CASE HISTORY OF A TYPICAL DREDGE-FILL PROJECT IN THE NORTHERN FLORIDA KEYS — EFFECTS ON WATER CLARITY, SEDIMENTATION RATES AND BIOTA

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I. INTRODUCTION

In the late 1960's and especially the early 1970's, the rate of development in the Florida Keys increased rapidly and undesirable side effects began to be reported. Significant problems included the shortage of potable water, lack of adequate sewage and solid waste disposal facilities, and excess traffic on the two-lane overseas highway; however, the problem mentioned most often in newspaper and magazine accounts was a supposed relationship between excess siltation produced by dredging and the decline in health of the coral reefs that lie several miles offshore. It appeared from these popular accounts that the only living coral reefs in the continental United States were in imminent danger of extinction and that Florida's most valuable park resource, the underwater John Pennekamp Coral Reef State Park, was being rapidly destroyed. Although the news stories concerning the decline of the reefs have been shown in our research to be more fictional than factual, they did serve the useful purpose of kindling scientific interest into the problems posed by development in the Keys and led directly to a decision by Dr. Eugene Wallen, then Director of the Harbor Branch Foundation Laboratory, to establish a field laboratory on Key Largo. To encourage this effort, the Florida Division of Recreation and Parks loaned the use of a small building in the Pennekamp Park, the University of Florida granted the writer a long leave of absence to serve as Project Director and Chief Scientist of the facility. Dr. Joseph Simon of the University of South Florida loaned some necessary field equipment, and the Trustees of the

Internal Improvement Trust Fund allowed Mr. Bill Stimmel to work with us in the field. With this valuable assistance, and especially the active encouragement of Dr. Wallen and Mr. J. Seward Johnson, the writer was able to establish the laboratory and mount the research program in a very short period of time, and by October 1972, the project was actively collecting data.

As originally conceived, a team of sedimentologists and biologists was to provide quantitative data on the type, quantity, distribution and effects of the effluent generated by typical dredge-fill projects in the upper Keys, especially within the offshore area of the Pennekamp State Park. This aim was expanded at an early stage to include a baseline study of natural water clarity throughout the upper Keys marine area, and other basic sedimentological, physical, and biological parameters. The limits of the expanded study area are shown on Figure 1, on which the boundaries of the Pennekamp State Park, the most important reefs, and our repeated water sampling traverses are indicated. These additional studies, to be reported in the scientific literature, were needed to provide a framework in which to evaluate the effects of dredging and other developmental activities and as a baseline against which to compare future environmental studies in the same area.

As it actually developed, during the active field term of the study (October 1972 to December 1973), a state imposed moritorium on new dredge permits resulted in decreased dredge activity, and only one major dredge-fill development actually occurred on the reef-side of the Park area—that of Joseph R. Harrison, Jr., in the Basin Hills area of upper Key Largo. However, that project was typical of dredge-fill practices in the Keys and was in most respects well suited as a model of the effects of dredging. The only non-ideal aspect was that dredging began before we had adequate time to establish the pre-dredging baseline conditions at the site. However, this defect was beyond our control, and contemporaneous studies in nearby control areas were substituted. In all, the Basin Hills project was monitored by the project for a full year, October 1972—October 1973, until dredging was completed on the Atlantic-side canals, plus several additional post-project months to observe any lingering effects. Other related studies continued for a second year.

During most of the monitoring period, the biological team monitored the health of a small coral patch reef 0.48 nautical miles to the NNE of the dredge site. This small reef formed a good biological indicator of water quality, and it was observed extensively from its discovery in November 1972 until a month after dredging had ceased.

II. GENERALITIES CONCERNING DREDGING METHODS IN THE FLORIDA KEYS

Dredge-fill projects of the type described here involve the excavation and transport of solid bedrock, not the unconsolidated sediments typically dredged elsewhere. Thus it seems pertinent to describe briefly the type of rock encountered and the geologic basis of some of its characteristics that affect dredging.

The bedrock throughout the upper Florida Keys, is a soft, highly fossiliferous, moderately cemented carbonate rock unit known as the Key Largo Limestone. Radiometric dating indicates that the limestone originated 115,000 to 145,000 years ago (Osmond, et al, 1965) a time when sea level was approximately 25 feet higher than at present. The fossil assemblage indicates that much of the Key Largo Limestone originated by the coalescence of an arcuate series of patch reefs, similar to Hen and Chickens Reef, or Mosquito Bank but more continuous and presumably a "climax" development of the inner reefs. After intermediate rises and falls, the sea rose to near its present level 5,000 years ago, and since that time the rate of rise has been relatively small.

During the periods of exposure to the atmosphere, leaching by fresh water produced numerous solution cavities and collapse fractures. These openings, combined with abundant original cavities, united to produce a rock so permeable that the rise and fall of the tide is transmitted completely through the islands.

In the Keys, dredging is accomplished by a technique that is usually associated with "hard-rock" mining; therefore, I refer to it as "hard-rock dredging". It is a relatively slow process, typically requiring several weeks or months to complete canals that in areas of loose sediment could be dredged hydraulically in days. The process involves: (1) drilling shot holes with a portable rotary rig,

(2) fracturing the rock with explosives, (3) removing the rubble with a dragline or clam-shell scoop, and (4) trucking the rubble to a fill site, typically a low area on the same property. The rubble is quite valuable as fill, and canals are usually dredged to depths greater than required for small boats in order to generate more rubble. Typical canals for residential developments are dredged to -10 to -20 feet below MSL, and depths of -25 feet are not uncommon. At least one marina in Tavernier has a depth of -50 feet, and even greater depths have been reported from the lower Keys.

III. DESCRIPTION OF DREDGE OPERATION AT BASIN HILLS

A. Location, Amounts Permitted, and Amounts Dredged

The Joseph R. Harrison property on Key Largo involves parts of Sections 9, 10, 15, and 16 of Township 60 South, Range 40 East, Monroe County, Florida. On USC & GS chart 141-SC it can be located by three old E-W dead end canals labeled "Basin Hills" in the northern third of the Key on the Barnes Sound side. The development extends the full 3/4 mile width of Key Largo and for a distance of approximately one mile along both the Hawk Channel and Barnes Sound coasts (Fig. 1). Three canals were dredged, but the only one monitored and specifically reported here is the entrance canal on the southeast side of the Key, between Key Largo and Hawk Channel (Canal 1 on Table 1).

Dredging of entrance channels into open water, such as the one we have studied at Basin Hills, requires two additional procedures or phases. During "an extension phase", the shot-hole rig, dragline, and bulldozer slowly work seaward at a rate on the order of 70-80 feet per working day, dredging a linear canal and extending a parallel pair of spoil fingers along the canal sides. The spoil fingers provide a working base and road for the dragline and trucks.

Upon reaching the permit limits, a "cut-back phase" ensues. Now the dragline works its way landward at a rate of approximately 50-60 feet per working day, removing the spoil fingers and loading the rock rubble into trucks. Ultimately, all spoil is removed from the offshore area, leaving only the canal flanked by strips of bare bottom marking the former spoil finger sites.

B. Bathymetry and Types of Natural Bottom (as of April 1973)

The dredge site is typical of the Atlantic side of Key Largo, with mean low water depths approximating 2 to 6 feet. Figure 2 shows the configuration

Table 1.—Canals Dredged in Connection with the Basin Hills Project, upper Key Largo (Florida TIITF Permit No. 253.03-168, Property Owner: Joseph R. Harrison, Jr.)

Canal	Length x Width x Depth Below Natural Bottom (ft.)	Approximate rock removed (yd^3)
1) Entrance canal from Hawk Channel	2000 x 50 x 8 (approx. avg.) (Note: Depth is based on our post-dredge survey; permitted depth was -8.0 ft. below MLW, not below natural bottom).	29,630 (Note: This is based on our post-dredge depth-recorder survey)
2) Perimeter canal along Hawk Channel shoreline	6000 x 50 x 8 (Based solely on developers plot plan.)	88,889 (Based solely on developers plot plan.)
3) Perimeter canal along Barnes Sound shoreline	9500 x 50 x 5 (Based solely on developers plot plan.)	87,963
	Total dredged	206,482 yd^3
	Total allowed by TIITF Permit No. 253.03-168	48,000 yd^3
	Amount evidently dredged in excess of permit (see footnote 1).	158,482 yd^3

[1]A large discrepancy can be noted in the total amount of material allowed by TIITF Permit No. 253.03-168 and the amount apparently dredged. The permit allowed only 48,000 cubic yards, whereas a note inscribed on the developers application plot plan indicated 97,500 cubic yards were to be dredged. However, our post-dredging depth recorder survey of the Hawk Channel entrance channel, (Fig. 2) indicates that it had been deepened to approximately -8 feet (average) below the natural bottom, or approximately -10 to 14 feet below MLW, whereas the allowed depth was only -8 feet below MLW. Our post-dredge depth, length, and width figures, combined with the developers proposed dimensions of canals (2) and (3) (Table 1) indicate that approximately 206,482 cubic yards were actually moved. This figure is 2.1 to 4.3 times the amounts noted respectively in the plot plan and the TIITF Permit.

of the shallow natural bottom and average axial depths along the completed canal. Depths were measured with a Raytheon Model DE-735 depth recorder at low tide. Diurnal tidal fluctuation normally does not exceed 2 feet.

To the north of the entrance canal as far as the patch reef (Fig. 2), the natural bottom was approximately 90 percent bare Key Largo Limestone bedrock, with a sparse population of sponges, bryozans, algae, and several genera of stress-tolerant coral indigenous to inshore locations (Porites, Siderastrea, etc.). Approximately 10 percent of the area was in widely scattered patches of Thalassia; the individual patches were not more than 20 feet in diameter, and within the patches the bottom was composed of loose, vegetatively trapped sandy-silt, usually making a layer less than 10 cm thick.

It was apparent that little sediment actually accumulates N. of the canal. Most fine sediment bypasses this area and accumulates either in deeper waters such as Hawk Channel, or is trapped vegetatively by the red mangrove fringe of Key Largo.

To the south of the canal—as far as the rounded promentory 0.3 mile south—the bottom was much more heavily vegetated. Lush, Thalassia covered 50-60 percent of the surface. In addition, thick unattached masses of bryozoa that roll about in the manner of tumbleweed obscure 16 percent, and various types of algae are aff xed to about 15 percent of the bottom. Limestone bedrock was exposed over approximately 5 percent of the area. Much of the bedrock was thinly covered by 2-3 cm tall growths of Halimeda, the platelets from which had accumulated in adjacent pockets in the bedrock. A few live patches of Siderastrea (15 cm diameter) were seen, with a moderate number of smaller individuals (5 cm diameter); all the Siderastrea colonies were actively secreting mucus and appeared healthy. A persistent linear band of healthy Porites divaricata paralleled the coast, approximately 100 feet offshore. Near the mangrove fringe decaying red mangrove leaves nearly covered the bottom, forming a wave resistant mat.

C. Progress of Dredging at Basin Hills and Comments on the Methods

To preserve the objective nature of the project, no communication was allowed between the members of our research project and the developers. Therefore, to determine the progress of the dredging, it was necessary for us to measure the length of the spoil fingers. This was done with a Signet electronic log, which registered to 0.01 n. mile (60 ft.). Results of 23 measurements between October 24, 1972 and October 24, 1973 are plotted against Project Days on Figure 3, on which October 23, 1972 is considered as Project Day 1. These measurements were combined with other forms of quantitative monitoring on each visit, and a narrative log of observations was also maintained.

The progress of dredging was far from linear and was in fact marked by surges of activity separated by inactive periods. The variable nature of the activity resulted, of course, in quite variable effects on water clarity. Some features observable on Figure 3:

1. During an initial extension phase (days 1-19) dredging advanced very slowly, because the volume of rock removed to reach project depth was greatest near shore. Following this initial phase, the rate increased rapidly.

2. Two stages of rapid extension were noted. During the first rapid stage (days 50-65) no turbidity diaper was used, and the dredge advanced at an approximate average rate of 76 feet per working day. This phase ceased abruptly at the end of 1972 (day 70), and a dormant period ensued for 5 1/2 months.

3. During the long dormant stage (days 70-206), the seaward end of the entrance canal was plugged while the dredge worked on the inland perimeter canals.

4. Work on the entrance canal resumed the middle of May 1973 (day 206), and for the first time a turbidity diaper was used. The canal extended rapidly during days 206-220 at an approximate average rate of 77 feet per working day.

5. The maximum length of 2000 feet was reached on or about June 1, 1973 (day 222). On this day, aerial photos and movies were taken of the dredge operation at its peak activity. In spite of a turbidity diaper, the photos show a linear plume that moved approximately 3000 feet ESE before curving to the NE and diffusing. The cut-back phase, in which the spoil was removed, began within several days thereafter.

6. During the maximum cut-back phase (days 262-291) the spoil fingers were removed at a rate of approximately 53 feet per working day. A turbidity diaper was used throughout the cut-back phase, but problems were often encountered with it, and large leaks were usually observed. Usually the leaks were at the corners where the anchor lines depressed the curtain, and turbid water leaked over the top.

7. By August 9 (day 291), the northerly spoil finger had been completely removed, and only 150 feet remained of the southerly finger. Turbid water leaked freely over the former position of the northerly spoil finger and along the shore, making the turbidity diaper ineffective.

8. The spoil was completely removed by approximately the middle of August (day 297). By September 7 (day 320) the dredge, bulldozer, and trucks were gone and the entrance and perimeter canals were open, connected, and functional. The project was completed.

9. Post-project data were collected on two additional trips, September 13 and December 13, 1973 (days 326 and 417), after which monitoring was terminated because no further activity seemed likely on the Atlantic side of Key Largo.

D. Concentration and Dispersal of Dredge Induced Fine Sediment

(1) Suspended sediment concentration near the source and the effect of a turbidity diaper—

Table 2 summarizes a number of plume measurements near the dredge. Since the dragline was actively working, and we did not have the cooperation of the operator, it was hazardous to sample the most turbid water generated as the bucket left the water. Thus the values may be somewhat less than the maximum.

The highest values actually measured, 212 and 120 mg/l, were both taken 2 feet outside of the edge of the turbidity diaper at places where "effluent" was escaping. Turbidity was obviously higher inside the diaper, as was intended. For example, on May 18, 1973, the concentration 2 feet inside the diaper was 66 mg/l, whereas along a continuous section of diaper the concentration in the water 2 feet outside was reduced to 18 mg/l within a background of 1-2.5 mg/l. However, five feet outside of the diaper at a leaky corner the fugitive water contained 38 mg/l.

On May 30, 1973 the diaper was leaking rather badly and water containing 212 mg/l, the maximum concentration detected in the project, was escaping over the edge. This leak formed a plume which was detected for 4038 feet to the NNE (Figure 4 and 5), the longest plume detected in the project.

The principal operational problems observed with the diaper, some of which could be corrected with better design or procedures, were:

(a) The anchor lines depressed the corners and edges, allowing effluent to escape and form a turbid plume. This condition was present nearly all the time. It could be corrected by increasing the buoyancy of the diaper corners. Or, the anchors could be attached to independent floats, set away from the diaper corners, with mooring lines from the floats to the

TABLE 2--MAXIMUM PLUME CONCENTRATIONS NEAR THE DREDGE

Date and (Project Days)	Concentration in Suspension (mg/l)		Location of Plume Sample and Remarks	Measurement Method[1]
	Plume	Background		
11 16 72 (25)	>40	1-2.5	200 ft. downcurrent from dredge. No diaper.	T-100
12 11 72 (50)	>40	2	200 ft. downcurrent from dredge. No diaper.	T-100
	48	1.4	138 ft. downcurrent from dredge	Scat.
12 26 72 (65)	>40	0.5-1	132 ft. downcurrent from dredge. No diaper.	T-100
05 18 73 (208)	66	1-2.5	2 ft. inside turbidity diaper	T-10
	18		2 ft. outside turbidity diaper; not in leaky area.	T-10
	38		5 ft. outside diaper at leaky corner	T-10
05 30 73 (220)	212	3	Over edge of diaper at leak.	T-100
06 01 73 (222)	37	2	30 ft. outside of leaky diaper.	T-10
	34		300 ft. downcurrent from leaky diaper edge.	T-10
08 07 73 (289)	22	2.5-5	186 ft. downcurrent from dredge, outside diaper.	T-10
	28		294 ft. from dredge in small turbid area nearshore.	T-10
08 09 73 (291)	120	1-2.5	Over edge of diaper at leak	T-10

[1]Measurement method abbreviations:

T-100 = 1 meter optical transmissometer _in situ_ (Hydro-Products Model 612).
T-10 = 10 cm. optical transmissometer _in situ_ (Hydro-Products Model 612).
Scat = Laboratory measurement of light scattering (Hach Model 2100A Turbidimeter).

diaper corners. Then the lengths of the mooring lines could be adjusted to reposition the diaper without frequent moving of the anchors.

(b) In the latter part of the cut-back phase, especially after the northerly spoil finger had been completely removed, large gaps occurred through which turbid water escaped. This condition existed on August 9, 1973, when water with 120 mg/1 was escaping, and the plume moved NNE along the shore for 0.5 n. mile (Fig. 17).

It seems that better positioning of the diaper, to enclose the northern spoil finger prior to its removal, would have prevented the leak on August 9. Poor operational procedure is indicated and should be corrected by better planning and supervision of future projects.

(c) The diaper does not filter the effluent water or cause the permanent removal of suspended particles. It merely forms a protected pocket of current-free water in which particles can gravity-settle to the bottom, hopefully into a sediment trap or "sink". The "sink" is actually the dredged canal bottom, and much of the fluffy sediment of interior canal bottom is of this origin. Therefore, unless the canal is dredged deeply enough to form a permanently wave-protected "sink", the fine sediment will be continually resuspended by waves, currents, and boat propellors after dredging ceases; it will gradually disperse over the area adjacent to the canal, contributing, in fact, to a chronic increase in inshore turbidity. The minimum "sink" depth required for permanent trapping of canal fluff depends on the orientation of the canal, its exposure to waves, tidal currents generated within its drainage basin, size of the boat traffic in the canal, and whether or not sediment-trapping vegetation (mainly Thalassia) colonizes the canal bottom. Because the "canal fluff" typically has the consistency of mushroom soup for many years after dredging, it does not form a favorable substrate for _Thalassia_. Typically, canal bottoms in which the fine dredge sediment has been trapped are not vegetated. The fluffy sediment forms a layer 2 to 5 feet thick that is, where found, evidence of very little current action or circulation in canal bottom waters. Thus, to cause the fluff to settle rather permanently, and thereby diminish the latent turbidity around dredge sites, the depth of canals dredged into exposed water bodies should exceed one-half the wave length of the normal storm waves of the area. A gross estimate of normal (non-hurricane) storm wave length at Basin Hills is 20 feet (which should be verified by actual measurement), indicating active resuspension if the canal bottom is more shallow than 10 feet. Of course, active tidal or other currents could easily effect flushing at much greater depths as could the prop-wash of large power boats.

In summary, it seems rather fruitless perhaps even inimical to longer-term water clarity, to confine the effluent within a turbidity diaper unless the entrance canal is dredged deeply enough to form an effective "sink" that will confine the "canal fluff" permanently. Otherwise, the fine particles of the fluff will merely be resuspended and dispersed by waves, currents, and prop-wash following completion of the canal, leading to a chronic increase in inshore turbidity.

(2) _Dispersal of the Dredge Effluent_—

(a) _Short Term Distribution_—The short term distribution of dredge induced surface turbidity was measured optically by towing a 1-m Hydro-Products Model 612 transmissometer along three or more traverse lines within 0.5 n. mile of the dredge. Measurements of percent light transmittance per meter of optical path (%T/m) were recorded automatically every 4 seconds by a Rustrak recorder.

Each days day's traverse grid required approximately 2 hours to complete, giving a reasonably synoptic view of turbidity distribution around the dredge site. Selected points along each record were corrected for instrumental non-linearity, and %T/m was converted to "optical mg/1" suspended sediment concentration. The latter conversion was made by reference to a working curve (Fig. 6) based on suspending known weights of dry, salt-free, <44 micron Pigeon Key lime mud in distilled water, which was circulated by several submersible pumps in a 250 liter test tank. Suspended sediment concentrations were then plotted on a map and contoured, using the traditional rules of contouring for extrapolation into unmeasured areas. Figures 4, 5, and 7-19 (a, b, c) indicate the transmissometer traverse tracks, dispersal pattern, and decline in concentration of surface suspended sediment away from the dredge site. Table 3 summarizes the stage of dredge activity, length of plume, and concentration of suspended material at 300, 600, 900, and 1200 feet from the dredge.

The shape and length of the plume varied greatly and is best expressed by the maps and tables. However, a few observations are described below; Table 3 contains an index to the appropriate Figure numbers:

1. The maximum detected length of the plume was 4038 feet, and the average length of the plume prior to completion was 2264 feet.

2. Surprisingly, the maximum plume length (4038 feet), and two of the other three relatively long plumes (3072, 3180 feet) were produced with the turbidity diaper in use, but leaking. The other long plume (3120 feet) was produced without a diaper.

3. Long plumes were produced during both extension (3120, 4038 feet) and cut-back phases (3072, 3180 feet).

Table 3--Measurements of Surface Water Suspended Sediment Concentrations at Various Distances and Different Types of Dredge Activity

Date and Project Days	Remarks-dredge activity	Dispersal pattern, Fig. no.	Length of spoil finger (ft.)	Max. detectable length of plume (ft.)	Concentration of background in plume area (mg/1)	Approximate concentration (mg/1) in plume at various distances from dredge (ft.)			
						300	600	900	1200
10 24 72 (2)	Pre-dredge; no activity.	7b	0	0	2.7	---	---	---	---
11 16 72 (25)	Active extension; without diaper.	8b,c	144	1968	1.8	30	4.5	6	6
12 11 72 (50)	" "	9b,c	300	3120	4.0	40	40	40	19
12 26 72 (65)	" "	10b,c	1080	2100	0.5	40	40	3.5	0.6
03 22 73 (151)	Dormant past 3 mo.; waves reworking spoil.	11b,c	1080	1110	2.4	5	2.6	2.5	2.4
05 14 73 (204)	" "	12b	1080	(900)	2.5	6	4	2.5	---
05 18 73 (208)	Active extension; with diaper.	13b,c	1320	1770	2.2	5	2.7	2.4	2.7
05 30 73 (220)	" "	4,5	1980	4038	2.7	99	50	31	23
07 11 73 (262)	Active cut-back; with diaper.	14b	1440	(950)	3	7	5	3	3
07 23 73 (274)	" "	15b,c	960	3072	2.5	16	14	13	4.8
08 07 73 (289)	" "	16b	420	(2700)	2.4	9	5	3	3
08 09 73 (291)	Active cut-back; N. spoil finger removed.	17b	150	3180	1.8	30	6.3	6.1	4.9
09 13 73 (326)	Dredging completed; all spoil removed.	18b	0	(600)†	2.8	4.5	3	2.8	---
12 13 73 (417)	" "	19b	0	(1400)†	2.5	(7.5)	(6.5)	(6)	(5)

†No real plume, but area of turbid water flanking channel.

( ) = Approximation

4. During the dormant period, months after the last prior dredging, waves producted a low intensity turbid area around the spoil fingers and extending downcurrent for considerable distances (1110, 900 feet). The sediment concentrations in this "plume" were low (<10 mg/l), but represented a chronic increase in turbidity that persisted for about 5.5 months, until the spoil fingers were removed.

5. The plumes moved north and south about equally, governed by wind and tidal movements.

6. A plume exceeding the background by 50 mg/l at a distance of 300 feet from the dredge was detected only once, May 30, 1973. The plumes on December 11 and 26, 1972 probably also exceeded the 50 mg/l limit, but this cannot be proven because the 1-m transmissometer used on those days had a practical maximum limit of 40 mg/l.[2]

7. After dredging had been completed, an area of slightly turbid water persisted in the former spoil area for at least 4 months (Fig. 18, 19). The turbidity was only 5 to 6 mg/l greater than background, but represented a chronic increase in turbidity over the local inshore area. Drainage from the perimeter canal system, plus erosion of the bare bottom in the old spoil area, produced the turbid water.

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[2] Florida regulations limit the dredge effluent in Class 3 (recreational) waters to 50 Jackson Turbidity Units (JTU) above background, which is supposed to be the optical scattering effect produced by 50 mg/l of suspended fine quartz. However, we found that 83.5 mg/l of <44μ Florida Keys $CaCO_3$ mud are actually required to produce the same optical effect as 50 mg/l of quartz. On only two days did we measure plume concentrations more than 83.5 mg/l above background, May 30, and August 9, 1973; both times while a turbidity diaper was in use (Table 2).

Concentrations in mg/l, as used in this report, can be converted to JTU by the simple relationship JTU = $\frac{mg/l}{1.67}$. Aliquots of the same samples used for transmissometer calibration were fed to a Hach 2100A Turbidimeter to develop this relationship.

8. The turbidity-tolerance limits of the native organisms are not known with any certainty, thus it is necessary to make various assumptions as to the effects of the turbidity levels we measured in the area. Natural background concentrations as high as 5 mg/l were observed numerous times during the traverses (Dec. 11, 1972; March 22, May 30, July 11, July 23, August 7, Sept. 13, and Dec. 13, 1973); it is therefore assumed that the indigenous organisms are adjusted to at least that level. If it is further assumed that twice the common maximum produces a stress condition with regard to respiratory functions or photosynthesis, then 10 mg/l may represent a "critical value". On this tenuous basis, reference to the plume maps shows that water with 10 mg/l or more suspended sediment was confined to a radius of 0.15 n. mile (900 feet) of the dredge on all but two occasions (Dec. 11, 1972 and May 30, 1973). The maps also indicate that the effluent plume generally moved longshore rather than seaward.

Therefore, it is concluded that the prime area of possible concern from this type of dredging lies within a radius of 0.15 n. miles (900 feet) of the dredge, forming a rectangular area 0.3 n. miles (1800 feet) wide and as long as the spoil fingers. For the Basin Hills project, the area of prime concern measured 0.3 n. miles (1800 ft) wide by 0.33 n. miles (2000 feet) long, or 0.1 square n. miles.

9. Turbidity at the small coral patch reef 0.48 n. miles NNE of the Basin Hills canal site was measured 12 times on various traverse days and 3 additional times as spot stations (Table 4). The mean natural concentration during the project period was 2.25 mg/l, and the probable 2 standard deviation natural range was 0 - 4.75 mg/l; this range suggests that the 4.9 mg/l concentration observed on May 2, 1973 was very close to the natural maximum except during exceptional storms.

TABLE 4--TURBIDITY AT THE SMALL CORAL PATCH REEF 0.48n. MILES NNE OF THE BASIN HILLS ENTRANCE CANAL.

Date	Suspended sediment concentration at reef (optical mg/l)	Concentration in excess of natural non-dredge background on same day (optical mg/l)	Remarks
A. Traverses			
11 16 72	0.5	0	---
12 11 72	4.6	0	High concentration due to 25-30k SE wind previous day.
12 26 72	0.6	0	---
03 22 73	1.6	0	---
05 14 73	1.8	0	---
05 18 73	2.2	0	---
05 30 73	(3)	0	---
07 11 73	2.8	0	---
07 23 73	3.7	+1.1	2.6 mg/l background used in computing natural average.
08 07 73	1.8	0	---
08 09 73	2.3	0	---
09 13 73	0.9	0	---
12 13 73	2.0	0	---
B. Spot Stations			
10 24 72	(2.2)	0	Prior to dredging
05 02 73	4.9	0	No dredge activity for previous 5 months. High turbidity due to 16-20k ESE winds.
06 05 73	2.8**	0	Higher than normal concentration probably produced by divers.

	All observations	Natural obsv. only
No. of Obsv.	15	15
mean conc.	2.33	2.25
std. dev.	±1.30	±1.25
1s range	1.03-3.63	1.00-3.50
2s range	0.27-4.93	0.0 - 4.75
min. obsv.	0.5	0.5
max. obsv.	4.9	4.9

* = Background value of 2.6 used in computation of natural $\bar{x}$ and s.
** = Not included in mean or standard deviation.
() = Extrapolated from nearby data.

Natural turbidity at the patch reef was increased by dredge effluent on only one occasion—a 1.1 mg/l increase over a natural background of 2.6 mg/l on July 23, 1973. The turbidity diaper was in use, but leaking, and a plume moved northward (Fig. 15 b, c). Near the outer edge of the plume, along the western edge of the reef, a detached parcel of plume water was noticed, the concentration in the parcel was 5.1 mg/l, and its edge led to the 1.1 mg/l increase in concentration over the reef.

Therefore, considering the natural turbidity level and the measured spread of effluent from the dredge, it seems that the patch reef was too distant to have been affected by the Basin Hills dredging. In other words, a reef situated at least one-half mile from a hard-rock dredge project in the Keys is not likely to be affected. This conclusion coincides with the results of the biological team. They monitored the health of the patch reef at the initiation of the project (November 1972) and after its termination (November 1973). Based on a quantitative quadrant survey, they reported that no detectable changes had occurred and that the percentages of live and dead coral were identical before and after (Griffin and Antonius, 1974, and as reported orally by Arnfried Antonius on two occasions: (1) at the Coral Reef Conference and Workshop, Harbor Branch Foundation Laboratory, Ft. Pierce, Fla., Feb. 13-15, 1974; (2) at the Florida Academy of Science, 13th Annual Meeting, Orlando, March 21-23, 1974).

(2) Dispersal of the Dredge Effluent (cont.)—

(b) Longer Term Distribution—Distribution of the plume over longer periods was monitored by sediment traps. Trap locations and numbers are indicated on Figure 20; they were serviced at average intervals of 23 days. Each trap contained a pair of plastic containers, with a known collecting area; dimensions and construction are indicated in Table 5. Sediment retained in each trap was filtered over 0.3 micron porosity Gelman A glass fiber filters to remove excess water, washed, dried at 105°C, weighed, and the weight of sediment retained per unit of aperture area per day ($mg/cm^2/day$) was calculated. If the amounts retained in the two traps of the pair were reasonably similar, they were averaged. If they differed significantly, and the reason could not be deduced, it was considered that the trap had been tampered with, and results were discarded. We have no way of knowing the nature of the tampering, but suspect that some traps were pulled up by fishermen expecting lobster traps, used as anchoring points, etc. Sometimes the traps were completely removed. The tampering and loss problem was worse during some periods than others and the affected traps often formed clusters. All in all, a considerable amount of data was lost in this way, as is indicated on the maps that follow.

The traps furnished a method of measuring the sediment dispersal through periods when bad weather prevented more direct observation, and were quite effective in measuring the relative quantities sedimented. However, several peculiarities of sediment traps need to be realized:

1. The quantities reported are systematically low. This is because sediment particles do not, except in still water, settle purely vertically; their motion is a complex function of lateral transport by currents plus vertical gravity settling. Thus, in the Basin Hills area, lateral transport by currents is at a rate near 10 cm/sec., while 16 micron particles settle vertically at a rate of only 0.143 cm/second. The vectoral result is a trajectory of 0° 4.9' below the horizontal, toward a trap opening that is a flat ellipse of greatly reduced area. Thus, the amounts reported are a valid indication of relative sedimentation rates throughout the area, but are not absolute rates.

TABLE 5—DIMENSIONS AND CONSTRUCTION OF SEDIMENT TRAPS

A. Shape and size of aperture.

Shape: round.
Height of aperture above seafloor = 25.0 cm.
Diameter = 2.9 cm.
Area = 6.605 cm^2.

B. Shape and size of collection bottle beneath aperture.

Shape: square.
Size of base = 10.2 x 10.2 cm = 104.0 cm^2.
Capacity = 1.89 l (0.5 U.S. gallon).
Composition = polyethylene

C. Construction.

Two 0.5 gallon plastic milk bottles tied into the openings in a standard builders concrete block. Connected to a surface float with 0.25 inch polypropylene line which serves to lower and lift the traps.

2. The traps retained material that otherwise would have been swept out of the area by natural water movement and wafted to more permanent sites; thus, a "potential sedimentation rate" is actually measured. In fact, extensive underwater observation of the bottom north of the dredge site showed negligible retention of sediment on the bare bedrock surface over which much of the dredge effluent traveled; more was retained to the south because of the more abundant vegetation there.

For each trap period the "natural accumulation rate" at that time and place was subtracted from the "total accumulation rate", to yield the "excess accumulation rate". Thus, the "excess rate" is the fraction produced either directly by the dredge or by secondary effects such as erosion of spoil banks. The "natural accumulation rate" was deduced by drawing dashed contours approximately parallel to the coast, with spacing and values governed by accumulation rates at control traps located at the fringes of the area. This extrapolation is possible because natural turbidity increases generally from the shore toward Hawk Channel. Actually, the clearest water coincides approximately with the leeward (shoreward) side of an irregular zone of *Thalassia* that typically lies 15 to 30 meters offshore. From the *Thalassia* zone, turbidity increases in both directions, but the increase toward Hawk Channel is relatively the larger and only this seaward increase was considered in drawing the "natural accumulation" contours.

Several observations can be made from the "total accumulation rate" maps (Figure 21 to 34) and from the summary of Table 6:

1. Natural accumulation rates at each station fluctuated seasonally over a wide range (e.g. from 7 to 200 mg/cm^2/day along the canal axis 2100 feet from shore). These rates correlated generally, but not perfectly, with the shear stress

at the air/water interface as measured by the average miles per day moved by a given parcel of air (Table 6).

2. The patch reef corals (almost entirely Siderastrea siderans) are apparently adapted to widely varying natural turbidity and sedimentation rates. During a windy spring period (March 14 to April 18) the corals apparently cleared at least 125 $mg/cm^2/day$ from their surfaces; but during the calmer early summer (May 11 to July 9) the rate was less than 10 $mg/cm^2/day$.

As to the "excess accumulation rate" maps (Figure 35 to 48):

1. Detectable amounts of "excess" (i.e. > 1 $mg/cm^2/day$) rarely were observed more than 0.5 n. mile alongshore from the canal axis, or more than 0.33 n. mile seaward from the coast. Thus, the area of excess sedimentation attributable to dredging was normally less than 0.17 square n. miles.

2. Most of the above area was exposed to such small amounts of "excess" that it could hardly be considered significant. However, during six periods there was an inner area near the spoil fingers in which the excess accumulation rate exceeded 100 mg, three periods with excess 200 mg, and one period with excess exceeding 300 $mg/cm^2/day$. If the dredge effluent is, in fact, a significant stress factor then it must be most significant in these high-excess areas, so they warrant further consideration (Table 7).

Surprisingly four of the six high-excess periods (including one of the 200+ periods) occurred after the dredge had been inactive for long periods (days 85-96, 96-115, 143-178, 178-201). At these times the excess was produced by wave action reworking the spoil fingers during the windy winter and spring.

TABLE 6--VARIATIONS IN THE POTENTIAL NATURAL ACCUMULATION RATE AT THE BASIN HILLS DREDGE SITE

Project Days	Dates	Canal length at end of period (ft.)	Wind-(Avg. miles moved/ day)**	Natural accumulation rate (mg/cm²/day)* at the indicated locations								
				Patch reef	In cove at Sed. Trap 103-4	Canal axis, distance from shore (feet)						
						300	600	900	1200	1500	1800	2100
25-46	11 16 72- 12-07-72	275	35	3	0.5	1	2	3	4	5	6	7
46-67	12 07 72- 12 28 72	980	59	35	5	8	18	28	38	48	58	68
67-85	12 28 72- 01 15 73	1080	46	25	2	9	20	23	27	29	34	41
85-96	01 15 73- 01 26 73	1080	60	42	7	16	25	31	34	37	40	43
96-115	01 26 73- 02 14 73	1080	75	112	10	30	84	96	105	112	118	124
115-143	02 14 73- 03 14 73	1080	62	26	9	14	16	19	22	26	29	32
143-178	03 14 73- 04 18 73	1080	89	125	9	21	50	110	130	155	180	200
178-201	04 18 73- 05 11 73	1080	94	70	31	37	47	55	75	98	119	140
201-221	05 11 73- 05 31 73	1980	50	7	5	6	6	7	8	9	9	10
221-260	05 31 73- 07 09 73	1660	50	9	4	6	7	9	10	11	13	14
260-284	07 09 73- 08 02 73	740	37	12	4	6	8	9	13	16	18	22
284-318	08 02 73- 09 05 73	0	36	31	8	17	22	24	32	37	42	46
318-345	09 05 73- 10 02 73	0	13	32	8	19	26	33	40	48	55	64
345-367	10 02 73- 10 24 73	0	18	22	4	8	15	21	25	28	32	46
			Mean	39	8	14	25	34	40	47	54	61
			Std. dev.	±37	±11	±12	±22	±34	±38	±44	±50	±56
			1 s range	2-76	0-19	2-26	3-47	0-68	2-78	3-91	6-104	5-117
			2 s range	0-113	0-30	0-38	0-69	0-102	0-116	0-135	0-154	0-173

* = Minimum potential rates, valid relative to others in the same time period.

** = Based on U.S. Weather Bureau data from Hialeah, Florida, approximately 50 miles NNW of the dredge site.

TABLE 7--PERIODS WITH EXCESS ACCUMULATION RATES EXCEEDING 100 $mg/cm^2/day$.

Days	Fig no.*	Approx. area with >100 $mg/cm^2/day$ (square n. miles)	Max. excess rate detected	Dredge Activity
45-67	36	0.04	218	Active extension entire period.
85-96	38	0.0045	109	Inactive at least 2 weeks prior.
96-115	39	0.0091	146	Inactive at least 3.5 weeks prior.
143-178	41	0.07	266	Inactive at least 10 weeks prior.
178-201	42	0.022	161	Inactive at least 15 weeks prior.
284-318	46	0.038	389	Active Cut-Back entire period; turbidity diaper in place but not very effective due to large gaps.

* Areas of >100$mg/cm^2/day$ are stippled on the appropriate figures.

The other two high excess periods occurred with the dredge working. In the first of these (days 45-67), there was no turbidity diaper, and the dredge was actively extending the canal. During the second (days 284-318), the last parts of the spoil fingers were being cut-back by the dredge, and a large gap existed between the turbidity diaper and the shore; this gap was caused by poor operator technique, and it resulted in the highest accumulation rate of the entire project (389 $mg/cm^2/day$).

3. After completion of the canal, an area of excess accumulation persisted for at least several months, as was also indicated by the transmissometer traverses described previously. During the period immediately following completion (days 318-345), the excess was largely due to mildly turbid water draining from the interior canal system. In the final period monitored (days 345-367), the excess was spread more widely, and its source was not definite; it may have been caused by a combination of several sources: (a) canal drainage, (b) reworking of the bare bottom beneath the former position of the spoil fingers, or (c) thinning of the mangrove fringe and isolation of the swamp from tidal influx by spoil emplacement, so that the sediment-trapping function of the coastal swamp system was impaired. This final period was the only one in which the greatest accumulation was not at trap 111-112, at the inner end of the canal. Now the maximum shifted to trap 103-104, in the mangrove-fringed cove, and it was also high at the two traps immediately seaward of 103-104.

E. Composition of the Dredge Plume and an Independent Quantitative Method for Measuring Dispersal of Effluent

The dredge plume represented calcareous fine debris produced by comminution of the Key Largo Limestone and the release of fine debris from pores and other cavities in the rock. Its production was incidental to the excavation of the rock, and the quantity of produced fines varied considerably during the life of the project as different facies of the limestone were mined, producing plumes with varying suspended matter concentration(Table 2).

Suspended matter from the plume was collected on several days, concentrated onto cellulose membrane and/or glass fiber filters, and subjected to various analyses. Techniques used included x-ray diffraction, light microscopy, scanning electron microscope, atomic absorption, and combustion at 950°C. Results are discussed in the several sections that follow.

(1) Chemical and Mineralogical Composition of the Dredge Plume and Natural Suspended Sediments—

In Table 8, the chemical and mineralogical compositions of representative plume and natural suspended sediment samples from the same area are compared. Both samples contained approximately 96% $CaCO_3$ and 4% organic matter. Also, the fractions soluble in 2 N HCl contained small but differing amounts of Sr, Al, Mg, and P.

The differing amounts of Sr and Mg in the dredge plume as opposed to the natural samples results from the differing crystal structures of the $CaCO_3$ component, and the differing abilities of these structures to incorporate ions that proxy for Ca. Thus, the $CaCO_3$ component of the dredge plume is rather pure rhombohedral $CaCO_3$ (normal calcite) with insignificant proxying; in contrast, the natural sample contains large amounts of orthorhombic $CaCO_3$ (aragonite) in which Sr proxying is important, and unstable, magnesium-rich rhombohedral $CaCO_3$ (Mg-calcite) in which Mg proxying is significant. The greater amounts of Sr and Mg in the natural sample are therefore due directly to their higher contents of aragonite and Mg-calcite.

Table 8--Chemical And Mineralogical Composition Of Dredge Plume And Natural Materials

Collected From The Basin Hills Project Area--North Key Largo

Location and Remarks	Weight Percent										
	$CaCO_3$	Organic Matter	Total C	Normal Calcite	Aragonite	Mg - Calcite	Sr	Al	Mg	P	Ca
Plume: 111672-1339. 200 ft. downcurrent from dredge; suspended sediment.	96.3 (c)	3.7 (d)	13.6 (a)	75 (e)	25 (a)	0 (e)	0.20 (b)	1.6 (b)	0.8 (b)	0.0011 (b)	n.d.
Natural: 111672-1533. At Marker 31 BH, Hawk Channel; Suspended sediment.	95.8 (f)	4.2 (d)	15.2 (a)	2 (e)	55 (e)	43 (e)	0.45 (b)	1.7 (b)	1.9 (b)	0.0069 (b)	38.4 (b)

Methods:
(a) Weight loss on combustion at 1000°C.
(b) Atomic absorption on 2N HCl Leachate.
(c) Difference between 1000° and 700°C weight loss.
(d) By difference.
(e) X-ray diffraction, using the working curves of Taft and Harbaugh (1964), and other techniques listed by Griffin (1971).
(f) Computed from Ca.

The mineralogical and chemical variations noted are normal and typical for situations of this type (Chave, 1952; Taft and Harbaugh, 1964; also Table 9). Marine plants and animals extract the ionic components of $CaCO_3$ from seawater and precipitate $CaCO_3$ polymorphs that would be unstable under purely inorganic temperature and pressure influences. These structures are used as stiffeners in the living tissues. The exact structural makeup of the $CaCO_3$ varies with the organism and to a much lesser extent with external temperature and pressure. However, the two principal components of biogenically generated $CaCO_3$—aragonite and Mg-calcite—are both unstable, and upon death of the organism, they alter gradually to a more stable form (normal calcite).

(2) Mineralogical Composition of the Key Largo Limestone—

Natural conversion of Mg-calcite and aragonite to normal calcite typically requires a time period on the order of 10^3 years, at a rate that depends on the post-depositional physical conditions. In the case of the 115,000 to 145,000 year-old Key Largo Limestone (Osmond, et al, 1965; Broecker and Thurber, 1965), the Mg-calcite has all reverted to normal calcite, whereas, part of the aragonite has not. The consistent lack of Mg-calcite from Pleistone limestones such as the Key Largo, and in the dredge rubble derived from such limestones is illustrated in Table 9.

(3) Use of Mineralogic Tracers to Map Dredge Effluent Distribution—

Because the natural suspended sediment of the area adjacent to the dredge site is relatively rich in Mg-calcite (35 to 54%), whereas the plume is devoid of Mg-calcite, it has been possible to develop and utilize a mineralogical method for distinguishing the proportion of dredge material contributed to the Basin Hills project area. The method is applicable to suspended material

TABLE 9--MINERALOGICAL COMPOSITION OF THE KEY LARGO LIMESTONE AND OTHER PLEISTOCENE LIMESTONES OF THE SOUTH FLORIDA-BAHAMAS REGION--COMPARED WITH SUSPENDED SEDIMENT FILTERED FROM THE BASIN HILLS DREDGE PLUME--ALL BASED ON X-RAY DIFFRACTION ANALYSIS.

Location	Normal Calcite	Aragonite	High Mg Calcite	Dolomite	Wt. % insoluble in 33% HCl	No. of Spl.	Reference
A. Dredge rubble from Key Largo Ls.							
Key Largo, Worlds Beyond Resort	77	23	0	0	0.02	1	This paper
Key Largo, Basin Hills Canal	100	0	0	0	0.06	1	" "
Key Largo, Ocean Reef Shores	100	0	0	0	0.54	1	" "
Windley Key, Tropic Winds Motel	81	19	0	0	0.27	1	" "
L. Matecumbe, Port Antigua	84	16	0	0	0.02	1	" "
Long Key, Layton P.O.	97	3	0	0	0.28	1	" "
B. Key Largo Ls., in situ:							
Key Largo, K. Largo Waterway	69-100	0-31	0	0	----	8	Stanley (1966)
Windley Key, quarry	57-100	0-43	0	0	----	12	" "
C. Other Pleistocene Limestones							
Cay Sal Bank, S. Anguila I.	45-67	33-55	0	0	----	3	Brown (1972)
" " " , E. Water Cay	58-60	40-42	0	0	----	2	" "
Bahamas, Andros I.	57	43	0	0	----	1	Goodell and Garman (1969)
" , N. Providence I.	36	64	0	0	----	1	" " "
"Pleistocene Carbonate Rocks from Florida"	27-100	0-73	0-19*	0	----	19	Stehli and Hower (1961)
D. Basin Hills Dredge Plume-Suspended Sediment.							
November 16, 1972	75	25	0	0	----	1	This paper
December 11, 1972	87	13	0	0	----	1	" "

*Only 2 samples contained high-Mg calcite; the other 17 contained 0%; location of the 2 abnormal samples was not specified.

concentrated by filtration of sea water as well as to the longer term collections in sediment traps. The basic parameter is the relative proportion of normal to Mg-calcite, expressed as the ratio: % normal calcite/ % Mg-calcite +1). The ratio is then compared to a working curve (Figure 49) to derive the % dredge material. End members of the working curve are composed of 2 dredge plume suspended sediment samples and 28 natural suspended sediment samples from Hawk Channel at the sites and times listed in Table 10. The accuracy is $\pm$10% of the dredge material reported.

Figures 50 to 63 indicate the percentage of dredge material collected in each trap during the various sediment trap periods; trap locations are on Figure 20. These maps constitute an independent method of assessing the long term spread of the dredge effluent. As a further interpretive aid, on Figures 64 through 67, the percentage of dredged material in each trap is plotted graphically as a function of project days, and the degree of dredge activity is also indicated.

From these maps and time-dependent plots, several trends are evident:

1. All of the traps showed compositional variations that directly reflected the type and amount of dredge activity in their vicinities.

2. In the early extension stage, the dredge material was collected mainly at the inshore traps (111-112, 103-104, and 105-106) where dredge-derived fallout composed 30-50 percent of the total sediment accumulated. Traps further offshore showed much smaller proportions—usually less than 10 percent—but some dredge material accumulated in all of the traps.

3. During the long inactive phase—project days 70 to 207—the proportion of dredge material accumulated in the traps gradually declined toward zero. At most of the outer stations, the dredge-induced fallout did,

TABLE 10—SUSPENDED SEDIMENT SAMPLES USED IN CONSTRUCTING FIGURE 49 BASED ON X-RAY DIFFRACTION ANALYSIS USING GLASS FIBER FILTER MOUNTS OF FILTERED BULK WATER SAMPLES, SOLUBLE SALTS REMOVED.

Location Date-Time	% Normal Calcite	% Aragonite	% High Mg Calcite	% Calcite / % Mg Cal.+1
(A) Caesar Creek abeam of Christmas Point.				
01 19 73 - 1420	7	50	43	0.16
02 07 73 - 1212	6	51	43	0.14
(B) Hawk Channel Marker "31BH".				
12 28 72 - 1330	5	52	43	0.11
01 15 73 - 1515	9	53	38	0.23
05 18 73 - 1432	8	50	42	0.19
(C) Hawk Channel Marker "33".				
01 25 73 - 1210	12	44	44	0.27
(D) South Sound Creek Marker "2".				
12 30 72 - 1005	11	36	54	0.20
01 18 73 - 1135	6	42	51	0.12
01 23 73 - 1416	14	47	40	0.34
(E) Hawk Channel Marker "35", Mosquito Bank.				
12 30 72 - 1040	4	50	46	0.09
01 18 73 - 1222	8	47	45	0.17
02 10 73 - 1445	4	53	43	0.09
06 1 73 - 1007	21	37	42	0.49
07 19 73 - 1305	7	54	39	0.18
09 12 73 - 1000	3	53	43	0.07
10 17 73 - 1500	7	56	38	0.18
12 04 73 - 1130	3	53	43	0.07
12 05 73 - 1035	3	50	48	0.06
(F) Hawk Channel Marker "39", Triangles Reef.				
11 1 72 - 1335	11	39	51	0.21
03 20 73 - 1237	15	47	39	0.38
04 09 73 - 1355	13	48	39	0.33
05 22 73 - 1315	26	39	36	0.70
06 15 73 - 1301	14	49	37	0.38
07 19 73 - 1635	10	49	41	0.24
08 15 73 - 1719	18	46	35	0.50
09 12 73 - 1301	21	43	35	0.58
10 25 73 - 1230	8	43	49	0.16
12 05 73 - 1355	7	47	47	0.15
ALL ABOVE:				$n = 28$ $\bar{x} = 0.24$ $s = 0.28$ 1s range ≈ 0 to 0.52

TABLE 10 (CONT.)—SUSPENDED SEDIMENT SAMPLES USED IN CONSTRUCTING FIGURE 49 BASED ON X-RAY DIFFRACTION ANALYSIS USING GLASS FIBER FILTER MOUNTS OF FILTERED BULK WATER SAMPLES, SOLUBLE SALTS REMOVED.

Location Date-Time	% Normal Calcite	% Aragonite	% High Mg Calcite	% Calcite / % Mg Cal.+1
(G) Dredge Plume, Basin Hills Canal, Key Largo.				
11 16 72 - 1339	75	25	0	75.0
12 11 72 - 1550	87	13	0	87.0
				$\bar{x}$ = 81.0
(H) Dredge Rubble from middle and upper Keys.				
Key Largo, Worlds Beyond	77	23	0	77.0
Key Largo, Basin Hills canal	100	0	0	100.0
Key Largo, Ocean Reef shores	100	0	0	100.0
Windley Key, Tropic Winds	81	19	0	81.0
L. Matecumbe, Port Antigua	84	16	0	84.0
Long Key, Layton P.O.	97	3	0	97.0
				n = 6
				$\bar{x}$ = 89.8
				s = $\pm$ 10

in fact, reach zero; but at some traps closest to the spoil fingers (111-112; 103-104), the accumulated sediment continued to contain 20-35 percent dredge-type material. Since the dredge was dormant, this dredge-type material must have come from erosion of the spoil fingers and/or continued migration of some of the fine debris that had previously sedimented onto the bottom. The same reworking effect was noted in the previous discussions of the transmissometer traverses and trap weights during the inactive period.

