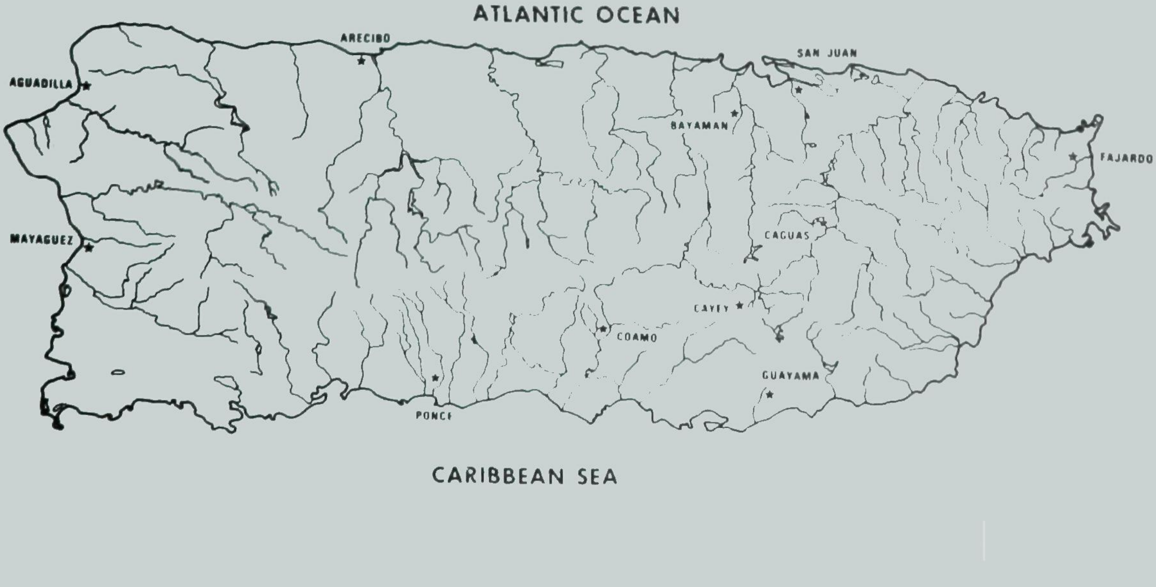
OCEANOGRAPHIC BASELINE DATA (1971-72)

FOR THE FORMULATION OF

MARINE WASTE DISPOSAL ALTERNATIVES FOR PUERTO RICO

VOLUME I: MAIN REPORT

FINAL REPORT-NOVEMBER 1974



OCEANOGRAPHIC BASELINE DATA (1971-72)

FOR THE

FORMULATION OF MARINE WASTE DISPOSAL ALTERNATIVES

FOR PUERTO RICO

VOLUME I: MAIN REPORT

FINAL REPORT - NOVEMBER 1974

Prepared For

ENVIRONMENTAL QUALITY BOARD
OFFICE OF THE GOVERNOR
COMMONWEALTH OF PUERTO RICO

Prepared By

OCEANOGRAPHIC PROGRAM
AREA OF NATURAL RESOURCES
DEPARTMENT OF PUBLIC WORKS
COMMONWEALTH OF PUERTO RICO

This study was jointly financed by the Commonwealth of Puerto Rico and the United States Environmental Protection Agency through a planning grant under PL 84-660, as amended.

PREFACE

This report was originally published in limited quantity in July 1972 by the Area of Natural Resources of the Puerto Rico Department of Public Works (now Department of Natural Resources). It has been reprinted for larger distribution by the United States Environmental Protection Agency with the cooperation of the Puerto Rico Environmental Quality Board and Department of Natural Resources.

In an effort to make this report quickly available, no stylistic changes have been made to the text and maps. Where necessary, minor corrections have been made to portions of the text and to some of the figures and tables. However, there still may be figures and tables that contain incorrect or mislabled station locations, data points and cruise vectors. The reader is cautioned to check seeming inconsistencies with the P.R. Environmental Quality Board.

This report was originally prepared while the Comprehensive Water Quality Management Plan for Puerto Rico was in the early stages of preparation and prior to enactment of the Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500). Therefore, some references in this report to primary and secondary treatment facilities and sites, regional divisions, population projections, etc. may not be in total agreement with existing laws, regulations, policies, and reports. The user of this report is cautioned to check with P.R. Environmental Quality Board for the latest information on these matters

CONTENTS

CONTENTS (cont.)

CONTENTS (cont.)

* The tables and figures contained in Appendices C through K are labeled sequentially, with a prefix indicating the appendix to which each belongs.

CONTENTS (cont.)

* The tables and figures contained in Appendices C through K are labeled sequentially, with a prefix indicating the appendix to which each belongs.

LIST OF TABLES

LIST OF TABLES (cont.)

LIST OF TABLES (cont.)

LIST OF TABLES (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

SECTION 1

SUMMARY

SECTION 1

SUMMARY

INTRODUCTION

A comprehensive Water Quality Management Plan for the Commonwealth of Puerto Rico is being prepared by the Puerto Rico Environmental Quality Board. This plan is being financed, in part, by Basin Planning Grant funds from the United States Environmental Protection Agency. One of the key data bases needed in order to formulate a water quality management plan is baseline oceanographic data for coastal waters, especially in areas near existing or anticipated locations of regional primary treatment facilities. Such information is required to provide a preliminary basis for evaluating the general feasibility of the marine disposal of wastewaters emanating from the regional facilities. Furthermore, it was decided to establish an operational on-island oceanographic study group capable of fulfilling the increasing need for physical and biological data on the marine environment in order to ensure effective utilization and/or protection of marine resources. The Environmental Quality Board contacted the Area of Natural Resources, of the Department of Public Works (now Department of Natural Resources), to establish this oceanographic study group and carry out the required studies.

At present, the proposed Plan recommends that the Commonwealth of Puerto Rico be divided into 13 regional basins. Treatment Facilities with ocean outfalls are planned at 16 locations. Some of these facilities will initially provide only primary treatment of wastewater.

The construction of these regional wastewater treatment facilities as primary level treatment is considered as a first step. As the Commonwealth construction program develops, the primary level facilities will be expanded to secondary treatment capability in accordance with present Environmental Protection Agency ocean disposal policy.

A key physiographic feature of each of the marine environments in the above regional basins is the width of the island coastal shelf. In many areas, such as Humacao/Yabucoa and Guayama, the coastal shelf has a width of several miles; however, in the remainder of the areas it is much narrower.

The probable wastewater treatment scheme to be used for most of the regional wastewater treatment facilities will include a primary treatment system coupled with an ocean outfall-diffuser system. The key feature in the feasibility of such a system is the level of performance achieved by the outfall-diffuser system; that is, the specifics of design and operation of a primary treatment/outfall-diffuser system is dependent on the initial dilution and subsequent attenuation of wastewater characteristics as the waste is dispersed by prevailing currents. Given this perspective, the basic approach to the resolution of coastal zone pollution problems around the island of Puerto Rico involves the assessment of the waste dilution/dispersion potential of nearshore waters and the determination of flow to maximize the utilization of this potential.

Based on the goals set for the Oceanographic Project, the immediate objectives were determined to be:

preliminary characterization of prevailing current patterns

characterization of the extent of vertical stratification in the receiving waters.

- water quality data (i.e., water transparency, dissolved oxygen, coliform organisms, etc.)
- background information on the coastal shelf
- coliform organism disappearance rates

DATA ACQUISITION

The Oceanographic Project acquired most of the required data by conducting three separate survey cruises around Puerto Rico, covering areas in the vicinity of the regional treatment basins. The dates of the beginning and end of each of the cruises are:

- Cruise 1 - April to July 1971
- Cruise 2 - August to October 1971
- Cruise 3 - December 1971 to February 1972

During Cruise 1 current measurements were made with an Ekman-Merz current meter at all but two of the sites, where drogues were used. Drogues were used for current measurements at all sites during Cruise 2. Salinity, temperature, and water quality measurements were also carried out during these cruises. Three newly-acquired in-situ recording current meters were used during Cruise 3 at a selected number of the sites covered during the preceding two cruises. In addition, coliform disappearance rate studies were conducted along the west and south coasts of the island during July 1971 and January 1972.

OVERVIEW OF DATA

Ocean Currents

The most satisfactory current data was obtained during Cruise 3 when the three in-situ recording current meters were used. A cyclic pattern, suggesting dominant tidal influences, was observed at all depths at the following sites: Carolina, Guayama, Ponce, Guayanilla, and Mayaguez.

Although the current patterns observed at San Juan and Humacao/Yabucoa do exhibit more-or-less cyclic tendencies, the pattern is not as definite as that observed at the preceding areas.

Density Structure

Vertical density gradients, computed from temperature and salinity data obtained at each site, were found to be small.

Water Quality

The lack of a data base against which to evaluate current water quality levels at each site makes it difficult to interpret the results obtained. The water quality data which was collected should be of value in the future when further measurements are made.

Coliform Disappearance Rate Studies

Several studies were conducted in the vicinity of the Mayaguez discharge plume. The results of trace studies show T_{90} disappearance rate values of 0.9 to 2.9 hours. Less definite results were obtained from the disappearance rate study conducted in the dispersed plume of the Guayama outfall. In this case the decrease in coliform concentration appears to have been due solely to dilution processes.

CONSIDERATION OF DILUTION POTENTIALS

The data bases on the coastal current patterns and vertical density gradients developed during the study were used to make estimates of initial dilution and subsequent dilution potentials. Based on an evaluation of this data it has been concluded that:

- the majority of potential initial dilution values will range from 50 to 200 for diffusers placed on the island shelf (i.e., at depths less than 600 feet.)

in eight of the eleven study areas, the approach to marine waste disposal will have to rely heavily on initial dilution processes. The areas in which wastewater management may be able to take advantage of the reduction in wastewater constituents due to dilution processes are: Humacao, Guayama, and Mayaguez.

SECTION 2

INTRODUCTION

SECTION 2

INTRODUCTION

GENERAL

The Environmental Quality Board (EQB), of the Commonwealth of Puerto Rico, is responsible for the preparation of a Comprehensive Water Quality Management Plan (Plan) for Puerto Rico. This effort is being financed in part by the United States Environmental Protection Agency (EPA through Basin Planning Grant Contract No. B-002025 as authorized by Section 3 (c) of the Federal Water Pollution Control Act, as amended.

Information on the basic physical characteristics of the coastal waters of Puerto Rico was determined by EQB as one of the key data bases needed to complete the Plan. This information is needed for two reasons: (1) to provide a preliminary basis for evaluating the general feasibility of marine disposal of wastewater, and (2) to develop background information on the local oceanographic conditions around the island.

It was decided to contract the desired oceanographic work out to the Department of Public Works (DPW) of the Commonwealth of Puerto Rico. The work was scheduled to begin 7 January 1971, to end 7 March 1972, and to have a budget of $234,000.

STUDY OBJECTIVES

Basically, the Oceanographic Study Program (Program) had one, major short-range and two, major long-range objectives to satisfy.

The short-range objective was to obtain the necessary baseline data required for engineering design studies on the feasibility of marine disposal of wastewater from Puerto Rico. This objective was accomplished through measurements and evaluations of ocean current, water stratification, nearshore topography, waste discharge volumes and locations, and rates of coliform disappearance at selected Study Areas. These areas were defined as the coastal waters in the vicinity of proposed Regional Wastewater Treatment Facilities.

One of the longer-range objectives was to furnish the Commonwealth and its agencies with a portion of the information base from which to develop plans for marine water resources management including the protection of designated beneficial-uses to be sustained along the coastal environments and for further development of its coastal marine environment. This objective was sought through the process of acquiring water-quality data in the specified Study Areas.

The other long-range objective was to initiate the training of Puerto Rican personnel and the development of on-island, oceanographic capabilities necessary to assist in the definition and resolution of coastal water pollution problems. Towards meeting this objective, the EQB and DPW established an Oceanographic Project Group (Project) within the DPW's Area of Natural Resources, and reassigned personnel and employed new personnel to form the Study Staff. It is planned to maintain this Project as a viable entity (in the new Department of Natural Resources) and have it actively participate in the gathering and evaluation of oceanographic information germane to the goals and needs of Puerto Rico.

PROJECT ORANIZATION AND MANAGEMENT

The line positions of EPA, EQB, DPW, Area of Natural Resources, and the Oceanographic Project are diagramed in the Project Organization Chart (Figure 2-1). To assist in the conduct and the management of the oceanographic work program, several staff positions were established. The Project Policy Board consisting of representatives of those agencies listed in Figure 2-1 was set-up to determine initially the overall direction for the oceanographic study. Members of this Board were instrumental in the preparation activities that resulted in this Ocenographic Study. The other major Board, the Project Control Board, was set up to review the progress of the work and to reorient the work program as necessary. The Technical Advisory Committee was established to review and make recommendations on the technical aspects of the Study. Unlike the Project Control Board which met at its own or the Executive Director of EQB's discretion, this Committee met at the discretion of the Oceanographic Project Director. Finally, the engineering firm of Engineering-Science, Inc. was retained as a consultant to the Oceanographic Project Director.

ACKNOWLEDGEMENT

Many individuals and organizations participated in and contributed to the conduct and completion of this study. These efforts as a whole are gratefully acknowledged. Special appreciation is extended to the members of the Project Control Board for their participation in the management and report review process:

Dr. E. Pearson (Chairman, July 1971 to March 1972)

Mr. A. Heres (Chairman, January to June 1971)

Dr. R. Vazquez

Dr. F. Lowman

Dr. W. Gates

Mr. P. Storrs

Also, the informal participation of representatives of EPA, Mr. N. Priede and Dr. D. Washington, is acknowledged.

Recognition is also extended to the Project staff for their day-to-day efforts in the filed as well as in the office towards the completion of this study. Specifically, these individuals are:

Mr. W. Metcalf (Project Director, January to December 1971)

Mr. F. Torres (Project Director, January to March 1972)

Mr. J. Cooper

Mr. K. McCarey

Miss C. M. Cham

Mr. C. Bauer

Mr. A. Lopez

Mr. N. Espar

Mr. W. Perl

Miss. A. Avillan

Appreciation is also due to staff members of Engineering-Science, Inc. The participation of the following individuals is acknowledged:

Dr. N. Armstrong

Dr. A. Kemmerer

Dr. G. Beers

Mr. J. Drucker

Mr. T. Smith

Mr. E. Jerome

Mr. M. Fluharty

Certain aspects of the field program were helped immensely by the loan of oceanographic equipment by Dr. E. Colon of the Institute of Water Resources Research at the University of Puerto Rico at Mayaguez, Puerto Rico.

Finally, appreciation is extended to the unidentified fisherman who on more than on occasion provided field help to Project personnel.

Environmental Protection Agency

Environmental Quality Board

Project Policy Board

Planning Board
Department of Agriculture
Fomento
Department of Public Works
Department of Health
Water Resources Authority
Aqueduct and Sewer Authority
Public Service Commission
Environmental Quality Board
Environmental Protection Agency

Department of Public Works

Area of Natural Resources

Project Control Board

Environmental Quality Board
Department of Public Works
Puerto Rico Nuclear Center
Consultant
Engineering-Science, Inc.

Technical Advisory Committe — Oceanography Project

Department of Public Works
Aqueduct and Sewer Authority
Environmental Quality Board
Environmental Protection Agency
Engineering-Science, Inc.

Engineering-Science, Inc.

Project Staff

PROJECT ORGANIZATION CHART

FIG 2-1

SECTION 3

THE OCEANOGRAPHIC PROJECT AND THE WASTEWATER MANAGEMENT PROGRAM

SECTION 3

THE OCEANOGRAPHIC PROJECT AND THE WASTEWATER MANAGEMENT PROGRAM

GENERAL

Many segments of the hydrosphere have been and are being used for the disposal of wastewaters. In the majority of cases, wastewaters are discharged into inland and coastal waters from shoreline and subsurface outfall systems. Less commonly, wastewaters are discharged into groundwaters by means of a variety of infiltration techniques and direct injection methods. In a very few cases, wastewaters have been disposed of in the atmosphere by means of evapotranspiration and evaporation methods.

The expectation of society for the desired beneficial uses of receiving waters at a particular geographic location determines to a large extent the limitations upon use of such waters as a wastewater disposal system. A wastewater treatment and outfall system can be viewed as a train of unit processes intended to reduce the concentration of selected constituents through conversion, separation, dilution, and dispersion to levels which will result in achieving environmental parameter levels equal to or less than the desired parameter levels.

There are a number of unit processes (1,2) designed to bring about one or more changes in the characteristics of the waste stream. Depending upon the economic, political, ecological, and technical constraints, there is usually more than one candidate unit process train for meeting the treatment and disposal objectives of introducing a wastewater into a particular receiving water. A listing of commonly used treatment process alternatives is presented in Table 3-1.

A common example of unit process train alternatives for marine waste disposal systems occurs in the situation in which the concentration of coliform organisms in the receiving water is of major concern. The typical tradeoff situation for the same level of wastewater treatment is:

(1) use of shorter, less expensive outfall in conjunction with a chlorination system to achieve the receiving water and littoral zone coliform standard; versus

(2) use of a longer outfall system to deeper waters without a chlorination system to meet the same objective.

CONTEXT FOR PUERTO RICO

The Commonwealth of Puerto Rico is in the initial stages of upgrading its wastewater management program on a regional basis. Sanitary and industrial wastewater treatment facilities on the island are, with few exceptions, inadequate. Presently, all but one of the 78 urban ceenters in Puerto Rico have some form of sanitary sewage facilities, however extensive areas are unsewered. Of the approximately 80 mgd handled by the facilities in the 78 urban centers, only about 13 mgd (15.8 percent) receives secondary treatment, about 47 mgd (58.7 percent) receives primary treatment, about 7.8 mgd (9.7 percent) receives septic tank and/or Imhoff tank treatment, and the reamainder (13 mgd, or 15.8 percent) is discharged to the ocean without any treatment. The seven locations of raw sewage discharge to the ocean are identified in Figure 3-1, along with the type of treatment provided at other sanitary facilities on the island. The locations of industrial waste discharge are also shown in Figure 3-1.

The projection of wastewater discharges from municipal and industrial sources for 1980 are 252 and 129 mgd, respectively. By 2020, the wastewater flows from municipal and industrial sources are projected to be about 648 and 209 mgd, respectively.

A candidate island-wide wastewater management program has been proposed to deal with existing and impending water pollution problems. Basically, the plan divides the island of Puerto Rico into 16 Water Quality Management Regions, as shown in Figure 3-2. Not shown in the figure is the region formed by the small offshore islands of Vieques and Culebra. These regional areas are consistent with the program being developed by the Commonwealth under the Federal Water Pollution Control Act, Section 3(c) Basin Planning Grant. The candidate plan of the Commonwealth (3) also identifies the regional basins as being one of two types, i.e. primary or secondary, as illustrated in Figure 3-2

The ten primary regions are scheduled to be provided with primary treatment systems in conjunction with long ocean outfalls, whereas the six secondary regions will be provided secondary treatment systems and/or wastewater re-use reclamation systems. Secondary and tertiary treatment facilities are planned for the more inland areas of the island, as identified in Figure 3-2.

The feasibility of operating a primary treatment system coupled with an outfall-diffuser is the level of performance which can be attained by the outfall-diffuser. This, in turn, is dependent upon the initial dilution and subsequent attenuation of wastewater characteristics achievable as a result of the physical, chemical, and biological interactions occurring in the receiving waters at and in the vicinity of the discharge. The lack of information on the nearshore oceanography prior to the present study was an outstanding technical gap that would constrain the planning and evaluation of many of the proposed treatment facilities on the shores of Puerto Rico.

Thus the immediate mission of the Oceanographic Project was to obtain nearshore oceanographic information, particularly as regards to water density stratification and current patterns, at the eleven study sites where primary treatment facilities have been proposed. For the purposes of this study nearshore was defined to mean within the 600 ft. (100 fathom) depth contour, as shown in Figure 3-3. The data obtained would provide an information base for use in subsequent preliminary feasibility studies of outfall-diffuser systems at the selected sites.

TABLE 3-1

COMMON UNIT PROCESSES UTILIZED IN WASTEWATER TREATMENT TRAINS

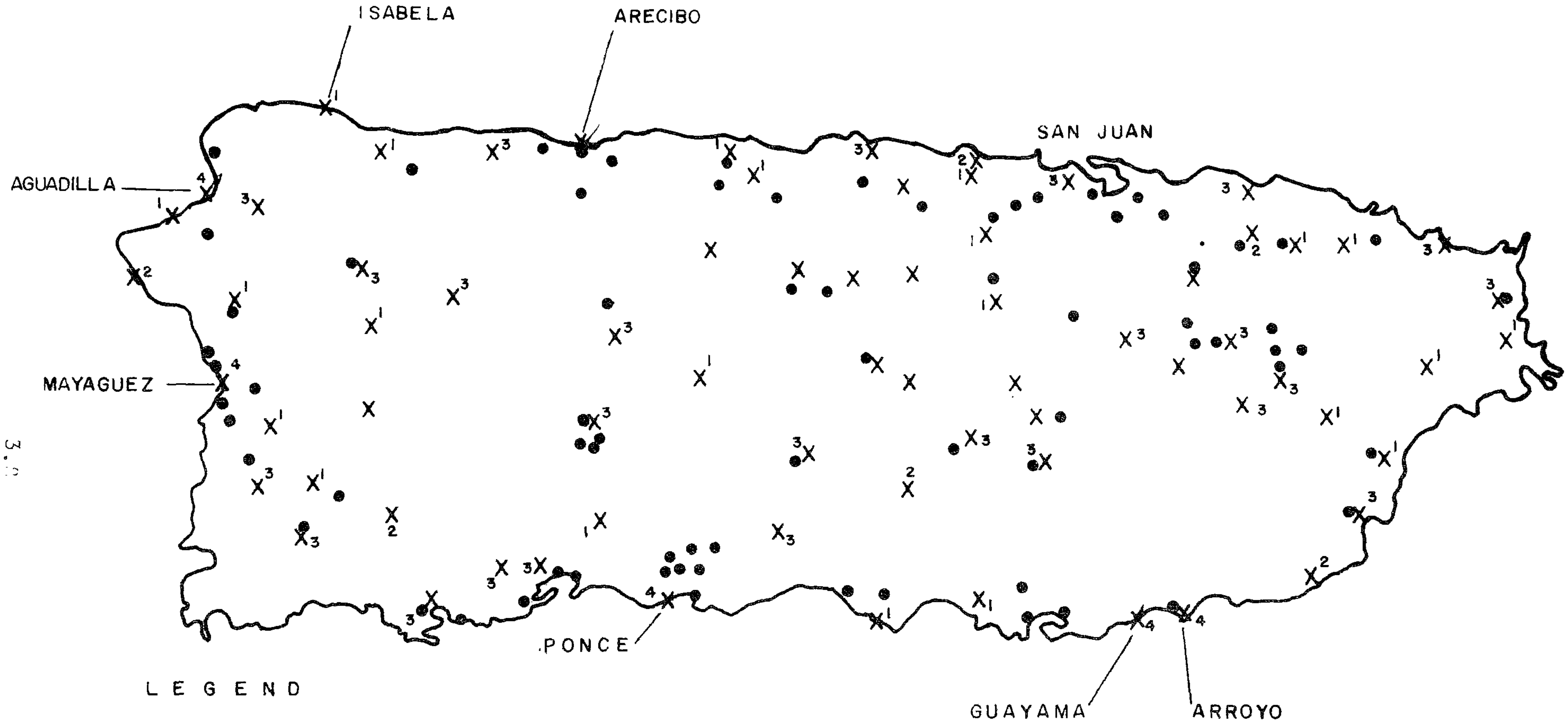
Principal Purposes of Unit Process	Unit Process
Grit removal	Grit chambers
Removal or grinding of coarse solids	Bar screens; Comminutors
Odor control	Prechlorination; Ozonation
Gross solids-liquid separation; BOD reduction	Plain primary settling
Gross removal of soluble BOD and COD from raw wastewater	Biological treatment
Removal of oxidized particulates and biological solids	Plain secondary settling
Decomposition or stabilization of organic solids; conditioning of sludge for dewatering	Anaerobic sludge digestion
Improve sludge dewatering characteristics	Anaerobic digestion; Thickening; gravity, flotation; Elutriation; Heat treatment; Ash conditioning; Chemical conditioning; chlorine, alum, lime, polymers, iron salts
Preparing organic or chemical sludge for disposal or further treatment	Dewatering organic or chemical sludge: air drying, centrifuging, vacuum filtration (coil septum, fabric septum, filter press)
Ultimate sludge disposal	Incineration: multiple-hearth, fluidized bed; Land disposal; Injection; Recovery and reuse of chemical sludges

TABLE 3-1 (cont.)

COMMON UNIT PROCESSES UTILIZED

IN WASTEWATER TREATMENT TRAINS

Principal Purposes of Unit Process	Unit Process
Removal of colloidal solids and turbidity from wastewater	Chemical treatment, sedimentation, and mixed-media filtration: alum, lime, polymers, iron salts
Phosphorus removal	Chemical coagulation, flocculation, and settling: lime, alum, iron salts
Nitrogen removal	Ammonia stripping
Removal of suspended and colloidal materials; protection of granular carbon beds or iron exchange beds from fouling or plugging	Mixed media filtration; Dual media filtration
Removal of dissolved trace refractory organics-MBAS, COD, BOD, color, odor, etc.	Granular activated carbon adsorption: upflow packed, upflow expanded, downflow series beds
Disinfection; bacteria and virus inactivation	Chlorination, Ozonation
Ultimate wastewater disposal	Land disposal; Injection; Ponding; Outfall-diffuser system



LEGEND

- ● INDUSTRIAL WASTE DISCHARGE
- X SANITARY SEWAGE DISCHARGE
- 1 SEPTIC OR IMHOFF TANK
- 2 SEPARATE PRIMARY SEDIMENTATION AND DIGESTION
- 3 SECONDARY TREATMENT
- 4 RAW SEWAGE

FIG 3-1
LOCATIONS OF EXISTING SANITARY AND INDUSTRIAL TREATMENT FACILITIES IN PUERTO RICO (FROM REFERENCE 10)

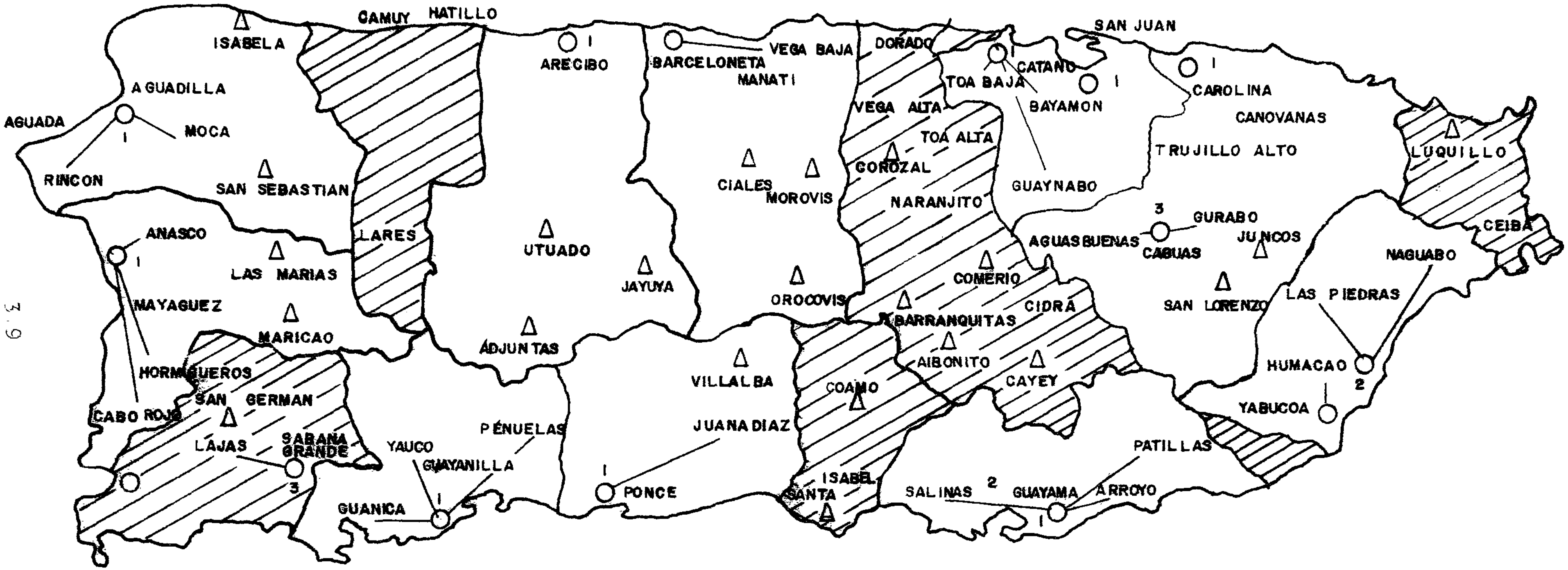


FIG 3-2
MAIN FEATURES OF THE PROPOSED REGIONAL
WASTEWATER MANAGEMENT PROGRAM

LEGEND

- ○ REGIONAL TREATMENT PLANT
- 1 PRIMARY TREATMENT PLANT
- 2 SECONDARY TREATMENT PLANT
- 3 TERTIARY TREATMENT PLANT
- Δ LOCAL SECONDARY TREATMENT PLANT

REGIONAL BASIN TYPE:

- (blank box) PRIMARY
- (hatched box) SECONDARY

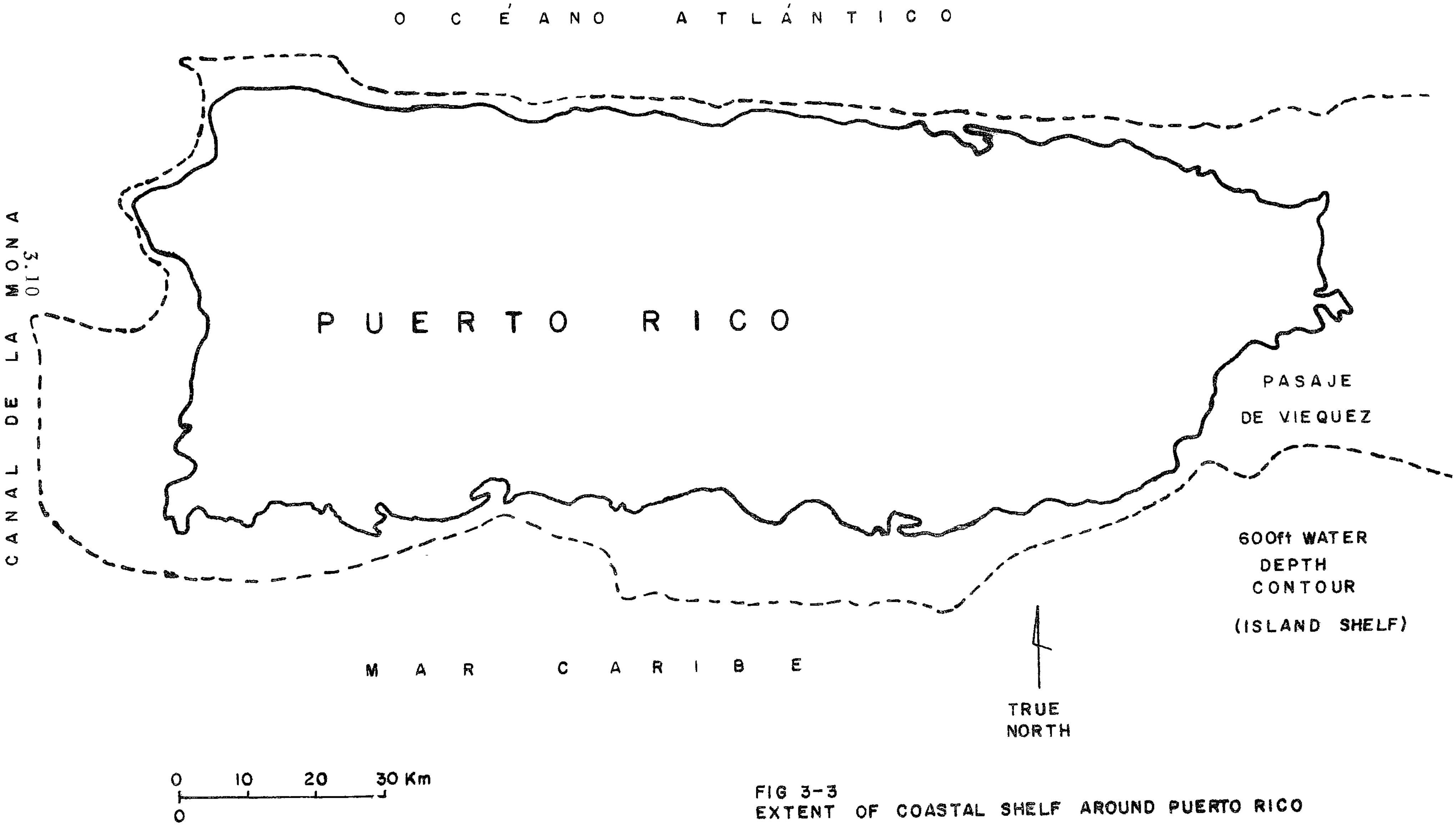


FIG 3-3
EXTENT OF COASTAL SHELF AROUND PUERTO RICO

SECTION 4

GENERAL DESCRIPTION OF STUDY AREAS

SECTION 4

GENERAL DESCRIPTION OF STUDY AREAS

GENERAL

The Commonwealth of Puerto Rico consists of a main island and several smaller islands located in the Caribbean, approximately 1,000 miles southeast of Miami, Florida (1). The nearest land mass of significant size is the island of Hispaniola situated approximately eighty miles to the west (1). Puerto Rico is shown in relation to other land features within the Northern and Western Hemispheres in Figure 4-1 (1).

Puerto Rico is roughly 110 miles from east to west and 35 miles from north to south, and lies in the region of the northeast trade winds. The mean tidal range is 1.1 feet, the neap tides being 0.6 feet and the spring tides being 1.4 feet (2).

In spite of its small size and the relative constancy of the trade wind belt climate, the marine environment is by no means without contrasts from place to place. Each of the four sides of the more or less rectangular island has its own distinctive climatic and environmental features. The North Coast is washed by the tropical North Atlantic Ocean and the South Coast by the Caribbean Sea. The passages between Puerto Rico and St. Thomas, Virgin Islands, to the east, and Hispaniola to the west, are broad and relatively shallow.

Extreme variations in rainfall have been recorded as Puerto Rico lies in the Caribbean hurricane belt and, at intervals of from 4 to 7 years, lies within or immediately adjacent to a hurricane path (1). Distribution of rainfall is shown in Figure 4-2 (1).

The rainfall is primarily orographic in nature. The air mass of the trade winds, which becomes moisture laden during its passage across the ocean, releases the moisture as the air is forced upward by the mountains of Puerto Rico. Most of the moisture is released in the northern and eastern slopes, which also get most of the watershed. The rain shadow effect of the Cordillera Central and Sierra de Luquillo is shown in the South Coast with its maximum effect in the southwest where annual rainfall averages 40 inches a year. Tropical storms and hurricanes, while infrequently hitting the island, present a potential threat of high winds and torrential rains from June through October.

As a rapidly developing industrial community with a very rapid population expansion, and a rugged terrain which tends to concentrate the population in relatively small densely settled areas, Puerto Rico is subjecting its environment to increasingly severe stress in the matter of waste disposal and consequences. As of April 1970, the population of Puerto Rico was 2,689,032 (3). This figure represents an increase of 340,388, or 14.5%, from the 2,349,544 inhabitants enumerated in the 1960 census (3). It was also estimated that the population of Puerto Rico will reach 5 million in the year 2020, an increase of 2.3 million over 1970. Table 6-1 presents population projections for several planning regions established for the purpose of the water pollution abatement basin plan (3).

COASTAL AREA DIFFERENCES

North Coast

The North Coast of Puerto Rico is marked by a relatively narrow continental shelf, rarely more than 2 or 3 miles wide before sloping very steeply down into one of the deeper basins of the North Atlantic Ocean. Offshore, the sea and swell generated by the very steady northeast trade winds over several thousand miles of open ocean are in many places obstructed from pounding directly on the shore by offlying shoals of beach rock formation. Nevertheless, the water as it reaches the shore is usually fairly turbulent.

The winds are practically always from the easterly quadrant, with northeast winds predominating. The mean annual velocity is 8.5 knots at San Juan Airport, which probably is typical for the North Coast as a whole. July is the windiest month, with average peak speeds of over 15 knots, and October and November have the lightest winds. Figure 4-3 illustrates the effects of onshore and offshore breezes upon the trade winds at four coastal sites (4).

