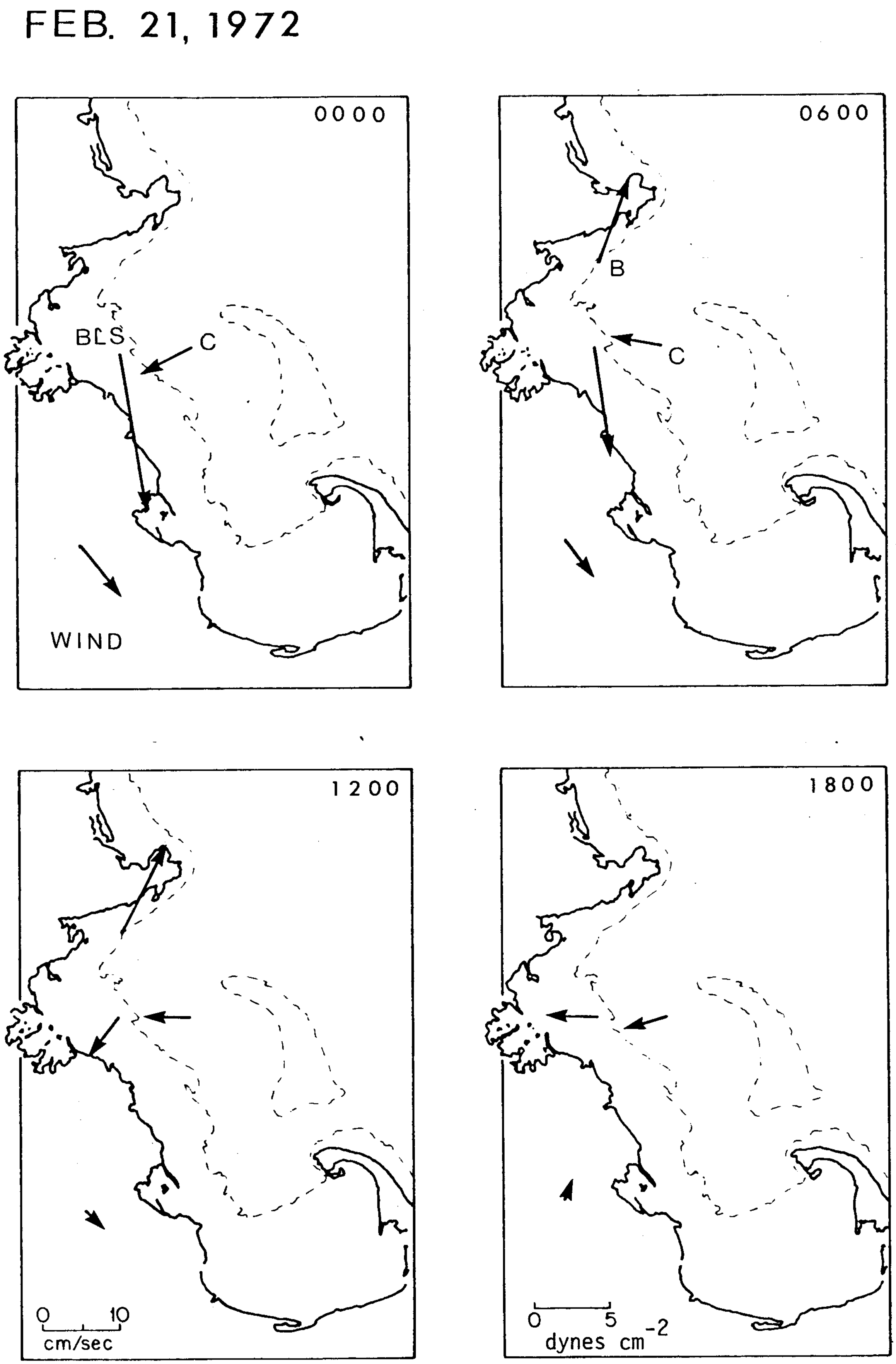

FEB. 21, 1972
0000
BLS
C
WIND
0600
B
C
1200
0
10
cm/sec
1800
0
5
dynes cm-2

Figure 1.13

Figure 1.14 Generalized response of bottom currents to wind constructed from measurements made at different times but under similar wind conditions. Magnitude of the current is not indicated, although some relative magnitudes are suggested for wind-stress on the order of 1 - 3 dynes $\cdot$ cm^{-2}. If no flow is indicated at a station, no measurement was made for that wind direction.