4. When dredging resumed about day 250, now with a turbidity diaper, the proportion of dredge material again rose to the 20-40% level in traps close to the canal (101-102, 123-124). The levels were as high as in the early extension stage that used no diaper.

5. The resumed extension phase with diaper (after day 250) had a slightly greater effect on the two trap stations astride the patch reef (129-130, 131-132) then had the earlier extension, diaperless phase. However, at both times, the dredge-induced fallout at the patch reef stations was less than 10 percent of the total.

6. Dredging was completed by approximately day 320. However, most of the traps, including those near the reef, continued to accumulate some dredge material through at least the day 345-367 period. At the outer stations, the dredge contribution was in the 5 to 20 percent range. However, at two inshore stations (103-104, 111-112), dredge material still furnished 20 to 30 percent of the total.

7. By projecting the trends that developed after completion of the project, it can be predicted that the composition of the suspended material should, within a period of 100 days or so, return to normal at the outer stations (129-130, 131-132, 119-120, etc.). But, the compositional change may persist for longer periods, perhaps permanently, at some stations close to

shore that will receive continual runoff from the rubble-filled area less than 25 feet landward of the mangrove coastal fringe (e.g. 111-112, 103-104, etc.).

F. Effects of the Dredge Effluent on Biota

(1) Effect on the Coral Patch Reef—

A full description of the biological analysis of the patch is not possible in this report because the project's coral specialist (Arnfried Antonius) plans to publish his results elsewhere. However, preliminary results have been presented orally on two occasions: (1) to the Florida Academy of Science at the Annual Meeting in Orlando (Griffin and Antonius, 1974), and (2) at the Coral Reef Conference and Workshop of the Harbor Branch Foundation Laboratory, Ft. Pierce, Florida, February, 1974, which a number of reef workers were invited to attend. On both occasions, and in a personal communication of September 11, 1974, Antonius reported that, in his opinion, the patch reef is in a stable healthy condition and did not undergo any detectable change during the year of nearby dredging.

Following termination of dredging in November, 1973, a quantitative line transect survey of the reef disclosed that 72% of the coral was alive and 28% dead. Antonius considers this partially dead condition to be typical and normal for the highly stressed inshore reefs under natural conditions.

The 400 square meter inner patch reef is composed almost entirely of Siderastrea siderea, which constitutes 94% of the reef corals. (A. Antonius, personal communication of September 11, 1974). Antonius' finding is particularly interesting in view of earlier experimental work by Franzisket (1970) on coral metabolism. Franzisket reported that Siderastrea tolerates considerably lower dissolved oxygen concentrations than do typical corals of the outer reefs; he related this important difference to the lower metabolic rate of Siderastrea and other large-polyped genera. It can therefore be projected that the lower metabolic rate of Siderastrea would allow it to selectively withstand other stresses and lead to its dominance on the inner patch reefs.

The potential natural physical stresses of the inshore patch reefs of the Florida Keys include low winter and high summer water temperatures, relatively high turbidity (compared to the outer reefs), and the possibility of partial exposure during very low hurricane tides. Exposure to large fresh water influxes from streams, a severe, even lethal, stress factor after exceptional rains in Jamaica (Goreau, 1964), Hawaii (Banner, 1968), Tahiti (Crossland, 1928), and Australia (Rainford, 1925), is not a serious threat in the Keys because of the insignificant size of the land area and the lack of stream drainage. Of these potential stresses, low water temperatures seem the most serious, and some of the temperatures we measured during the 1972-73 winter were, in fact, below the 20°C commonly considered as the minimum temperature for hermatypic corals. However, MacIntyre and Pilkey (1969) consider the minimum temperature to be approximately 10°C for tolerant types such as Siderastrea and Solenastrea. The lowest temperature actually measured in the dredge area was 15.9°C, but this was very close to shore; 16.2°C, was the lowest measured close to the Siderastrea patch reef (Table 11).

The conclusions of Antonius regarding the stable, rather healthy condition of the control patch reef, and in particular its lack of damage by dredging, correlate well with the sedimentological data reported here. The amount of dredge-induced suspended material that actually reached the patch reef was very small, as documented by: (1) quantities collected in sediment traps, (2) transmissometer surveys of instantaneous distribution, and (3) the composition of material that accumulated in traps near the patch reef. Thus, the amounts of material that reached the patch reef must have been sub-lethal.

(2) Effect on Sea Grasses, and Other Organisms of the Inshore Area—

In April 1973, approximately in the middle of the dredge project, the inshore grass flat area was examined underwater by the sedimentological group for several days in order to establish the condition of the seagrasses and other benthos after a considerable amount of dredge effluent had been generated. The area of interest extended from the red mangrove fringe to 300 feet offshore, and extended 1800 feet north and south of the canal.

To the north of the spoil fingers, the bottom was approximately 90% bare limestone, with some scattered patches of *Thalassia* less than 20 feet in diameter. These patches had acted as natural sediment traps, but the total thickness of unconsolidated sediment in the grass patches was less than 10 cm (4 inches); this thickness is certainly not abnormal, and is only slightly greater than the minimum of 9 cm needed to allow extension of *Thalassia* rhizomes (Scoffin, 1970). The grass had a lush aspect and appeared quite healthy and unaffected by the nearby dredge project. The bare limestone surface had a sparse population of sponges, bryozoa, algae, and a very few corals of genera indigenous to the nearshore area, such as *Porites divaricata*. All of the coral colonies were actively secreting mucus, and the other organisms seemed quite healthy and unaffected by the dredging.

To the south of the spoil fingers, 60-100 ft. offshore from the mangrove fringe, the bottom was much more vegetated than on the north. Lush, dense, apparently healthy *Thalassia* covered 50-60% of the bottom. The remainder

TABLE 11--MINIMUM TEMPERATURES MEASURED IN THE BASIN HILLS AREA - UPPER KEY LARGO - WINTER OF 1972-73

Date-Time	Location	Sampling depth (ft.)	Water Temp. (°C)		Air Temp. (°C)		Remarks
			Surface (1 ft.)*	Bottom*	Basin Hills*	Islamorada**	
12 28 72-1100	Sed. Trap 111-112	1	16.8	----	17.9	----	Waning stage of cold front
12 28 72-1145	" " 103-104	2	17.6	----	18.2	----	-------------------------
12 28 72-1150	" " 105-106	3	16.8	----	----	----	-------------------------
12 28 72-1200	" " 107-108	5.5	18.0	----	18.6	20.0	Islamorada temp. at 1200
12 28 72-1330	Hawk Channel, Mkr. "31BH"	13	20.5	20.3	20.3	----	-------------------------
01 15 73-1345	Sed. Trap 111-112	2	16.5	----	16.0	----	Waning stage of cold front
01 15 73-1230	" " 125-126	2.5	15.9	16.1	15.4	15.0	Islamorada temp. at 1200
01 15 73-1335	" " 103-104	2.5	16.9	----	16.1	----	-------------------------
01 15 73-1500	1000 ft. offshore; 50 ft. from canal end	5	16.4	----	16.2	15.6	Islamorada temp. at 1500
01 15 73-1130	Sed. Trap 127-128	5	16.2	----	14.2	----	Near <u>Siderastrea</u> patch reef 0.45 n. mile N. of canal
01 15 73-1515	Hawk Channel, Mkr. "31BH"	12	17.8	----	17.5	----	-------------------------

* = Measured with thermister calibrated against Hg thermometer

** = Reported at 3-hour intervals - U.S. Coast Guard Station - Islamorada. Data from U.S. Weather Bureau.

was covered by mobile masses of bryozoa that gently swayed back and forth in a layer approximately 20 cm (8 inches) thick, and dense Thalassia and other fixed forms that could be glimpsed through gaps in the layer. The same bryozoan layer had been observed here and elsewhere along the shore of upper Key Largo in early October 1972, prior to the start of dredging. Masses of algae covered approximately 15% of the bottom, apparently forming a sediment trap, but much less effectively than the Thalassia. Bed rock surface was exposed over about 5% of the area, often largely covered by 2-3 cm (1 inch) growths of Halimeda, the platelets from which were accumulating in adjacent depressions. Penicillus and Udotea were also present, the latter with relatively large fans up to 10 cm (4 inches) across. Six patches of Siderastrea with a diameter of 15 cm (6 inches) were seen scattered throughout the inshore area, including within 20 feet of the spoil finger; all were actively secreting mucus and appeared healthy. Along the mangrove fringe, the bottom was partly covered by blackened, decaying mangrove leaves; these sometimes form a continuous mat on the bottom.

Further offshore, about 300 feet from the mangrove, much Porites divaricata was observed, forming a linear zone parallel to shore. Individual limbs were about 15 cm (6 inches) long and formed intertwined masses rising 5-10 cm (2-4 inches) above the sea floor. Some of the colonies appeared to have been undermined by currents, but none were covered with sediment, and they were actively secreting mucus and cleansing themselves. There was no indication of excess sediment from the dredge, although it was into this area that most of the dredge plumes flowed during the early stage of dredging.

One exception to the above was an irregular area centered approximately 600 feet SSW of the spoil and 60-100 feet offshore. Here, for a distance of several hundred feet, everything had a dead, sedimented appearance. The area was surrounded by healthy growth on all sides. Had it been adjacent to the spoil, where the sedimentation rate was highest, its poor condition would have been easier to understand; here, it can be assigned only questionably to dredge influence.

Along the base of the spoil finger, numerous small fish were seen occupying cavities in the rubble. Moss was beginning to cover the spoil in the intertidal zone. All in all, there was no apparent adverse effect of the former turbid plume from the dredge except possibly in the isolated area mentioned above. Most of the fine sediment appears to have bypassed the area, being trapped within the mangrove fringe on flood tides, or escaping into Hawk Channel on the ebb.

IV. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE DREDGE PROJECTS

A. Summary

A typical "hard-rock" dredge-fill project on the Atlantic side of Key Largo was monitored for 390 days in order to document the amount of suspended sediment produced, its distribution, and the effects on water clarity and benthos near the dredge. The total project involved excavation of a 2000 x 50 x 10 foot entrance canal into Hawk Channel, plus 15,500 feet of perimeter and other interior canals; only the entrance canal was monitored in this study, as it had the greatest potential for detrimental effects on water clarity and biota. To insure the unbiased nature of the study, there was no cooperation or contact of any kind between the research team and the developers.

Effects of dredging on water clarity, and on the potential sedimentation rate, were determined by three independent methods:

1. The short term distribution of the dredge plume was measured 15 times by towing an optical transmissometer along a traverse grid surrounding the dredge site; results were converted to optical equivalent suspended matter concentrations in mg/l and presented as concentration contour maps and concentration vs. distance plots.

2. The longer term potential sedimentation rate was monitored by an array of 18 sediment trap stations, each of which contained a pair of collectors. The traps were serviced at average 23-day intervals. Natural variations in concentration, mostly related to seasonally varying wind stresses, were subtracted from total accumulations by a controlled contour method.

Resultant "excess accumulations", due directly or indirectly to the dredge, were calculated in terms of $mg/cm^2/day$; values were contoured and presented as maps of dredge fallout distribution.

3. The $CaCO_3$ mineralogy of the dredge effluent differed significantly from that of the natural Hawk Channel environment. A quantitative method, based on X-ray diffraction analysis, was developed to distinguish the percentage of dredge-derived sediment in each sediment trap collection. Results, in terms of % dredge material, are presented on maps for 15 periods of dredge operation.

Data from the above three methods re-enforced one another and allowed the extent and amount of excess dredge-derived suspended sediment to be clearly defined, on both a short (2-hour) and a longer term (weekly or monthly) basis.

Due to the proximity (0.48 n. mile) of a small patch reef, it was possible to use the health of the reef as a biologic indicator of dredge effects. This reef was observed and measured by a coral specialist during dredging and following its completion. The health of seagrasses and associated benthic organisms was observed in a reconnaissance manner.

B. Conclusions

From the above measurements and observations, the following were concluded:

1. The dredge generated turbid plumes that varied in concentration near the source from approximately 37 to 212 mg/l at the water surface. Background turbidity at the same times varied from 2 to 3 mg/l.

2. The maximum distance to which the plume could be detected with a 1-m transmissometer, sensitive to variations of approximately 1 mg/l (approximately 1 ppm), varied greatly at different stages of the project. During an active

extension stage without a diaper, it extended from 1968 to 3120 feet; with a diaper from 1770 to 4038 feet.

During active spoil removal with a diaper, the plume extended from 950 to 3180 feet. A dormant period of approximately 4 1/2 months was interspersed, during which the spoil was eroded, causing a low intensity plume detected for 900-1100 feet. After completion of dredging, an area of mildly turbid water remained, and this was detectable for a radius of 600-1400 feet.

However, through the various stages mentioned above, the area of relatively intense plume, greater than 40 mg/l, rarely extended more than 300-600 feet from the dredge.

Concentration vs. distance plots show that the plume suspensate settles normally, with surface concentration declining in a logarithmetic manner and gradually fading into the background turbidity. In general, the area of plume influence rarely exceeds the limits of an area extending 0.3 n. mile alongshore and 0.33 n. mile offshore, or 0.1 square n. mile.

3. The turbidity diaper was capable of significantly reducing the fugitive concentration in the plume. For example, 2 feet inside the diaper, concentration was 66 mg/l, whereas, 2 feet outside it was only 18 mg/l. However, gross leaks in the diaper were noticed frequently, especially at the points to which anchors were attached. At these leaks, concentrations as high as 120 mg/l were measured in the fugitive plume. Other gross leaks were noted when the diaper was not properly repositioned to follow the dredge. Therefore, it is concluded that turbidity diapers need to be redesigned to eliminate leaks, and that operators need to exercise more attention to their proper positioning.

Also, the diaper is of little value unless the canal is dredged below wave and current base, so that it can act as a permanent trap for the effluent. Otherwise, the fine debris that settles behind the diaper will be re-suspended and cloud the water following completion of the project, producing latent increases in turbidity of the inshore waters.

4. Very little dredge effluent actually reached the coral patch reef 0.48 n. mile NNE of the canal; this was shown by all three independent types of measurement. On only one occasion was surface turbidity at the patch reef actually increased by the dredge—a 1.1 mg/l increase over a background level of 2.6 mg/l. At that time the turbidity diaper was in use but leaking badly. The biological teacm could detect no abnormal changes in the reef during the project year. Likewise there was no detectable influence of the dredge on the sea grasses or other inshore biota near the canal, except denudation of the parallel strips used for the spoil fingers. Otherwise, the sea grasses and scattered inshore corals tolerated the increased turbidity without apparent change.

5. Natural turbidity varied moderately in the dredge area, from 0.5 to 4.9 mg/l at the control patch reef 0.48 n. miles to the NNE, and up to approximately 7.5 mg/l near the eventual end of the canal. These natural variations are related to wind stress, resulting in higher turbidity during the winter and spring.

6. Sediment trap studies indicated that the corals at the patch reef, which are almost entirely <u>Siderastrea siderea</u>, must have cleared at least 125 mg/cm^2/day of fine sediment from their surfaces during March and April 1973: the dredge was inactive during this period and the sediment at the reef was almost entirely of natural origin. This value can be compared to the artificial excess fallout rates attributed to the dredge and affecting the bottom close to the

spoil fingers: during six test periods of several weeks each, the excess fallout near the spoil fingers exceeded 100 mg; for three periods it exceeded 200 mg; and for one period it exceeded 300 $mg/cm^2/day$. (No studies have been made to document the actual effect these higher rates would have on the coral species of the inner patch reefs; the effect of turbidity on corals in general is very poorly known.) Surprisingly, four of these "high periods" occurred when the dredge had been inactive for months, and were produced by waves eroding spoil during the windy winter and spring.

7. Zones of excess accumulation migrated as the spoil fingers were extended and then cut-back. Thus, the zone of potential impact shifted, and only the trap within 100 feet of the inner end of the canal was affected through the whole project period. The shifting of zones probably reduced the potential impact on the benthos at any one place.

8. The fact that the dredge project extended over a time period of a year, with an intervening inactive period of approximately 5 months, was a favorable biologic factor. Thus, fine sediment generated by the dredge during the first phase had time to disperse before material from the second phase arrived, lessening the period of continual interaction.

9. Waves and currents wafted nearly all of the fine grained dredge effluent out of the project area. The ultimate fate of this material is not known with any certainty. It is presumed to have been trapped in part by the sea grasses, in part trapped by the fringing red mangrove swamp, and in part merged into the relatively high turbidity of the Hawk Channel; in interior canals much similar dredge sediment is trapped within the canal itself, forming several feet of fluffy sediment over the canal bottoms.

10. Compared to hydraulic dredging, "hard-rock" dredging as practiced at Key Largo has less impact on water clarity, sedimentation rates, and biota. This is largely because the concentration in the plume is much lower (a few hundreds of mg/l maximum vs. several thousand in hydraulic dredging). Also, the material being dredged is the rather inert Key Largo Limestone, which is less apt to contain pesticides, toxic metals, or oxygen-demanding organic debris than is the natural suspended sediment of Hawk Channel. The particles in the plume are greater than 95 percent $CaCO_3$ in the form of stable calcite and aragonite. The dredge material settles at a rate that does not differ significantly from the natural suspended material of the area.

C. Recommendations Concerning Future Dredge Projects in the Keys

Because dredging of the entrance canal at Basin Hills appears to have had no detectable impact on the coral patch reef 0.48 n. miles to the NNE or on the remaining grass flat areas, it seems reasonable that future dredging regulations in the Keys and other coral reef areas could use this project as a minimum model, at least until it is proved that the system can tolerate greater stresses. Based on this general philosophy, it is suggested that future regulations include consideration of these criteria prior to approval:

1. Significant reefs composed of hermatypic corals, and more than 20 percent alive, within one n. mile of the proposed canal must be located and mapped by diving scientists. Canals and related temporary or permanent spoil areas should be positioned so as to approach no closer than 0.5 n. mile to such reefs in order that they be protected from excess sedimentation. The more or less continuous linear zones of low (less than 1 foot high) non-reef forming *Porites divaricata* and other similar corals that occur within several hundred yards of shore should not be included in this restriction.

2. Locations where the surface of the nearshore bottom is composed predominantly of bare limestone bedrock should be favored for entrance canals, and areas of significant Thalassia beds should be avoided. In this way, the sediment trapping ability of the Thalassia will continue to aid in water clarification.

3. Also to aid in sediment trapping and water clarification, a fringe of red mangrove should be preserved along the shoreline, and care must be taken to preserve its vitality during and after dredging. The width of this zone should be determined by future research; for the present it is suggested that it be at least 100 feet, or no less than the pre-existing width if that should be less than 100 feet. (The natural width of the mangrove fringe along Key Largo varies from approximately 60 feet to several hundred yards; it is easily discerned on color aerial photos.)

All spoil shall be deposited no closer to the coastline than the width of this fringe. There should probably be no objection to stilt or catwalk structures, or piers over parts of this fringe zone, so long as they do not involve removal of vegetation or otherwise interfere with healthy growth of the mangrove.

4. The number of dredged entrance canals should be limited so as to avoid excessive turbidity during dredging, and also to avoid the low-level turbidity that persists after dredging. A periodicity averaging one entrance canal per linear mile of coast seems reasonable, with the actual canal site selected so as to avoid the live coral reefs and grass flats, which must be mapped, as prescribed in 1. above.

5. Between entrance canals, perimeter canals, separated from the coast by the mangrove fringe described in 3. above, seem on the whole to be a desirable alternative to an excessive number of entrance canals. However, legislation

seems necessary to force perimeter canal owners to allow new connections into them by adjacent developments. Perhaps entrance and perimeter canals should be dedicated for public use in the same way as streets in inland subdivisions.

The allowable depth of perimeter canals should be dictated by the depth required for adequate water exchange with adjacent natural open water bodies. Otherwise the perimeter canals quickly become oxygen depleted, with resulting fish mortality and diminished recreational usage. Also, adequate numbers of vents to open water must be provided for oxygen ventilation. It is suggested, in lieu of further research, that vents be provided every 200 linear feet of perimeter canal, and that these be open channels 3 feet deep and 10 feet wide to allow limited passage of small boats. These vents should not extend more than approximately 50 feet seaward of the mangrove fringe.

6. No additional artificial "cross-key" waterways should be allowed between the Atlantic side of the Keys and the Florida Bay, Barnes Sound, Card Sound, side. This restriction would prevent greater influx of the more turbid bay waters into the reef tract area. In addition to higher turbidity, the bay waters also undergo much greater seasonal temperature and salinity fluctuations than the Hawk Channel waters, and all of these factors are detrimental or even lethal to growth of coral and other sensitive organisms of the reef tract area.

7. The hard-rock dredge techniques described earlier, as employed at Basin Hills, produce much less turbid water than hydraulic dredging. Therefore, it is recommended that no other type of dredging be permitted in the Keys or similar areas elsewhere.

Also, because the rates of effluent generation and dispersal are important in assessing effects on water clarity and possible biologic damage, it is recommended that, in lieu of further research, the rate of dredging in the Keys be restricted to that at Basin Hills, i.e. approximately 570 cubic yards per 8-hour working day. In addition, the total rate of fallout should be monitored by sediment traps 100 feet away on both sides of the canal extension, and limited to a maximum 200 $mg/cm^2/day$, averaged over a one-week period. If the total fallout exceeds this amount, dredging should pause for one week, to allow the natural dispersive forces to clear the organisms of sediment.

8. Turbidity diapers seem beneficial only if the dredge operator repositions them frequently, so as to close gaps. Attention to this seems especially necessary, in the final phase, when one of the parallel spoil fingers has been completely removed, leaving a large potential opening. Also, gross leaks were frequently observed at anchor points on the corners of the diaper. This suggests that a redesign of diapers is needed to eliminate the depression of the corners.

The diaper allows suspended matter to settle to the bottom instead of being dispersed immediately as a turbid plume. However, no permanent benefit is obtained from this unless the entrance canal is dredged deeply enough to form an effective sediment trap; otherwise, natural waves and currents and boat wakes will re-suspend the fines whenever the diaper is removed. Therefore, it is suggested that regulations requiring a diaper, to be effective in reducing turbidity permanently, must be coupled with a requirement that that canal be dredged to several feet below the effective base of the expected disturbances. The minimum required depth would have to be determined by further research, but is probably at least on the order of 8 to 10 feet. This depth would exceed the maximum of 6 feet previously recommended by the Florida Department of Pollution

Control (1973) for all canals. Perhaps the previous recommendation should be re-examined and possibly applied only to perimeter and other interior canals.

9. Lastly it is recommended that research into the technology of dredging and its potential effects continue. At present there is insufficient quantitative knowledge of at least five points: (a) the tolerance limits of organisms to increased sedimentation and turbidity; (b) the width of mangrove fringe and/or <u>Thalassia</u> beds necessary to provide adequate natural suspended sediment traps (i.e. natural water clarification); (c) the ultimate depositional site of the excess particles generated by the dredge; (d) the optimum methods of providing oxygen bearing water to the perimeter and other interior canal systems; and (e) the size-distribution of the dredge effluent, and the possible effects of changes from the natural size distribution on the respiration of some of the important organisms of the inshore area.

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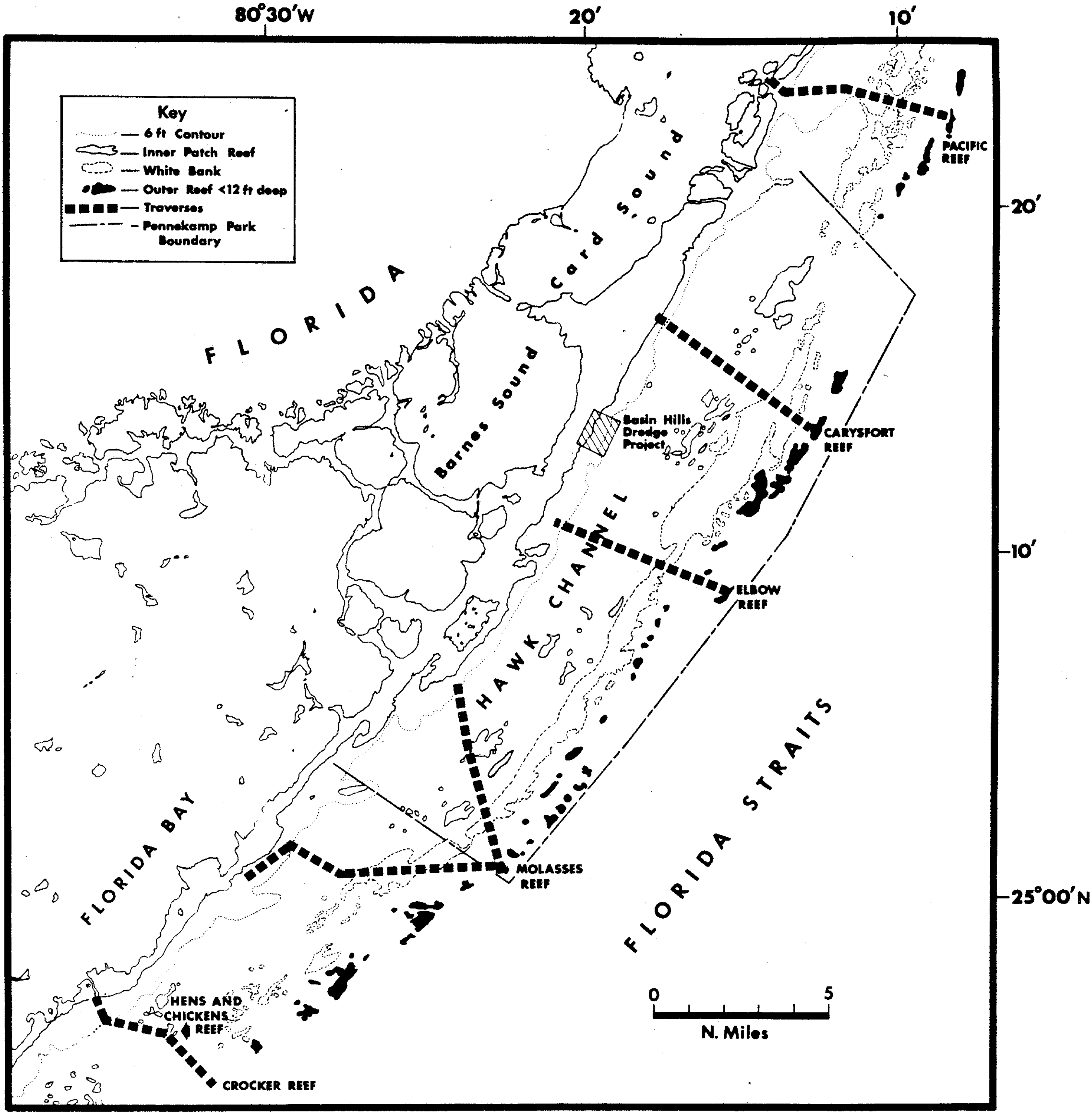
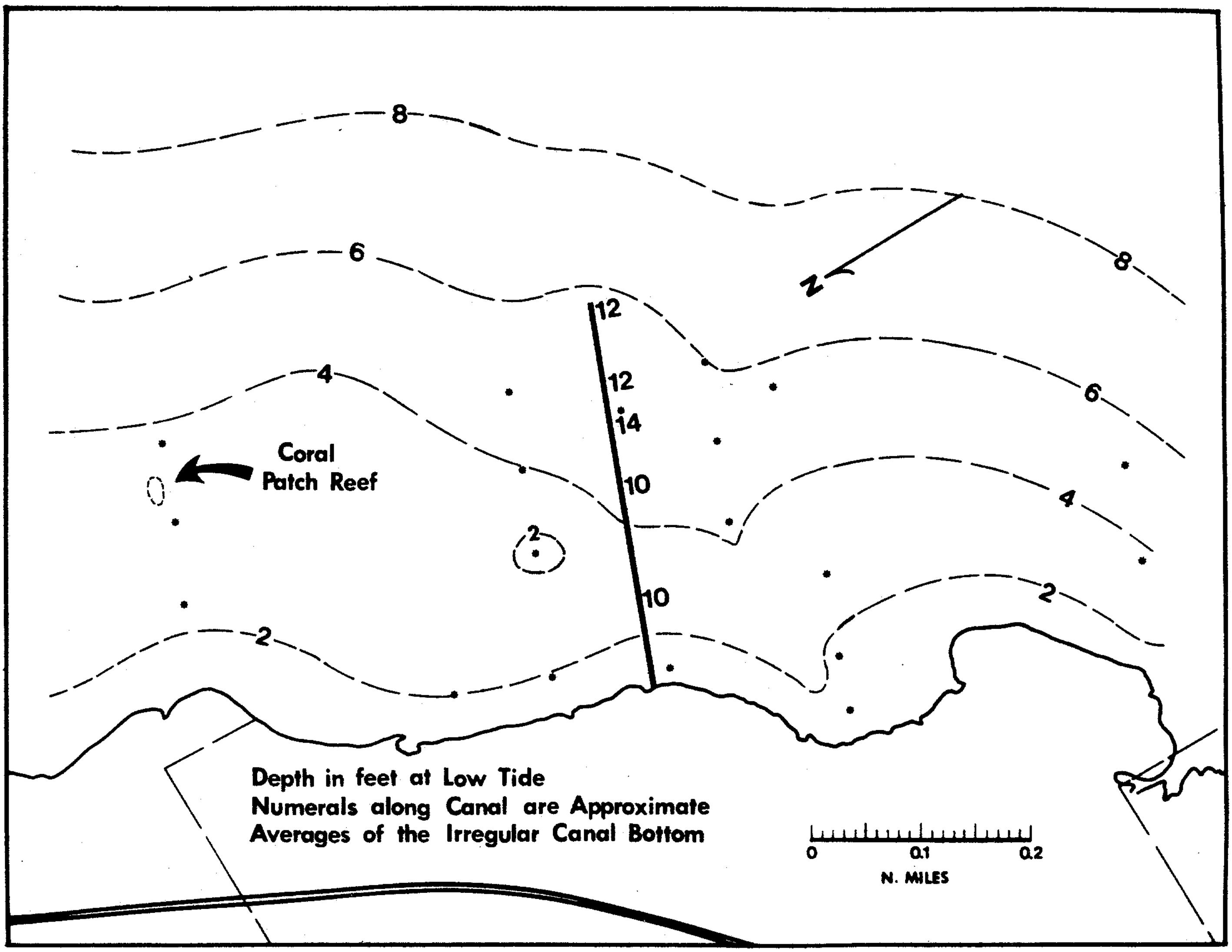
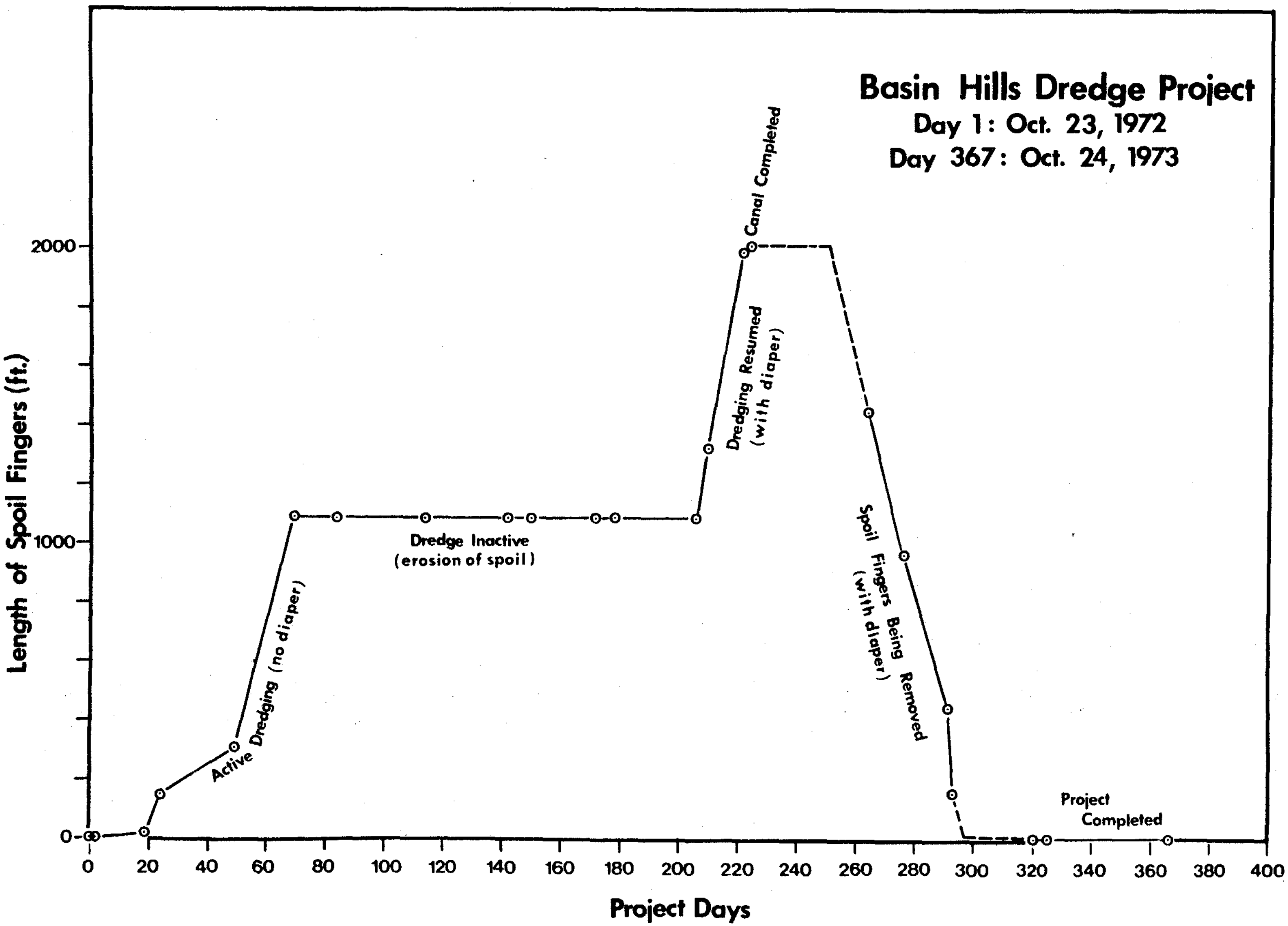


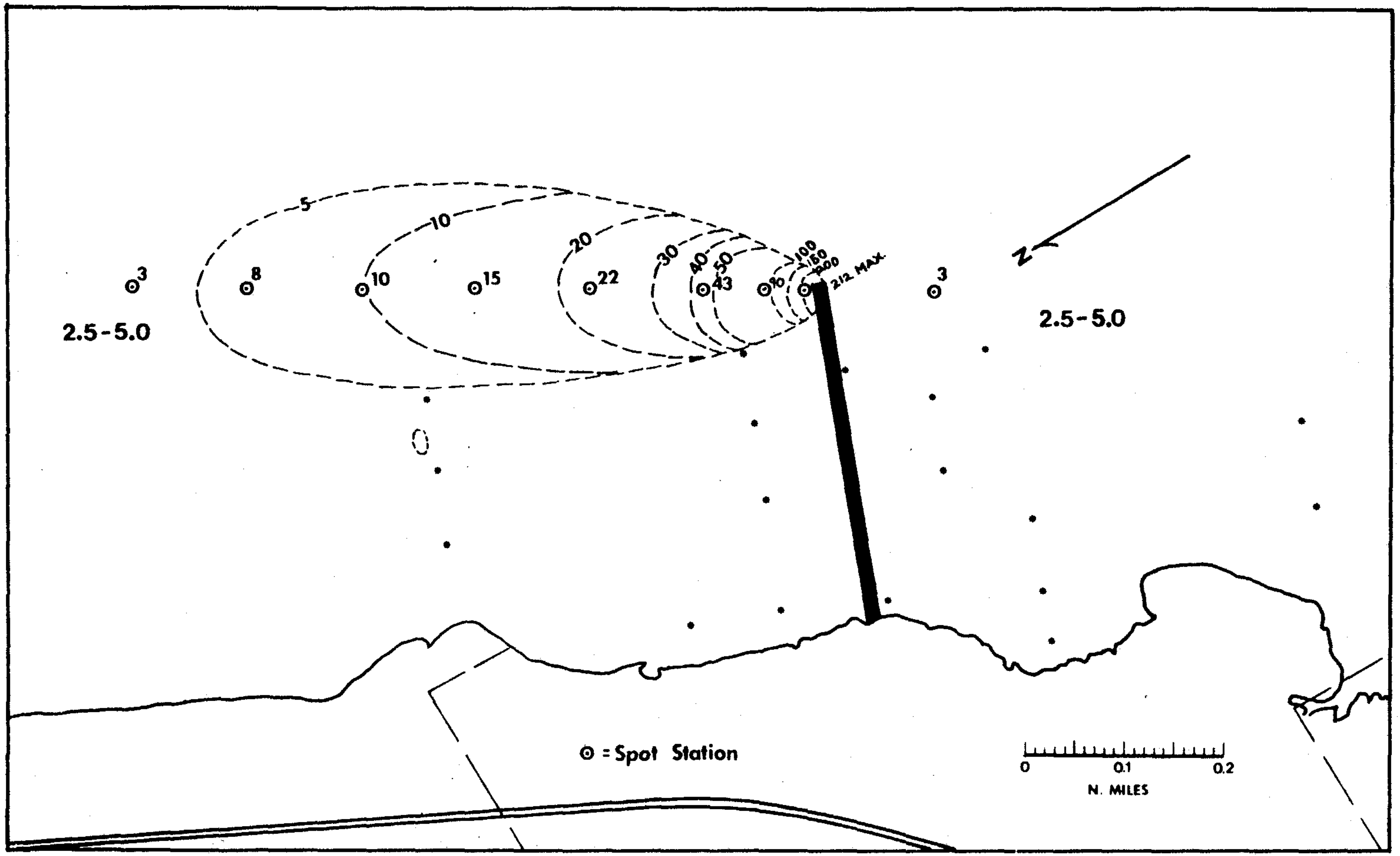
Fig. no. 1 Map of the expanded study area, showing the important reef and bank areas, the Basin Hills dredge site, and the monthly transmissometer traverse lines used to establish background conditions.



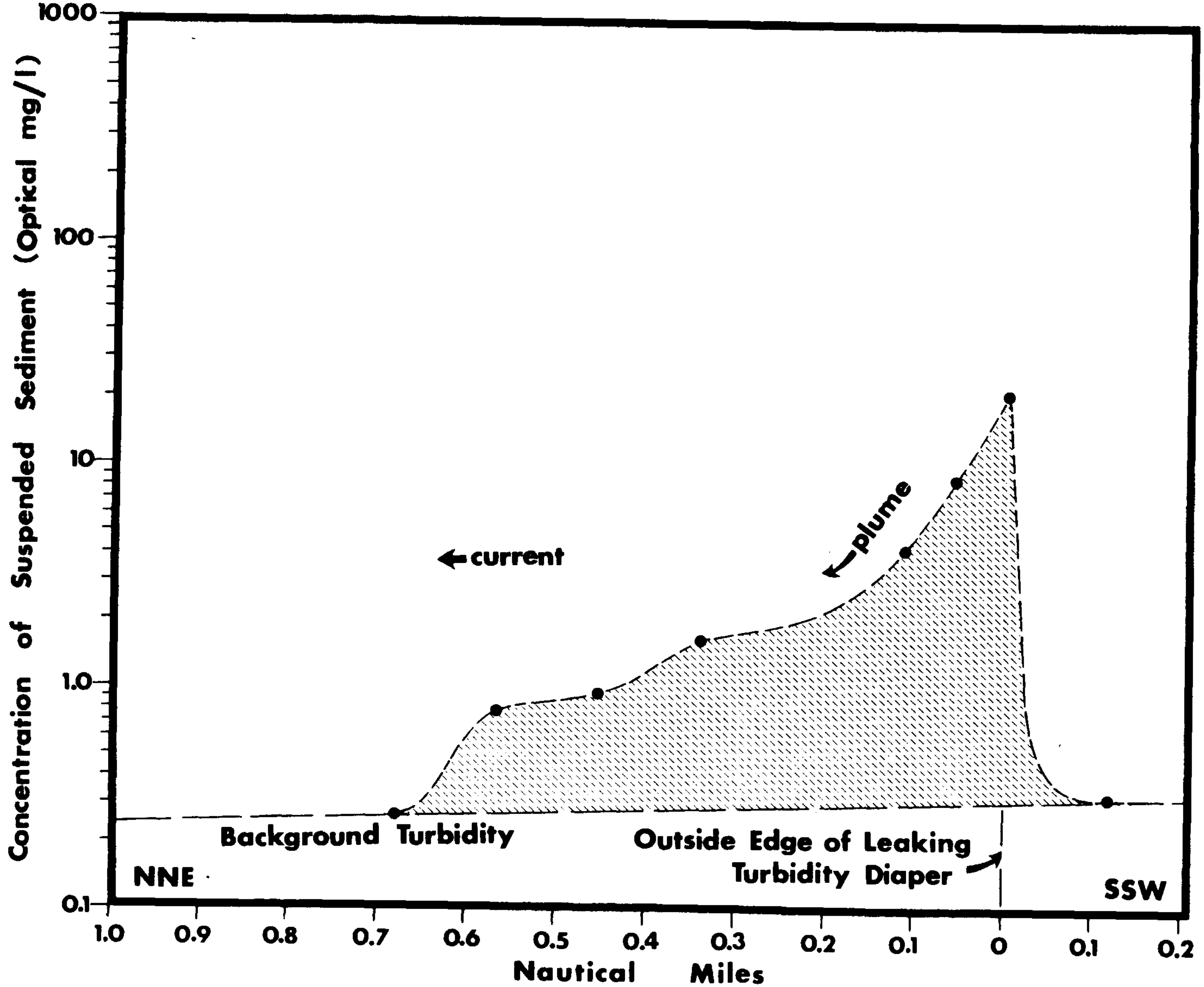
2 Bathymetry of the Basin Hills dredge site, also showing the axial depths of the completed canal, and the coral patch reef used as a biological indicator. Depths in feet at low tide.



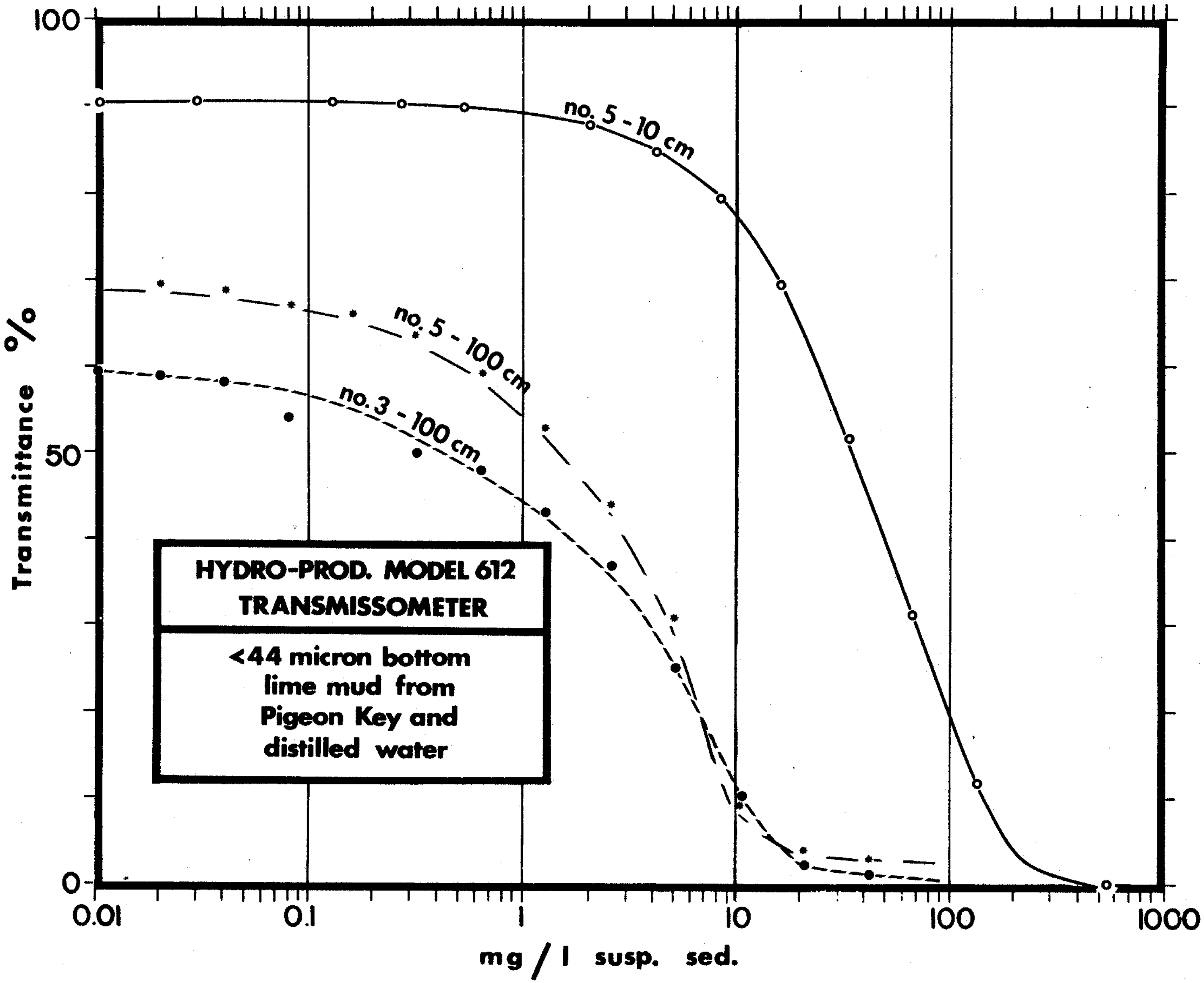
3 Progress of dredging at the Basin Hills project. Length of the spoil fingers was measured on days indicated by circles.



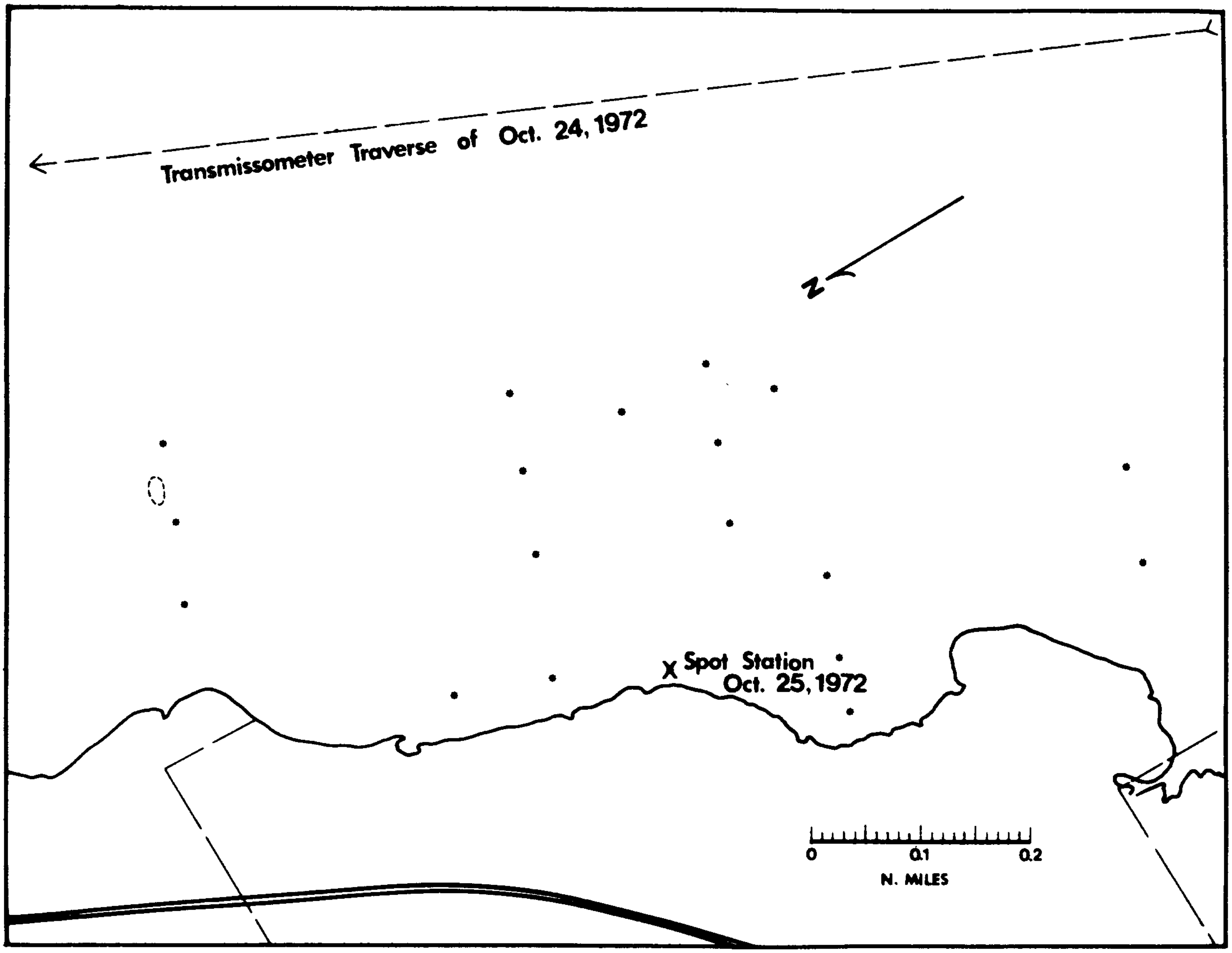
4 Dredge plume on May 30, 1973 (Project day 220) near the end of the active extension phase, with the turbidity diaper leaking badly. Both the maximum concentration (212 mg/1) and the maximum plume length (4038 feet) were observed at this time. The lateral boundaries of the plume are approximate, based on visual description; length and concentration are based on spot measurements at the points indicated.