Although the tidal range has a mean value of only 1.1 ft., and 1.3 ft. during spring tides (2), there are pronounced semi-diurnal tidal components to the currents off the North Coast. In the open Atlantic offshore from Puerto Rico, the North Equatorial Current has a generally constant flow to the west with an average speed varying from about 0.3 knot in the winter to 0.7 knot in the summer, according to the Pilot Charts. However, it may be that the passage of major atmospheric pressure systems in the open ocean, combined with the tidal components and the local geographical effects of the capes and inlets, is responsible for complicating the current picture. At any rate, the North Coast currents flow most of the time to the west rather than to the east in most places.

East Coast

The East Coast of Puerto Rico is marked by a broad shallow shelf which reaches out to the islands to the east. The passage between Puerto Rico and Isla Vieques, for example, is about 7 miles wide at its narrowest point and only 16 meters deep at its deepest point. Islands and shallow waters protect the coast in some degree from open-ocean waves. The trade winds are extremely steady from the east in this area with an average velocity ranging from just under 6 knots in October to 9 knots in July.

In Pasaje de Vieques, the shallow passage between Puerto Rico and Vieques Island, the tidal component predominates in the current picture. Daily current predictions are listed in the Tidal Current Tables (2). It should be mentioned that in the shallow bays and inlets lining the East Coast, the times of current reversal and directions of flow may vary markedly from those listed for the middle of the channel in the current tables.

Tidal currents are further complicated by the fact that near the southeastern corner of Puerto Rico, the tidal pattern is affected by the semidiurnal tide that predominates along the North Coast and the diurnal mixed tide commonly found in the Caribbean Sea.

South Coast

Being partially in the shadow of the main bulk of the island as far as the trade winds are concerned, the South Coast of Puerto Rico has a wind pattern distinctly different from the patterns found along the North and East Coasts of the island. As a broad generalization, it can be said that the wind is generally from the eastern quadrant with a strong onshore (SE) component developing during the heat of the day and a strong offshore (NE) component predominating during the night and cooler parts of the day (5). However, this is an over-simplification, and the pattern frequently is quite complex. The windiest month is March, with an average of 7.7 knots from the east-southeast.

The precipitation in the eastern quarter of the South Coast is similar to that found along the North Coast. The average is 60-80 inches a year, falling away to about half of that towards the west (see Figure 4-2).

The continental shelf along the South Coast is over 5 miles wide in most places before dipping steeply into the Venezuelan Basin of the Caribbean Sea. Small coral and mangrove islands protect the South Coast at many places.

The average tidal range is about 1.1 foot and the pattern is complex.

Basically, this is a region of diurnal tides, but during part of the lunar month a distinct semidiurnal perturbation is superimposed on the diurnal base (2).

A further complicating factor is that the daily predictions for the South Coast tides are based on the tidal cycle at Galveston, Texas, and at least part of the time the relationship between the two areas is rather casual.

West Coast

The West Coast of Puerto Rico is in the shadow of the island as far as the trade winds are concerced, which brings about a pronounced modification of the wind pattern. At Mayaguez, on the western end of the island, the effect of the land and sea breeze acts in almost opposite directions and lessens the strength of the trade winds to such an extent that it frequently becomes dominant and a westerly wind is observed (5).

Along the southern half of the West Coast the 100 fathom contour extends westward for 10 to 15 miles, while it is much closer, typically about 2 miles offshore, along the northern half of this coast. Depths of 300 to 500 fathoms prevail across Mona Passage to Hispaniola, which is considerably less than typical off-shore depths found along the North and South Coasts, while being much deeper than the waters in the vicinity of Vieques Passage off the East Coast.

The tides of the West Coast are of a semidiurnal nature. According to the Pilot Chart, there is a pronounced flow of water from the Caribbean Sea to the Atlantic Ocean during the winter months, and from the Atlantic Ocean to the Caribbean Sea during the summer. This can be expected to make a complicated seasonal shift in the pattern of the currents along the West Coast of Puerto Rico.

FIG 4—1
COMMONWEALTH OF
PUERTO RICO VICINITY MAP

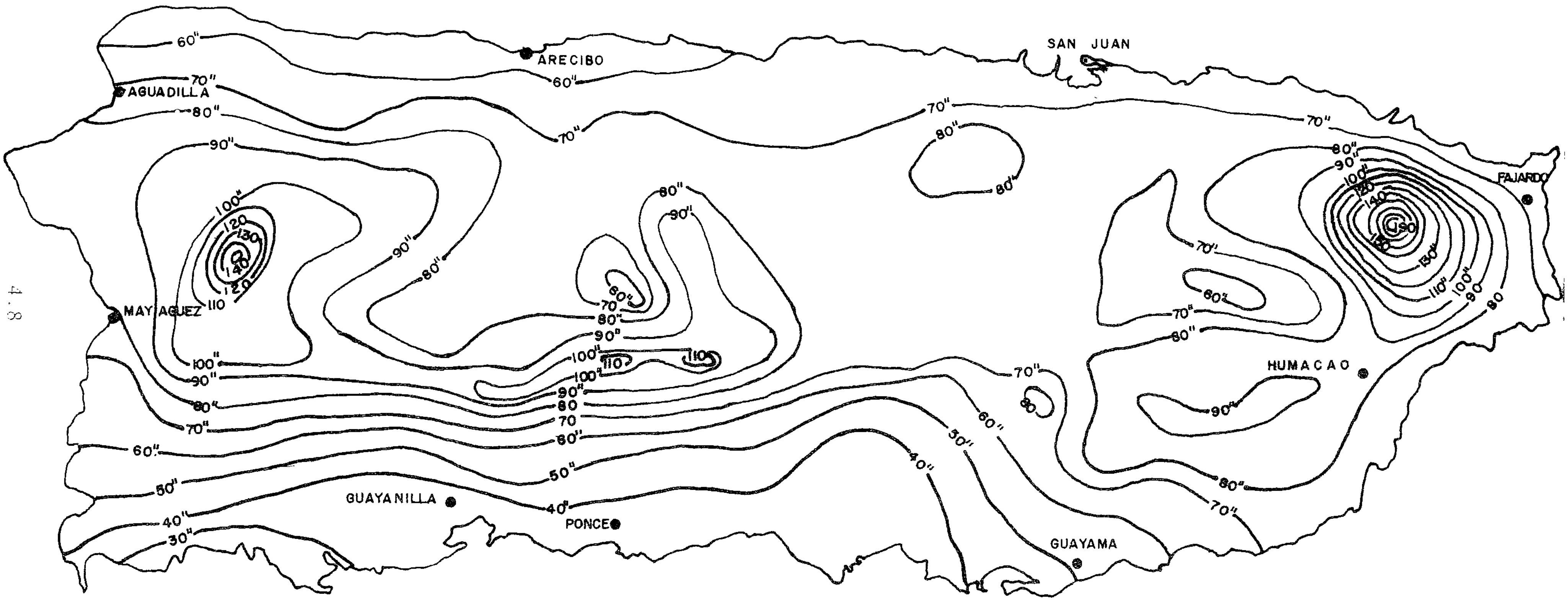


FIG 4—2
DISTRIBUTION OF RAINFALL IN PUERTO RICO

NOTE: CONTOURS SHOW INTENSITY OF RAINFALL IN INCHES PER YEAR

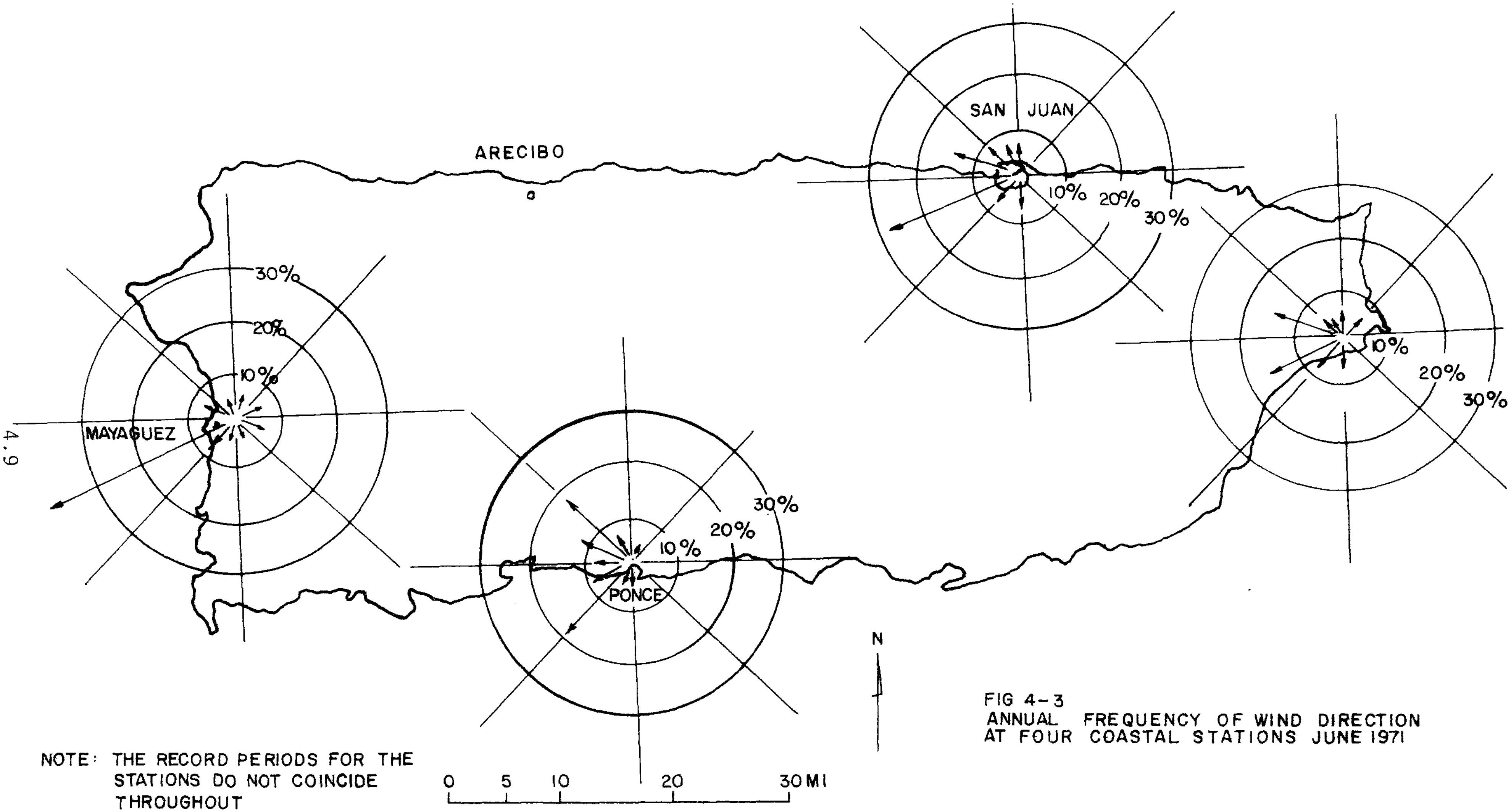


FIG 4-3
ANNUAL FREQUENCY OF WIND DIRECTION
AT FOUR COASTAL STATIONS JUNE 1971

NOTE: THE RECORD PERIODS FOR THE STATIONS DO NOT COINCIDE THROUGHOUT

TABLE 4-1

HISTORIC AND PROJECTED POPULATION
OF PUERTO RICO 1960-2020

	1960	1970	1980	1990	2000	2020
Primary Regions:						
San Juan	608,503	748,412	1,035,460	1,200,676	1,401,777	1,952,907
Ponce	191,868	211,166	297,045	326,787	359,661	436,228
Barceloneta	135,439	141,101	152,916	156,629	160,521	168,881
Guayama	87,232	88,887	106,433	110,169	114,119	122,688
Aguadilla	163,999	168,207	191,369	197,427	203,775	217,423
Yabucoa	97,405	101,512	109,189	110,936	112,801	116,861
Arecibo	144,619	140,774	154,669	154,192	153,787	153,199
Guayanilla	80,830	83,943	90,789	92,495	94,257	97,947
Carolina	252,719	379,908	471,817	550,173	647,648	923,419
Subtotal	1,901,021	2,210,480	2,781,010	3,075,422	3,429,131	4,380,745
Secondary Regions						
Lajas	69,843	69,712	75,287	75,822	76,374	77,537
Camuy	79,974	81,711	85,627	85,755	85,904	86,271
Dorado	203,536	223,261	256,553	269,678	283,646	314,451
Santa Isabel	40,624	42,202	48,684	50,351	52,090	55,793
Fajardo	35,978	43,206	39,682	39,408	39,142	38,634
Maunabo	10,785	10,817	10,875	10,740	10,606	10,345
Vieques	7,210	7,817	6,241	5,846	5,476	4,804
Culebra	573	726	408	358	314	242
Subtotal	448,523	479,452	523,357	537,958	553,552	588,077
TOTAL	2,349,544	2,689,932	3,304,367	3,613,380	3,982,683	4,968,822

SECTION 5

DATA ACQUISITION

SECTION 5

DATA ACQUISITION

DATA REQUIREMENTS

The following specification of data requirements was given high priority in the Oceanographic Project:

- characterization of coastal current patterns in the vicinity of the eleven planned Primary Treatment Facilities
- characterization of vertical density stratification patterns at the eleven sites

To the extent possible, it was also desired to obtain data concerning the following:

- water transparency
- dissolved oxygen
- coliform organisms
- BOD
- silica
- phosphate
- pH

FIELD PROGRAM

Initially, four cruises around the island, roughly corresponding to the four climatological seasons, were planned. It was intended that each of the sites be visited once during each cruise. Due to delivery delays and other difficulties in procurement of equipment, difficulties in recruiting personnel with the required skills, problems associated with obtaining, equipping, and maintaining a suitable vessel, equipment failures, and delays caused by bad weather, three cruises were actually carried out. The third cruise was interrupted before its completion. Except for one Ekman-Merz current meter and a 23 ft. sport fishing boat unsuited to the task, there was very little occanographic equipment available as the study began in early 1971. Only during the last few months of field activity did equipment resources approximate what was needed at the start of the study.

During Cruises 1 and 2 the sampling design at each site was as follows:

- five station transects were laid out normal to the general trend of the coastline
- the middle of the five transects at each study area was aligned along what was considered to be the most probable outfall-diffuser alignment
- hydrographic stations (locations where a string of Nansen bottles are lowered for temperature and salinity measurements) were spaced roughly at half mile intervals along each transect starting as close to the shoreline or surf zone as feasible and extending offshore for a distance of either three miles or to the 100 fathom isobath, whichever came first
- a single current station (current meter location as well as drogue release point) was positioned at each study area on the middle transect where the water depth was about five fathoms

The general features of this design are shown schematically in Figure 5-1. Concurrent with the execution of the above program, water-quality measurements were carried out at all sites.

During Cruise 3 newly acquired in-situ recording current meters were used at six of the eleven sites. One instrument was placed 6 to 10 meters below the surface and another about 15 meters above the bottom at approximately the same location in water between 130 and 150 feet (or 40 and 46 meters) deep. A third instrument was placed 6 to 10 meters below the surface at a point roughly mid-way between the other instruments and the shoreline, in water about 50 feet (15 meters) deep. It was necessary to modify this scheme at certain locations, as explained in Appendix A.

ON-STATION PROCEDURES

Water depth:

A small portable battery-operated recording echo sounder (Foruno FG-11 Mark-3) was used to obtain the depth of water at each station. Early in the development of the work plan it was suggested that a continuous bathymetric record be made of each transect. During the course of running these transects very frequent stops, starts, changes in speed and direction, and prolonged periods of drifting made it quite impractical to try to reconstruct any reasonable bathymetry without increasing the time spent at each station beyond the time which had been alloted. Thus in general the echo sounder was used only on the approaches to stations and at the stations. Soundings were read from the scale in fathoms and converted to meters.

Water transparency:

A Seechi disc was used for measuring water transparency. This is a white disc 30 em in diameter weighted with a lead sinker on the lower side. The disc was lowered into the water until it was no longer visible from above the water surface, at which point a reading of the depth of the disc was taken. This reading provides an index of the relative clarity of the water. Secchi disc readings are subject to side effects dependent upon the angle of the sun, cloud cover, and roughness of the sea surface, but in general the results obtained when the sun is well above the horizon are consistent.

Current measurements:

One tidal cycle is the minimum time period desireable for current measurements, but in practice this was not always feasible with the Ekman-Merz current meter or with the drogues which were used during Cruises 1 and 2. The usual procedure involved putting to sea at dawn, but in many cases one to three hours of travel time was required to reach the site. Therefore, current measurements during these two cruises typically covered periods of the order of 8 to 10 hours.

During Cruise 1 an Ekman-Merz current meter on loan from the Aqueduct and Sewer Authority was used at all but the last two sites. The practice with this meter was to anchor at roughly the place where the outfall pipe would probably terminate. In shallow areas regular observations of 5 to 15 minutes duration were made in sequence at about 5 meters below the surface and about 5 meters above the bottom. In deeper areas observations were also made at mid-depth.

When a current meter is used from an anchored boat the movement of the boat at the end of the anchor line affects the readings in an indeterminate manner. Largely for this reason it was decided to use drogues instead of the Ekman-Merz meter, and steps were simultaneously taken to obtain several internally recording meters. Drogues were used at the last two sites during Cruise 1, and at all sites during Cruise 2. Three drogues were generally released at a time at three different depths. After two or three hours, another set was put in, and then a third, all starting at the same location. The position of each drogue was fixed at intervals of one or two hours. Fixes were obtained by using a sextant to measure two horizontal angles between three landmarks. The position was then plotted on the chart with a three-arm protractor.

During Cruise 2 an internally recording current meter was borrowed from the Water Resources Research Institute, University of Puerto Rico, Mayaguez. It was moored somewhat above mid-depth at most of the sites, at the starting point for drogue observations. As in the case of positioning of the Ekman-Merz meter during Cruise 1, this location was in the vicinity of the probable termination of an outfall pipe. The meter was supported by a sub-surface float. It was left in position during the drogue operations and then recovered. A malfunction was discovered in this instrument at Ponce, and attempts to correct this were not successful. The data obtained with this instrument during Cruise 2 has therefore not been included in this report.

During Cruise 3 three newly acquired in-situ internally recording current meters (Hydro Products, Model 502) were used. These were moored to the bottom with 100 to 150 pound scrap iron weights, and supported by sub-surface flotation. A corrodable link rigged to a small pop-up marker float was used with each instrument in order to discourage theft or vandalism. Positioning of these instruments has already been described. These meters were left in place at each site for periods of up to around 140 hours.

Water temperature:

The water temeperature was measured by deep sea reversing thermometers used in Nansen Bottles. Temperatures were read to the nearest hundredth of a degree centigrade immediately at each station. Later, in the laboratory ashore, the various routine thermometric corrections were applied. These rarely changed the field reading by as much as a tenth of a degree. Under normal sea conditions, experienced observers can obtain sea water temperatures accurate within two hundredths of a degree.

pH:

A self-contained battery operated pH meter was not obtained until near the end of the first cruise. Once in the field, it was found that the instrument would not function properly aboard the rolling vessel. The use of the meter was discontinued early during Cruise.2.

Meteorological observations:

Only very simple meteorological observations were made. Wind speeds were determined either from a hand-held anemometer reading in knots or else estimated from the effect on the sea surface according to the Beaufort scale.

Water sampling:

At each hydrographic station, teflon lined Nansen bottles were used to obtain water samples. In shallow water, the bottles were placed on the steel hydrographic cable no closer than five meters apart. The deepest bottle was about 3 meters above the weight on the end of the cable. At some stations the weight was actually bumping the bottom with the rolling of the vessel. Five Nansen bottles were used where the depth of water permitted, and in the deeper water, the bottles were spaced further apart to obtain suitable sampling intervals. The top bottle was always just below the surface, and if a mixed layer was present above a thermocline or halocline, the other bottles were placed in positions to delineate these features as well as could be estimated at the time.

The Nansen bottles hold about 1.3 liters of water which was transferred to various styles and sizes of glass and plastic bottles depending on what analysis was being made. For example, the salinity samples were stored in well-rinsed glass bottles of about 100 ml with plastic cones in the caps to prevent evaporation.

Dissolved oxygen samples were collected in 125 ml dark glass bottles with ground glass stoppers. These bottles were filled with a rubber filling tube to prevent air bubbles from entering. The chemical reagents to "fix" the oxygen were then added.

The samples for biological oxygen demand were collected in special "BOD" bottles and set aside for later incubation and analysis.

Coliform samples were also drawn from the Nansen bottles. The method by which the coliform analyses were made was changed in the course of the program as mentioned below.

ANALYTICAL PROCEDURES

Dissolved oxygen, biochemical oxygen demand, and coliform organism determinations were conducted in accordance with Reference 5.1 Except for the coliform determinations on water samples collected at Mayaguez and Aguadilla on the first cruise which employed the multiple test fermentation technique, all coliform analyses were made using the membrane filter technique.

Phosphate (reactive) and silicate determinations were conducted in accordance with Reference 5.2.

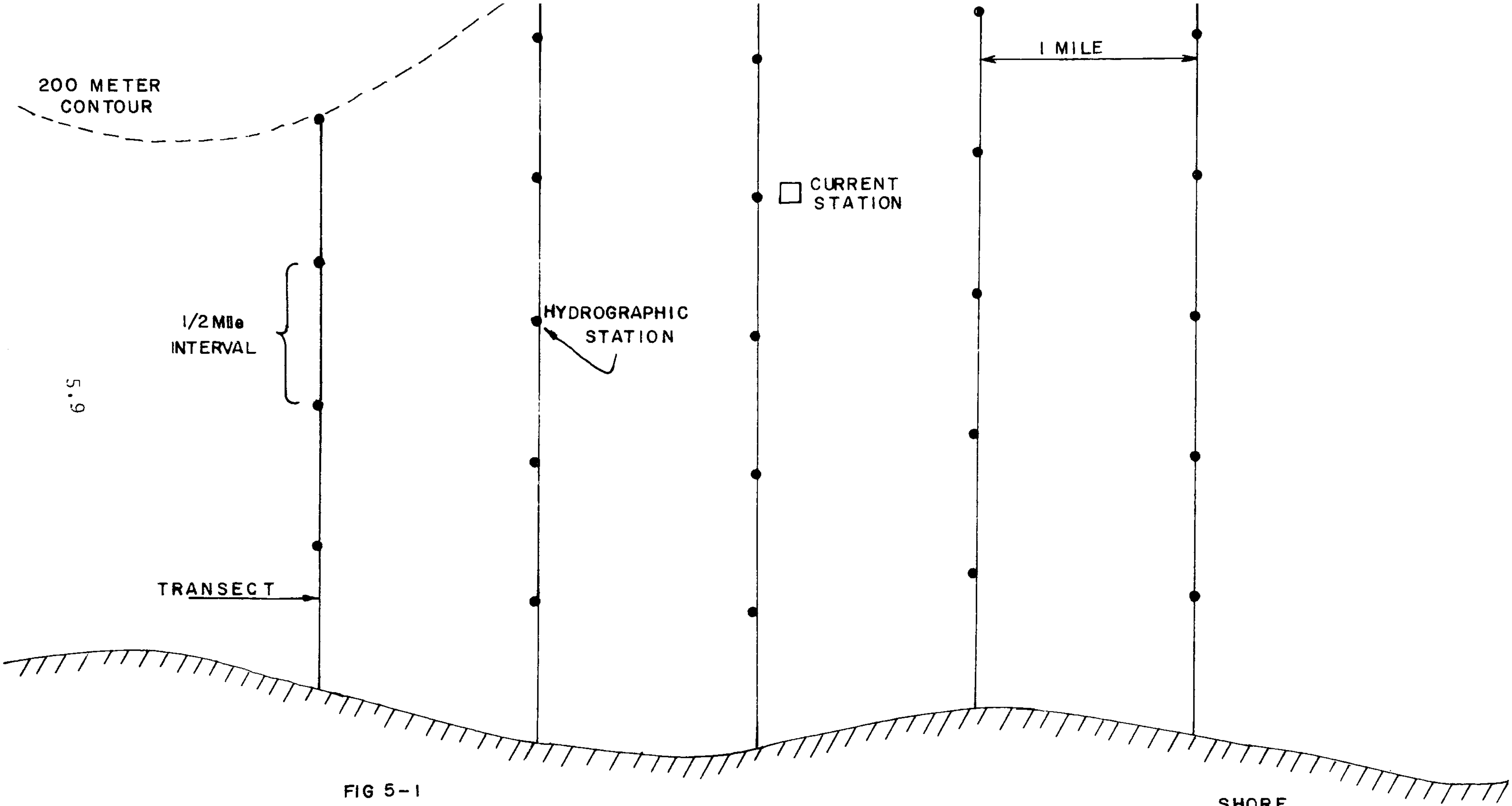


FIG 5-1
SCHEMATIC PRESENTATION OF
SAMPLING DESIGN

SECTION 6

CHARACTERIZATION OF THE NEARSHORE PHYSICAL OCEANOGRAPHIC FEATURES AT THE ELEVEN STUDY AREAS

SECTION 6

CHARACTERIZATION OF THE NEARSHORE PHYSICAL OCEANOGRAPHIC FEATURES AT THE ELEVEN STUDY AREAS

INTRODUCTION

The ocean current, water termperature and salinity (density), water quality, and special coliform organism disappearance rate data are presented and considered in this section of the report. These considerations are presented by study area and the data bases are defined in the stated order. The study areas are considered in the following sequence:

- San Juan
- Carolina
- Humacao
- Yabucoa
- Guayama
- Ponce
- Guayanilla
- Mayaguez
- Aguadilla
- Arecibo
- Barceloneta

San Juan Site

Description of Study Area

The San Juan Metropolitan Area is composed of the six municipalities of San Juan, Bayamón, Cataño, Guaynabo, Trujillo Alto and Carolina. The Metropolitan Area is located on the North Coast of Puerto Rico and surrounds the city of San Juan. San Juan, capital of the Island of the Commonwealth of Puerto Rico, is located at 18° 28'N latitude and 66°07'W longitude. The mountainous terrain to the south of the metropolitan area is steeply sloped. To the north the land falls away to become a flat coastal plain. Within the plain there are numerous bays, lakes, and mangrove swamps (1). The area is drained by Río Bayamón, Río Piedras and Río Grande de Loíza. Of these, Río Bayamón and Río Piedras discharge into San Juan Bay.

The San Juan Metropolitan Sanitary District contains 115 square miles of which approximately 80 square miles are served presently by sewage facilities (1). Collection systems bring sewage to the main Puerto Nuevo treatment plant and 13 smaller treatment plants. The Puerto Nuevo plant provides primary treatment for an average flow of 46 MGD for 1971, which is its maximum capacity. Plans for expansion of the plant to 60 MGD are in progress. Plant effluent is discharged into San Juan Bay.

Hydrodynamic Data

Current data in the vicinity of San Juan Bay was not available prior to this study. Tidal Current Tables (2, 3) indicate that currents for Bahía de San Juan are too weak and variable to be predicted. Turbid water plumes provide an effective tracer on the surface current flow (4). The path of the turbid waters reaching Bahía de San Juan shows a complex pattern on the surface circulation. The plume shows a prevailing westward flow. However, on occasion the plume veers to the east and a tongue of turbid water can be observed reaching the hotel sector of El Condado.

The currents off San Juan were studied during the three cruises. The station locations for each cruise are given in Figure SJ-1.

An Ekman-Merz current meter was used during Cruise 1. Results are given in Figure SJ-2. Winds from the ENE prevailed. A shear in the water column was evident during the morning hours, and a shift towards the east occurred around the time of high tide at 1132, as can be seen in Figure SJ-2.

Drogue tracking was used during Cruise 2. Results are given in Figure SJ-3. On this occasion a strong westward component was found in surface waters and a weaker shoreward flow, with an eastward or westward component, was found in deeper layers.

A Hydro Products Model 502 in-situ recording current meter was anchored during Cruise 3 about 600 yards off Isla de Cabras. The water depth was 13 meters, and the depth of the sensor was ten meters. This was the first current measurement carried out with the recently acquired recording meters. One meter was anchored, with the intention of retrieving it the next day. However, a winter storm developed shortly after the meter was released and, as a consequence, the meter was left in place for a period of five days.

The data obtained from the meter represents a current pattern under different meteorological conditions from those of the first cruise since strong winds and swells prevailed from the second day the meter was set (see Appendix C). Higher velocities were recorded during the stormy weather period (velocities greater than 0.6 knot). This, however, does not necessarily represent the real speed values as the high seas might have some wave-induced motion at the depth of the sensor (10m), creating a higher speed resultant. Sharp current direction shifts to E or SE are evident in Figure SJ-4. These fall at periods close to high tide, and prevail up to the low tide periods when the current veers to W or SW again. Figure SJ-5 shows net flow current vectors with lengths proportional to the amount of flow in each of eight direction sectors corresponding to the cardinal and inter-cardinal points. The flow vectors shown for each octant, together with their net resultant, were computed from data obtained during 85.3 hours of continuous observation. As can be seen from the figure, current flow was in the direction of the SW octant for almost 43 percent of the total time of observation, with a relatively high average speed of 0.6 knot. The average speeds given in this figure refer specifically to the corresponding directions, and the average speed shown for the resultant is the net average in this direction. The method followed for this analysis is described more fully in Appendix B.

The current data acquired at San Juan during the three cruises indicated a fairly variable pattern in which there seems to be some tidal influence. In all the current observations at San Juan, no northward currents were seen, while strong onshore flows often prevailed. Tabular data of the current studies is given in Appendix C.

Hydrographic Data

Hydrographic station locations are shown in Figure SJ-6. Since the density structure as a function of salinity and temperature is the parameter used in the engineering design aspect, only this parameter will be discussed here. The data on temperature and salinity is given in Appendix C.

The surface density (sigma-t) pattern for Cruises 1 and 2 is shown in Figures SJ-7 and SJ-8. Isopycnal lines were not connected for Cruise 2 (Figure SJ-7) since the data obtained was from two separate dates; instead surface values for each station were recorded. In both cases, decreasing density values were observed as the bay was approached. The gradient is steeper in the east-west direction, suggesting a generally westward flow of the less dense bay water. The surface sigma-t values ranged from 22.08 sigma-t units at Station 16 to 24.15 at Station 2 during Cruise 1, and from 22.89 at Station 9 to 23.11 at Station 8. The average surface sigma-t value for Cruise 1 (in April) was 23.21, and for Cruise 2 (in August) was 22.98. This suggests a seasonal variation. A more reliable basis for determining seasonal variations was obtained from the average value at 10m depth, where local short-term atmospheric conditions show no immediate effect. The values obtained were 24.04 sigma-t units for Cruise 1 and 23.01 for Cruise 2.

Density profiles for Cruises 1 and 2 are shown in Figure SJ-9. These represent the central section for each cruise. A strong density gradient was found during both cruises between surface and 160m. Cruise 1 showed a difference of 2.83 sigma-t units and Cruise 2, 2.51 sigma-t units. However, since the gradient is steeper in the upper levels the difference between surface and 60 meters was about 2 sigma-t units. This is the section which cuts directly through the plume of warm, less saline water emerging from San Juan Bay. The area in this central section has the greatest density contrast between the surface and the maximum practical depth for an outfall (see Appendix C). Thus, with suitable mixing of the waste material, this is the area where waste-water discharge is least likely to reappear at the surface.

Water Quality

Water quality data for the San Juan site for Cruises 1 and 2 are given in Appendix C. Secchi disc readings can be seen to follow the shoreline, with no major tongues of turbidity during either cruise (Figures SJ-10 and SJ-11). The Silica and phosphate levels were low on both cruises. Silica values ranged from 0.02 to .50 mg/l (1.00 mg at/l to 8.00 mg at/l). Phosphate levels ranged from 0.000 to 0.12 mg/l (1.26 mg at/l). North Atlantic values for Silicate as given by Rhodes (5) range from 0.5 to 35 mg at/l, and nitrate from 0.25 to 1.0 mg at/l in equatorial Atlantic oceanic waters.

On the second cruise DO, BOD and coliform index were also obtained. DO values ranged from 3.92 to 6.65 mg/l, and Coliform level from 0.0 to 400 MF/1001. BOD values ranged from 0.31 to 0.50 mg/l.