BASIN RESPONSE (BOTTOM)

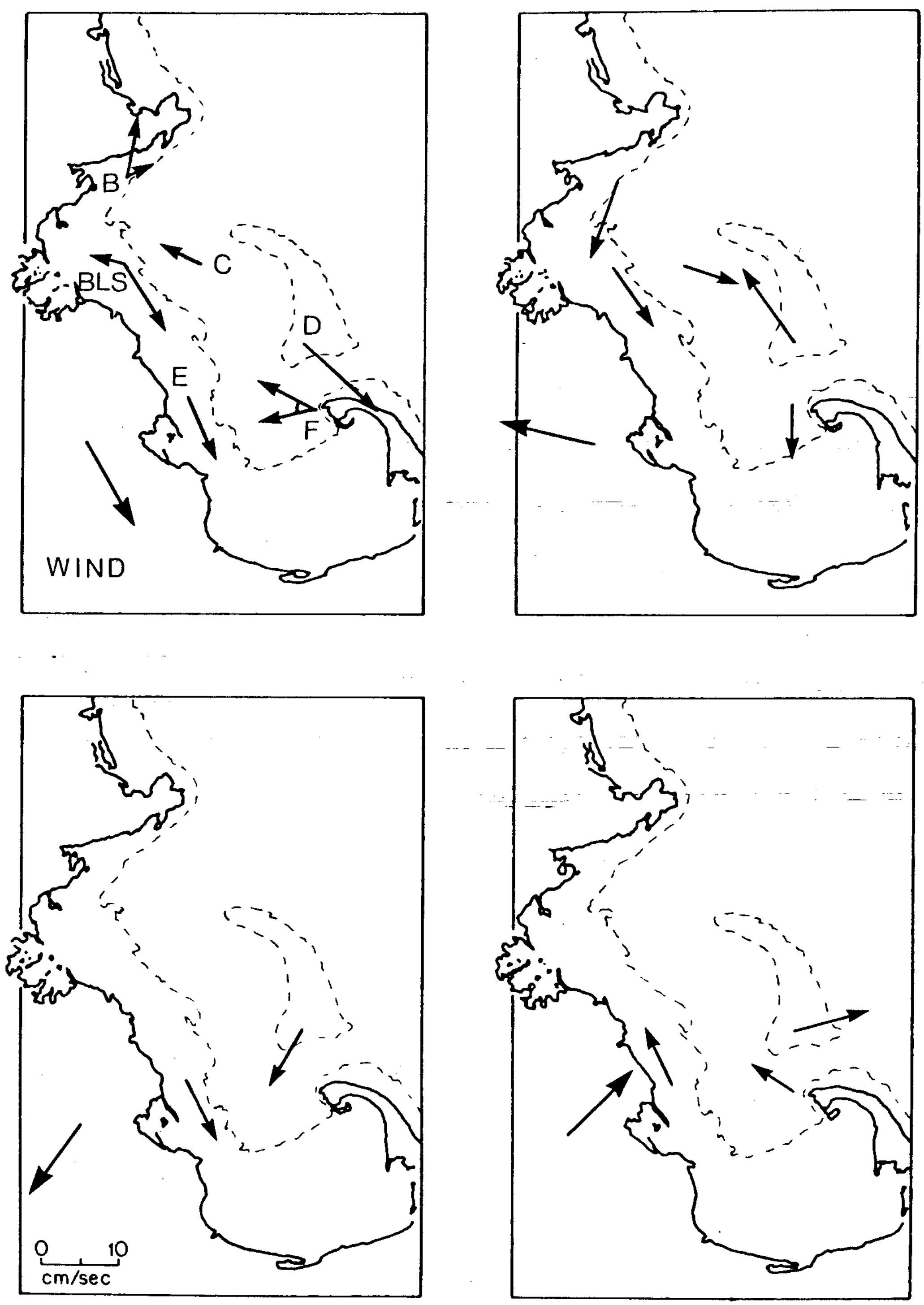


Figure 1.14

not continue down the coast.

In summary, the response of sea level and of the bottom currents in Massachusetts Bay in winter to strong windstress was as follows:

(1) A sea-surface setup in the direction of the wind. Superimposed on this setup were changes in the absolute level of the Bay controlled primarily by sea level in the Gulf of Maine. Local setup was established in less than one hour; absolute changes required 6-12 hours.

(2) The bottom current was coherent over basin scales during strong wind events. Flow was in the direction of the wind in the shallow parts of the basin and opposite to the wind in the deep basin. Flow was more complicated near the ends and corners of the Bay where the current adjusted to the coast. On Stellwagen Bank, flow was either in or out of the basin as sea level adjusted to the level of the Gulf of Maine.

(3) Locally, bottom currents were established approximately 12 hours after the wind stress was applied; they remained basically unchanged even if the wind-stress lasted as long as 24 hr. In some cases, however, the time to establish the flow pattern was as long as 18 - 24 hours, particularly in the corners of the basin; further the flow varied slightly with time.

F. Summary and Conclusions

The bottom currents in Massachusetts Bay have been monitored over a one year period in areas of different sediment types, bottom roughness and water depth. With the reservations about stress estimates, (neglect of surface waves) critical erosion stress, and the effects of bioturbation, the data suggests that the bottom sediments are in equilibrium with the bottom currents; the observed currents were not sufficient to move existing material regularly, except possibly on Stellwagen Bank and in the shallow nearshore regions. The bottom speeds were primarily determined by the strong tidal currents.

In the winter, the net near-bottom current was dominated by strong wind events. Although the data are limited, a two-gyre flow pattern was indicated for the Bay, with flow in the direction of the wind in the shallow areas and opposite to the wind in the central basin. Sea level was determined both by the local winds over the Bay, and by sea level in the Gulf of Maine. Inflow and outflow over the shallow bank at the mouth of the Bay was observed as sea level in the Bay adjusted to the Gulf. The net bottom flow pattern observed during winter storms could be important in redistributing fine material from the shallow bank and nearshore areas, where occasional incipient sediment motion is expected.