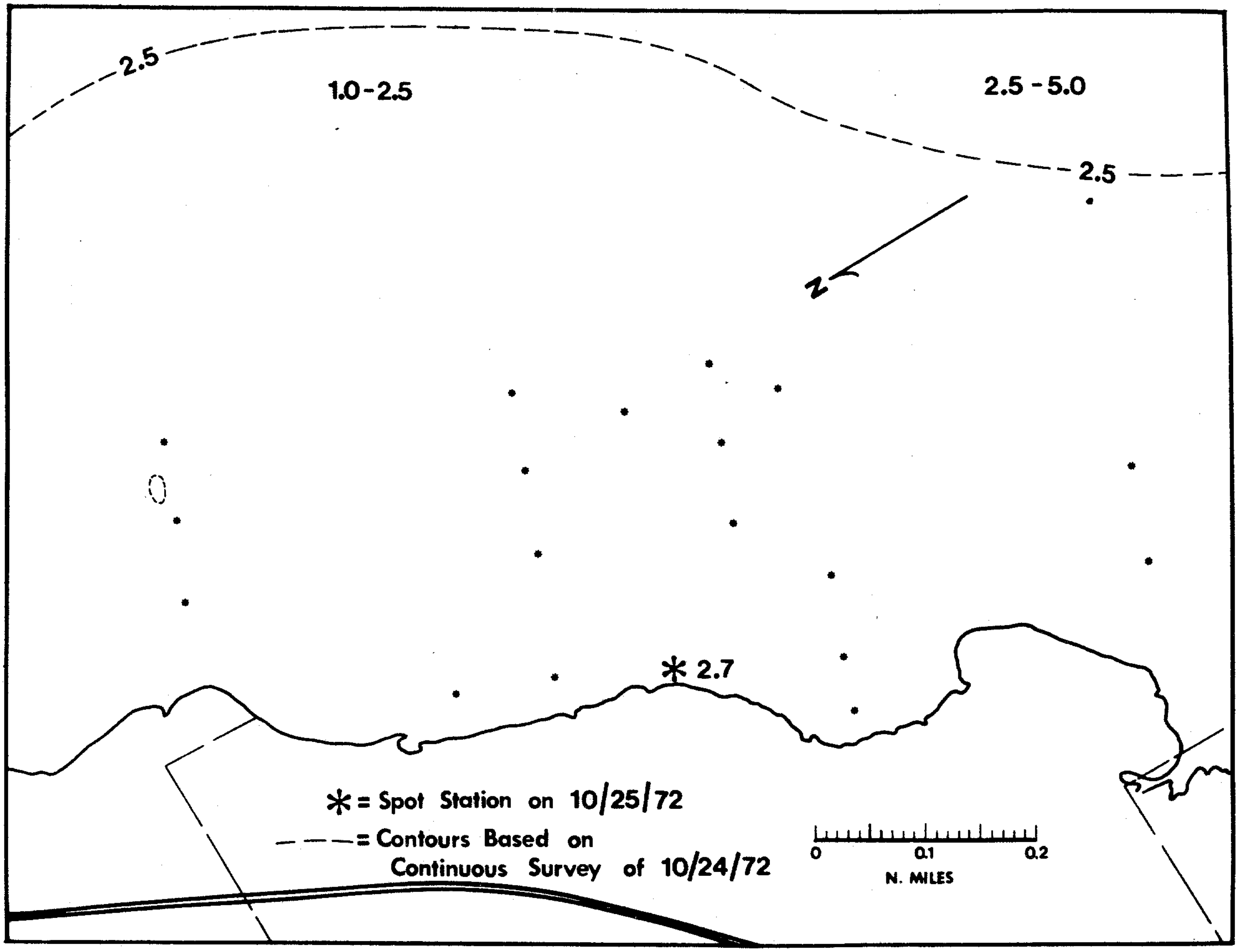
5 Concentration of suspended sediment in the most intense part of the plume vs distance from the dredge on May 30, 1973 (Project day 220). Dredge was actively extending the spoil fingers, with a turbidity diaper in place but leaking badly. Both the maximum concentration (212 mg/1) and the maximum plume length (4038 feet) were observed at this time.



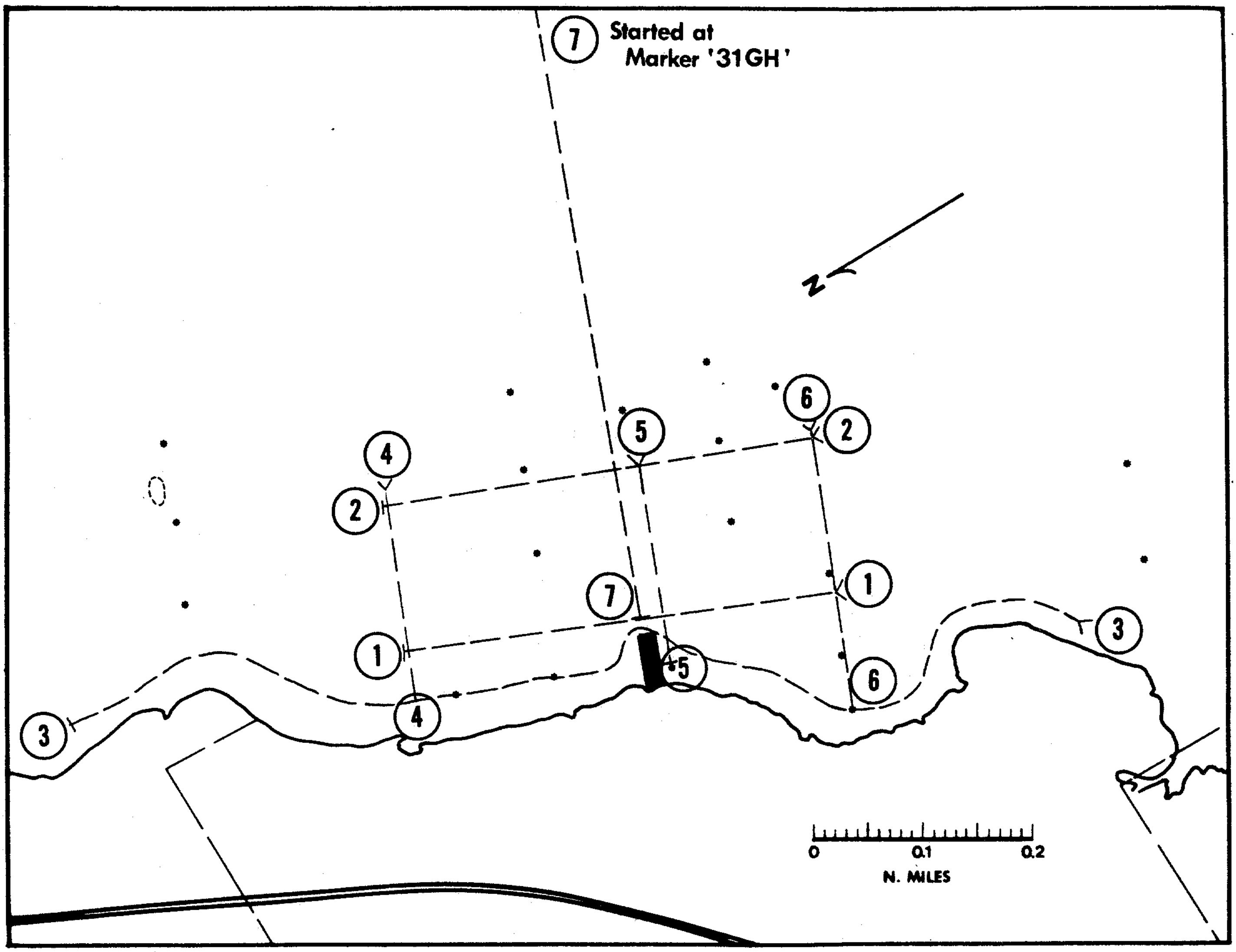
6 Working curve of light transmittance (%) versus suspended sediment concentration (mg/l) for path lengths of 10 cm and 100 cm. Determined in a laboratory test tank with two Hydro-Products Model 612 transmissometers (our No. 3 and No. 5), distilled water, and known weights of salt-free, <44 micron $CaCO_3$ mud from a shoal 100 yd. west of the U. of Miami marine station on Pigeon Key.



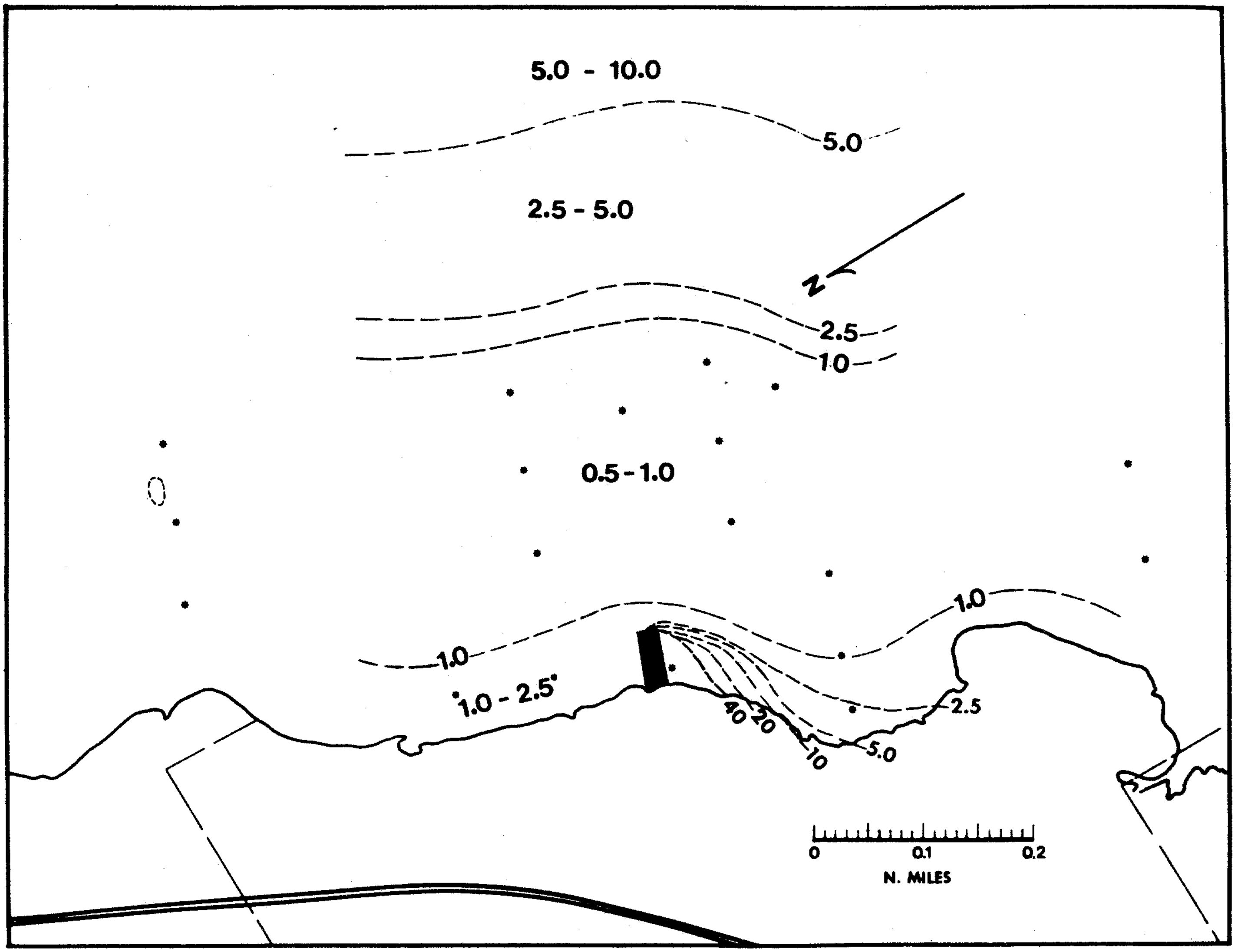
7a Locations of transmissometer traverse of October 24, 1972, and spot station of October 25 (Project days 2 and 3). Dredging had not yet begun.



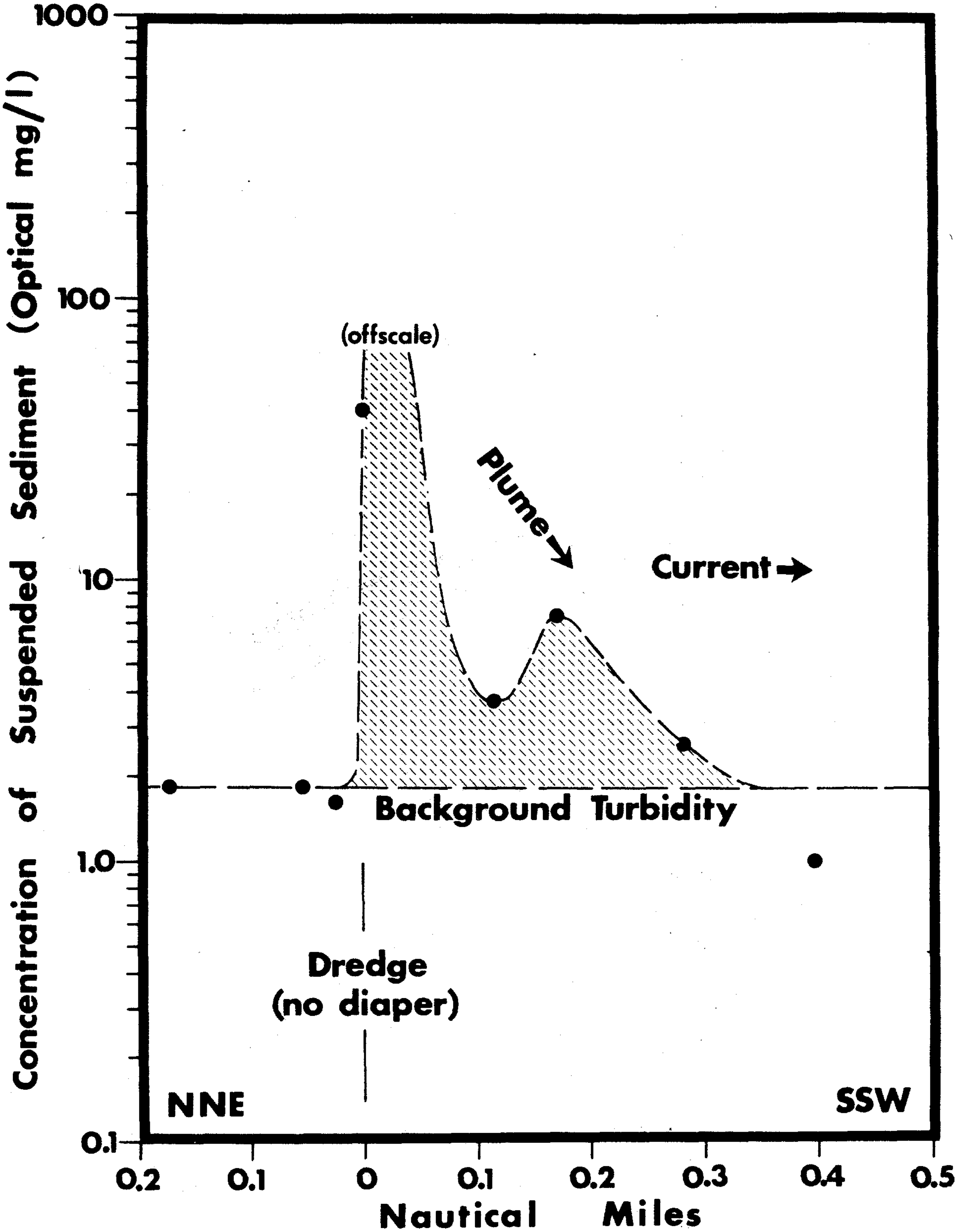
7b Concentration of suspended sediment in surface water on October 24-25, 1972 (Project days 2 and 3). Dredging had not yet begun.



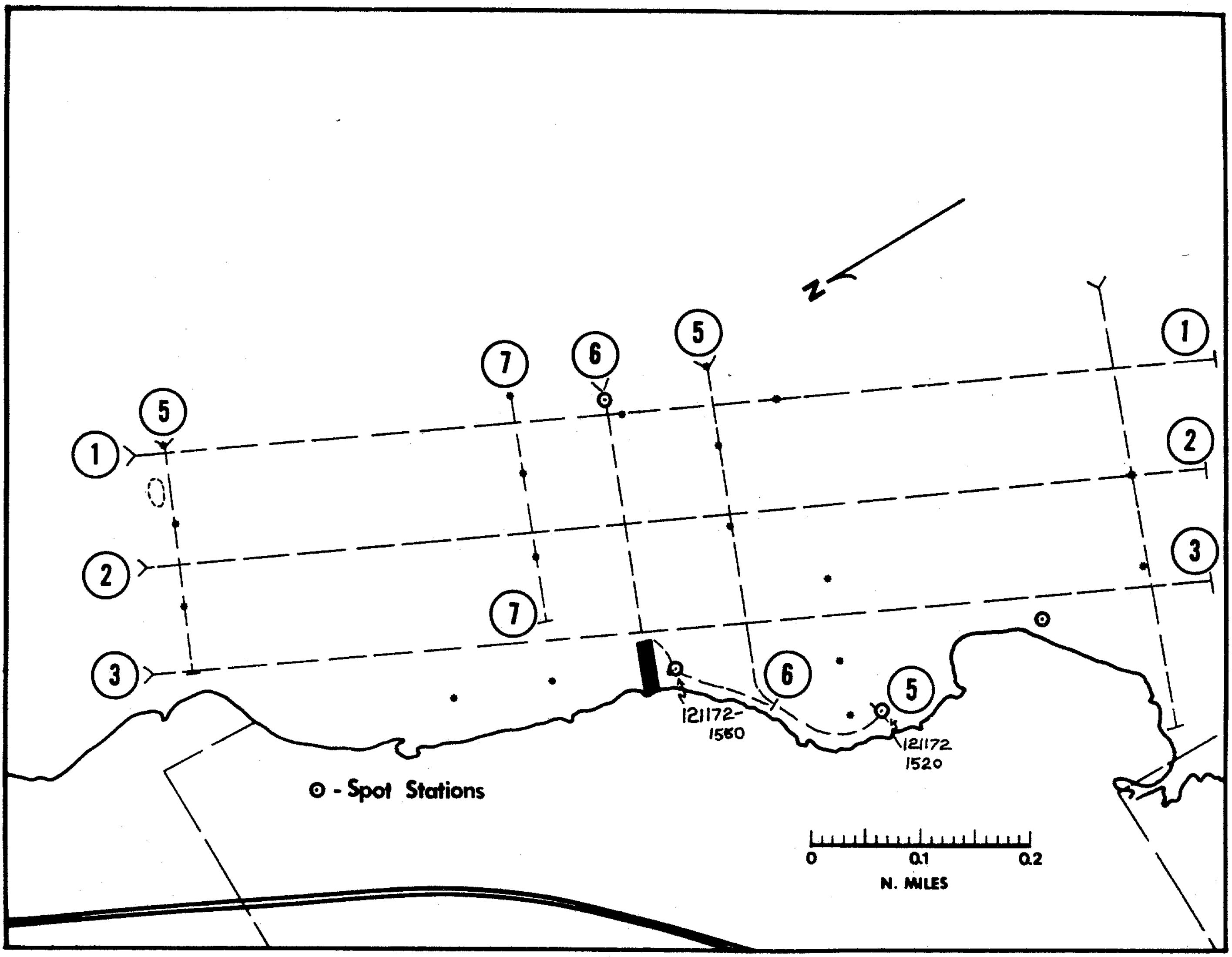
8a Location of transmissometer traverses on November 16, 1972 (Project day 25).



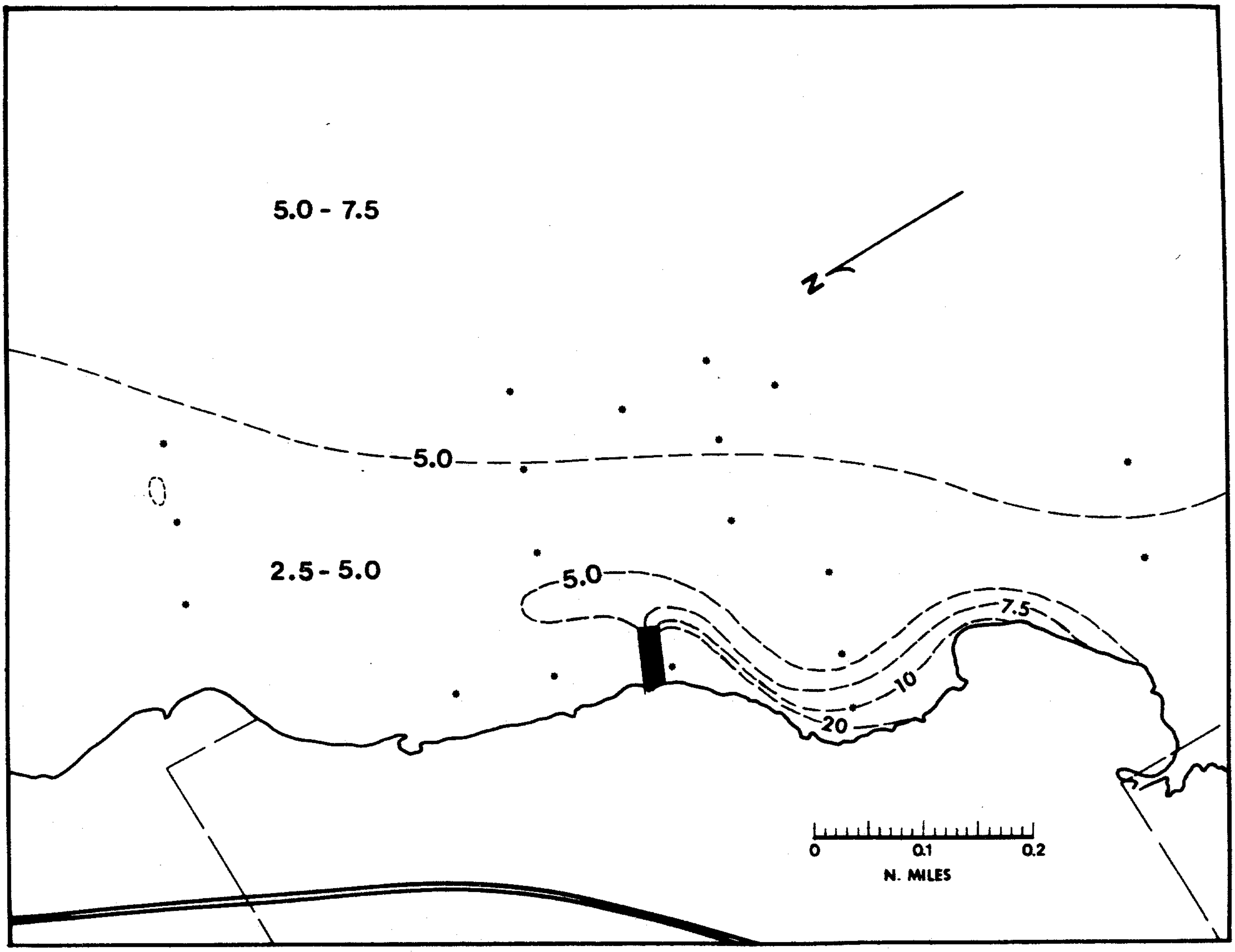
8b Concentration of suspended sediment in surface water on November 16, 1972 (Project day 25). Dredge was active, without turbidity diaper.



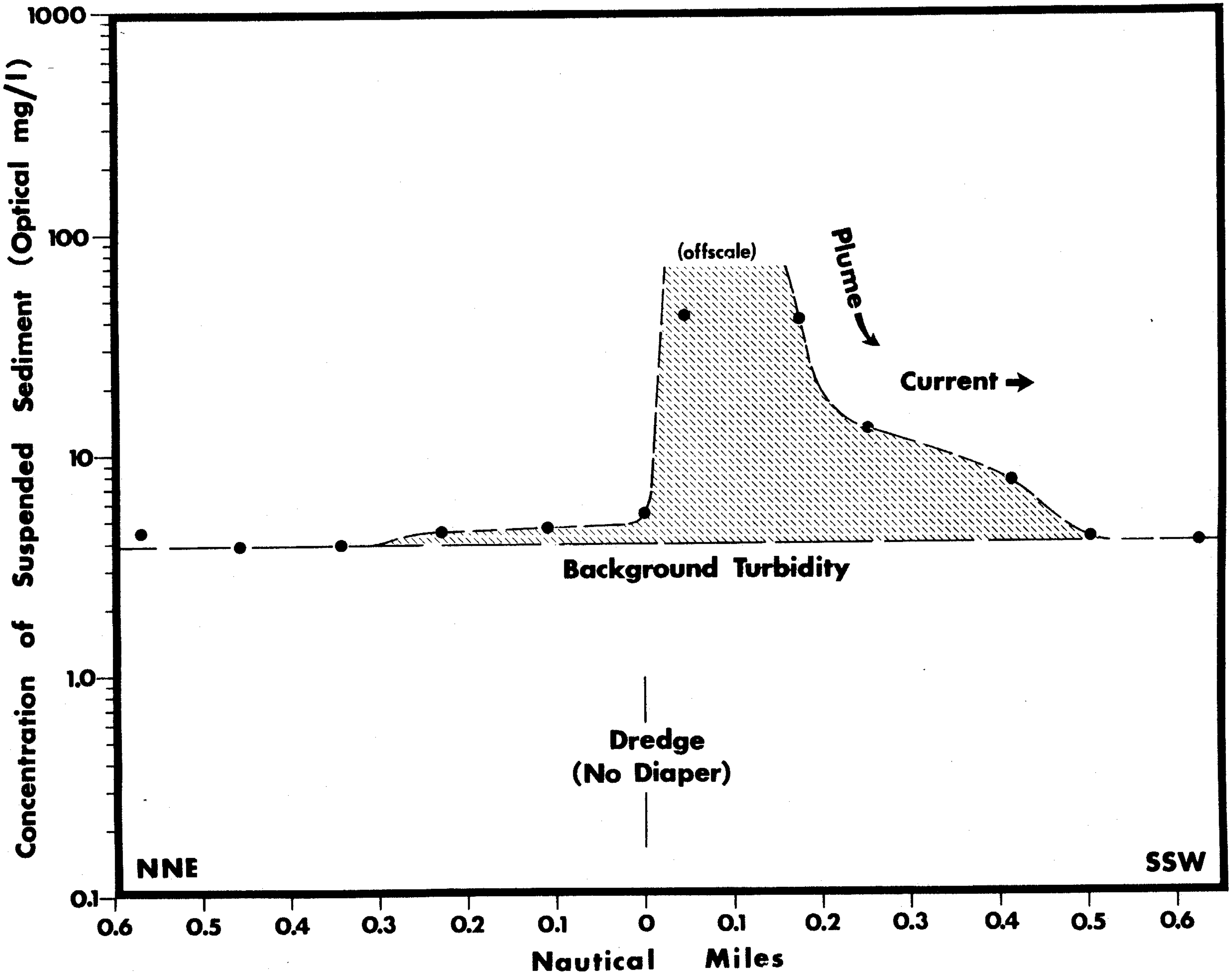
8c Concentration of suspended sediment in the most intense part of the plume vs distance from the dredge, November 16, 1972 (Project day 25). The maximum values were offscale on the 1-m transmissometer. Dredge was active, without turbidity diaper.



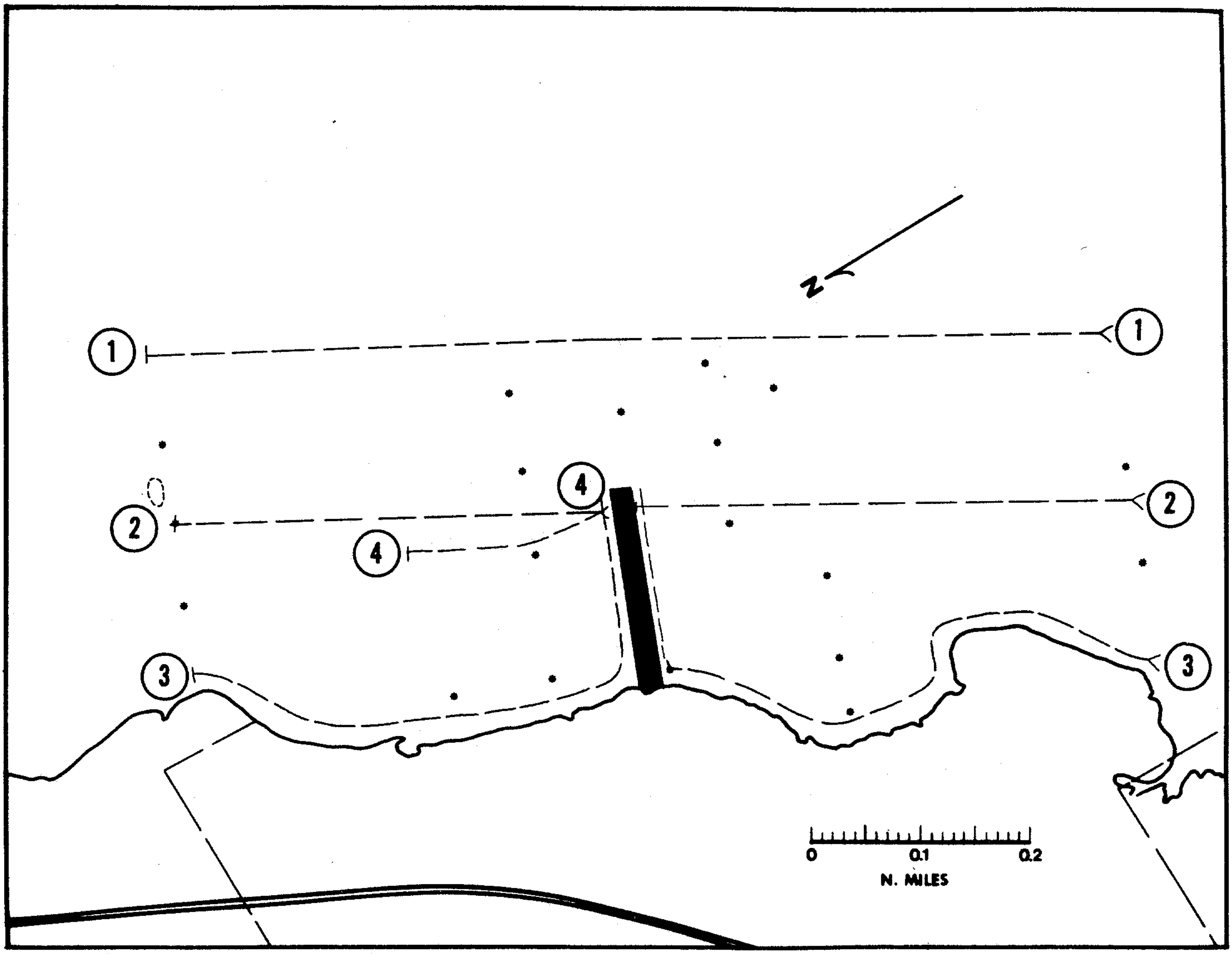
9a Location of transmissometer traverses on December 11, 1972 (Project day 50).



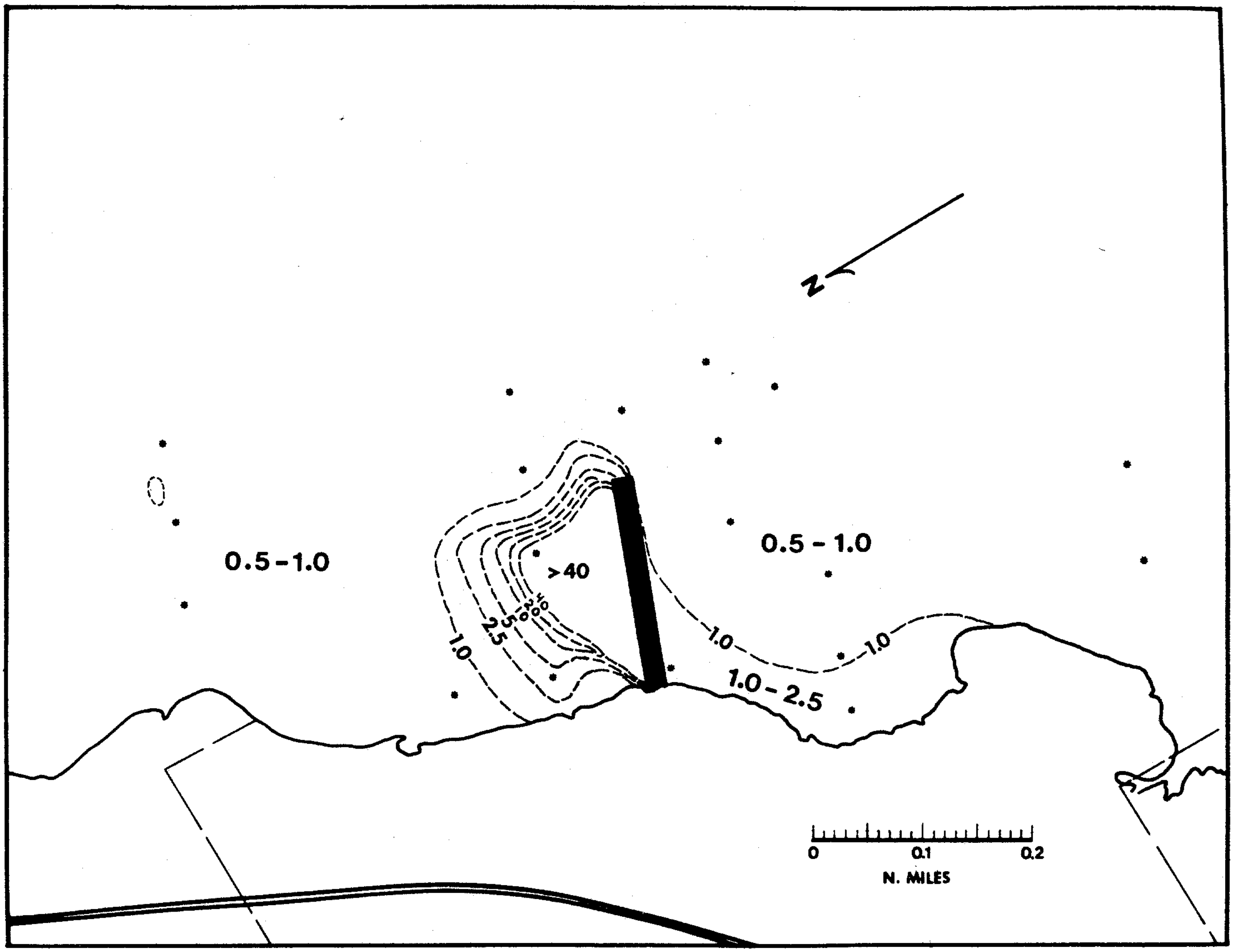
9b Concentration of suspended sediment in surface water on December 11, 1972 (Project day 50). Dredge was active, without turbidity diaper.



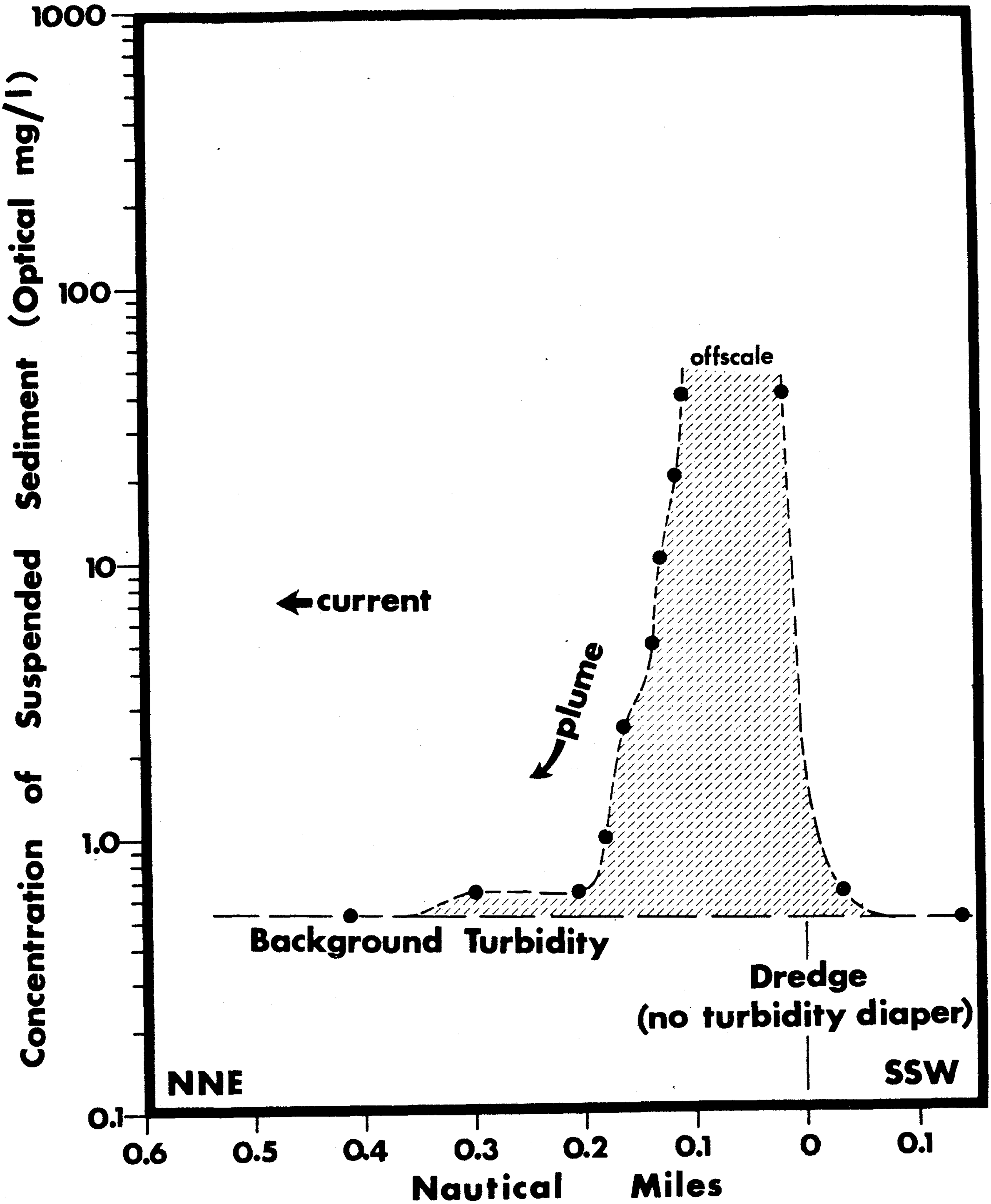
9c Concentration of suspended sediment in the most intense part of the plume vs distance from the dredge, December 11, 1972 (Project day 50). The maximum values were offscale on the 1-m transmissometer. Dredge was active, without turbidity diaper.



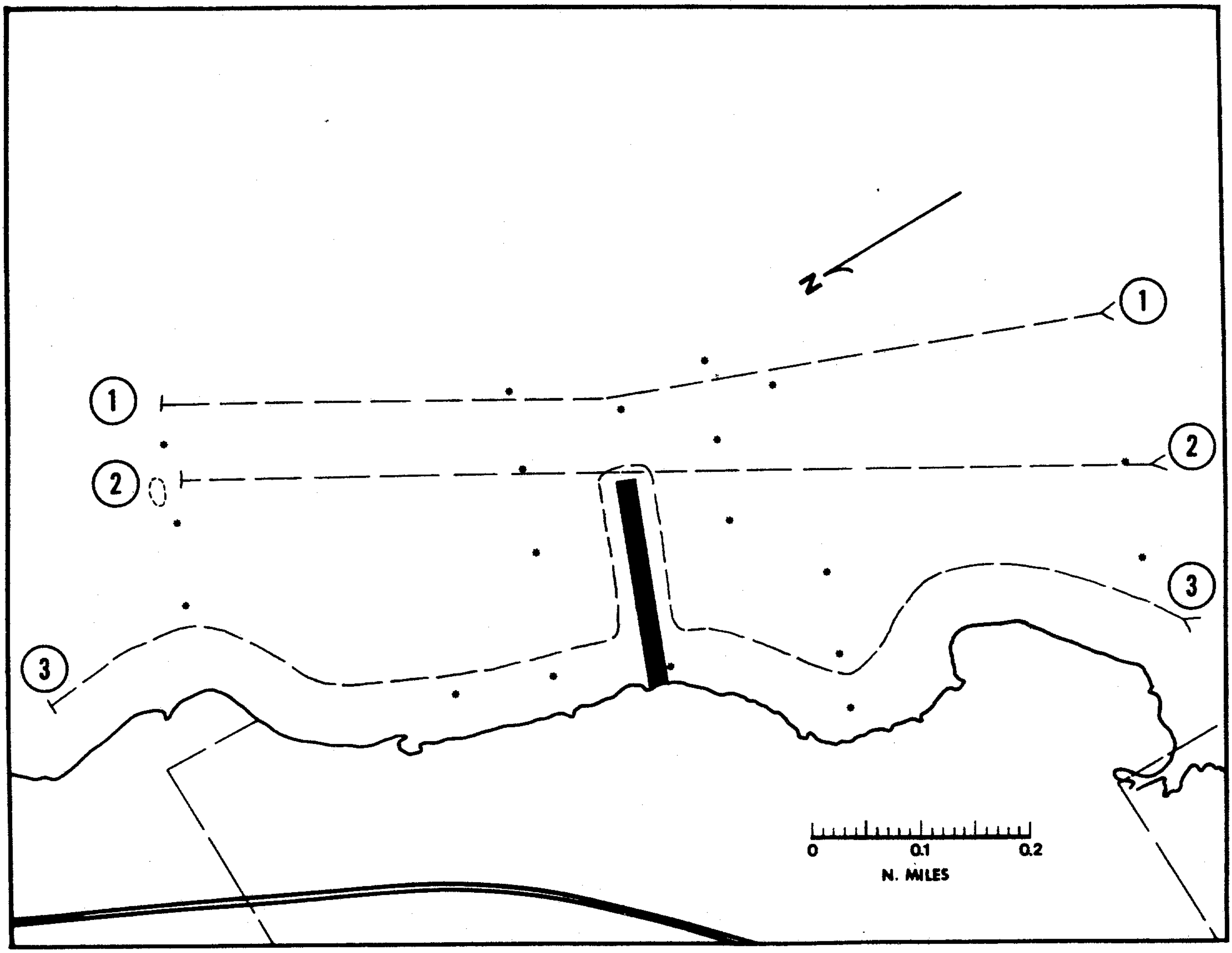
10a Location of transmissometer traverses on December 26, 1972 (Project day 65).



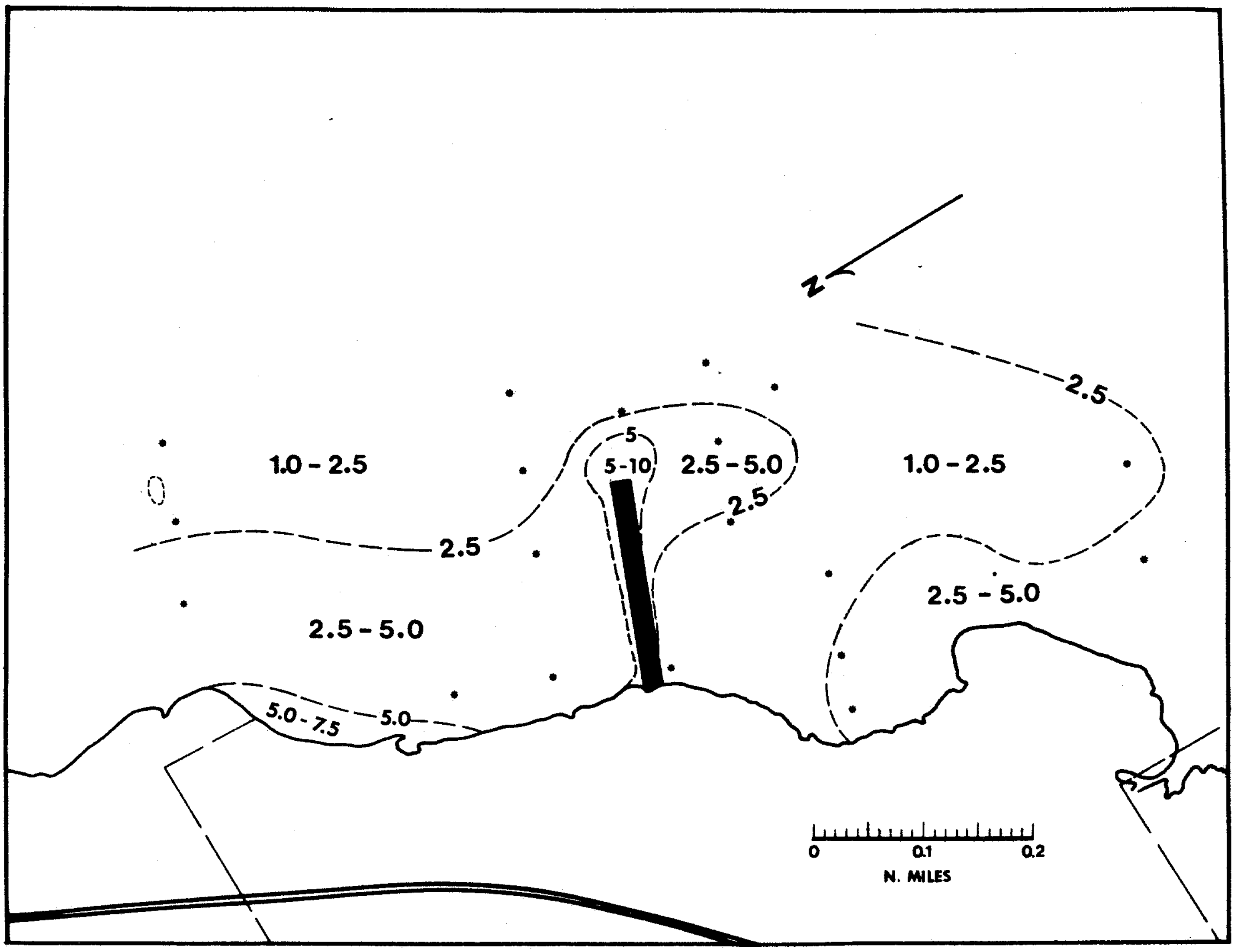
10b Concentration of suspended sediment in surface water on December 26, 1972 (Project day 65). Dredge was active, without turbidity diaper.



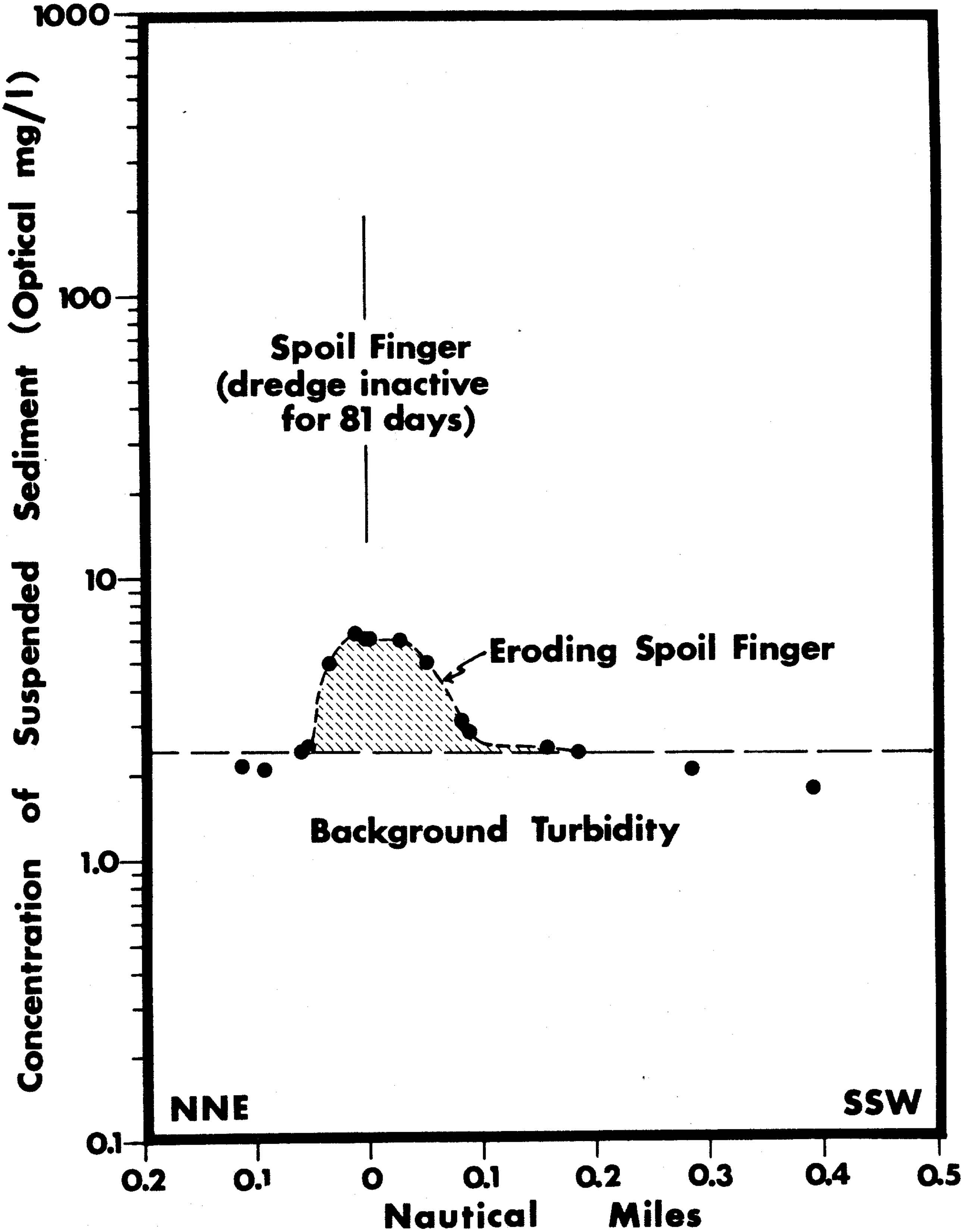
10c Concentration of suspended sediment in the most intense part of the plume vs distance from the dredge, December 26, 1972 (Project day 65). The maximum values were offscale on the 1-m transmissometer. Dredge was active, without turbidity diaper.