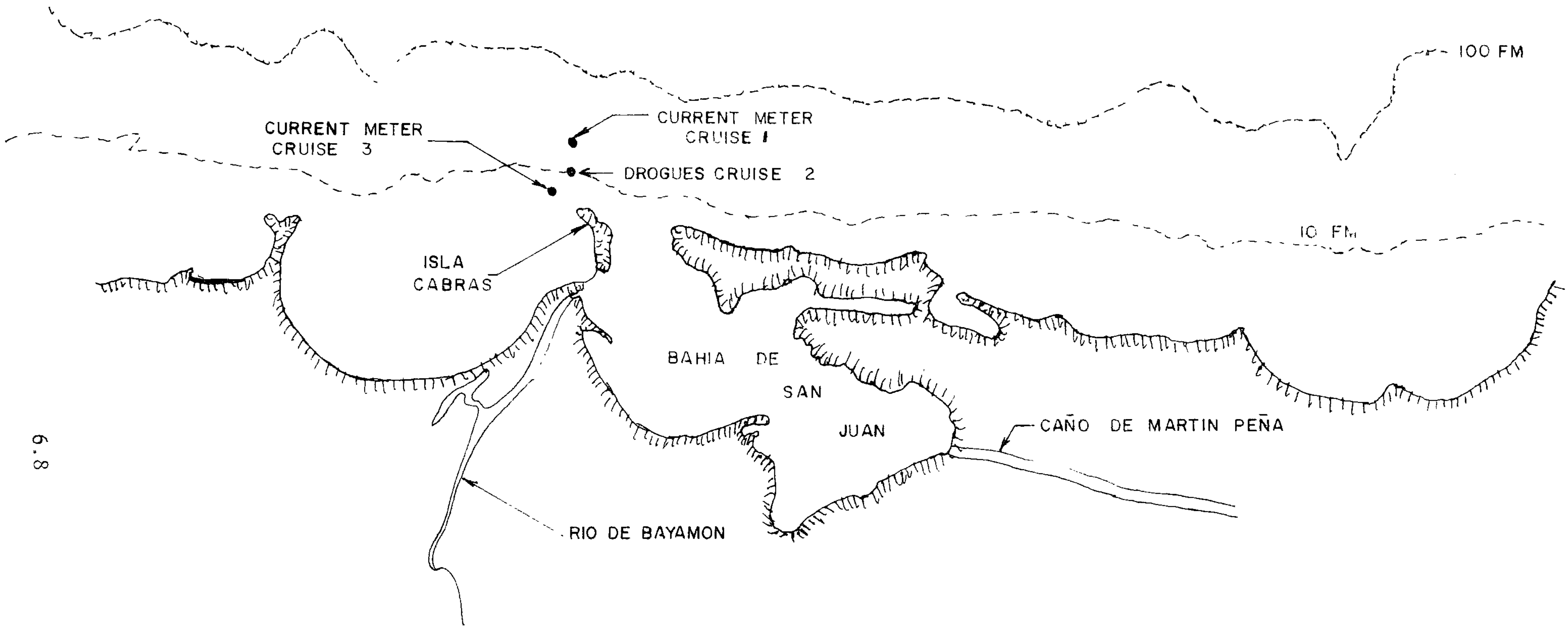
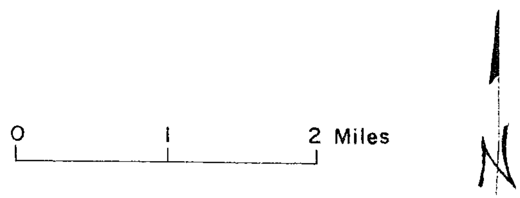


FIG SJ-I
CURRENT STATION LOCATIONS
SAN JUAN SITE



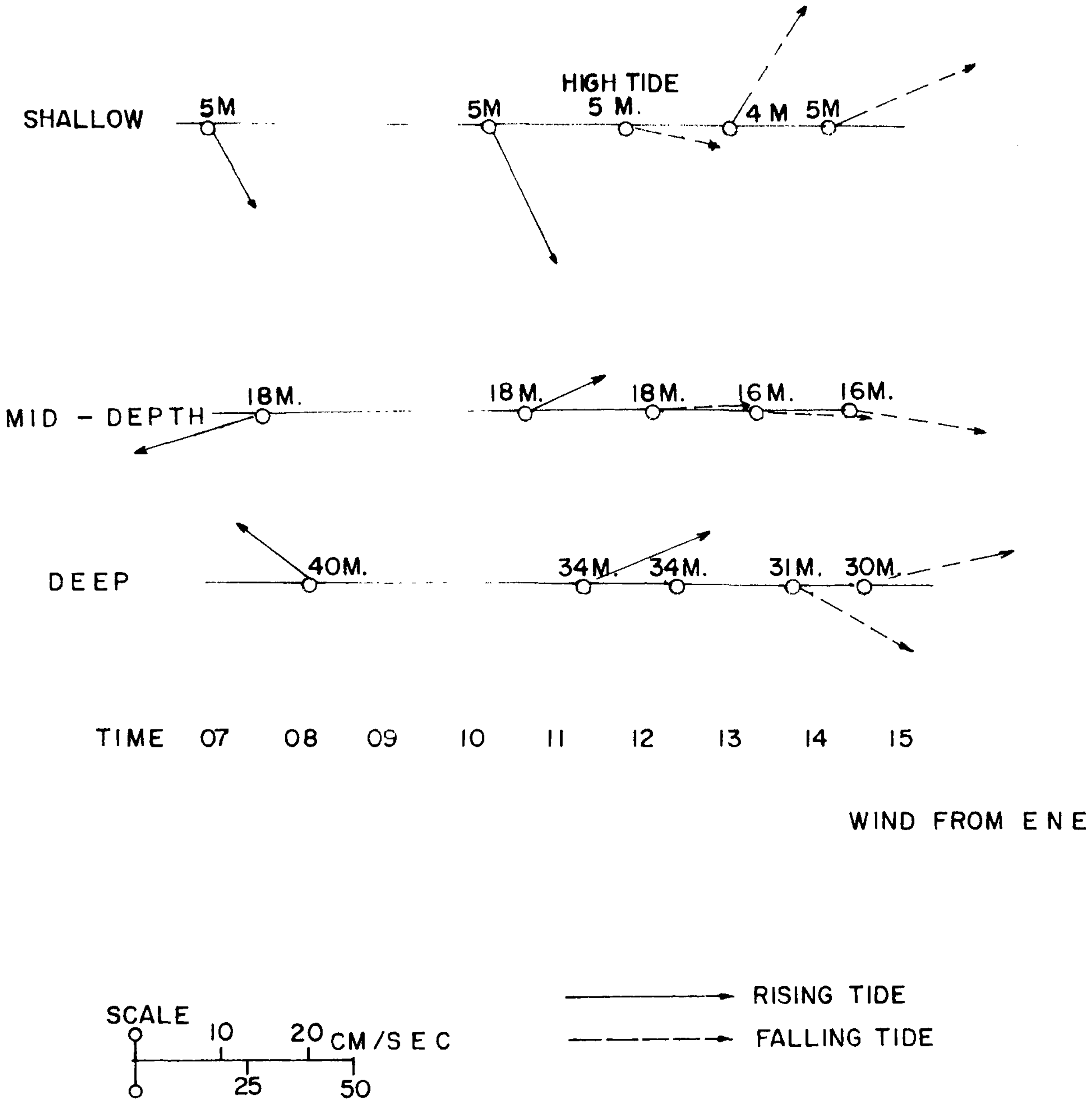


FIG SJ-2
CURRENT VECTORS
SAN JUAN SITE
CRUISE I APRIL 20, 1971
WATER DEPTH 42 M
HIGH TIDE 1142

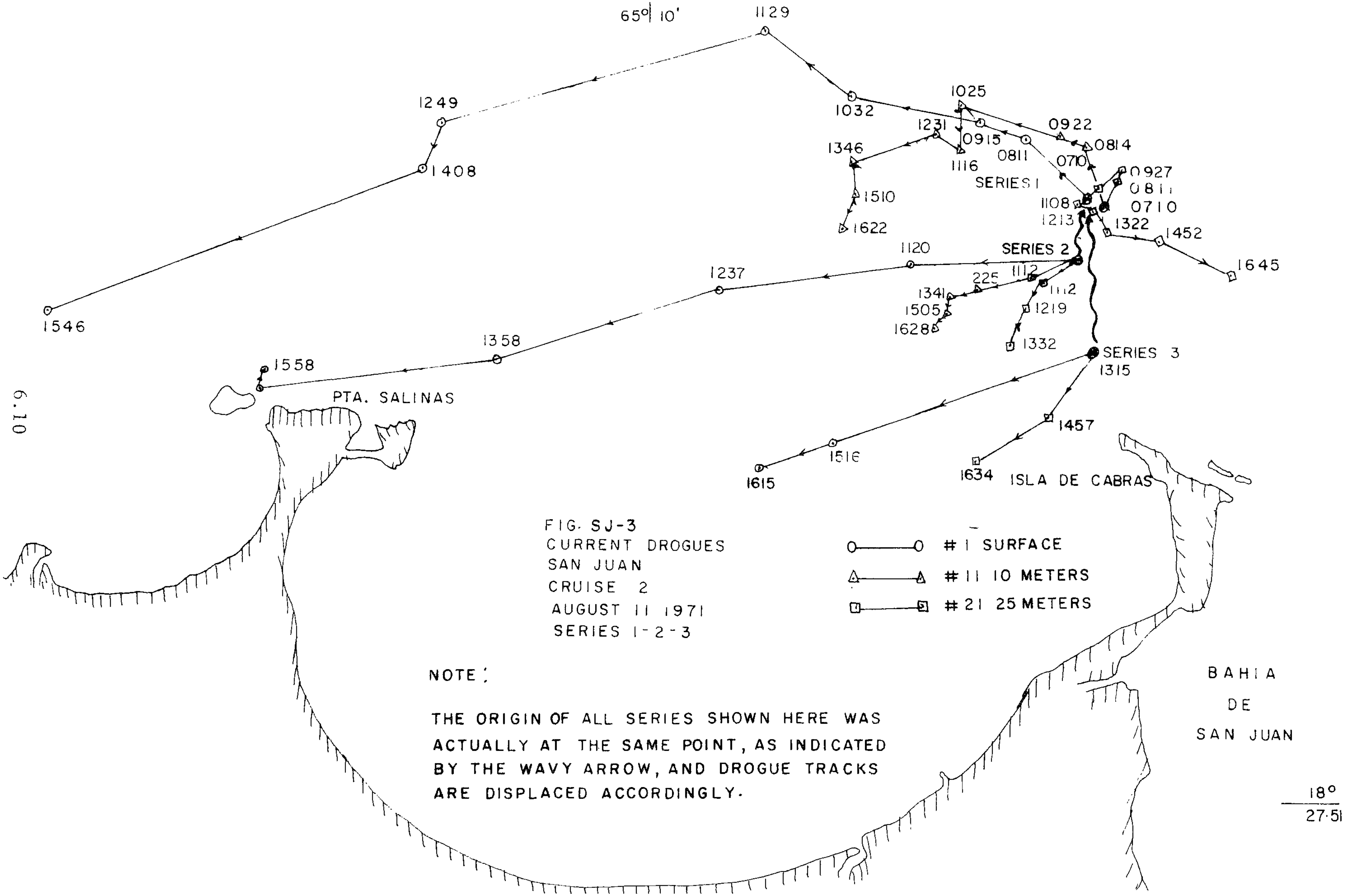


FIG. SJ-3
CURRENT DROGUES
SAN JUAN
CRUISE 2
AUGUST 11 1971
SERIES 1-2-3

NOTE:

THE ORIGIN OF ALL SERIES SHOWN HERE WAS ACTUALLY AT THE SAME POINT, AS INDICATED BY THE WAVY ARROW, AND DROGUE TRACKS ARE DISPLACED ACCORDINGLY.

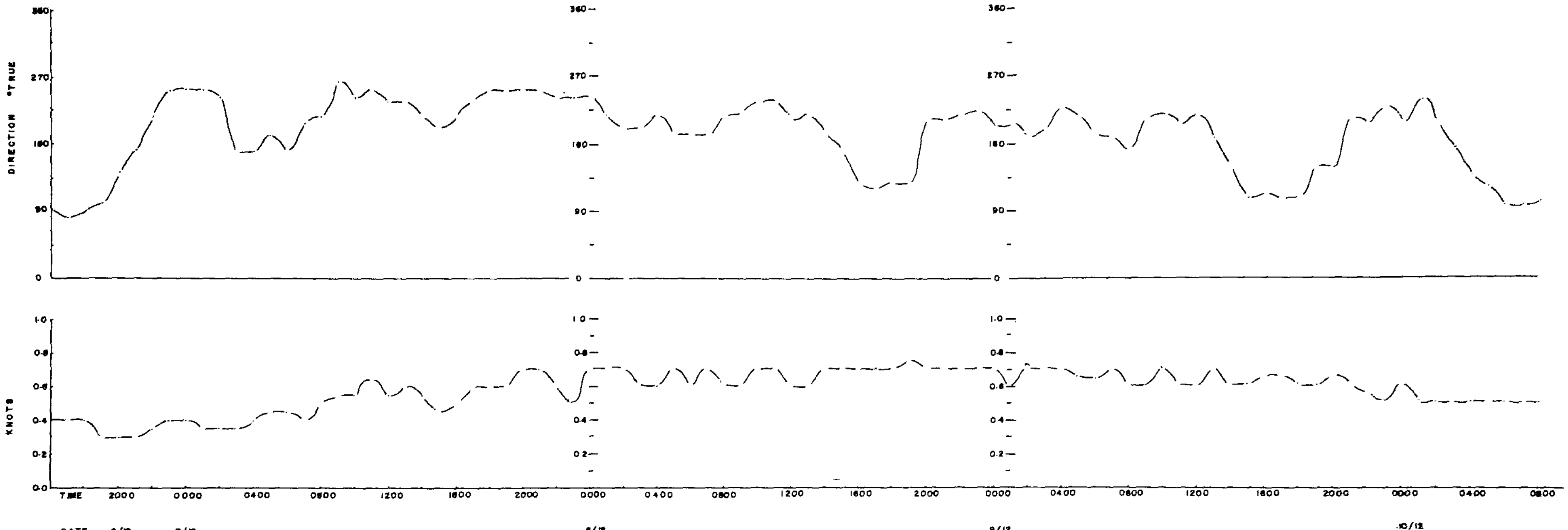


FIG SJ-4
CURRENT VELOCITY
CRUISE 3 6-10 DECEMBER 1971
SAN JUAN

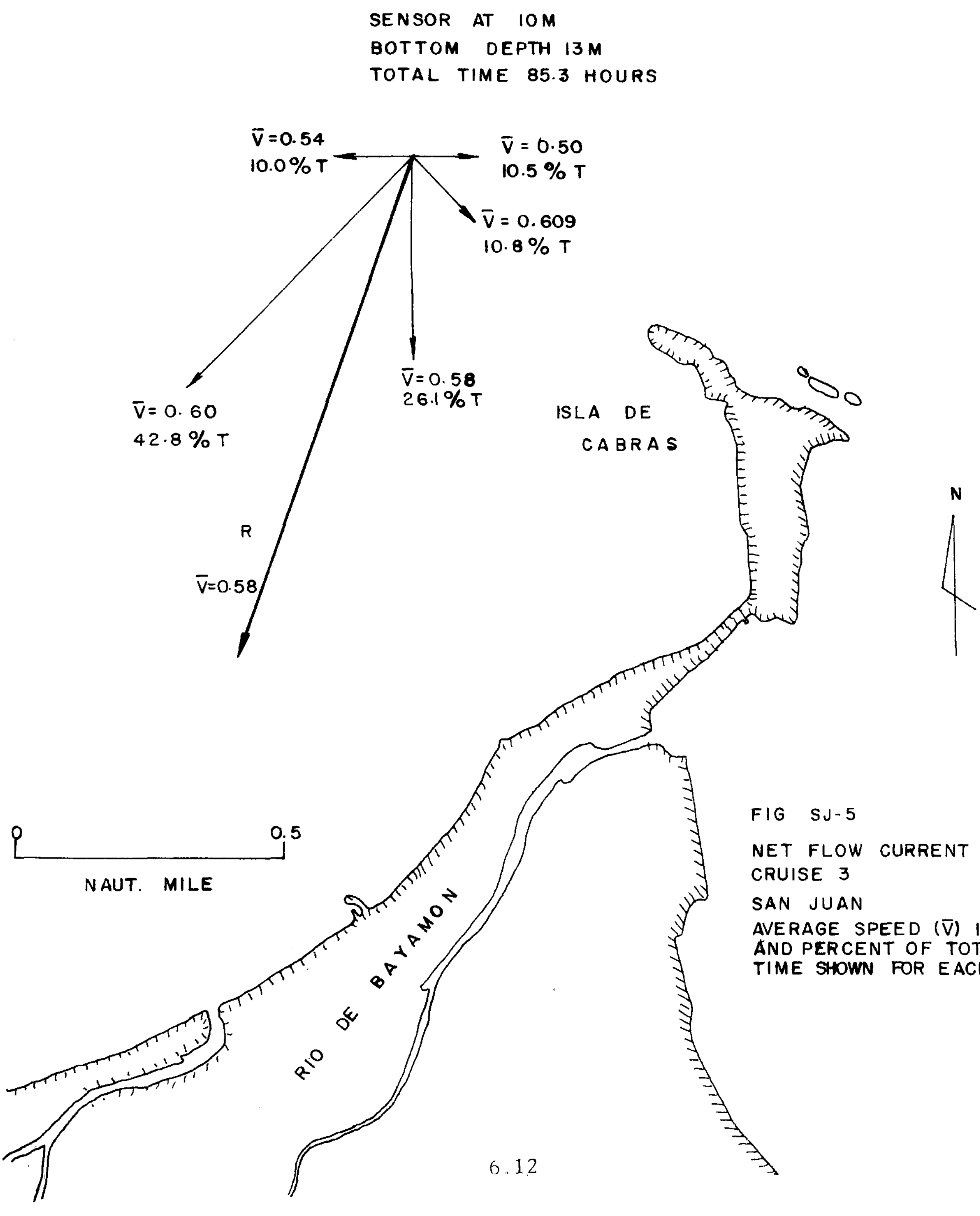


FIG SJ-5

NET FLOW CURRENT VECTORS
CRUISE 3
SAN JUAN
AVERAGE SPEED (V̄) IN Kn
AND PERCENT OF TOTAL
TIME SHOWN FOR EACH OCTANT

Figure SJ-6a
HYDROGRAPHIC STATION LOCATIONS
SAN JUAN
CRUISE 1   14-20 APRIL 1971

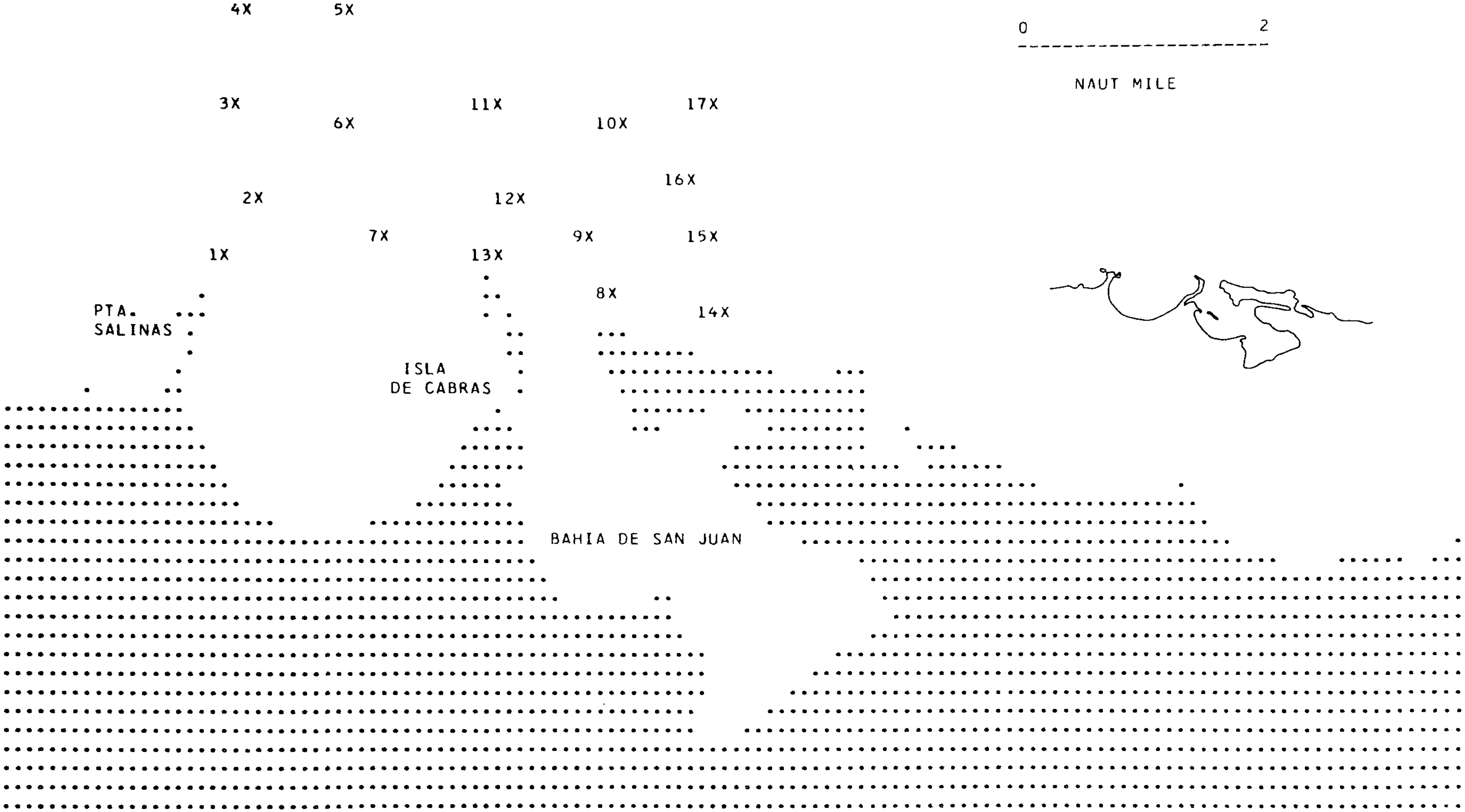


Figure SJ-6b
HYDROGRAPHIC STATION LOCATIONS
SAN JUAN
CRUISE 2 12-23 AUGUST 1971

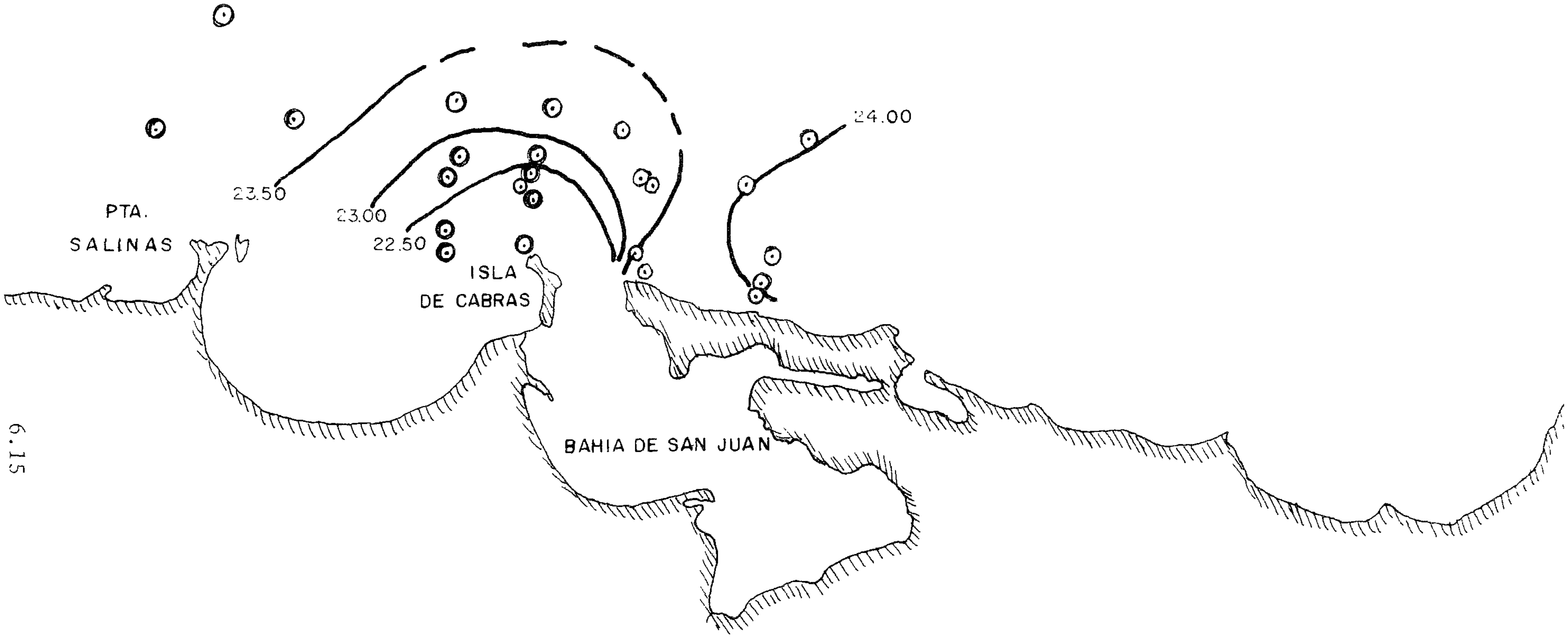


FIG SJ-7
SURFACE DENSITY (σ_t)
AT SAN JUAN SITE
CRUISE 1 14-22 APRIL 1971

N

0 1 2 Miles
SCALE

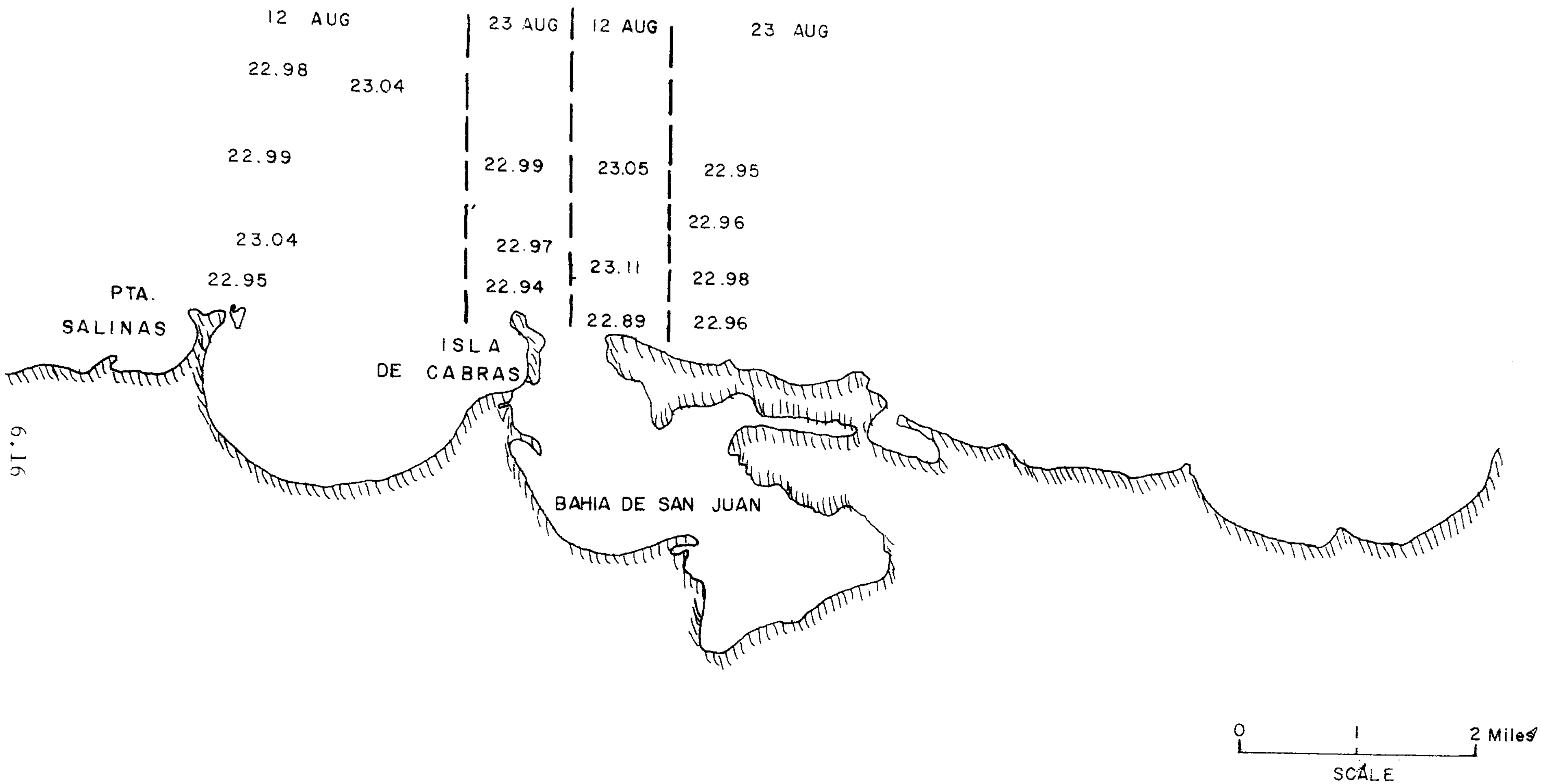


FIG SJ-8
SURFACE DENSITY σ_t
AT SAN JUAN SITE
CRUISE 2 12-23 AUGUST 1971

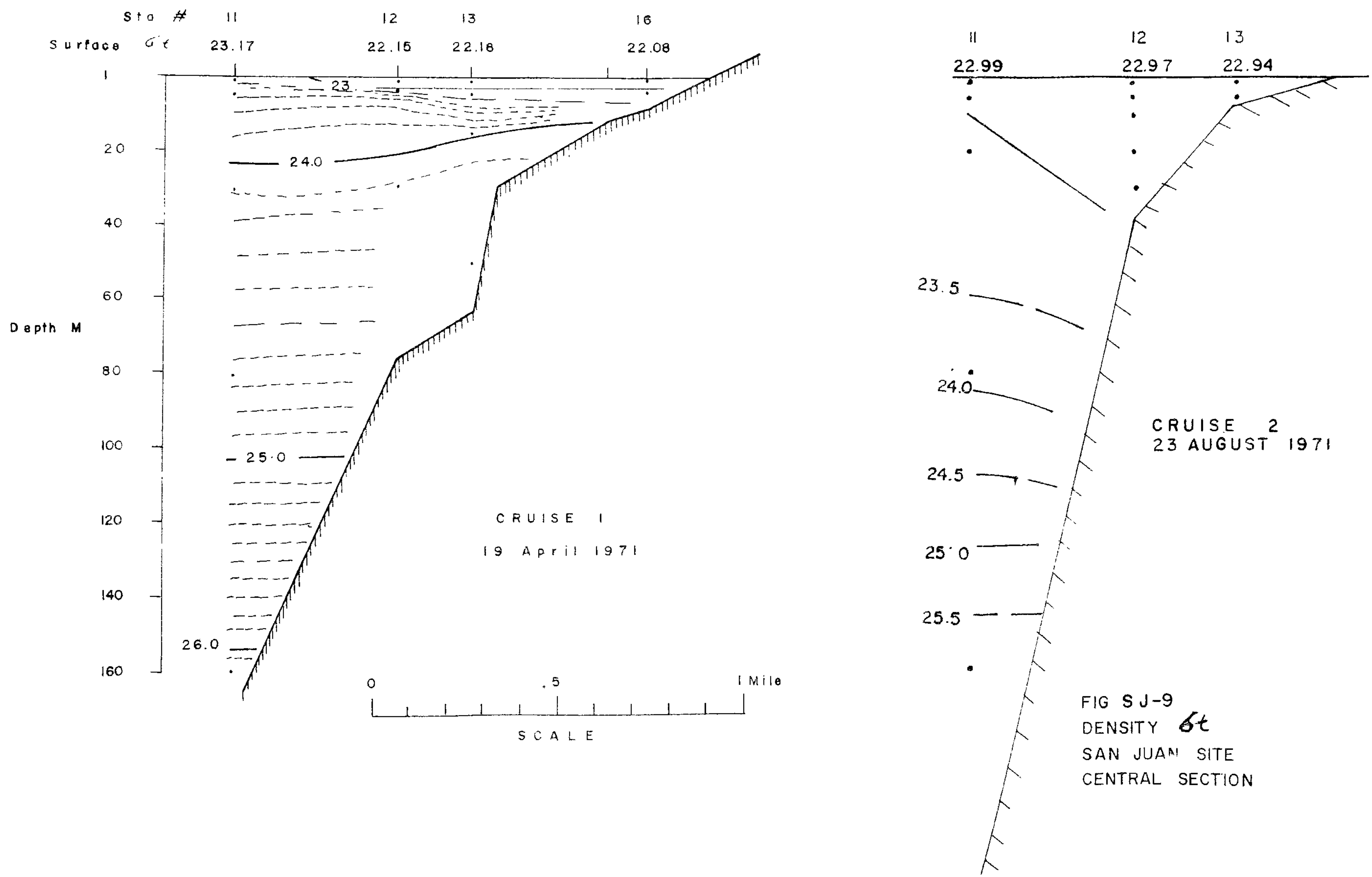
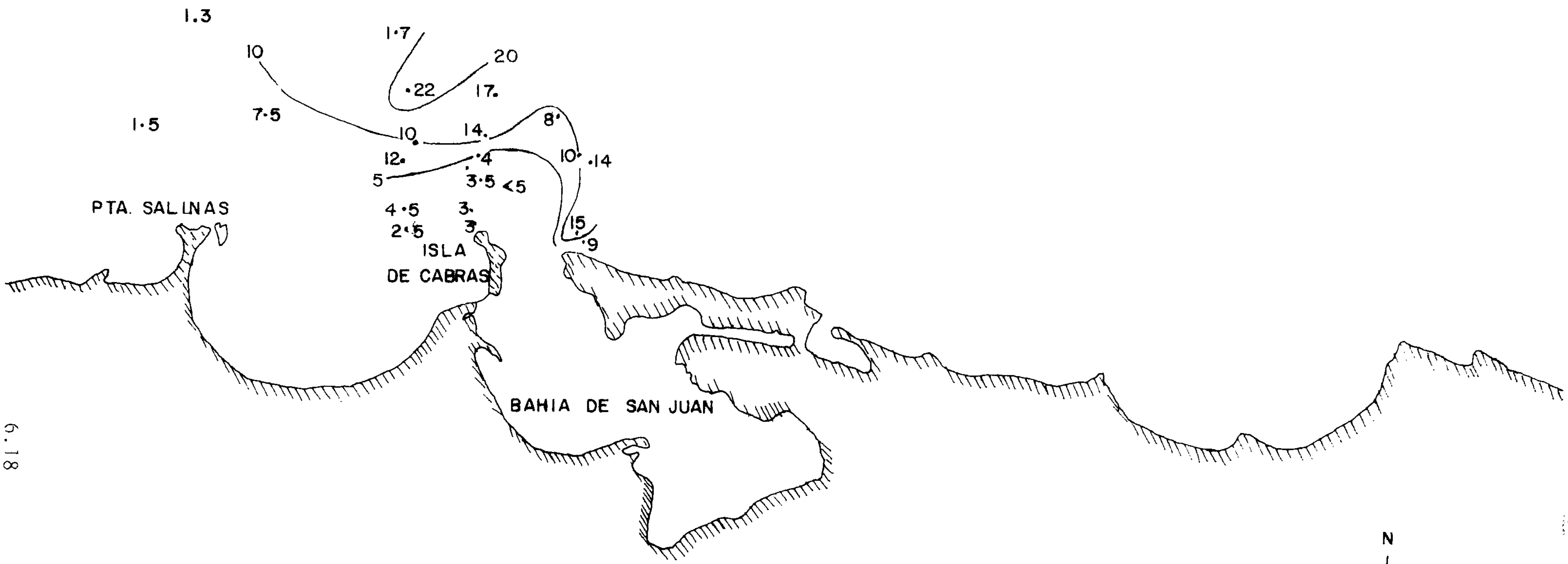


FIG SJ-9
DENSITY σt
SAN JUAN SITE
CENTRAL SECTION



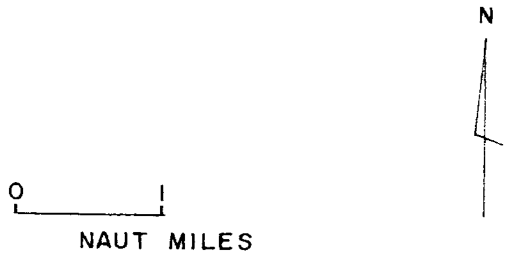


FIG SJ–10
WATER TRANSPARENCY
SAN JUAN SITE
SECCHI DISC READINGS IN METERS
CRUISE I 14, 22 JUNE 1971

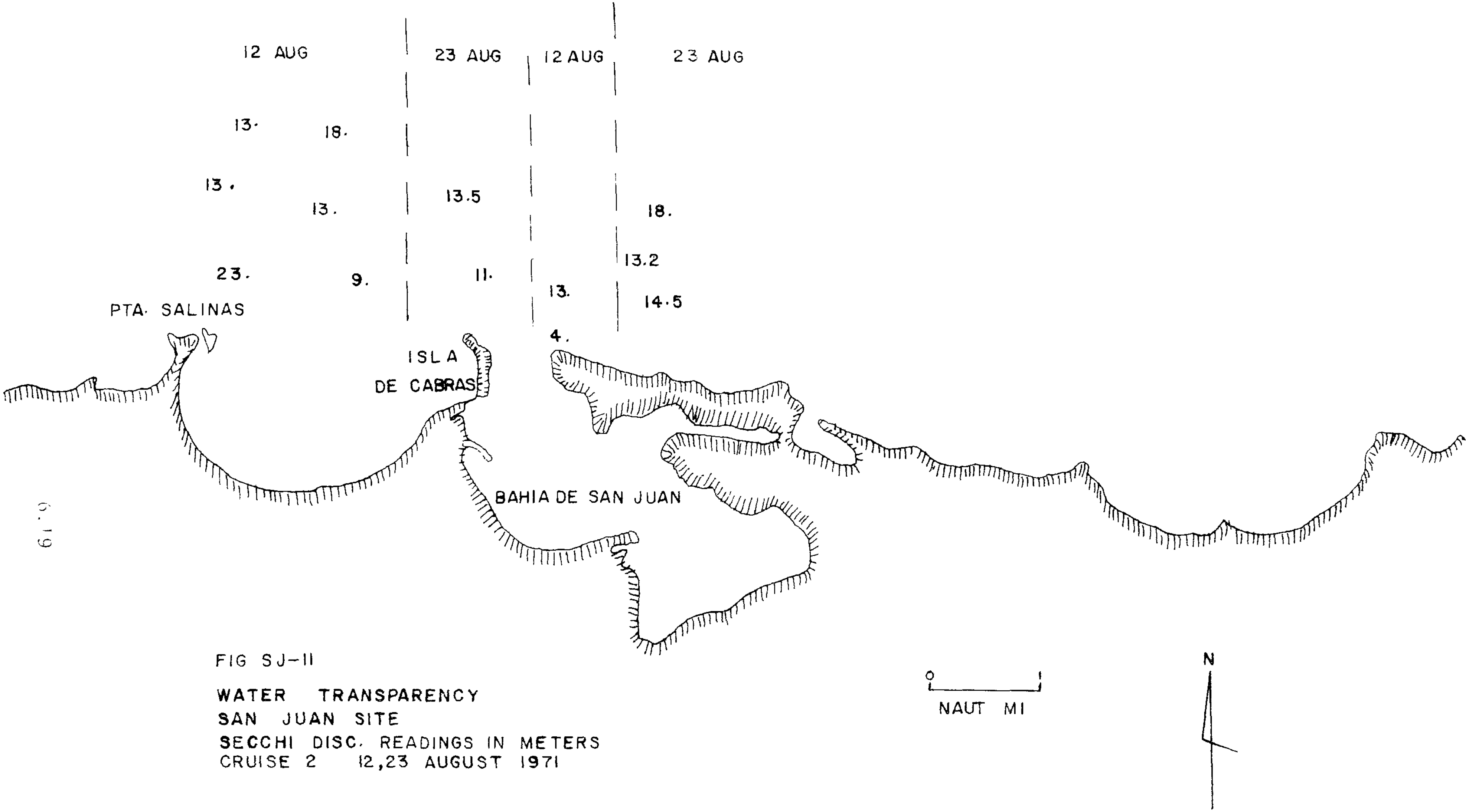


FIG SJ-11

WATER TRANSPARENCY
SAN JUAN SITE
SECCHI DISC. READINGS IN METERS
CRUISE 2 12,23 AUGUST 1971

CAROLINA

Description of Study Area

Carolina is located on the north coast of Puerto Rico near the eastern end of the Island, approximately 15 miles east of San Juan. The Río Grande de Loíza discharges into the Atlantic Ocean about 5 miles east of Carolina after the following major tributaries join it: Río Turabo, Río Caguitas, Río Bairoa, Río Gurabo, Río Cañas and Río Canóvanas. The Loíza watershed comprises an area of 207 square miles (1). A considerable area of this watershed is marshland and a number of drainage canals flow into the river bed. The larger canals are the Gallardo, San Irido, and Narberto. The water of the Río Loíza in this three-mile-wide coastal band of marshlands is deeply colored due to "humic acid", a product of decaying vegetable matter.