PART II

Suspended Matter in Massachusetts Bay September-October 1970

by

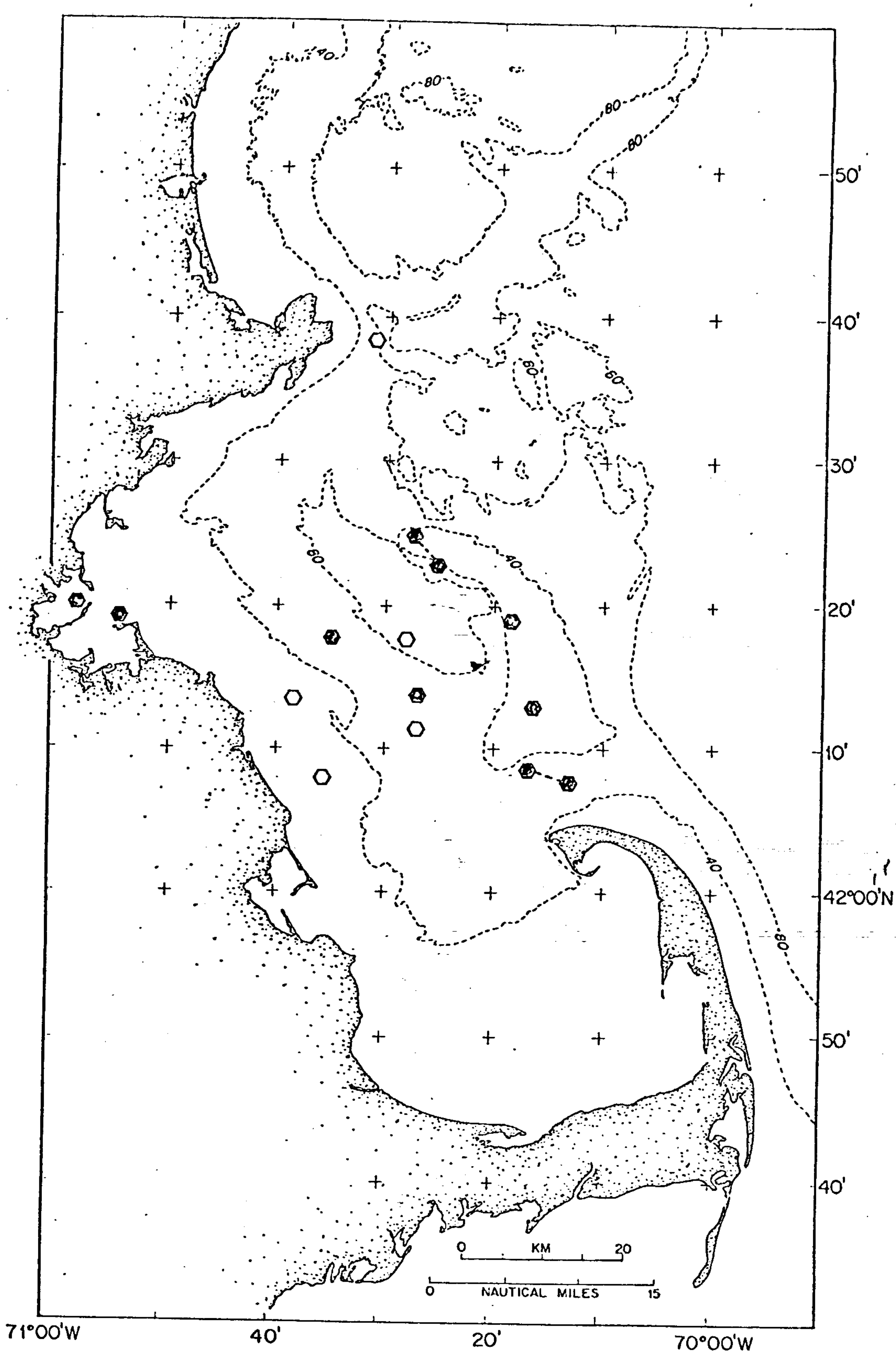
Charles J. O'Hara and Robert H. Meade

On two cruises, one each in September and October 1970, we sampled the suspended matter in the waters of Massachusetts Bay. At 8 stations where the vessel was anchored overnight, we sampled the waters at 2 or 3 depths several times (usually 4 times) over a period of 8 to 10 hours during different parts of the tidal cycle. At 5 other stations we took samples a single time from 2 or 3 depths. In all, we collected and analyzed 96 samples (Figure 2.1 and Table 2.1).

Procedures

We collected samples by lowering an open polyvinyl chloride bottle (modified Niskin-type, capacity about 5 liters) to a preselected depth and then closing the bottle by dropping a weighted messenger down the wire. In most cases we usually took one sample within 1 or 2 meters of the sea bottom, another within 5 meters of the surface, and (where the water depth exceeded 50 meters) one sample from an intermediate depth. After we retrieved each sample, we transferred two aliquots into two bottles. The aliquot in one bottle was stored and eventually taken ashore to be used in measuring salinity. The water in the other bottle was filtered aboard ship within 2 or 3 hours of the time it was collected.