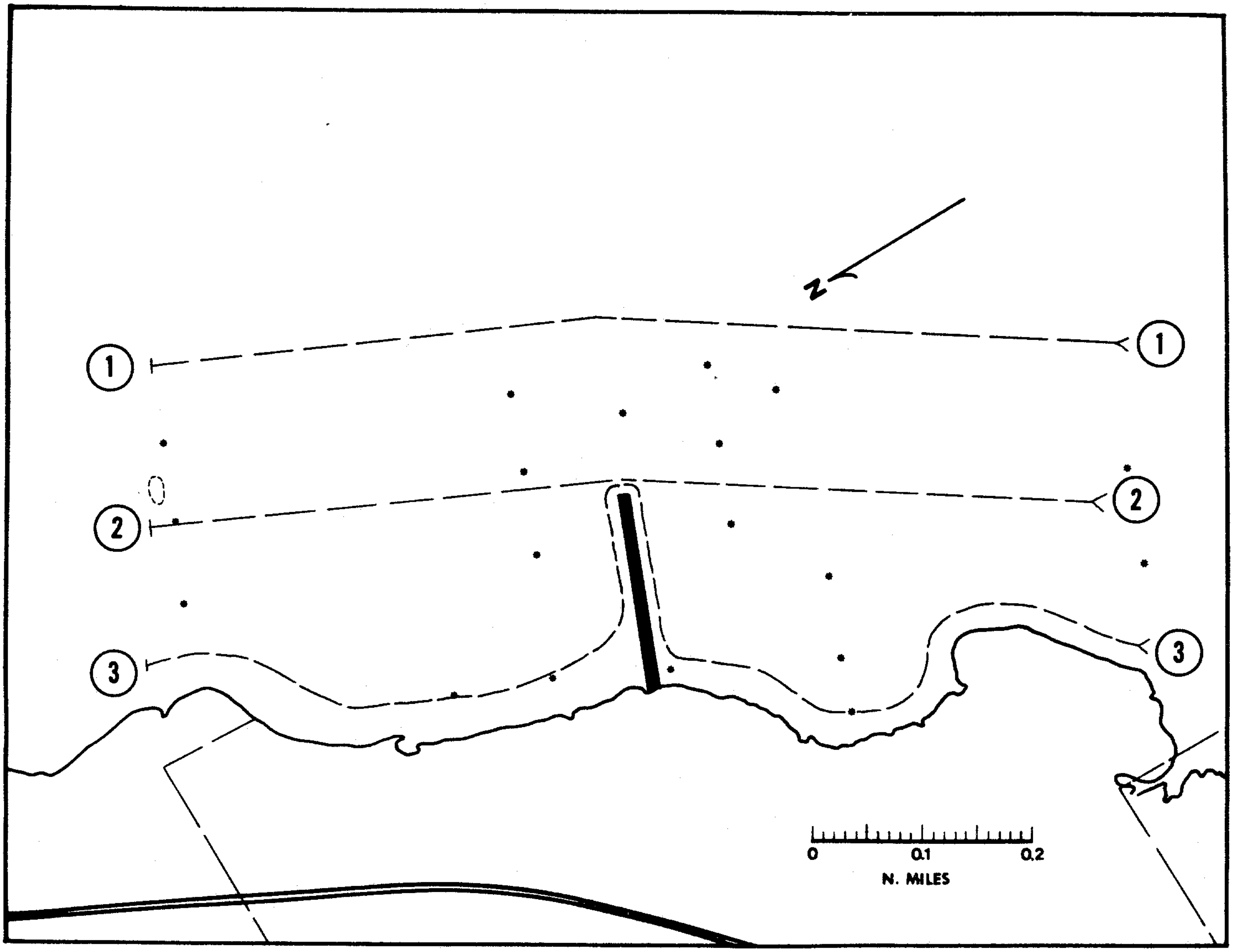
11a Location of transmissometer traverses on March 22, 1973 (Project day 151).



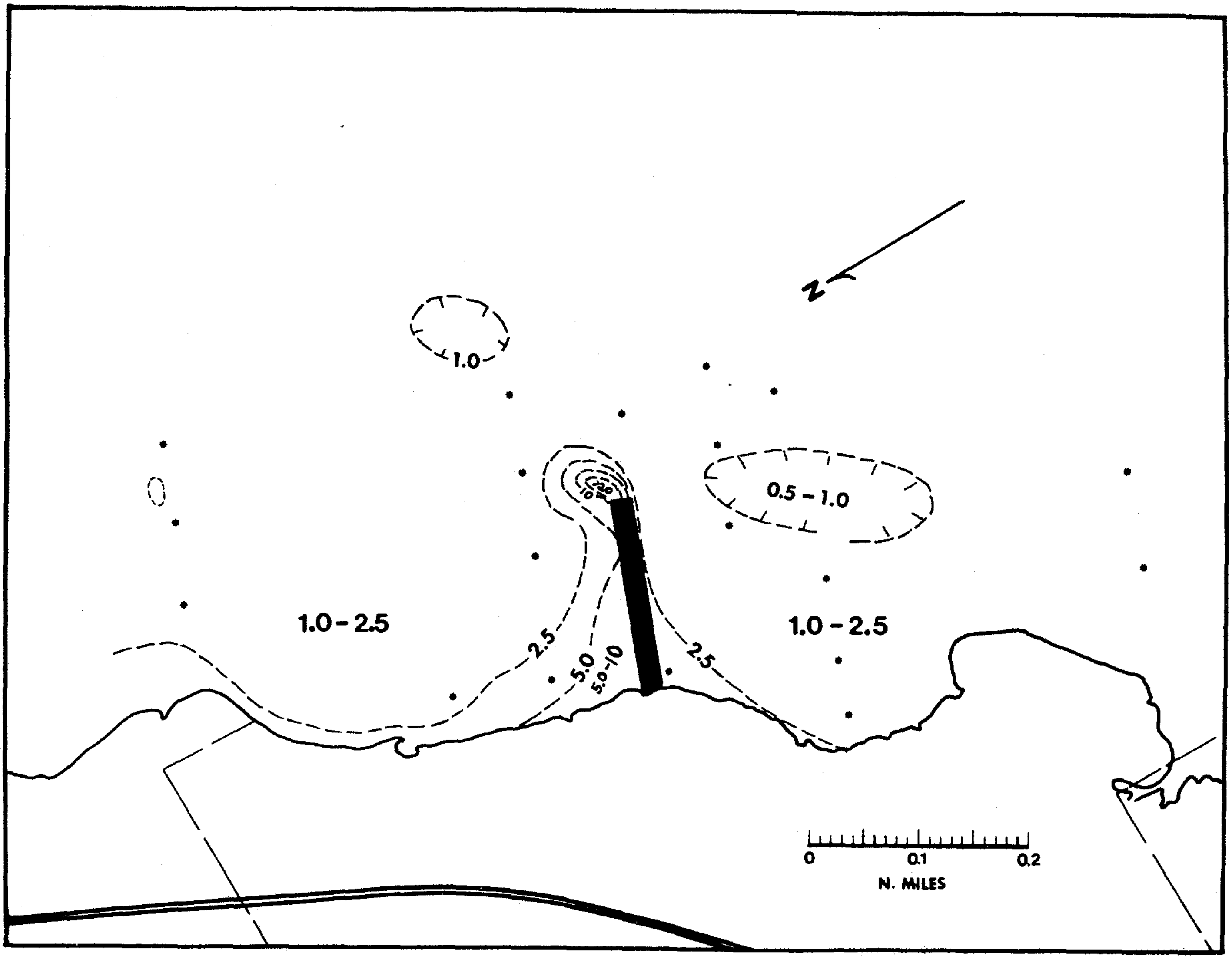
11b Concentration of suspended sediment in surface water on March 22, 1973 (Project day 151). The dredge had been inactive for the previous 81 days, and the spoil fingers were being eroded by waves.



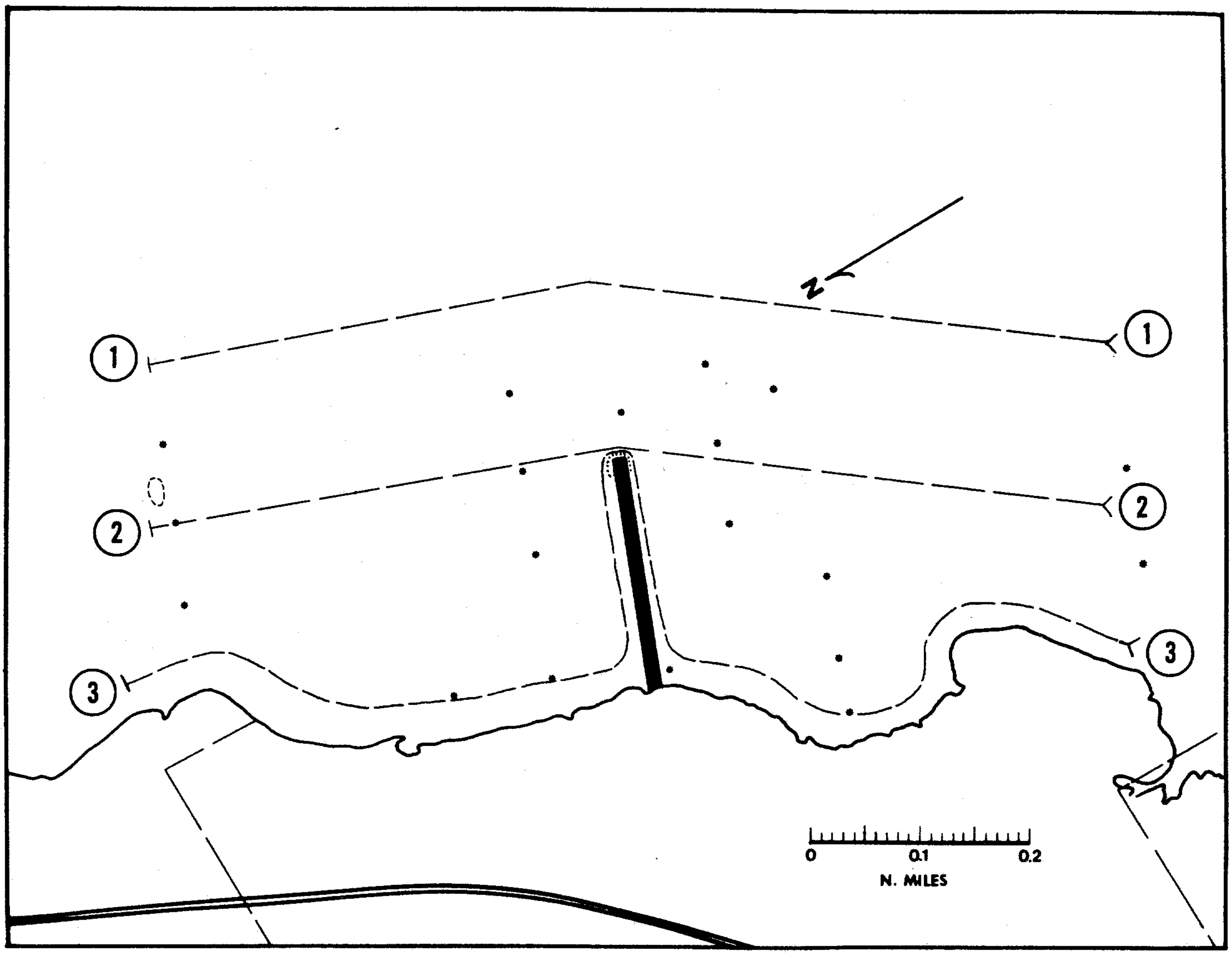
11c Concentration of suspended sediment in the low intensity "plume" surrounding the spoil fingers on March 22, 1973 (Project day 151). The dredge had been inactive for the previous 81 days, and the spoil fingers were being eroded by waves.



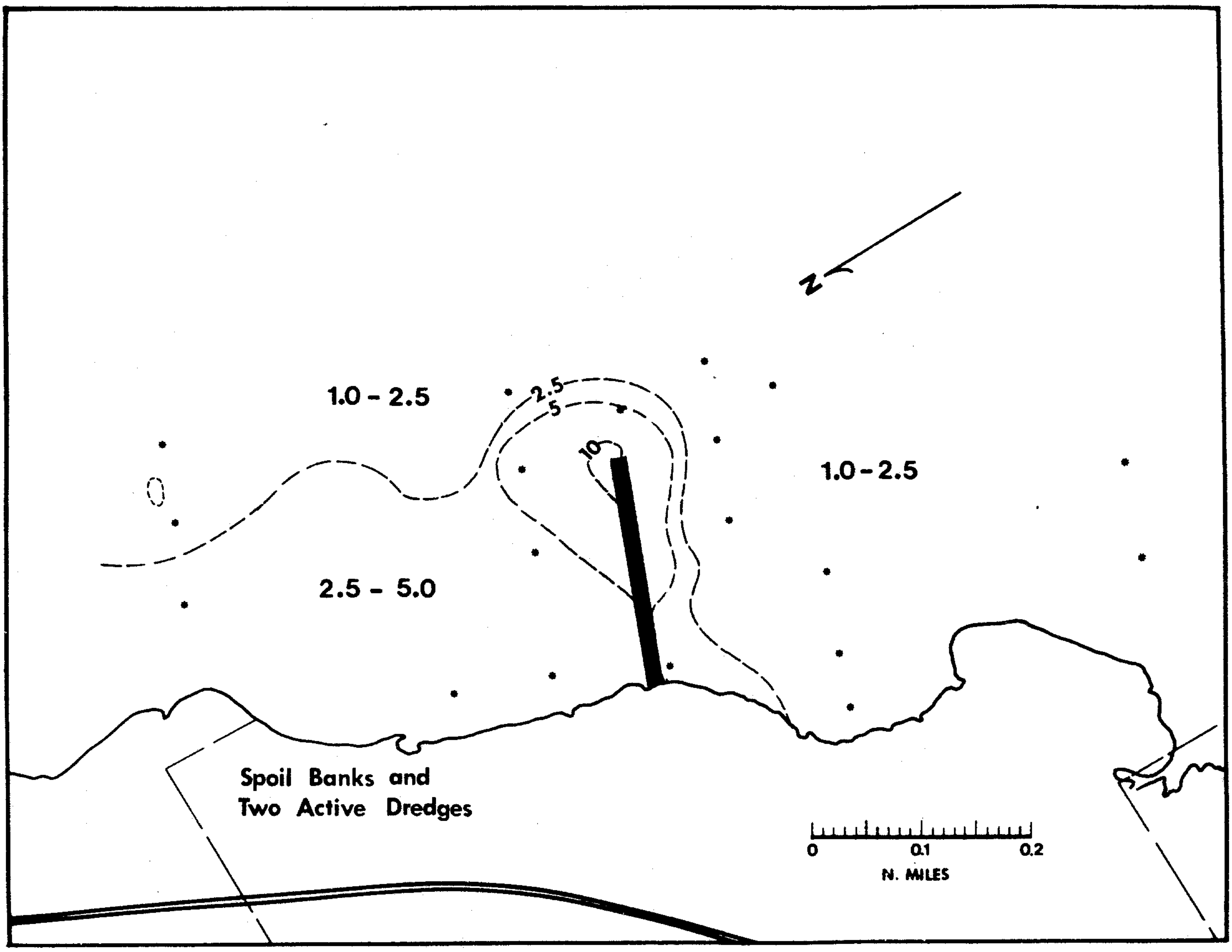
12a Location of transmissometer traverses on May 14, 1973 (Project day 204).



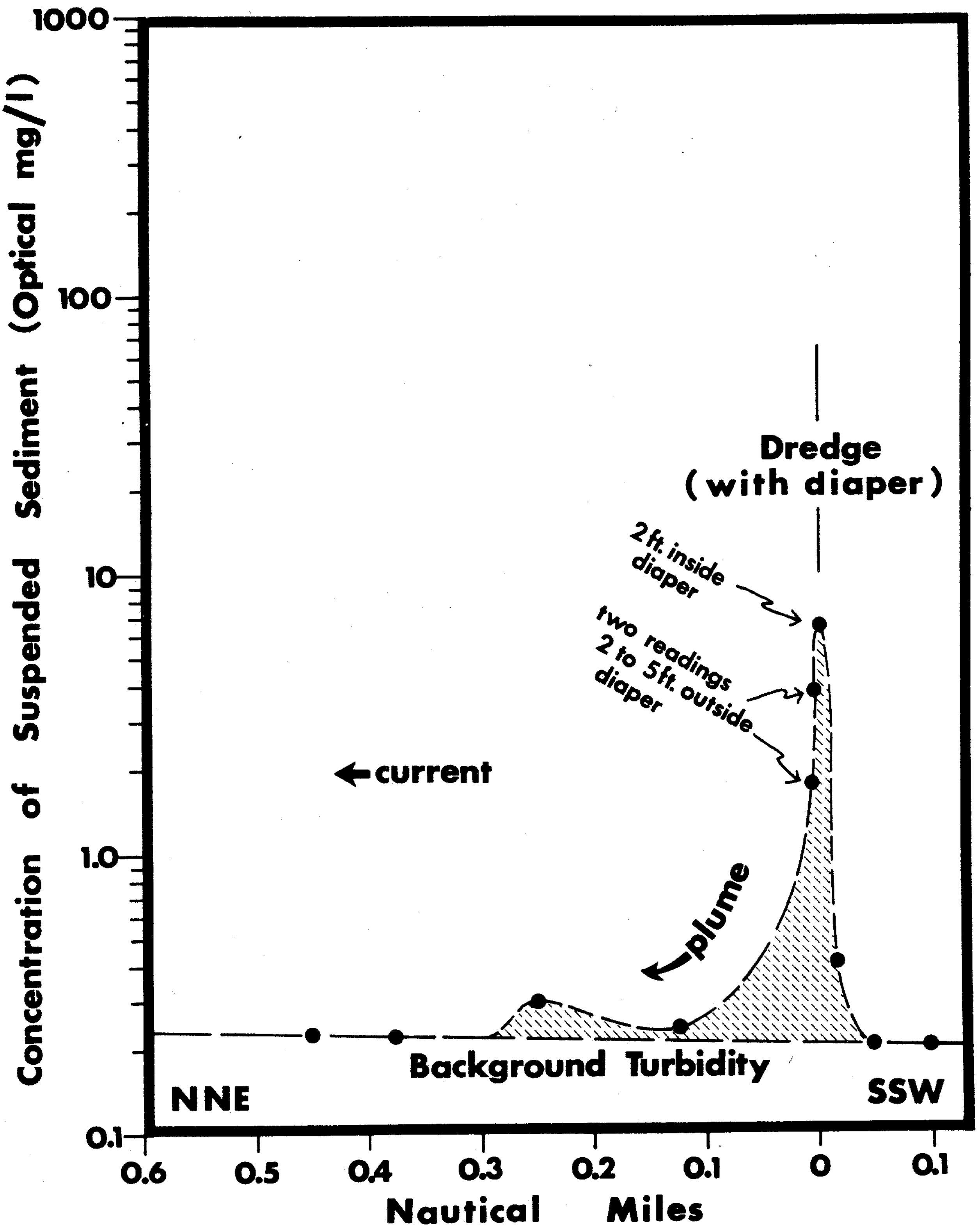
12b Concentration of suspended sediment in surface water on May 14, 1973 (Project day 204). The dredge had been inactive for the previous 134 days, and the spoil fingers were being eroded by waves.



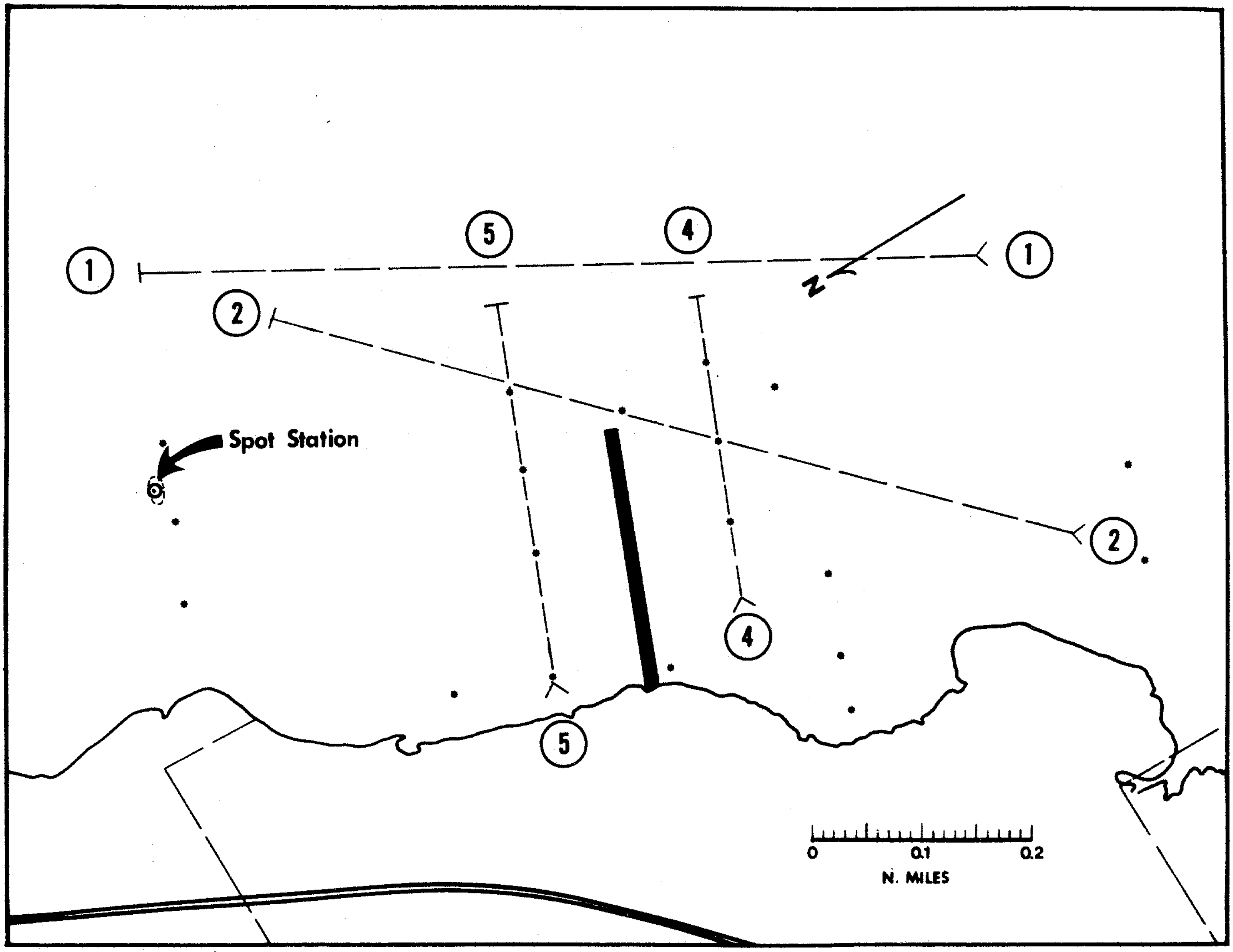
13a Location of transmissometer traverses on May 18, 1973 (Project day 208).



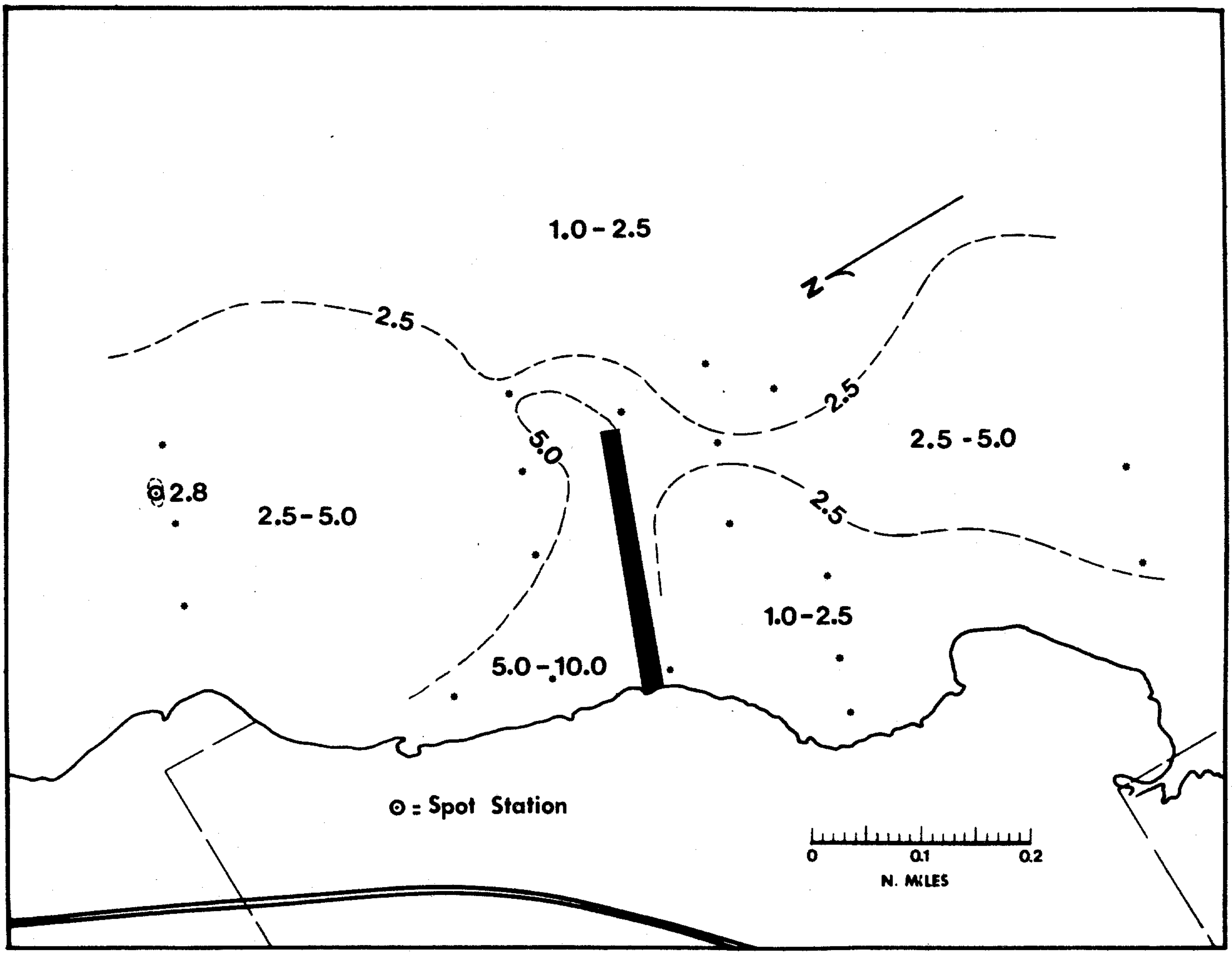
13b Concentration of suspended sediment in surface water on May 18, 1973 (Project day 208). Dredge was active, with a turbidity diaper for the first time.



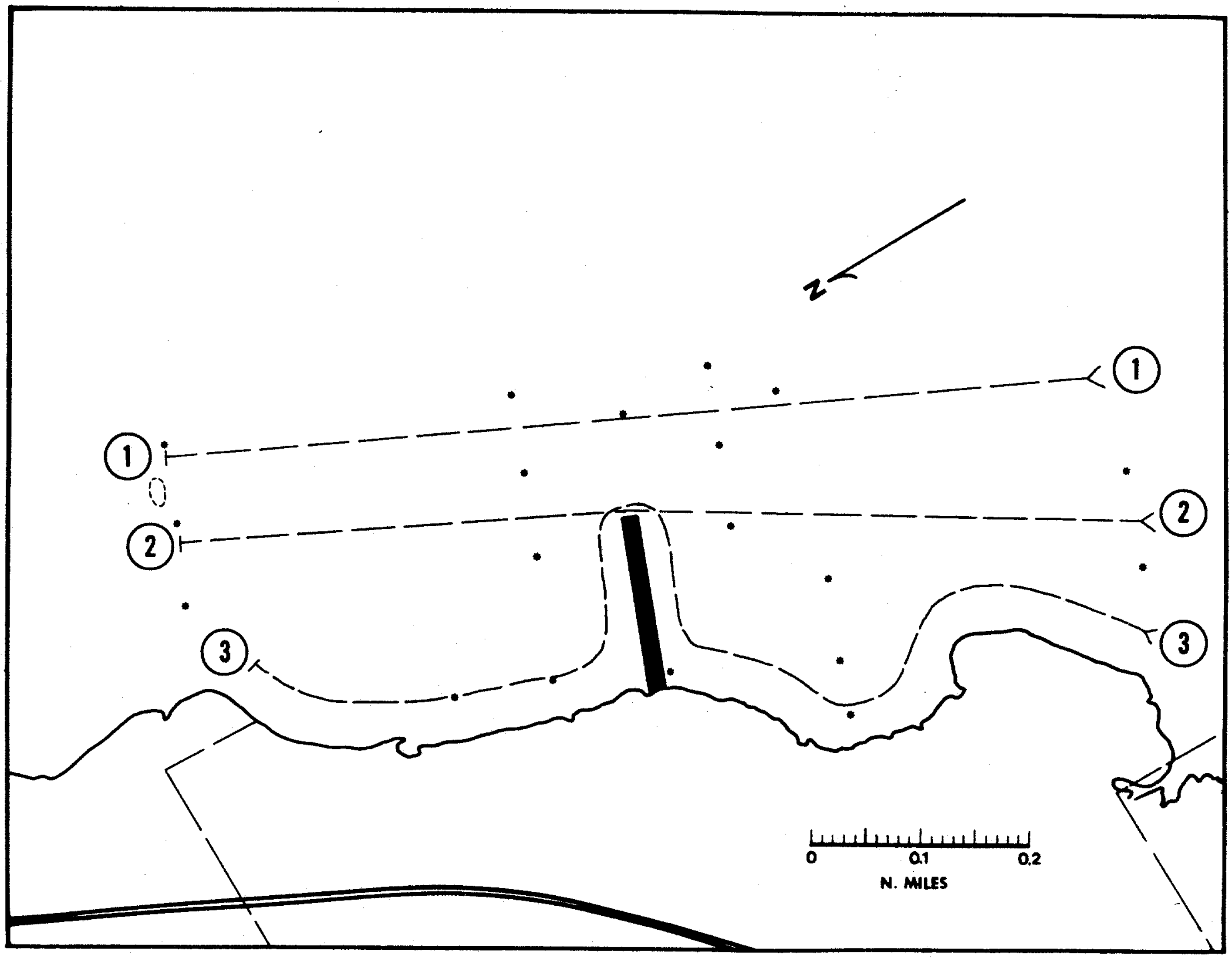
13c Concentration of suspended sediment in the most intense part of the plume vs distance from the dredge, May 18, 1973 (Project day 208). Dredge was active, with a turbidity diaper for the first time. Note the large differences in concentration inside and outside the turbidity diaper.



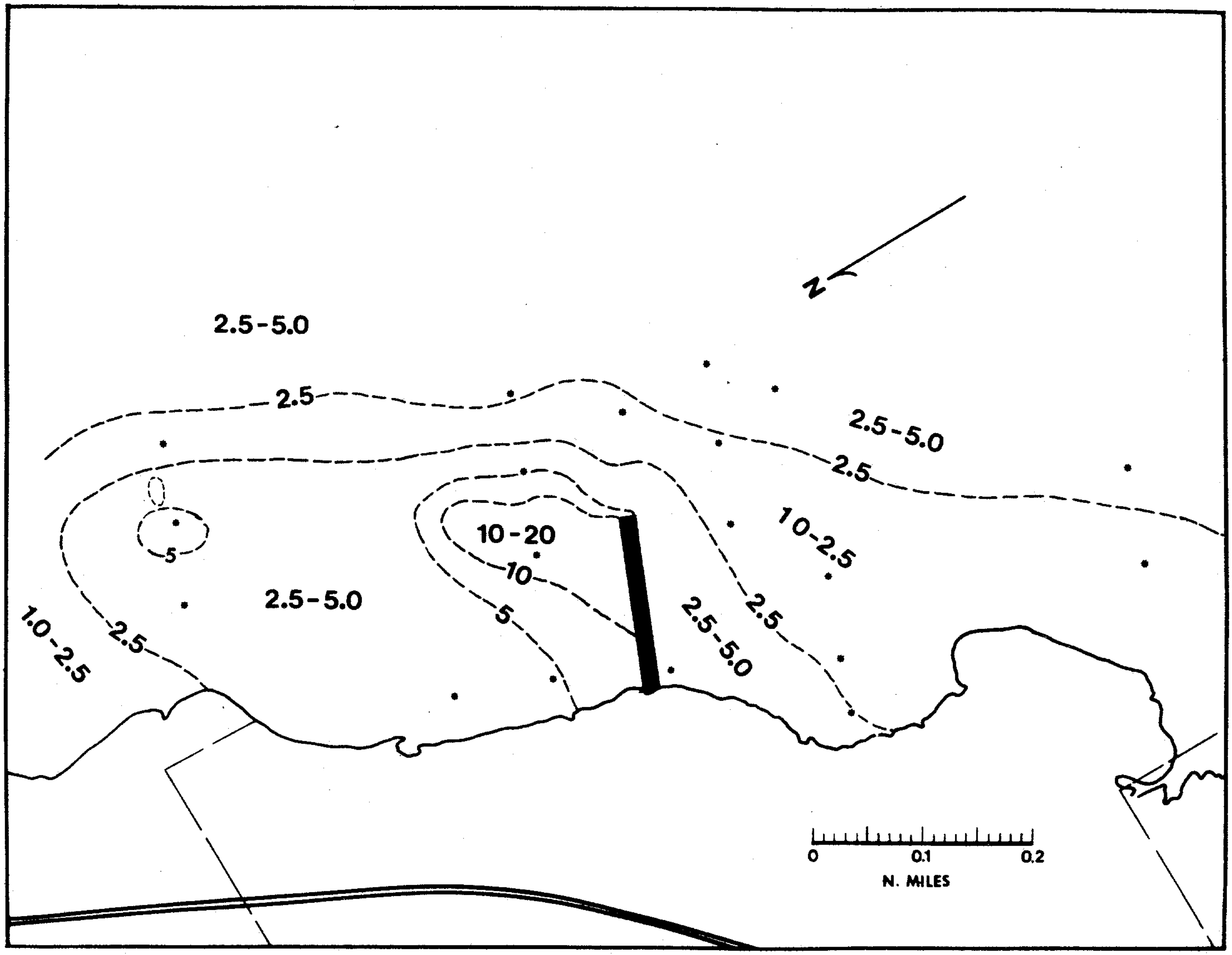
14a Location of transmissometer traverses on July 11, 1973 (Project day 262).



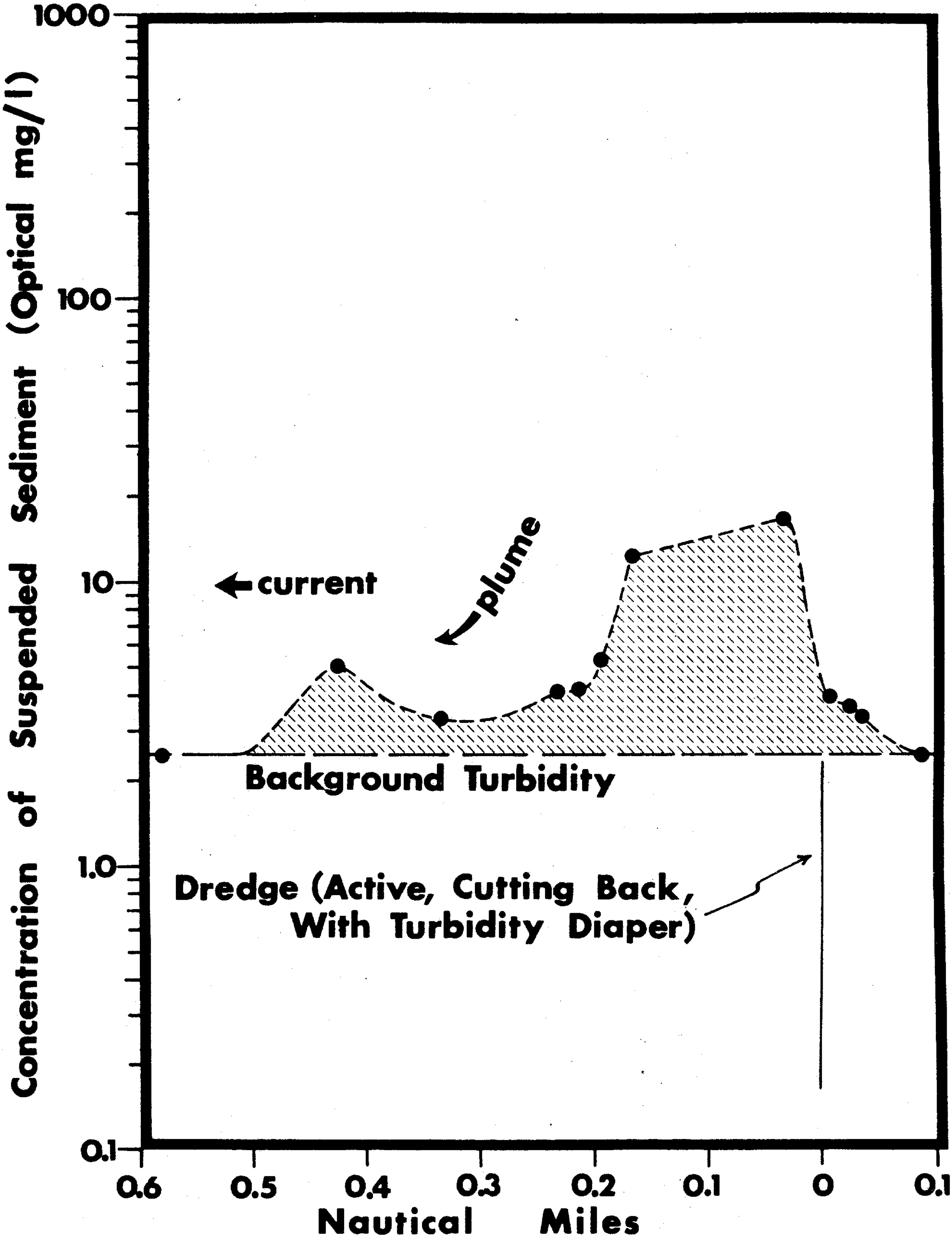
14b Concentration of suspended sediment in surface water on July 11, 1973 (Project day 262). Dredge was actively removing the spoil fingers, with a turbidity diaper.



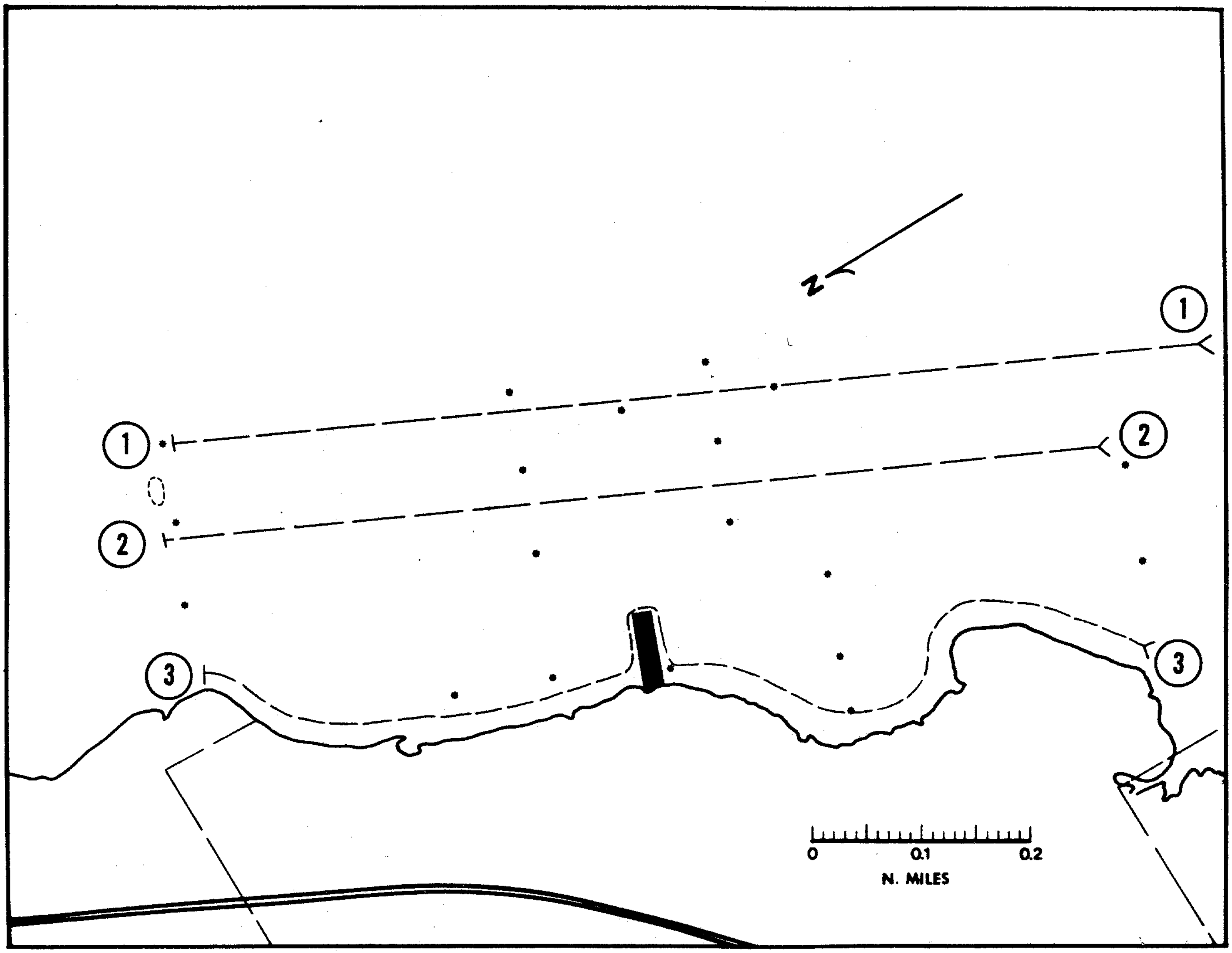
15a Location of transmissometer traverses on July 23, 1973 (Project day 274).



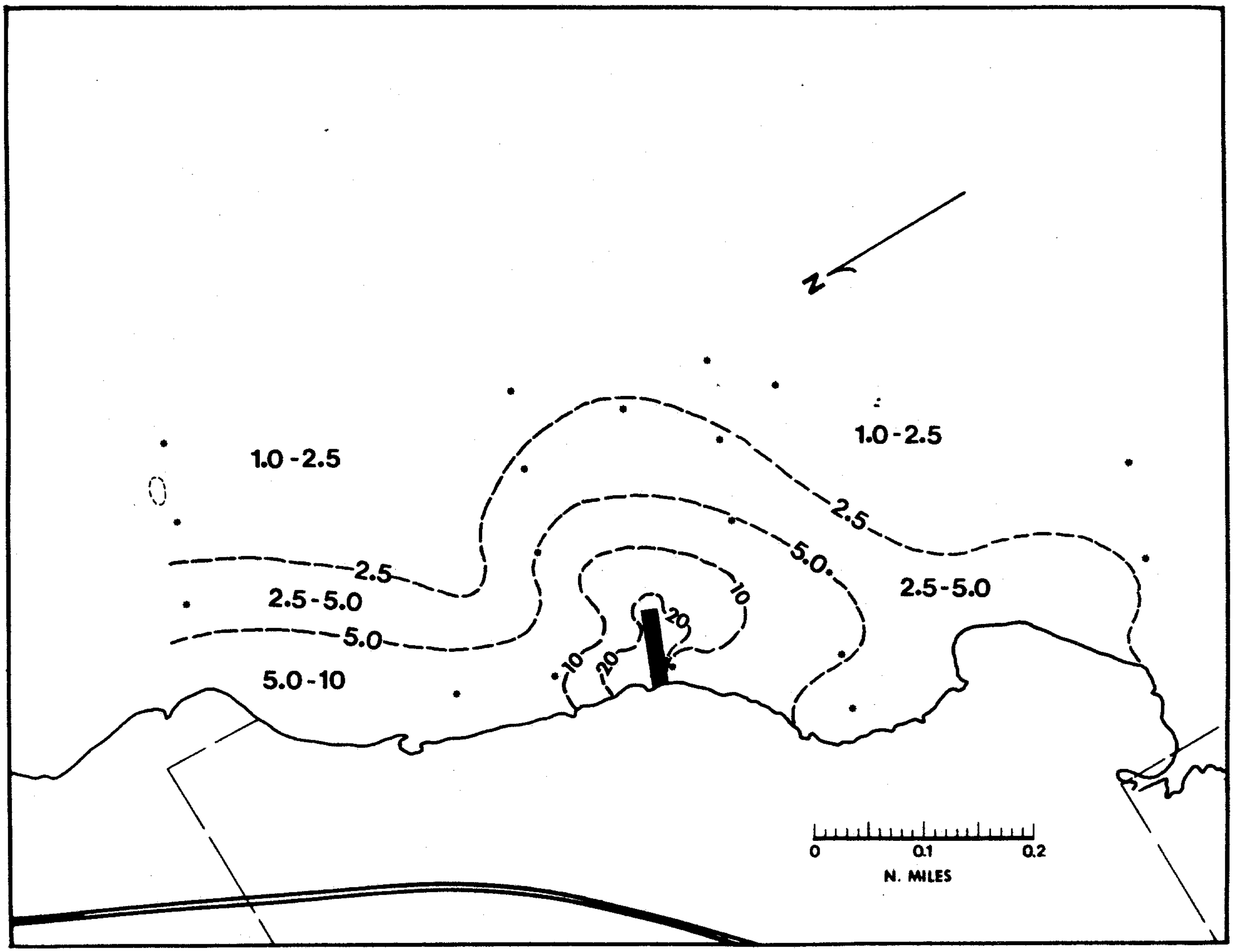
15b Concentration of suspended sediment in surface water on July 23, 1973 (Project day 274). Dredge was actively removing the spoil fingers, with a turbidity diaper.



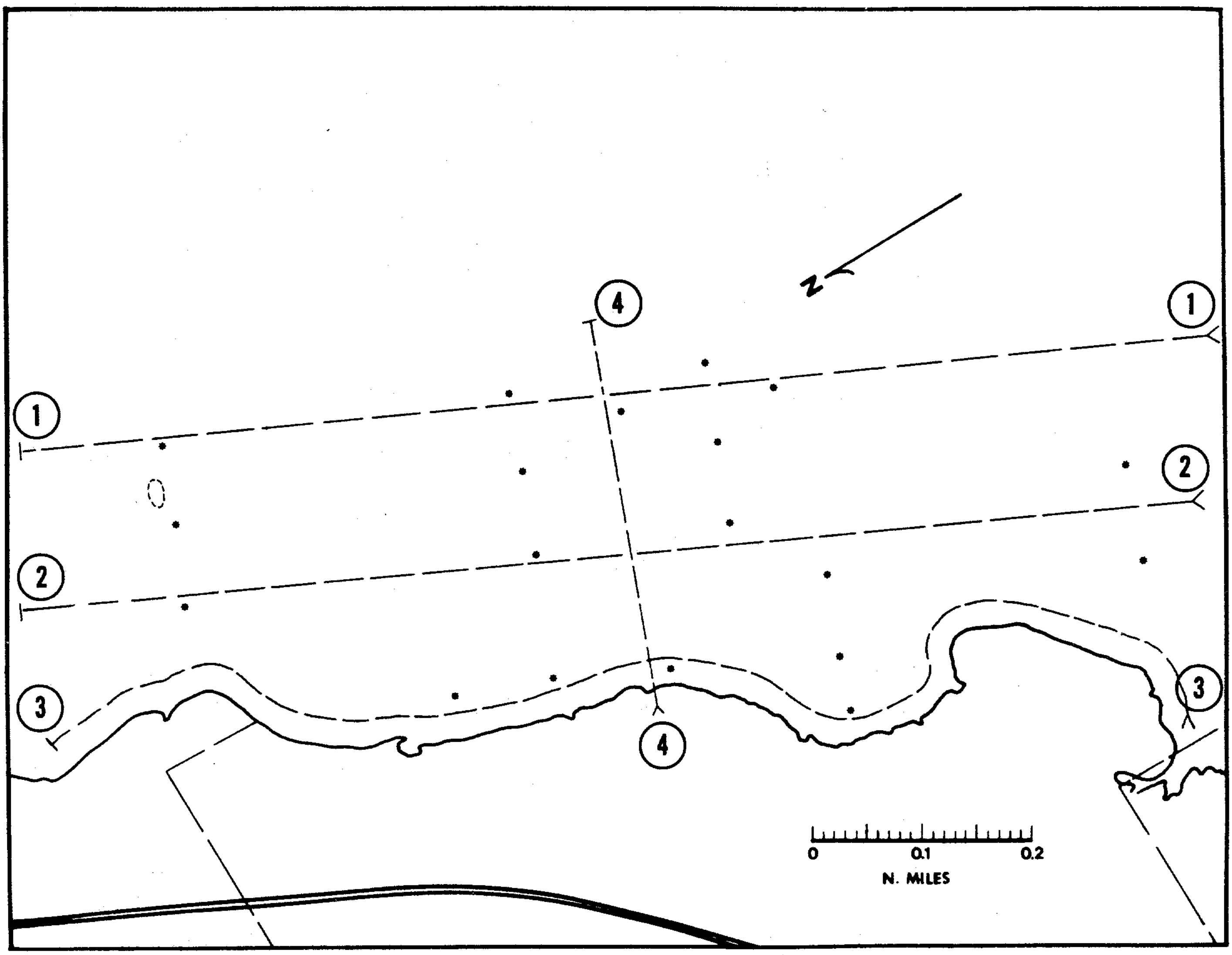
15c Concentration of suspended sediment in the most intense part of the plume vs distance from the dredge, July 23, 1973 (Project day 274). Dredge was actively removing the spoil fingers, with a turbidity diaper.



