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REMOTE SENSING OF ESTUARINE FRONTS AND THEIR EFFECTS ON POLLUTANTS

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Abstract

Estuarine fronts represent regions of extremely high gradient or discontinuity in various parameters of physical interest, the most important being the water velocity and density fields. Such fronts strongly influence pollutant dispersion, by capturing oil slicks and other pollutants concentrated in surface films and drawing them down into the water column. Aircraft and boats were combined to study the behavior of different types of fronts in Delaware Bay and their effect on pollutants in order to provide a basis for improving an oil drift and spreading model. Imagery from the LANDSAT satellites provided the most effective means of determining the location and extent of frontal systems over all portions of the tidal cycle. This information is being used to modify the oil drift and spreading model.

Introduction

Estuaries are the zones of transition between rivers and the sea*. As such they are subject to a number of sources of environmental stress: industrial thermal and waste discharges, sewerage inputs from the great and small coastal cities, and spills of oil and other materials associated with the world's maritime transport. At the same time estuaries serve as spawning and nursery grounds for many important species of fish and shellfish, as well as being the conduits through which nutrients pass into productive coastal waters. It is, therefore, important that we understand and be able to model the estuarine processes controlling the dispersal of pollutants floating on the surface as well as those suspended or disolved in the water column.

Current estuarine chemistry and pollution studies are based on classical notions of estuarine circulation. The classical picture of circulation in a partially mixed estuary which has been brought to a state of quantitative understanding by the work of Prichard, Bowden, Hansen, Rattry and others, has recently been reviewed.[1] It is one in which dilute sea water moving up the bottom of the estuary is mixed and advected upward into an upper layer of relatively fresh water moving downstream. It is two-dimensional (axial and vertical) in its essential features, and salinity variations and flows in the transverse direction are viewed as effects of minor significance which can be dealt with as perturbations on the basic two-dimensional scheme. Moreover, the classical picture is one in which the dynamical quantities vary smoothly in the horizontal plane.

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* "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water from land drainage."[2]

Remote sensors mounted on aircraft or satellites are now capable of providing a synoptic view of surface and near-surface water conditions in real time over large coastal areas. Useful results have been obtained in estuarine circulation studies, particularly when aircraft or satellites have been combined with boats gathering water samples and making other measurements as the remote sensors view the scene from above.[3] In some cases remotely tracked dyes and drogues have been used to trace currents. In coastal waters remote sensors benefit significantly from naturally occurring tracers, such as suspended sediment, or color differences between water masses.[4]

In Delaware Bay one can observe a variety of tide lines, color fronts, foam lines, shear boundaries, etc., some of which seem random while others appear repeatedly in the same general location. These observations, together with boat-based field work lead one to severely question the simplicity of the classical view of estuarine circulation discribed above, particularly its assumption of smooth horizontal variations. It is clear from our work that regions with extremely strong transverse gradients of velocity and density exist in estuaries and that these regions play an important role in the dynamical and chemical processes of the system. These regions are called "fronts".

Fronts are a major hydrographic feature in Delaware Bay and other estuaries. Horizontal salinity gradients of 4°/oo in one meter have been observed and convergence velocities of the order of 0.1 m/sec. are typical. Often, fronts extend for tens of miles; generally parallel to the axis of the Bay's channels. They are observed on both sides of the Bay and along every channel where we have looked for them. Fronts have also been observed near the mouth of the Bay where they appear to be associated with the tidal interaction of shelf and estuarine water.

Aquatic fronts are similar to atmospheric fronts in that the denser fluid tends to under-ride the lighter fluid giving rise to an inclined interface. This dynamical behavior produces a marked surface convergence. In our investigations in Delaware Bay, we have observed that these convergences results in the concentration of foam, surface films and oil slicks at fronts.

Surface films and their resulting coalescence as foam lines are a complex mixture of organic and metallic compounds which are orders of magnitude more concentrated in pollutants than their underlying waters. The organic portion of these materials is made up of both natural and anthropogenic compounds, including a host of hydrocarbons, fatty acids, alcohols, and even pthalates[5,6]. Of the nine metals which federal agencies list as toxic to marine and estuarine organisms[7] at least seven are found concentrated in surface films. Barker et al.[8], determined that zinc and copper could concentrate by factors of ten to a hundred in surface microlayers compared to underlying Hawaiian water. Szekielda et al.[6], found that when such microlayers were collapsed into foam lines along estuarine fronts, metal enrichment of thousands could result for chromium, copper, lead, mercury, silver, and zinc. These workers showed that phytoplankton chlorophyll also collects along such boundaries, and is carried down into the water column by the down-welling convergence.

Therefore no serious effort to model the circulation dynamics and pollutant transport in Delaware Bay and similar estuaries can neglect the effect of frontal systems. The purpose of this article is to demonstrate how remote sensing techniques have been used to establish the location, frequency of occurrence, extent, movement, shear and convergence properties of coastal fronts and their effect on certain pollutants, such as oil slicks.

Description of the Delaware Estuarine System

The physical oceanography and morphology of the Delaware Estuary have been reviewed by Polis and Kupferman.[9] There is some terminological confusion about what constitutes the Delaware Estuary with various authors using discordant definitions. Polis and Kupferman established a nomenclature for the Delaware system which should be used by all workers. The following terms provide a fixed geographical basis for discussion:

Delaware Estuary: The entire water area from Capes May and Henlopen to Trenton (the head of tide, see Figure 1).

Delaware Bay: The water area from Capes May and Henlopen to a line between the stone markers at Liston Point, Delaware and Hope Creek, New Jersey.

Tidal River: The portion of the Delaware Estuary above the Delaware Bay.

The following terms are based on dynamical considerations and are more useful for physical oceanographic discussions:

Lower Estuary: That portion of the Delaware Estuary to the furthest upstream influence of oceanic salinity. This upstream limit is defined as the point where the chloride content of the water drops below 250 parts per million. Chloride is the ion found in greatest concentration in seawater. 250 ppm chloride is the commonly accepted maximum for

potable water. The location at which this chloride level is found varies with river flow and tidal stage. It is normally found in the region between Wilmington and Philadelphia.

Upper Estuary: That portion of the Delaware Estuary upstream of the Lower Estuary.

The estuary has an overall length of 213 km. Delaware Bay proper has a length of approximatlely 76 km., a maximum width of 49 km and a maximum depth of 46 m below mean low water. Its mean depth is approximately 10.4 m. The bottom topography is characterized by alternate shoals and fingers of deep water, expecially on the Delaware side of the bay, as can be seen in Figure 2. This topography is intimately related to the generation of fronts[11].

Oceanography of Estuarine Fronts

From the oceanographic point of view, estuarine fronts represent the surface expression of regions of extremely high gradient (verging on discontinuity) in various parameters of physical interest, the most important of these being the velocity and density fields. Indeed, this characterization may well be taken as the oceanographic definition of a front.

In Delaware Bay, surface and water column observations tend to show a pattern in the relationship between the time of occurence in terms of tidal current phase and the geographical location of the front, with flood associated fronts being more prominent on the New Jersey side of the Bay while the fronts in the deeper channels of the Delaware side are most frequent during the ebb portion of the tidal cycle. The occurence of flood associated fronts on the New Jersey side coupled with their absence on the Delaware side may be explained in some measure by the action of Coriolis force. This causes the New Jersey side to have a larger tidal range and its channels to have unusally strong flood currents.

The focus of detailed kinematical and dynamical studies has, however, been on the Delaware side where interest (and funding) has been drawn by extensive oil lightering operations. What follows is based upon the preliminary analysis of a number of experiments conducted by one of the authors (D.F.P) in deep channels of Delaware Bay and to a lesser extent on previous work of both authors with Drs. Szekielda and Kupferman and reported upon by Szekielda et al.[6] and Kupferman et al.[12] A more detailed account of these experiments will be reported elsewhere.

An examination of low altitude aerial photographs reveals that some fronts are associated with a foam line (Figure 3) while others have their visual manifestion in a sharp color boundary unassociated with a foam line (Figure 4).

Often, foam and color boundaries are found parallel to each other, but separated by few meters as shown in Figure 5. The foam found in some fronts is generally associated with lines of detrital material, predominantly marsh grass fragments, but these detrital lines are often displaced from the foam toward the paralleling color boundary. All of this was taken as presumptive evidence of a convergence; however, the displacement of foam (surface) detrital (near surface- upper 2-3 mm.) and color (bulk) boundaries argue for the distortion or stretching of the convergence zone in the surface boundary layer as shown in Figure 6. From our first encounters with fronts, we had known that they were associated with extremely strong salinity, and hence density, differences.[6] Figure 6 therefore shows the convergence being associated with a density interface. For reasons of continuity it is necessary that, except at the exact surface (marked by the foam line), the density interface be below the line of convergence.

Given this picture of the foam marked boundaries, we had assumed that the foamless color boundaries were essentially incipient zones of convergence which had not yet had time to collect noticable foam and detritus. As will be seen below we now have reason to abandon, or at least to severely modify, this interpretation.

Our assumption of convergence associated with the fronts was confirmed by experiments using anchored and drifting dye packets which showed that one front on the Delaware side had a convergence velocity with respect to the frontal interface of 12 cm/sec while the interface moved laterally at the rate of 54 cm/sec so that the lateral current component was 66 cm/sec on the back side of the advancing front.[12] These results were reported by Kupferman et al.

In October 1974, an experiment was undertaken to attempt to understand the intratidal cycle dynamics of the deep channel in Delaware Bay. During the course of that experiment, a front passed a station occupied by one the boats in that experiment (Station S in Figure 7). Figure 8 shows the

isohalines as a function of time and depth. From this it is clear that the frontal structure does not extend to the bottom of the channel in general, but more important, that it is associated with the normal estuarine pycnocline (region of high vertical density gradient) generally ascribed the two-layered estuarine circulation.

In an experiment conducted in January 1975, the three dimensional structure of a complex frontal system in this same region was mapped out. For the purposes of this paper it will suffice to show a pair of cross channel sections of the frontal system as manifested in its lateral velocity structure. The cross-channel velocity component, v_y, is taken as positive toward the Delaware shore Figure 9 and 10 show isotachs of v_y, in a cross-channel section looking up stream through stations Wo-1, Wo-2, and Wo-3 (see Figure 7 for station locations) at 1115 and 1340 hours respectively. As these stations were occupied successively by the R. V. Wolverine, the vertical structure for stations Wo-1, and Wo-2 are based on temporal interpolations of earlier and later observations; however, the sections seem to be consistent with all available data. It will be noticed (1) that there are both zones of convergence and of divergence, and (2) that the entire structure appears to be migrating toward the New Jersey shore. This is borne out by the aerial photographs taken as a part of this experiement. Upon close examination the photographs also show a color boundary associated with the divergence on the right. The divergence on the left apparently had no clear visual manifestation. Thus it now appears that the color boundaries lacking foam may be associated with divergences. The photographs also show another foam line outside (to the left) of station Wo-1. Thus we have in this channel at least two divergences and two convergences. All of these observations were taken on the ebb portion of the tidal cycle.

On the flood portion of the cycle, the fronts on the Delaware side of the Bay break up. Thus while there still exist weak color boundaries on the

scale seen by LANDSAT, surface observations indicate a very patchy and disorganized picture in the upper few meters of the water column. Thus it appears from boat observations that the long, linear frontal structures generated on ebb tide in this region degenerate into meanders, eddies or lenses of lighter water which become largely mixed into a vertically homogeneous water column by the end of flood, as shown in Figure 8.

Effect of Fronts on Oil Slick Movement

Approximately 70 percent of all the oil that is delivered to the east coast of the United States moves by water up the Delaware Bay and River. Much of this oil is transferred from large deep-draft tankers to barges (lighters) or to small tankers to reduce the draft of the large tankers and allow navigation up the Bay and River for unloading at docks. This transfer operation takes place within Delaware Bay in the anchorage area off Big Stone Beach (see Figure 1). In a typical year, more than 50 million short tons of crude petroleum are transported through the Bay using the Big Stone anchorage area within the bay.

Due to the growing demand for imported oil, the oil transport through Delaware Bay and transfer activities in the Bay are expected to increase markedly in the future. National and regional concern over such development focuses in large measure on environmental vulnerability due to oil spills. Central to environmental repercussions, facility development, and clean-up operations, is information regarding the physical movement and distribution of an oil spill.

A computer simulation model has been developed for tracing oil spills in the Delaware Bay.[13] The model takes into account two aspects of transport: drifting and spreading. The modelling of drift is based on the fact that oil on water drifts under the combined influence of water current, wind effects, and the earth's rotation. The physical processes governing the spreading of the slick are divided into three stages. In the initial stage, the spreading is predominantly governed by the balance of the forces of gravity and inertia. In the second stage, the spreading involves the balance of viscous and inertial forces. In the third and final stage of the spreading, a turbulent diffusion model is employed. Based on these processes and the approximation of radial symmetry, the rate of spreading is computed.

The input requirements include the boundary conditions (the geometry and bottom topography), the tidal current, the wind conditions, and the nature of the oil spill - viz., the size of the spill, location of the initial spill and the nature of the oil. Historical tidal current information and present wind conditions in the Delaware Bay region are now being used as input.

The wind conditions can be entered in either of two ways: either deterministically or stochastically to make Monte Carlo calculations based on historical wind data. The first way is used in an oil tracking routine, while the second yields information on the probability of various oil spill distributions.

The interactive nature of the model allows for information transfer between the computer and the users who may or may not be familiar with computer programming. The details of oil spill tracking are displayed on a Tektronix television-type screen. A number of output options are available.

In order to verify and improve the model, aircraft and boats were combined to track actual oil slicks under various conditions of wind, current, waves, etc. During these field verification exercises it became obvious that by capturing and holding oil slicks, frontal systems significantly influence the dynamic behavior of oil slicks in Delaware Bay. The tendency of oil slicks to line up along fronts during certain parts of tidal cycle was illustrated by an oil spill which occurred as a result of a lightering operation in the anchorage area on 10 January 1975, at the same time as the data shown in figure 9 and 10 was obtained. As shown in Figure 11, at 0930 hours the spill consisted of four large slicks and numerous smaller ones almost randomly dispersed throughout the area. The wind was about 10 knots from the east-southeast. The flood tide cycle was coming to an end with a near slack current, as measured with current meters and air-tracked small drogues. At this time no boundaries were observed. As shown in Figure 12 by 1100 hours the current had turned to the ebb direction with a velocity of 0.6 knots. Two convergent boundaries were clearly visible on either side of the oil

slicks and were starting to attract some of the slicks. Results of an oceanographic study of these boundaries were discussed in the previous section and the right boundary corresponds to the convergence BB in figures 9 and 10. Changing to a smaller scale (higher altitude photography), one can see from Figure 13 that by 1500 hours most of the oil was aligned along the boundaries and stretched into two five-mile long slicks.

Mapping Fronts with Satellites

In order to modify the predictive model to include the effect of boundaries on oil slick movement one must determine where in the Bay boundaries form repeatedly and prevail over major portions of the tidal cycle. Aircraft have been most useful in finding fronts, photographing them, and guiding boats to collect data in frontal zones. However, to map the extent and repeatability of fronts over the entire bay under different tidal conditions, satellite imagery is more effective. Imagery and digital tapes from thirty-six passes over Delaware Bay of the LANDSAT-1 and LANDSAT-2 atellites were used in our work. The LANDSAT imagery was produced by the four-channel multispectral scanner (MSS) having the following bands:

Band 4	0.5 - 0.6 Microns
Band 5	0.6 - 0.7 Microns
Band 6	0.7 - 0.8 Microns
Band 7	0.8 - 1.1 Microns

From an altitude of 920 km, each frame covered an area of 185 km by 185 km and had a resolution of about 80 meters. In addition to the 9-track 800 bpi magnetic tapes, reconstructed negative and positive transparencies in 70 millimeter format and prints in nine-inch format were obtained from NASA. Before visual interpretation, some of the imagery was enhanced optically, using density slicing and color additive techniques. Annotated thematic maps were prepared by computer analysis of digital tapes and by direct photointerpretation of the transparencies reconstructed by NASA.[14] LANDSAT image radiance of Band 5 was also correlated with suspended sediment concentration and Secchi depth data obtained from boats and helicopters during the satellite overpasses[3]. A suspended sediment concentration map based on LANDSAT image radiance correlation with water sample analyses is shown in Figure 14.