Figure 2.1 Location of suspended sediment samples. Night station indicated with solid marks.



40
80
80
80
60
60
40
60
40
80
50'
40'
30'
20'
10'
42°00'N
50'
40'
0 KM 20
0 NAUTICAL MILES 15
71°00'W
40'
20'
70°00'W

Figure 2.1

Table 2.1. Suspended matter and associated data, Massachusetts Bay, September - October 1970.

(Total suspended matter determined in laboratory by Lois Toner; ash concentrations by C.J. O'Hara.)

	Latitude (minutes north of 42° N)	Longitude (minutes west of 70° W)	Date 1970	Time EDT	Water depth (m)	Sample depth (m)	Suspended matter: Total (mg/l)	Suspended matter: Ash (mg/l)	Suspended matter: Ignition Loss (mg/l)	Ignition Loss (% of total)	Salinity (parts per thousand)	Temperature (°C)	Velocity (cm/sec): At time of Sampling	Velocity (cm/sec): Range during previous hour	Bottom Sediment
Nantasket Roads	19.3	53.5	14 Sep	2230	10	9	1.33	0.67	0.66	50	31.54	12.0	15	15-40	Sandy gravel
				2230	10	0	1.35	.63	.72	53	31.44	13.7	-	-	
			15 Sep	0040	10	9	2.06	.97	1.09	53	31.43	13.2	40	20-50	
				0050	10	0	0.76	.34	0.42	55	31.44	13.8	-	-	
				0220	10	9	1.28	.90	.38	30	31.37	14.0	55	30-55	
				0230	10	0	1.75	1.20	.55	31	31.36	14.0	-	-	
				0415	10	9	1.34	0.70	.64	48	31.34	14.1	-	-	
				0425	10	0	1.53	1.08	.45	29	31.33	14.1	-	-	
				0607	10	9	1.91	1.38	.53	28	31.32	14.3	-	-	
				0611	10	0	1.24	0.85	.39	31	31.32	14.3	-	-	
				0820	9	8	0.85	.38	.47	55	31.44	13.7	60	45-70	
				0820	9	0	.93	.38	.55	59	31.42	13.7	-	-	
President Roads	20.3	57.7	19 Oct	2120	20	19	2.05	1.44	0.61	30	31.61	11.0	-	-	Muddy sand
				2130	20	1	1.63	1.11	.52	32	31.38	11.2	-	-	
				2357	?	11?	2.74	1.92	.82	30	31.46	11.2	-	-	
			20 Oct	0005	?	1	5.89	1.78	4.11	70	31.32	10.8	-	-	
				0300	20	1	2.58	1.59	0.99	38	31.49	10.7	-	-	
				0325	20	18	3.14	1.22	1.92	61	31.82	10.6	35	35-105	
				0545	20	1	1.99	1.16	0.83	42	31.55	10.7	-	-	
				0555	20	19	3.52	1.84	1.68	48	31.77	10.6	20	5-45	
Stellwagen Bank	24.7	27.4	16 Sep	1900	31	28	0.21	0.10	0.11	52	32.17	8.0	5	5-15	Medium-coarse sand
				1900	31	5	.62	.15	.47	76	31.51	14.9	-	-	
				2051	31	28	.22	.10	.12	55	32.20	7.9	30	10-30	
				2056	31	5	.59	.13	.46	78	31.50	14.9	-	-	
				2240	31	28	.28	.10	.18	64	32.07	8.2	35	10-50	
				2259	31	29	.26	.09	.17	64	32.09	8.1	35	10-40	
	24.7	27.4	17 Sep	0105	31	5	.54	.10	.44	82	31.51	14.8	-	-	
				0112	31	28	.17	.07	.10	58	31.84	8.8	20	10-35	
	location uncertain-- dragging anchor			0305	55	5	.40	.06	.34	85	31.51	14.7	-	-	
				0315	55	50	.85	.71	.14	16	32.15	5.5	-	-	