Three towns are located within the Río Loíza watershed: Trujillo Alto, Carolina, and Canovanas. The waters from this river and its tributaries converge in Lake Carraízo, just south of Trujillo Alto. On its course to the Carraízo Dam, the river receives wastes from a sugar mill at Juncos, five domestic sewage treatment plants, two slaughterhouses, and a hide tannery (1). North of the site, four rock quarries and gravel pits situated close to or on the river bank contribute suspended solids and turbidity to the water (2).

Hydrodynamic Data

Current measurements were obtained in three surveys for Carolina. The station locations for each survey are shown in Figure C-1. The results of the first cruise are given in Figure C-2. One of the interesting characteristics of Carolina currents as observed from an analysis of the data is the prevailing easterly flow, which contrasts with the general belief in the existence of a westerly flow pattern along the north and south coasts of Puerto Rico. A prevailing easterly flow was observed during Cruise 1, with a shift in direction for surface water during time of high tide. Average speed was 0.6 knot for the surface water, 0.7 knot for mid-depth, and 0.7 knot for deep water (see Appendix D).

Figure C-3 shows the results of drifting drogues for Cruise 2. An eastward path prevailed throughout the entire period of observation. Surface speed values ranged from about 0.2 to over 0.8 knot, with an average value of 0.45 knot. Mid-depth values ranged from 0.5 to over 0.8 knot, with an average speed of 0.73 knot. The average speed in deep water was 0.58 knot. The significant difference between surface average speed and speed of deeper waters may reflect the wind influence on the surface, as wind was blowing from the east with speeds ranging from 10 to 19 knots (see Appendix D).

The limitations of the first two cruises relate to the short period of observation where less than a tidal cycle is covered each time and no relationship with lunar cycle could be established. In the third cruise in-situ current meters were used as described in Section 5. The original intention was to set the meters for a 48-hour observation period, but due to a combination of factors, namely a failure of the corrodable links and rough weather, the units were not retrievable for a week. Thus, fortuitously, currents at Loíza were recorded continuously for about 140 hours. These results are tabulated in Appendix D. A graphical representation of this data is given in Figures C-4 to C-6.

The first half of Figure C-4 shows cyclic shifts in the current direction with a velocity maximum at every other shift to the east. The pattern slowly fades at the end of the graph. Since the direction cycle is semi-diurnal and the observation period of the first half corresponds to spring tides (full moon) it suggests a tidal influence on the speed and direction of the currents regulated as well by the monthly lunar periodicity (spring-neap tides). However, longer periods of observation will be required as tides seem to be only one of many factors affecting the currents of this area.

The speed maxima corresponding to the eastward flow has a strong influence in the analysis shown in Figures C-5 and C-6 (net flow current vectors). A detailed description of the computation of flow values for the octants N, NE, E, SE, S, SW, W, NW is given in Appendix B. The vectors represent sums of products of speed and duration of flow in each of these octants. Figure C-5 corresponds to the inner shallow and outer shallow meters. The east and west vectors were the longest in both cases, thus they tend to cancel each other, giving a SW and just west of south resultant at the outer and inner meters, respectively. It should be noted that throughout the entire period of observation, parallel-to-shore or on-shore currents prevailed with little, if any, off-shore component.

The results in Figure C-6 show an ESE resultant with an average speed of 0.40 knot. It is possible that the general trend of flow for the entire water mass for this period was in this direction, but that the wind had an effect in reducing or deflecting the eastward component, giving a southward resultant for surface waters. Wind data records of the weather bureau at the Isla Verde Airport showed a prevailing E to ENE direction for the period of observation, with speeds of up to 20 knots recorded on December 16. Winds from the S-SE prevailed at night, but the speed was low (five knots or less).

One can conclude from the results of the three cruises that the current patterns at Carolina are very complex, and that a strong tidal influence in both speed and direction exists. The spring tides have a stronger influence than neap tides in affecting speed and direction. Based on an analysis of the data, it appears that an easterly flow occurs on the falling tide and a flow to the west during the rising tide for the majority of the observations (see Figure C-4). These results seem to be contrary to those presented in the Barceloneta report (4) for another north coast area. The observation periods for current data at Barceloneta did not exceed a period of 25 hours. Wind has an apparent influence in reducing and/or deflecting easterly surface currents up to a maximum depth of ten meters. The importance of prolonged current observations, covering periods of full lunar cycles, becomes evident from Cruise 3 data, where the strong influence of tidal effects is apparent.

Hydrographic Data

Hydrographic station locations are shown in Figure C-7. The tabulated data and graphs of temperature and salinity values are given in Appendix D.

Surface density values obtained during Cruise 1 (Figure C-8) show no negative gradient, with the lower values closer to shore which one might well expect in this region which comprises the mouth of Río Grande de Loíza, the largest river on the Island. The values ranged from 23.60 to 23.80

sigma-t units, with an average value of 23.79. Values obtained during the second cruise ranged from 22.00 to 23.05 sigma-t units, with a small but well-defined gradient (Figure C-9). The average value of sigma-t was 22.82. The observed gradient was small when compared to results at San Juan where a change of over two sigma-t units was observed within a shorter distance. The strong prevailing currents in the area may account for this low gradient as the river water may be rapidly dispersed.

Density profiles are given in Figures C-10 and C-11. The important feature to mention from the standpoint of the density is that values between 60 meters (the deepest that Engineering-Science suggests is at all feasible for locating the waste outfall) and the surface varied from 0.40 to 0.80 sigma-t units during the first cruise and from 0.58 to 0.61 during Cruise 2. This is in contrast to a change of 2.0 sigma-t units which were found in the San Juan area. The greater density gradient in the San Juan area was primarily the result of the low density surface water emerging from San Juan Bay. This is evidence for the rapid removal or dispersion by the currents of the low density water from the mouth of Río Grande de Loíza.

Water Quality

One of the most immediately noticeable features of the sites was that on the 23rd of April, the area studied was marked by a great deal of turbidity due obviously to run-off from the Río Grande de Loíza. On the 27th of April, the waters were clear throughout the region. Figure C-12 shows the Secchi disc readings in meters as an index of transparency. On the basis of the values alone, one would be tempted to conclude that there is a central plume of turbid water extending out into clear water. However, this is due entirely to the differences in time. That is, on April 23rd, all the water in the general area was turbid, and on the 27th, all the water was clear. These changes in turbidity appear to be a combination of the amount of rainfall in the watershed and the efficiency of the currents in removing the turbid waters rather than the stirring up of bottom particles by high seas, since the shallow water of this area was characterized by a rocky bottom and coarse sand. Second cruise readings (Figure C-13) showed a plane of turbid water west of the mouth of Rio Loiza.

The nutrient values obtained during both cruises were, as in San Juan, very low. Since values were slightly higher than those of San Juan, ranging from 0.20 to 0.60 mg/l for Cruise 1. Cruise 2 showed even lower values, ranging from 0.04 to 0.18 mg/l. Phosphorous values were so low that they could be considered as traces (see Appendix C). The Coliform levels at two stations off Punta Vacia Talega varied from 40 to 800 mf/100 ml. Dissolved oxygen ranged from 4.93 mg/l to 6.69 mg/l. Tables of water quality data re included in Appendix D.

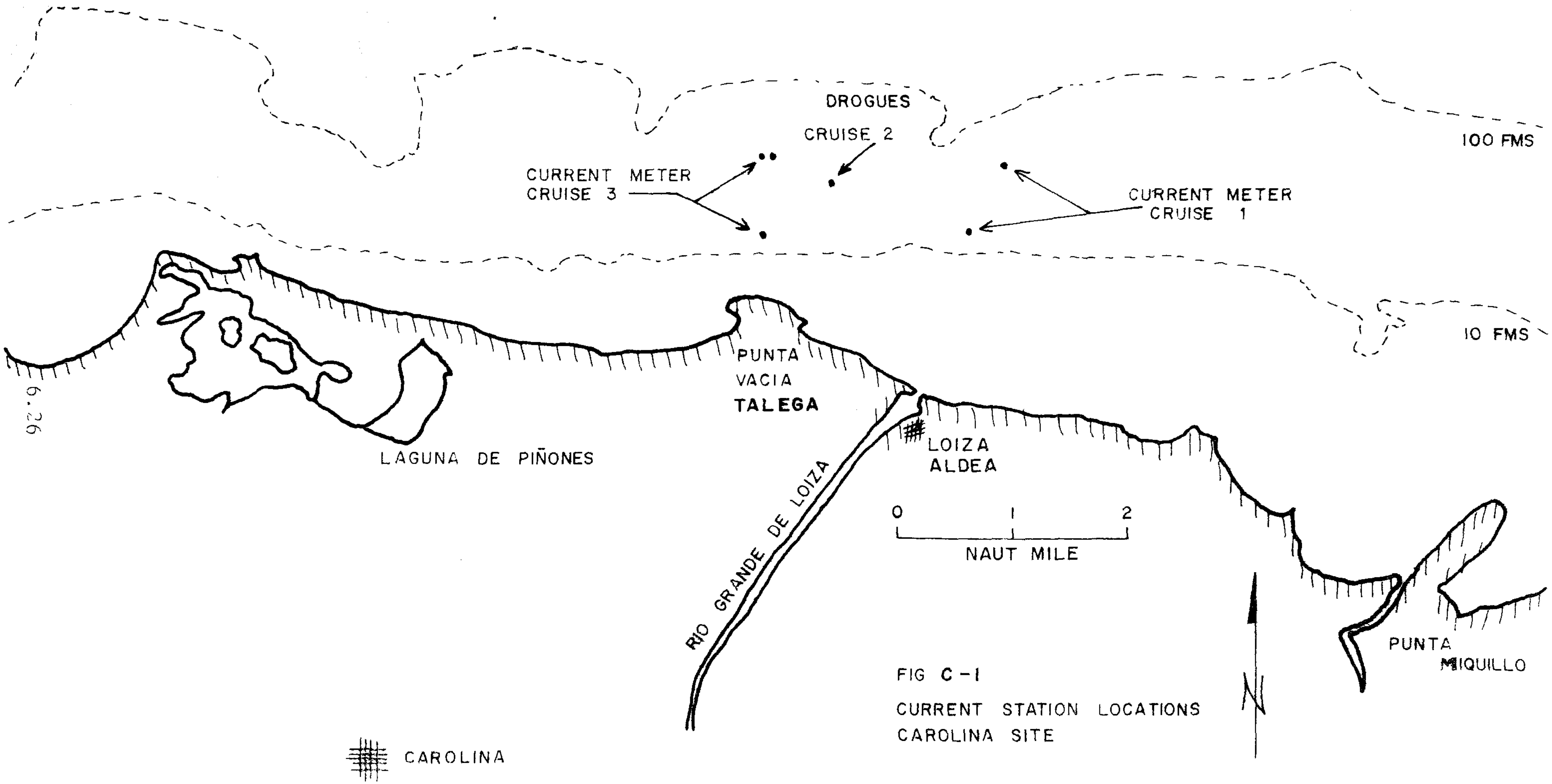


FIG C-1

CURRENT STATION LOCATIONS
CAROLINA SITE

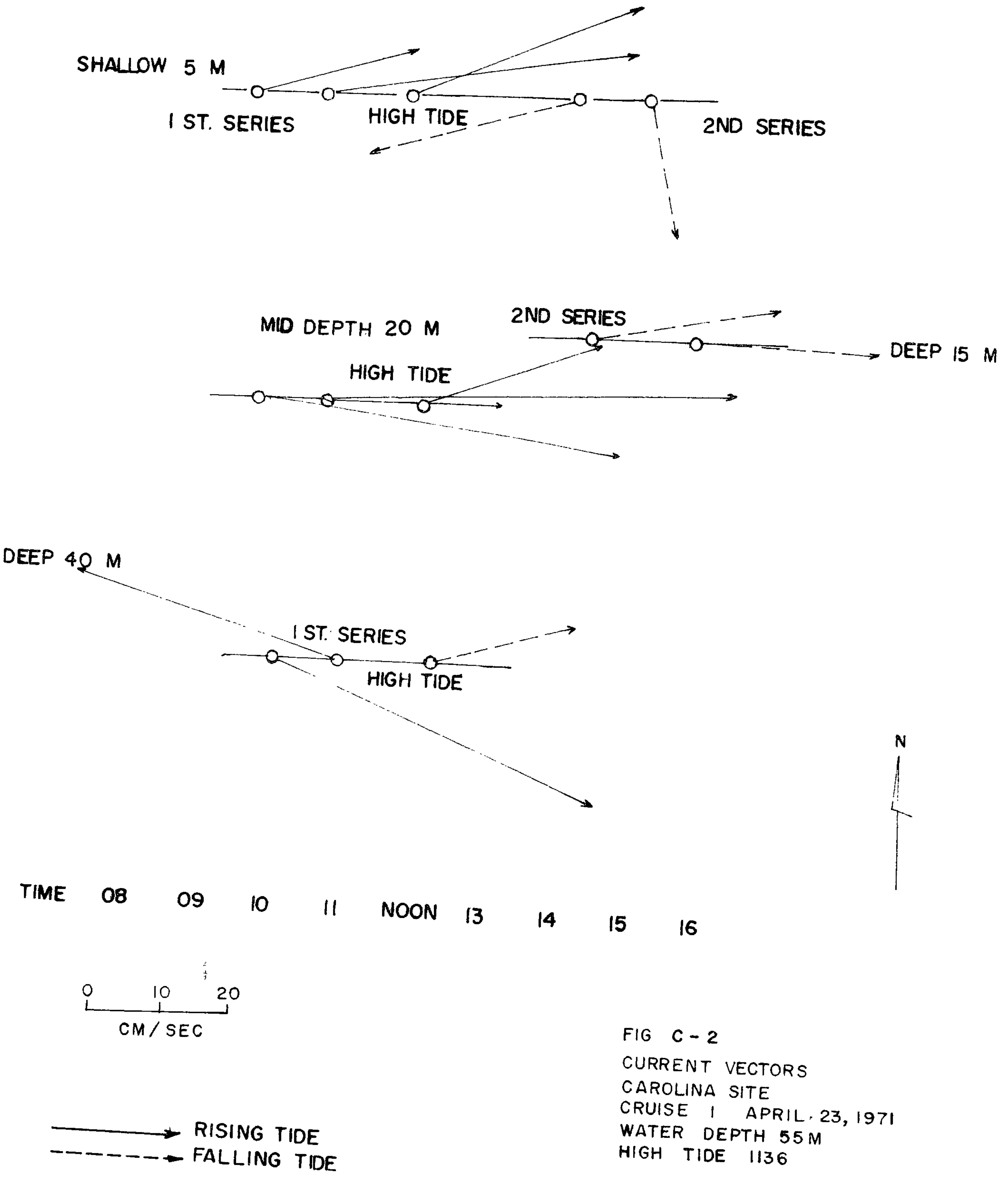


FIG C-2
CURRENT VECTORS
CAROLINA SITE
CRUISE I APRIL 23, 1971
WATER DEPTH 55M
HIGH TIDE 1136

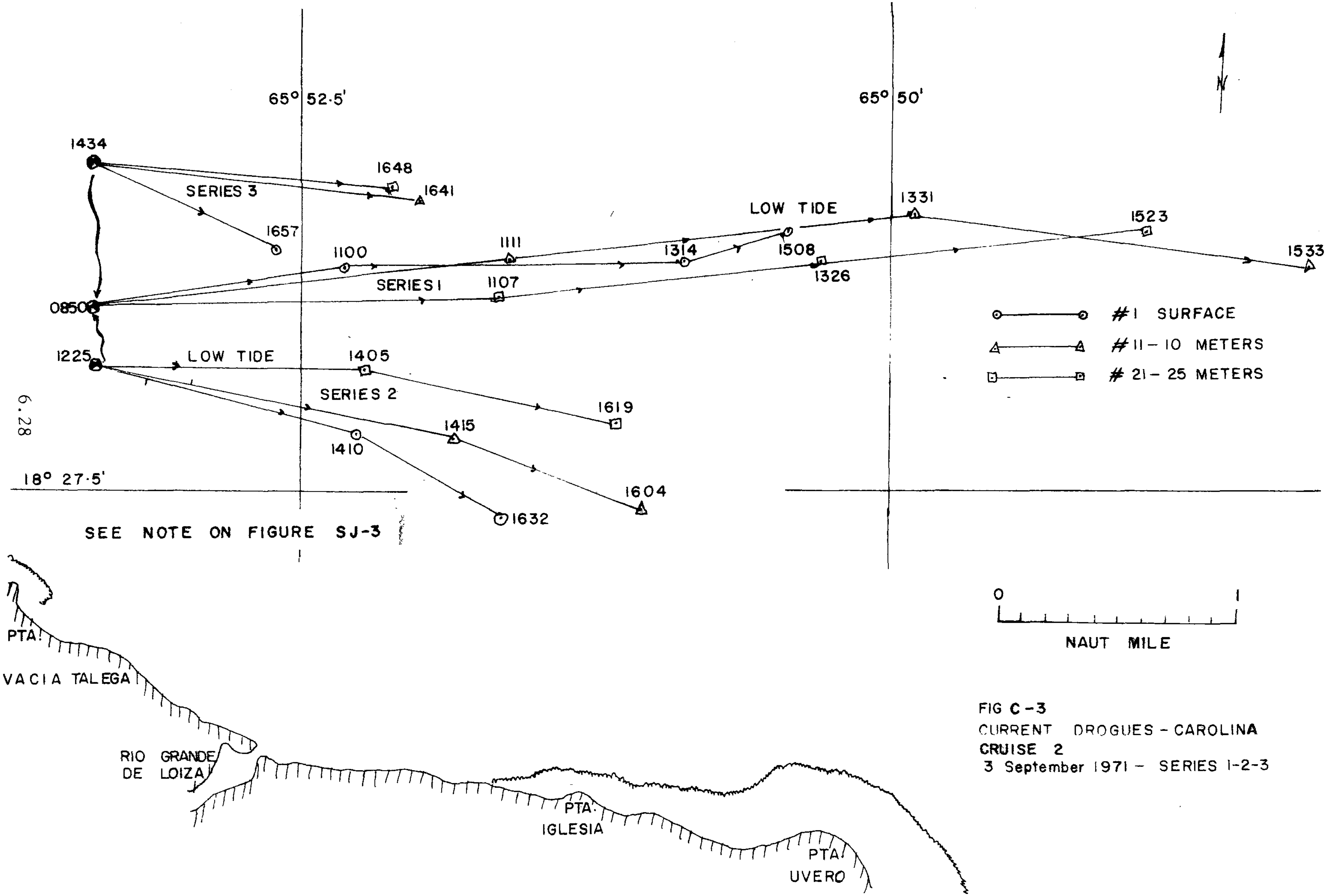


FIG C-3
CURRENT DROGUES - CAROLINA
CRUISE 2
3 September 1971 – SERIES 1-2-3

PAGE NOT

AVAILABLE

DIGITALLY

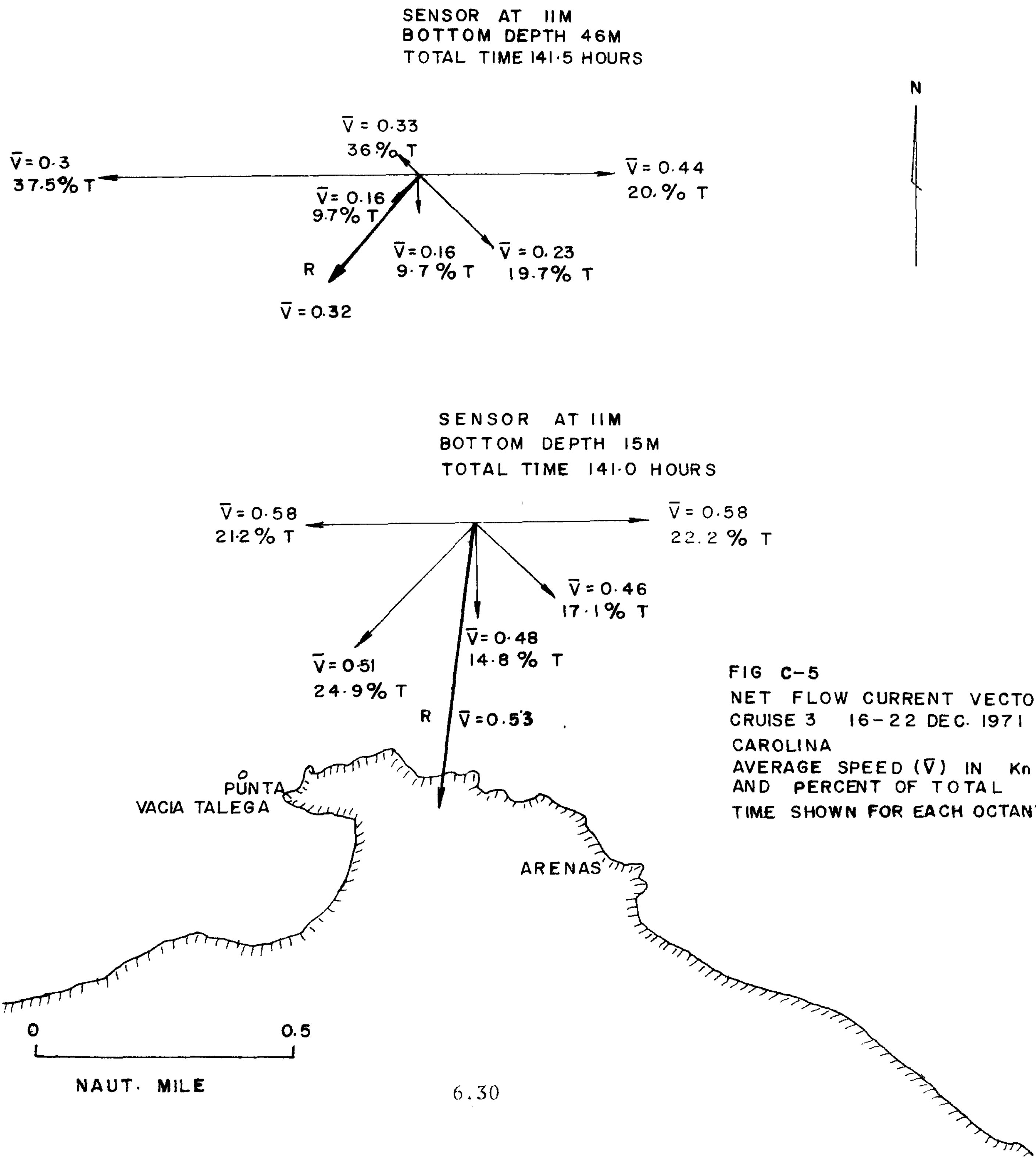


FIG C–5
NET FLOW CURRENT VECTORS
CRUISE 3 16–22 DEC· 1971
CAROLINA
AVERAGE SPEED (V̄) IN Kn
AND PERCENT OF TOTAL
TIME SHOWN FOR EACH OCTANT

SENSOR AT 33M
BOTTOM DEPTH 45M
TOTAL TIME 142.2 HOURS

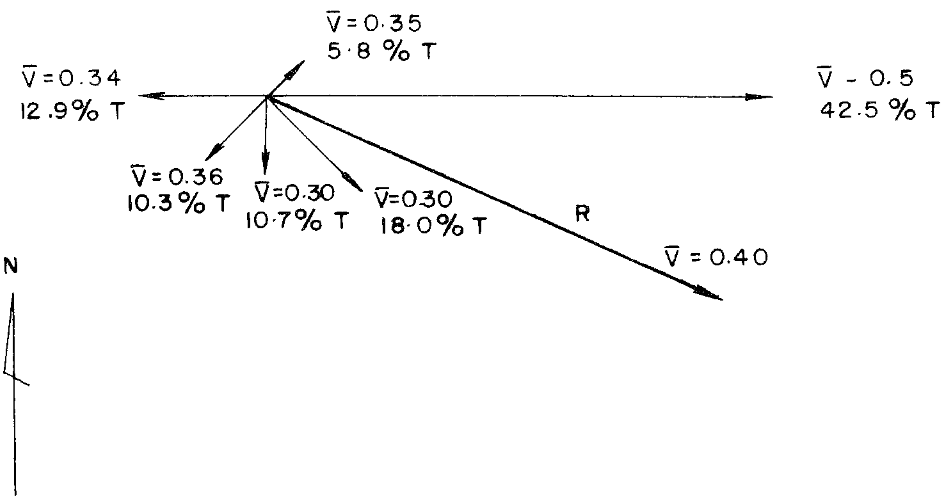
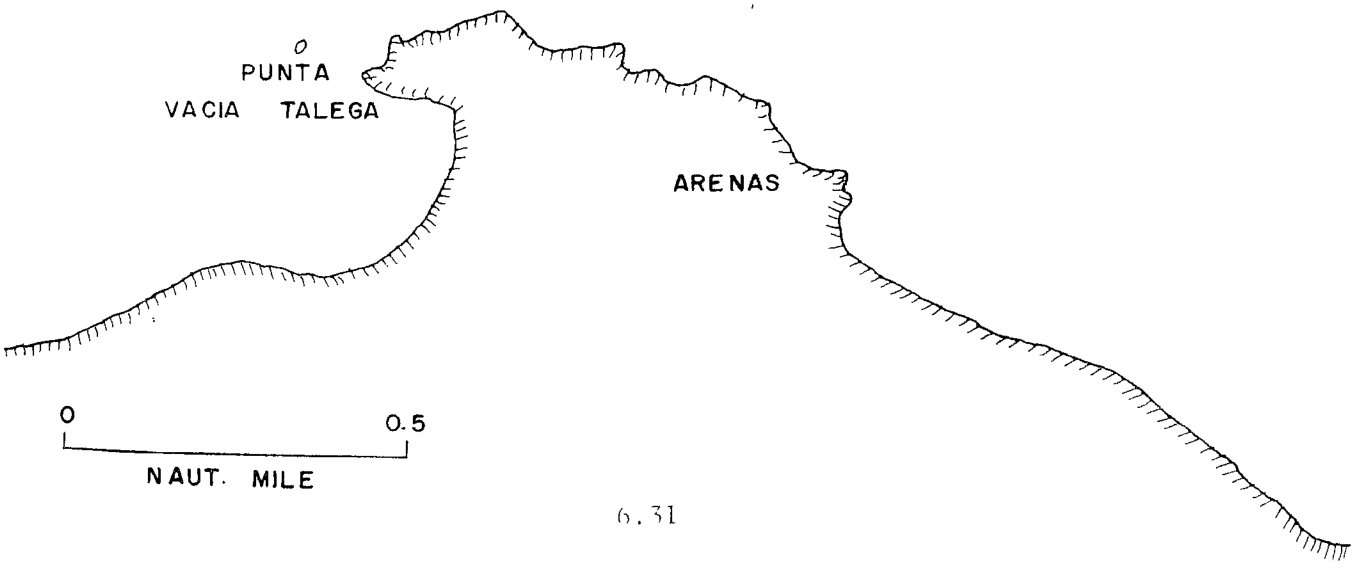


FIG C-6
NET FLOW CURRENT VECTORS
CRUISE 3 16-22 DEC 1971
CAROLINA
AVERAGE SPEED (V̄) IN Kn
AND PERCENT OF TOTAL
TIME SHOWN FOR EACH OCTANT