Figures 15 and 16 contain LANDSAT pictures and NOAA-NOS tidal current charts for Delaware Bay. Only MSS Band 5 images are show, since this "red" band was found to give the best contrast in delineating suspended sediment concentration in the upper one meter of the water column. Each LANDSAT picture is matched to the nearest predicted tidal current chart within ± 30 minutes. The current charts indicate the hourly directions by arrow, and the velocities of the tidal currents in knots. The Coast and Geodetic Survey made observations of the current from the surface to a maximum depth of 20 feet in compiling these charts[15,16]. The current magnitudes shown on the charts are somewhat higher than mean and need to be scaled down as explained in the introduction to the charts.[16]

The satellite picture in Figure 15, was taken on October 10, 1973, two hours after maximum flood at the entrance of Delaware Bay. Masses of highly turbid water are visible around the shoals near the mouth of the bay and in the shallow areas on both sides of the bay. Since at that time strong currents and considerable waves were prevailing in most of the bay, some of the sediment in suspension seems to be locally generated over shoals and shallow areas of the bay resulting in a higher degree of backscatter from shallower waters. During flood tide at the mouth of the bay, considerable correlation was found between the depth profile and image radiance, even though the water depth exceeded the Secchi depth by at least a factor of three in all areas. Maximum velocity of flood currents is occurring in the upper portion of the bay, where sharp boundaries parallel to edges of the deep channel can be seen. The boundaries are visible in the satellite imagery primarily because water masses near the shore appear more turbid than the water in the middle of the river. The distinctness of the boundaries implies a strong gradient in suspended sediment concentration across the boundary. The direction and shape suggest that shear is present. Unfortunately the spatial resolution of LANDSAT cameras is too poor to determine whether these boundaries are capped by foam, which would indicate

lateral convergence. An aireraft photograph of a similar frontal system is shown in Figure 17.

The satellite overpass on February 13, 1973 occurred about one hour after maximum ebb at the mouth of Delaware Bay. The corresponding LANDSAT image and predicted tidal currents are shown in Figure 16. Strong sediment transport out of the bay in the upper portion of the water column is clearly visible, with some of the plumes extending up to 20 miles out of the bay. Small sediment plumes along New Jersey's coast clearly indicate that the direction of the nearshore current at that time was towards the north. The image in Figure 16 contains good examples of tidal fronts and flow-lines In particular, note the sharp demarcation of the tidal plumes at the mouth of Delaware Bay. Strong gradients in suspended sediment concentration can be seen across these fronts with gradients in density, salinity and occasionally temperature likely.

In order to determine where in the bay fronts tend to form during different portions of the tidal cycle, thirty-six LANDSAT images such as the ones shown in figures 15 and 16, were analyzed. The tidal conditions in each satellite image were matched to one of the twelve U.S. Coast and Geodetic Survey tidal current charts, where each chart represents current conditions in Delaware Bay during an one-hour segment of the tidal cycle. Thus an average of three satellite images were associated with each of the twelve current charts. As shown in Figures 18 through 29, the fronts discerned in each image were superimposed on the appropriate tidal current chart.

The identification of fronts was based primarily on strong turbidity gradients or discontinuities. As discussed in a previous section, some of the fronts are likely to have foam lines, temperature gradients and salinity gradients associated with them. Foam lines, which can be mapped from aircraft, are too thin to be resolved by LANDSAT. Temperature and salinity gradient monitoring

would require different sensors that those presently on LANDSAT.

Two types of boundaries were distinguised - "strong" and "weak," depending on the magnitude of the turbidity gradient or discontinuity. The strong boundaries not only contain strong gradients but also are likely to exhibit considerable shear. The "weak" boundaries are either strong boundaries whose contrast has been degraded by atmospheric effects; or convergent boundaries observed during their formative or decaying states; or divergent boundaries and, in a few cases, edges of river plumes.

The twelve charts containing current velocities and boundaries shown in Figures 18 through 29 are presently being used to establish locations where boundaries tend to prevail. A subroutine is being developed for the oil slick movement model to handle oil slicks that enter these front-infested areas. The subroutine will include dynamic effects, such as shear currents, at a finer scale. At the present time LANDSAT appears to offer the most effective means of identifying front-infested areas, i.e. where fronts tend to form, how extensive they are, how long they prevail, how much they move about, and how strong and abrupt their gradients are.

Conclusions

Imagery from LANDSAT-1 and LANDSAT-2 proved valuable in determining the location, type and extent of estuarine fronts under different tidal conditions. Neither ships nor aircraft alone could provide as complete, synoptic and repetitive an overview as did the satellites. Since estuarine fronts influence the movement of oil slicks and dispersion of other pollutants, clean-up operations depending on real-time use of oil slick movement prediction models will benefit not only from aircraft tracking the actual slicks but also from real-time satellite observations of surface currents and the location of frontal systems.

Acknowledgements

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Figures

Figure 1. The Delaware Estuary

Figure 2. Submerged contours of Delaware Bay. Tongues of deeper water radiate from the bay entrance into the bay.[10]

Figure 3. Estuarine front with foam line photographed from an aircraft at a scale of about 1:20,000. This front was observed just north of the lightering area inside Delaware Bay, with the more turbid water, indicated by a lighter shade of gray, being on the Delaware side of the front, as is also the case in figure 4.

Figure 4. Estuarine front without foam line photographed from an aircraft at an approximate scale of 1:10,000 in the middle of the lower portion of the bay. Note the shear displacement of ship wakes as they cross the boundary.

Figure 5. Front with a displaced foam line photographed from an aircraft at a scale of about 1:20,000, eight kilometers outside the mouth of the bay.

Figure 6. Schematic diagram of a vertical section perpendicular to a frontal convergence zone. Note displacement of surface, near surface and main zones of convergence as marked by foam, detritus, and color lines respectively.

Figure 7. Station locations for boat observations of fronts October 1974 and January 1975.

Figure 8. Salinity in parts per thousand versus time and depth for station 5, 1 October 1974. Dots indicate water samples taken, Note change from vertical homogeneity to stratification with frontal passage, also overturning during flood between 0715 and 0930 hours.

Figure 9. Isotachs of cross-channel velocity component, v_y, for a section looking up-bay at 1115 hours, 10 January 1975. Three lines of $v_y = 0$ are labeled AA, BB and CC. Of these, AA and CC represent regions of horizontal divergence while BB is the frontal convergence marked by a foam line.

Figure 10. Isotachs of cross-channel velocity component, v_y, for a section looking up-bay at 1340 hours, 10 January 1975. Lines AA, BB and CC are those similarly labeled in Figure 9; however, they are now deeper and further to the right as a result of the advance of the frontal system.

Figure 11. On 10 January 1975, the shown oil slick pattern was encountered at the oil lightering area in lower Delaware Bay. At 0950 hours flood tide currents were near slack and no boundaries were observed.

Figure 12. By 1100 hours the tidal currents assumed an ebb direction, and the oil slicks were attracted by convergent boundaries which had appeared around 1030 hours. Results of oceanographic investigations of these particular boundaries are shown in Figures 9 and 10.

Figure 13. A higher altitude view of the area shows most of the oil lined up in 5-mile long narrow slicks along the two boundaries.

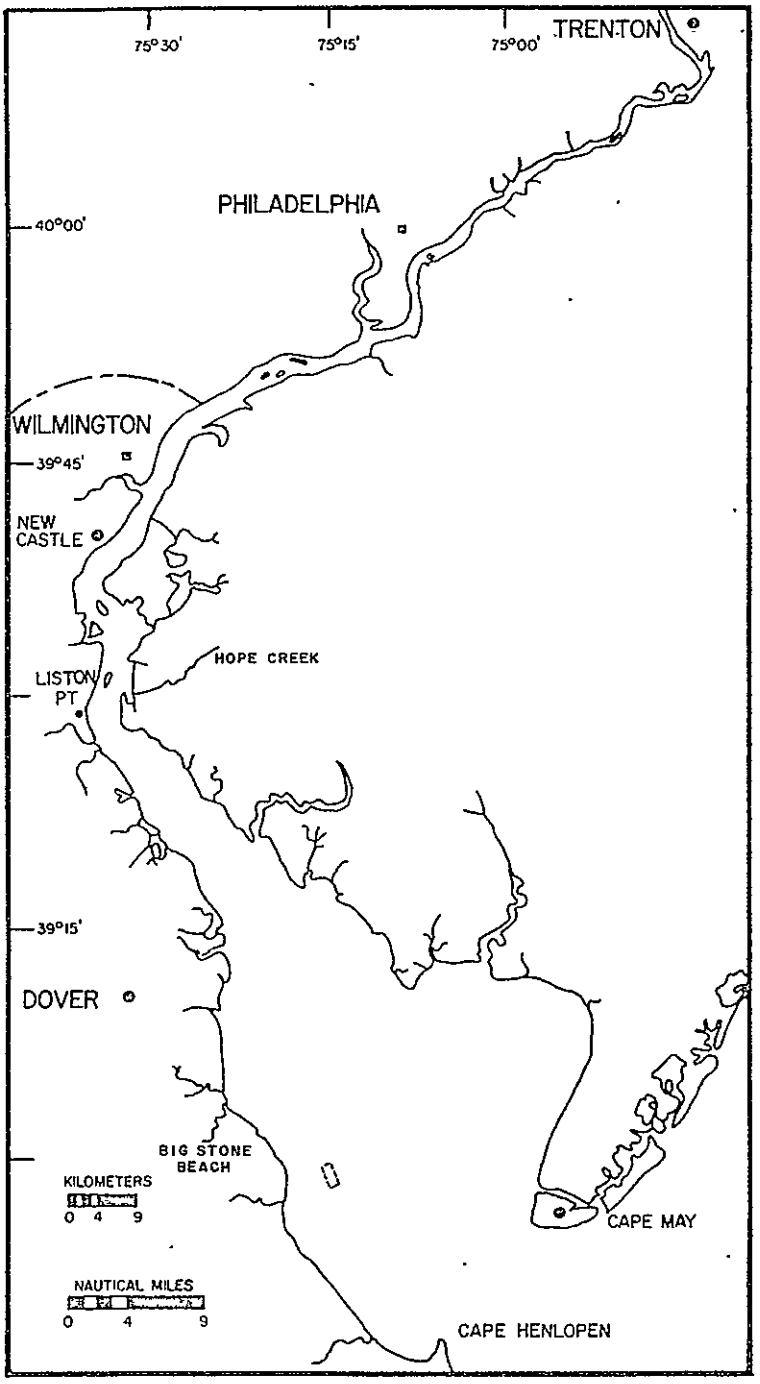
Figure 14. Suspended sediment concentration map for Delaware Bay obtained by correlating LANDSAT imagery radiance values with water samples.

Figure 15. Predicted tidal currents and LANDSAT-1 MSS band 5 image of Delaware Bay obtained on 10 October 72 (I.D. No. 1079-15133).

Figure 16. Predicted tidal currents and LANDSAT-1 MSS band 5 image of Delaware Bay taken on 13 February 1973 (I.D. No. 1205-15141).

Figure 17. Estuarine front similar to that shown in Figure 15, photographed from an aircraft at a scale of 1:80,000 near Woodland Beach, Delaware. This frontal system is at least 6 km long, has an average distance of 2 km from the shoreline, and separates more turbid water near shore from the bay's clearer water.

Figures 18-29. Location and extent of frontal systems in Delaware Bay, derived from LANDSAT images such as figure 15 and mapped on U.S.C. & G.S. tidal current chart.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75°15'
75°00'
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PHILADELPHIA
40°00'
WILMINGTON
39°45'
NEW CASTLE
HOPE CREEK
LISTON PT
39°15'
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NAUTICAL MILES
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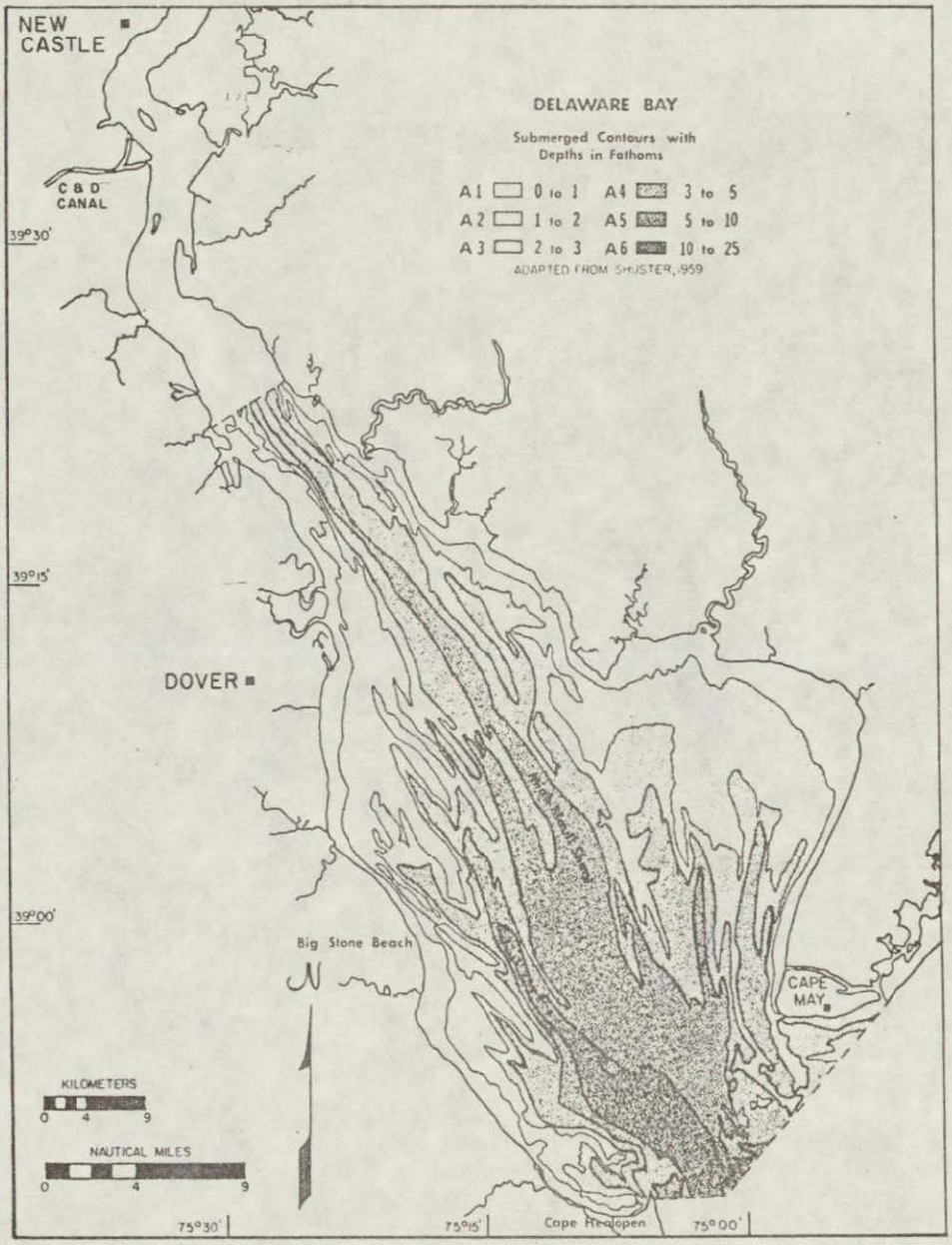
CAPE MAY
CAPE HENLOPEN

Figure 1


NEW CASTLE
DELAWARE BAY
Submerged Contours with Depths in Fathoms
A1 0 to 1
A2 1 to 2
A3 2 to 3
A4 3 to 5
A5 5 to 10
A6 10 to 25
ADAPTED FROM SHUSTER, 1959
C & D CANAL
39°30'
39°15'
DOVER
39°00'
Big Stone Beach
CAPE MAY
KILOMETERS
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NAUTICAL MILES
0 4 9
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75°15'
Cape Henlopen
75°00'