Location	Latitude (minutes north of 42° N)	Longitude (minutes west of 70° W)	Date 1970	Time EDT	Water depth (m)	Sample depth (m)	Suspended matter: Total (mg/l)	Ash (mg/l)	Ignition Loss (mg/l)	Ignition Loss (% of total)	Salinity (parts per thousand)	Temperature (°C)	Velocity (cm/sec): At time of Sampling	Range during previous hour	Bottom Sediment
	22.8	25.1	17 Sep	0505	50	5	.58	.13	.45	78	31.51	14.8	-	-	
				0520	50	40	.53	.21	.32	60	32.18	5.8	10	5-15	
Stellwagen Bank	19.0	18.5	21 Oct	2157	29	27	0.86	0.65	0.21	24	32.12	9.8	-	-	Gravelly sand
				2206	29	1	.51	.13	.38	75	31.96	11.8	-	-	
			22 Oct	0040	29	26	.72	.62	.10	14	32.17	8.4	-	-	
				0045	29	1	.37	.10	.27	73	31.97	10.9	-	-	
				0350	29	27	.54	.35	.19	35	32.04	8.5	20	20-25	
				0355	29	1	.40	.13	.27	67	31.99	10.9	-	-	
				0725	29	27	1.94	1.60	.34	18	-	9.3	25	20-30(?)	
				0730	29	1	0.39	0.13	.26	67	31.92	10.8	-	-	
Stellwagen Bank	12.8	16.5	22 Oct	1005	24	23	0.43	0.24	0.19	44	31.93	11.1	-	-	Coarse sand
				1110	24	1	.48	.20	.28	58	31.93	12.0	-	-	
Stellwagen Basin	11.3	27.2	17 Sep	2345	63	61	1.42	0.04?	?	?	32.13	6.6	15	10-20	Sandy silt
				2350	63	40	0.63	.42	0.21	33	32.11	6.9	-	-	
				2355	63	5	.48	.13	.35	73	31.55	15.5	-	-	
			18 Sep	0235	63	5	.38	.15	.23	61	31.55	15.6	-	-	
				0245	63	40	.15	.04	.11	73	32.08	7.0	-	-	
				0255	63	61	.26	.21	.05	19	32.14	6.3	10	5-15	
				0503	63	5	.34	.10	.24	71	31.53	15.6	-	-	
				0512	63	40	.10	.05	.05	50	31.99	7.2	-	-	
				0514	63	61	.90	.70	.20	22	32.13	6.4	15	10-20	
				0750	62	50	.80	.60	.20	25	32.13	-	-	-	
				0750	62	60	1.16	.91	.25	22	32.13	-	10	5-15	
Stellwagen Basin	17.9	35.0	20 Oct	2145	65	1	0.55	0.14	0.41	75	31.94	11.0	-	-	Silty sand
				2155	65	64	2.81	2.13	.68	24	32.39	-	<5	<5(?)	
			21 Oct	0020	65	65	0.76	0.52	.24	32	32.36	8.2	-	-	
				0027	65	31	.34	.14	.20	59	32.06	10.7	<5	<5	
				0030	65	1	.42	.16	.26	62	31.94	12.0	-	-	
				0310	65	64	1.82	.48	1.34	74	32.38	8.0	-	-	
				0318	65	30	0.29	.18	0.11	38	32.01	11.1	<5	<5	
				0325	65	1	.78	.15	.63	81	31.94	11.9	-	-	
				0605	65	64	1.29	.94	.35	27	32.38	8.2	-	<5	
				0610	65	32	0.36	.23	.13	36	32.10	9.5	<5	<5(?)	
				0611	65	1	.36	.14	.22	61	31.94	11.8	-	-	

	Latitude (minutes north of 42° N)	Longitude (minutes west of 70° W)	Date 1970	Time EDT	Water depth (m)	Sample depth (m)	Suspended matter: Total (mg/l)	Suspended matter: Ash (mg/l)	Suspended matter: Ignition Loss (mg/l)	Suspended matter: Ignition Loss (% of total)	Salinity (parts per thousand)	Temperature (°C)	Velocity (cm/sec): At time of Sampling	Velocity (cm/sec): Range during previous hour	Bottom Sedimen
Stellwagen Basin	17.6	28.2	21 Oct	1800	86	84	1.63	0.47	1.16	71	32.39	7.8	-	-	Clayey silt
				1808	86	43	0.38	.28	0.10	26	32.36	9.1	-	-	
				1812	86	1	.52	.12	.40	77	31.95	12.2	-	-	
Stellwagen Basin	13.7	27.0	22 Oct	1350	71	68	2.07	1.77	0.30	14	32.36	7.8	10	5-15(?)	Clayey silt
				1355	71	35	0.76	0.52	.24	32	32.08	9.5	-	-	
				1358	71	1	.49	.19	.30	61	31.87	11.7	-	-	
Off Cape Ann	38.5	31.3	15 Sep	2200	78	76	0.09	0.05	0.04	44	32.33	6.5	15	5-20	Silty mud (hard)
				2200	78	40	.07	.02	.05	71	32.28	7.9	-	-	
				2200	78	5	.32	.07	.25	78	31.60	14.9	-	-	
	38.5	31.4	16 Sep	0105	75	5	.29	.07	.22	76	31.61	14.7	-	-	
				0125	75	40	.10	.03	.07	70	32.33	8.0	-	-	
				0135	75	73	.35	.11	.24	69	-	7.2	15	15-25	
	38.5	31.5		0400	73	5	.27	.06	.21	78	31.64	14.3	-	-	
				0407	73	40	.15	.06	.09	60	32.10	7.4	-	-	
				0415	73	71	.13	.05	.08	61	32.28	6.8	5	5-10	
	38.6	31.6		0700	71	69	.14	.06	.08	57	32.30	6.9	10	5-15	
				0707	71	35	.18	.04	.14	78	32.12	7.6	-	-	
				0715	71	5	.42	.15	.27	64	31.63	14.0	-	-	
Off Race Point	07.6	13.1	22 Oct	2300	60	59	0.36	0.21	0.15	42	32.46	9.8	25	15-25(?)	Coarse sand
				2305	60	30	.41	.18	.23	56	32.47	10.4	-	-	
				2310	60	1	.44	.15	.29	66	32.01	11.5	-	-	
	position changed (anchor dragged) sometime between 2300 and 0946		23 Oct	0410	58	57	.56	.41	.15	27	32.37	9.6	-	-	
				0415	58	30	.28	.13	.15	54	32.29	10.9	-	-	
				0417	58	1	.37	.10	.26	70	32.00	11.6	-	-	
				0630	58	57	.36	.25	.11	31	32.46	10.2	-	-	
				0635	58	30	.28	.16	.12	43	32.29	11.0	-	-	
				0638	58	1	.30	.12	.18	60	32.06	11.7	-	-	
	08.6	17.0		0946	-	-	-	-	-	-	-	-	-	-	