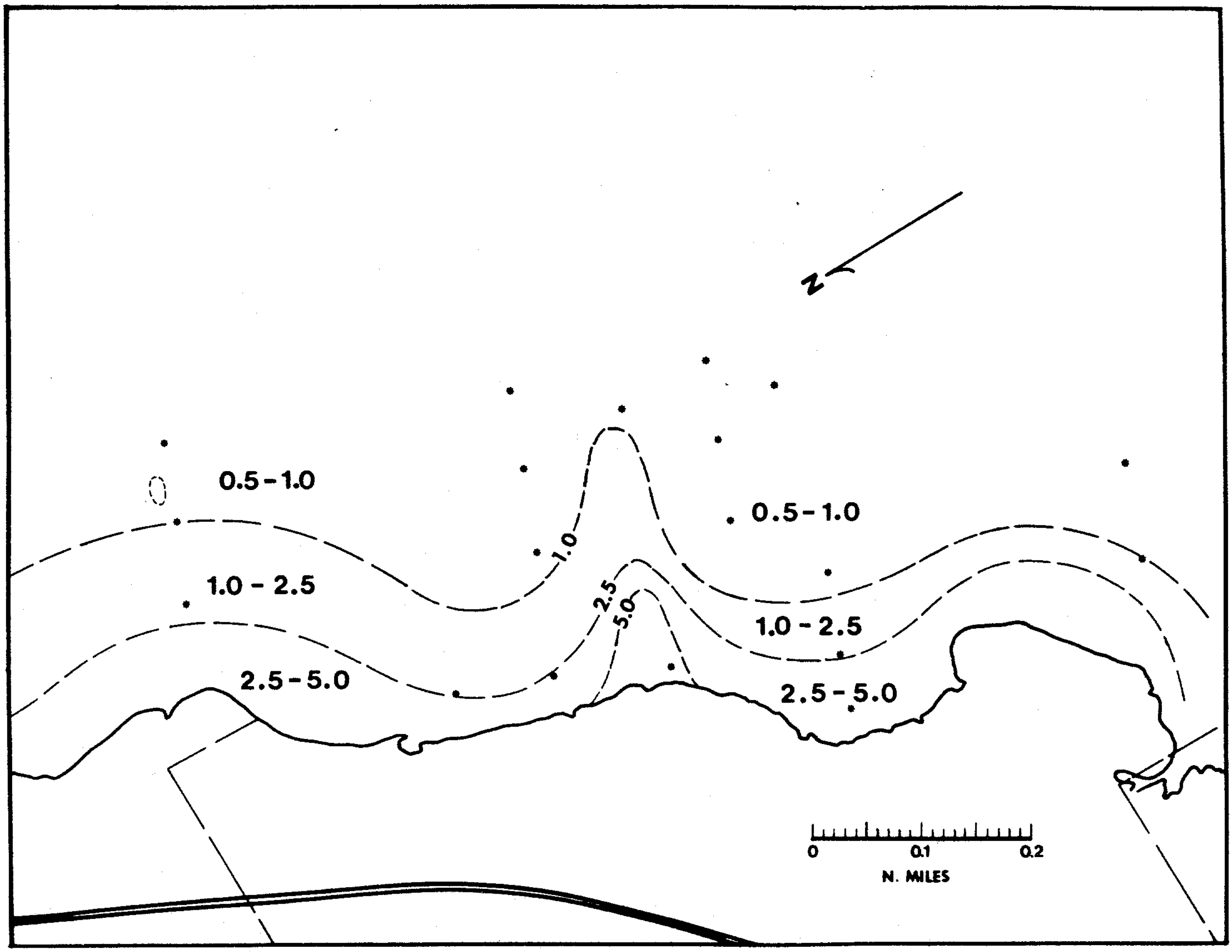
16a Location of transmissometer traverses on August 7, 1973 (Project day 289).



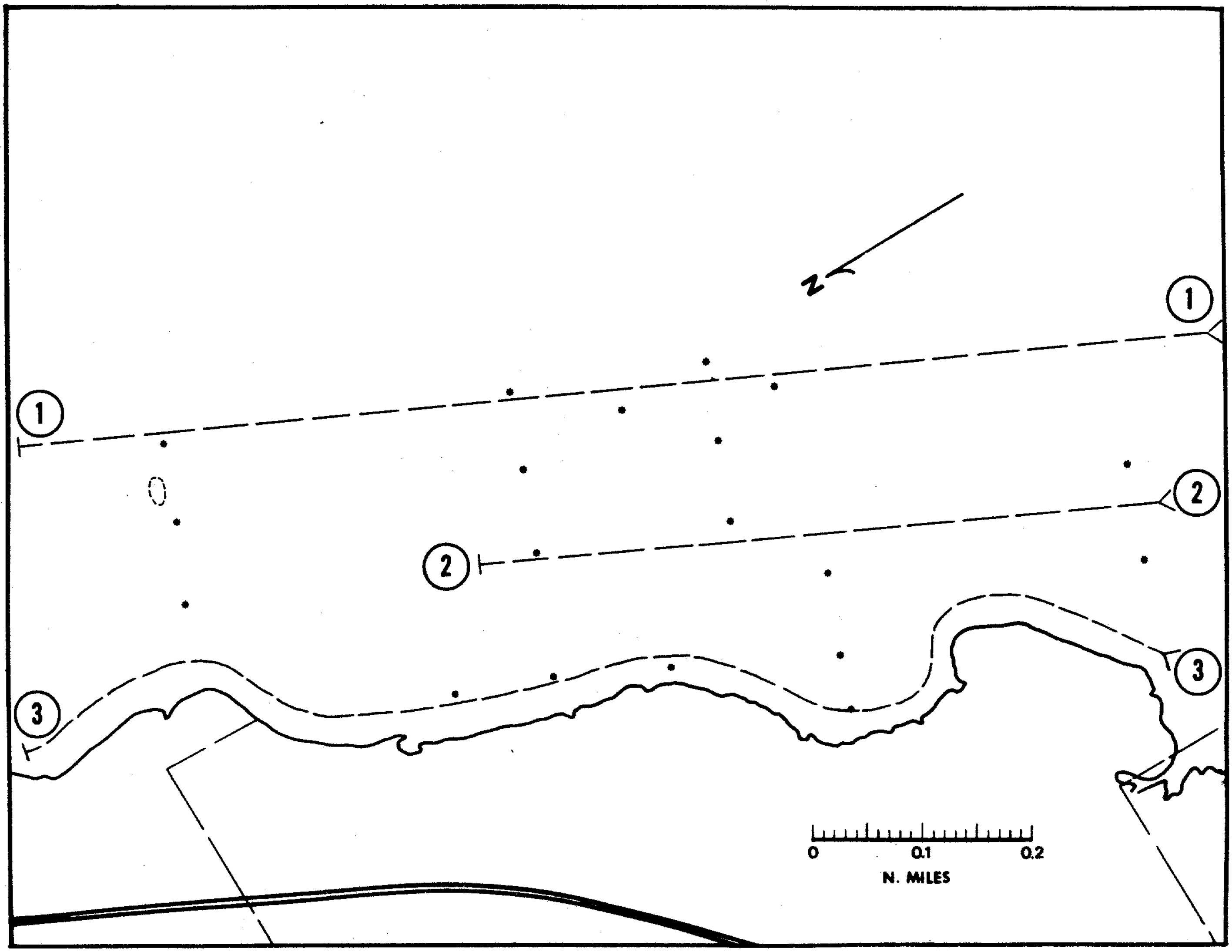
16b Concentration of suspended sediment in surface water on August 7, 1973 (Project day 289). Dredge was actively removing the spoil fingers, with a turbidity diaper.



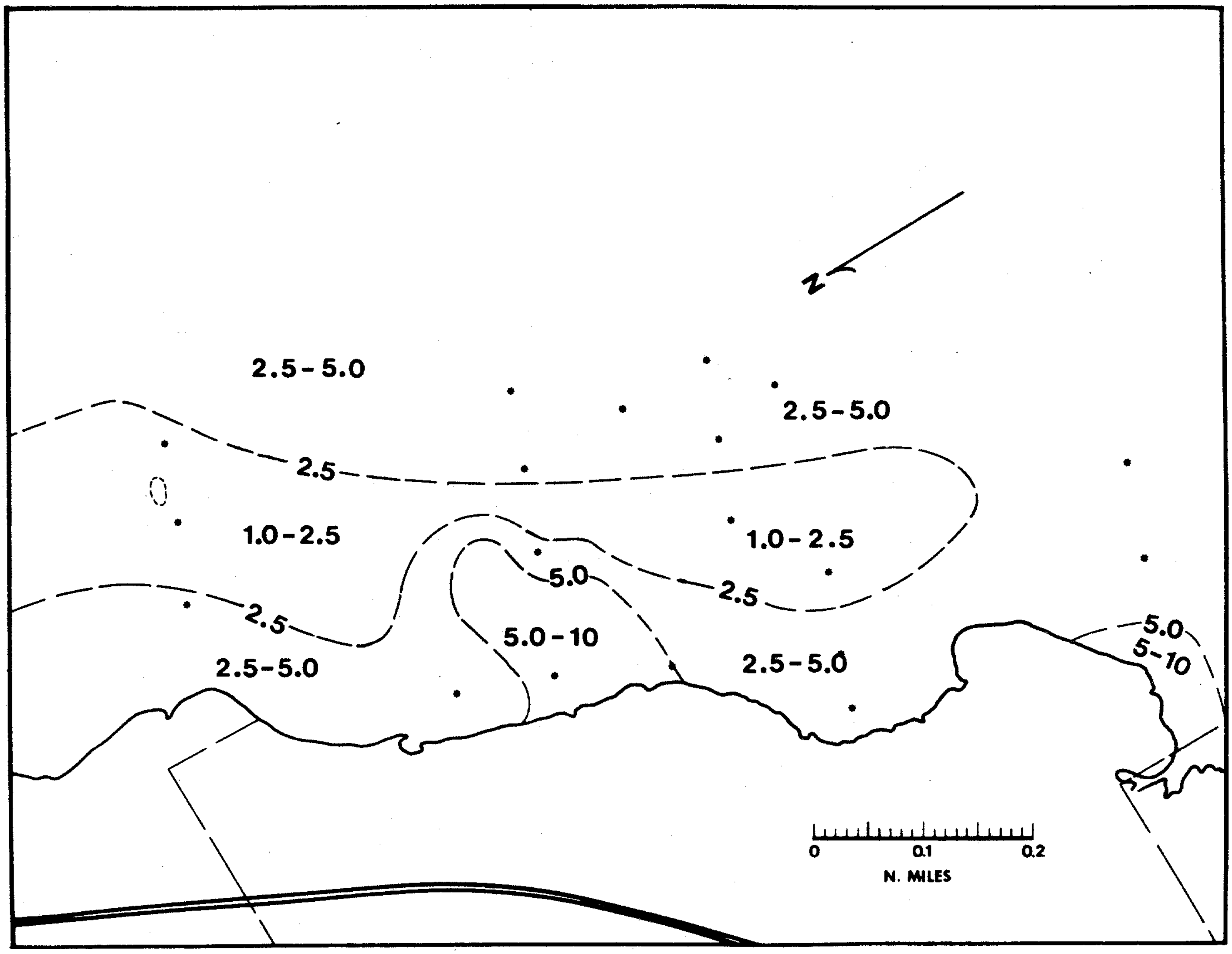
18a Location of transmissometer traverses on September 13, 1973 (Project day 326).



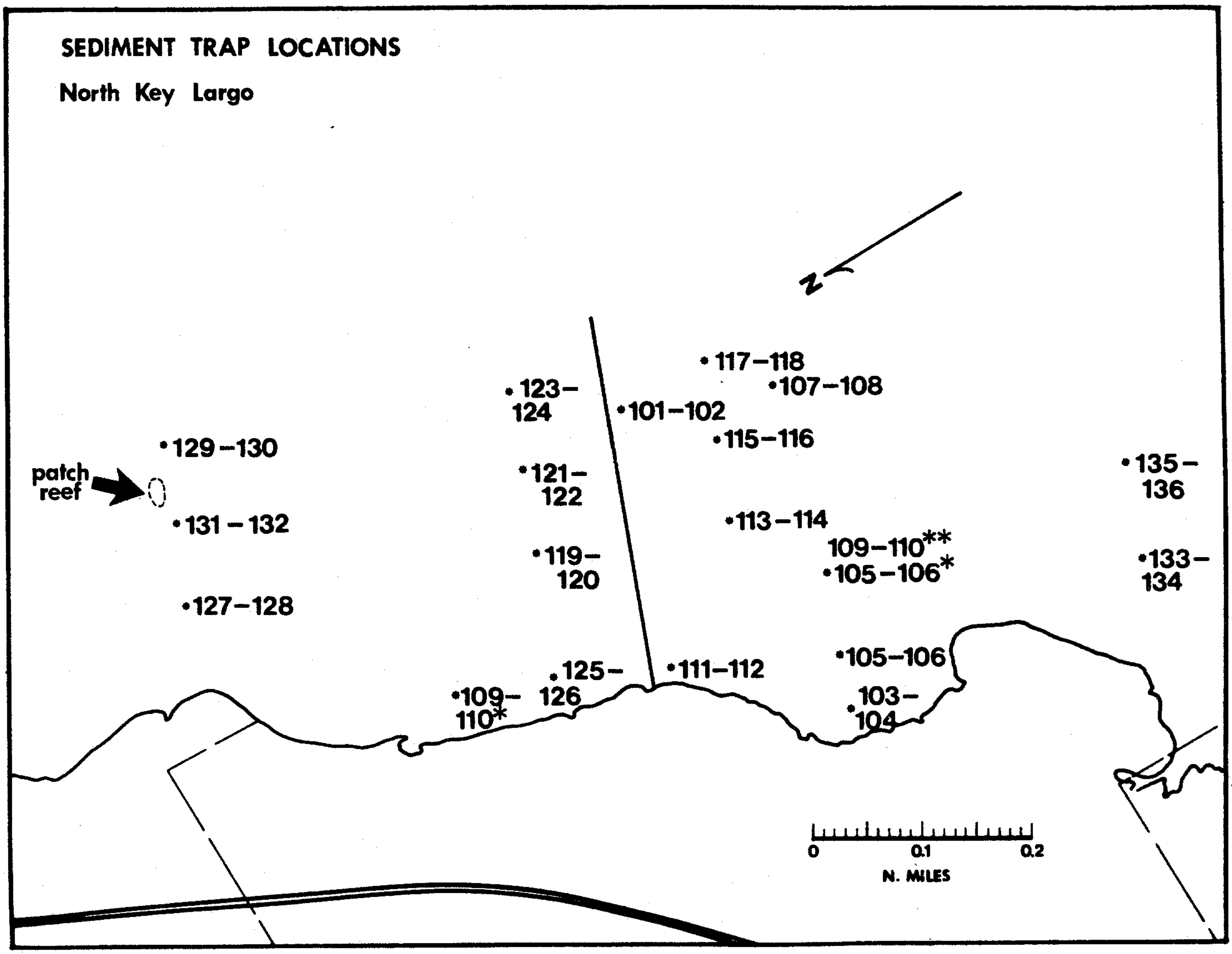
18b Concentration of suspended sediment in surface water on September 13, 1973 (Project day 326). Dredging had been completed approximately 30 days earlier, but some residual turbidity remains near the canal.



19a Location of transmissometer traverses on December 13, 1973 (Project day 427).

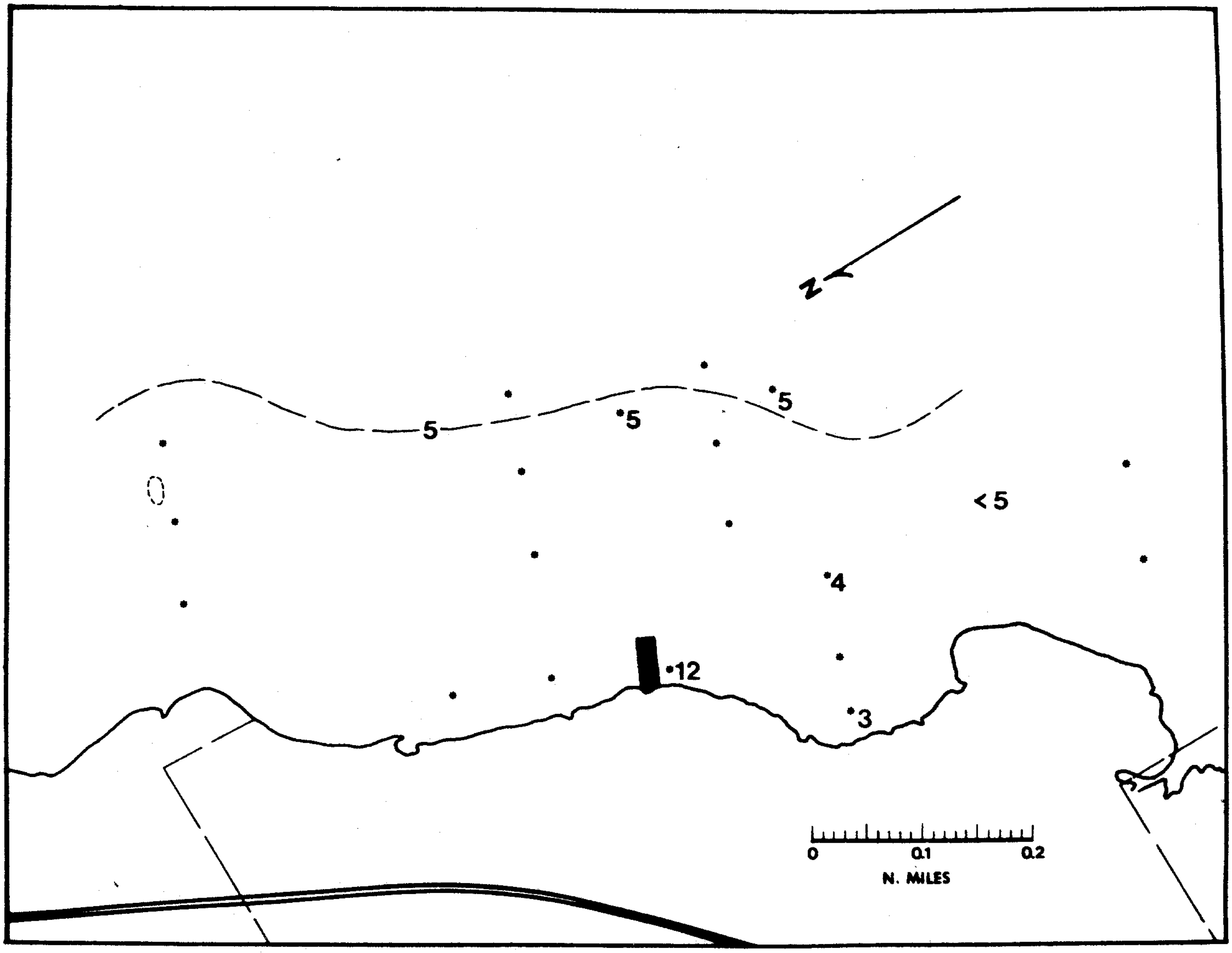


19b Concentration of suspended sediment in surface water on December 13, 1973 (Project day 427). Dredging had been completed approximately 90 days earlier, but some residual turbidity remains near the canal.

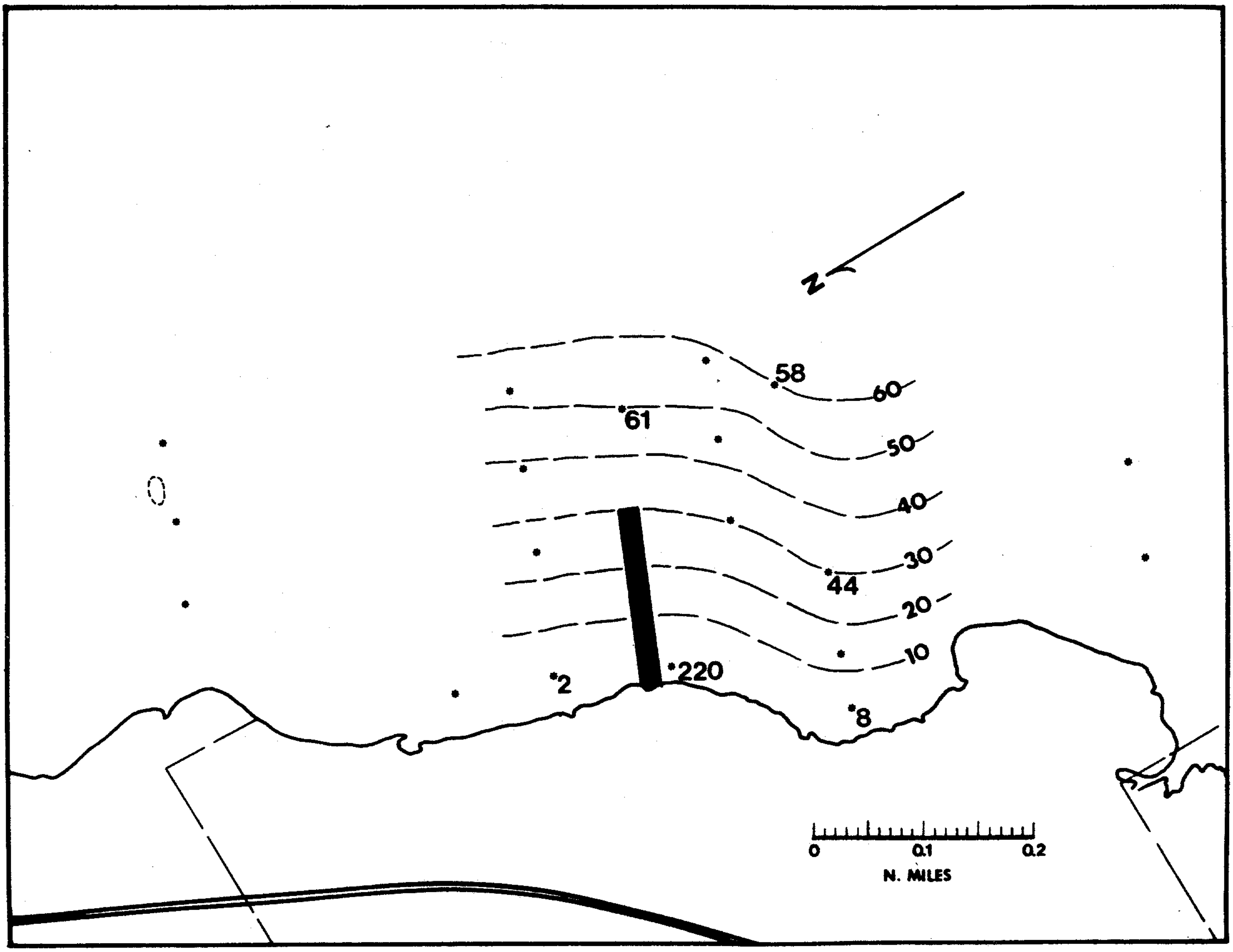


*–prior to 122872 **–after 122772

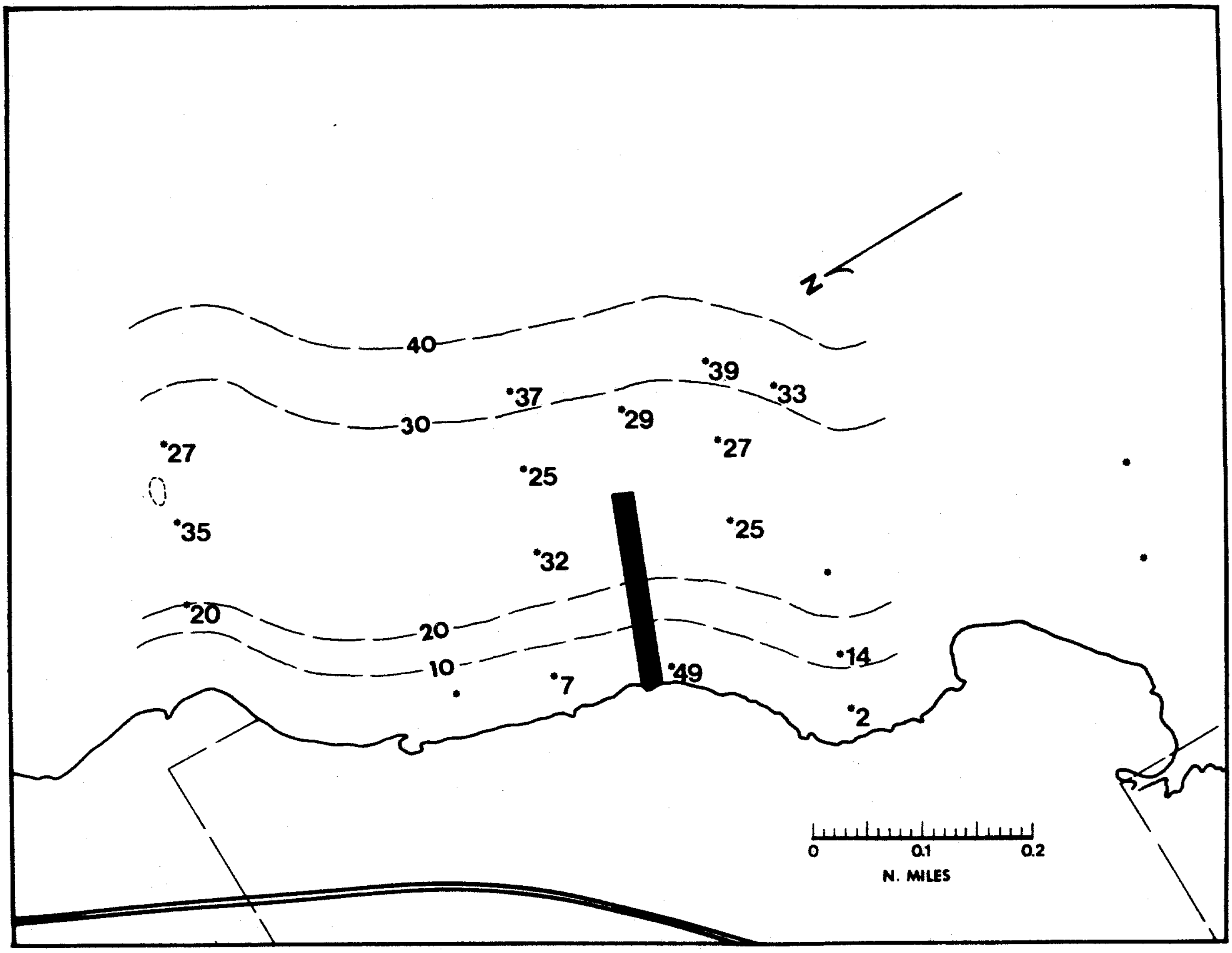
20 Location of sediment traps.



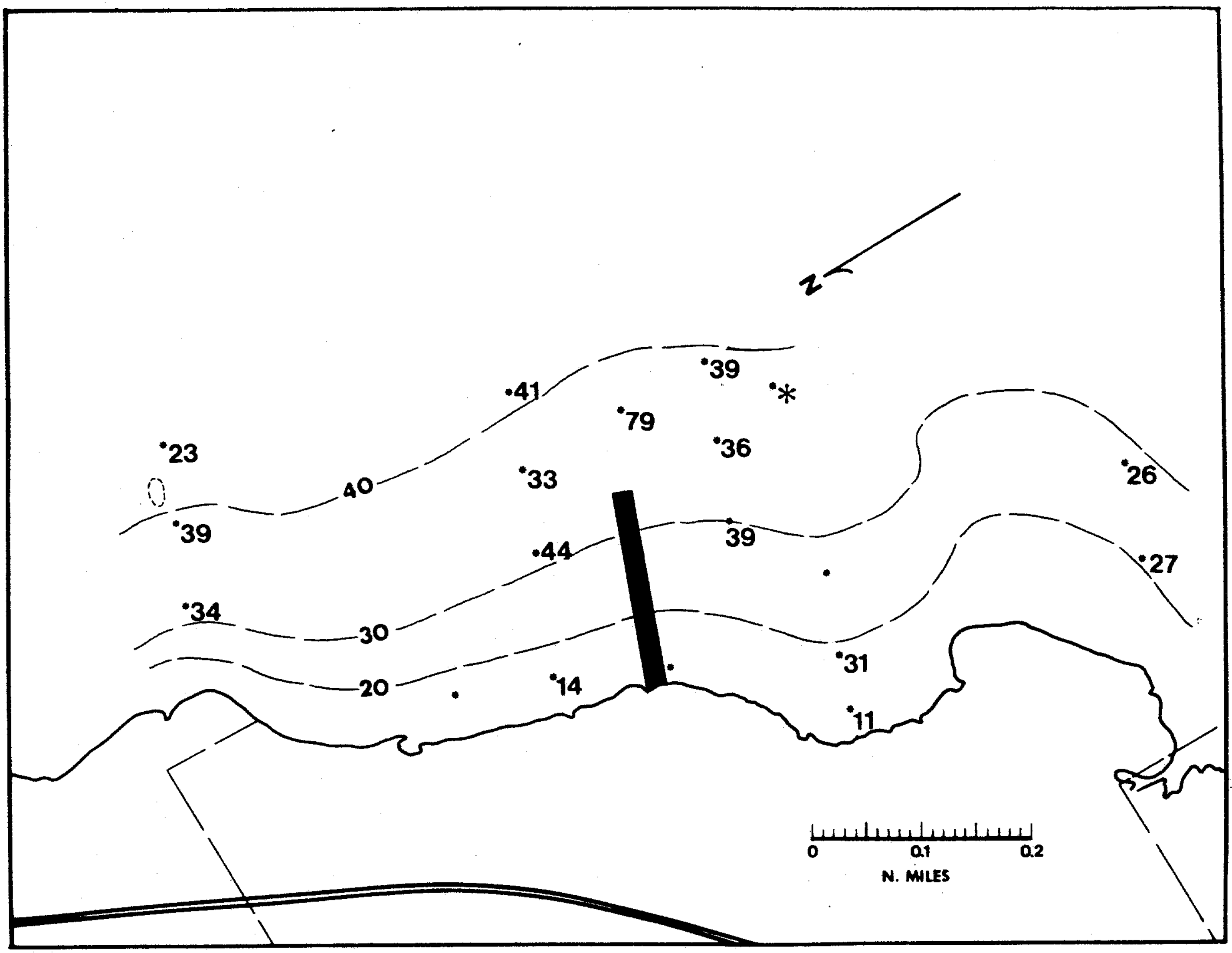
21 "Total rates of accumulation" of suspended sediment in $mg/cm^2/day$ for November 16 to December 7, 1972 (Project days 25-46). Values shown by the large dots represent the average dry weight accumulated in a pair of sediment traps, divided by the aperature area of a trap, and further divided by the number of days in the collection period. Dashed contour lines are the "natural accumulation rates" for the same period (i.e. the supposed rates in the absence of the dredge), as explained further in the text. Length of spoil fingers is indicated by the broad line extending ESE from the shoreline; a narrower line on later figures in this series locates the dredged canal after the spoil fingers were removed. Dots without numbers indicate lost, damaged, or otherwise omitted traps. The small dashed ellipse in the northern part of the figures in the coral patch reef.



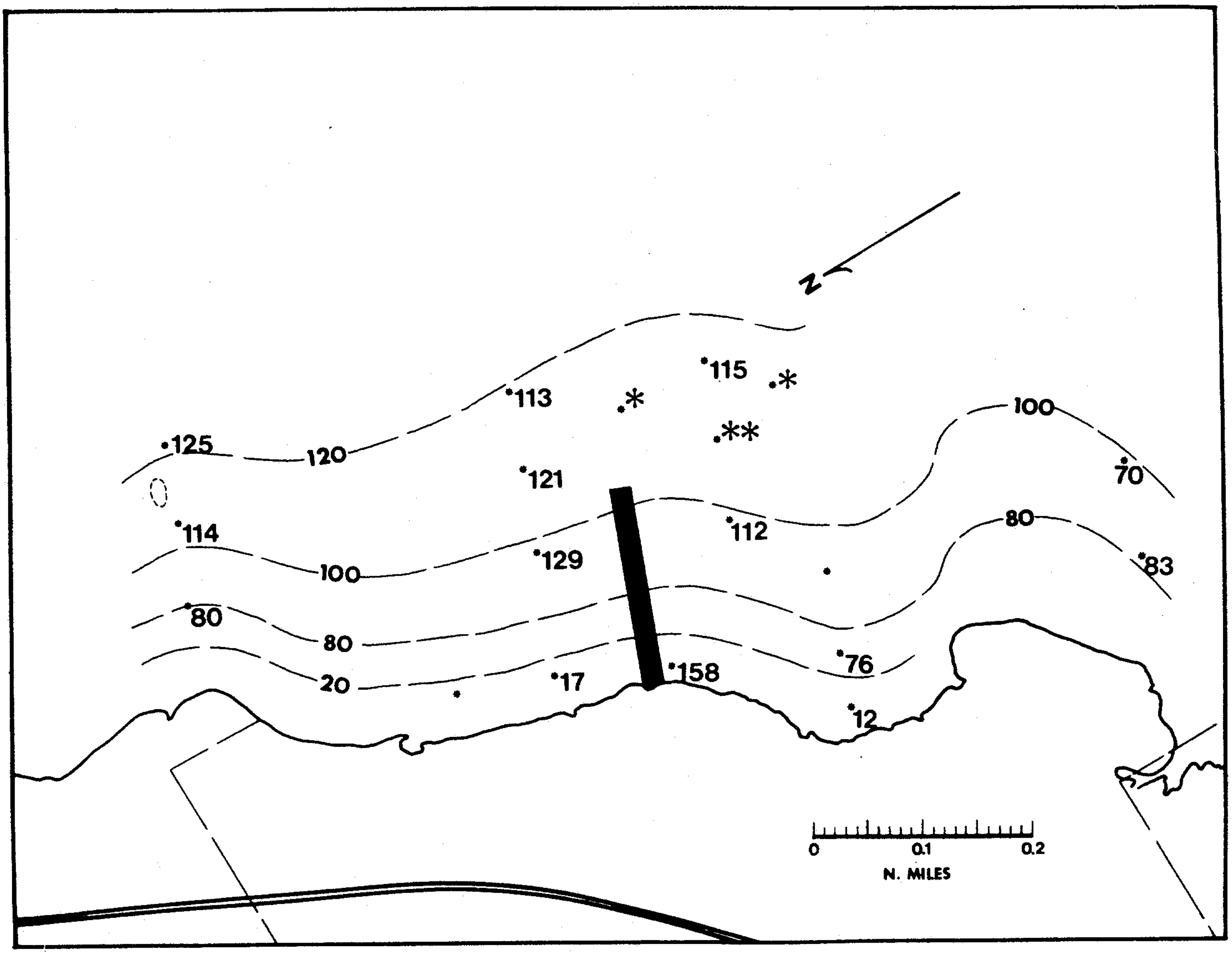
22 "Total rates" and "natural rates" of accumulation for the period December 7 to December 28, 1972 (Project days 46-67). See Figure 20 for explanation.



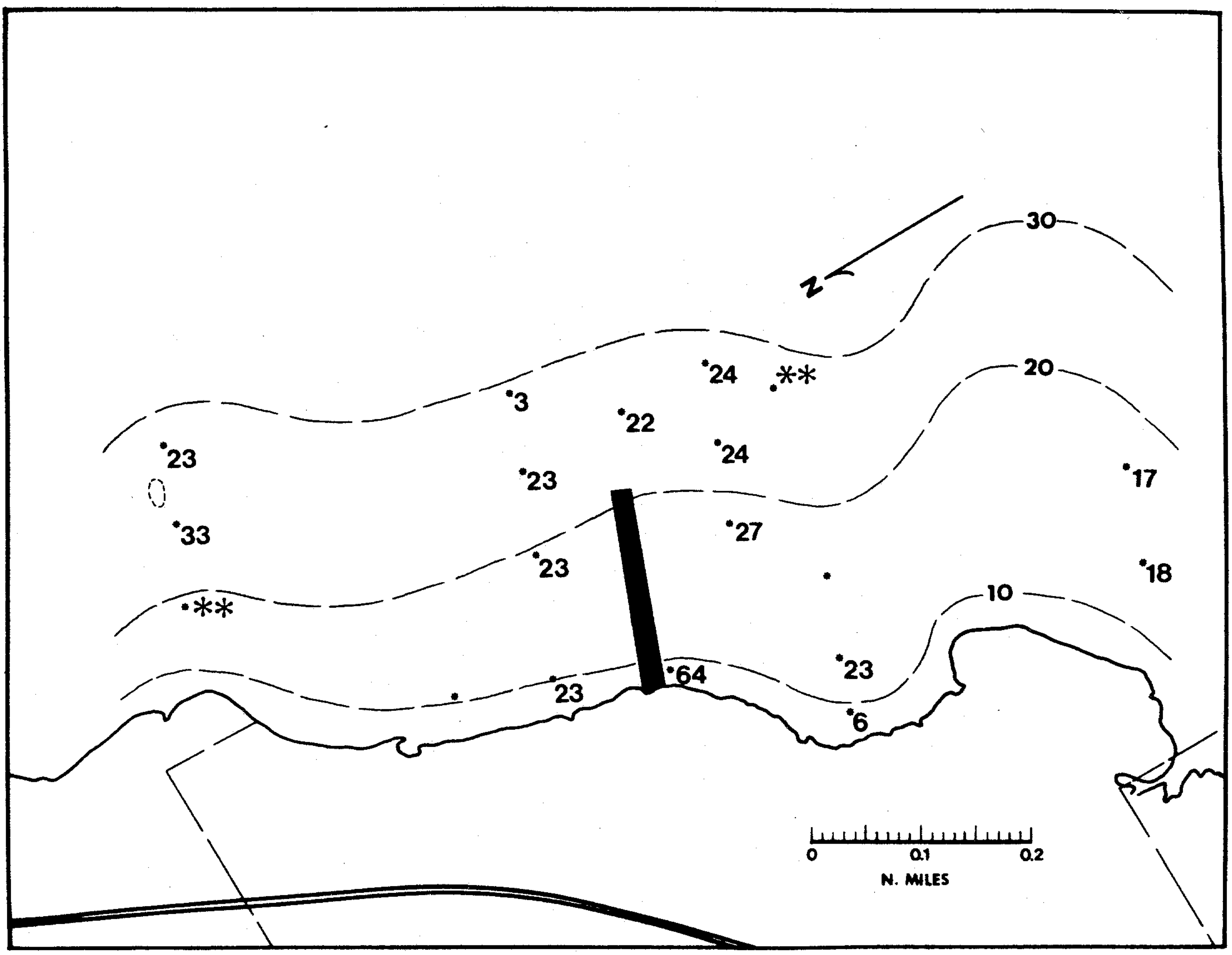
23 "Total rates" and "natural rates" of accumulation for the period December 28, 1972 to January 15, 1973 (Project days 67-85). See Figure 20 for explanation.



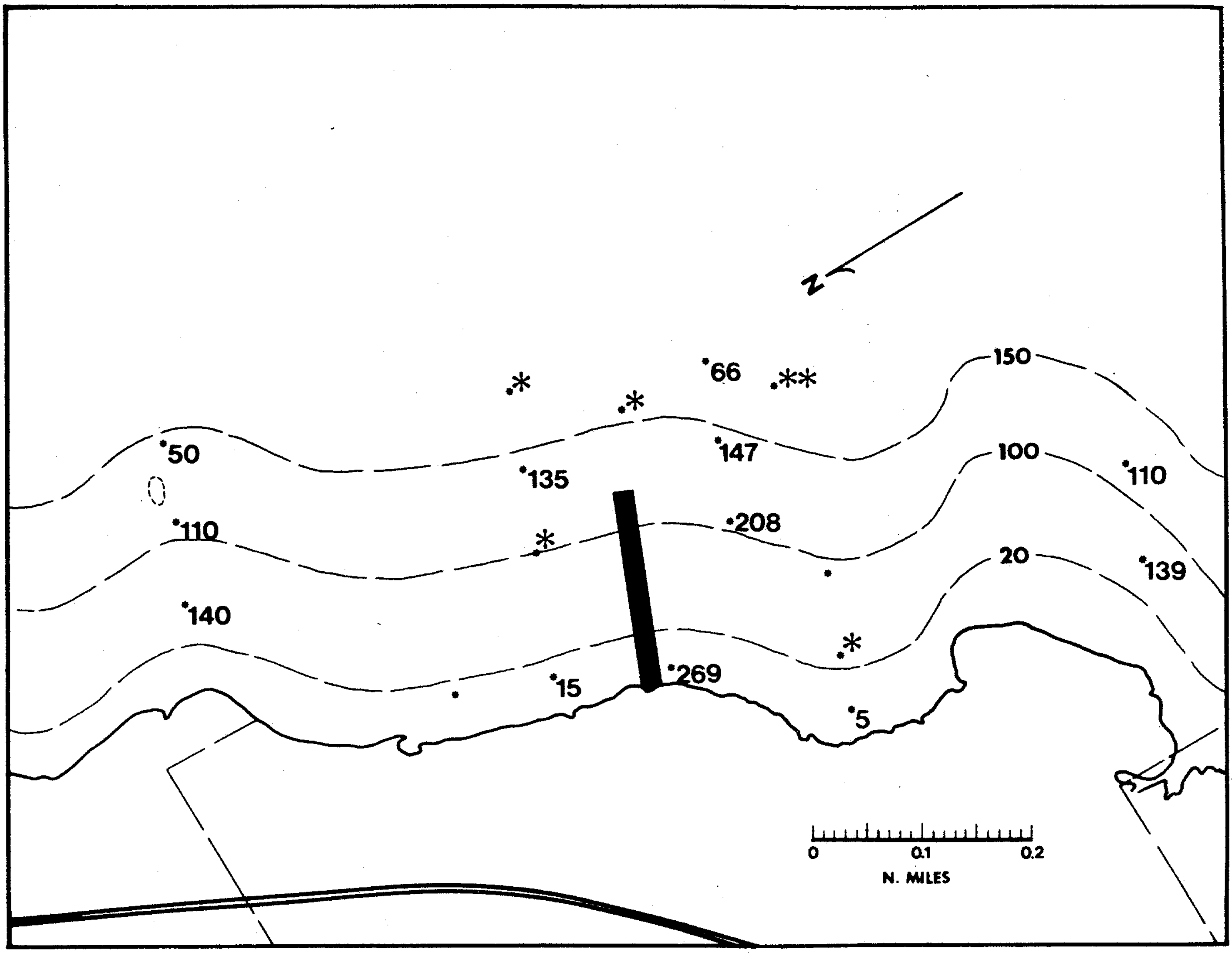
24 "Total rates" and "natural rates" of accumulation for the period January 15 to January 26, 1973 (Project days 85-96). See Figure 20 for explanation.



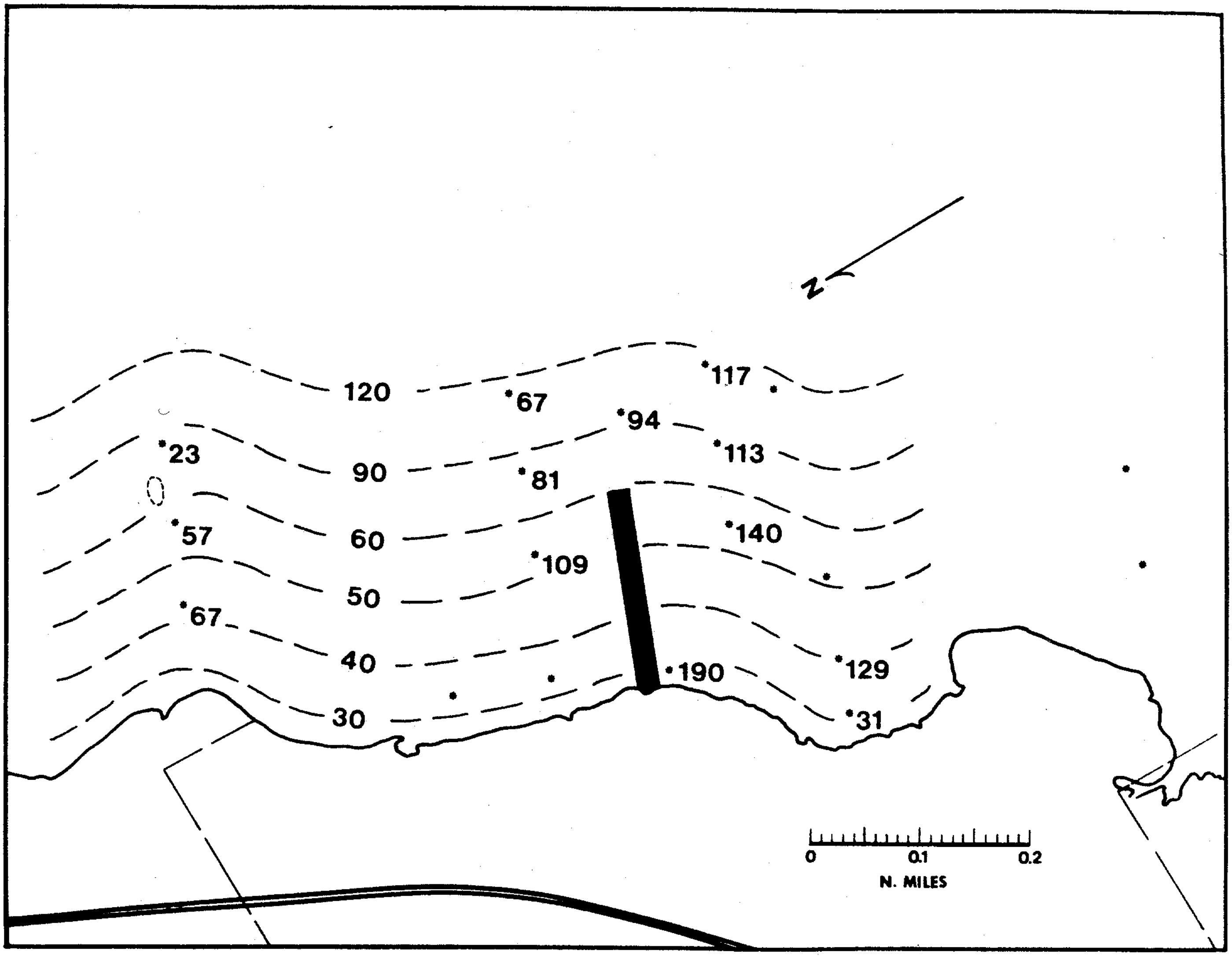
25 "Total rates" and "natural rates" of accumulation for the period January 26 to February 14, 1973 (Project days 96-115). An unusually severe cold front caused the abnormally high accumulation rates.



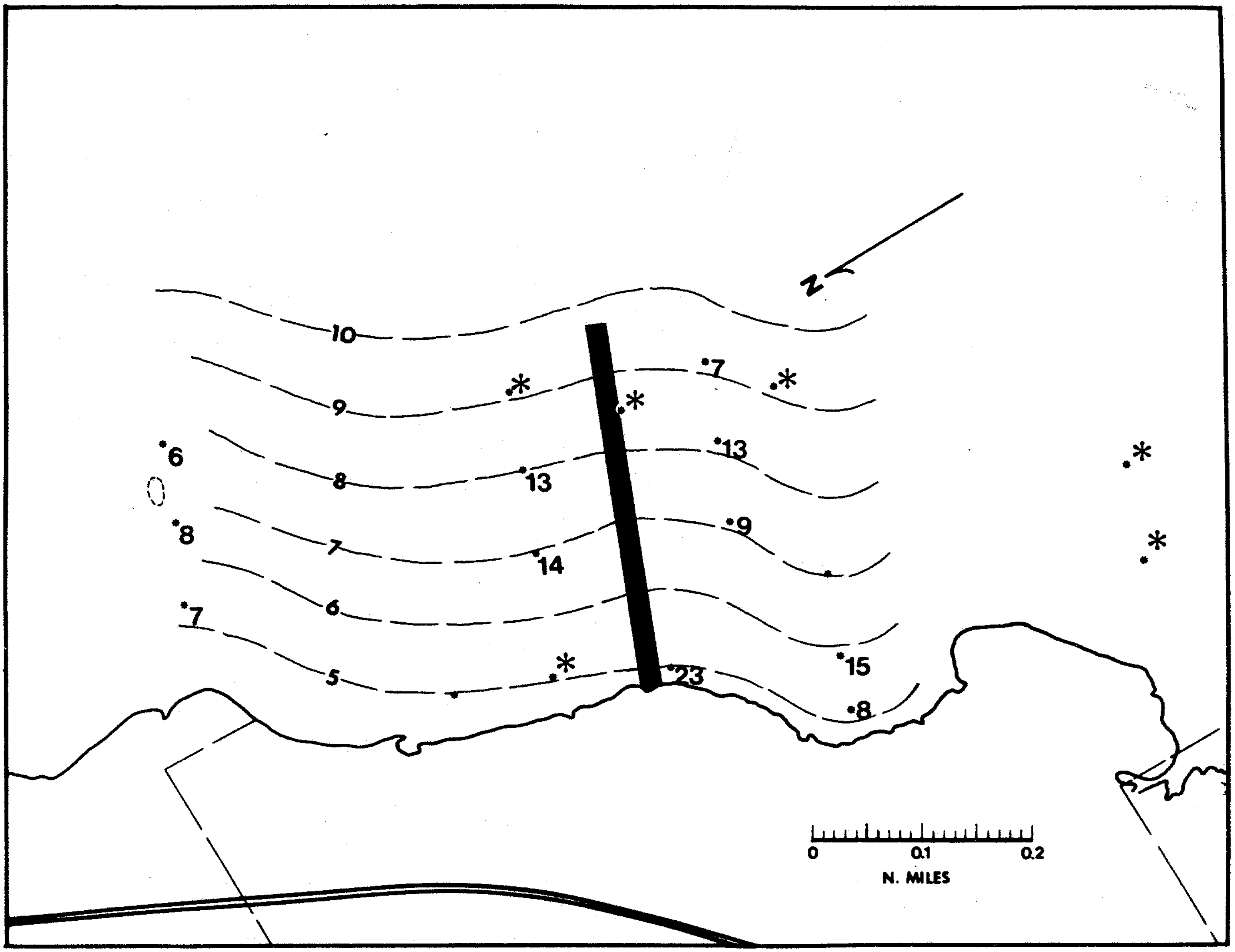
26 "Total rates" and "natural rates" of accumulation for the period February 14 to March 14, 1973 (Project days 115-143).