Figure 2

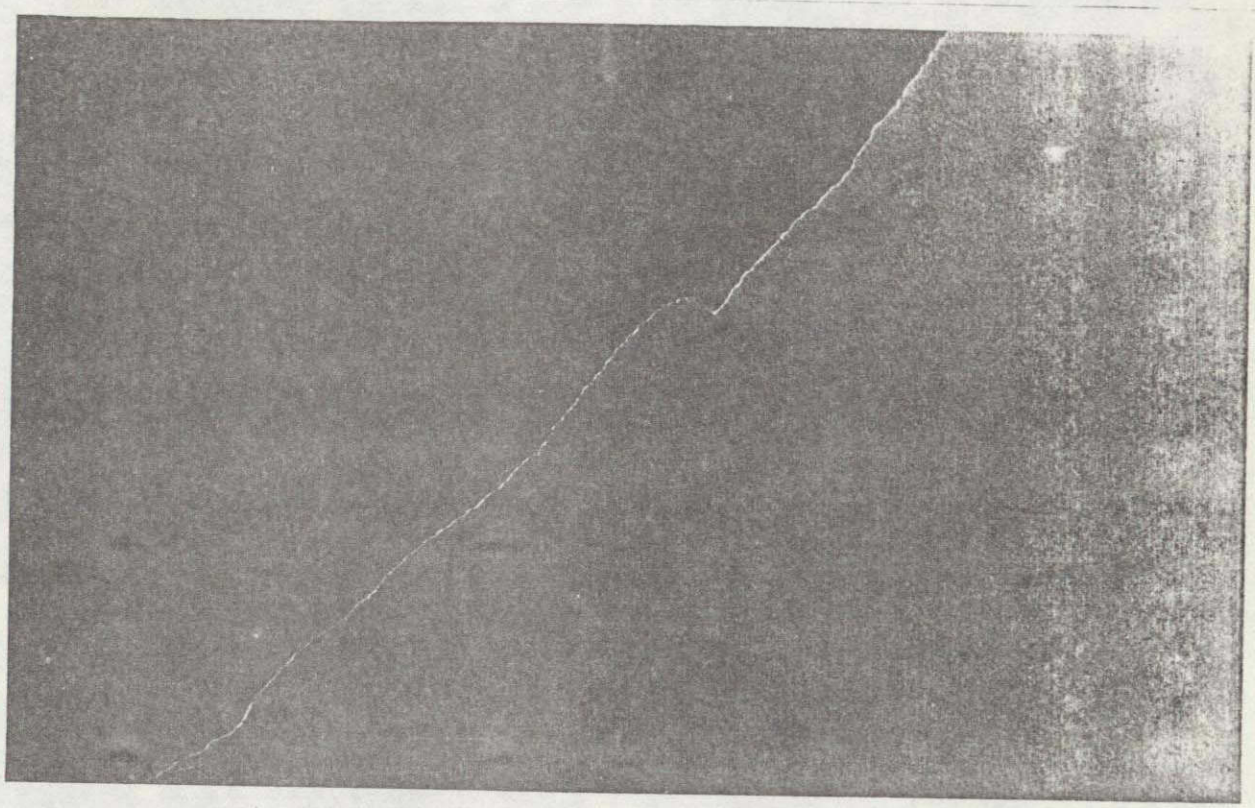


Figure 3

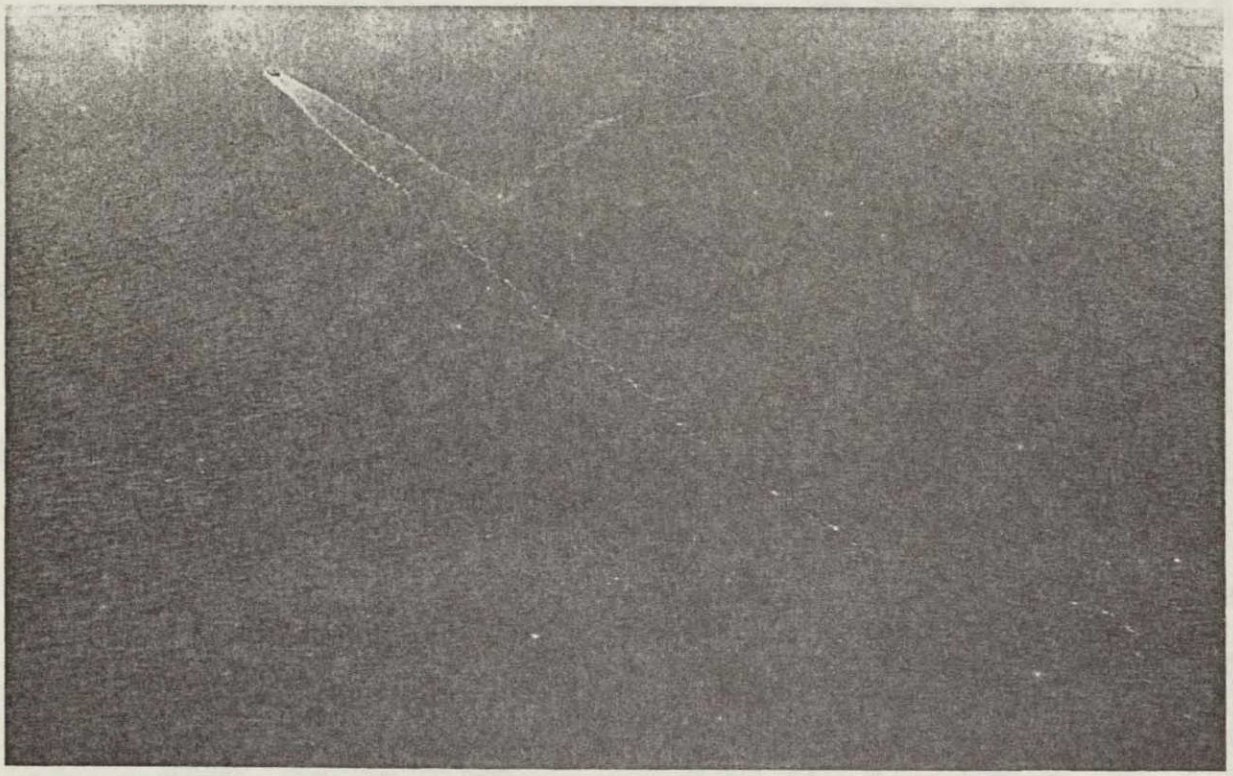


Figure 4

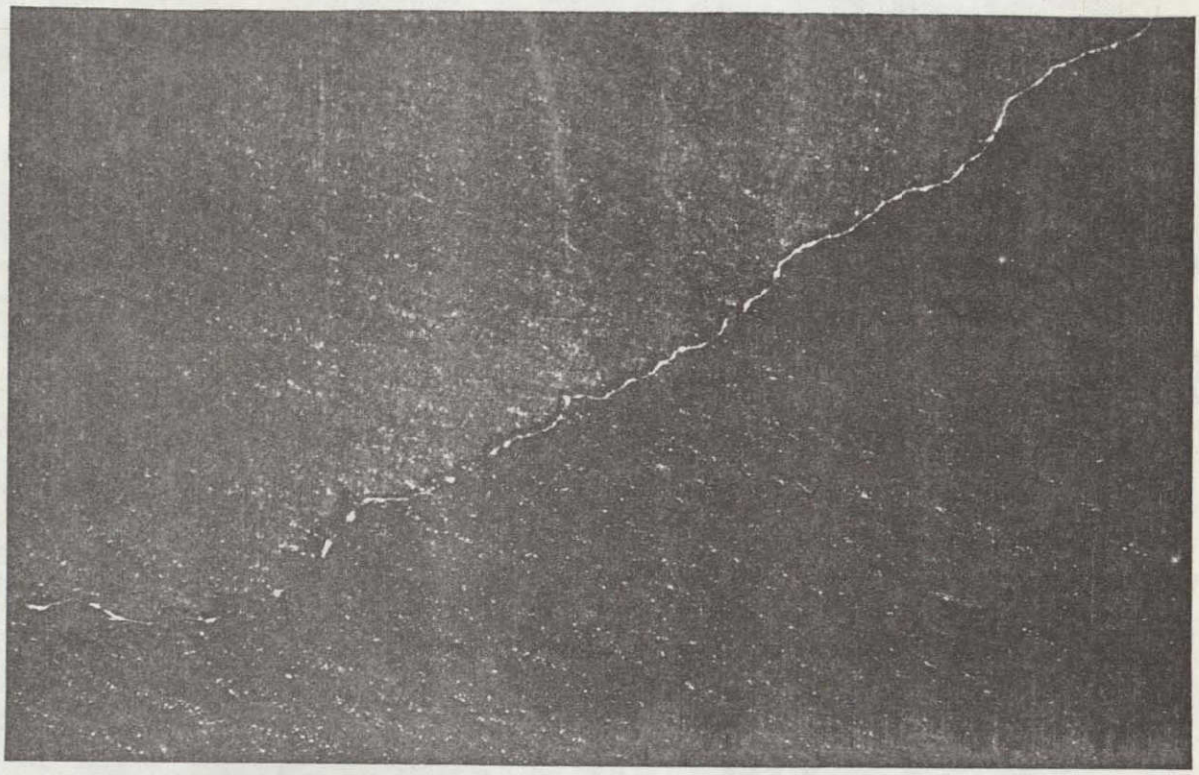


Figure 5

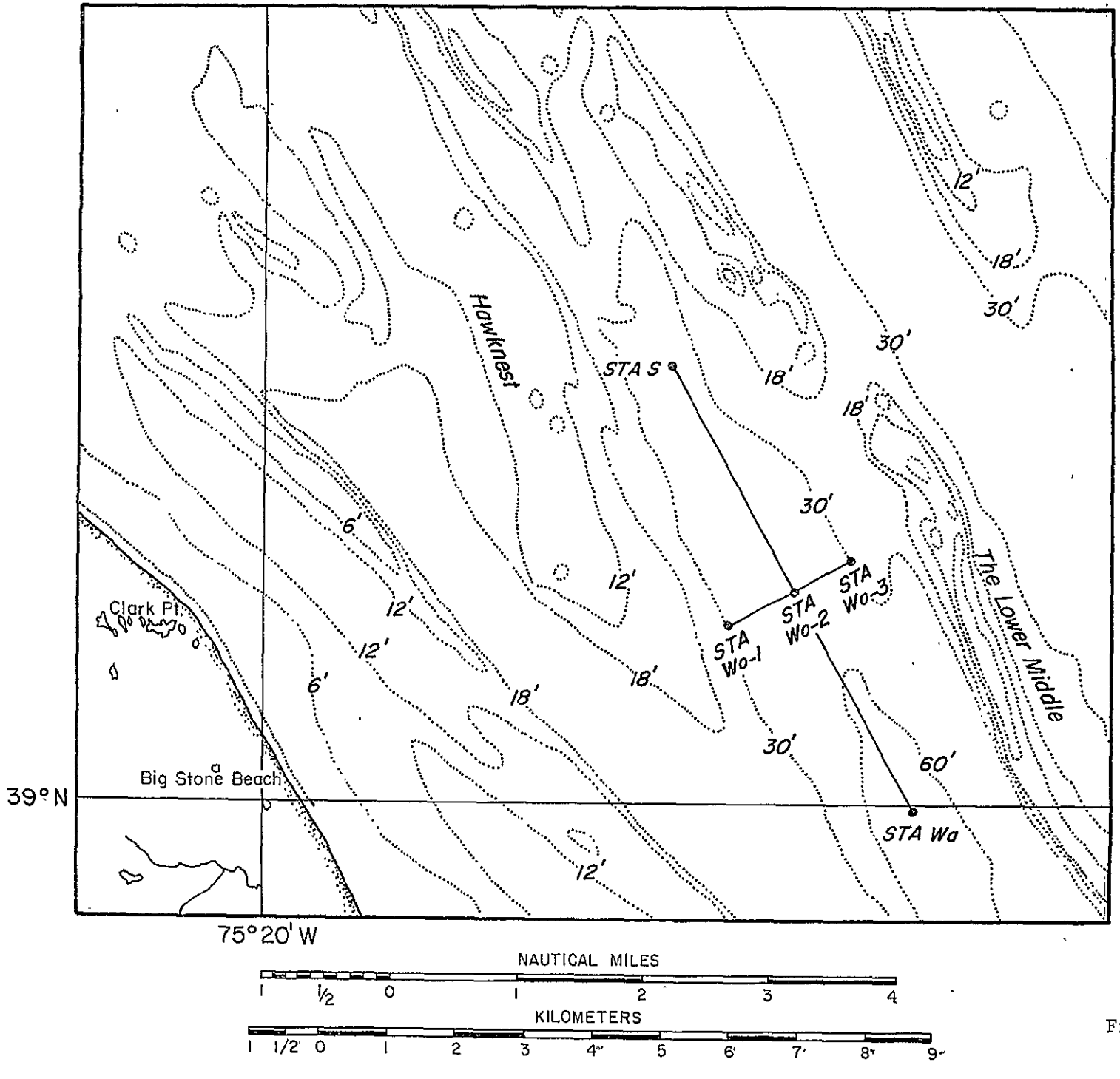

Hawknest
STA S
STA Wo-1
STA Wo-2
STA Wo-3
STA Wa
The Lower Middle
Clark Pt.
Big Stone Beach
39°N
75°20'W
12'
18'
30'
6'
60'
NAUTICAL MILES
1 1/2 0 1 2 3 4
KILOMETERS
1 1/2 0 1 2 3 4 5 6 7 8 9

Figure 7

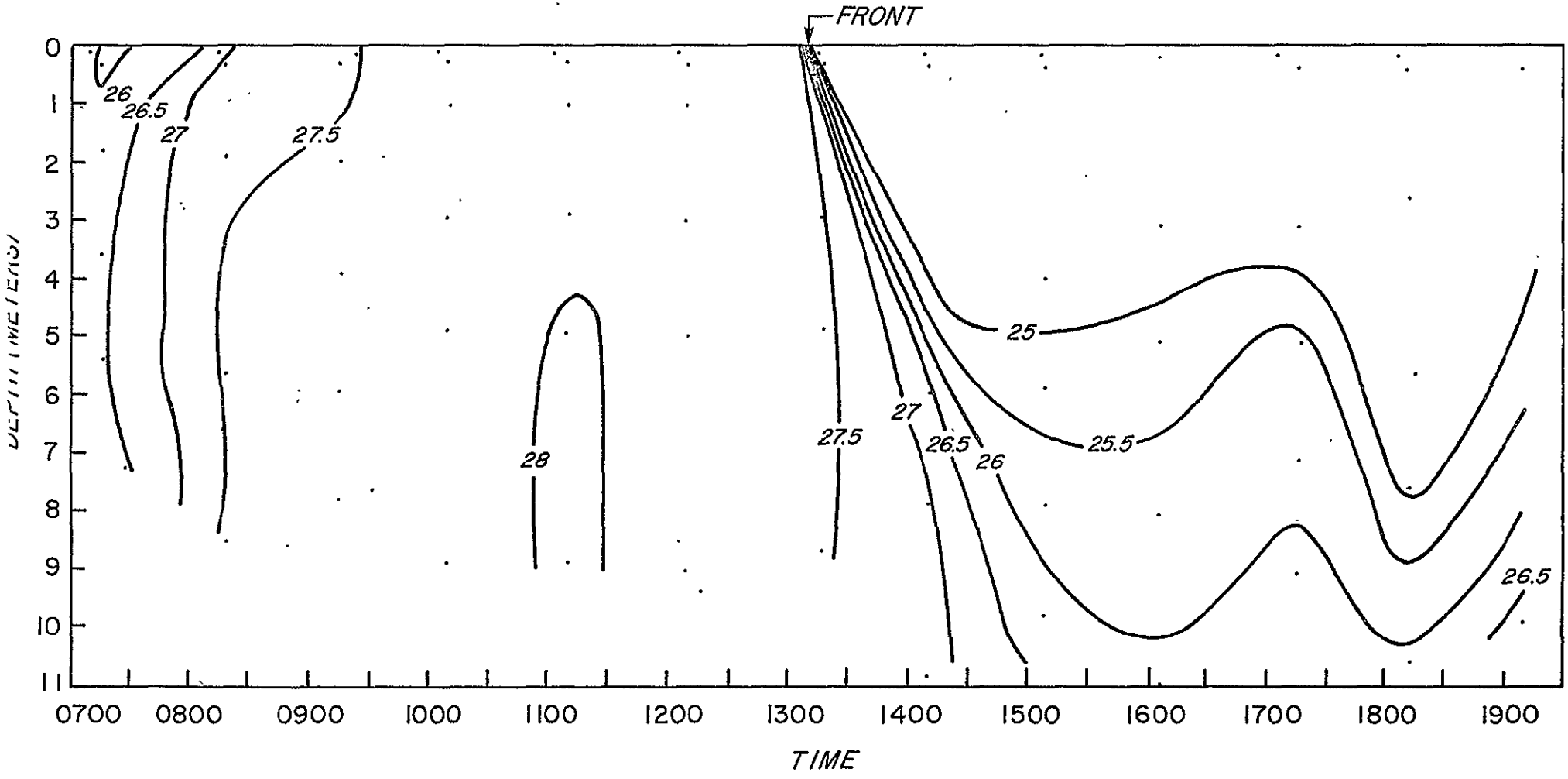

FRONT
26
26.5
27
27.5
28
25
25.5
27
26.5
26
27.5
26.5
0
1
2
3
4
5
6
7
8
9
10
11
0700
0800
0900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
TIME