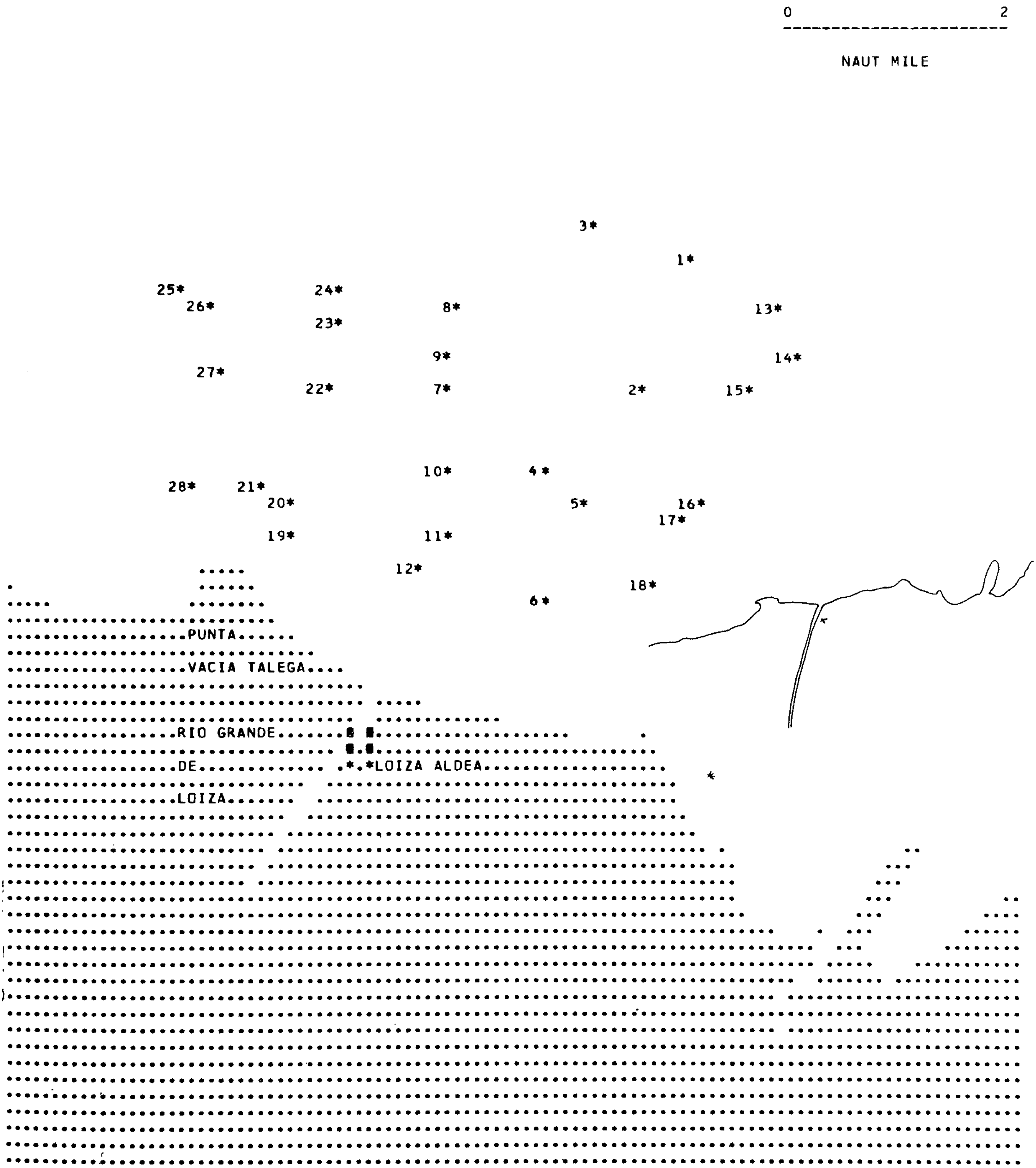


Figure C-7a
HYDROGRAPHIC STATION LOCATIONS
CAROLINA
CRUISE 1 23, 27 APRIL 1971

Figure C-7b
HYDROGRAPHIC STATION LOCATIONS
CAROLINA
CRUISE 2 24, 26 AUGUST 1971

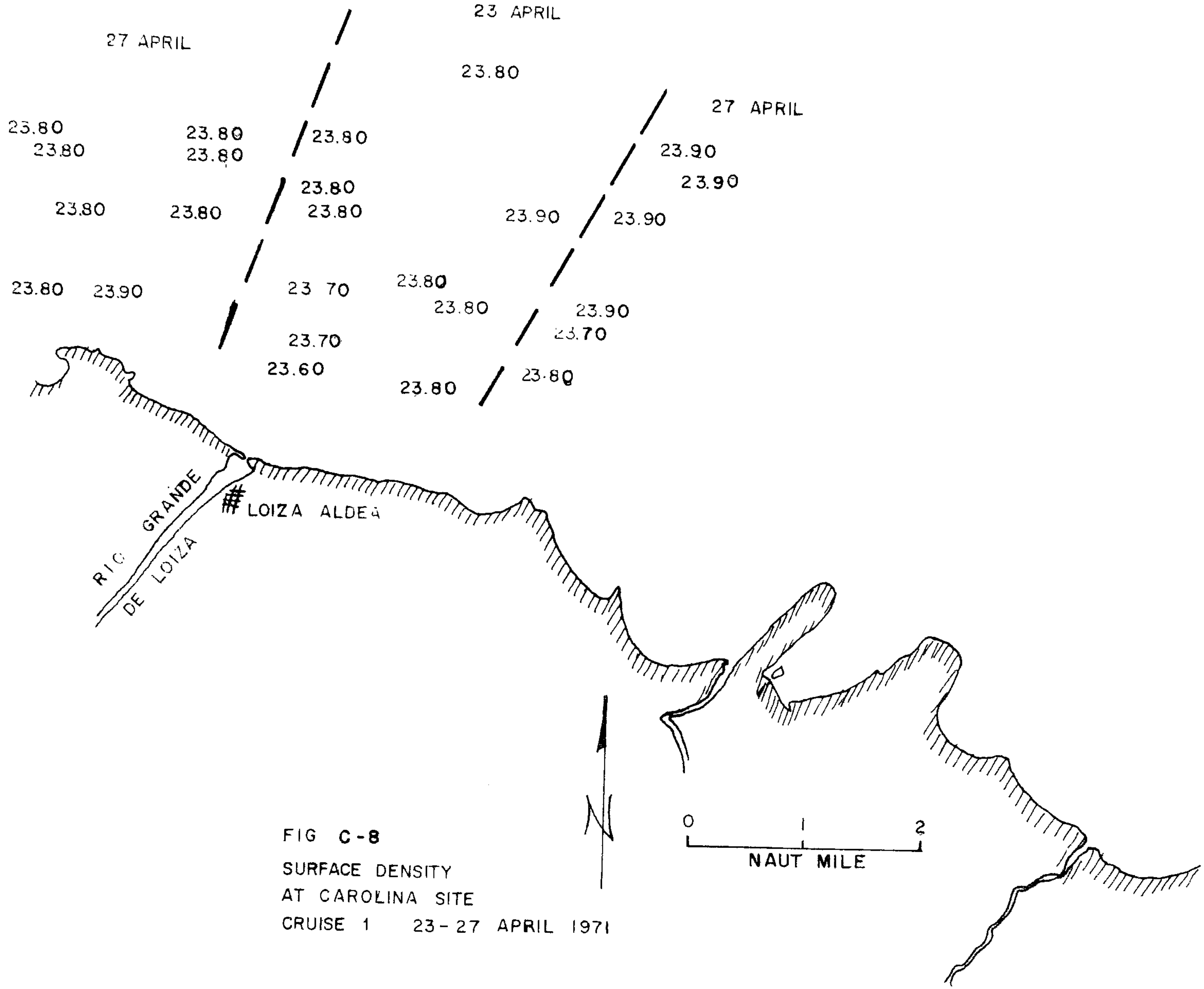


FIG C-8
SURFACE DENSITY
AT CAROLINA SITE
CRUISE 1 23-27 APRIL 1971

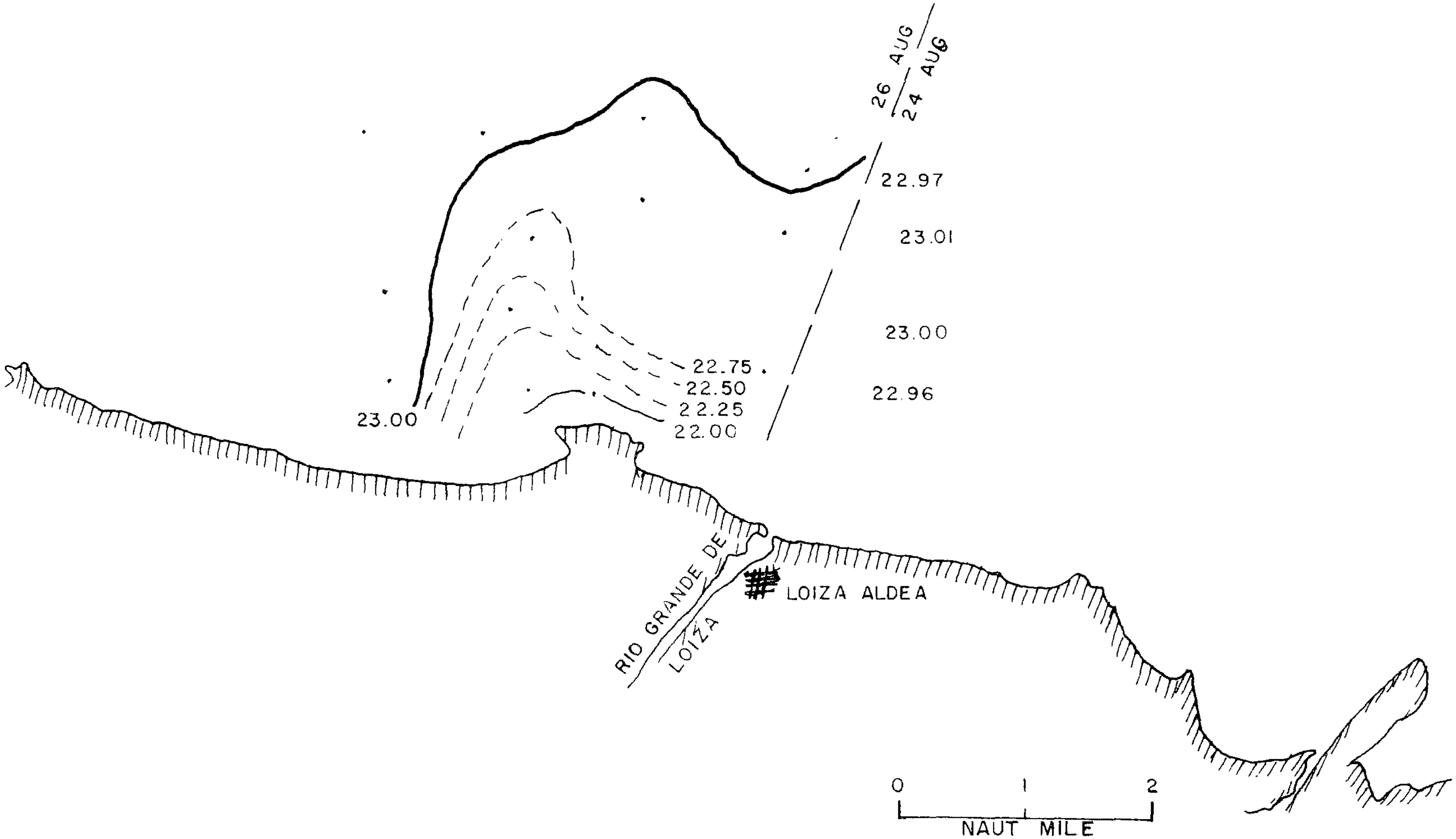


FIG C-9
SURFACE DENSITY
AT CAROLINA SITE
CRUISE 2 24-26 AUGUST 1971

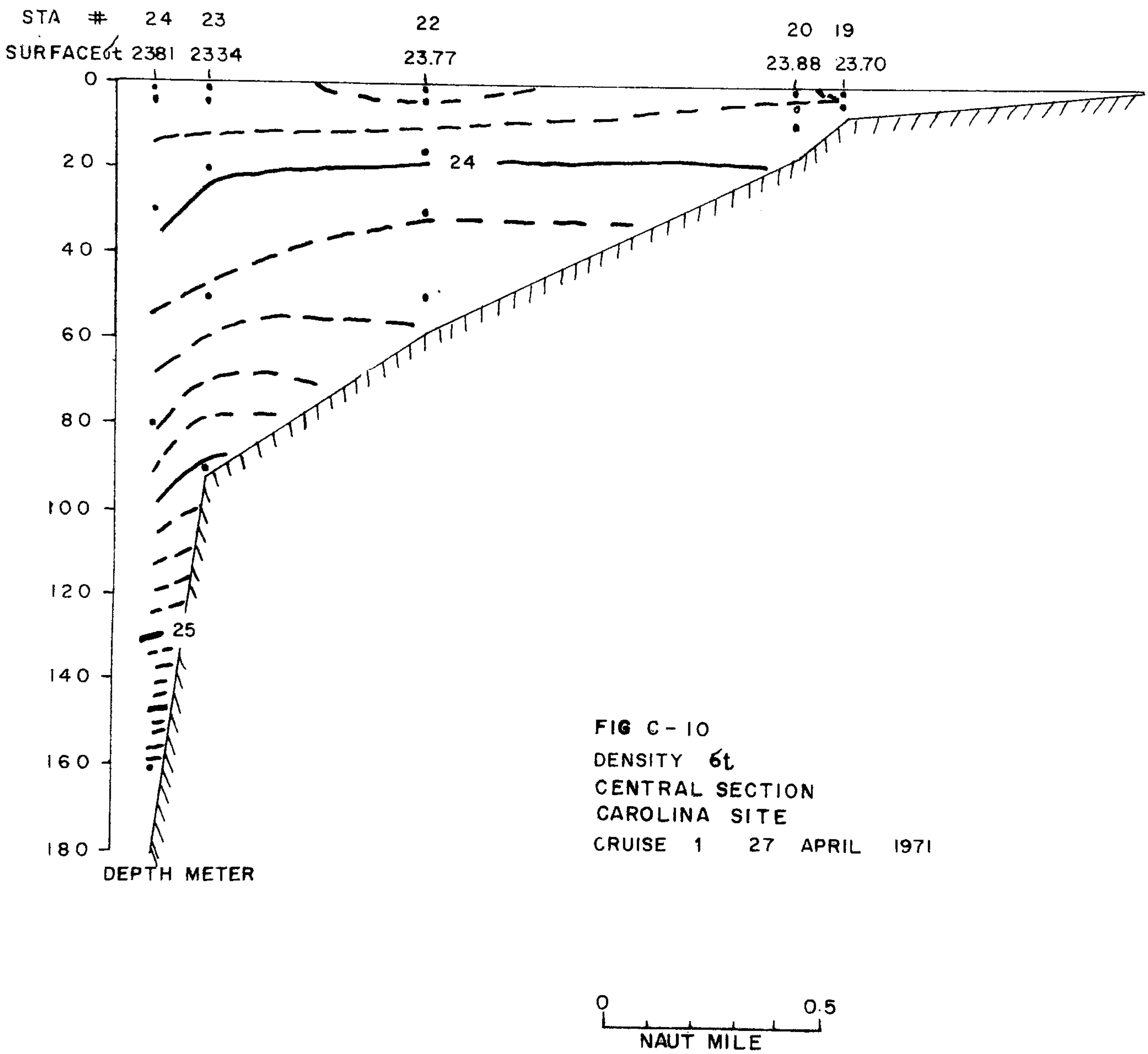


FIG C-10
DENSITY σt
CENTRAL SECTION
CAROLINA SITE
CRUISE 1 27 APRIL 1971

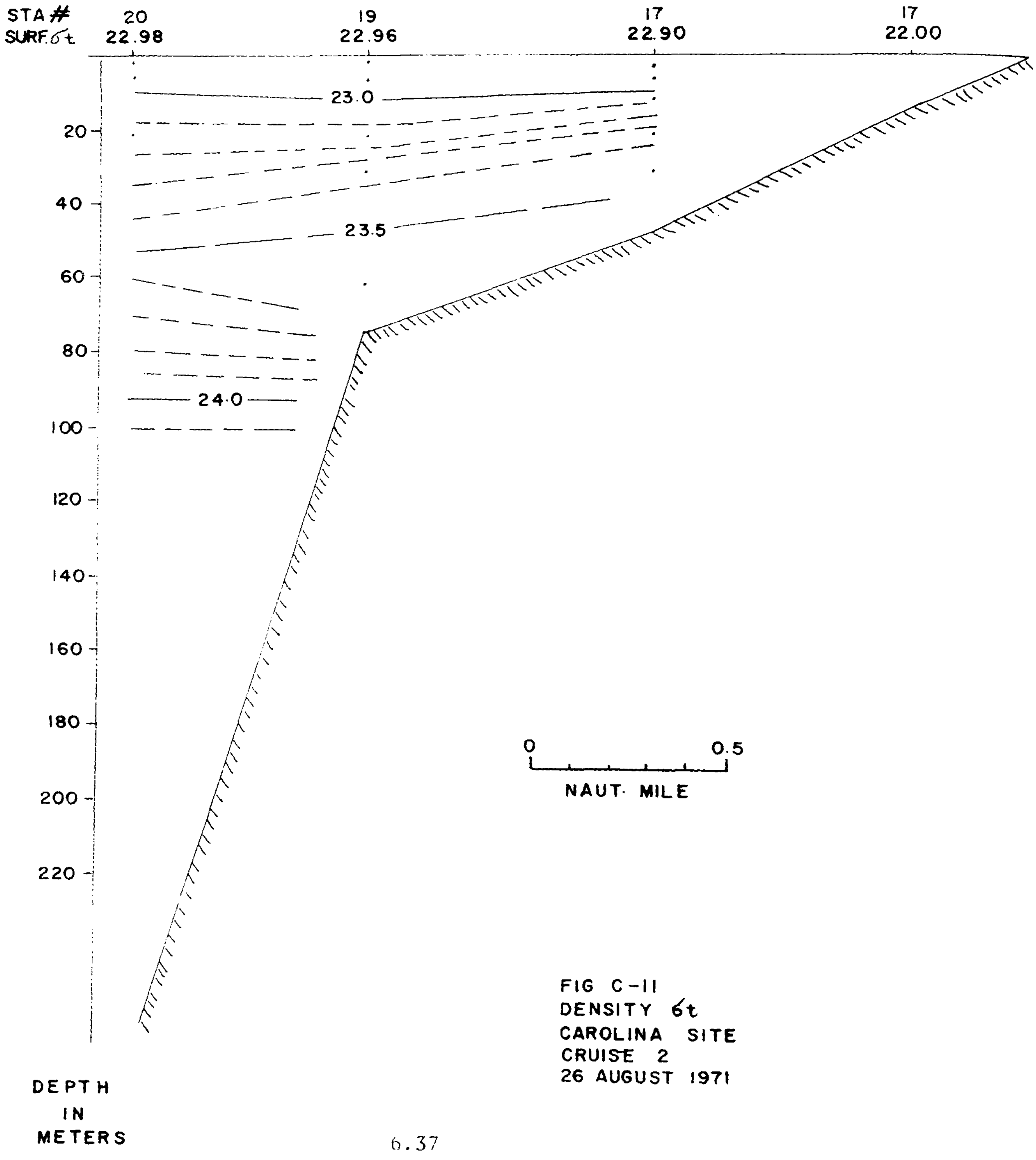


FIG C-11
DENSITY σt
CAROLINA SITE
CRUISE 2
26 AUGUST 1971

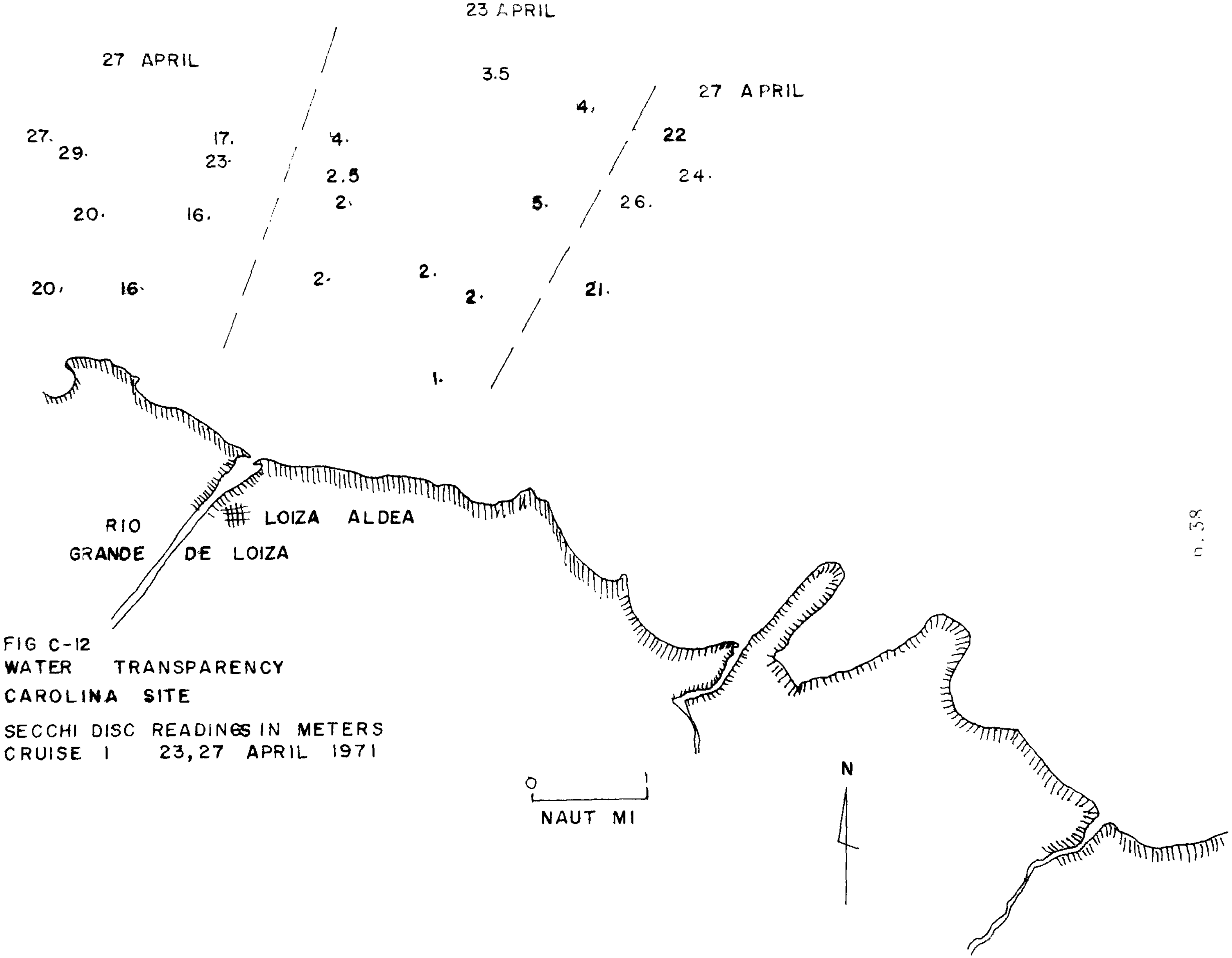


FIG C-12
WATER TRANSPARENCY
CAROLINA SITE
SECCHI DISC READINGS IN METERS
CRUISE I 23,27 APRIL 1971

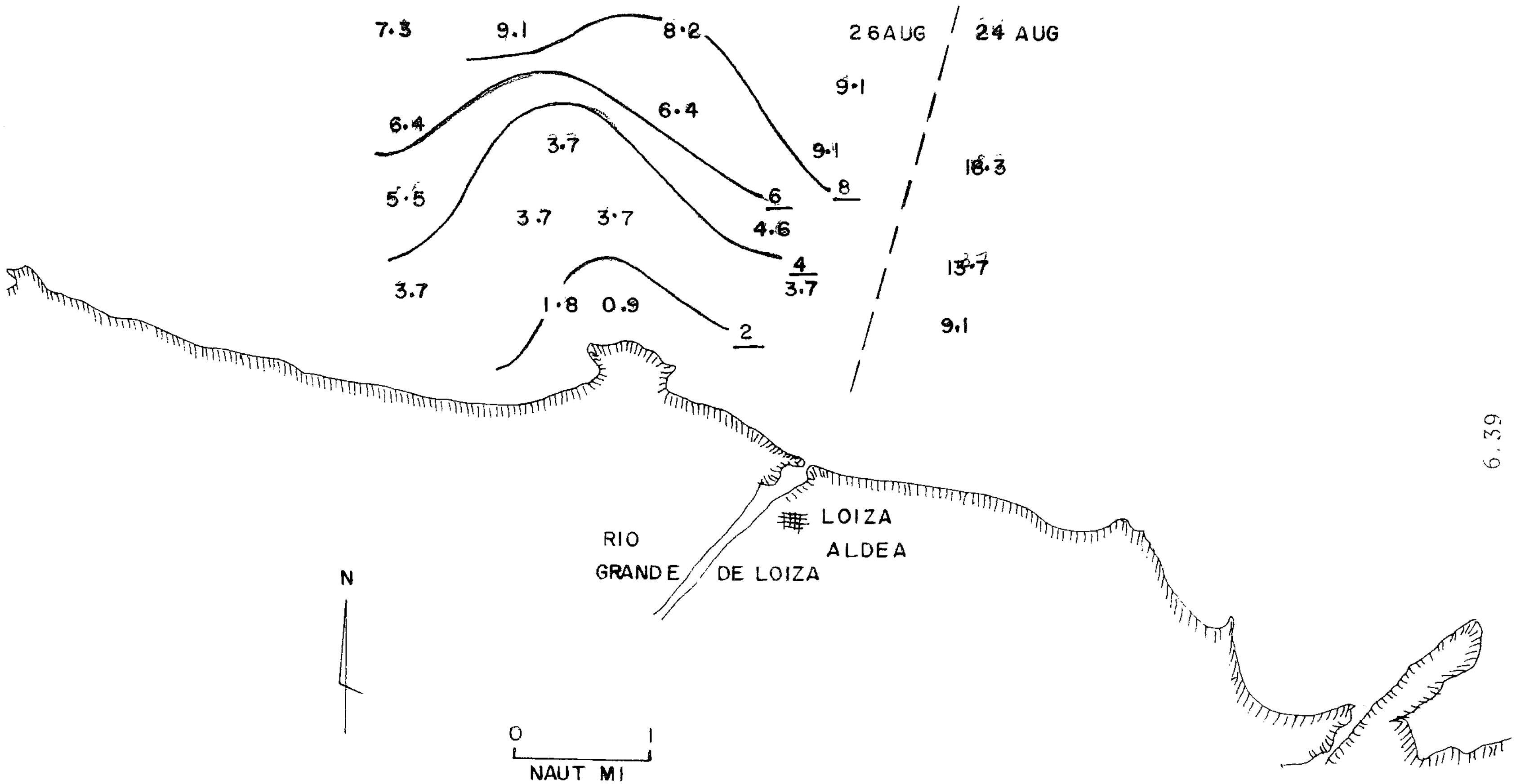


FIG C-13
WATER TRANSPARENCY
CAROLINA SITE
SECCHI DISC READINGS IN METERS
CRUISE 2 24,26 AUG 1971

HUMACAO/YABUCOA

Description of Study Areas

Because of the close proximity of the Humacao and Yabucoa sites, they will be considered together in this section.

Puerto Yabucoa is situated on the southeast coast of Puerto Rico facing eastward toward the Caribbean Sea. The bay stretches for 3.5 miles from Punta Guayanes to the north to Punta Quebrada Honda to the south. Puerto Yabucoa, which marks the eastern limit of the fertile valley of Yabucoa, is unsheltered by reefs and thus is subjected to the strong prevailing ocean currents.

Rivers draining into Puerto Yabucoa are the following:

(1) Río Guayanes - the largest river in southeast Puerto Rico.

(2) Río del Ingenio - flows to the southeast and joins the Río Guayanes one half mile before the latter reaches Puerto Yabucoa.

(3) Río Santiago - passes through the city of Yabucoa and enters Puerto Yabucoa at the same point as the Río Guayanes.

(4) Two additional small streams run to the southeast and discharge into Puerto Yabucoa.

At the present time, industrial activities in the vicinity of Puerto Yabucoa are limited to a sugarcane processing plant and a recently constructed petrochemical plant. Processing and waste waters from the sugar mill are discharged into what is known as Barras Creek, which ultimately joins the Río Santiago (1). The degree of treatment and point of discharge of petrochemical waste is unknown.

Sanitary wastes are collected in septic tanks and no further treatment is provided to the effluents which discharge into the Río Santiago and eventually Puerto Yabucoa (1). Most dwellings in the community called Playa de Guayanes discharge domestic wastes through pipes or ditches into Río del Ingenio which, as mentioned above, joins the Río Guayanes before discharging into Puerto Yabucoa.

The Río Humacao originates in the mountainous section of Tejas in the municipality of Las Piedras, Puerto Rico. Its point of origin is the highest point in the watershed with an elevation of 1,025 feet above sea level (2). The Río Humacao is 21 miles long and in its course runs mostly through mountainous and unpopulated country until it reaches the flat lowlands of Humacao City. Here, the terrain is flat all the way to the coast, where the river flows into the Caribbean Sea (2). The Del Inglés Creek, the Del Obispo Creek and the Cataño Creek are the main tributaries of the Río Humacao.

In 1967 there were not more than ten industrial plants located along the Río Humacao watershed (2). Today there are numerous other industries situated on the Río Humacao, the largest of which is a recently constructed pharmaceutical manufacturing plant.

The sewage treatment plant serving the town of Humacao consists of an Imhoff tank with a BOD removal efficiency of about 25 percent and a suspended solids removal efficiency of 30 percent (2). In addition to the effluent from this obsolete system, leachates from the garbage disposal site located 1.5 miles southeast of Humacao undoubtedly contribute to the poor sanitary quality of the Río Humacao (2). Also, as has been observed in many other areas of Puerto Rico, people living in houses close to the river use its water for disposal of their domestic wastes.

Hydrodynamics - Humacao

The only information available on currents for the Humacao region prior to this study were those given in the "Tidal Current Tables for the Atlantic Coast of North America" (3) and the report on "Wastewater Treatment and Ocean Disposal for Humacao Area" (4). The maximum currents for Vieques passage according to (3) is 0.6 knots in a direction of 250° during flood tide and 0.7 knots in a direction of 55° during ebb tide. These values are, however, for a sound that is a considerable distance (9 kms) from Humacao and which differs in bathymetric features from the study site. The data obtained by (4) showed a clockwise tidal reversal flow.

Three current surveys were carried out during the study at Humacao. Figure H/Y-1 shows the location of the stations for each survey. Tabular results for the first cruise, using an Ekman-Merz current meter, are given in Appendix E, and current vectors are shown in Figure H/Y-2. The general flow was roughly westerly (towards shore) in the surface and mid-depth waters, and south to southeast in bottom waters. The average speed was 0.28 knots for the surface waters, 0.26 knots for mid-depth, and 0.34 knots for bottom waters.

Figure H/Y-3 shows the results obtained with drogues during the second survey. The general direction obtained with the drogues was to the NW for the surface water with an average speed of 0.31 knots. The mid and deep drogues showed a somewhat erratic course and a considerably lower speed.

Current meter studies were carried out during the same period but due to a malfunction, which was discovered only later during the study at Ponce, this data has not been included as it is considered suspect.

More extensive observations were obtained during Cruise 3 when Hydro Products Model 502 recording current meters were anchored for 27 hours. The data obtained with the current meters is presented in Appendix E and Figure H/Y-4. As shown in Figure H/Y-4, a fairly stable pattern is indicated with minor changes in speed and direction. No significant differences were found in the current structures of inner and outer stations. The general direction was southerly, with a change in direction toward the east during the first half of rising tide periods. Drogue studies carried out in conjunction with the current meter measurements showed considerably more variation in direction, and lower resultant speed values. Such differences are difficult to interpret because of rapid changes in the bottom contour over small horizontal distances, with corresponding sudden changes in current values to be expected. Also, because of the nature of the bottom, no drogue data was obtained for currents as close to the bottom as the sensors of the current meters. When attempts were made to do this, the drogues ran aground almost immediately. The speed values obtained with the in-situ recording meters agree roughly with the values obtained with the Ekman-Merz meter during Cruise 1. A drogue was lost on January 17 and recovered on the 19th. Its path was toward the south-west at an average speed of 0.1 knot. Current flow vectors, computed from the data obtained with the in-situ recording meters, are shown in Figure H/Y-5. The length of the component vectors corresponds to the actual quantity of flow (the sum of products of duration of flow and average speed) for each octant. Average speed values, and percent of total time of flow in each octant, are also given together with the average speed in the direction of the resultant (labeled R in the figure). A detailed description of the method used in this analysis is given in Appendix B.

Hydrodynamics - Yabucoa

Station locations for each of the three surveys are shown in Figure H/Y-1. Cruise 1 tabular data is given in Appendix E, and Figure H/Y-6 illustrates the results. Only two observations (with the Ekman-Merz meter) could be made on May 6, 1971, due to weather conditions which caused the anchor line to break. On this occasion there was a southerly current of a little over 0.4 knot in the shallow (5m) water, and a slightly weaker current at mid-depth (12m). The site was revisited on May 19, 1971. Results with the Ekman-Merz meter were rather erratic, particularly at mid-depth (Figure H/Y-6), giving a low value of current speed. The wind velocities were unusually low, varying from two to eight knots (see Section 4). Also, these observations were made during a period close to the time of neap tides, so that tidal influences were weaker than usual.

Drogue studies were carried out during Cruise 2 in winds of 12 to 16 knots from the ESE (Appendix E). The prevailing current was generally eastward from mid-morning to early afternoon (see Figure H/Y-7), with average speeds higher than comparable values obtained during Cruise 1. During the afternoon the currents shifted towards the north, as illustrated in Figure H/Y-8. Tabular results of these current observations are given in Appendix E.

Only one of the in-situ recording current meters was anchored during Cruise 3 due to the very narrow shelf and abrupt slope, as explained in Appendix A. Current meter results, based on 24 hours of continuous observation on January 17 , 1972, are shown in Figures H/Y-4 and H/Y-10, and tabular data is included in Appendix E. Figure H/Y-10 shows the relative quantities of water flowing in each octant, corresponding to the cardinal and inter-cardinal points of the compass, together with the net resultant current flow, as explained in Appendix B. In this case the current direction and speed, as recorded by the in-situ meter, was unusually constant. Current drogue tracks obtained during Cruise 3 on January 18, 1972, are shown in Figure H/Y-9.

Hydrographic Data

Hydrographic station locations at Humacao and Yabucoa are shown in Figure H/Y-11. Hydrographic data, including temperature and salinity values from which density (sigma-t) values discussed here were computed, are given in Appendix E. Generally, the changes in water characteristics from surface to bottom in shallow water and from place to place throughout Puerto Yabucoa and the coastal waters of Humacao are slight. Figures H/Y-12 and H/Y-13 show the surface density (sigma-t) values obtained. There is little consistent structure, probably due to the fact that this is a lee shore where the wave action of the incessant on-shore winds keeps the waters well mixed, though there is a tendency for slightly lower density values to be found closer to shore.

Profiles of the center section of the Humacao and Yabucoa sites, illustrating isopycnals at various depths, are shown in Figure H/Y-14, H/Y-15 and H/Y-16. The values given were computed from temperature and salinity values obtained during Cruise 1 and 2.

Water Quality

Water quality surveys for the Humacao and Yabucoa areas were combined because of the proximity of these areas, and the continuity of the data. Tables of data obtained during Cruise 1 and 2 are included in Appendix E.

During Cruise 1, Secchi disc readings varied between 2.5 and 22 meters at these sites, as shown in Figure H/Y-17. As a rule, the depth contours followed the coastline, indicating that no turbid plumes projected out into the ocean. Silica concentrations varied between 0.1 and 0.6 mg/l, and phosphorus was below measurable values in most of the samples, reflecting the low phosphorus levels generally found in the Caribbean Sea.

On the second cruise, Secchi readings varied between 3 and 42 meters, as shown in Figure H/Y-18. These readings are consistent with prior observations except for a plume off Morro de Humacao, which may have been caused by the outflow of Río Humacao. Oxygen concentration was found to be between 5.39 and 6.73 mg/l, showing little oxygen depletion. Silica concentrations varied from 0.09 to 0.51 mg/l, and phosphorus was found in concentrations between 0.008 and 0.020 mg/l, neither of which is deemed significant. The coliform MPN levels varied between nil and 200/100 ml.