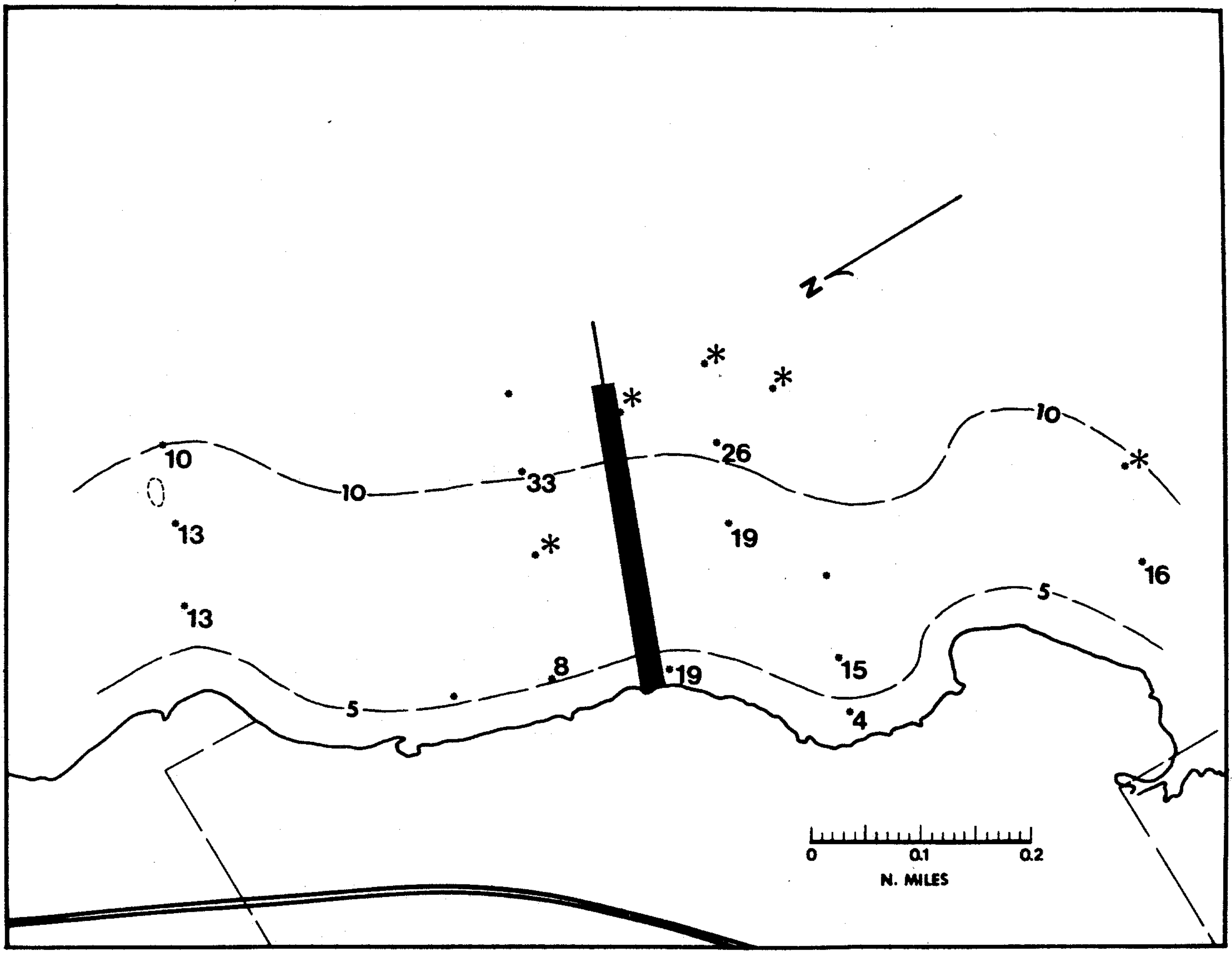
27 "Total rates" and "natural rates" of accumulation for the period March 14 to April 18, 1973 (Project days 143-178).



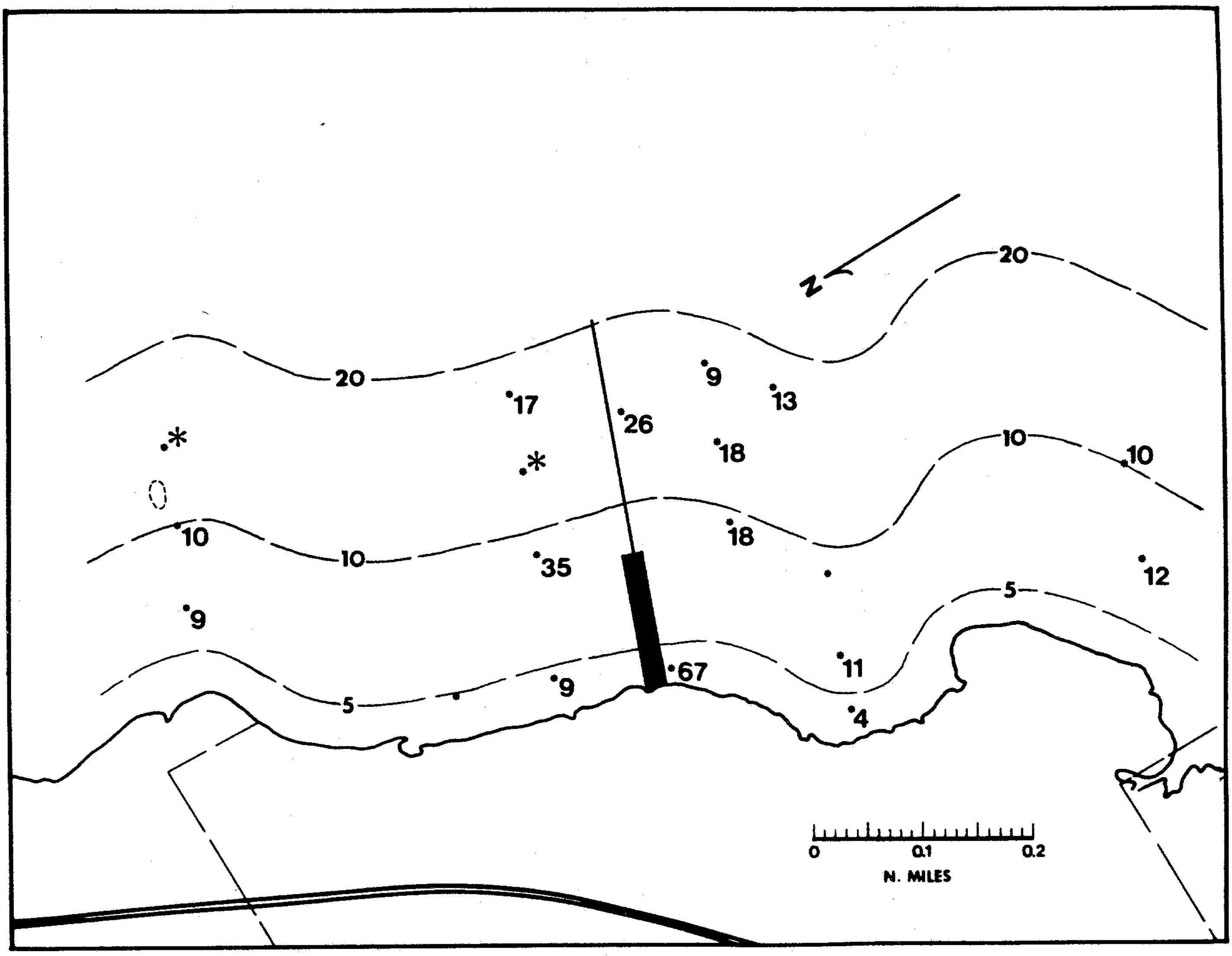
28 "Total rates" and "natural rates" of accumulation for the period April 18 to May 11, 1973 (Project days 178-201). The "natural" rate contours for this period are very uncertain.



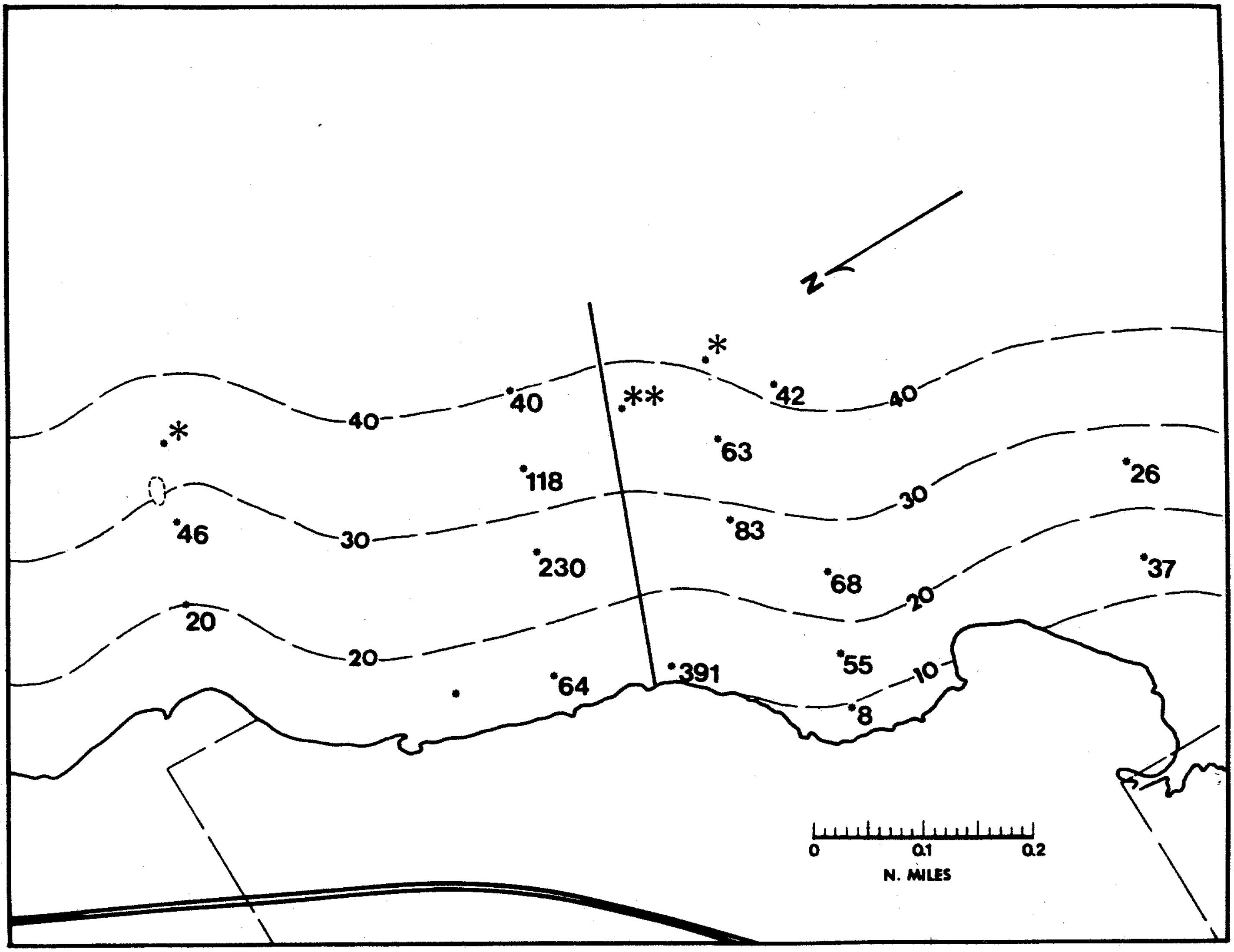
29 "Total rates" and "natural rates" of accumulation for the period May 11 to May 31, 1973 (Project days 201-221).



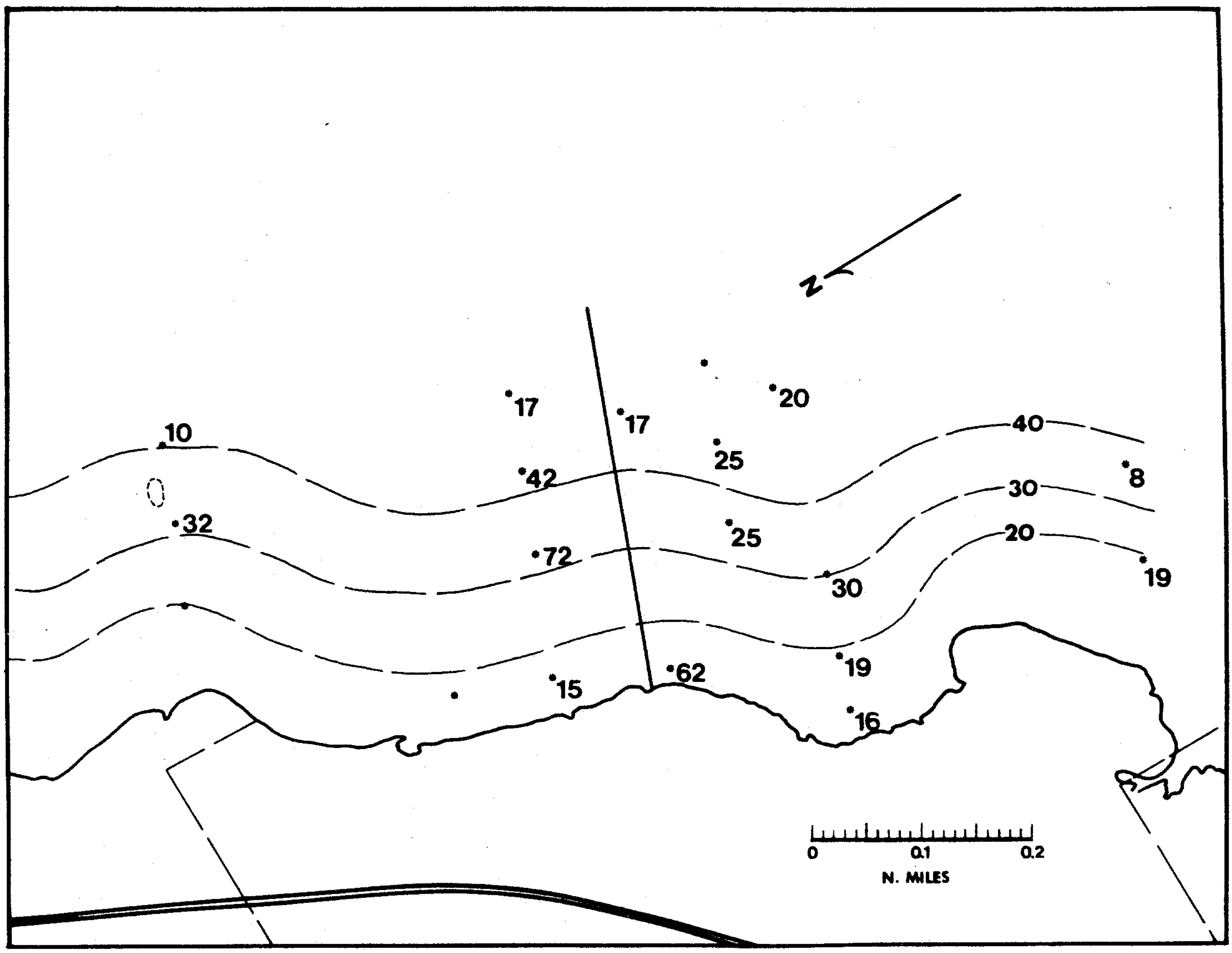
30 "Total rates" and "natural rates" of accumulation for the period May 31 to July 9, 1973 (Project days 221-260).



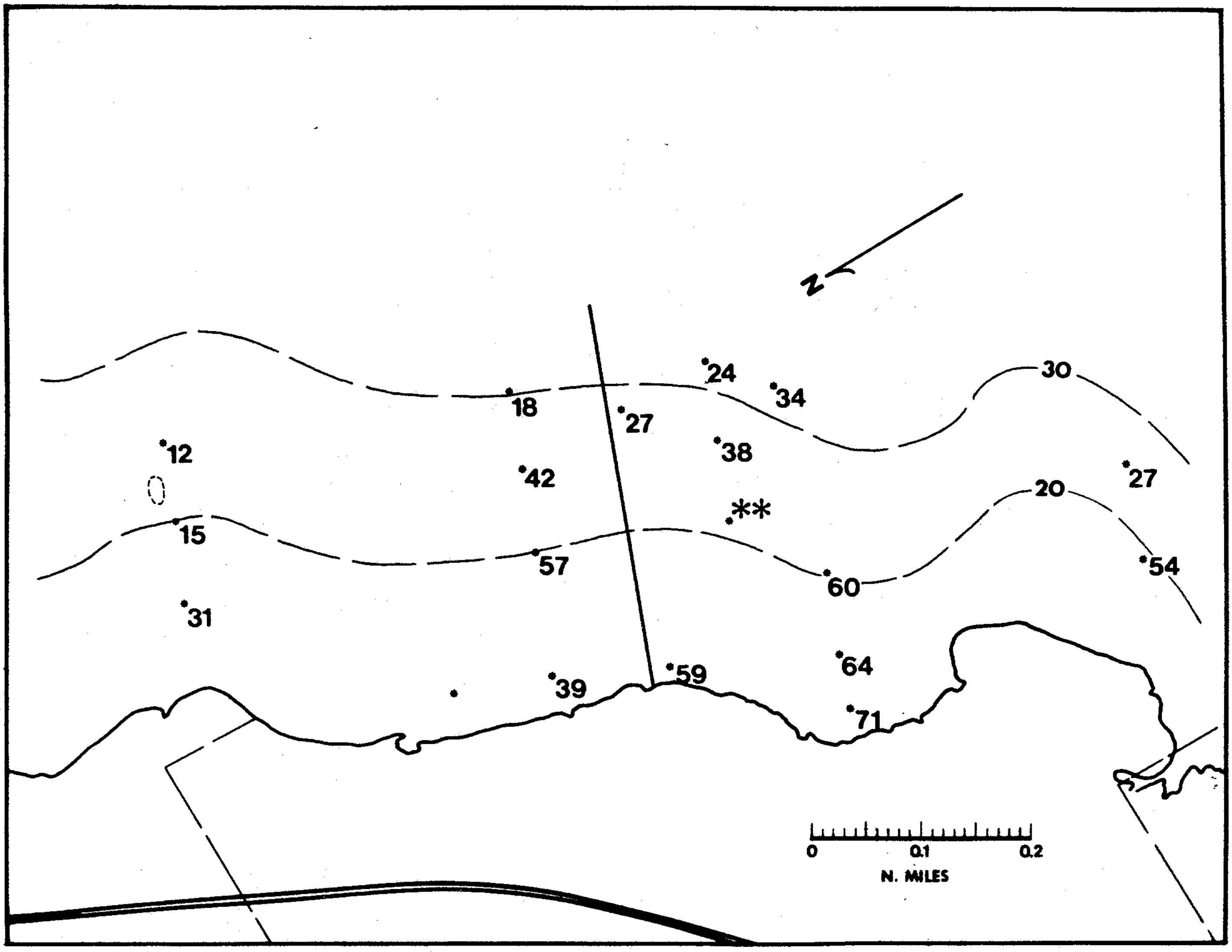
31 "Total rates" and "natural rates" of accumulation for the period July 9 to August 2, 1973 (Project days 260-284).



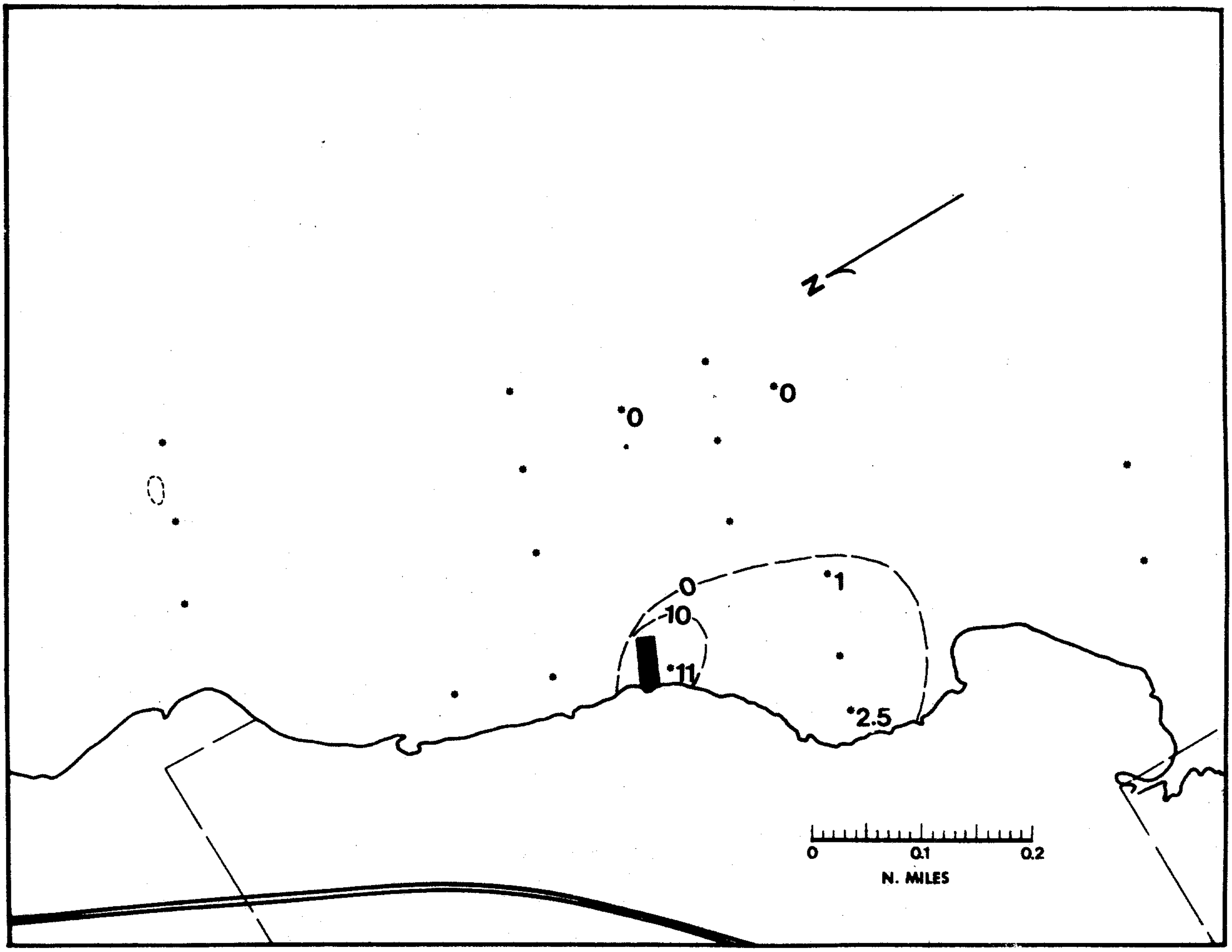
32 "Total rates" and "natural rates" of accumulation for the period August 2 to September 5, 1973 (Project days 284-318).



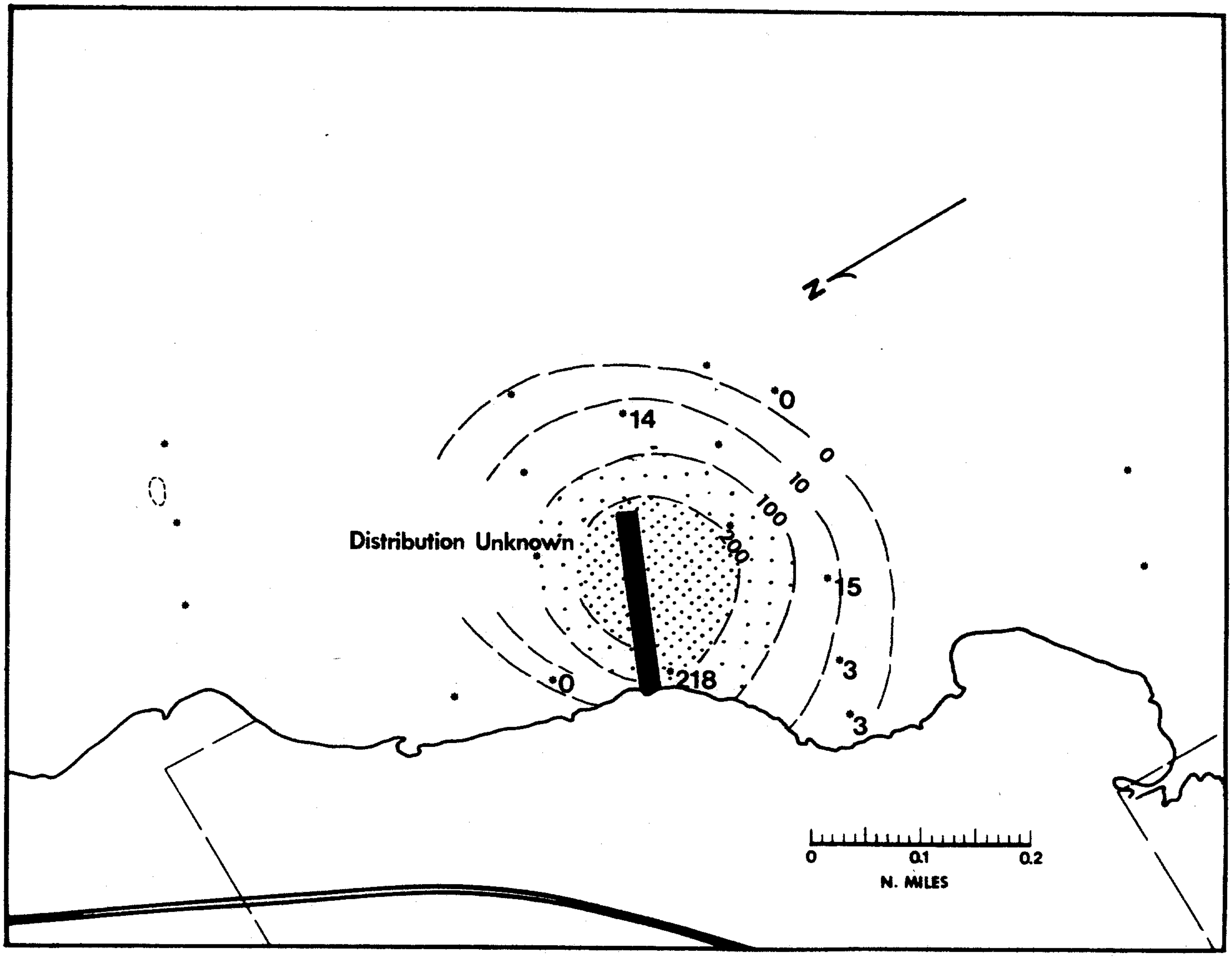
33 "Total rates" and "natural rates" of accumulation for the period September 5 to October 2, 1973 (Project days 318-345).



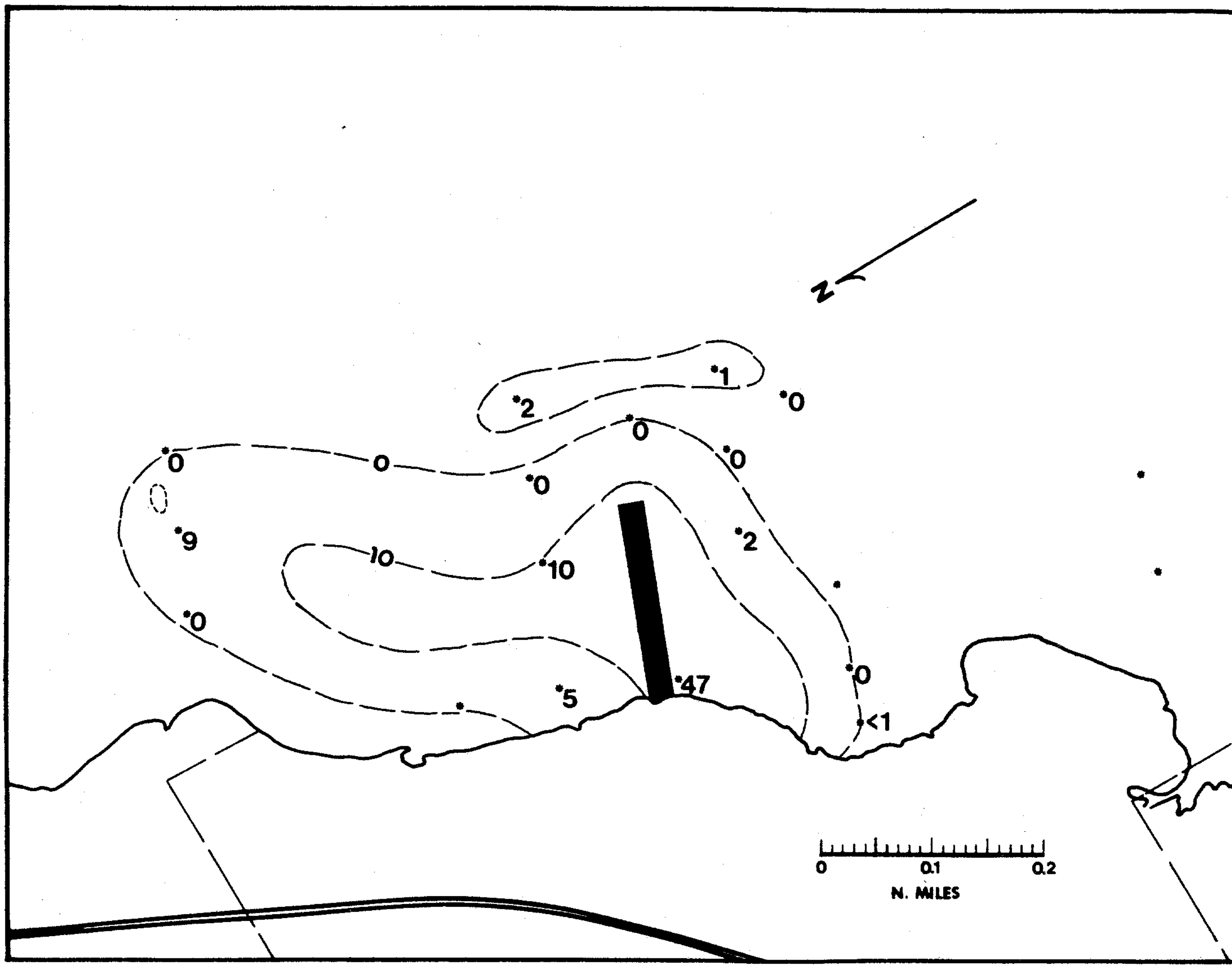
34 "Total rates" and "natural rates" of accumulation for the period October 2 to October 24, 1973 (Project days 345-367).



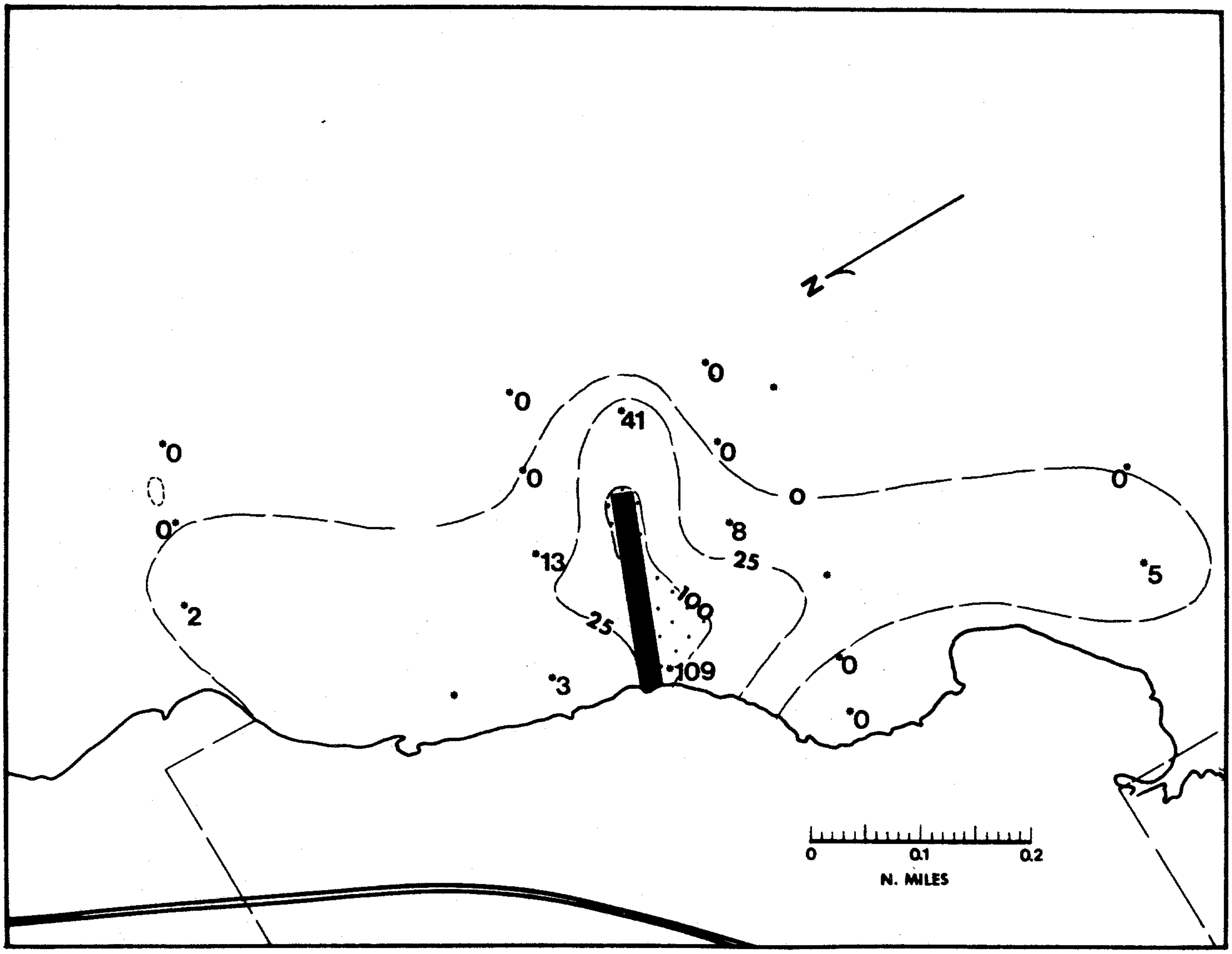
35 "Excess rates" of accumulation of suspended sediment attributable to the dredge project during the period November 16 to December 7, 1972 (Project days 25-46). Values shown by the large dots are the arithmetic difference between the "total" and the "natural" accumulations from Figures 21-34. These "excess rates" indicate the part of the total accumulation that was induced directly by the dredging, by erosion of spoil, or by other factors resulting from the presence of the project. The "excess rate" is contoured by dashed lines; all values are in mg/cm^2/day. Spoil fingers are indicated by a broad band; on later figures the location of the completed canal, after spoil removal, is shown by a narrow line. Dots without numbers indicate lost, damaged, or otherwise omitted traps. The dredge was actively extending the canal, without a turbidity diaper.



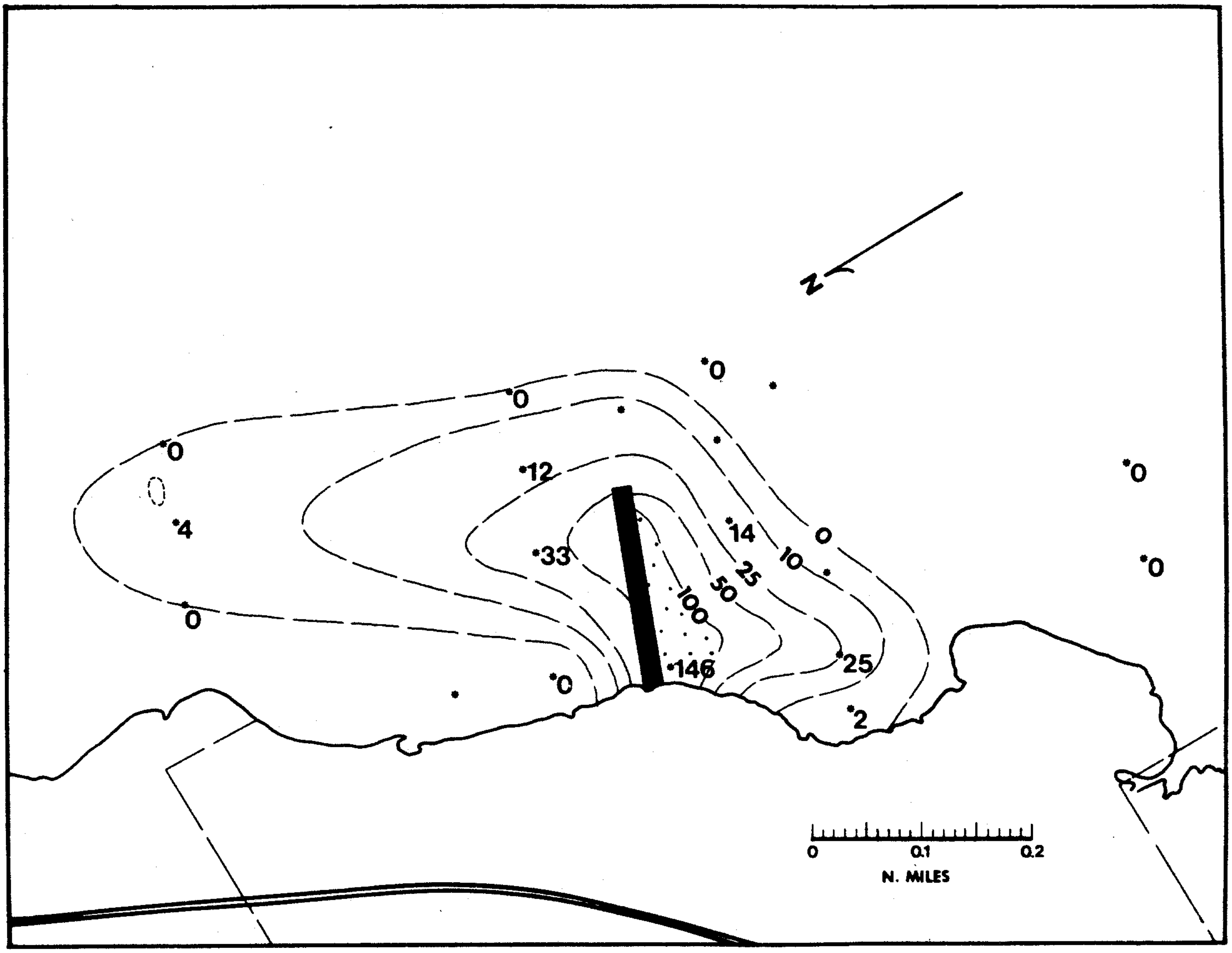
36 "Excess rates" attributable to the dredge project for the period December 7 to December 28, 1972 (Project days 45-67). The dredge was actively extending the canal. An area of relatively intense dredge-induced siltation (>100 and >200 $mg/cm^2/day$) is indicated by stippling. See Figure 35 for explanation of symbols.



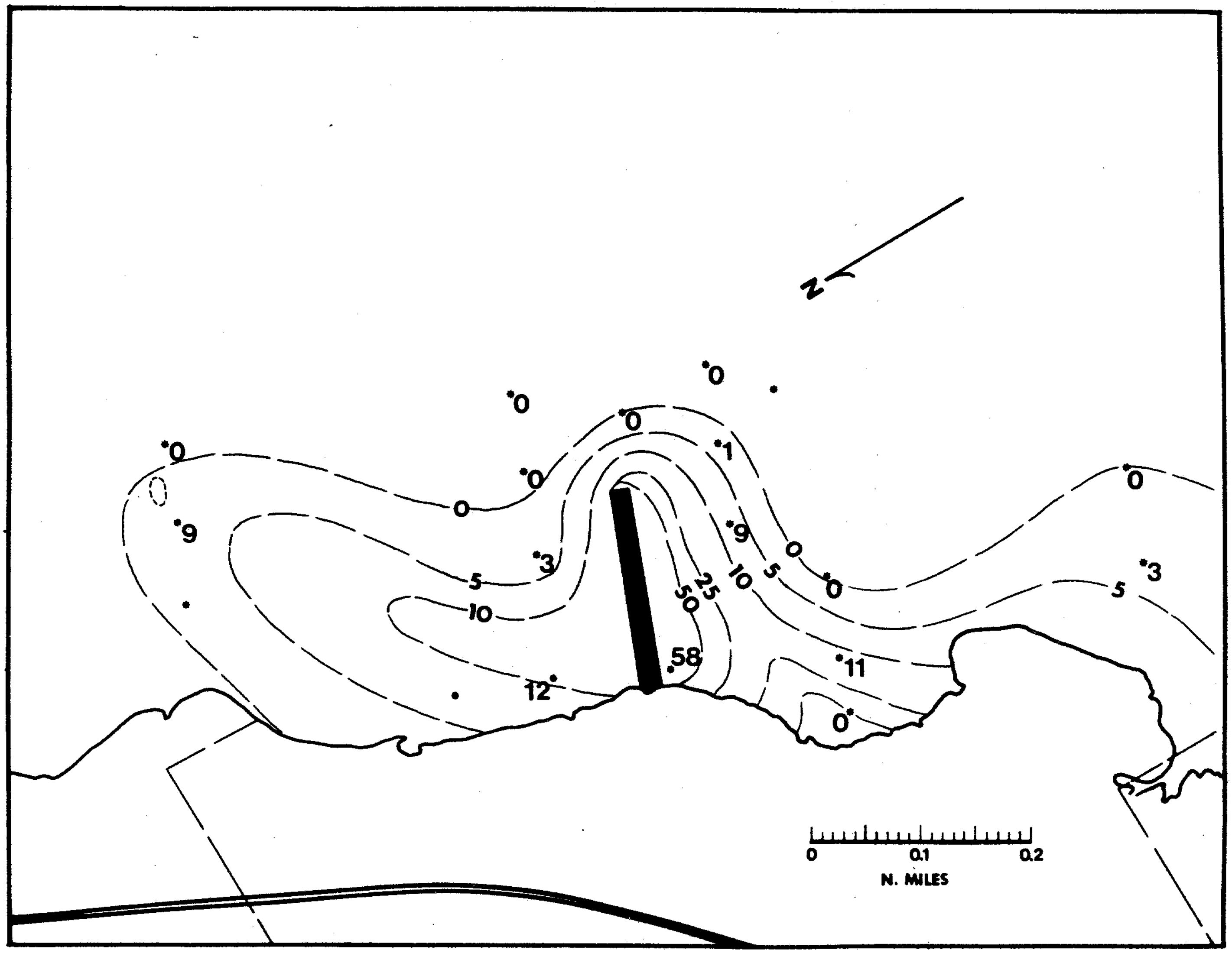
37 "Excess rates" attributable to the dredge project for the period December 28, 1972 to January 15, 1973 (Project days 67-85). The dredge actively extended the canal only until December 31, after which it plugged the canal end and withdrew for 4 1/2 months. A very small amount of excess sediment (9 $mg/cm^2/day$) reached the coral patch reef. See Figure 35 for explanation of symbols.



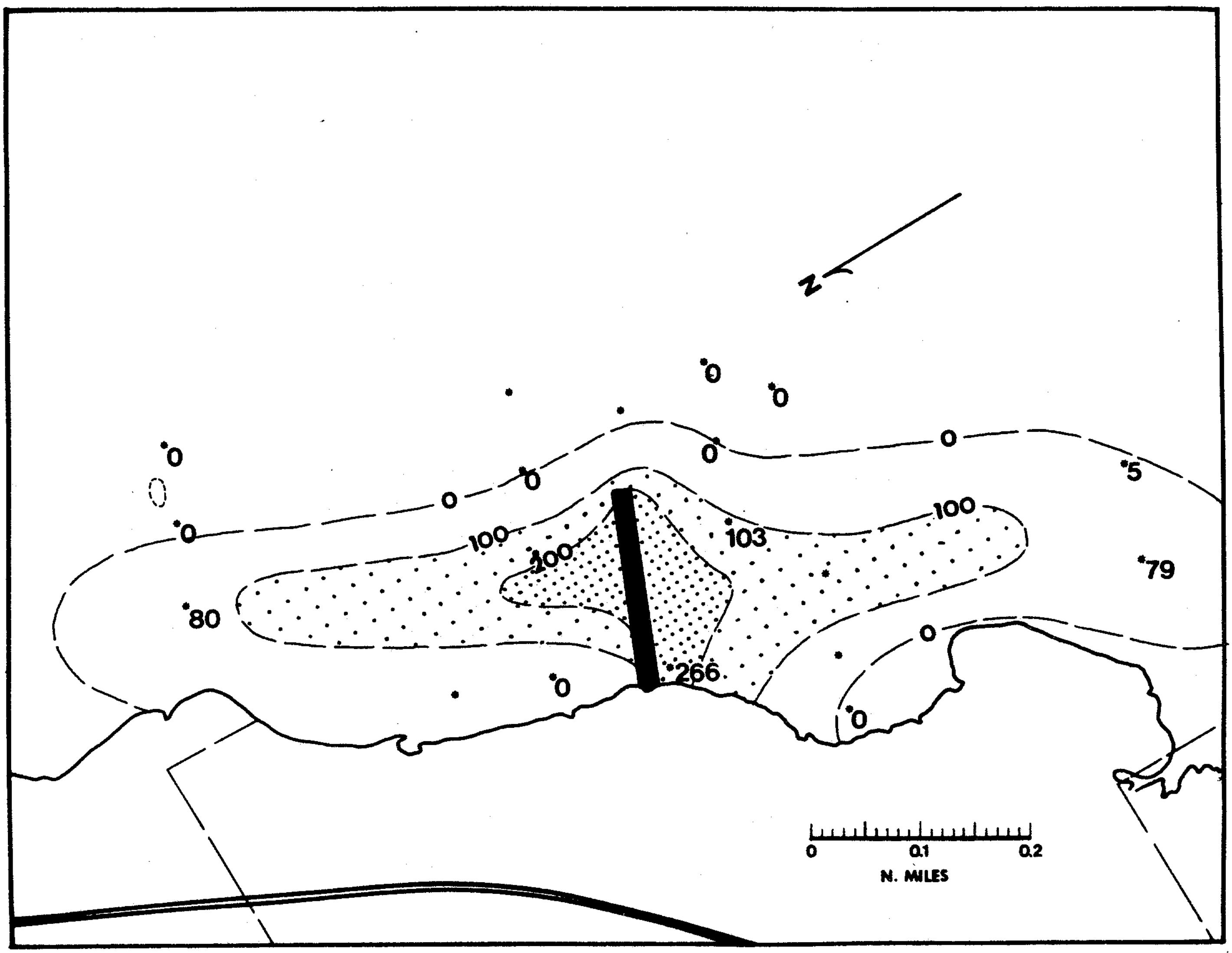
38 "Excess rates" attributable to the dredge project for the period January 15 to January 26, 1973 (Project days 85-96). The dredge was dormant, but erosion of the spoil by waves produced a zone of excess fallout exceeding >100 mg/cm^2/day in the stippled area. See Figure 35 for an explanation of symbols.



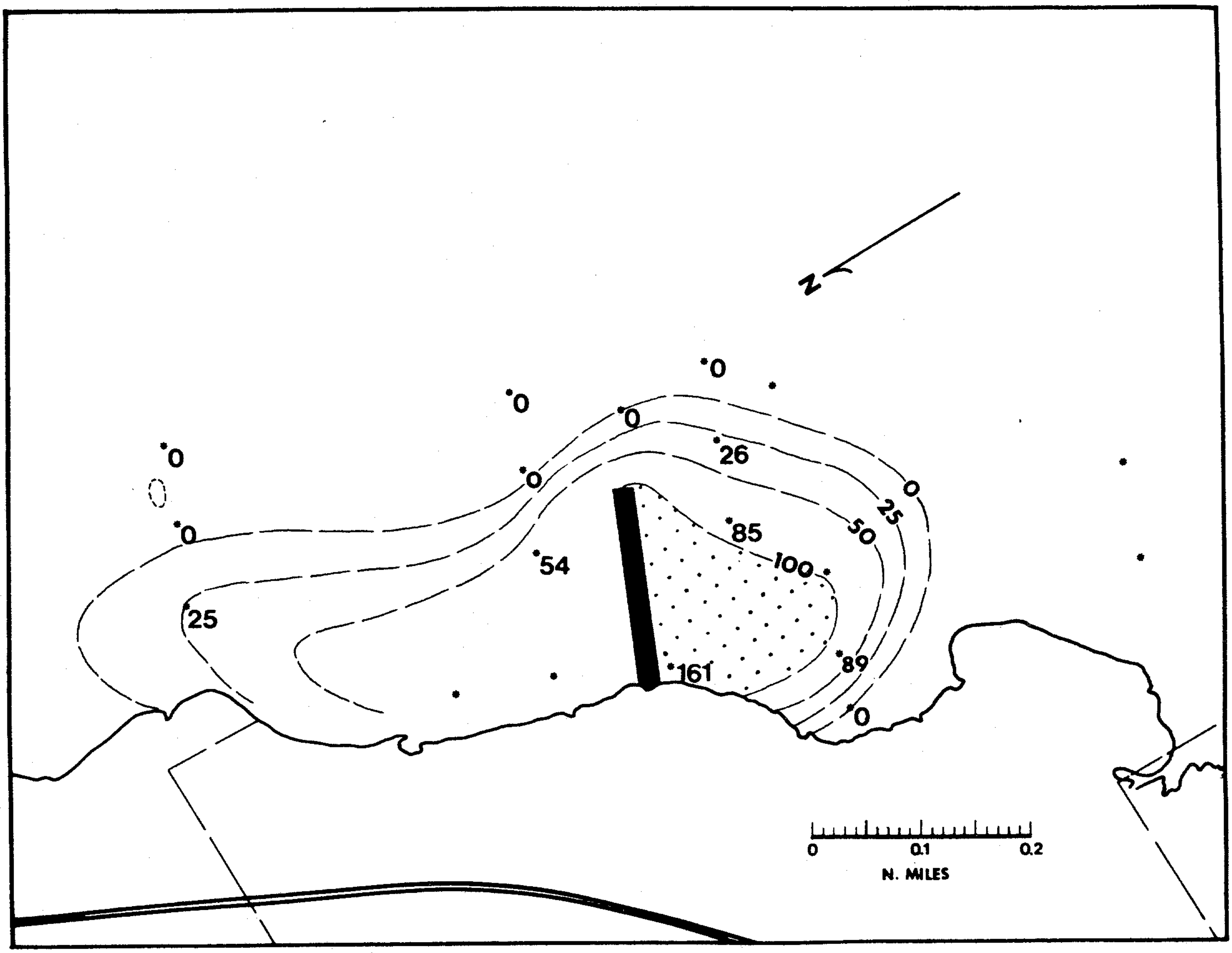
39 "Excess rates" attributable to the dredge project for the period January 26 to February 14, 1973 (Project days 96-115). The dredge was dormant, but continued erosion of the spoil by waves, accelerated by a severe cold front, produced a zone of excess fallout, exceeding >100 mg/cm^2/day in the stippled area. A very small amount of excess sediment (4 mg/cm^2/day) reached the coral patch reef. See Figure 35 for an explanation of symbols.