Figure 8

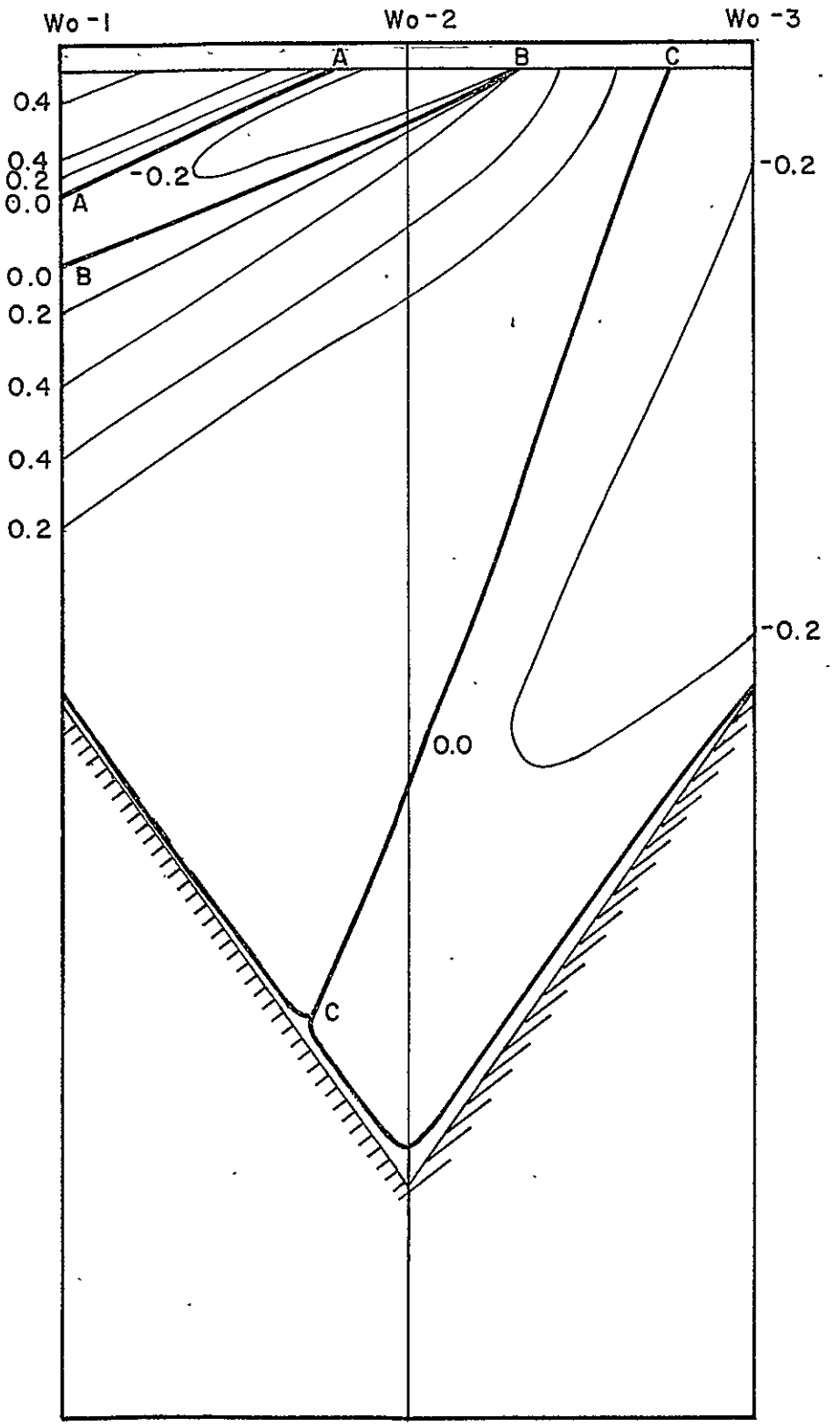


Figure 9

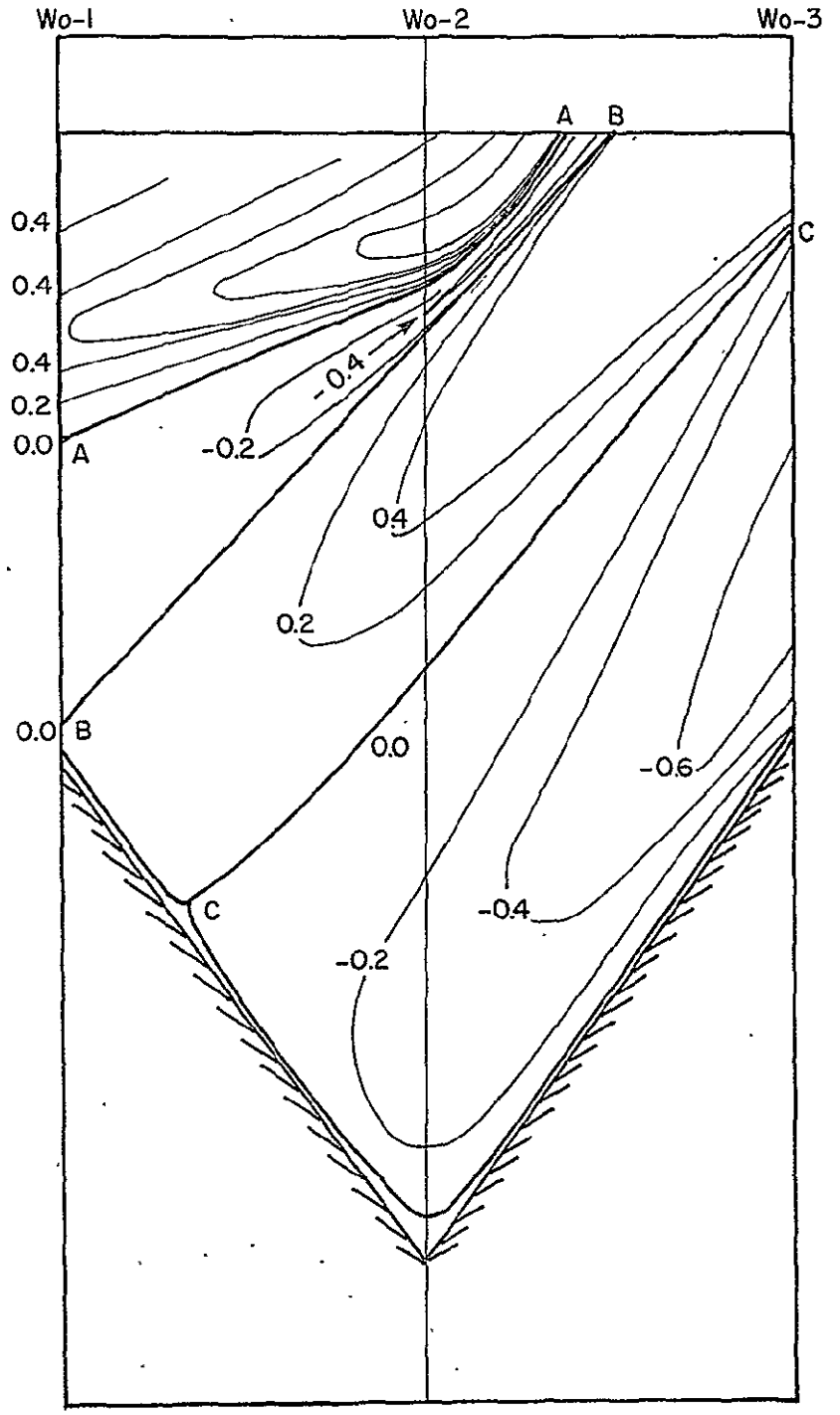
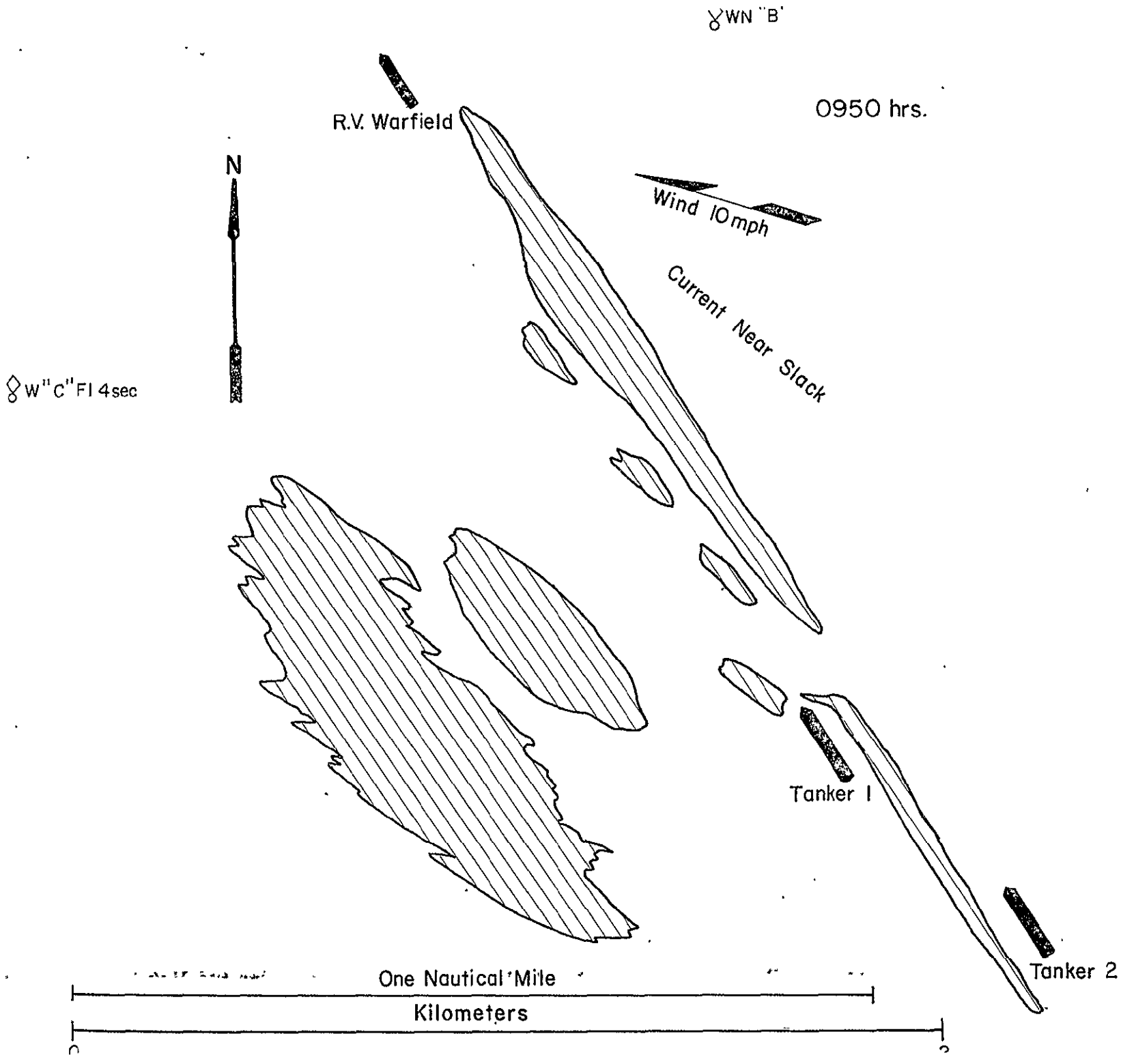
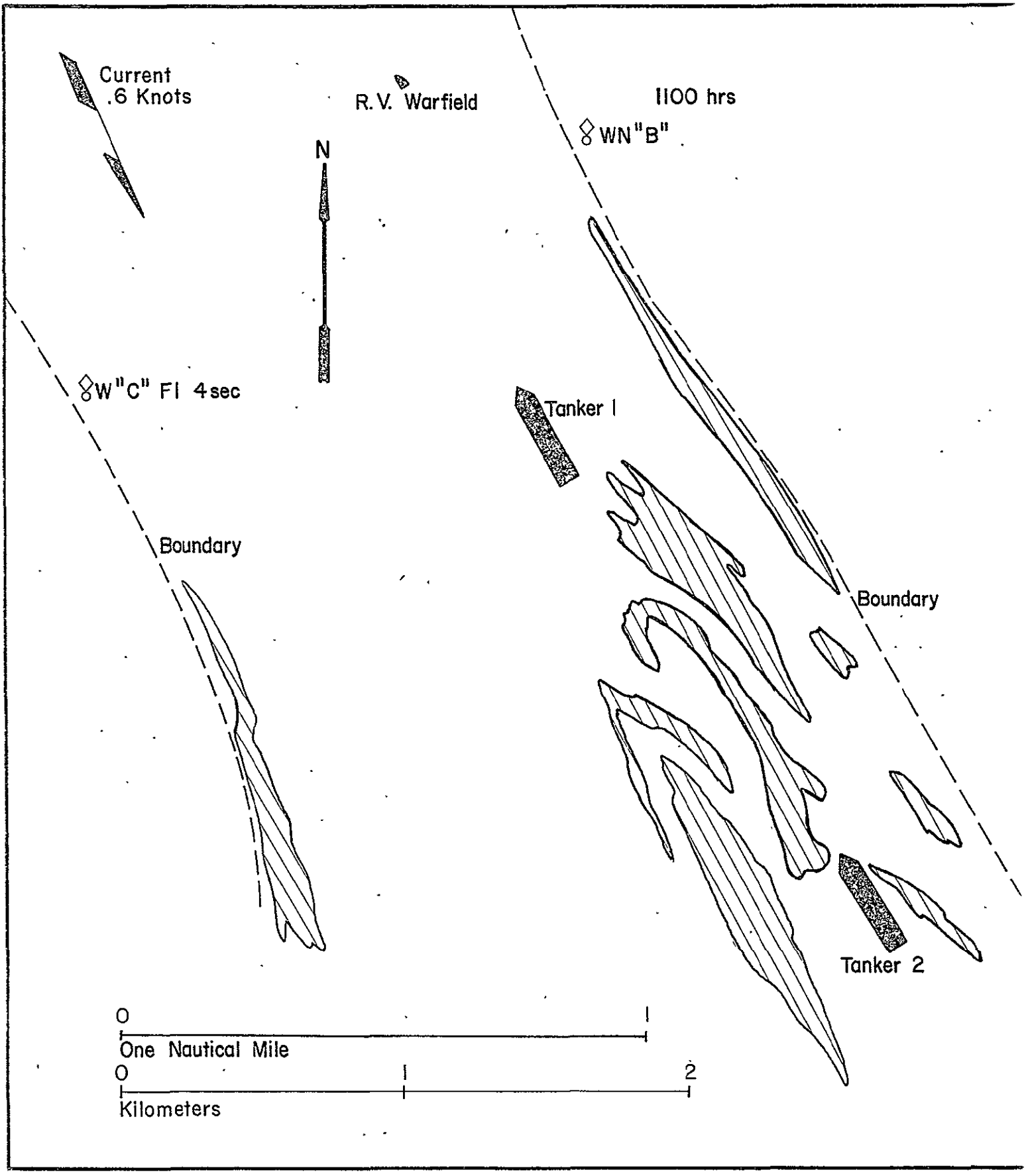
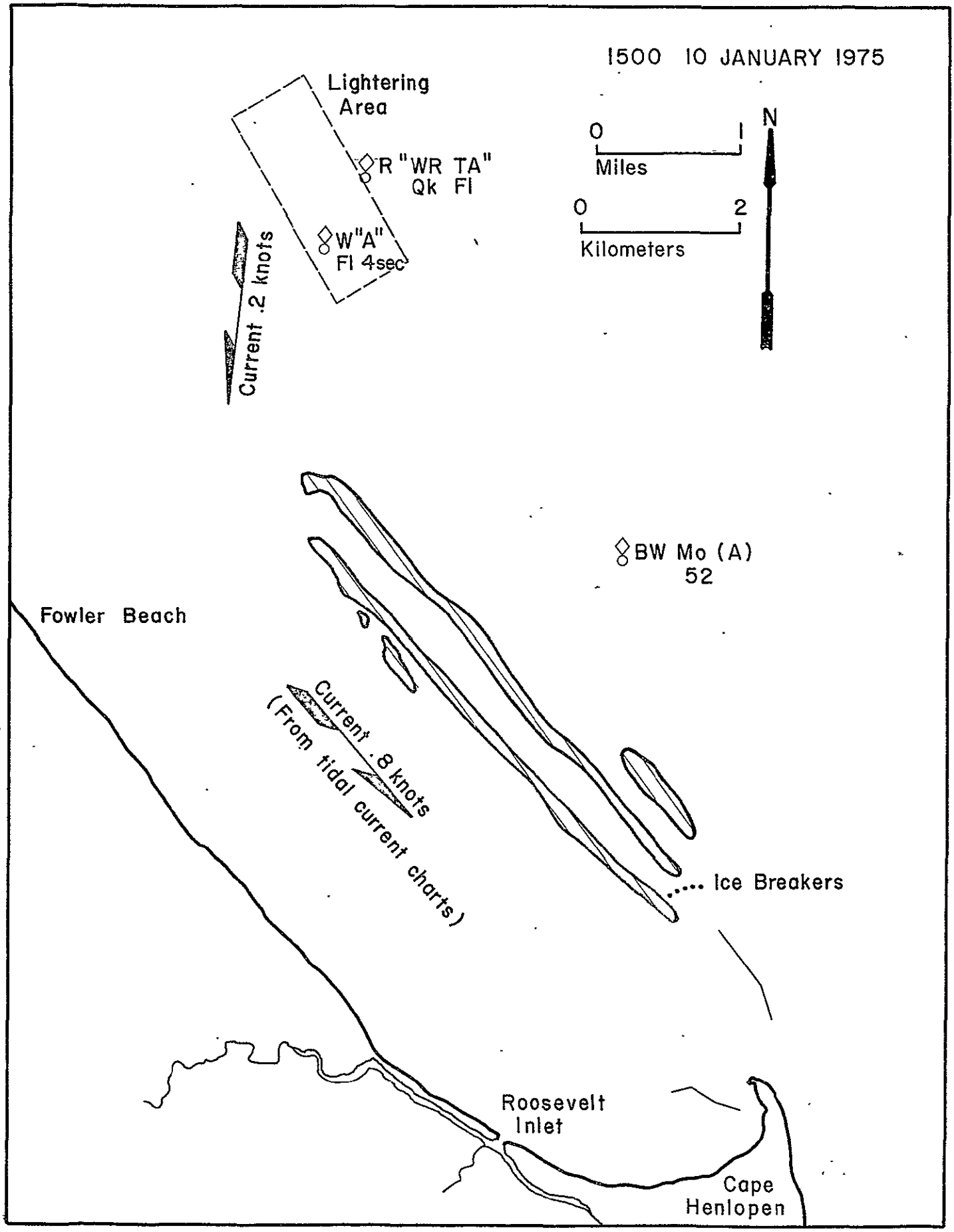