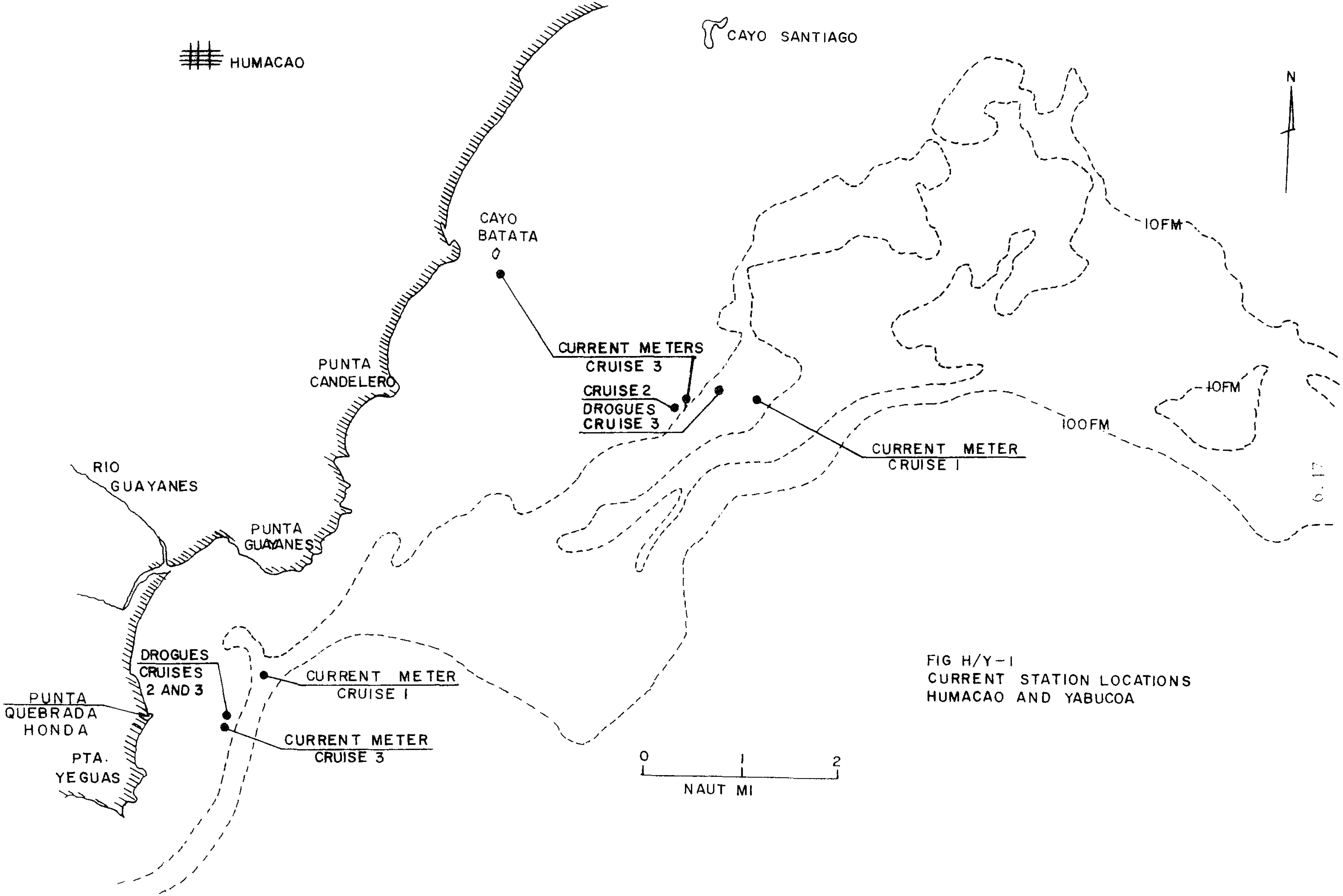


FIG H/Y-1
CURRENT STATION LOCATIONS
HUMACAO AND YABUCOA

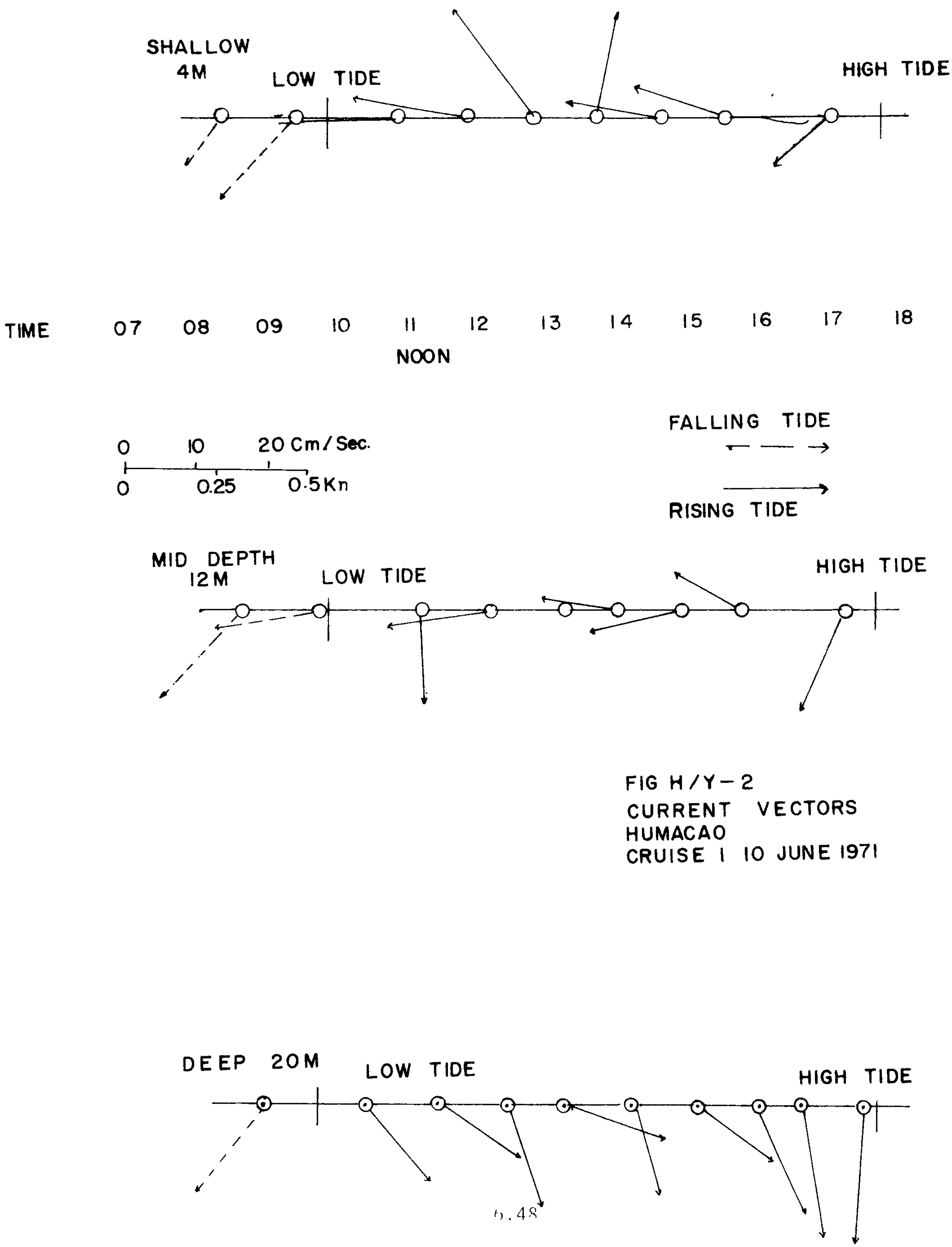


FIG H/Y-2
CURRENT VECTORS
HUMACAO
CRUISE I 10 JUNE 1971

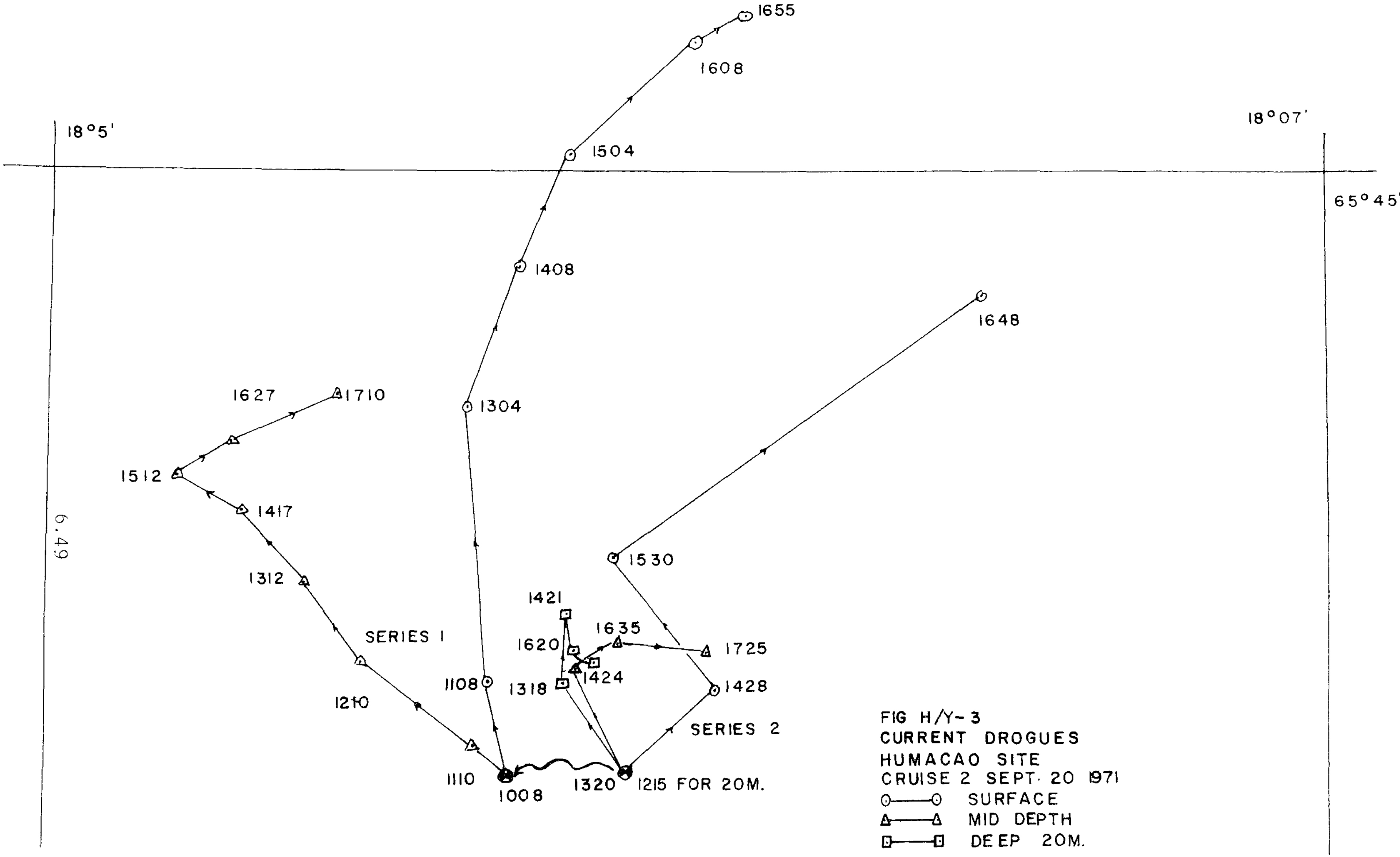


FIG H/Y-3
CURRENT DROGUES
HUMACAO SITE
CRUISE 2 SEPT. 20 1971

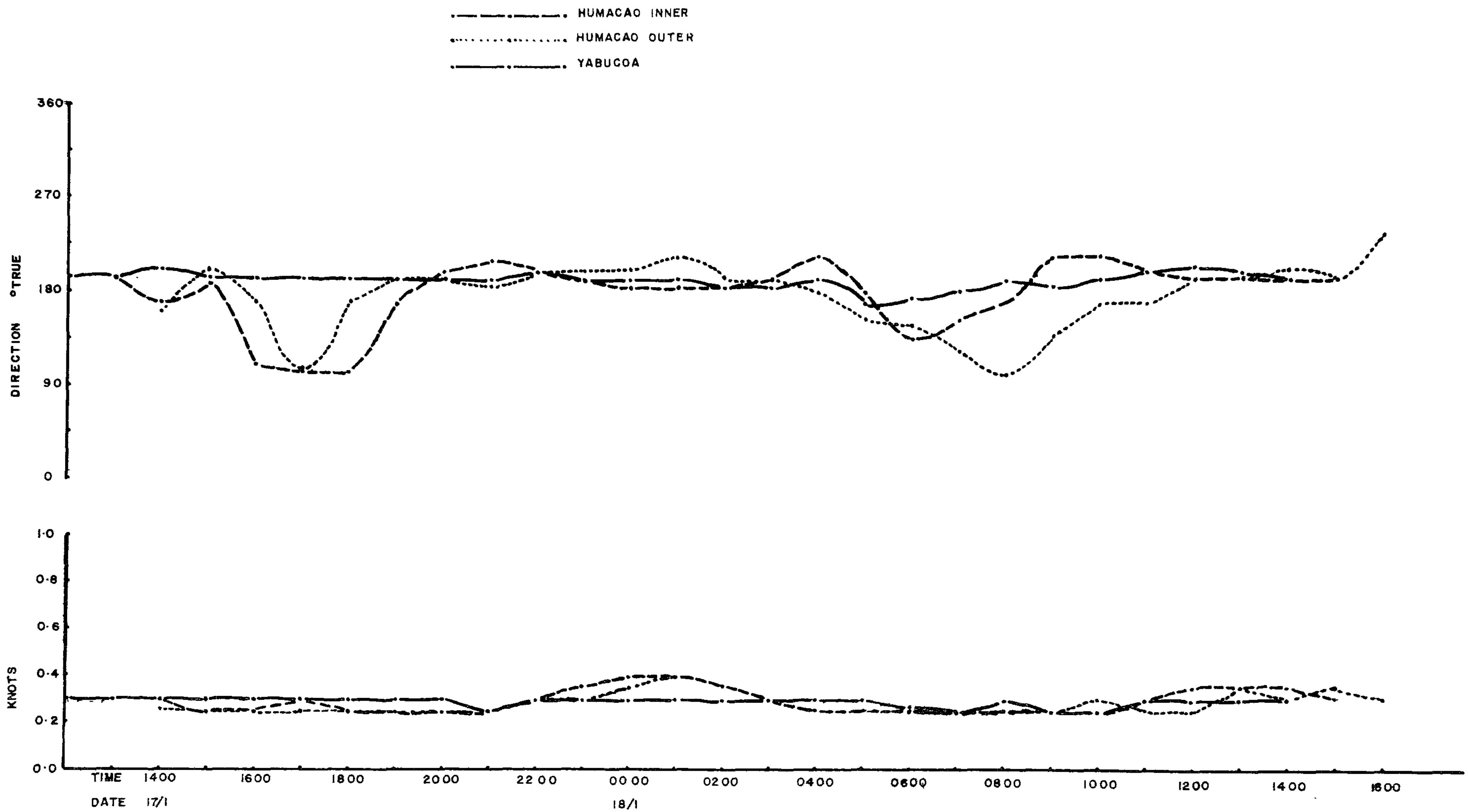


FIG H/Y-4
CURRENT VELOCITY
CRUISE 3 17-18 JANUARY 1972
HUMACAO AND YABUCOA

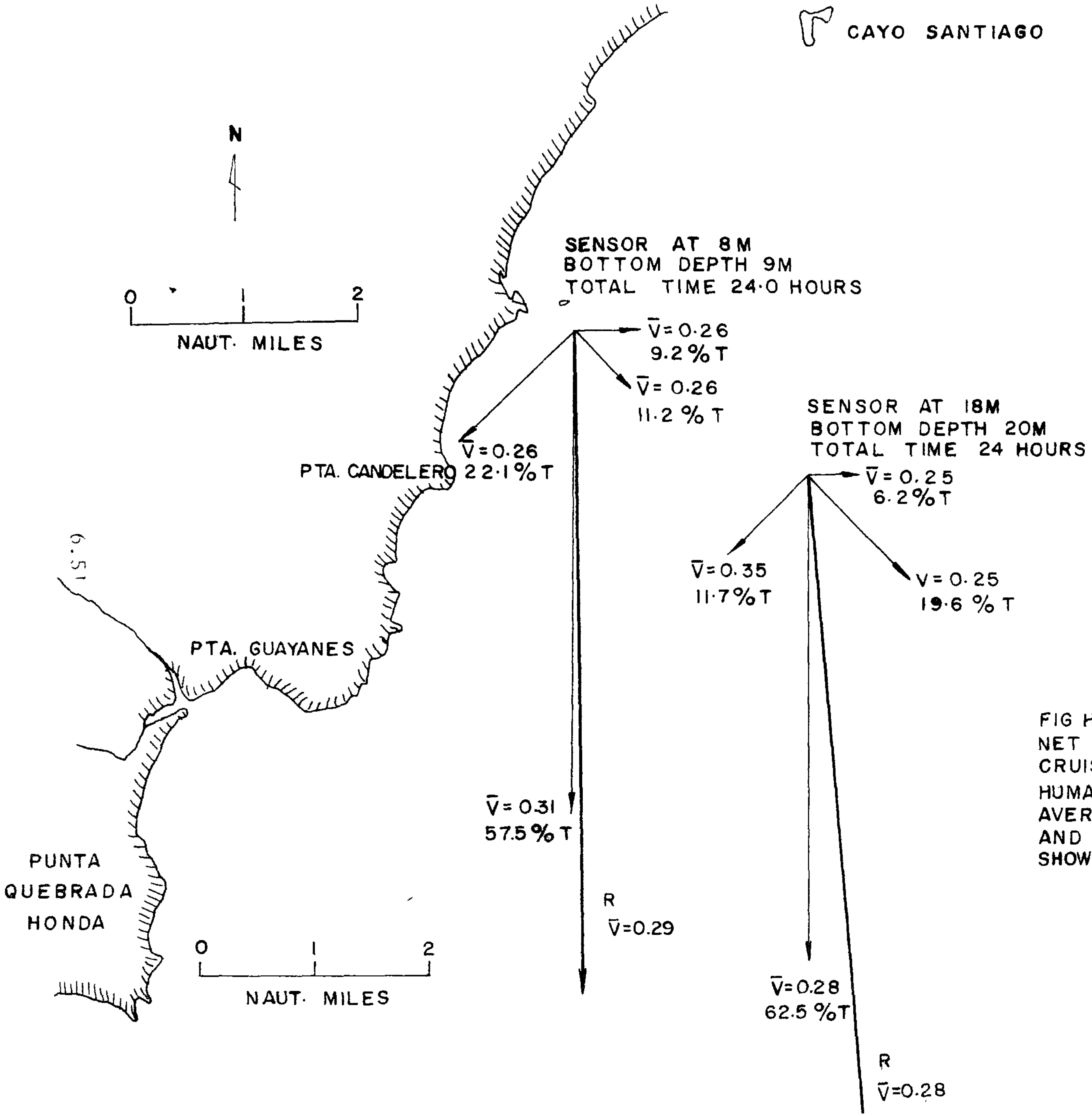
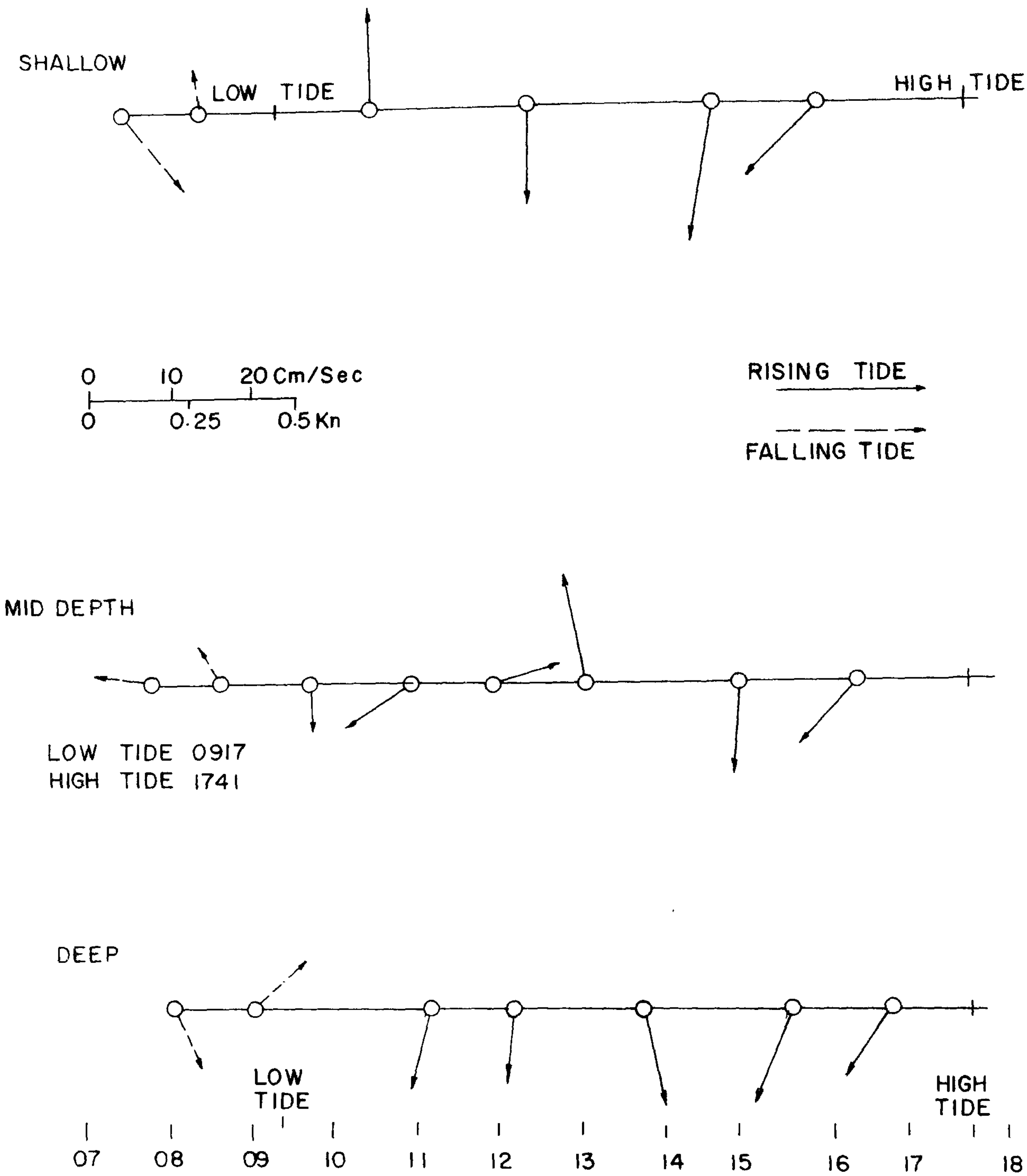


FIG H/Y-5
NET FLOW CURRENT VECTORS
CRUISE 3 17-18 JANUARY 1972
HUMACAO
AVERAGE SPEED (V̄) IN Kn
AND PERCENT OF TOTAL TIME
SHOWN FOR EACH OCTANT



WATER DEPTH 35-40 M.
WIND EAST FORCE 2-3

FIG H/Y-6
CURRENT VECTORS
YABUCOA
CRUISE I 19 MAY 1971

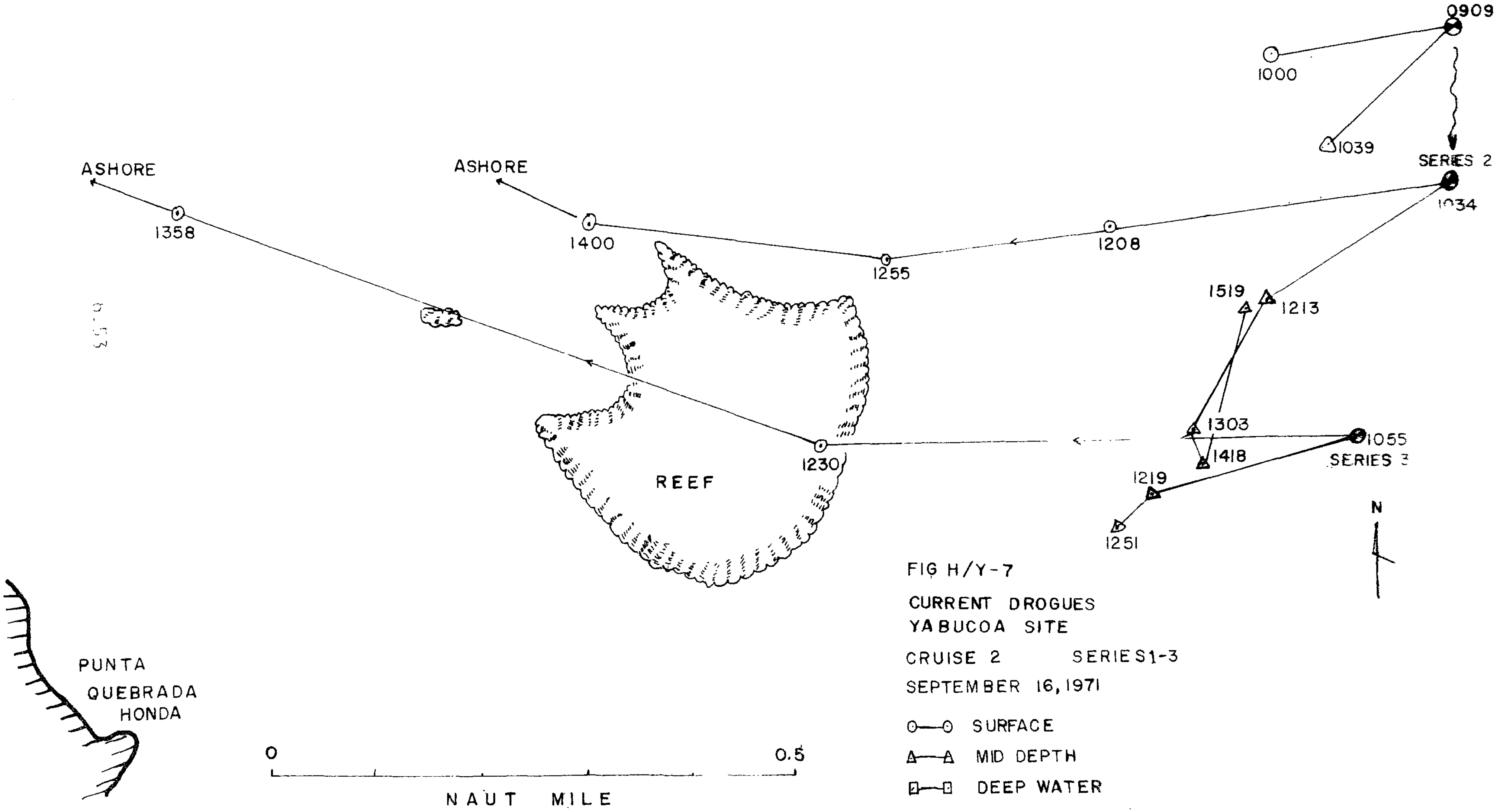


FIG H/Y-7

CURRENT DROGUES
YABUCOA SITE

CRUISE 2 SERIES 1-3

SEPTEMBER 16, 1971

O—O SURFACE

Δ—Δ MID DEPTH

□—□ DEEP WATER

SEE NOTE ON FIGURE SJ-3

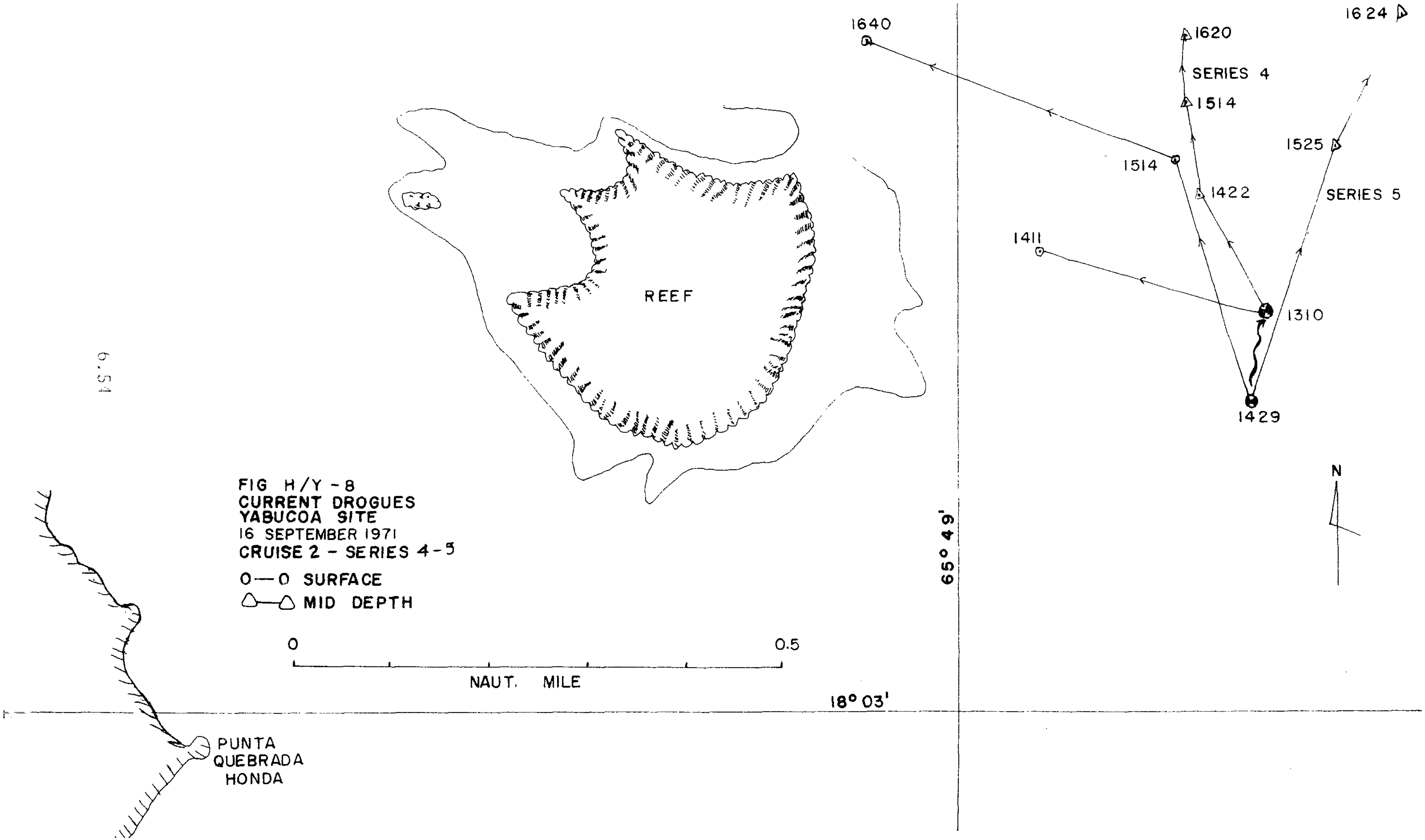


FIG H/Y-8
CURRENT DROGUES
YABUCOA SITE
16 SEPTEMBER 1971
CRUISE 2 - SERIES 4-5

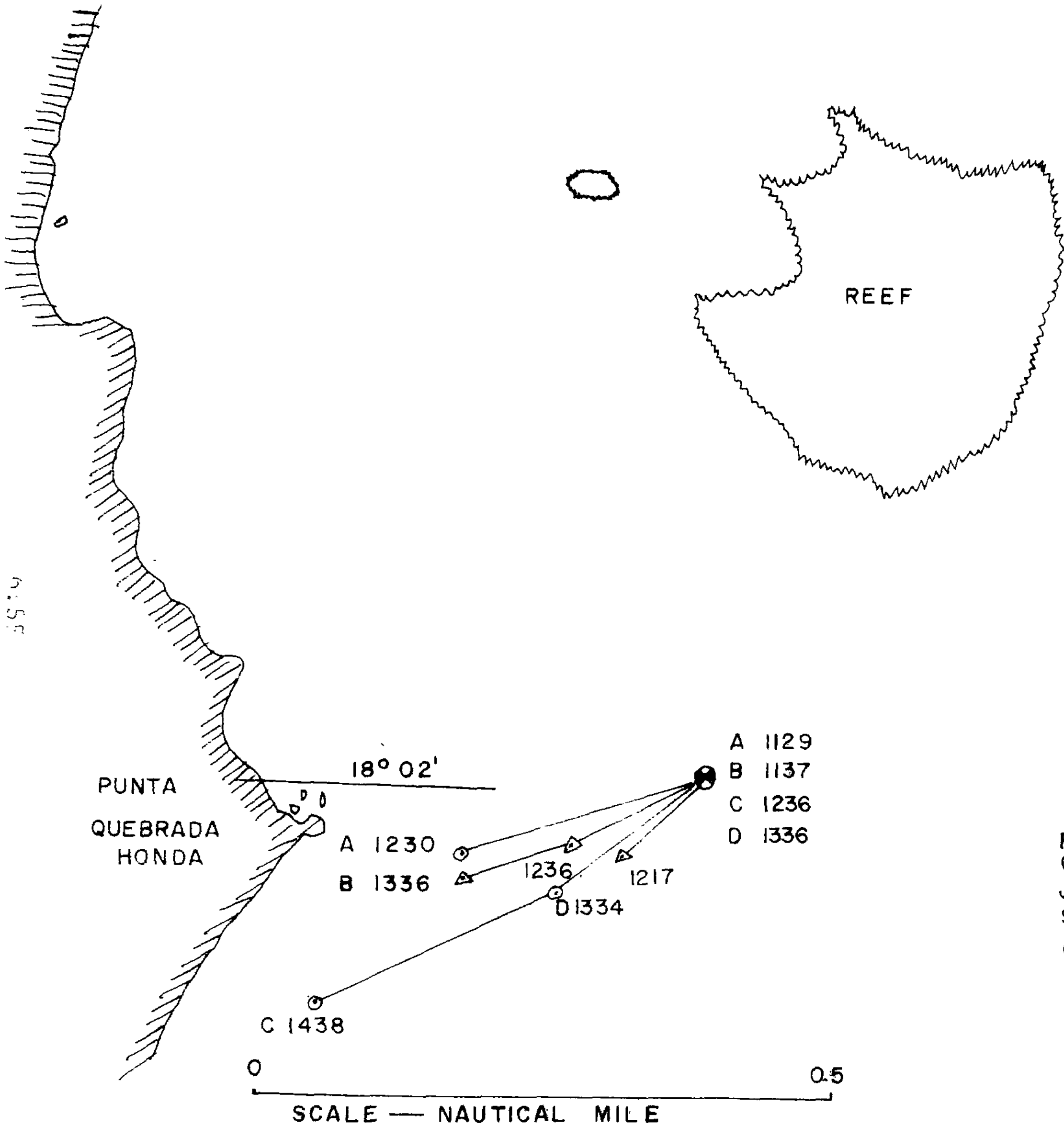


FIG H/Y-9
CURRENT DROGUES AT YABUCOA SITE
JANUARY 18, 1972 CRUISE 3
SERIES
O—O SURFACE
Δ—Δ MID-DEPTH 5M.

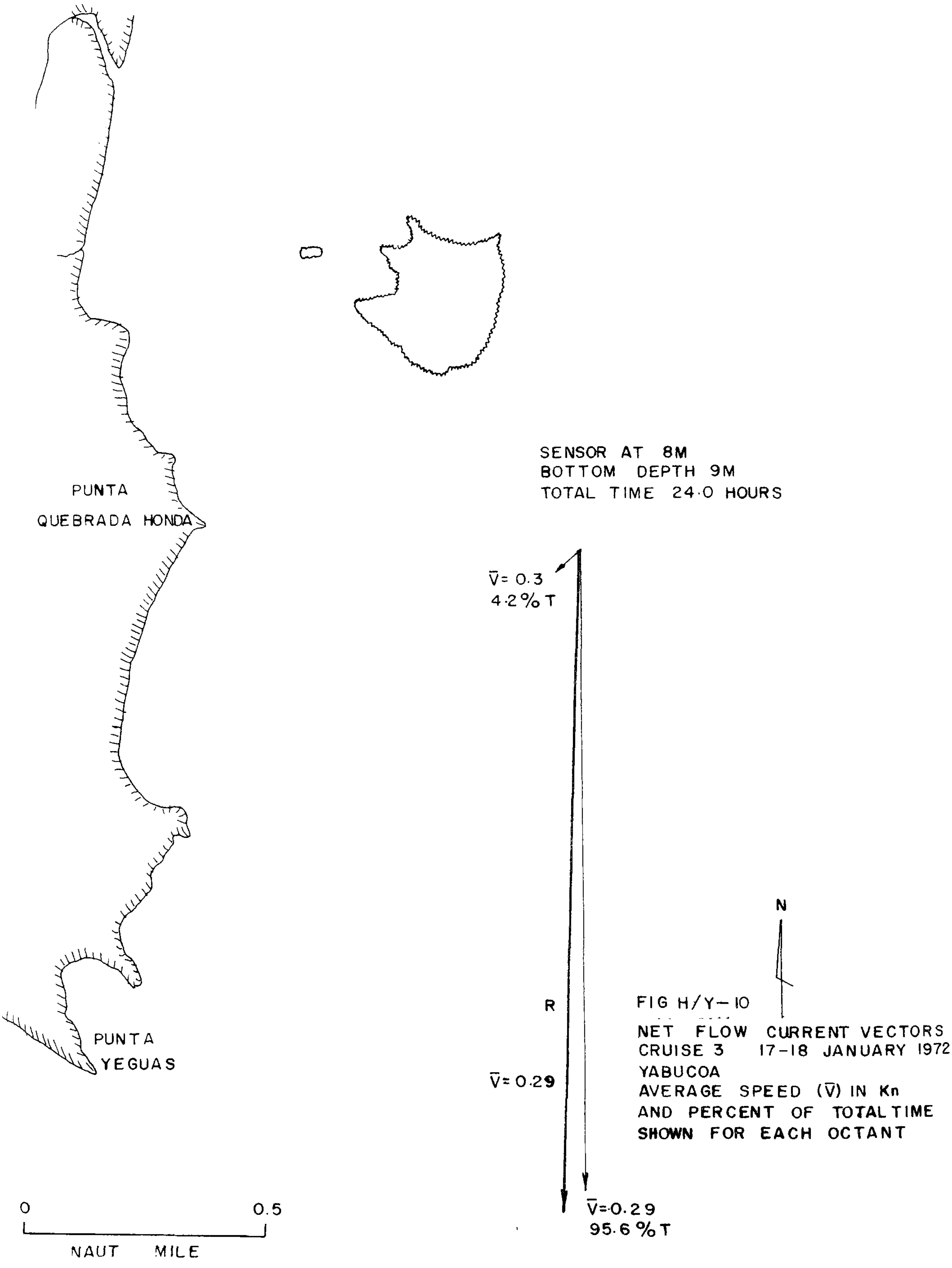


FIG H/Y-10
NET FLOW CURRENT VECTORS
CRUISE 3 17-18 JANUARY 1972
YABUCOA
AVERAGE SPEED (V̄) IN Kn
AND PERCENT OF TOTAL TIME
SHOWN FOR EACH OCTANT