	Latitude (minutes north of 42° N)	Longitude (minutes west of 70° W)	Date 1970	Time EDT	Water depth (m)	Sample depth (m)	Suspended matter: Total (mg/l)	Suspended matter: Ash (mg/l)	Suspended matter: Ignition Loss (mg/l)	Suspended matter: Ignition Loss (% of total)	Salinity (parts per thousand)	Temperature (°C)	Velocity (cm/sec): At time of Sampling	Velocity (cm/sec): Range during previous hour	Bottom Sediment
Off Scituate	13.5	38.5	21 Oct	1425	25	24	0.58	0.46	0.12	21	32.06	10.8	-	-	Rocky bottom
				1429	25	10	.49	.24	.25	51	31.88	12.1	-	-	
				1434	25	1	.36	.11	.25	69	31.87	12.5	-	-	
Off Green Harbor	08.0	35.8	22 Oct	1755	26	25	0.71	0.63	0.08	11	32.03	10.4	10	5-15(?)	Gravelly sand
				1800	26	1	.52	.28	.24	46	31.80	11.6	-	-	

We filtered each sample through a pair of preweighed Millipore HA filters (sample and control filters back to back, as recommended by Eaton and others, 1969) having a nominal pore size of 0.45 μm and a diameter of 47 mm. A vacuum pump and a special stainless steel filter holder were used. The vacuum pump provided a pressure differential across the filters of about 1.0 atmosphere. The volume of water filtered for each sample was time dependent and averaged about one liter in the entrances to Boston Harbor (Nantasket and President Roads, where the particulate concentrations were greatest) and about two liters at most of the other stations. After filtering, each pair of filters was washed 6 to 8 times with 5 to 10 ml of distilled water to remove salts. The filters were then stored in small plastic Petri dishes, dried in air, and transferred to the laboratory in which they had been weighed initially. In the laboratory, the filters were allowed to reach equilibrium with the ambient humidity before they were weighed. The change in weight of the lower (control) filter of each pair was used as a blank correction for the weight of the suspended matter trapped on the upper filter. Ignition loss was determined by ashing half of the upper filter in a 2.5-μm platinum-foil crucible and weighing on a microbalance. The procedure is similar to that outlined by Manheim and others (1970). The salinity was measured in the laboratory with an induction salinometer that had been calibrated against Copenhagen standard sea water to within 0.01% or less.

Although we did not look at the ash component of the suspended matter in detail, we are confident from the results of other studies of suspended matter over the continental shelf south of Cape Cod (Manheim and others, 1970; Meade and others, 1975) that it consists of mineral matter from the land, mineral matter resuspended off the bottom, and the skeletons of organisms. We suspect that, in overall abundance, in Massachusetts Bay, the skeletal matter is the most significant noncombustible constituent and the mineral matter washed seaward from rivers or coastal erosion is least significant. Resuspended bottom sediment is a locally significant consitituent in areas like Stellwagen Basin where the bottom is muddy. Spencer and Sachs (1970) present data from other mud-floored basins in the Gulf of Maine where resuspended bottom sediment is the principal constituent in suspension.

Distribution of Suspended Matter

In general, the total concentrations of suspended matter are greater nearshore than offshore, greater near the bottom than near the surface, and greater over muddy bottoms than over sandy ones. At none of the overnight stations did we detect differences in suspended concentration from one part of the tidal cycle to another that could be related to differences in the velocity of the tidal current. However, our samples may not have been taken at short enough time intervals to show such differences.

The temperature and velocity of the water were also recorded at the same stations where suspended matter was collected (Table 2.1). Temperatures at the water surface were measured with a bucket thermometer; those below the surface were measured with a bathythermograph. The horizontal velocity of the water was measured at some of the sampling depths (usually the ones nearest bottom) by a Marine Advisors continuous recording current meter (Model Q-15).

Composition of Suspended Matter

On the average, about half of each sample we collected was organic -- that is, it was lost on ignition at 500°C. Combustible organic matter is usually more concentrated near the sea surface than nearer bottom, because it is produced in the upper parts of the water column where light penetrates. It is also more concentrated near the mouth of Boston Harbor (although it represents a smaller proportion of the total suspended matter there) because of the input of essential plant nutrients from land drainage or sewer outfalls.