Figure 10


WN "B"
0950 hrs.
R.V. Warfield
N
Wind 10mph
Current Near Slack
W "C" Fl 4sec
Tanker 1
Tanker 2
One Nautical Mile
Kilometers
0
2


Current
.6 Knots
R.V. Warfield
1100 hrs
WN"B"
N
W"C" Fl 4sec
Tanker 1
Boundary
Boundary
Tanker 2
0
1
One Nautical Mile
0
1
2
Kilometers



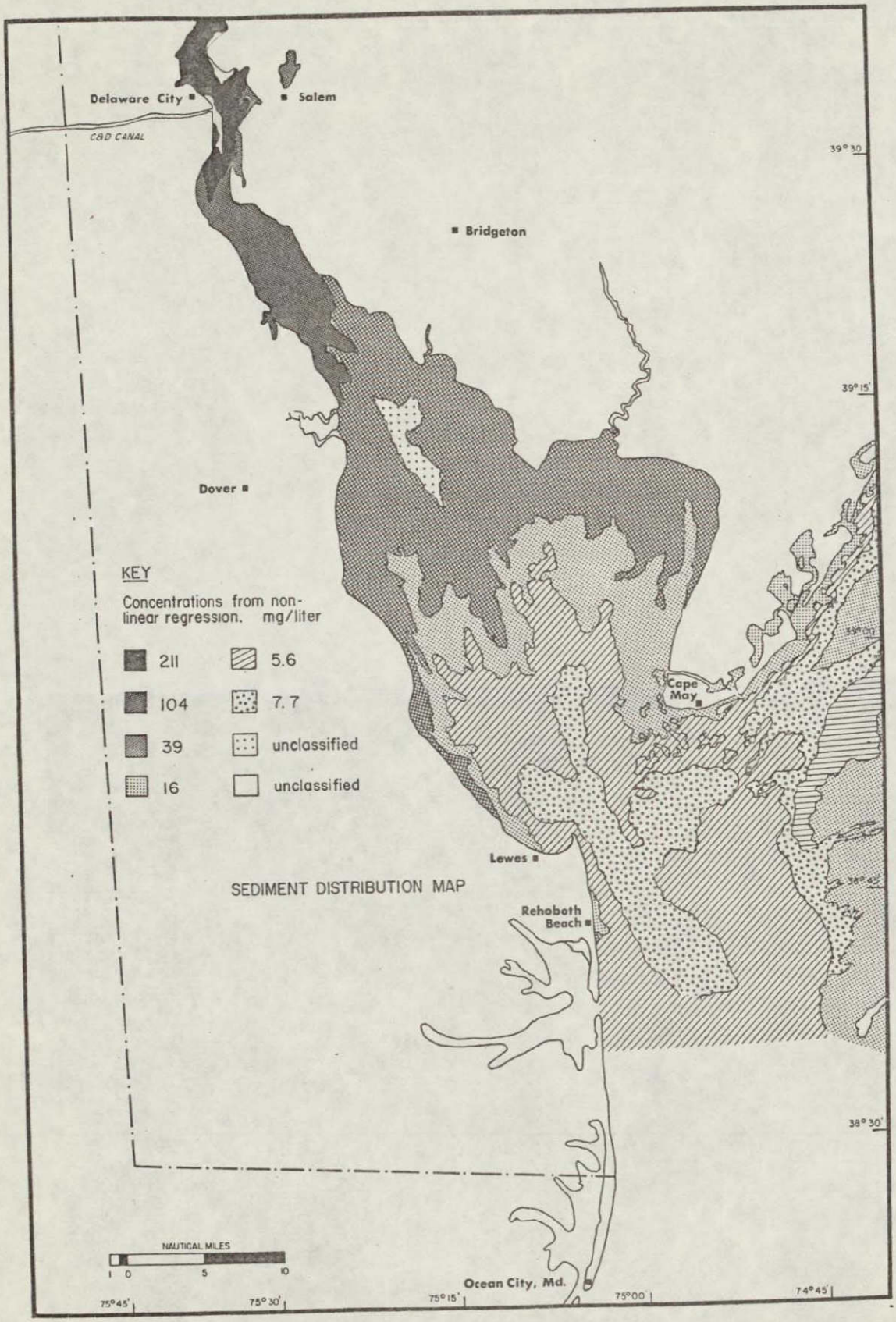

Delaware City
Salem
C&D CANAL
Bridgeton
Dover
39°30'
39°15'
KEY
Concentrations from non-linear regression. mg/liter
211
104
39
16
5.6
7.7
unclassified
unclassified
Cape May
Lewes
SEDIMENT DISTRIBUTION MAP
Rehoboth Beach
38°45'
38°30'
NAUTICAL MILES
1 0 5 10
Ocean City, Md.
75°45'
75°30'
75°15'
75°00'
74°45'

Figure 14

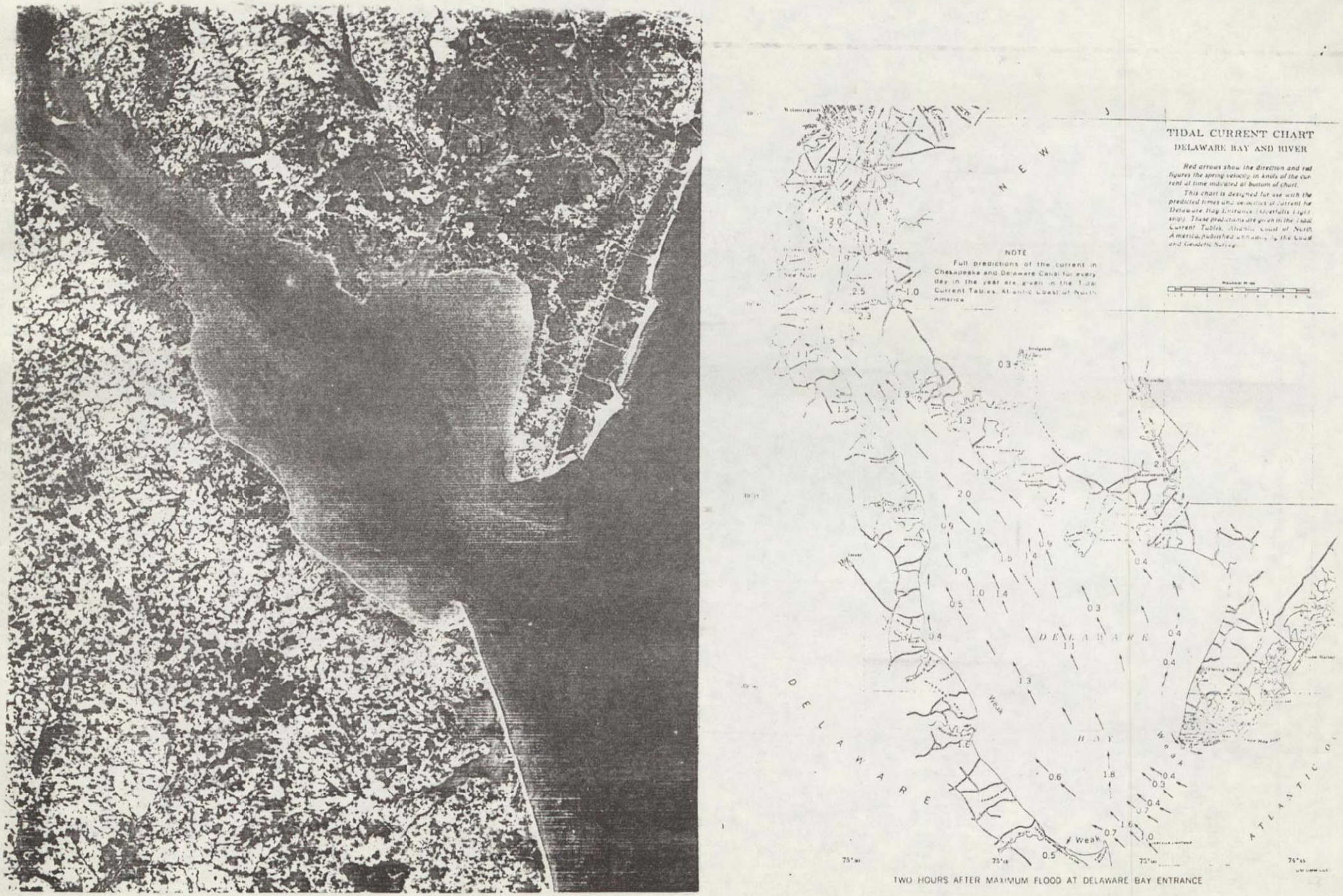
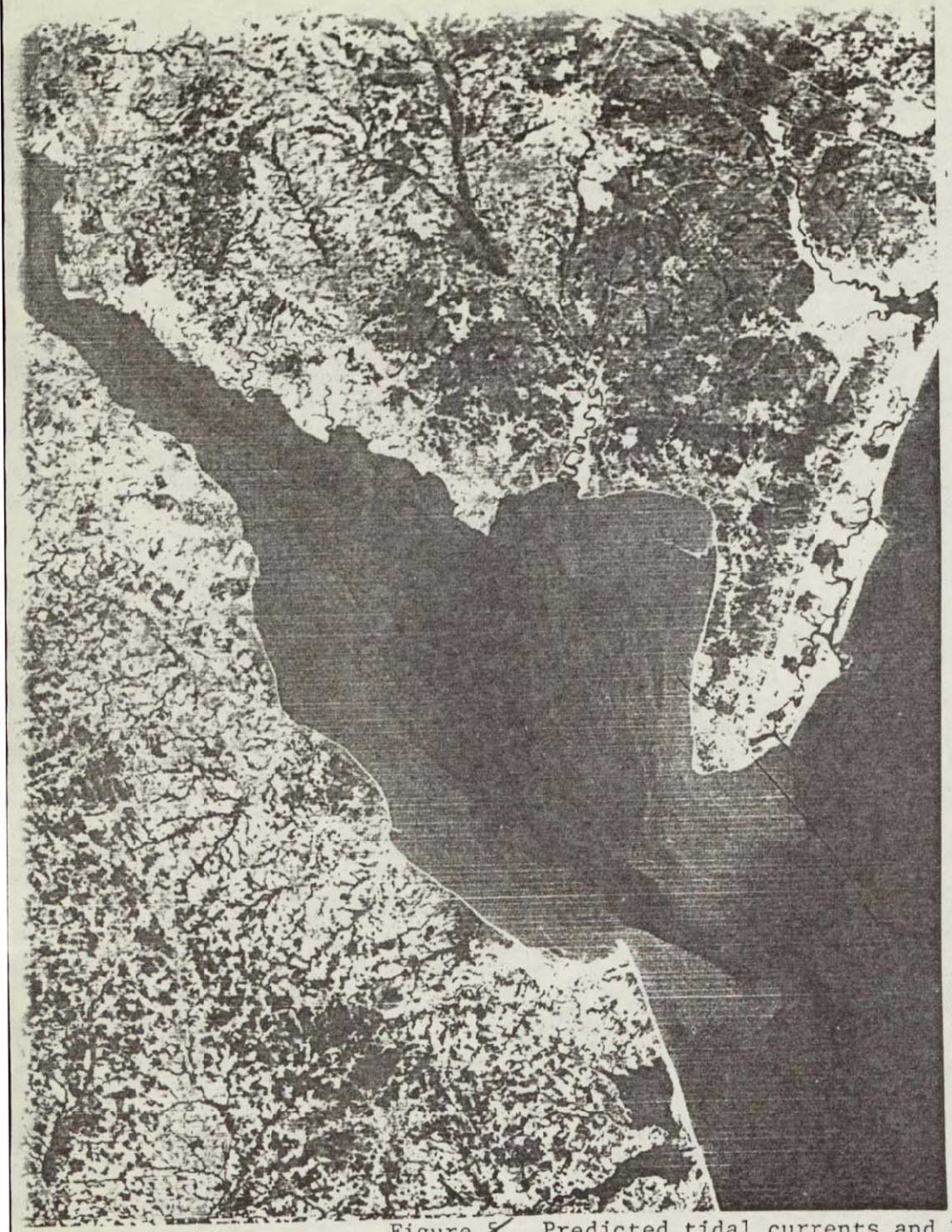


Figure 4. Predicted tidal currents and ERTS-1 MSS band 5 image of Delaware Bay obtained on October 10, 1972 (I.D. No. 1079-15133).