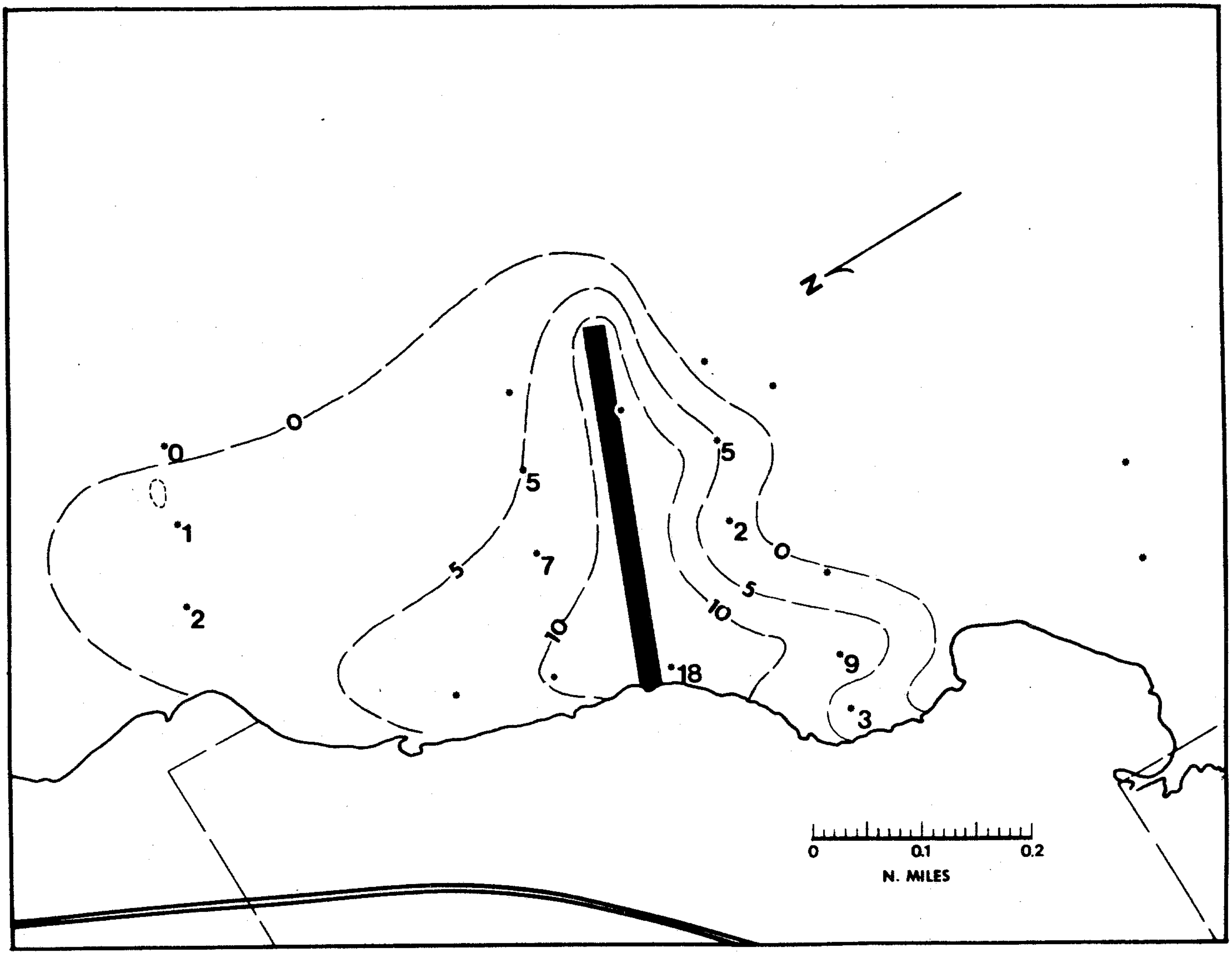
40 "Excess rates" attributable to the dredge project for the period February 14 to March 14, 1973 (Project days 115-143). The dredge was dormant, but an area of excess fallout was produced by waves eroding the spoil. A very small amount of excess (9 mg/cm^2/day) reached the coral patch reef. See Figure 35 for an explanation of symbols.



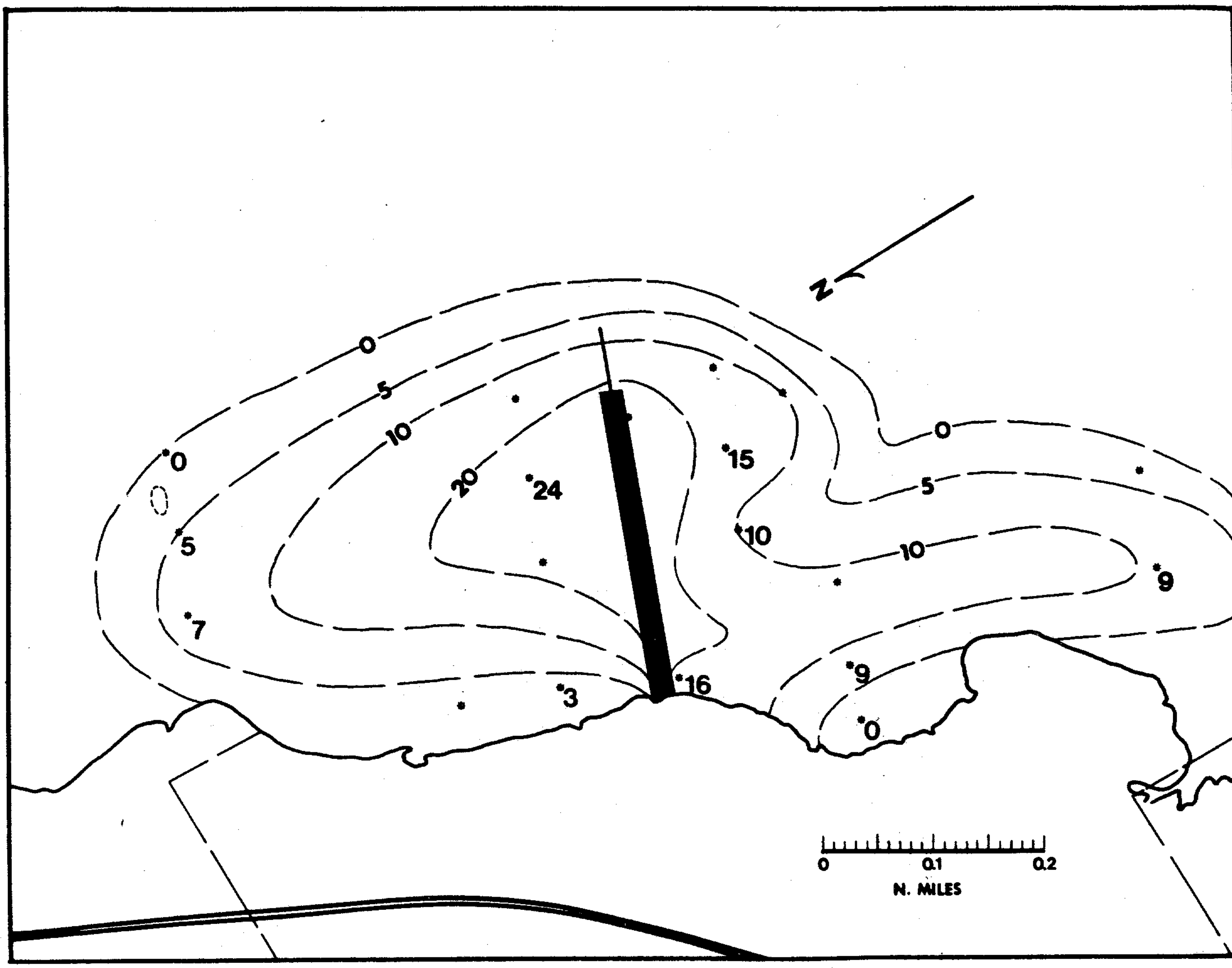
41 "Excess rates" attributable to the dredge project for the period March 14 to April 18, 1973 (Project days 143-178). The dredge was dormant, but continued erosion of the spoil by waves produced a relatively intense fallout zone as indicated by stippling. See Figure 35 for an explanation of symbols.



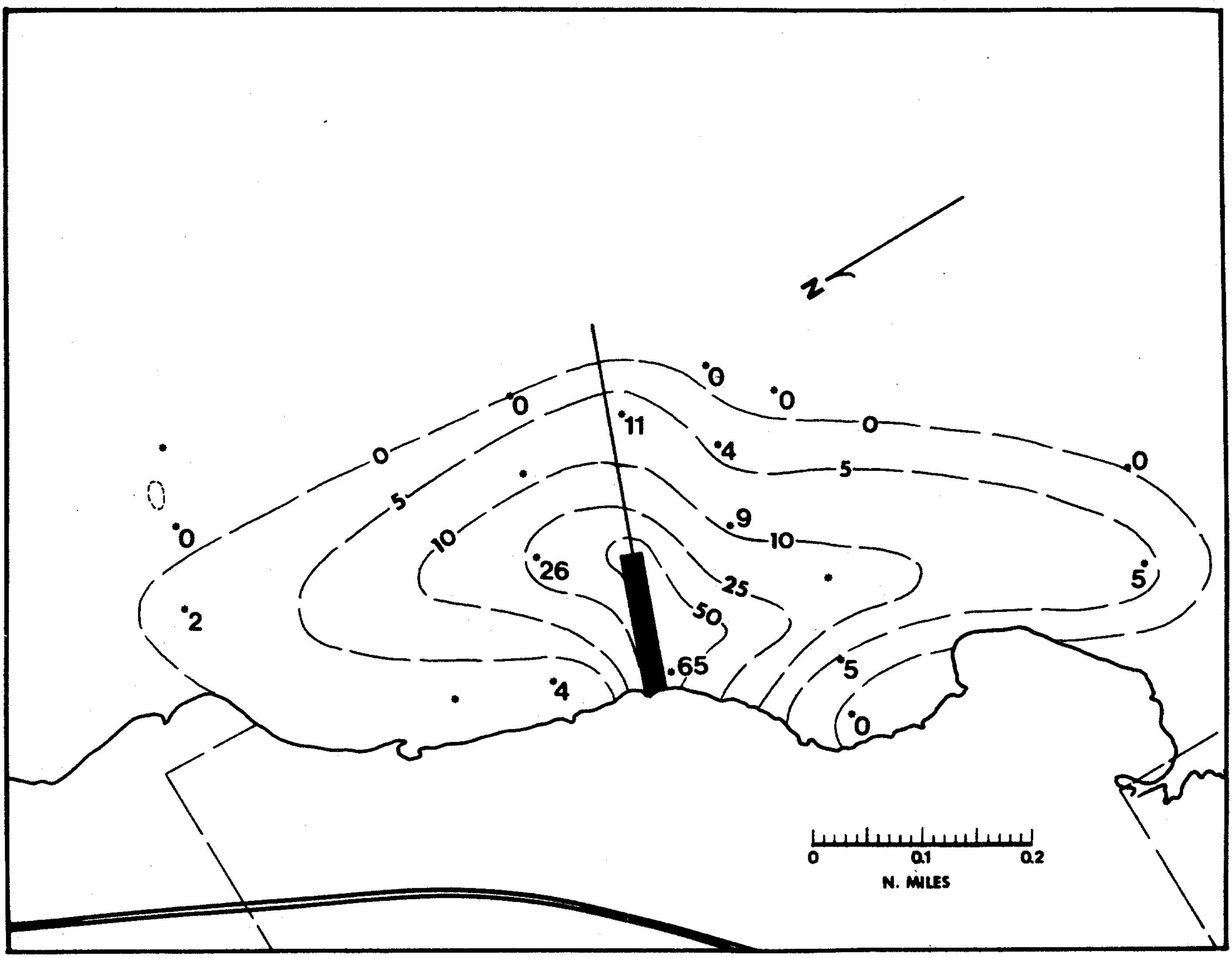
42 "Excess rates" attributable to the dredge project for the period April 18 to May 11, 1973 (Project days 178--201). The dredge was dormant, but continued erosion of the spoil by waves produced a moderate fallout zone as indicated by stippling. See Figure 35 for an explanation of symbols.



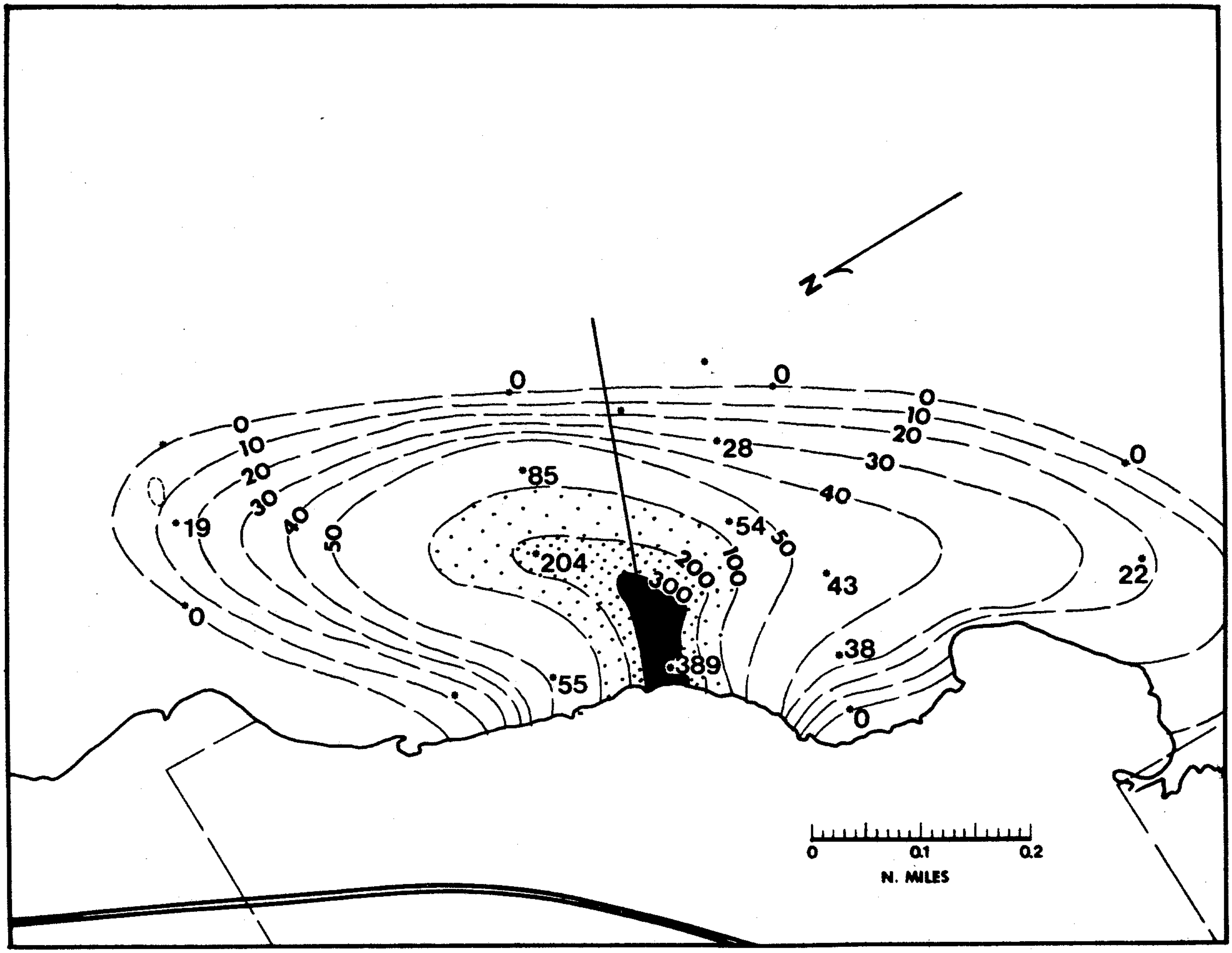
43 "Excess rates" attributable to the dredge project for the period May 11 to May 31, 1973 (Project days 201-221). The dredge resumed extending the canal about May 15 (day 205), now with a turbidity diaper for the first time, and reached its maximum extent on approximately May 31 (day 221). It was during the latter part of this period, on May 30 (day 220), that the maximum plume concentration (212 mg/l) and maximum plume length were reached (Tables 2 and 3; Figures 4 and 5). A very small amount of excess (1 $mg/cm^2/day$) reached the coral patch reef. See Figure 35 for an explanation of symbols.



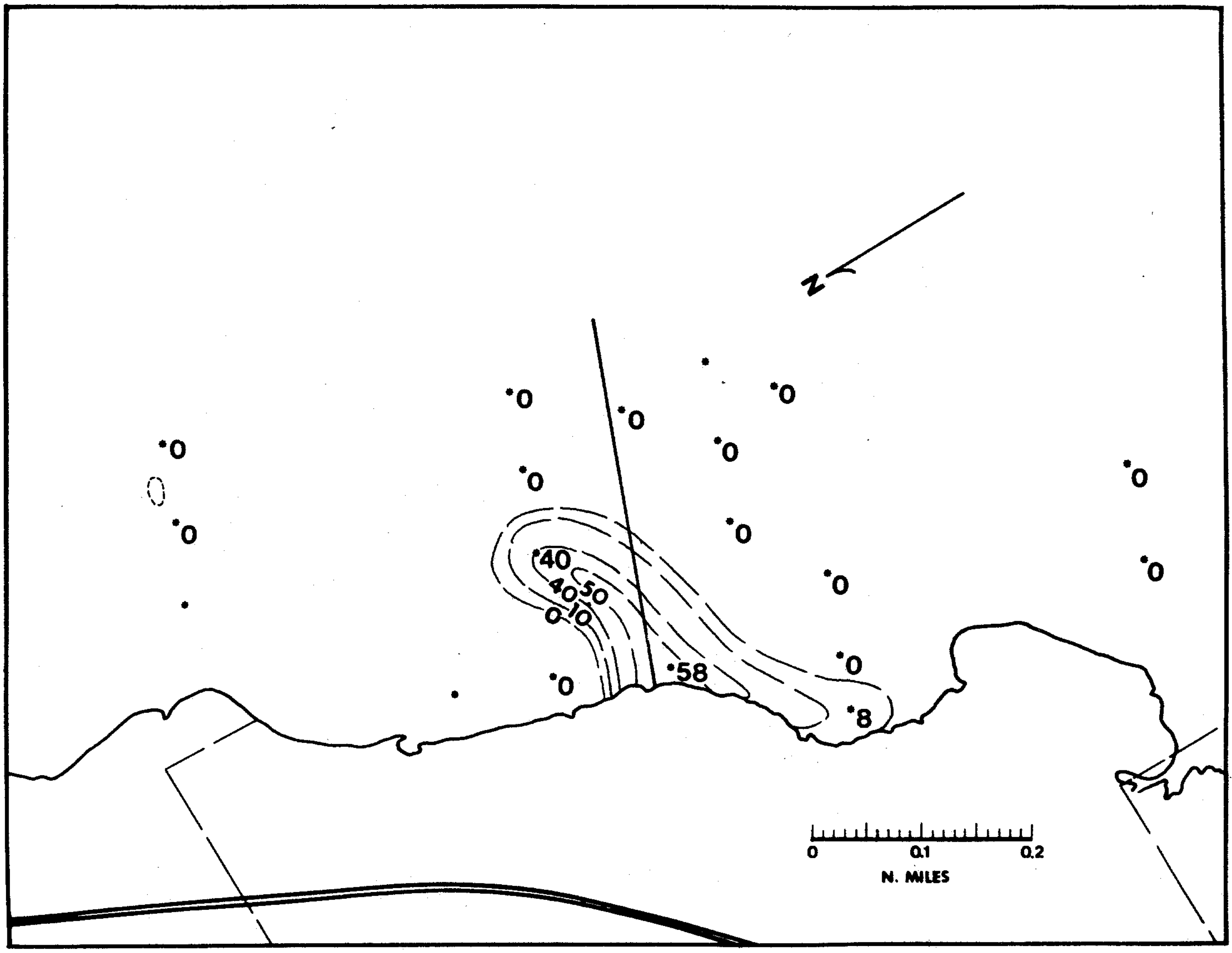
44 "Excess rates" attributable to the dredge project for the period May 31 to July 9, 1973 (Project days 221-260). The dredge, using a turbidity diaper, actively removed spoil. A very small amount of excess (5 mg/cm^2/day) reached the patch reef. See Figure 35 for an explanation of symbols.



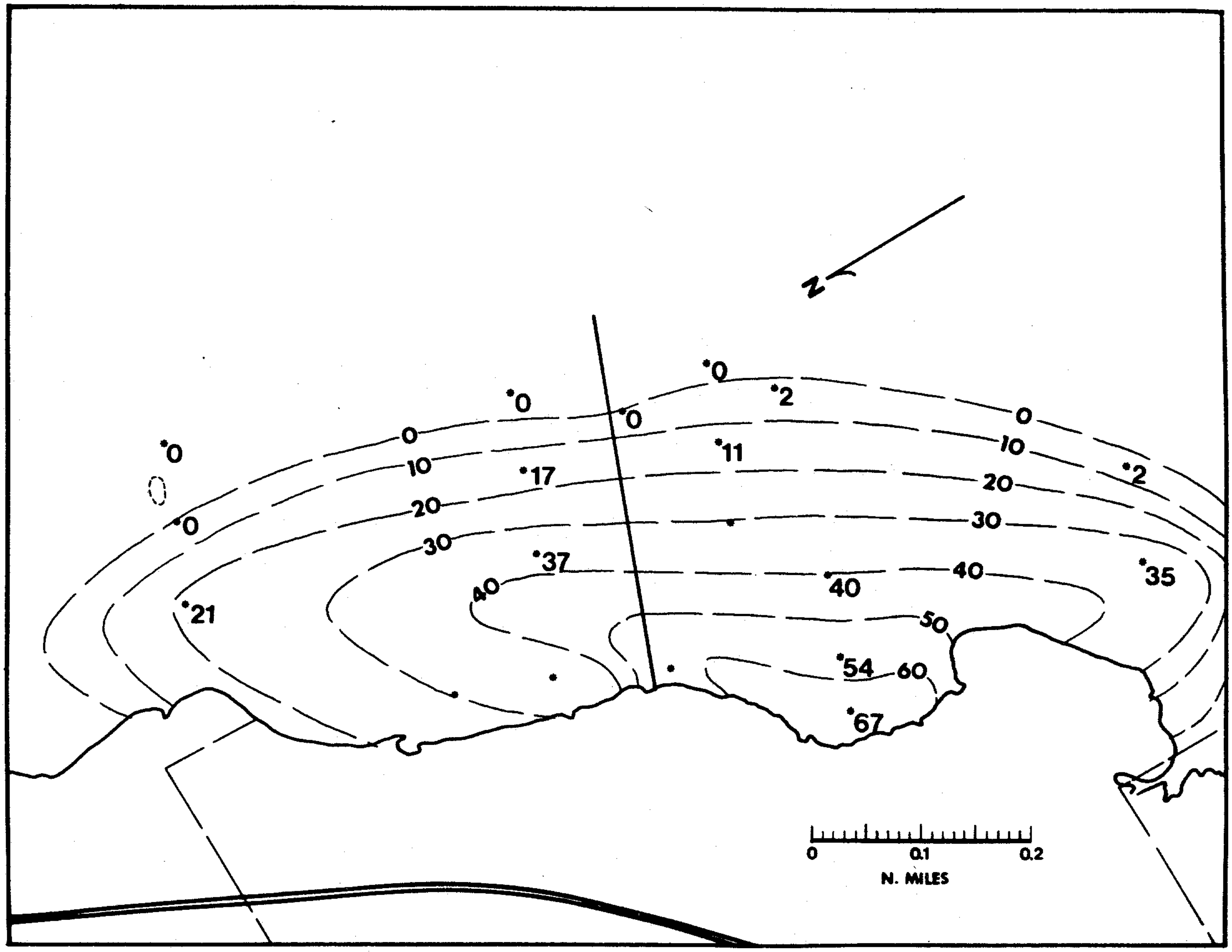
45 "Excess rates" attributable to the dredge project for the period July 9 to August 2, 1973 (Project days 260-284). The dredge, with a turbidity diaper, continued removing spoil. No excess was detected at the coral patch reef. See Figure 35 for an explanation of symbols.



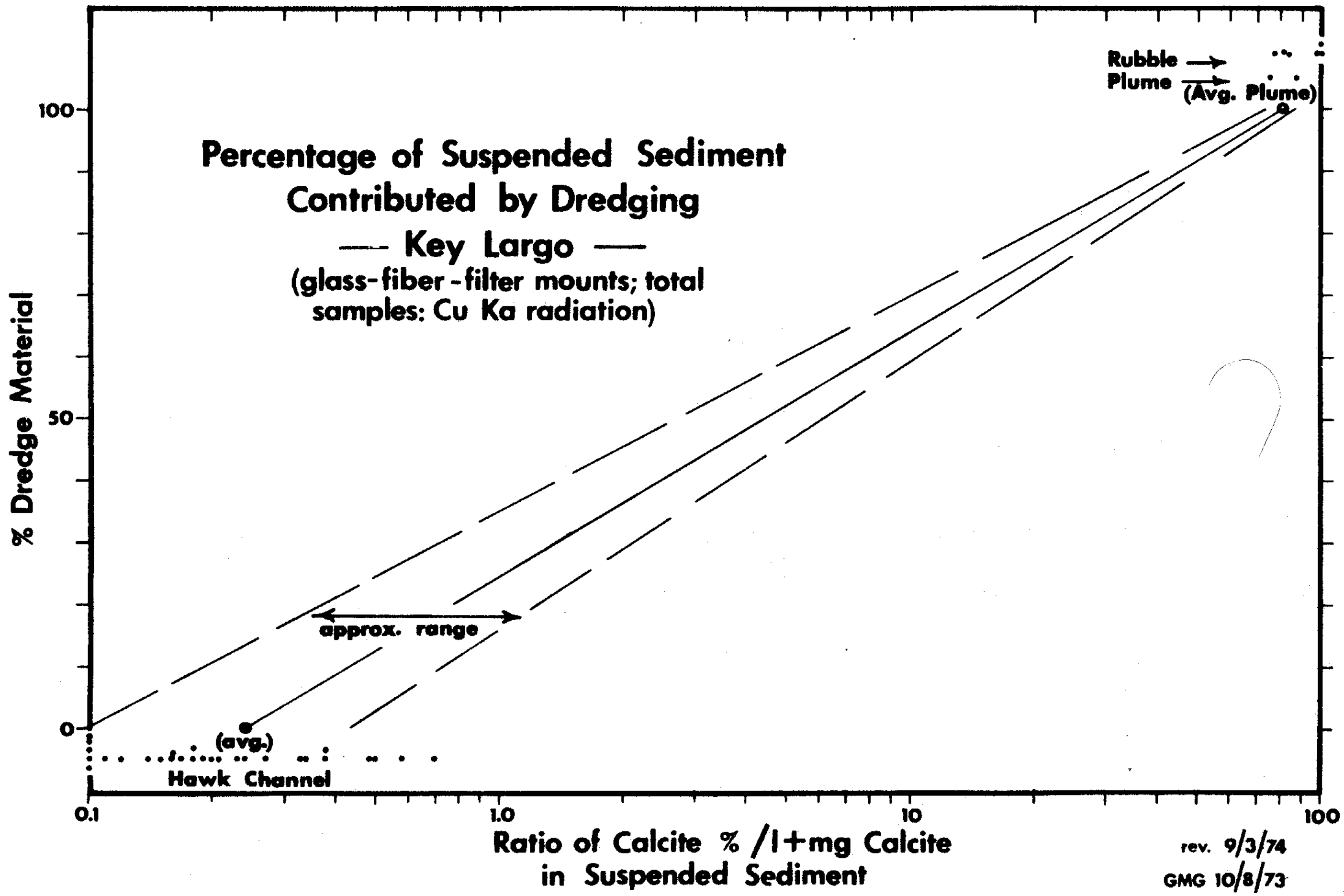
46 "Excess rates" attributable to the dredge project for the period August 2 to September 5, 1973 (Project days 284-318). The dredge completed removing the spoil fingers, and, although a turbidity diaper was in use, it leaked badly. The resulting excess fallout was the greatest of the project, exceeding 300 mg/cm^2/day in the area shown in black; the area of 100 to 300 mg/cm^2/day is indicated by stippling. In addition, more excess reached the coral patch reef (19 mg/cm^2/day) than during any other period. See Figure 35 for an explanation of symbols.



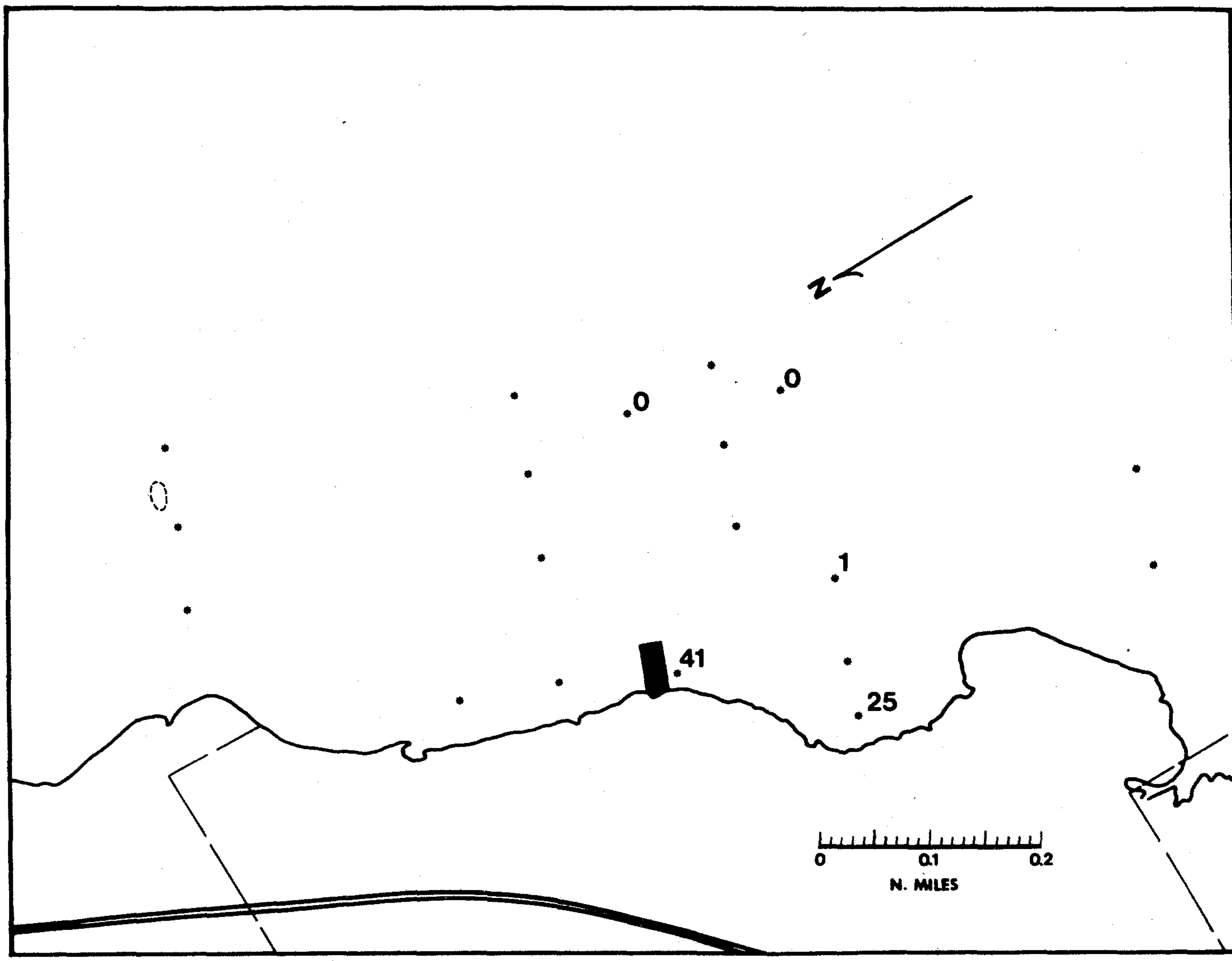
47 "Excess rates" attributable to the dredge project for the period September 5 to October 2, 1973 (Project days 318-345). Dredging was completed in the previous period (about day 300), so the excess noted here is residual, due to drainage of inland spoil, and possibly also to reworking of the bare bottom beneath the former spoil fingers, and flushing of "dredge fluff" from the canal axis. No "excess" was detected at the coral patch reef. See Figure 35 for an explanation of symbols.



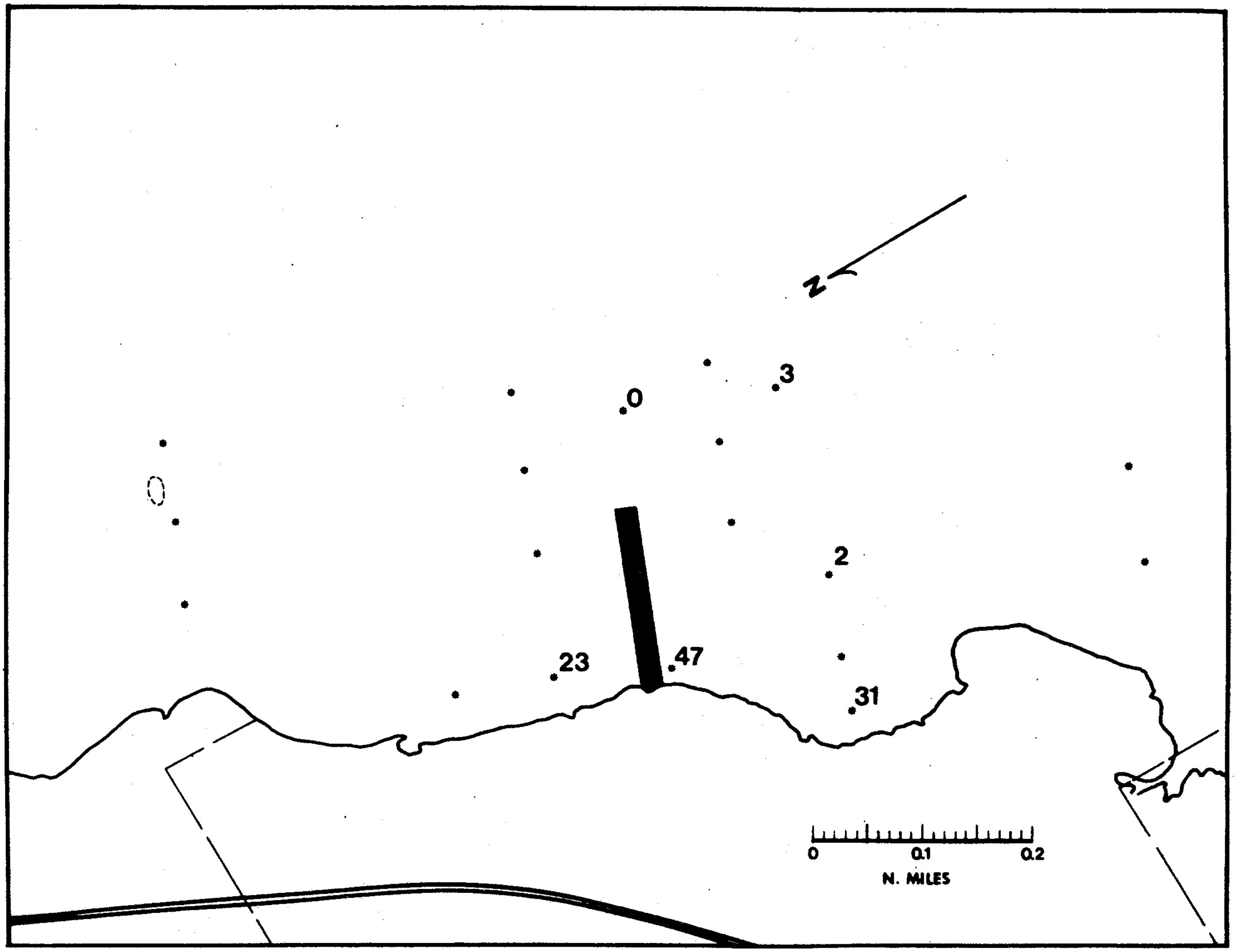
48 "Excess rates" attributable to the dredge project for the period October 2 to October 24, 1973 (Project days 345-367). Dredging was completed much earlier (about day 300). The latent effect noted here appeared to result from a combination of drainage of interior spoil areas, and possibly erosion of the bare bottom beneath the former spoil fingers, and possibly resuspension of diaper-trapped fines in the canal bottoms (from both the perimeter and entrance canals). No excess reached the coral patch reef. See Figure 35 for an explanation of symbols.



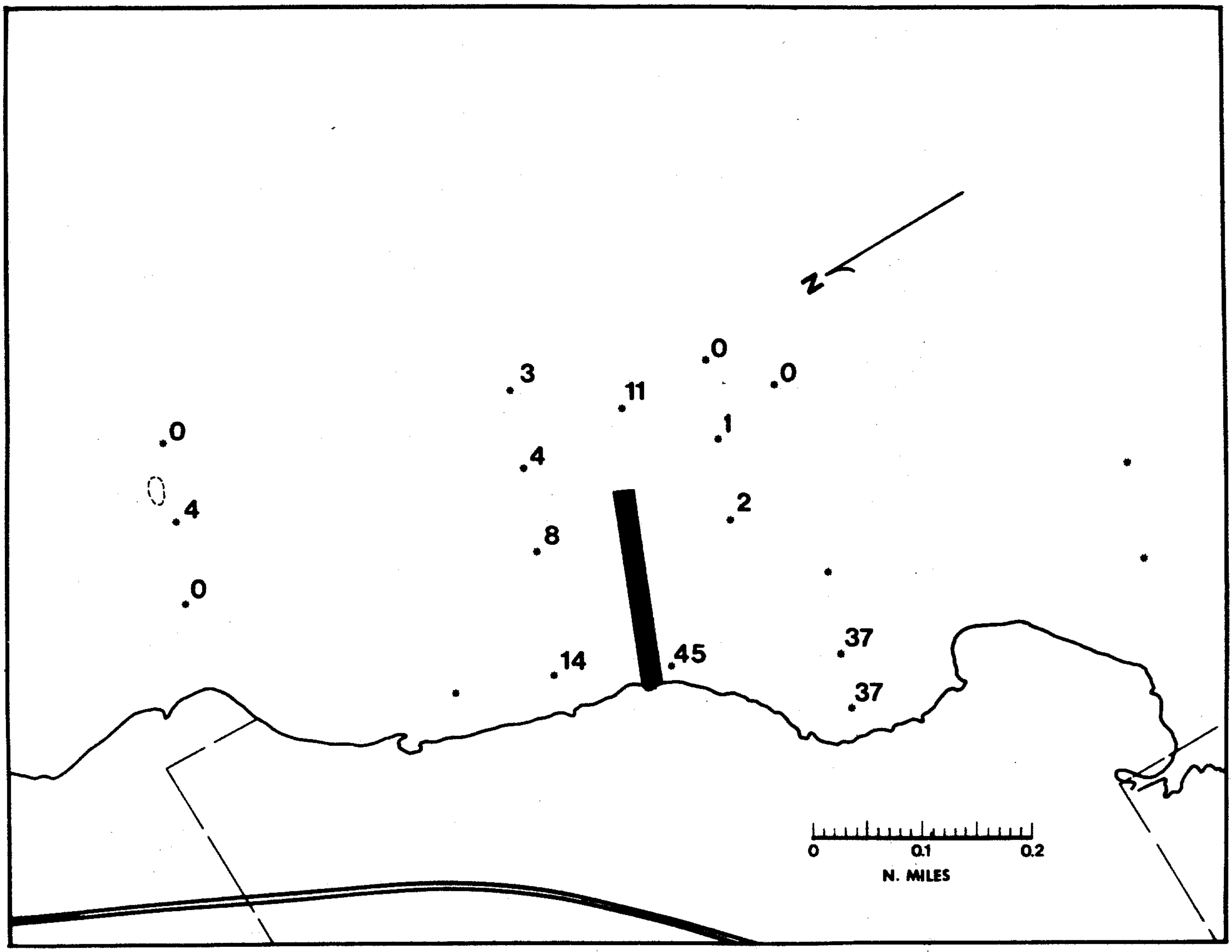
49 Working curve to deduce mineralogically the origin of the material collected by the sediment traps. End-member compositions, listed in Table 10, include dredge plume and rubble at the right and natural suspended matter from Hawk Channel at the left. Proportions of calcite and magnesian calcite in the trap collections were measured by x-ray diffraction and used to calculate the ratio of % calcite/ % magnesian calcite +1. From this ration, the % of dredge material in the trap was determined from the curve intercept.



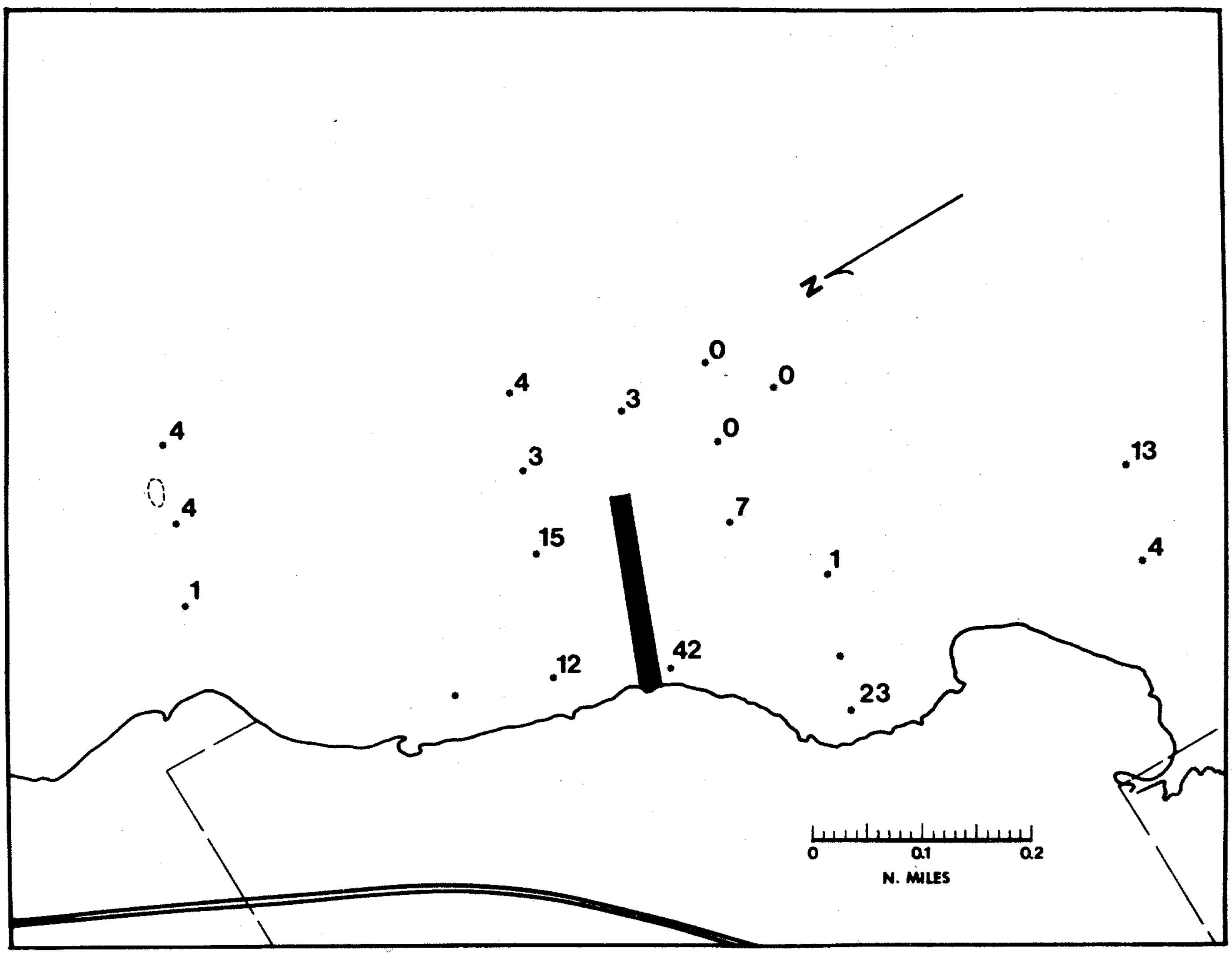
50 Percentage of dredge-derived sediment accumulated in sediment traps during the period November 16 to December 7, 1972 (Project days 25-46). The dredge was actively extending the canal, without a turbidity diaper. A broad band indicates the parallel spoil fingers; on later figures in this series, a narrow line indicates the position of the completed canal after spoil removal. Dots without numbers indicate lost, damaged, or otherwise unavailable traps.



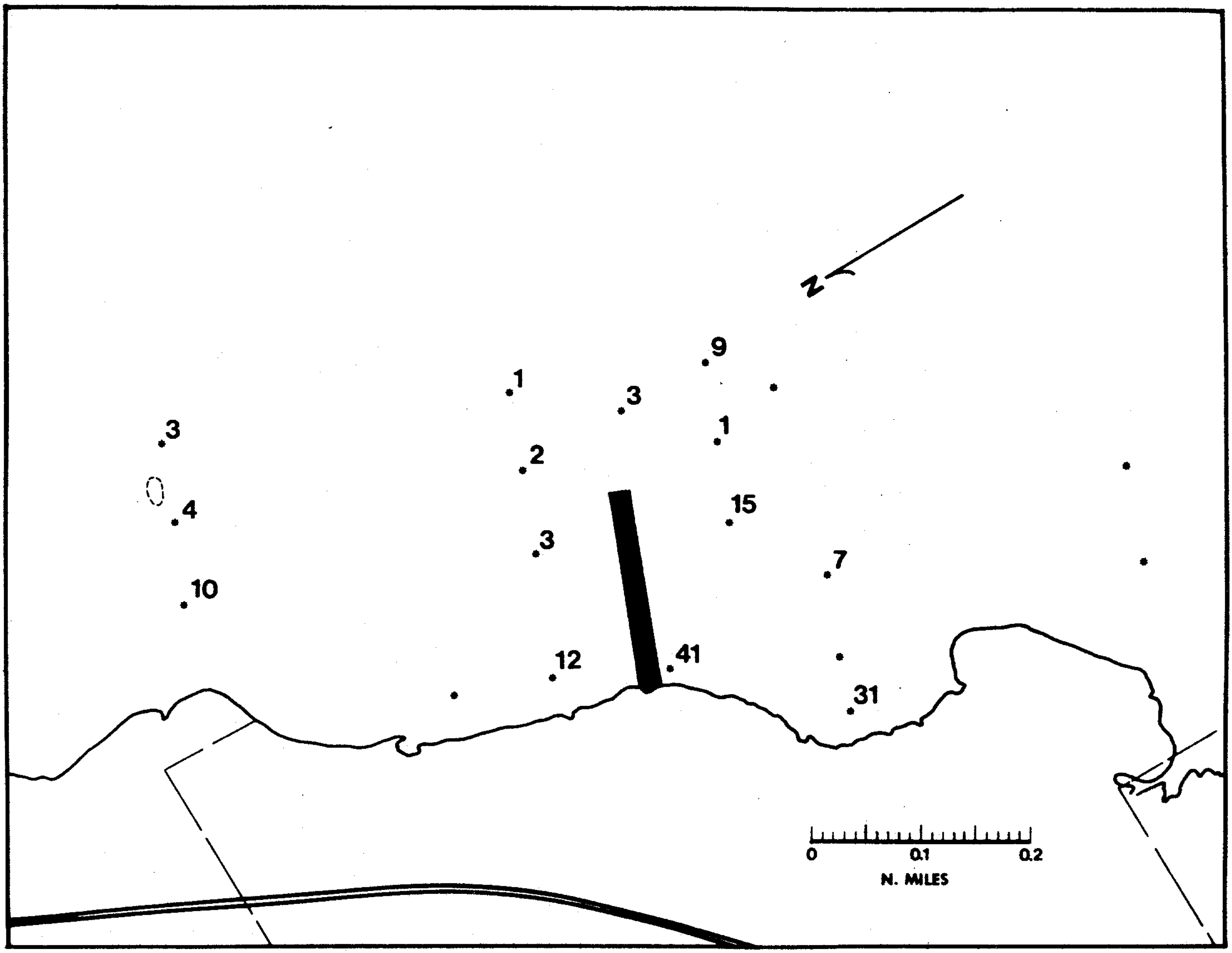
51 Percentage of dredge-derived sediment accumulated in sediment traps during the period December 7 to December 28, 1972 (Project days 46-67). The dredge was actively extending the canal, without a turbidity diaper. See Figure 50 for an explanation of symbols.



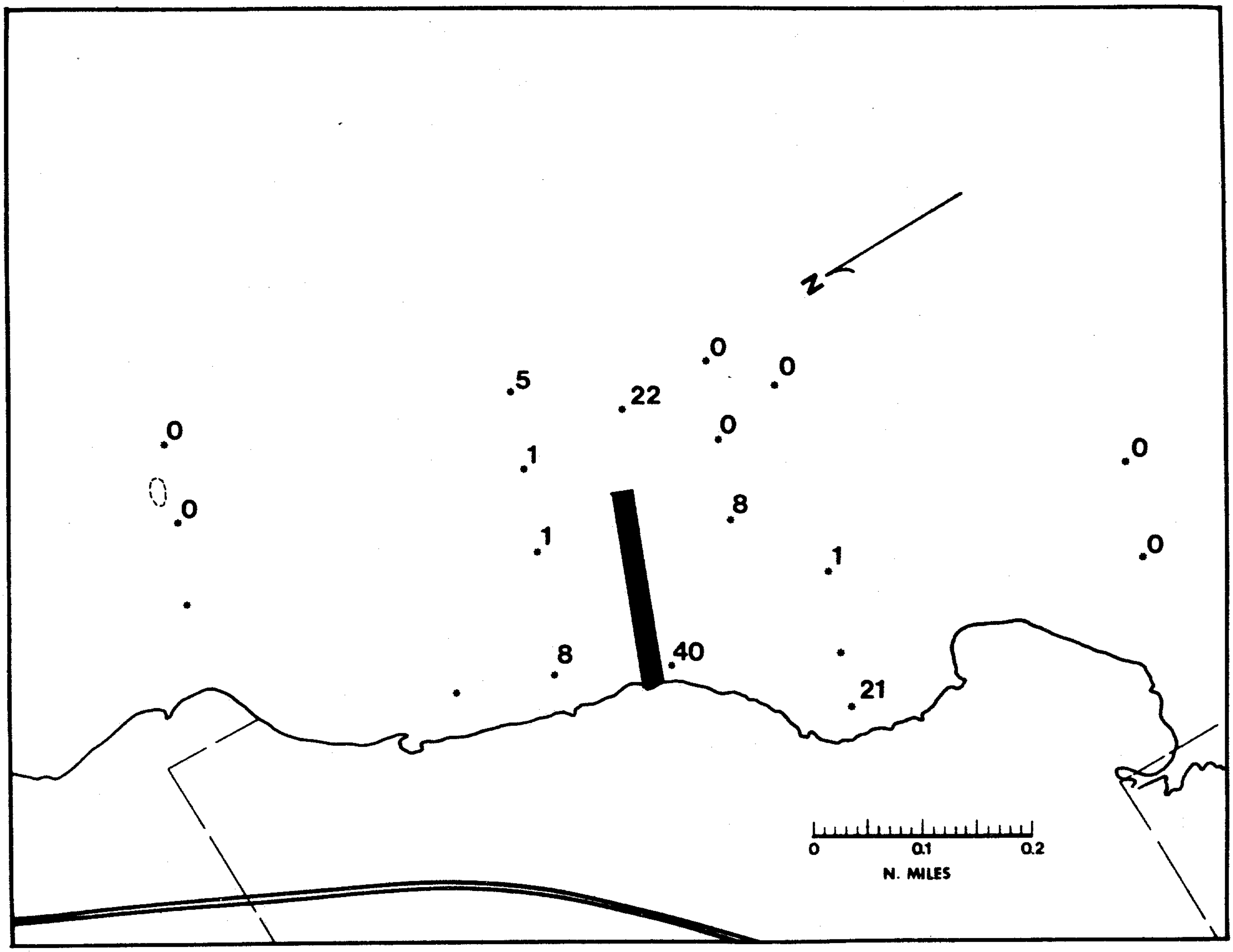
52 Percentage of dredge-derived sediment accumulated in sediment traps during the period December 28, 1972 to January 15, 1973 (Project days 67-85). The dredge was active only until December 31, after which it plugged the canal end and withdrew for 4 1/2 months. Most of the dredge effluent moved northward; about 4% of the sediment reaching the coral patch reef was of dredge origin. See Figure 50 for an explanation of symbols.