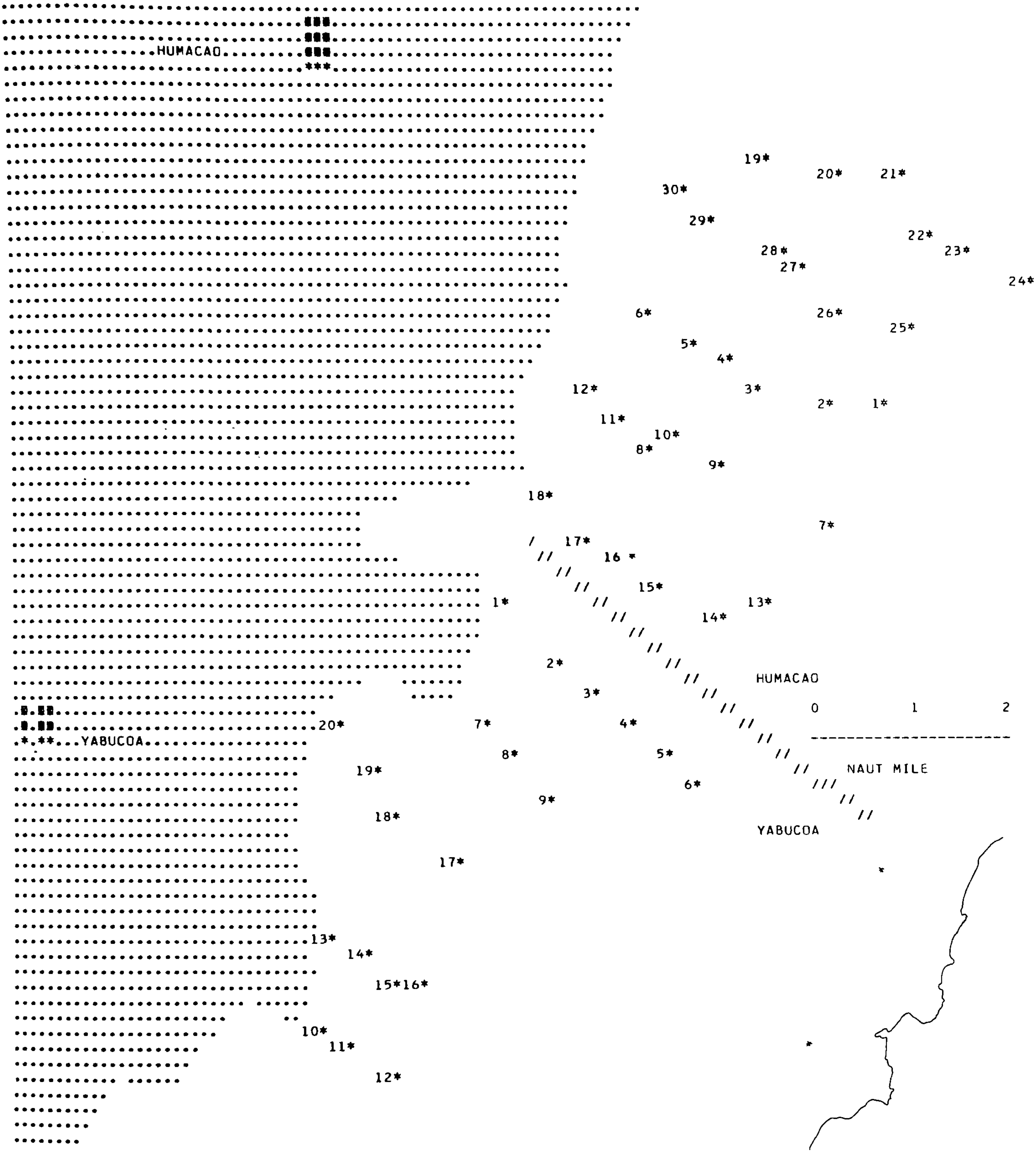


Figure H/Y-11a
HYDROGRAPHIC STATION LOCATIONS
HUMACAO-YABUCOA
CRUISE 1 30 APRIL, 5, 18 MAY 1971

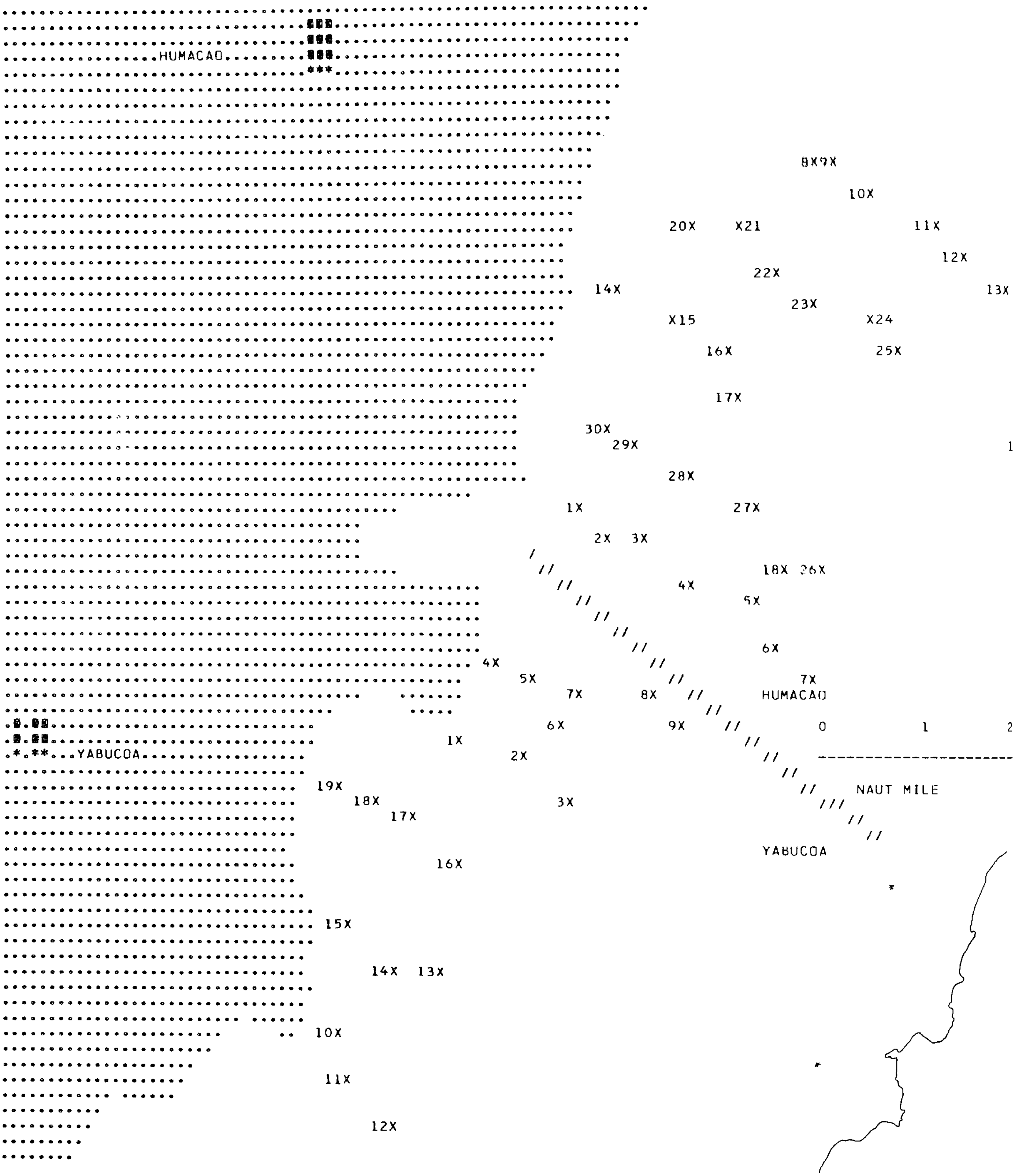


Figure H/Y-11b
HYDROGRAPHIC STATION LOCATIONS
HUMACAO-YABUCOA
CRUISE 2 9, 14, 15 SEPTEMBER 1971

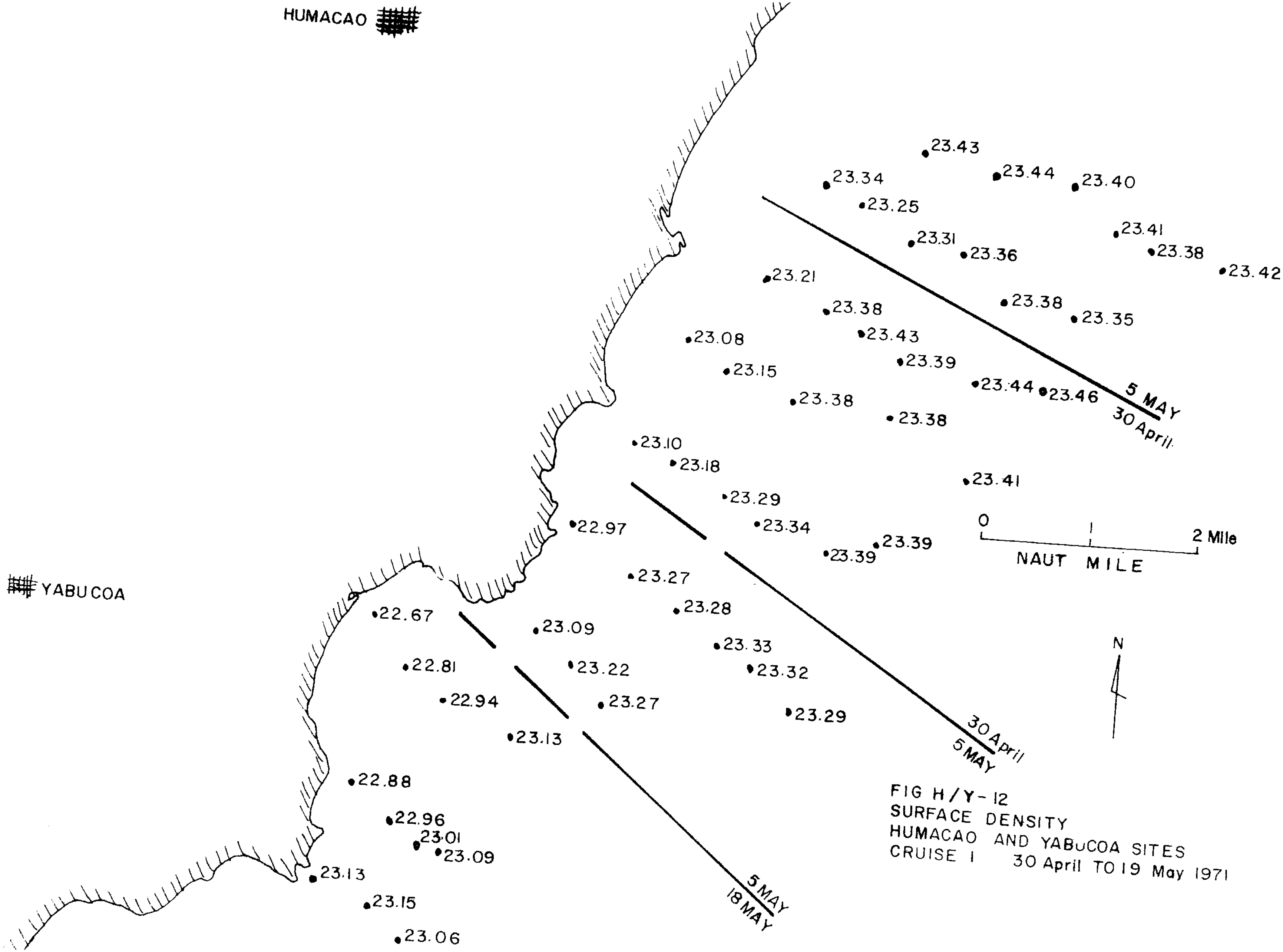


FIG H/Y-12
SURFACE DENSITY
HUMACAO AND YABUCOA SITES
CRUISE I 30 April TO 19 May 1971

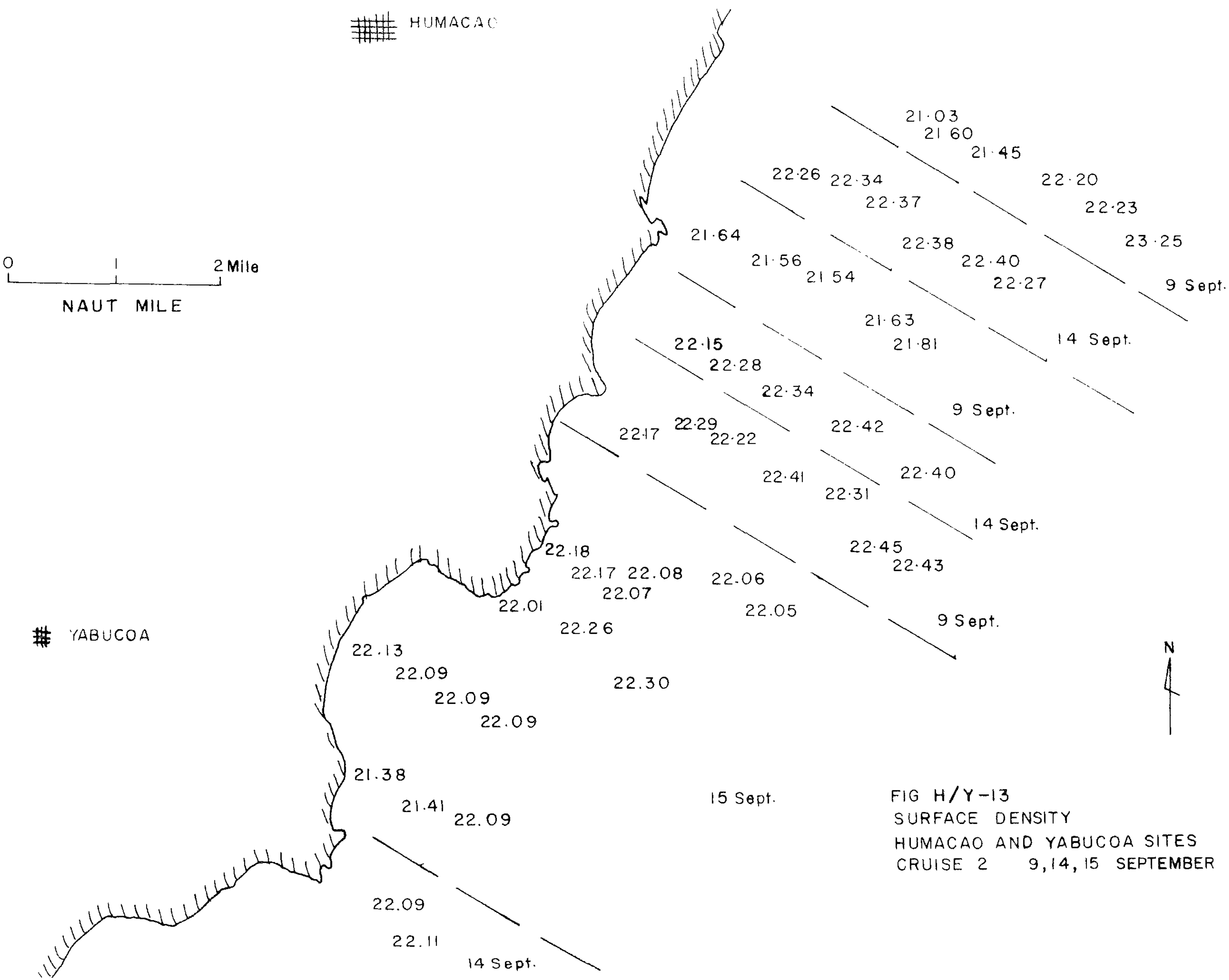


FIG H/Y-13
SURFACE DENSITY
HUMACAO AND YABUCOA SITES
CRUISE 2 9, 14, 15 SEPTEMBER 1971

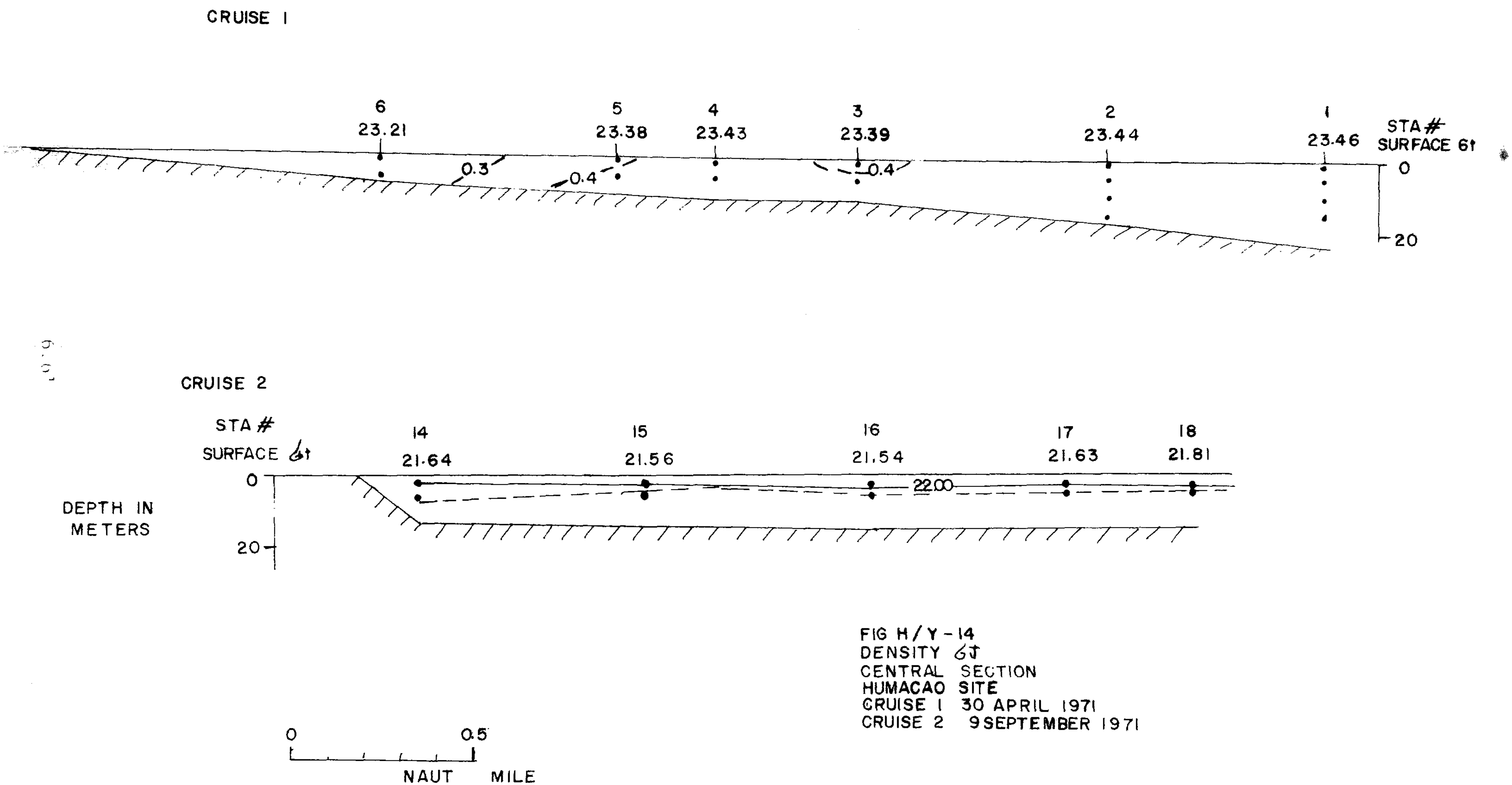


FIG H/Y-14
DENSITY σt
CENTRAL SECTION
HUMACAO SITE
CRUISE 1 30 APRIL 1971
CRUISE 2 9 SEPTEMBER 1971

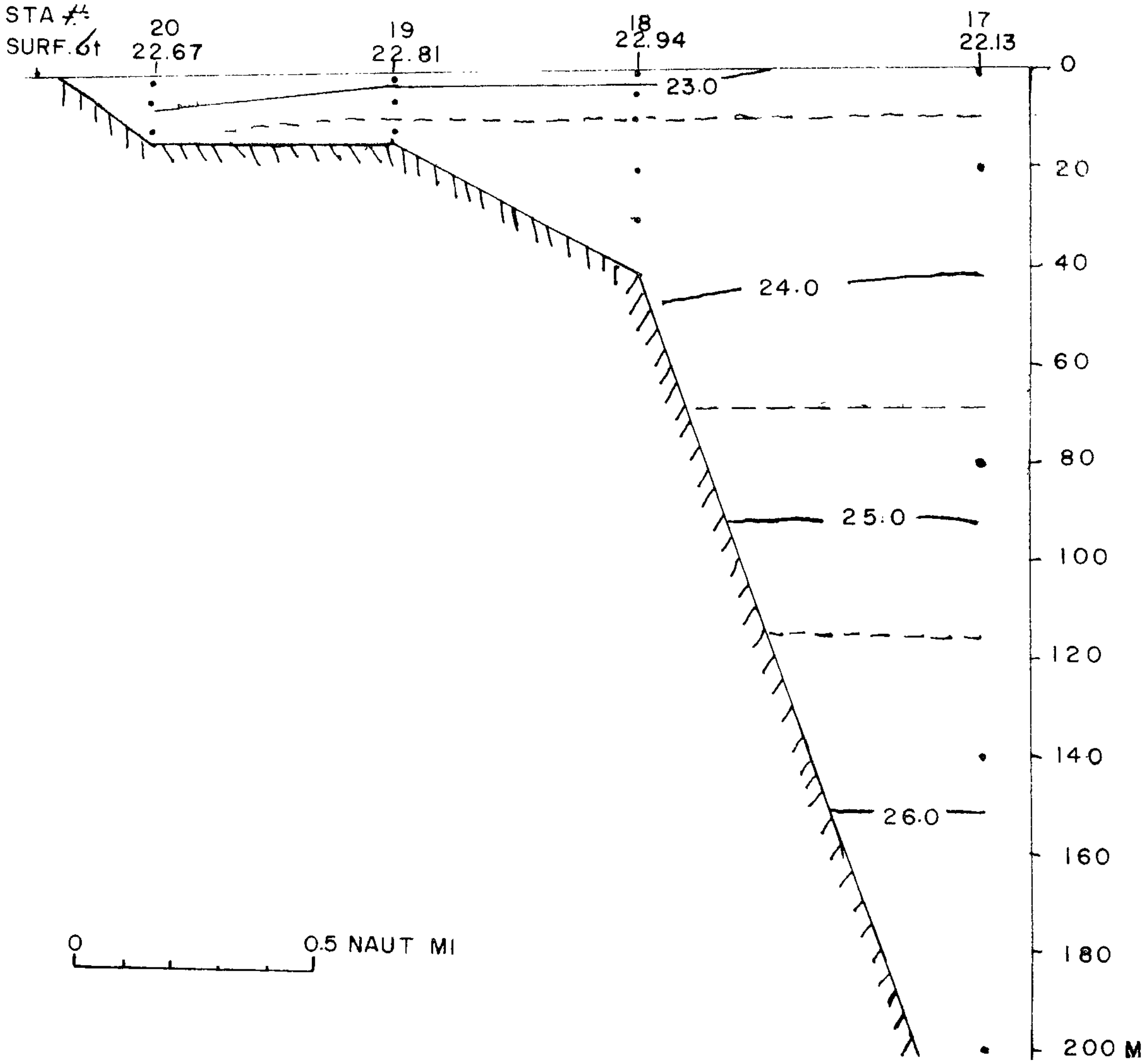
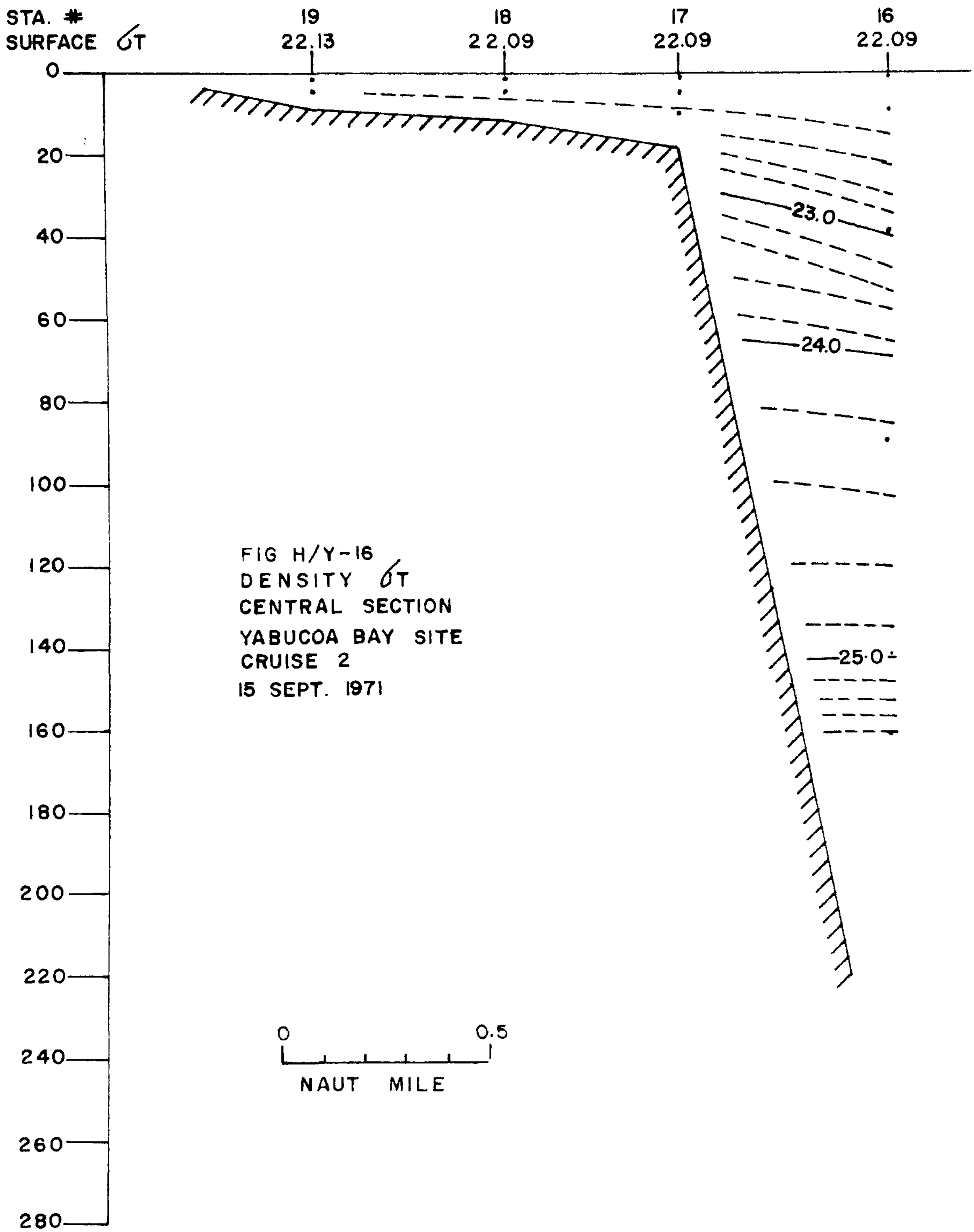


FIG H/Y-15
DENSITY σt
CENTRAL SECTION
YABUCOA SITE
CRUISE I 18 MAY 1971


STA. #
SURFACE σT
19
22.13
18
22.09
17
22.09
16
22.09
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
23.0
24.0
25.0
FIG H/Y-16
DENSITY σT
CENTRAL SECTION
YABUCOA BAY SITE
CRUISE 2
15 SEPT. 1971
0
0.5
NAUT MILE

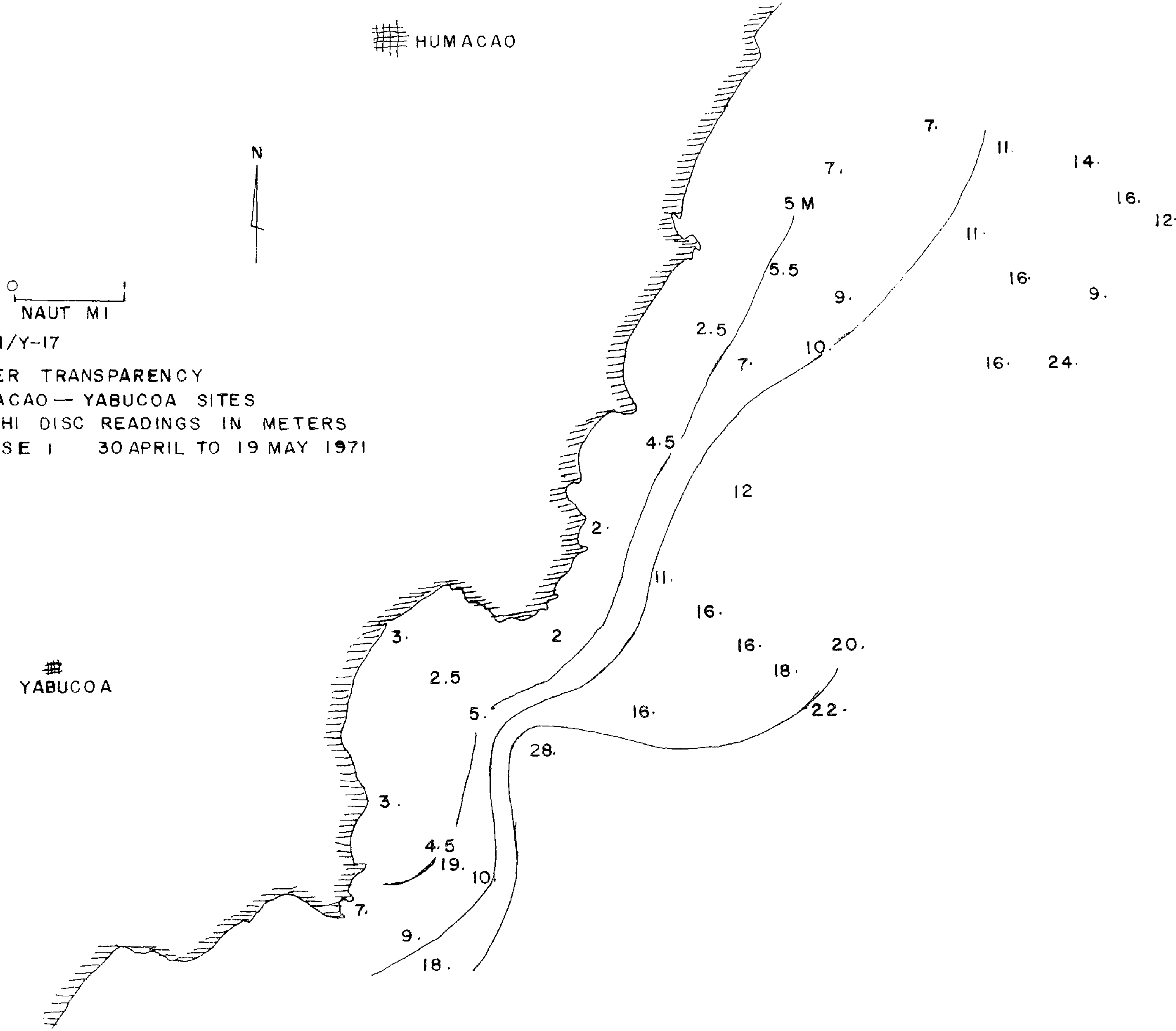


FIG H/Y-17

WATER TRANSPARENCY
HUMACAO — YABUCOA SITES
SECCHI DISC READINGS IN METERS
CRUISE I 30 APRIL TO 19 MAY 1971

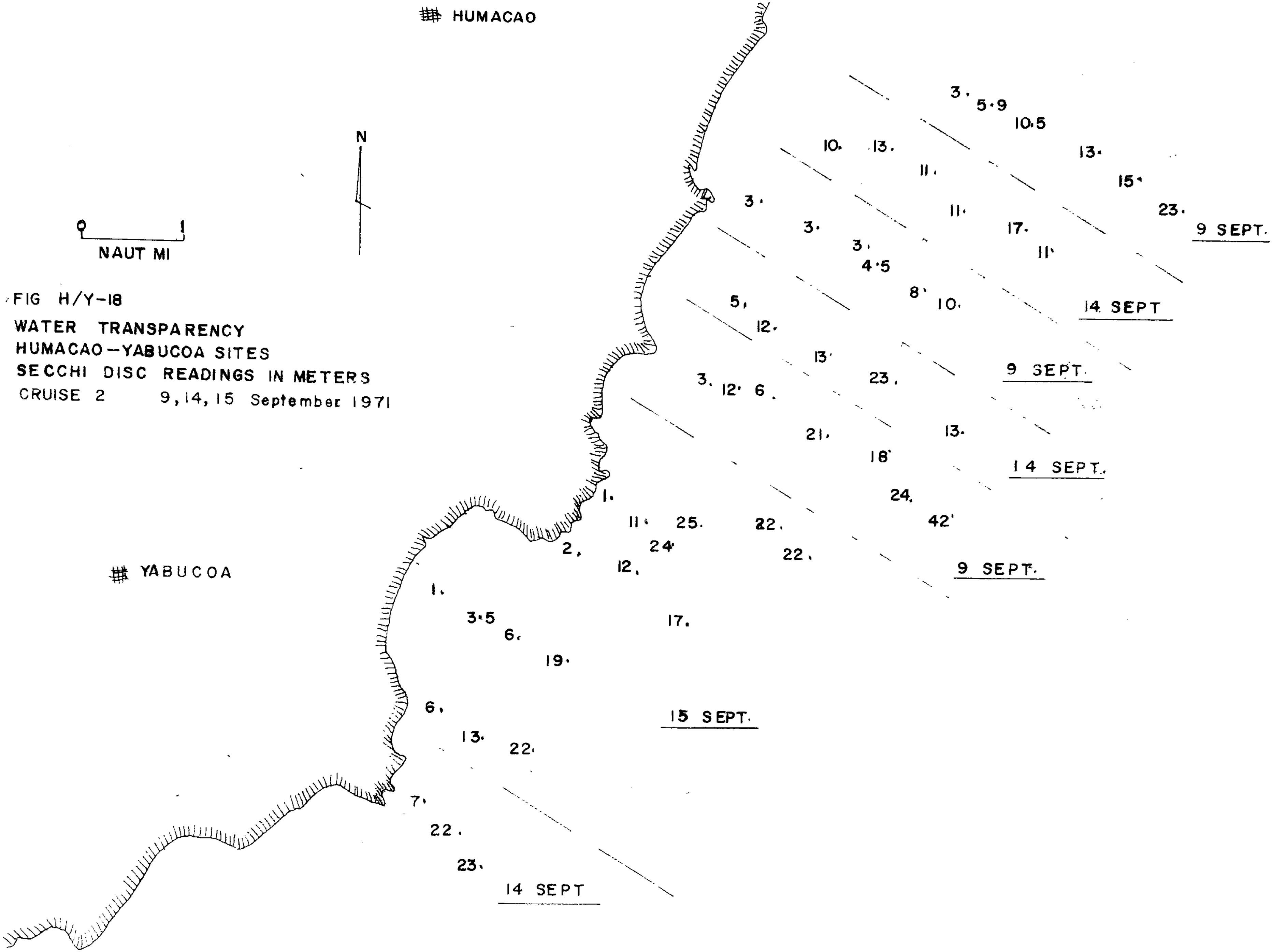


FIG H/Y-18
WATER TRANSPARENCY
HUMACAO–YABUCOA SITES
SECCHI DISC READINGS IN METERS
CRUISE 2 9, 14, 15 September 1971

6.65

GUAYAMA

Description of Study Area

The area considered in this section lies along the southern coast of Puerto Rico between Punta Figuras and Punta Ola Grande. The major urban centers in this area are Guayama and Arroyo. Generally, the coast is highly irregular with numerous sparsely-vegetated projections. Shoals and fringing reefs, either partially or totally awash, are abundant. Most of the time the sea is rough and choppy even at short distances from shore (1). Rainfall is considerably less than in most other parts of the Island, averaging 60 inches a year at Guayama (1). Río Nigua and Río Guamani at Arroyo and Guayama, respectively, are the only streams of importance which discharge into the Caribbean Sea between Punta Figuras and Punta Ola Grande (1).

A preliminary waste water management report (2) provides the following information on domestic and industrial waste water in this region. The city of Guayama is partially sewered, the raw sewage being discharged directly into the Caribbean through an 18 inch cast iron outfall built in 1937. The discharge is about three feet above the water level and 100 feet from shore on a trestle at a point called Punta Barrancas due south of Central Machete. Calculated flows through this pipe fluctuated from a high of 2.72 mgd to a low of 0.88 mgd.

In March 1971, there were 25 industries operating in Guayama, 17 of which are connected to the sewage system (2). The most important industrial operations affecting the quality of coastal waters are an oil refinery, two sugar mills, a pharmaceutical products manufacturing company (produces vitamin B-12 and other vitamins) and three fabric dyeing plants (1). Plant washings and excess process water generated in these operations are discharged into the Caribbean Sea in this area. Plant cooling water, excess process water, and domestic waste from Central Machete sugar mill, however, are conveyed directly into Guayama's main sewer pipe.

Hydrodynamic Data

Various current measurements had been made prior to the present study in the Guayama coastline area. They all were done with the constraint of the present study, i.e., a limited time of continuous observation. The first report, including current measurements, was conducted by Muñoz (1967) under the sponsorship of the Department of Health (1). Drifting drogues submerged three feet below the surface were used at distances of 50, 100, and 300 meters from shore. The general flow of the current was found to be to the west at speeds fluctuating between 0.1 and 0.4 knots. A semi-circular gyre about 300 meters in diameter was observed from the drogue paths at Punta Barranca.

A second study was carried out in the same year by P.R.A.S.A. (3). The method used was to follow the path of wood blocks. A Gurley current meter was used to confirm the velocity results. The general flow path was found to be westward with an onshore component being evident in the majority of the observations.

The most comprehensive study of currents at Guayama was carried out by Heres (2) who released large numbers of drogues at different depths at various locations between Punta Figuras and Punta Conzuelo. Again, the general flow was to the west at varying speeds. However, an eastward flow prevailed on April 16, 1970. Unfortunately, the time when current measurements were taken was not provided in any of the reports. In some, not even the date is included, thus no analysis of the influence of tides can be made.

The station locations for the current measurements obtained during the three cruises of the present study are given in Figure Gm-1. The current meter data is listed in tabular form in Appendix F, and graphs of the data are shown in Figures Gm-2 through Gm-7.

In 20 of the 36 individual current measurements made with the Ekman-Merz meter during Cruise 1, bi-modal currents may have been present as shown by the distribution of balls in two separate sectors of the compass cup. As was done in the cases of this nature off the east coast of Puerto Rico, the average direction was calculated using all the data, and the bi-modal currents were calculated by treating the two main sectors separately. Both the single and the bi-modal currents are listed in tabular form in Appendix F. Only the single mode currents are illustrated in Figures Gm-2 and Gm-3.

It is sometimes claimed that the yawing of the boat at anchor is responsible for the apparent double current. The boat does, indeed, swing slowly back and forth several times during the recording period, which is usually 10 minutes for each observation. However, if this view is accepted, one is then forced to explain why this bi-modality occurs in more than half of the observations at the Guayama site, less than half the observations in the Humacao River and Yabucoa Bay sites, and not at all on the north coast of the Island at the San Juan and Carolina sites. Presumably, the boat was yawing more or less the same at all these places.

The outstanding feature of the results of the Cruise 1 current measurements off Guayama is the reversal of the current at depth. This is shown clearly in Figures Gm-2 and Gm-3. Figure Gm-3 illustrates resultant net flow vectors for each of the three depths, where the length of each vector is proportional to the relative quantity of water flowing in the indicated direction, and the average speed ($\bar{v}$), which is simply a numerical average of the speed at the corresponding depth without regard to direction, is also given (see Appendix B).

As can be seen in Figure Gm-2, vectors illustrating surface currents as measured by the Ekman-Merz meter are predominantly westerly with a spread of 47° between the two most divergent vectors. During the last four hours of observation of surface currents no vector differed by more than 2° from 275° true. No hint of bi-modal currents was found during this period. Only three of the 12 observations at the surface showed signs of bi-modality. At ten meters the current was similarly towards the west, at a slightly lower speed. The flow wavered back and forth more than at the surface, and an analysis of the data suggests the presence of bi-modal currents in nine of the 12 observations. At the 20 meter level, which is only two meters off the bottom, the current was directed strongly towards the east with a resultant direction of 112° true. During the last 2.5 hours of observation, this current slowed down and turned towards the northwest. There is no way of knowing whether this might be related to a tidal factor or not. The wind was blowing steadily from E by S (southeast quadrant) between nine and 16 knots (Appendix F). The observed pattern at the three different depths suggests a strong wind effect on the surface waters.

Drogue studies were carried out during Cruise 2. Results are illustated in Figure Gm-4, and tabular data is given in Appendix F. At the surface, the current was initially towards the west and south, with a shift towards the north (shoreward) at around 1230 hours. According to the Tide Tables (4), low tide occurred at Arroyo, about 5.5 miles to the east of Punta Ola Grande, at 1130 hours, but because of complicating factors resulting from the fact that the tides (again, according to the Tables) are chiefly diurnal in this area, the times computed from the Tables are of doubtful accuracy. Surface current continued generally towards the north, with some shifting towards the east, during the following four hours. Maximum speed was about 0.7 knot. The five meter (mid-depth) drogue spiraled very slowly for almost four hours, then settled down on an ENE track at about 0.3 knot. The eight meter (deep) drogue remained practically stationary for about five hours, as can be seen in the figure. It is to be noted that the strong north-bound surface current was not observed during the other cruises. Wind was from the E or ENE at speeds generally between nine and 15 knots (see Appendix F).

Three in-situ recording current meters were anchored during Cruise 3. Failure of the corrodable links prevented retrieval of the instruments at the time scheduled, and recording of current data was continued for a period of six days. The results of the third cruise current measurements are shown in Figures Gm-5, Gm-6 and Gm-7. Tabular data for speed and direction is given in Appendix F. Figure Gm-5 shows graphs of current speed and direction plotted against time as recorded by the three instruments. Figures Gm-6 and Gm-7 illustrate the results of an analysis giving the actual quantity of flow into each of eight direction sectors centered about the cardinal and inter-cardinal points of the compass (see Appendix B).

From the figures it is apparent that the general direction of flow is in the south-western quadrant, with the outer deep meter registering the most southerly flow. Cyclic variations in direction, corresponding roughly to a semilunar period, are also apparent in Figure Gm-5. The Tide Tables list the tides at Arroyo, about 5.5 miles to the east of Punta Ola Grande, as being chiefly diurnal. Thus, tide data from the Tide Tables does not agree with the timing of what appear to be tidal effects in Figure Gm-5.

Hydrographic Data

The Guayama hydrographic stations were situated near Punta Ola Grande on the southern coast of the Island on a broad (seven miles wide or more), shallow (25 fathoms deep or less) shelf. About ten miles eastward along the coast the shelf suddenly narrows to about 1.5 miles.

Tables of data for temperature, salinity, and density (sigma-t) are given in Appendix F. The locations of these hydrographic stations are shown in Figure Gm-8. Figures Gm-9 and Gm-10 illustrate surface density patterns observed during Cruise 1 and 2, respectively, and Figure GM-11 shows density profiles of the center section of the site as observed during the two cruises. The largest temperature variation in the profiles in only 0.3°C., and the largest salinity variation is 0.21. As can be seen in the density profiles shown in Figure Gm-11, the greatest variation in sigma-t is about 0.25. Thus, though there appears to be an overall seasonal variation in density, the water remains well mixed and probably no amount of mixing of waste water with ocean water at the bottom will prevent the waste water from rising to the surface. The prevailing wind is from the east, with an onshore component during the day, and an offshore component at night. Consequently, there is a possibility that wastes on the surface would be blown ashore.