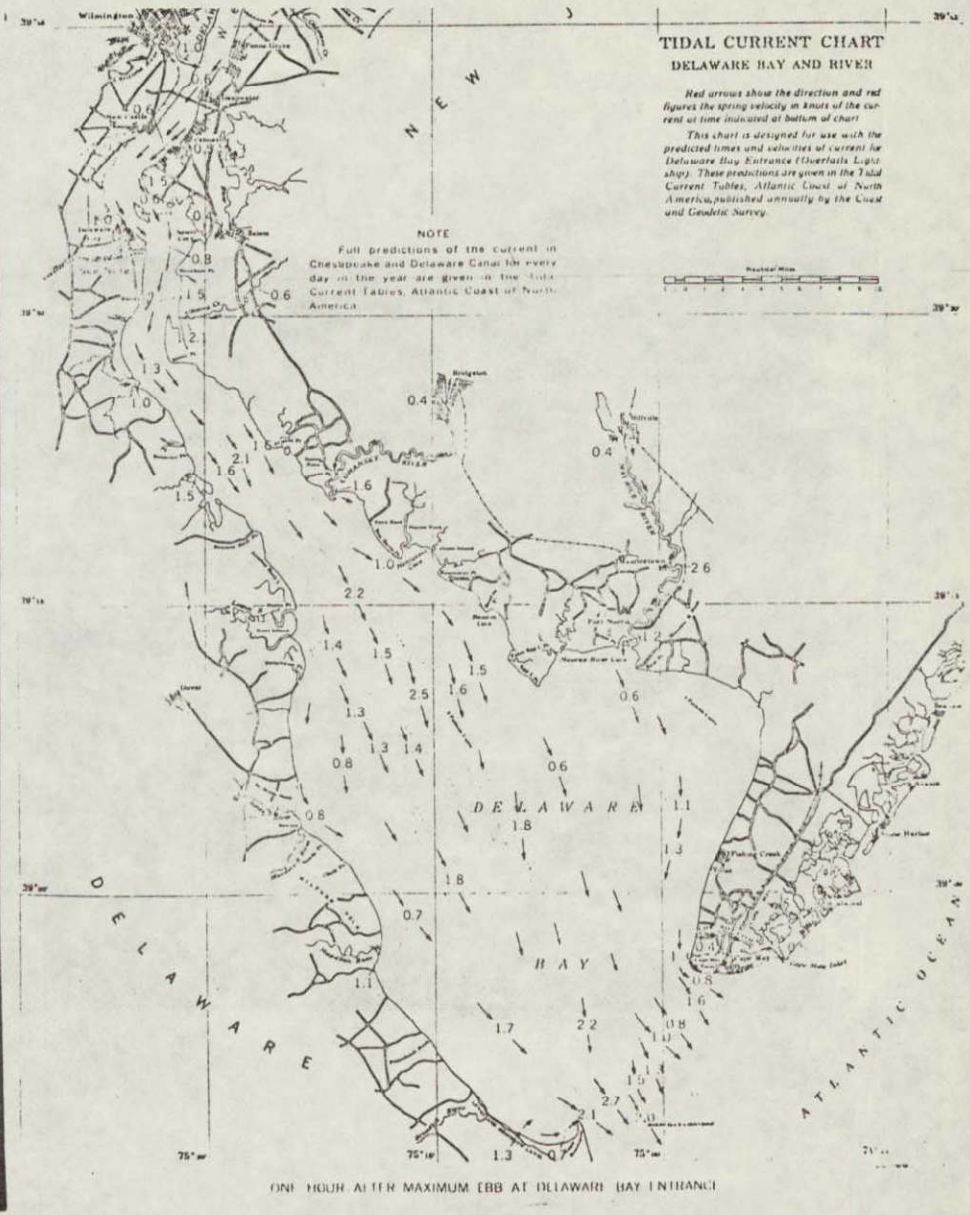


Figure 8. Predicted tidal currents and ERTS-1 MSS band 5 image of Delaware Bay taken on February 13, 1973 (I.D. No. 1205-15141).

16

Figure 17

Figure 19

Boundaries visible in Landsat images of Delaware Bay taken one hour before maximum flood at the entrance of the bay.

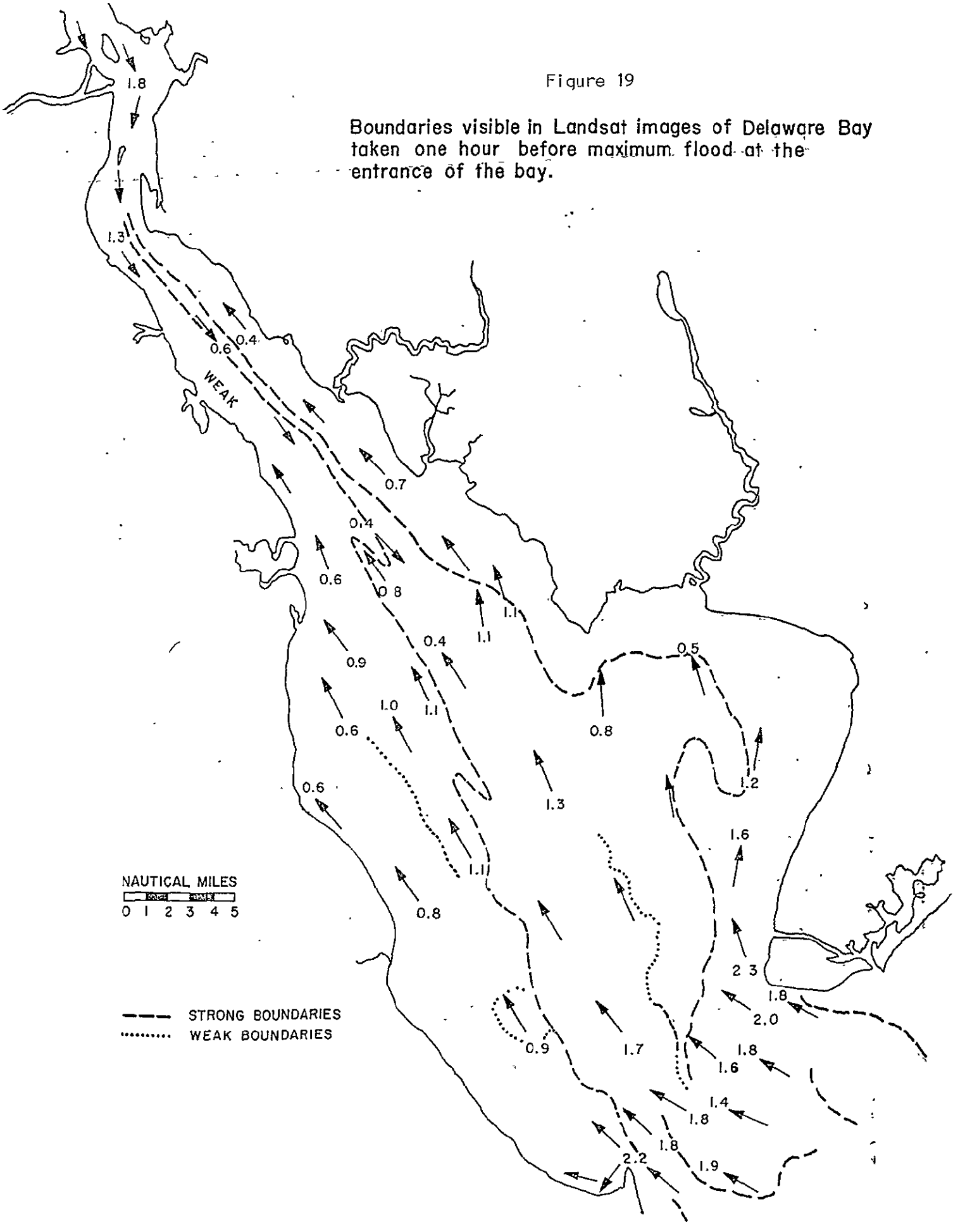


Figure 20

Boundaries visible in Landsat images of Delaware Bay taken at maximum flood at the entrance of the bay.

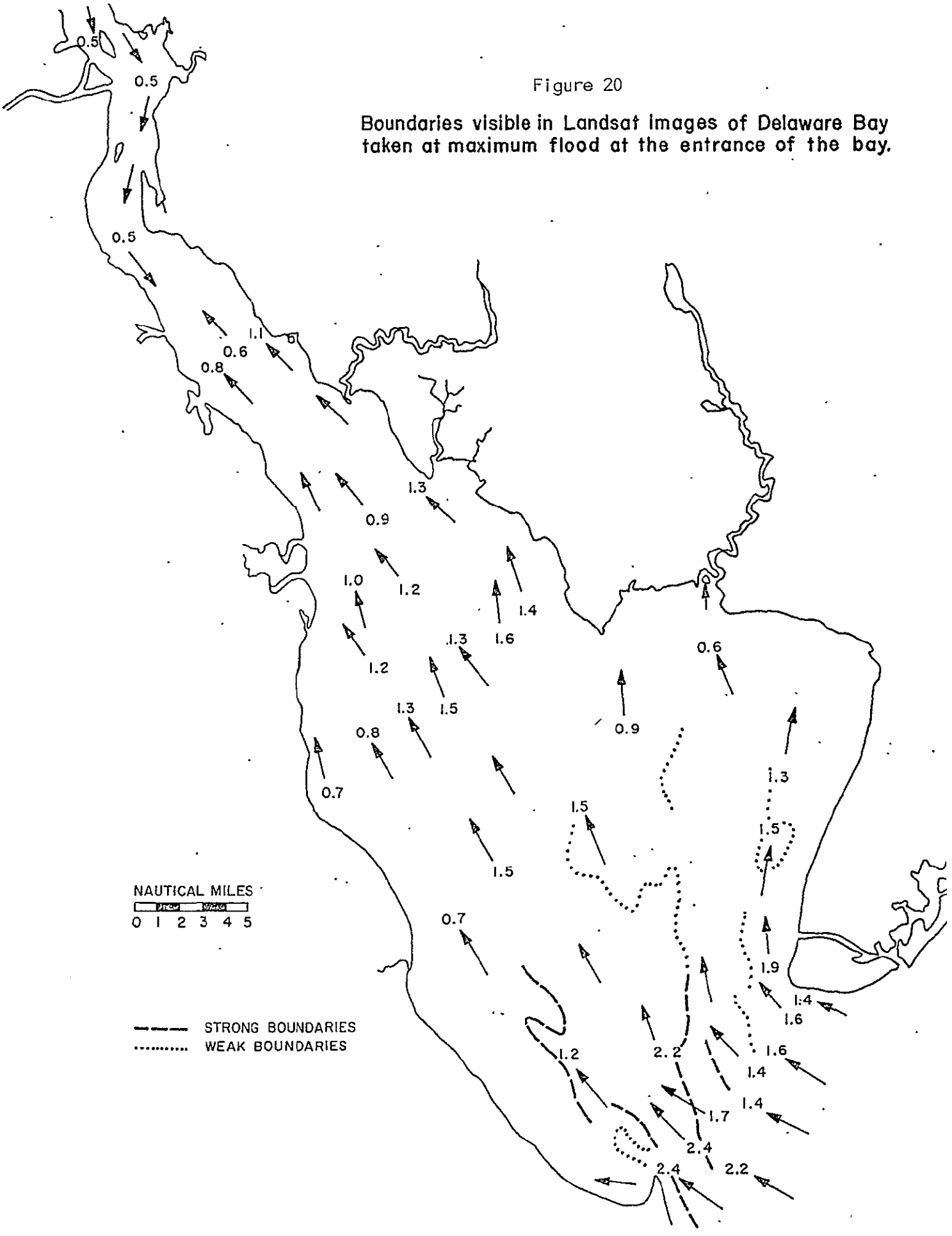


Figure 21

Boundaries visible in Landsat images of Delaware Bay taken one hour after maximum flood at the entrance of the bay.

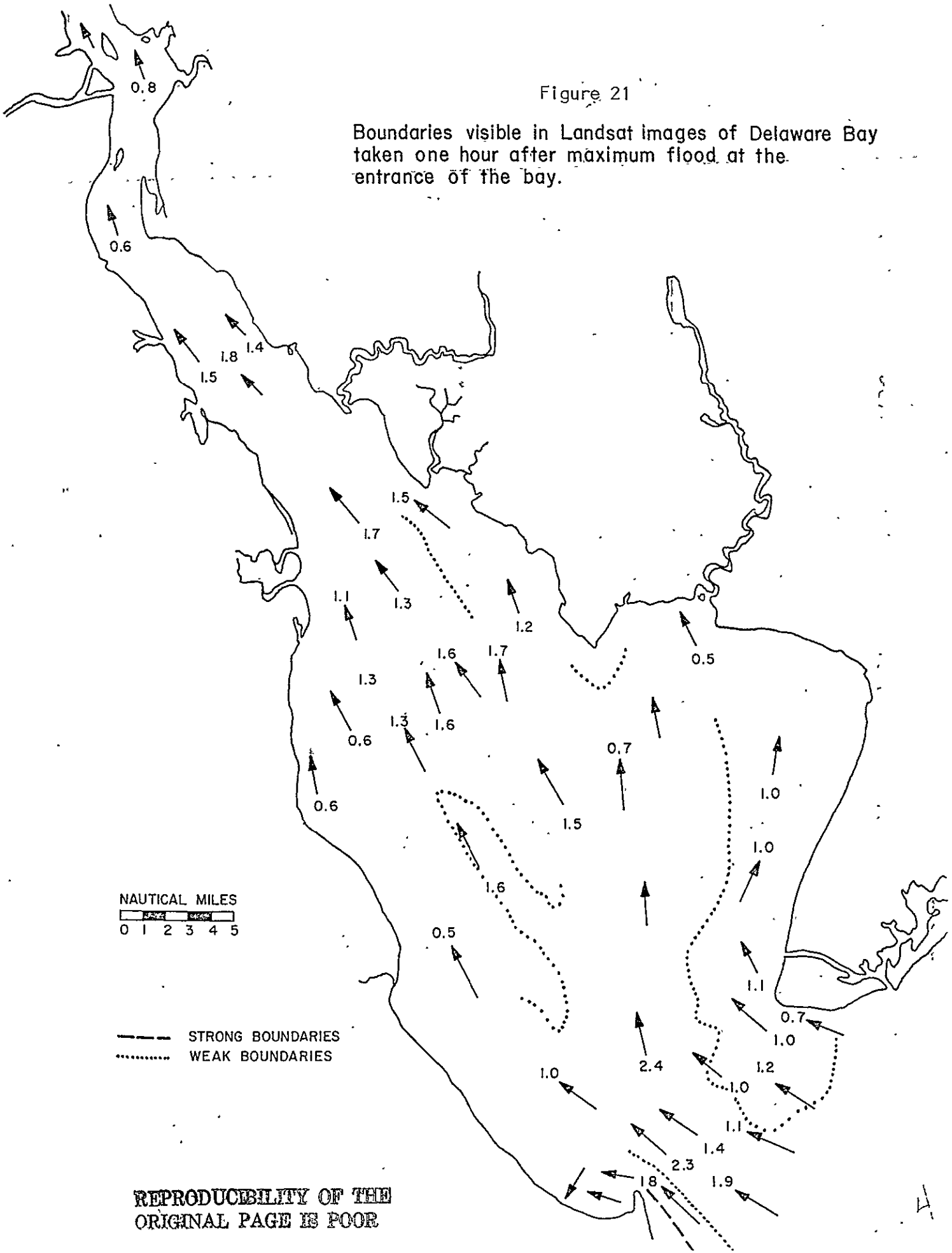


Figure 22

Boundaries visible in Landsat images of Delaware Bay taken two hours after maximum flood at the entrance of the bay.