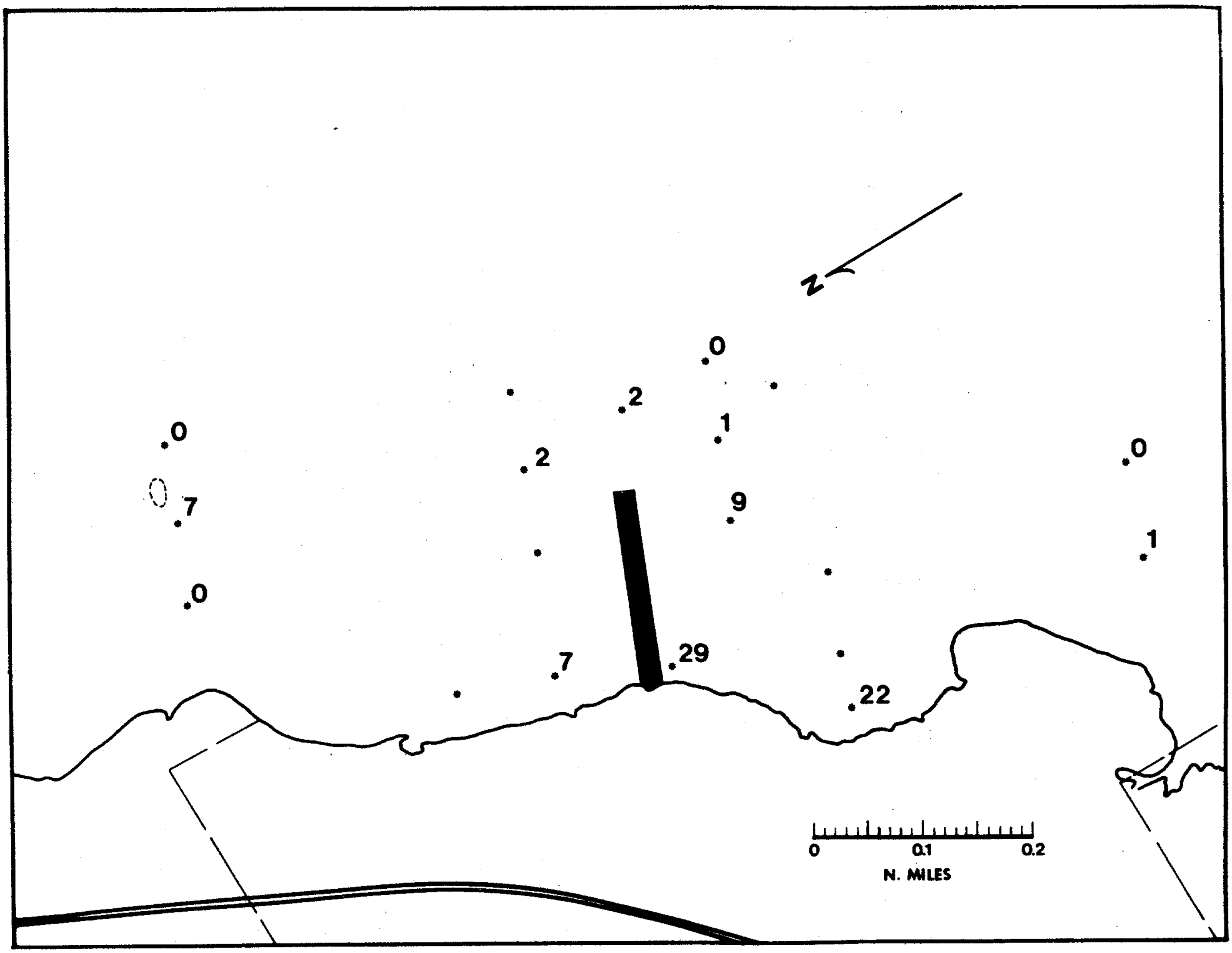
53 Percentage of dredge-derived sediment accumulated in sediment traps during the period January 15 to January 26, 1973 (Project days 85-96). The dredge was dormant, but the spoil fingers were being eroded by waves. See Figure 50 for an explanation of symbols.



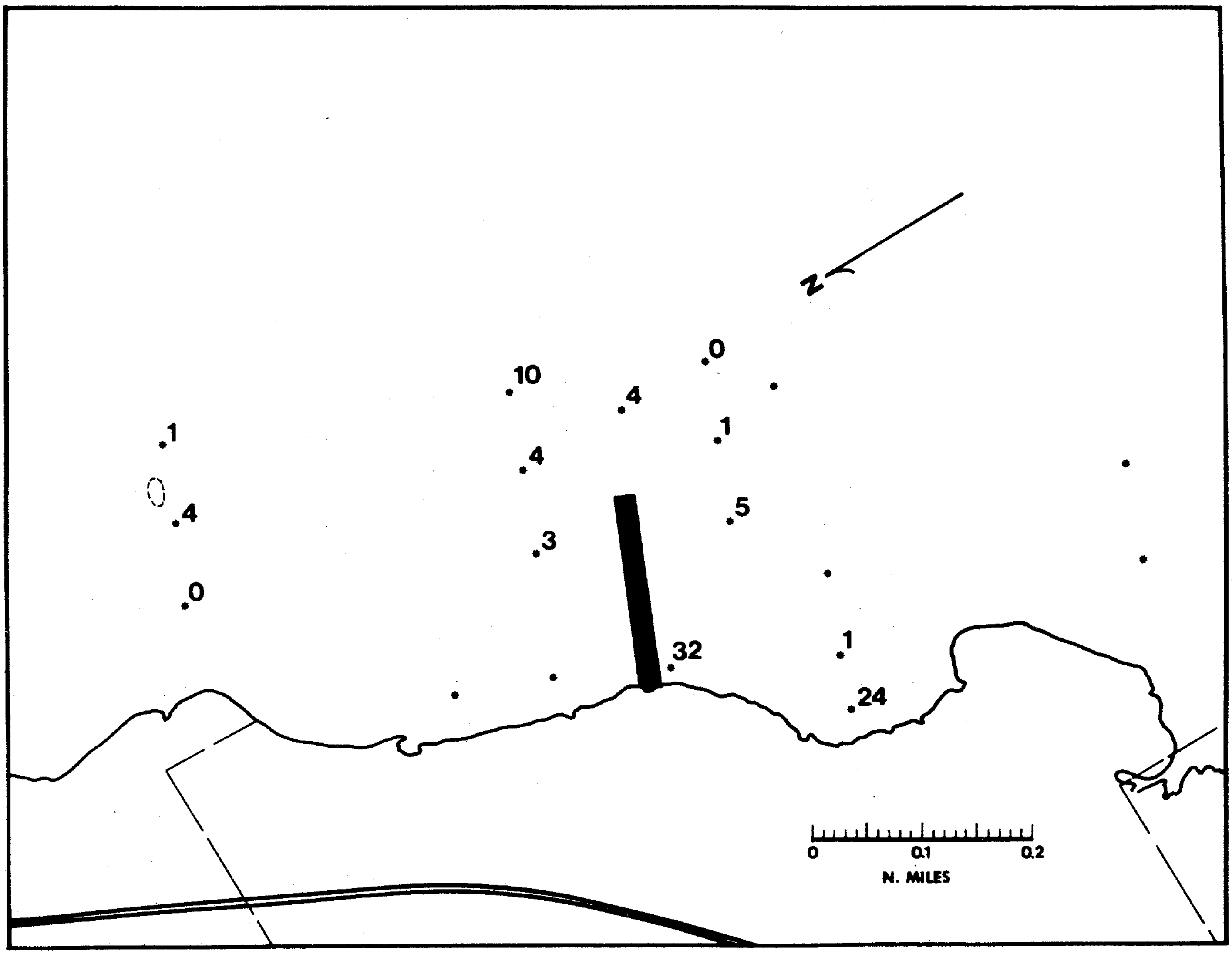
54 Percentage of dredge-derived sediment accumulated in sediment traps during the period January 26 to February 14, 1973 (Project days 96-115). The dredge was dormant, but continued erosion of the spoil by waves is evident in the distribution of dredge material. See Figure 50 for an explanation of symbols.



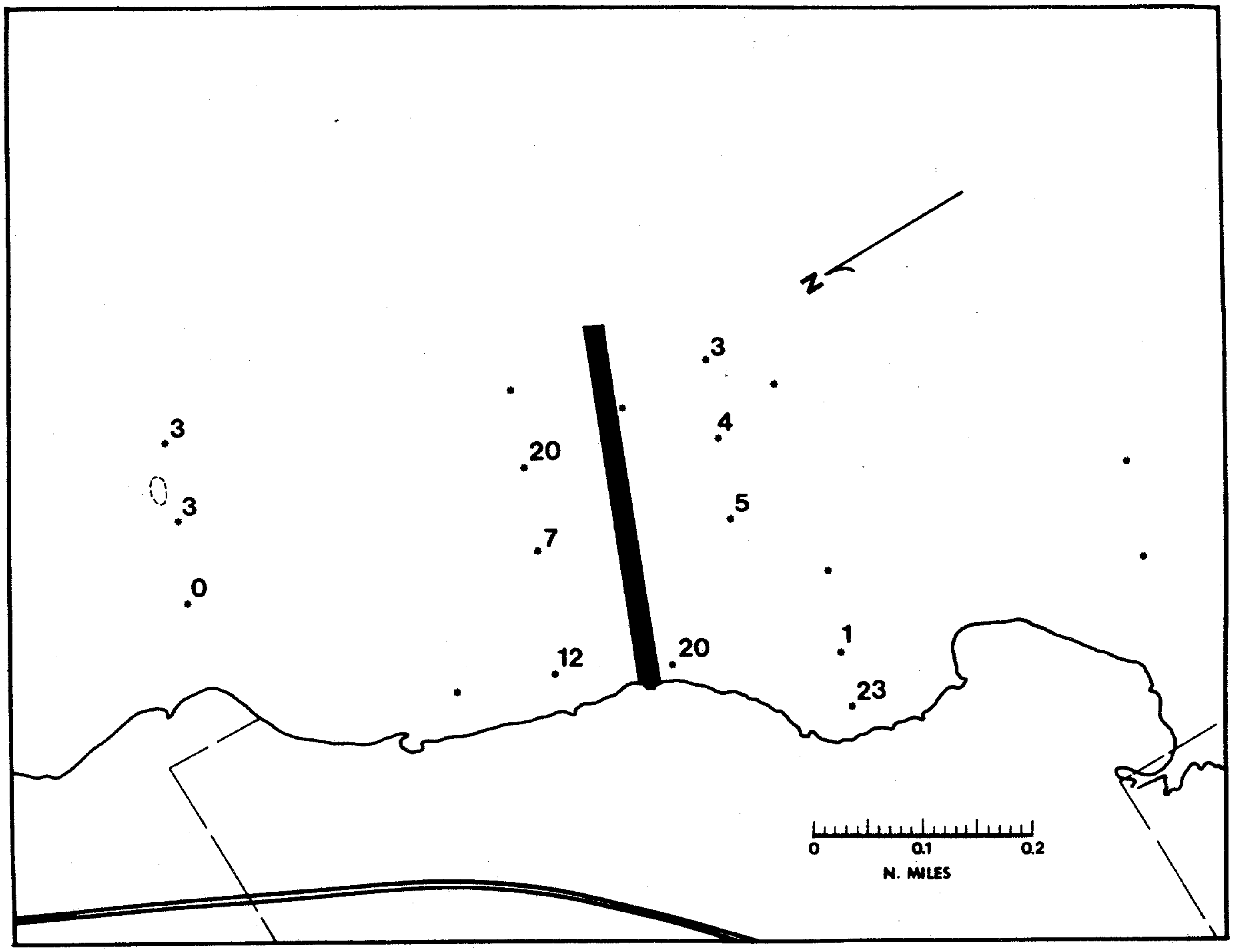
55 Percentage of dredge-derived sediment accumulated in sediment traps during the period February 14 to March 14, 1973 (Project days 115-143). The dredge was dormant, but waves continued to erode the spoil fingers. See Figure 50 for an explanation of symbols.



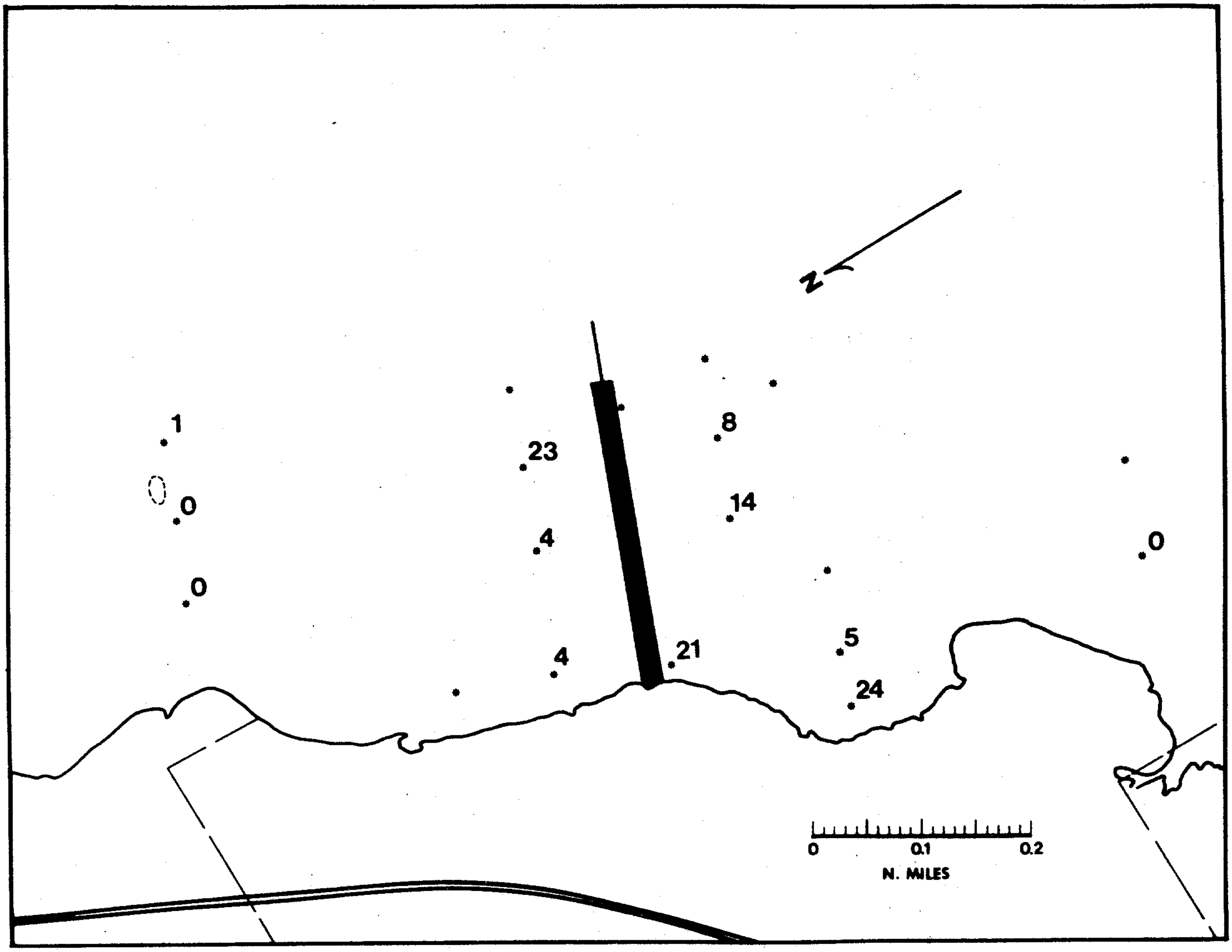
56 Percentage of dredge-derived sediment accumulated in sediment traps during the period March 14 to April 18, 1973 (Project days 143-178). The dredge was dormant, but erosion of the spoil fingers continued. For an explanation of symbols, see Figure 50.



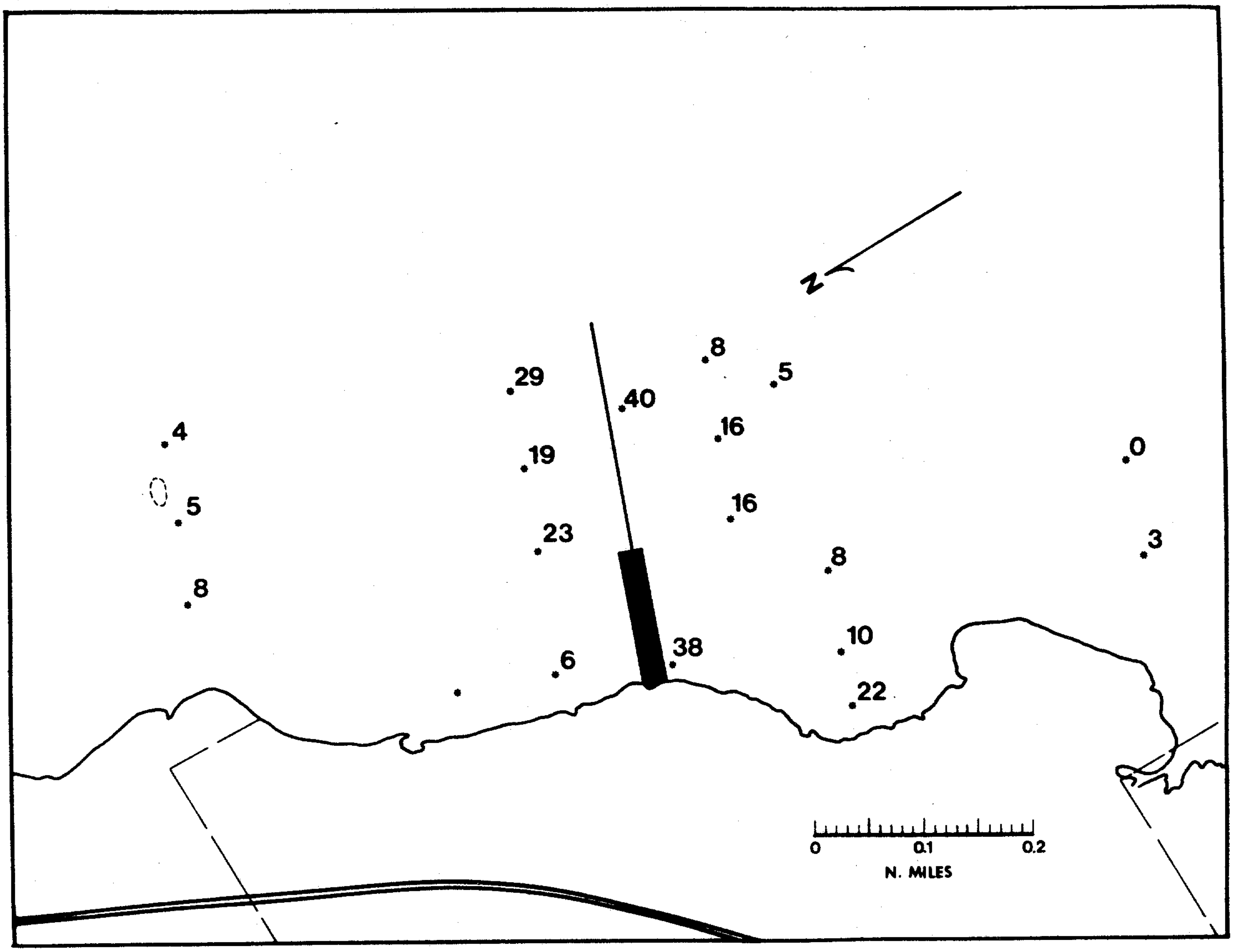
57 Percentage of dredge-derived sediment accumulated in sediment traps during the period April 18 to May 11, 1973 (Project days 178-201). The dredge was dormant, but erosion of the spoil fingers continued. For an explanation of symbols, see Figure 50.



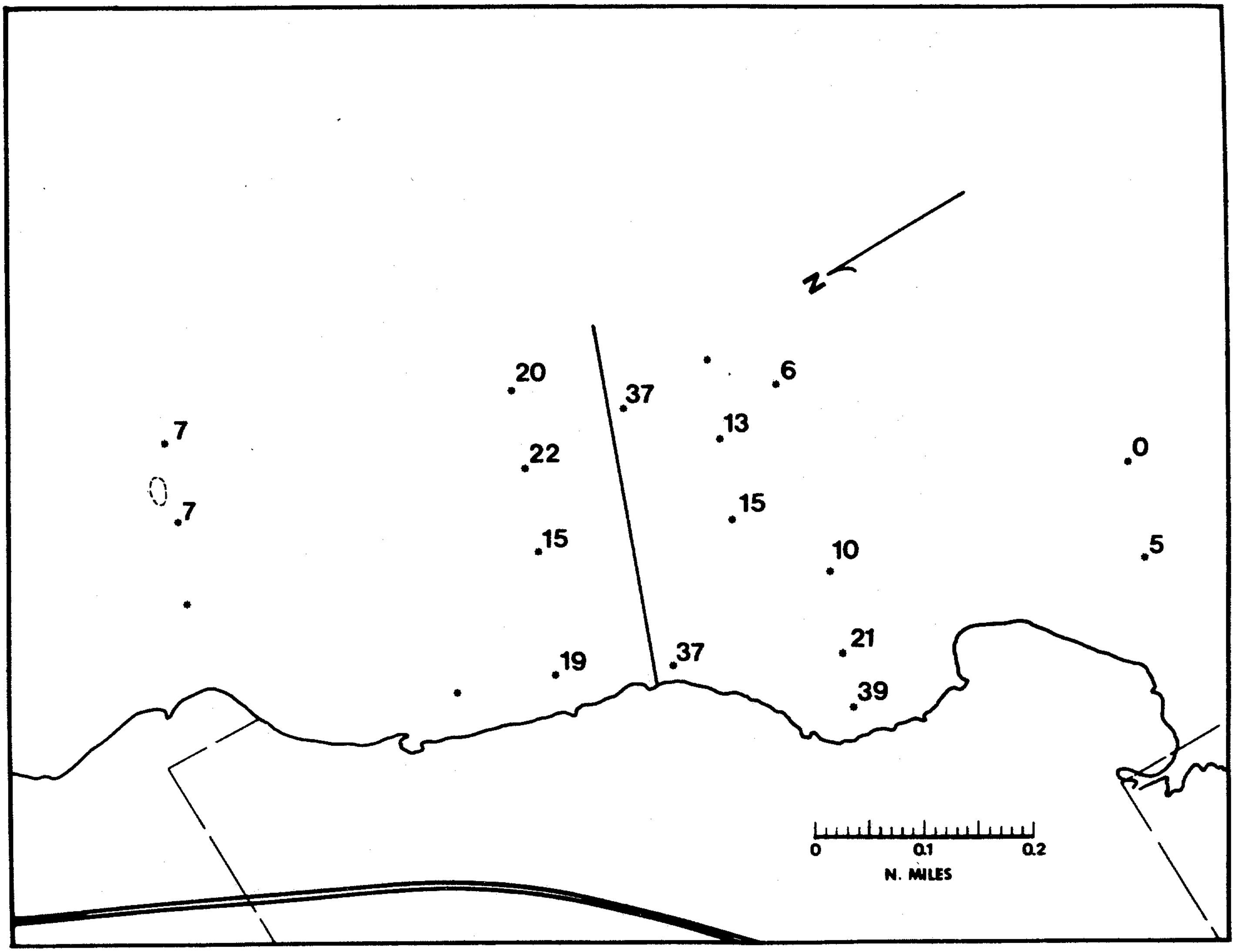
58 Percentage of dredge-derived sediment accumulated in sediment traps during the period May 11 to May 31, 1973 (Project days 201-221). The dredge resumed extending the canal about May 15 (day 205), now with a turbidity diaper for the first time, and reached its maximum extent approximately May 31 (day 231). On May 30 (day 230), the maximum plume concentration (212 mg/1) and maximum plume length were reached (Tables 2 and 3; Figures 4 and 5). See Figure 50 for an explanation of symbols.



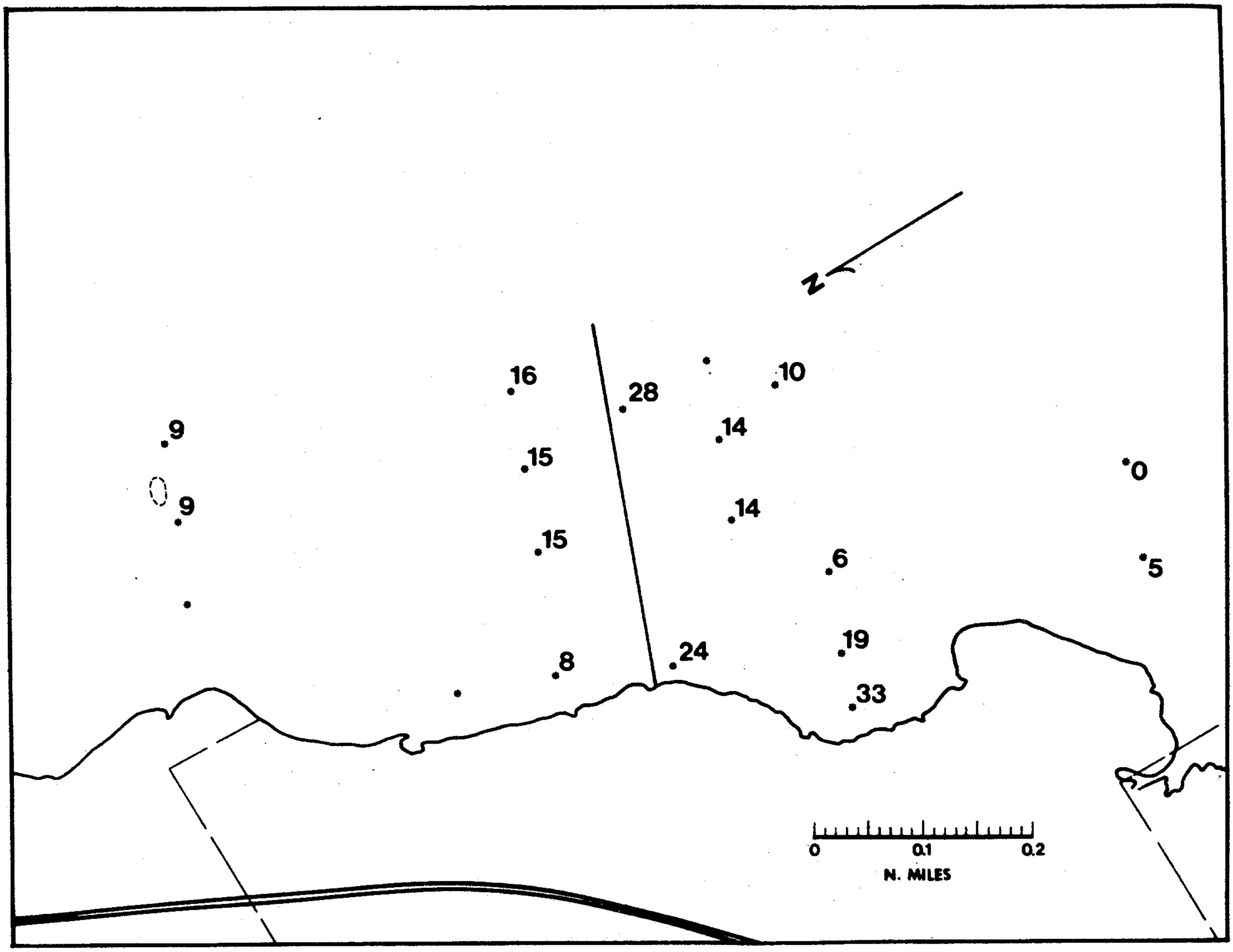
59 Percentage of dredge-derived sediment accumulated in sediment traps during the period May 31 to July 9, 1973 (Project days 221-260). The dredge, using a turbidity diaper, actively removed spoil. See Figure 50 for an explanation of symbols.



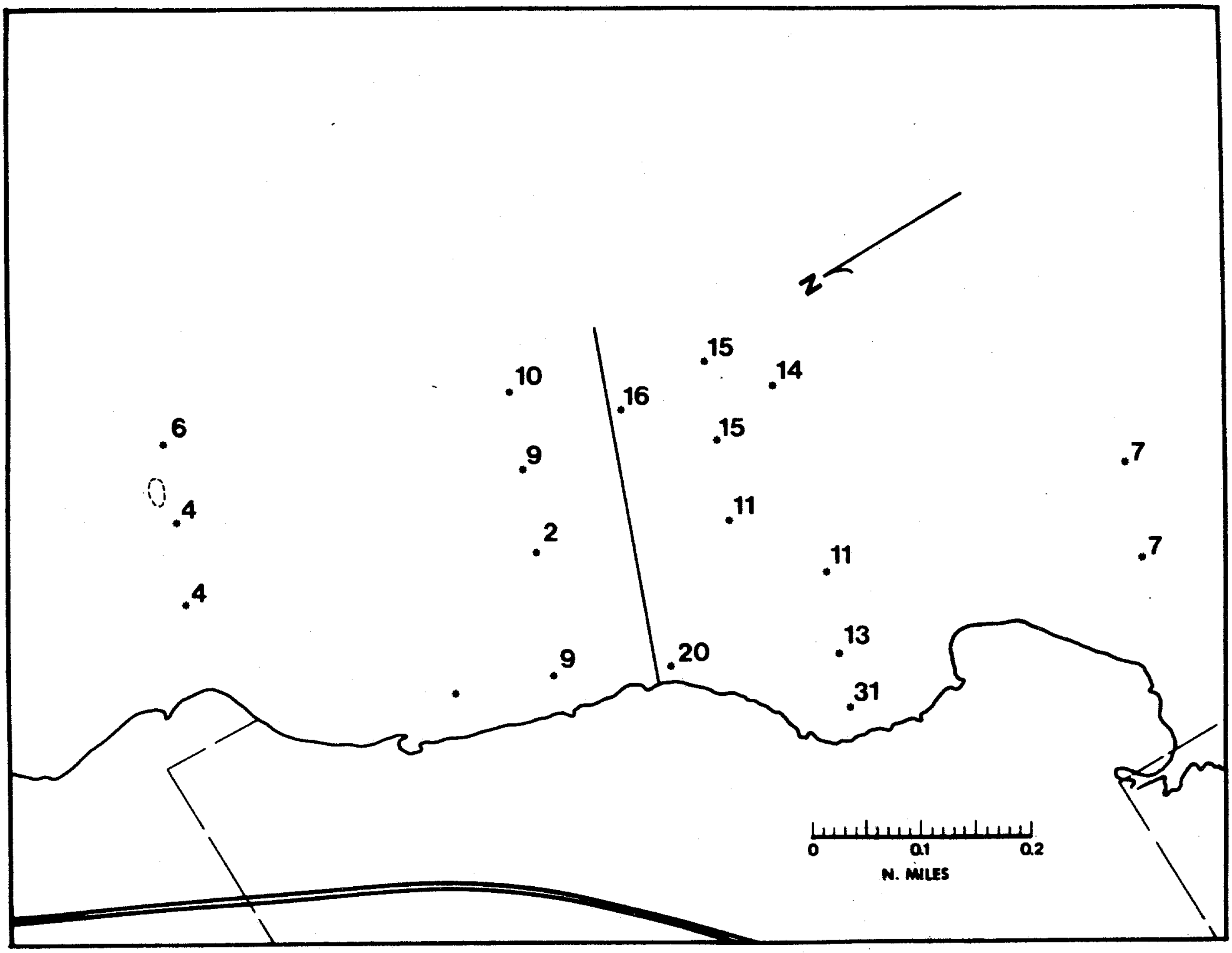
60 Percentage of dredge-derived sediment accumulated in sediment traps during the period July 9 to August 2, 1972 (Project days 260-284). The dredge, with a turbidity diaper, continued removing spoil. The outer traps near the canal were affected more than in previous periods, possibly due to escape of some dredge-derived fines previously trapped in the canal bottom as "canal fluff". For an explanation of symbols, see Figure 50.



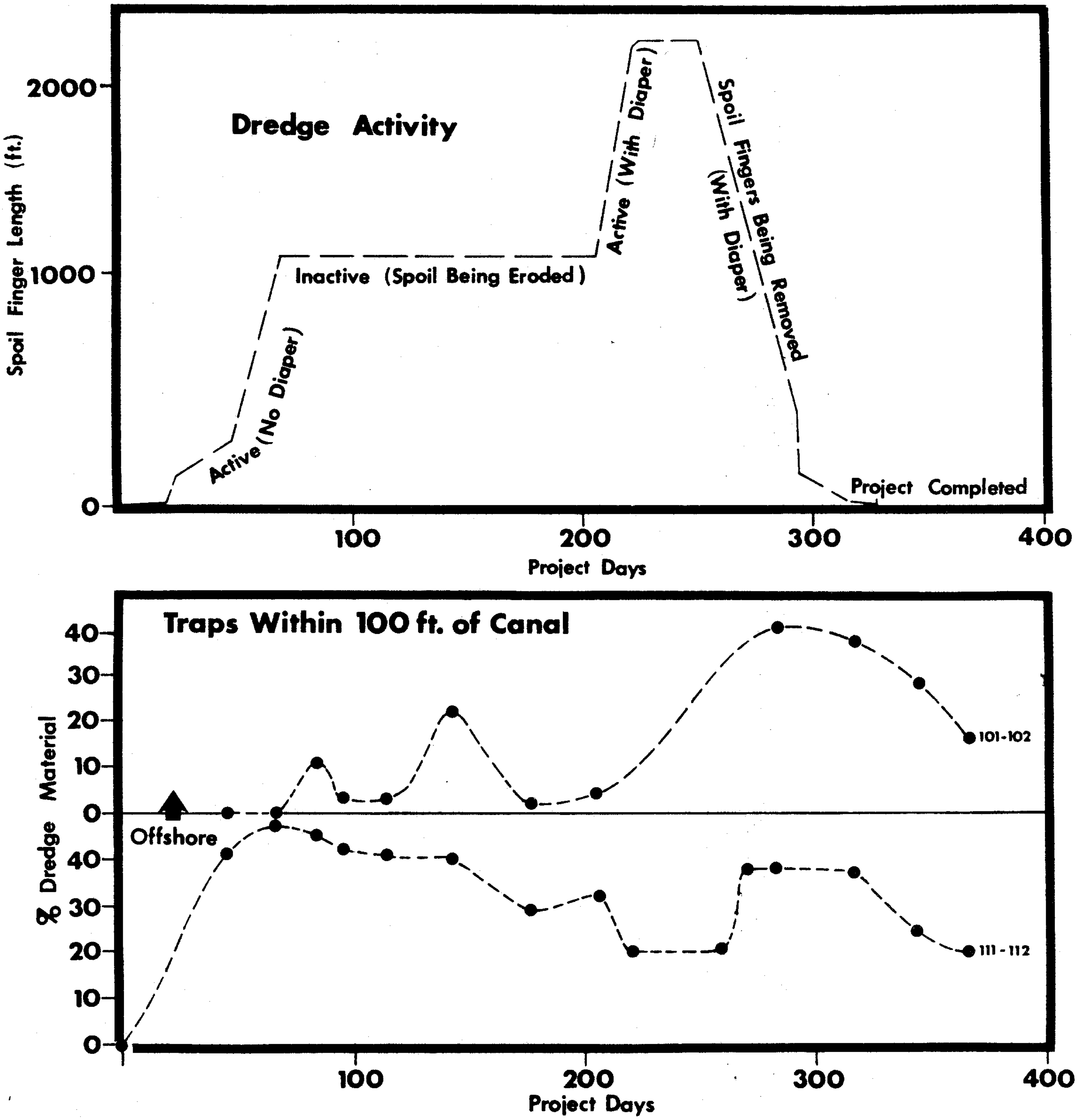
61 Percentage of dredge-derived sediment accumulated in sediment traps during the period August 2 to September 5, 1973 (Project days 284-318). The dredge completed removing the spoil fingers, and, although a turbidity diaper was in use, it leaked badly (cf. Figure 46). As with the previous period, traps near the canal axis collected large percentages of canal-derived debris. Symbols are explained on Figure 50.



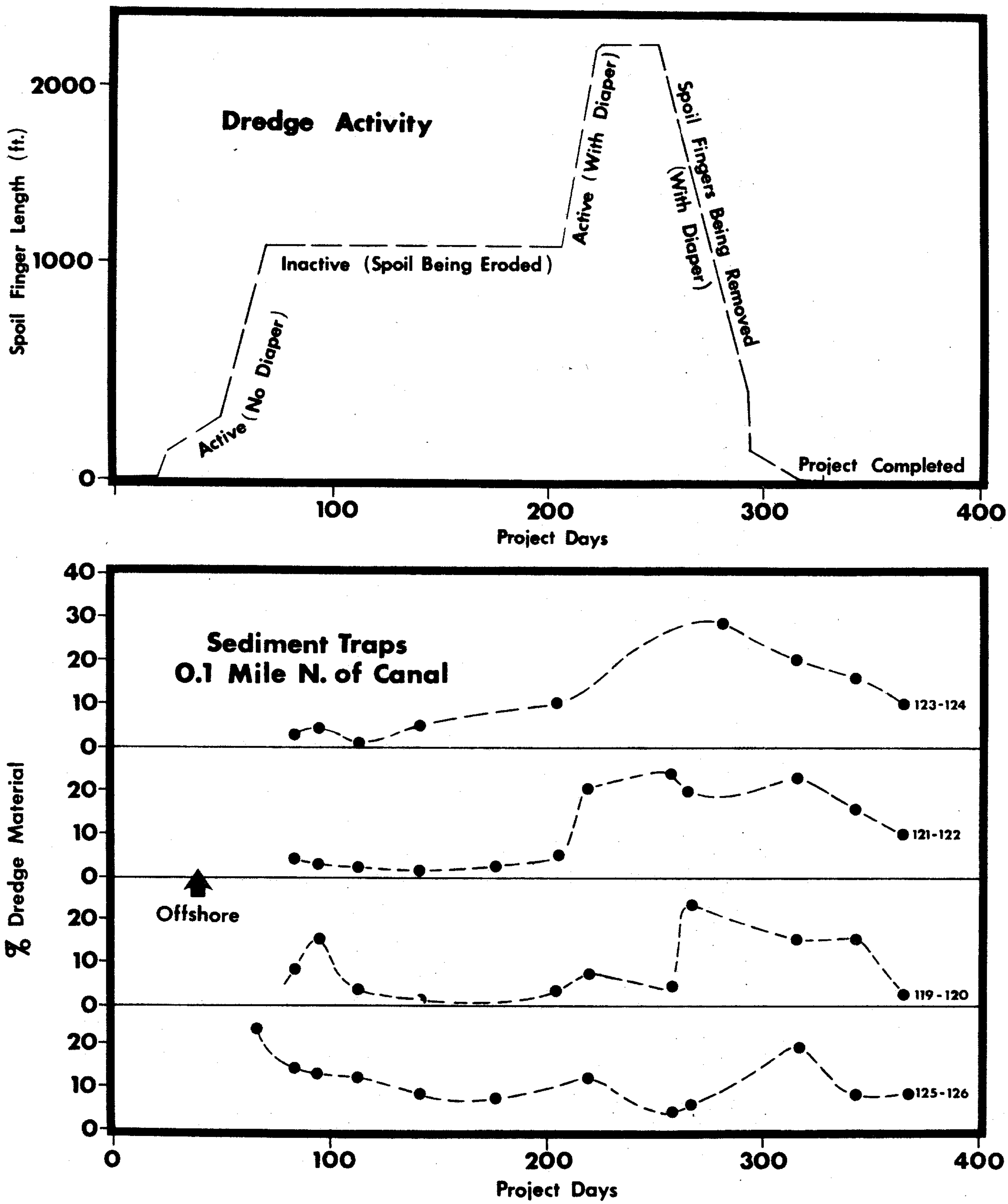
62 Percentage of dredge-derived sediment accumulated in sediment traps during the period September 5 to October 2, 1973 (Project days 318-345). Dredging was completed in the previous period (about day 300), so the dredge-derived sediment that continued to collect is residual, due to drainage of inland spoil, and possibly also to reworking of the bare bottom beneath the former spoil fingers, and to flushing of "canal fluff" from the canal axis. Symbols are explained on Figure 50.



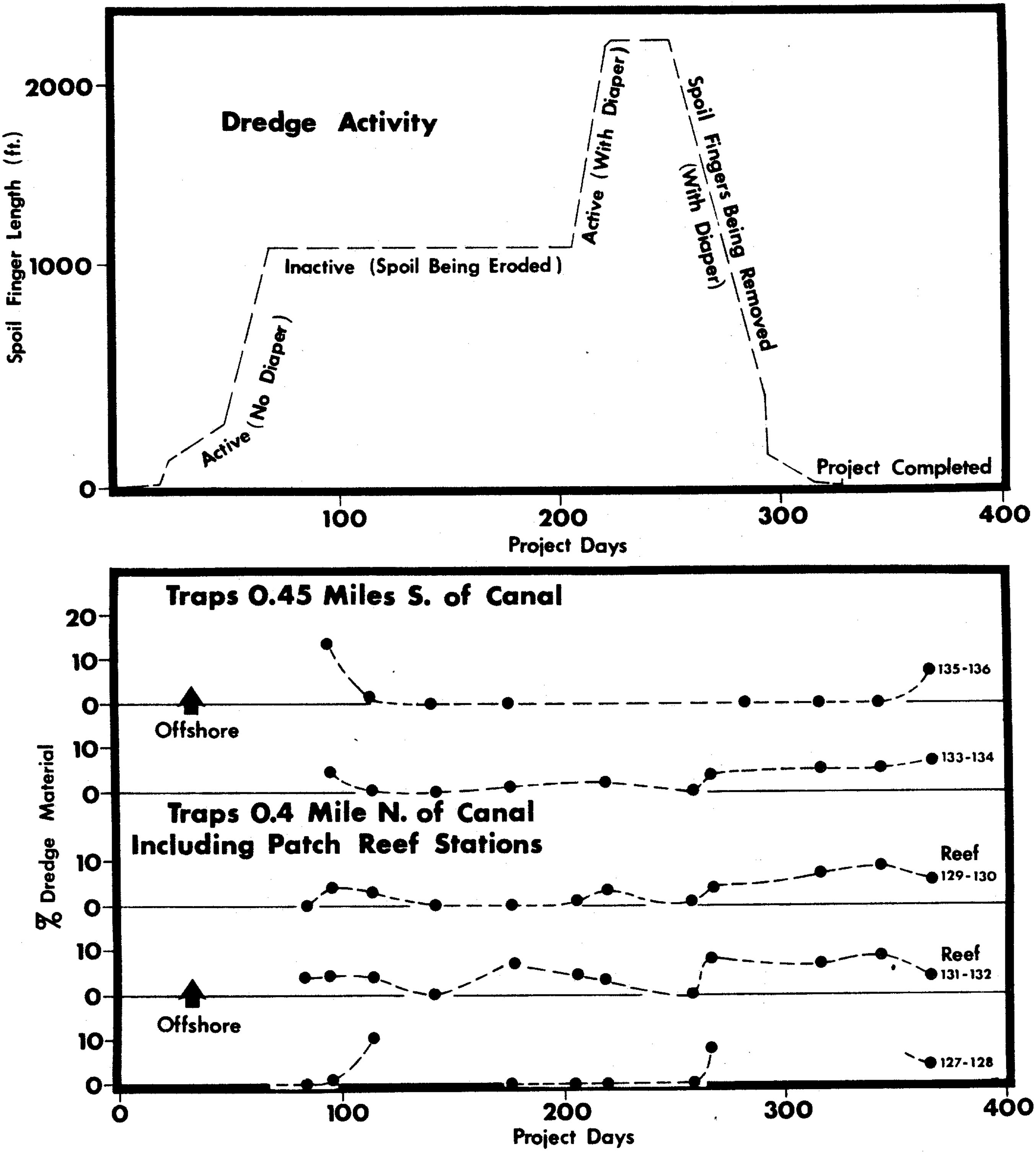
63 Percentage of dredge-derived sediment accumulated in sediment traps during the period October 2 to October 24, 1973 (Project days 345-367). Dredging was completed much earlier (about day 300). The latent effect noted here appeared to result from a combination of drainage of interior spoil areas, possible erosion of the bare bottom beneath the former spoil fingers, and possible resuspension of diaper-trapped fines in the canal bottoms (from both the perimeter and entrance canals). Symbols are explained on Figure 50.



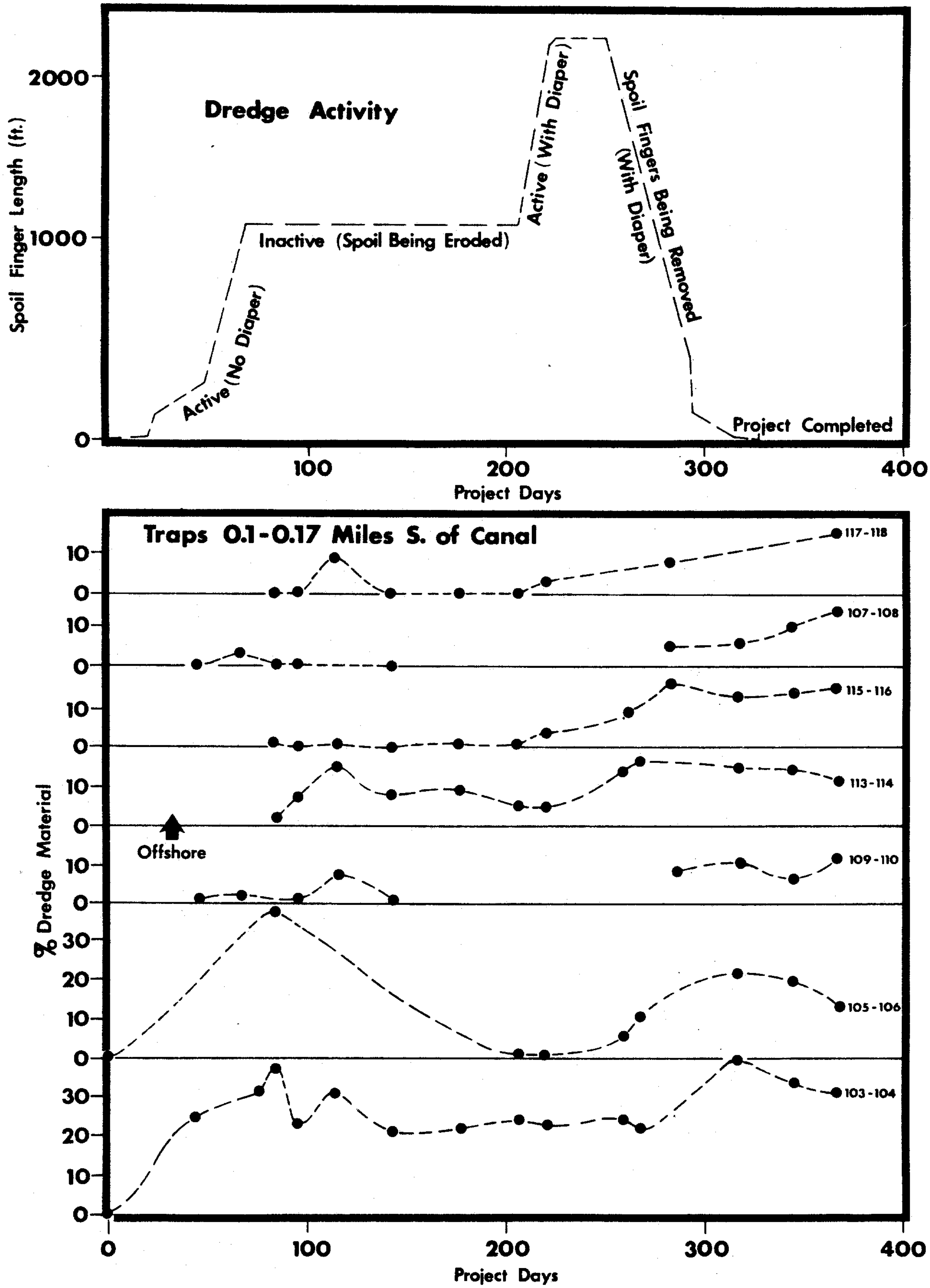
64 Percentage of dredge-derived sediment accumulated in traps within 100 feet of the canal, plotted as a function of project days, and compared with dredge activity. The most inshore trap (111-112) is plotted at the bottom of the figure. The percentage of dredge derived sediment reflected the proximity and activity of the dredge.



65 Percentage of dredge-derived sediment accumulated in traps along a line 0.1 n. mile north of the canal, plotted as a function of project days, and compared with dredge activity. The most inshore trap (125-126) is plotted at the bottom of the figure. The percentage of dredge-derived material increased as the dredge approached the various trap sites.



66 Percentage of dredge-derived sediment accumulated in traps along a line 0.45 n. mile south of the canal, and another line approximately 0.4 n. mile north of the canal, including the two stations nearest the coral patch reef. The percentages tended to increase toward the end of the project.



67 Percentage of dredge-derived sediment accumulated in traps along a line approximately 0.1-0.17 n. miles south of the canal. The percentages reflect the activity of the dredge and its proximity to the trap site.