In the outlets to Boston Harbor, the concentrations of suspended matter were usually greater than 1-2 mg/l (Nantasket Roads) or greater than 2 mg per liter (President Roads). These high concentrations are due to the nearness of sources of material (land drainage, shore erosion, harbor pollution) and to the strong tidal currents that keep sediments in suspension. Concentrations near the bottom were similar to those at the surface, as were the relative proportions of ash and combustible organic matter.

In the waters over Stellwagen Bank, the total concentrations of suspended matter are generally less than 1 mg/l. Combustible organic matter is the principal component in surface waters where it accounts for two thirds or more of the total weight. In two series of samples taken overnight on Stellwagen Bank, the total concentration was less near bottom than at the surface on one occasion (16-17 September) and greater near the bottom on the other (21-22 October). When the bottom concentration was smaller than the surface concentration, the difference was mainly due to a lesser amount of organic matter near the bottom. When the concentration near bottom was greater than at the surface, the difference was due probably to the resuspension of inorganic sediments.

In samples taken in Stellwagen Basin, the concentrations near bottom are consistently greater than those at the surface or at middepth. These greater concentrations represent mainly inorganic material resuspended off the muddy bottom. The low velocities recorded through the tidal cycle in near-bottom waters in Stellwagen Basin suggest that the current is not a major factor in resuspending material. The resuspension is more likely the work of benthic organisms such as the ones that have been observed reworking the fine-grained bottom areas of Buzzards Bay and Cape Cod Bay (Rhoads and Young, 1970, 1971. Young and Rhoads, 1971). In spite of the greater velocities in the near-bottom waters over Stellwagen Bank, the suspended concentrations near bottom are generally greater in the Basin (where the bottom is silty) than over the Bank (where the bottom is more sandy).

In the other two places where we collected suspended matter at overnight stations--off Cape Ann and Race Point--total concentrations of suspended matter were generally half a milligram per liter or less. Differences between the compositions of material near surface and near bottom were generally in the form of higher proportions of organic matter near surface and (in one instance--off Race Point) greater proportions of noncombustible matter near bottom.

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APPENDIX A

TABLE A.1

TIME, DEPTH, AND LOCATION OF NEAR BOTTOM CURRENT METER RECORDS

Station and Record	Deployment Start	Deployment Stop	Length (Hr)	Inst. Depth	Sta. Depth (m)	Location Lat.	Location Long.	Comments
BLS2	710601 -	710629	672	25	30	42 20.6	70 45.5	
BLS3	710629 -	710727	667	25	"			
BLS4/1	710727 -	710806	236	25	"			
BLS4/2	710811 -	710913	792	19	"			
BLS5	710914 -	711002	428	21	"			Hit bottom
BLS6	711019 -	711204	1107	21	"			Ship relocated
BLS8	720118 -	720201	334	21	"			
BLS9/1	720211 -	720311	694	21	"			Ship relocated
BLS9/2	720316 -	720401	389	21	"			
BLS10	720404 -	720516	1005	21	"			
BLS11	720516 -	720617	1006	21	"			Direction (?)
A2	711109			82	83	42 37.7	70 31.1	Time base
A3	720319 -	720425	873	84	85	"	"	
B1	711005 -			46	47	42 30.3	70 44.75	Time base
B2	720211 -			46	"	"	"	Time base, partially corrected
B3	720617 -	720716	680	46	"	"	"	
C1	710831 -	710908	175	89	90	42 19.8	70 26.1	Fisherman picked up
C2	720211 -	720318	853	71	72	42 20.5	70 33.6	
C3	720425 -	720527	749	65	66	"	"	
D1	710626 -	710728	780	26	27	42 10.4	70 17.5	
D2	720113 -	720211	694	26	"	"	"	
D3	720605 -	720712	886	26	"	"	"	
E1	710501 -	710527	627	24	25	42 05.45	70 35.75	Compass (?)
E3	711214 -					"	"	Time base
E4	720320 -	720405	388	18	19	"	"	Drifted
F1	710528 -	710625	681	64	65	42 04.6	70 16.8	
F2	710830 -	710907	182	"	"	"	"	Short, timer malfuncti
F3/1	720116 -	720122	130	"	"	"	"	Time base, corrected
F3/2	720125 -	720211	408	"	"	"	"	
F4	720425 -	720504	219	"	"	"	"	Short
RP1 (Vertical Array)	720720 -	720727	162	40	60	42 04.6	70 16.8	
RP2	720720 -	720727	162	55	60	"	"	