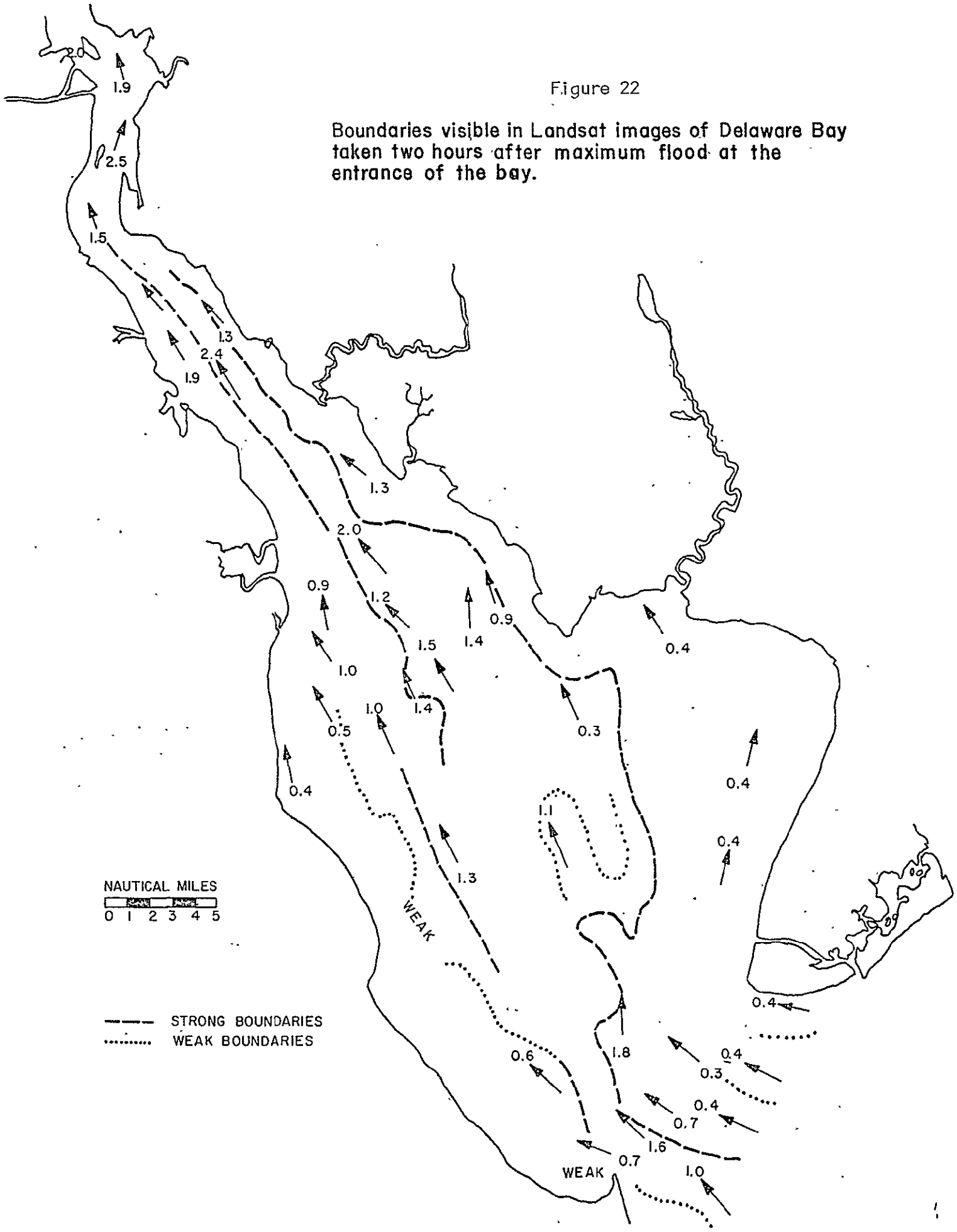


Figure 23

Boundaries visible in Landsat images of Delaware Bay taken three hours after maximum flood at the entrance of the bay.

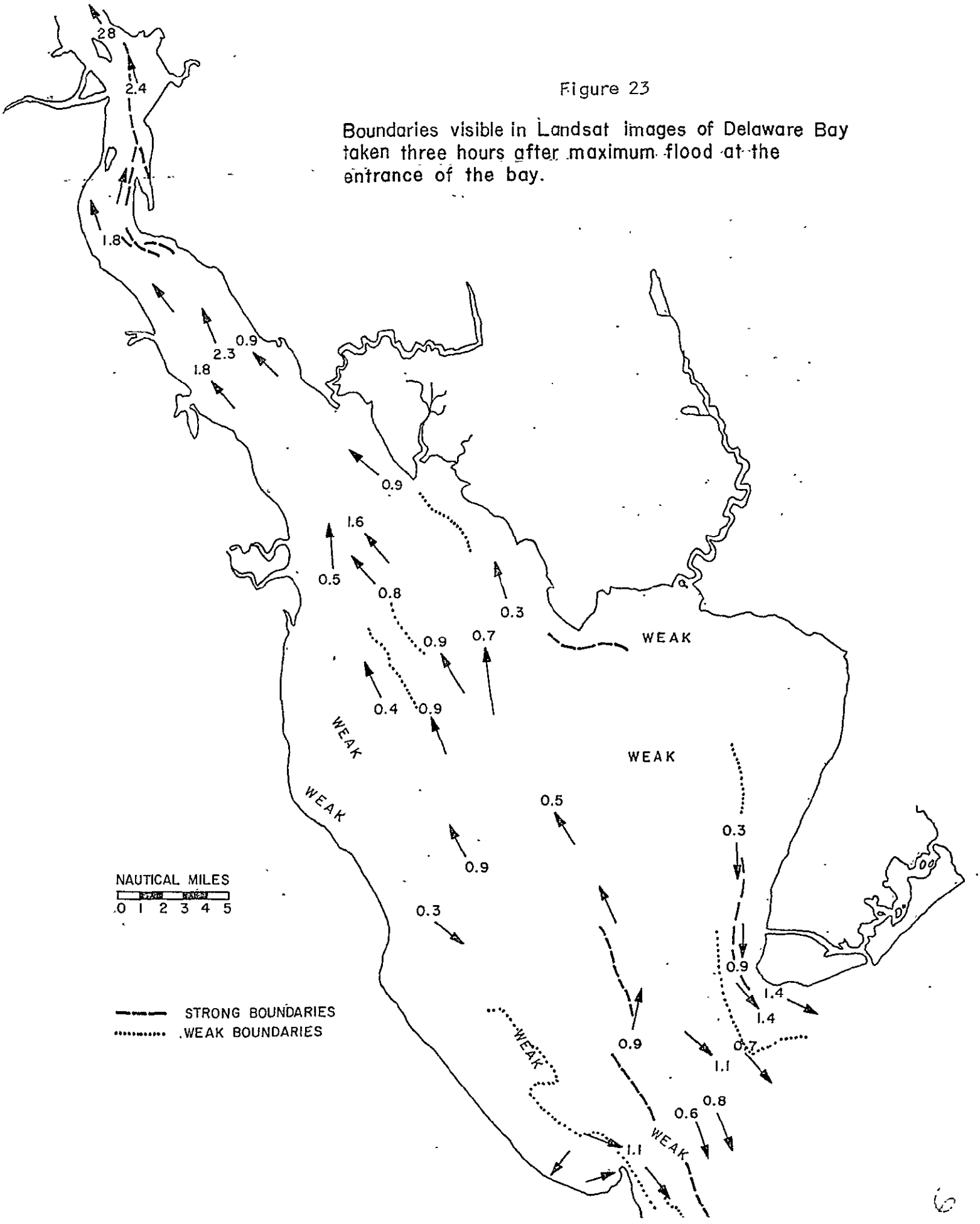


Figure 24

Boundaries visible in Landsat images of Delaware Bay taken two hours before maximum ebb at the entrance of the bay.

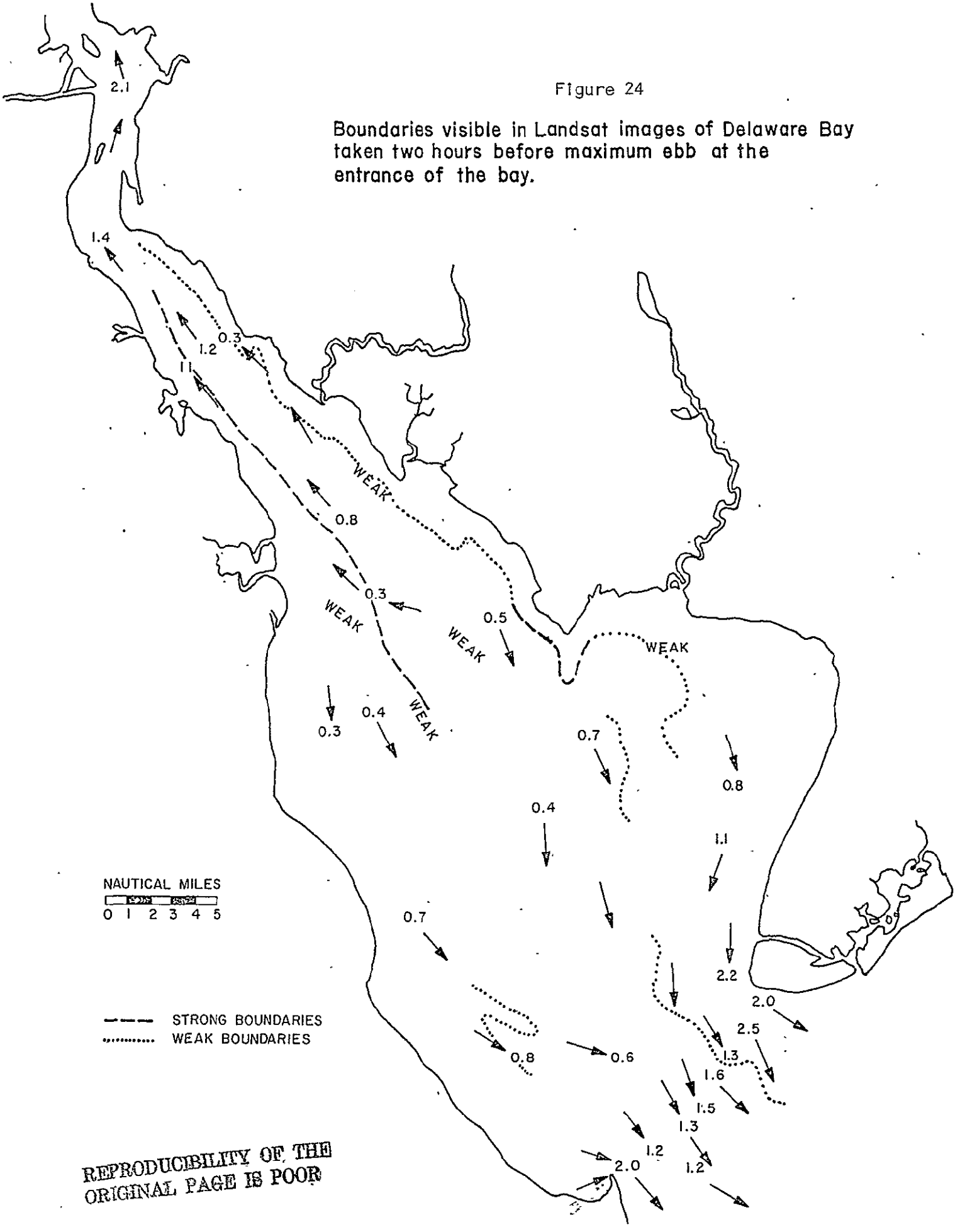


Figure 25

Boundaries visible in Landsat images of Delaware Bay taken one hour before maximum ebb at the entrance of the bay.

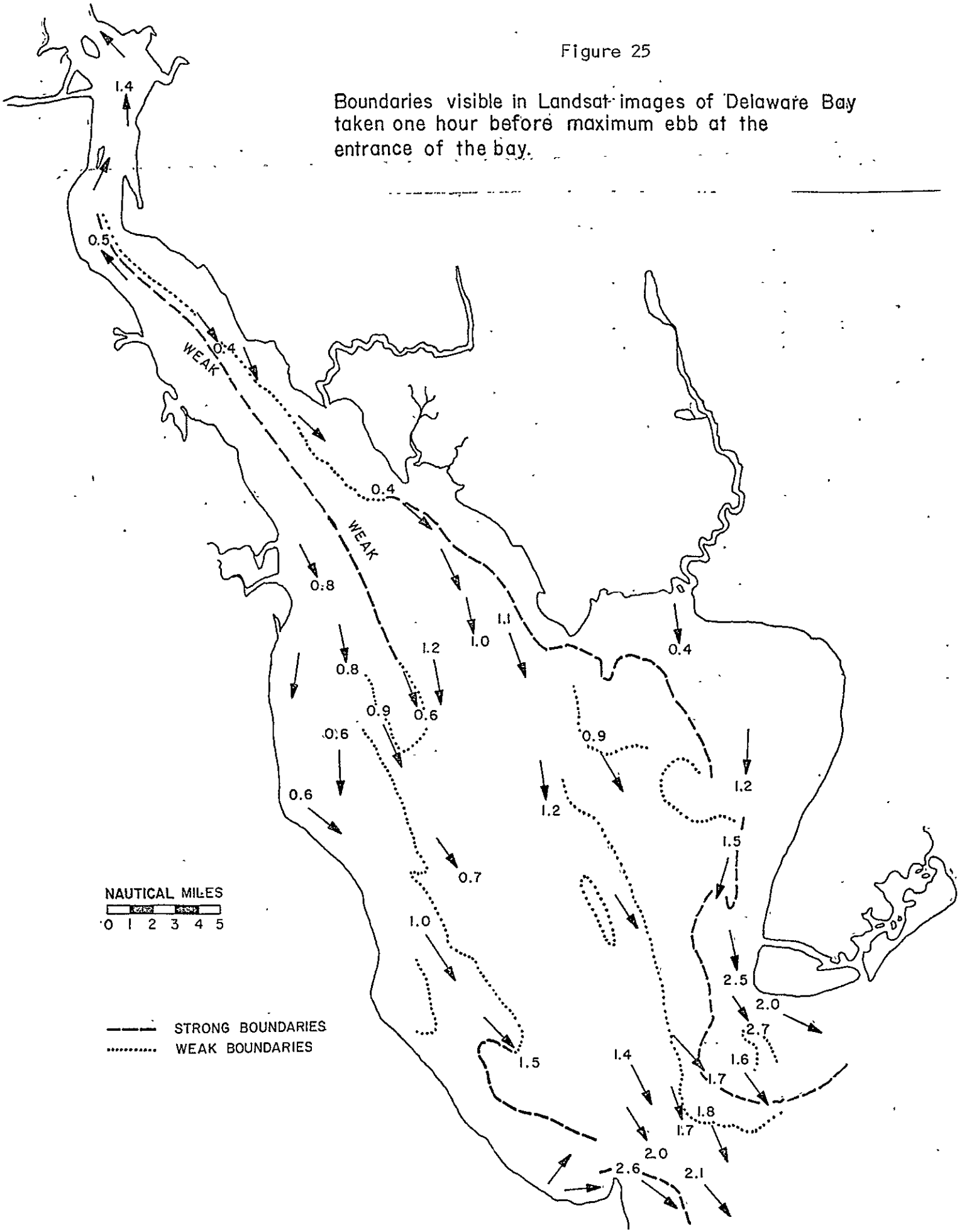


Figure 26

Boundaries visible in Landsat images of Delaware Bay taken at maximum ebb at the entrance of the bay.

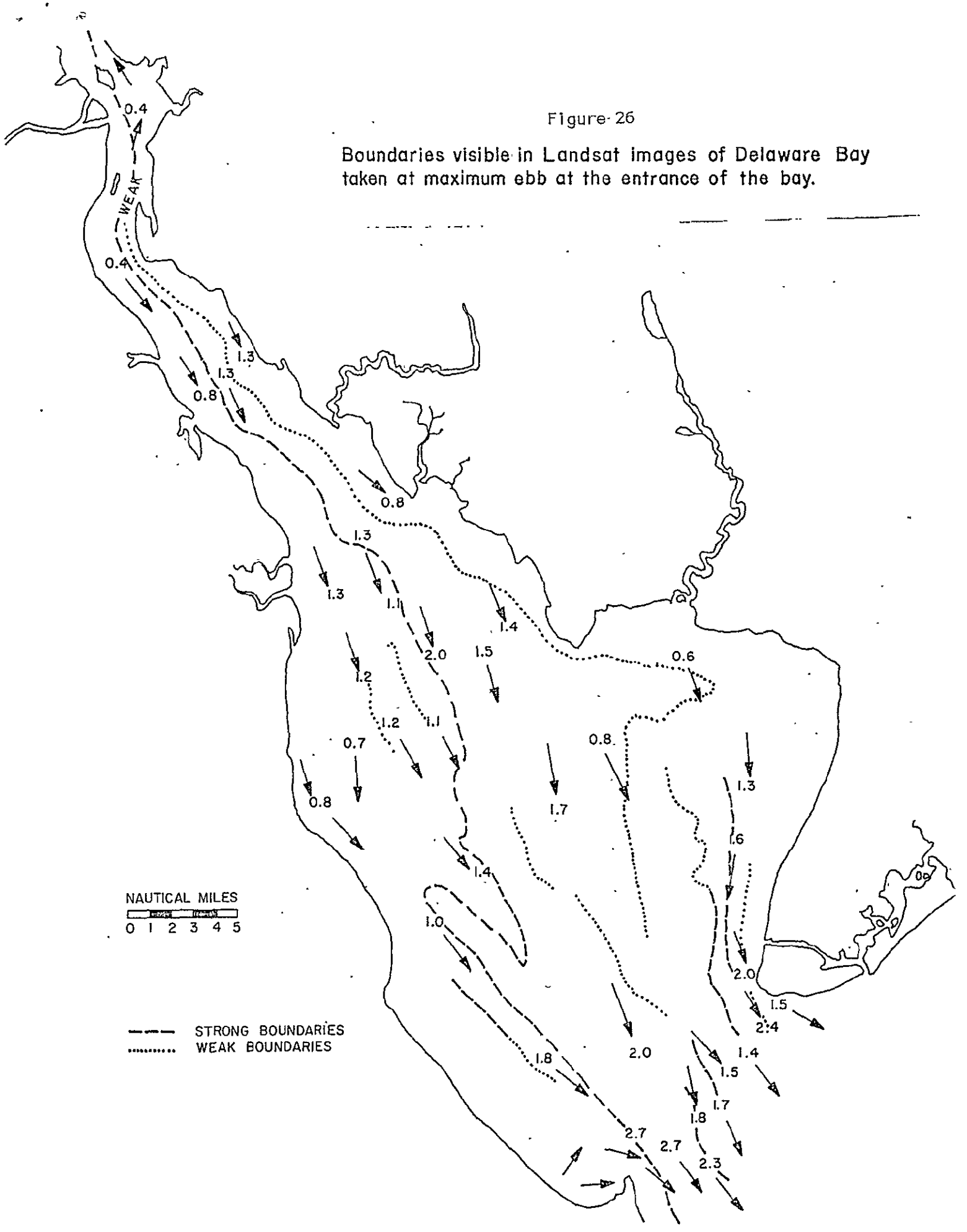


Figure 27

Boundaries visible in Landsat images of Delaware Bay taken one hour after maximum ebb at the entrance of the bay.

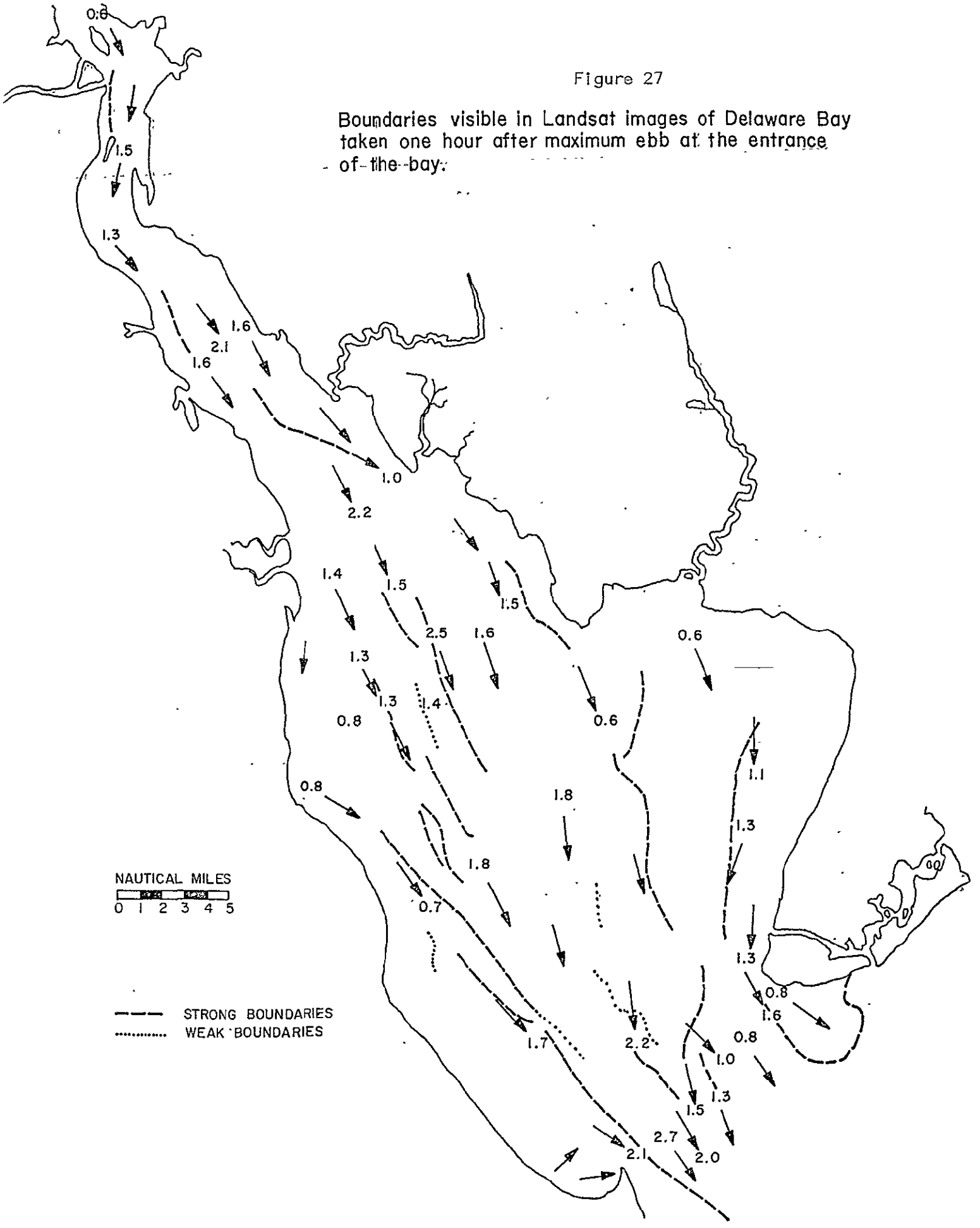


Figure 28

Boundaries visible in Landsat images of Delaware Bay taken two hours after maximum ebb at the entrance of the bay.

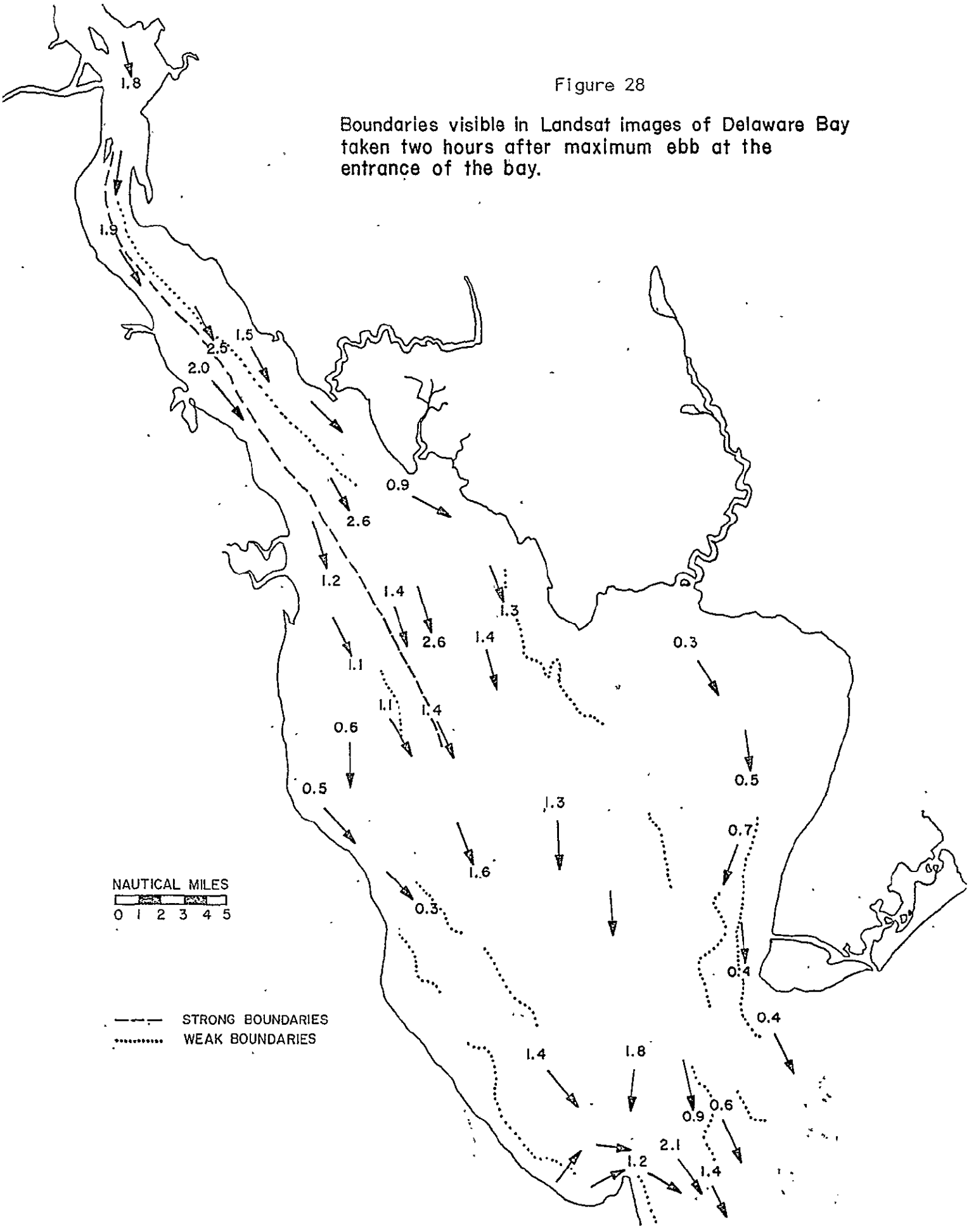
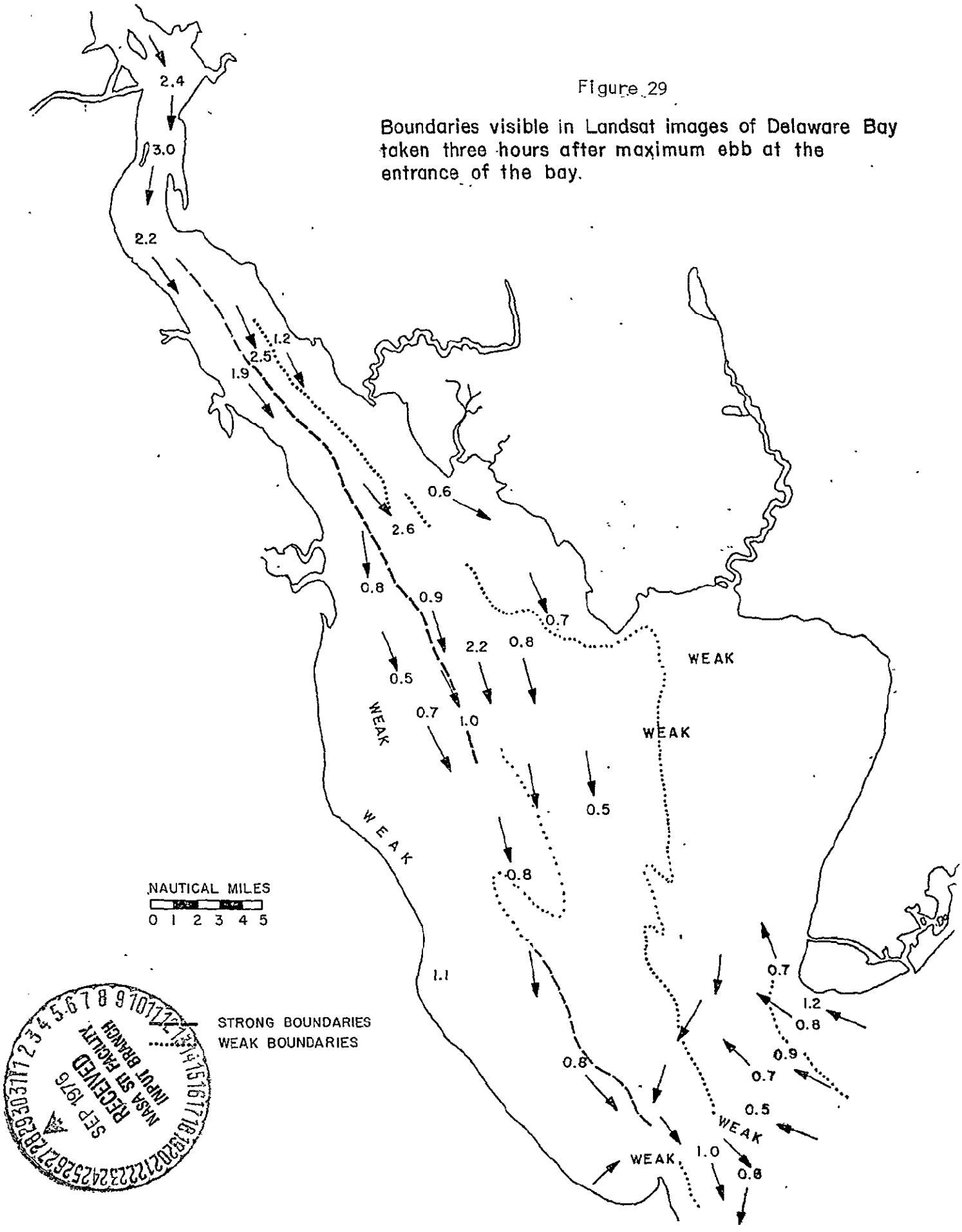


Figure 29

Boundaries visible in Landsat images of Delaware Bay taken three hours after maximum ebb at the entrance of the bay.



@abs The author has identified the following significant results.

Imagery from Landsat 1 and 2 proved valuable in determining the location, type, and extent of estuarine fronts under different tidal conditions. Neither ships nor aircraft alone could provide as complete, synoptic, and repetitive an overview as did the satellites. Since estuarine fronts influence the movement of oil slicks and dispersion of other pollutants, cleanup operations depending on real time use of oil slick movement prediction models will benefit not only from aircraft tracking the actual slicks but also from real time satellite observations of surface currents and the location of frontal systems.