APPENDIX B

GAUSSIAN FILTER

In this study a Gaussian filter is used to filter time series of currents and sea level. The filter is a standard one employed by the Woods Hole Buoy Group (see write-up of program TAPDIS). For data spaced at uniform intervals, the filter is performed as follows in the time domain:

$$U_1(t_i) = \text{original time series},$$

$$U_2(t_i) = \text{filtered time series},$$

$$U_2(t_j) = A \sum_{k=k_1}^{k=k_2} U_1(t_k) \exp(-\alpha(t_k - t_j)^2),$$

$$A^{-1} = \sum_{k=k_1}^{k=k_2} \exp(-\alpha(t_k - t_j)^2),$$

$$k_1 = j - (N),$$

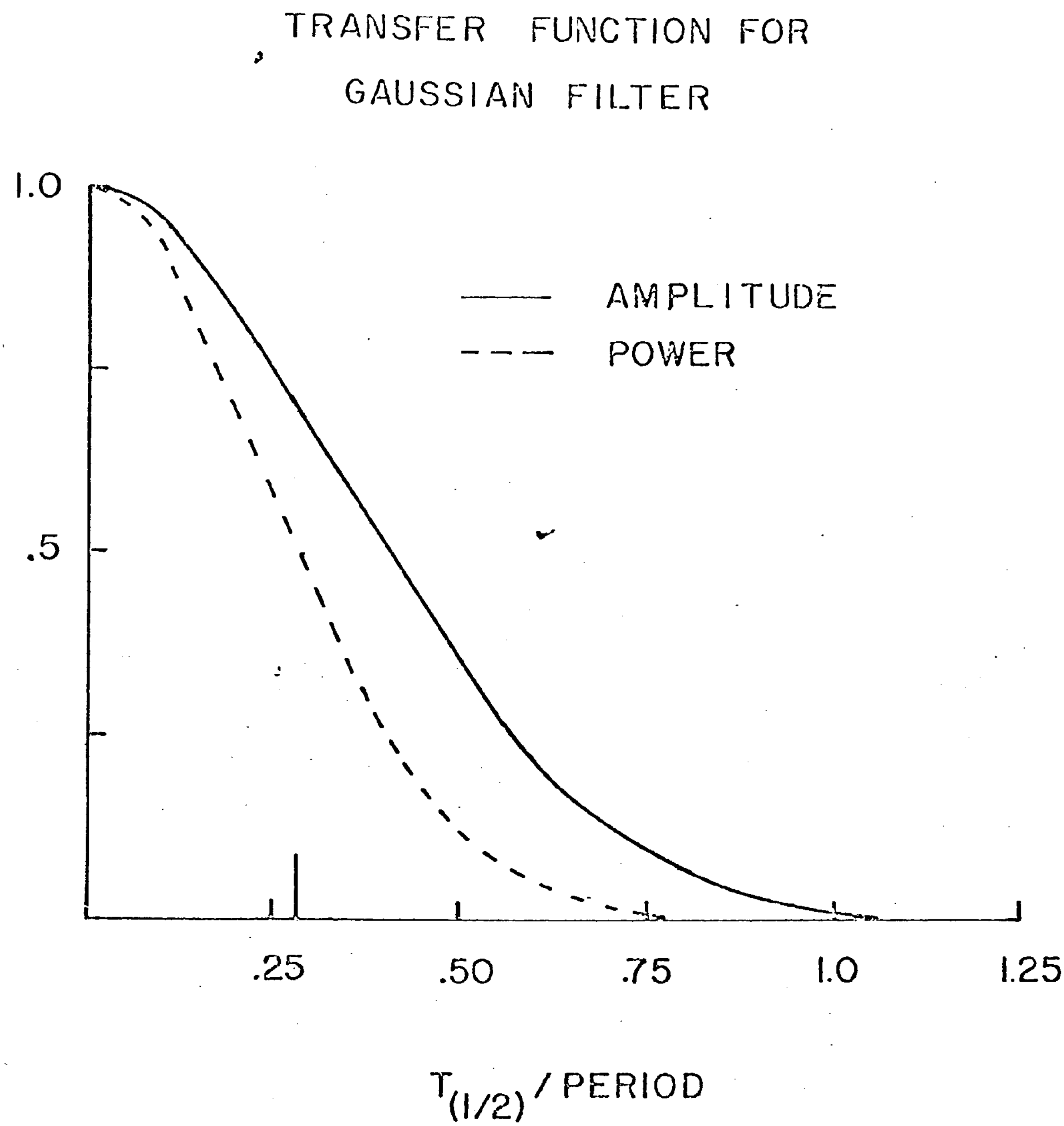
$$k_2 = j + (N),$$

$$N = \text{number of data points in time } T_{\frac{1}{2}},$$

$$\alpha = \pi^2/4.5\, T_{\frac{1}{2}}^2 .$$

In the frequency domain, by the convolution theorem (Bracewell, 1965), the result of the filtering is to multiply the Fourier transform of the original series by the Fourier transform of the filtering function. In this case the transform of the Gaussian filter in time is also Gaussian in frequency. The transfer function for the Gaussian filter as a function of $T_{\frac{1}{2}}$, the parameter which determines the frequency response at the filter is shown in figure B.1. The half-power point of the filter occurs approximately where $T_{\frac{1}{2}}/T = .275$.

Figure B.1 Transfer function for Gaussian filter. Half-power point indicated.



TRANSFER FUNCTION FOR
GAUSSIAN FILTER
1.0
.5
AMPLITUDE
POWER
.25
.50
.75
1.0
1.25
T(1/2) / PERIOD

Figure B.1

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