Water Quality Data

Tables of water quality data obtained during Cruises 1 and 2 are included in Appendix F. Only Secchi disc readings and samplings for silica and phosphorus were taken during Cruise 1. The transparency readings showed there to be no major zones of turbid water or decreases in transparency close to shore, as can be seen from Figure Gm-12. Silica and phosphorus readings were low (0.0 to 0.1 mg/l and 0.00 to 0.08 mg/l, respectively).

On the second cruise, Secchi disc readings showed an area of turbidity east of Las Marens with little turbidity elsewhere (Figure Gm-13). Dissolved oxygen concentrations were uniformly in the 6-7 mg/l range. Silica, where measured, was in the range of 0.20 to 0.35 mg/l, and phosphorus readings varied from 0.0007 to 0.0014 mg/l. Coliform MPN levels varied from 1 to 100/100 ml.

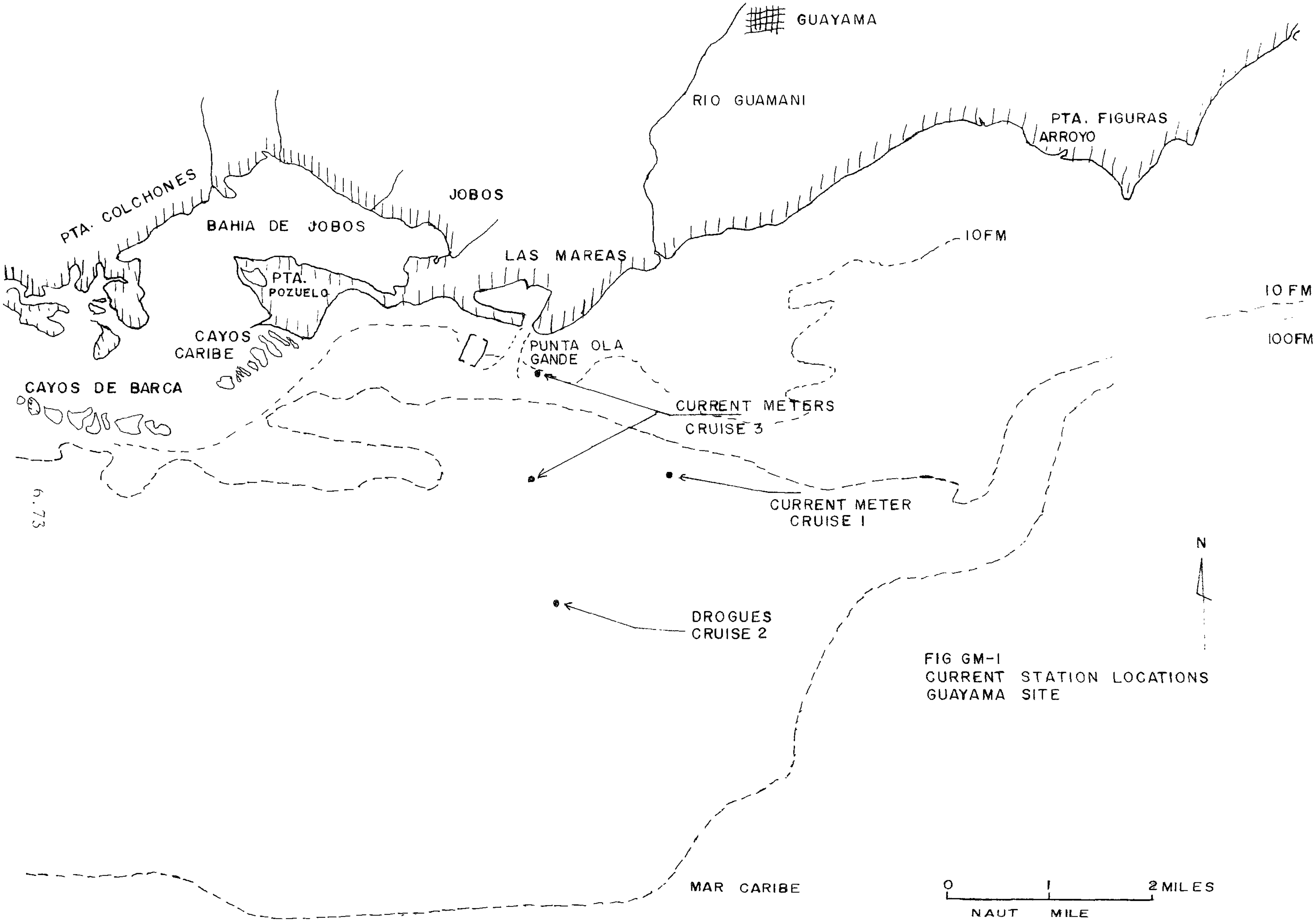


FIG GM-1
CURRENT STATION LOCATIONS
GUAYAMA SITE

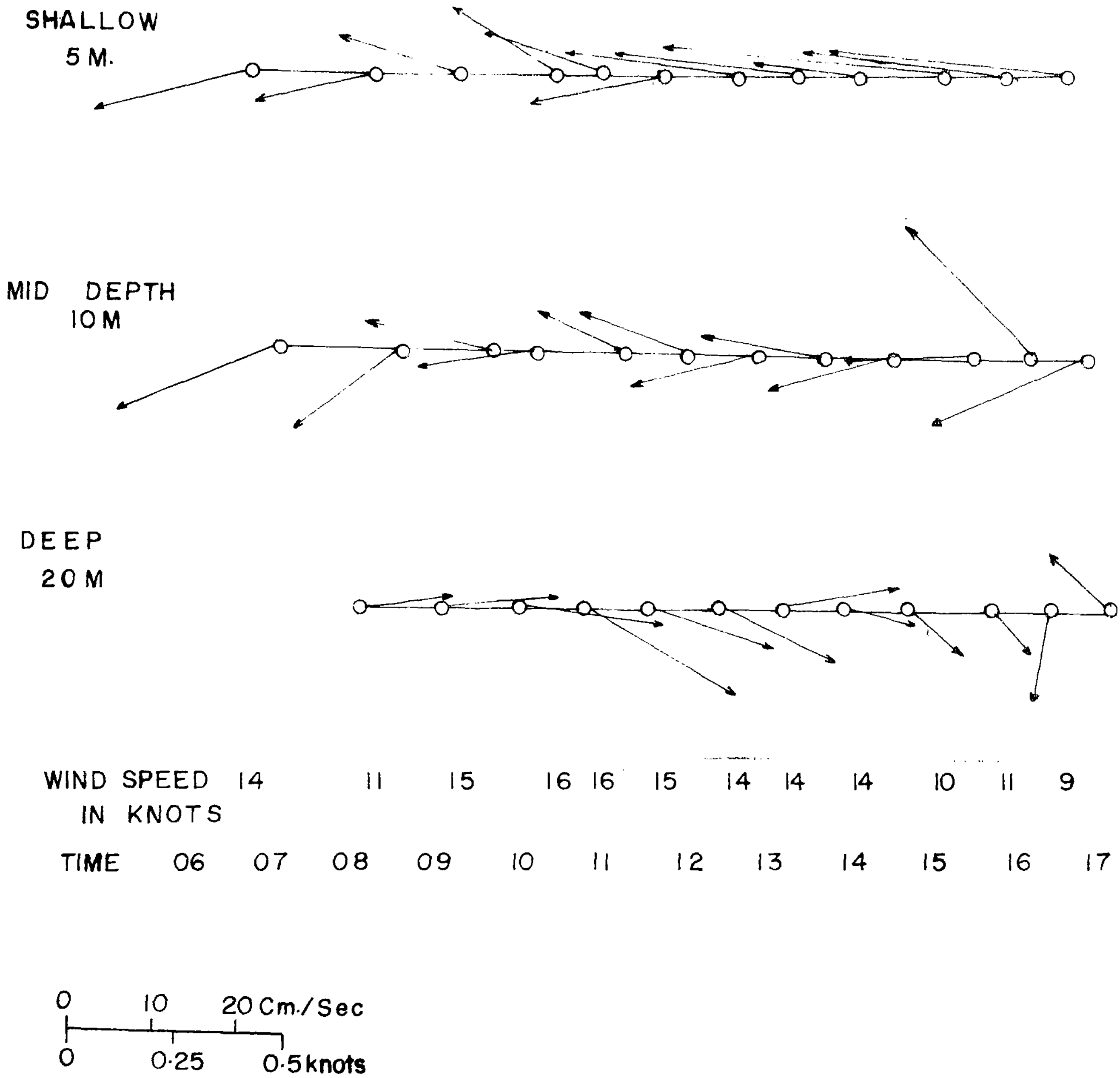


FIG GM-2
CURRENT VECTORS
GUAYAMA
CRUISE 1 JUNE 1 1971
DEPTH OF WATER 22M.

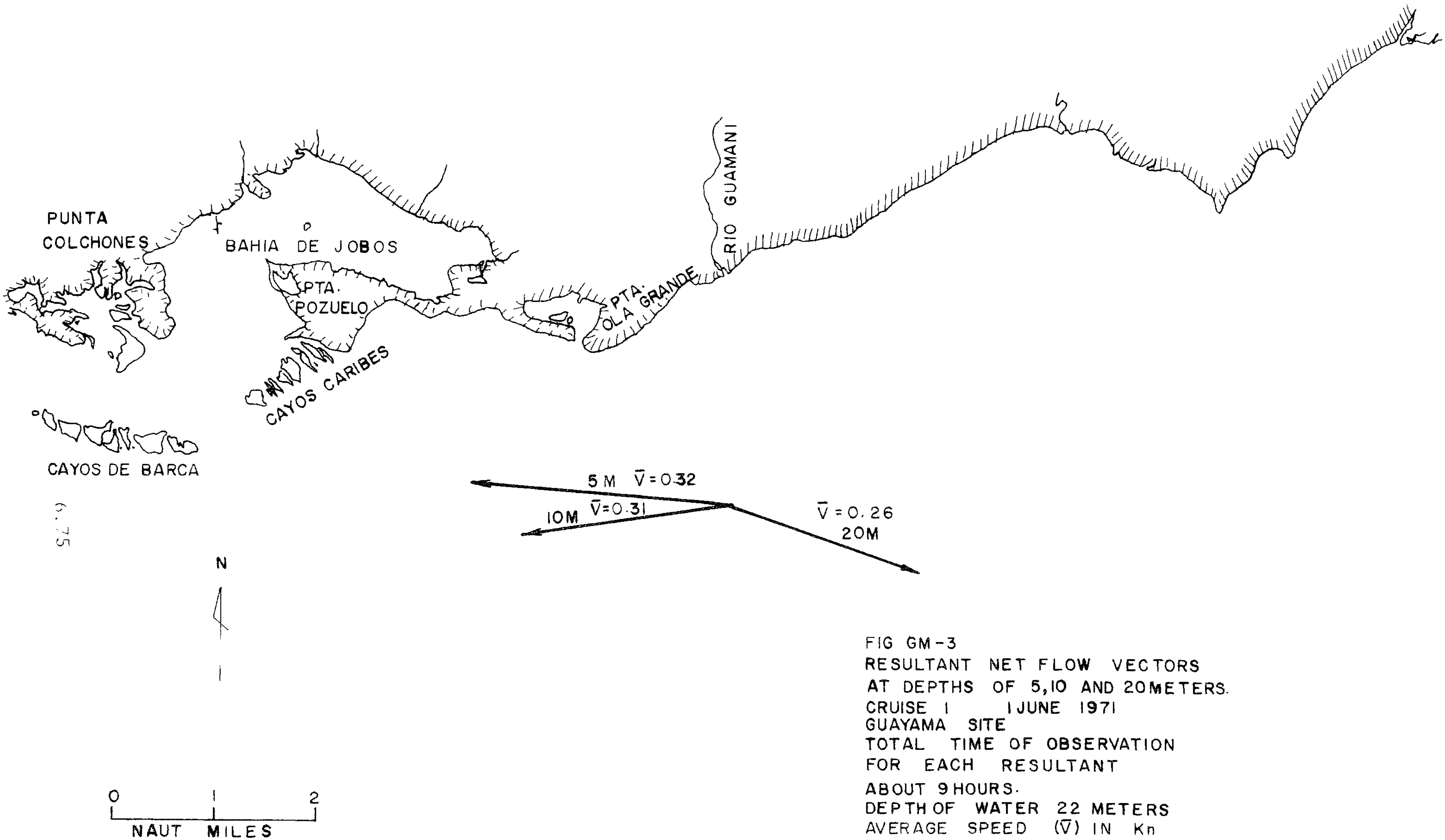
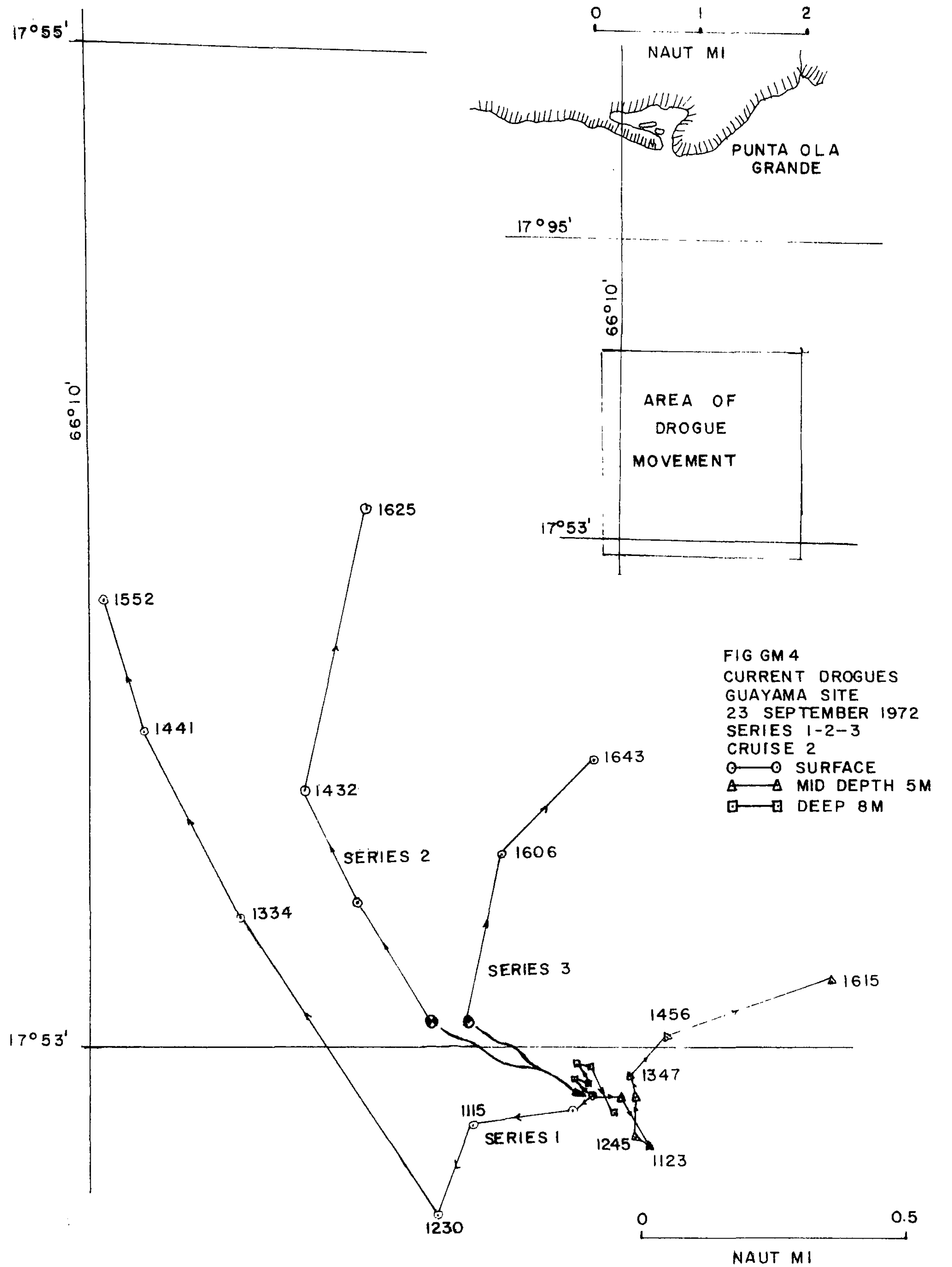


FIG GM-3
RESULTANT NET FLOW VECTORS
AT DEPTHS OF 5,10 AND 20 METERS.
CRUISE 1 1 JUNE 1971
GUAYAMA SITE
TOTAL TIME OF OBSERVATION
FOR EACH RESULTANT
ABOUT 9 HOURS.
DEPTH OF WATER 22 METERS
AVERAGE SPEED ($\bar{V}$) IN Kn


17°55'
66°10'
17°53'
0
1
2
NAUT MI
PUNTA OLA
GRANDE
17°95'
66°10'
AREA OF
DROGUE
MOVEMENT
17°53'
1625
1552
1441
1432
1643
SERIES 2
1606
1334
SERIES 3
1615
1456
1347
1115
SERIES I
1245
1123
1230
0
0.5
NAUT MI
FIG GM 4
CURRENT DROGUES
GUAYAMA SITE
23 SEPTEMBER 1972
SERIES 1-2-3
CRUISE 2
SURFACE
MID DEPTH 5M
DEEP 8M

PAGE NOT

AVAILABLE

DIGITALLY

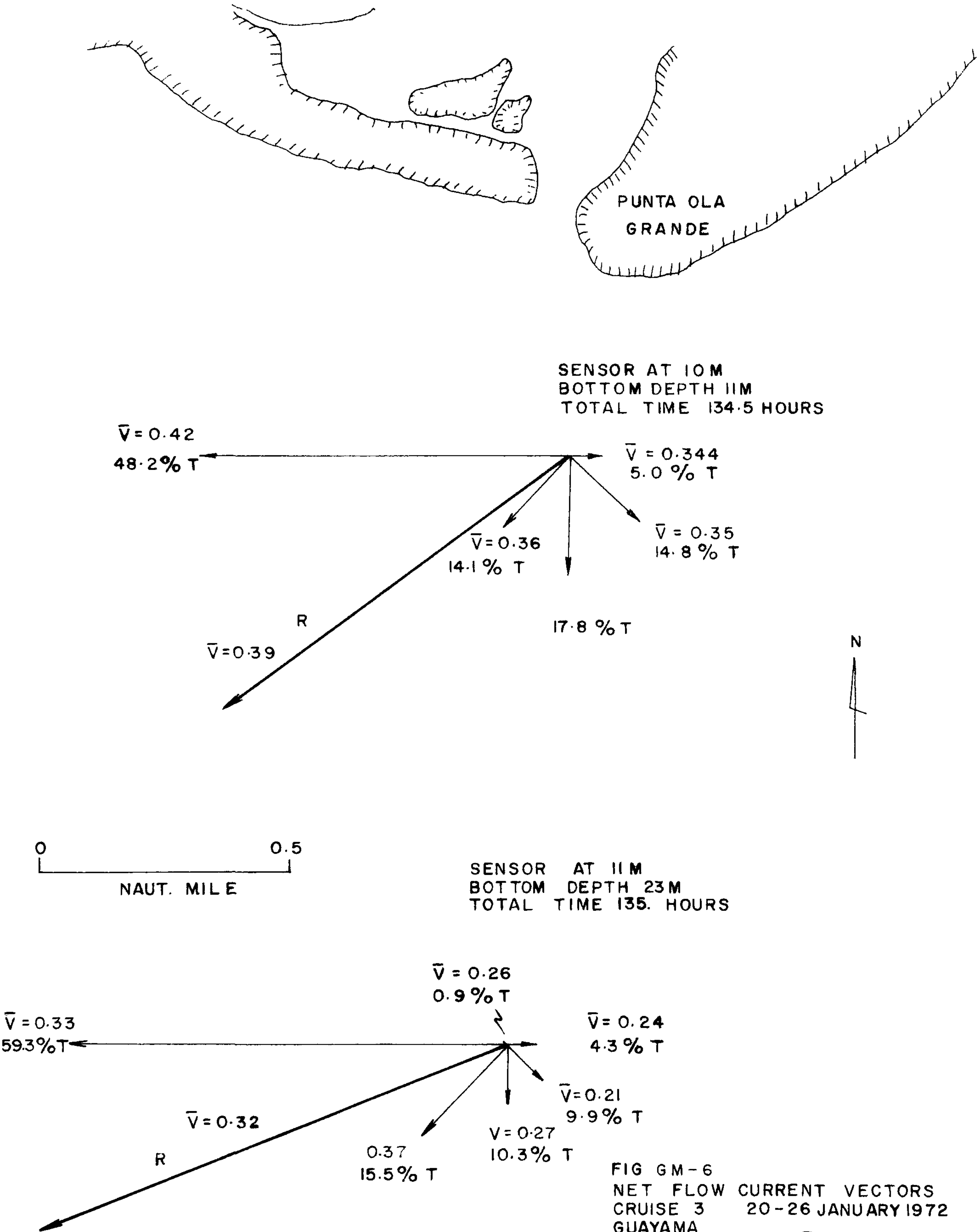


FIG GM-6
NET FLOW CURRENT VECTORS
CRUISE 3 20-26 JANUARY 1972
GUAYAMA
AVERAGE SPEED (V̄) IN Kn
AND PER CENT OF TOTAL
TIME SHOWN FOR EACH OCTANT

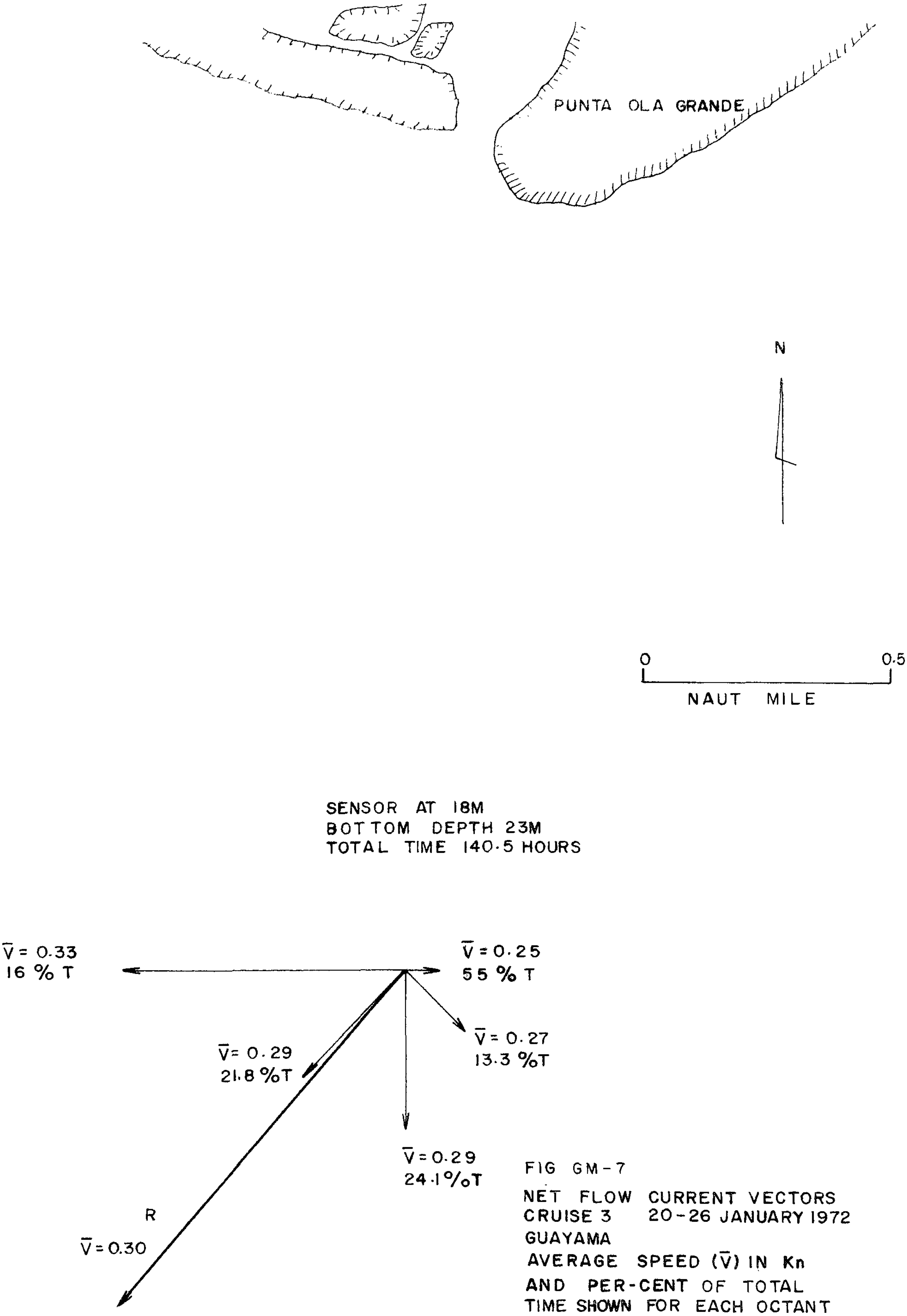


FIG GM-7

NET FLOW CURRENT VECTORS
CRUISE 3 20-26 JANUARY 1972
GUAYAMA
AVERAGE SPEED ($\bar{V}$) IN Kn
AND PER-CENT OF TOTAL
TIME SHOWN FOR EACH OCTANT

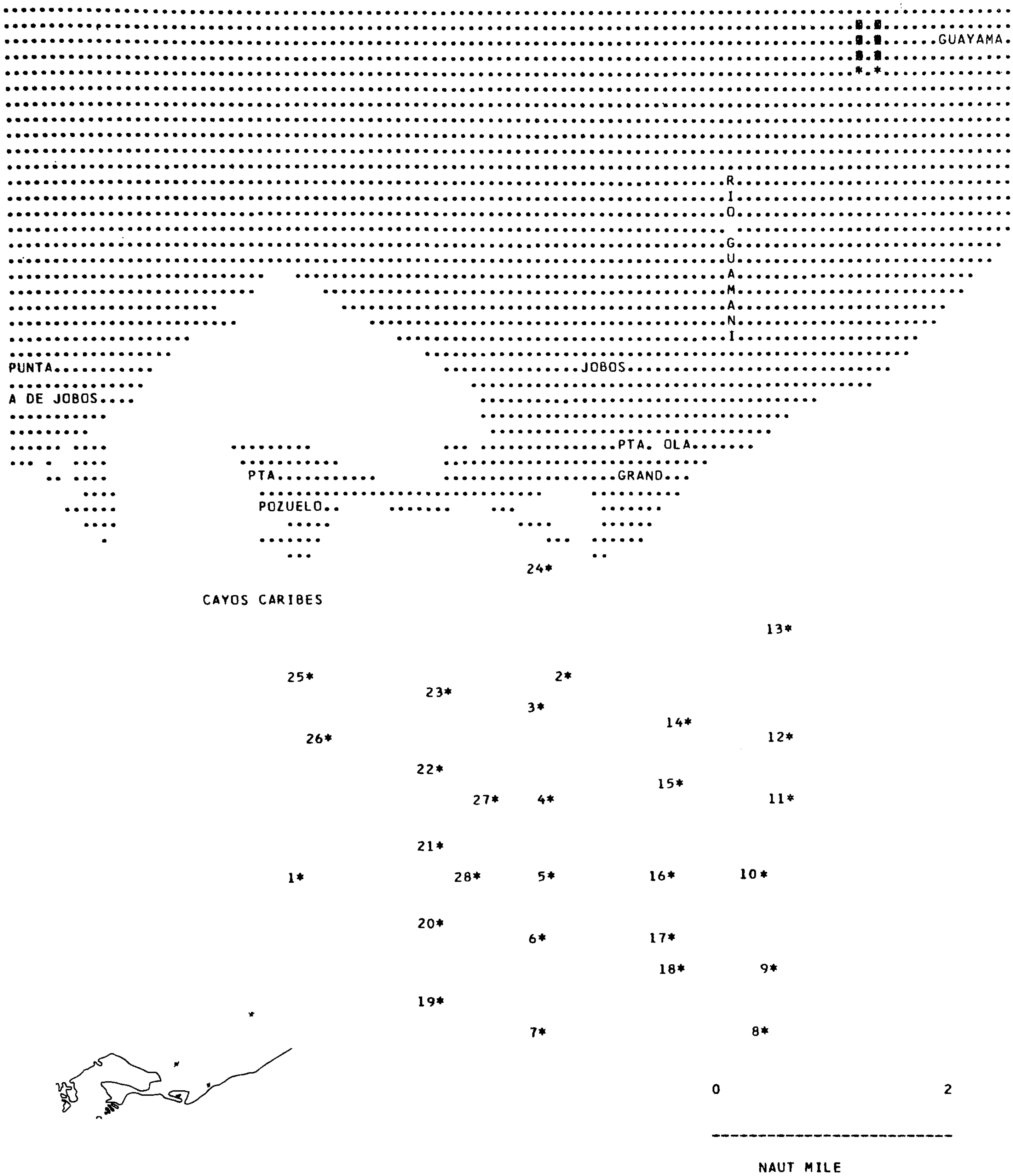


Figure GM-8a
HYDROGRAPHIC STATION LOCATIONS
GUAYAMA
CRUISE 1 25, 26 MAY 1971

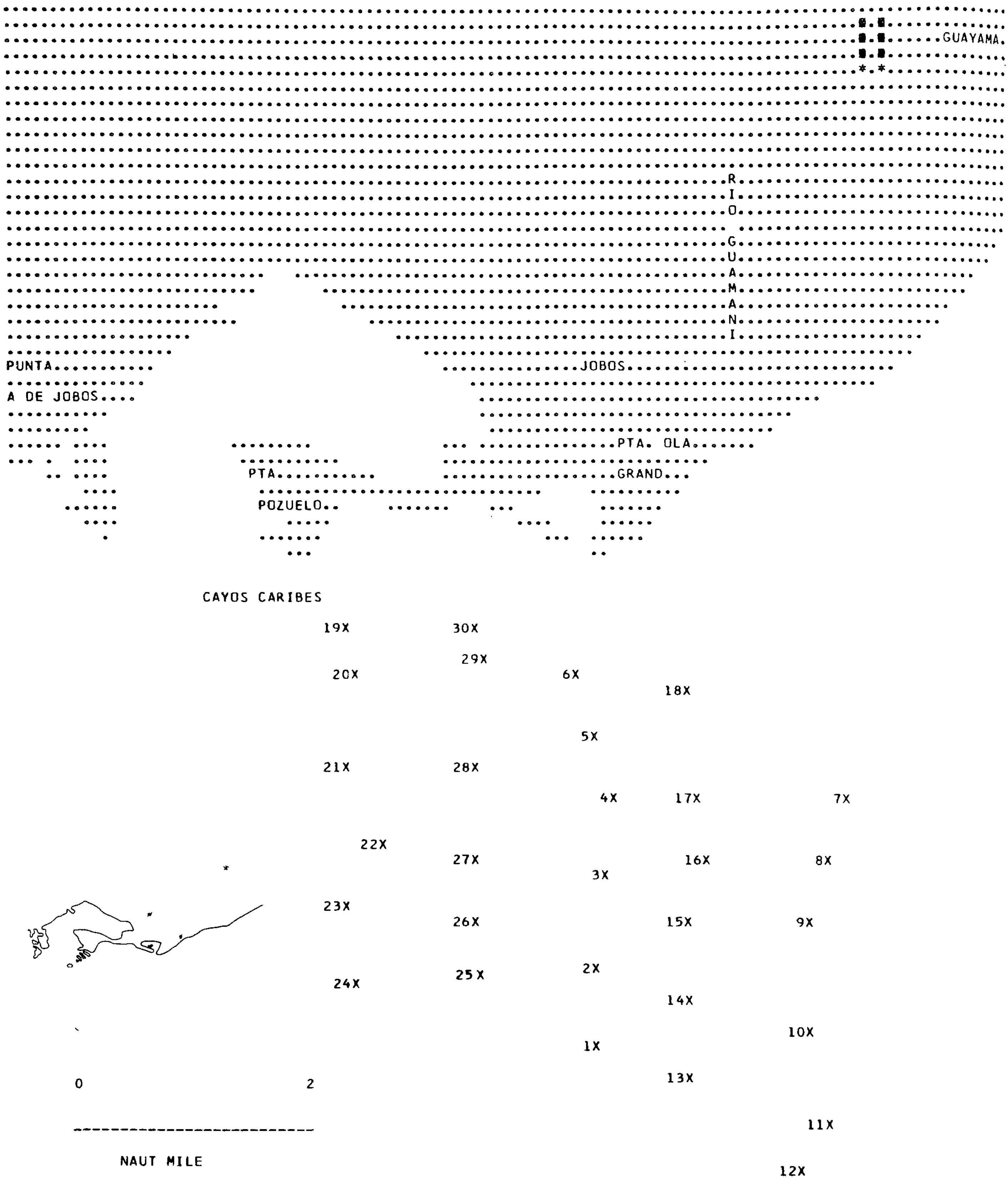


Figure GM-8b
HYDROGRAPHIC STATION LOCATIONS
GUAYAMA
CRUISE 2 23 SEPTEMBER 1971

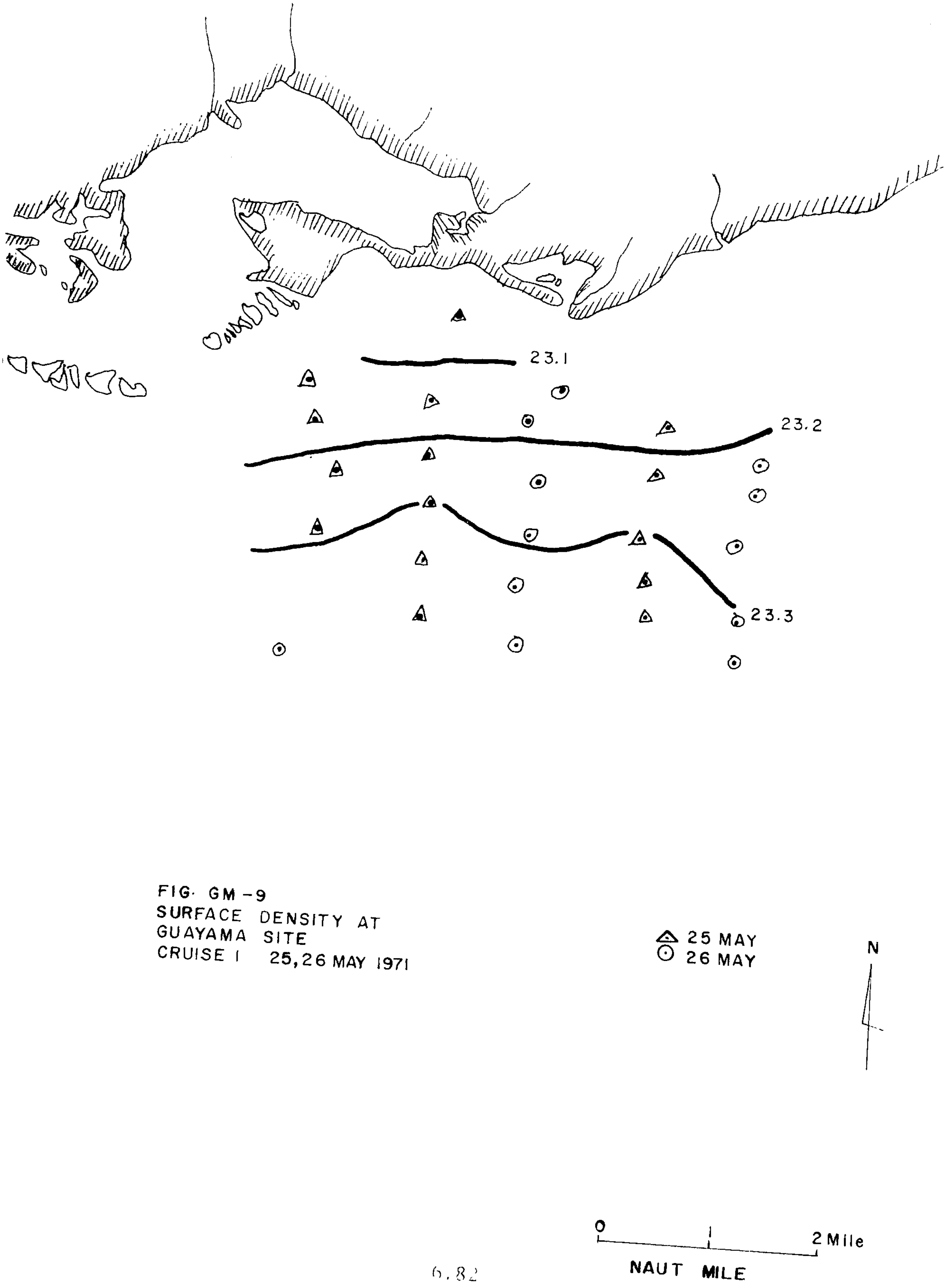


FIG. GM-9
SURFACE DENSITY AT
GUAYAMA SITE
CRUISE I 25,26 MAY 1971

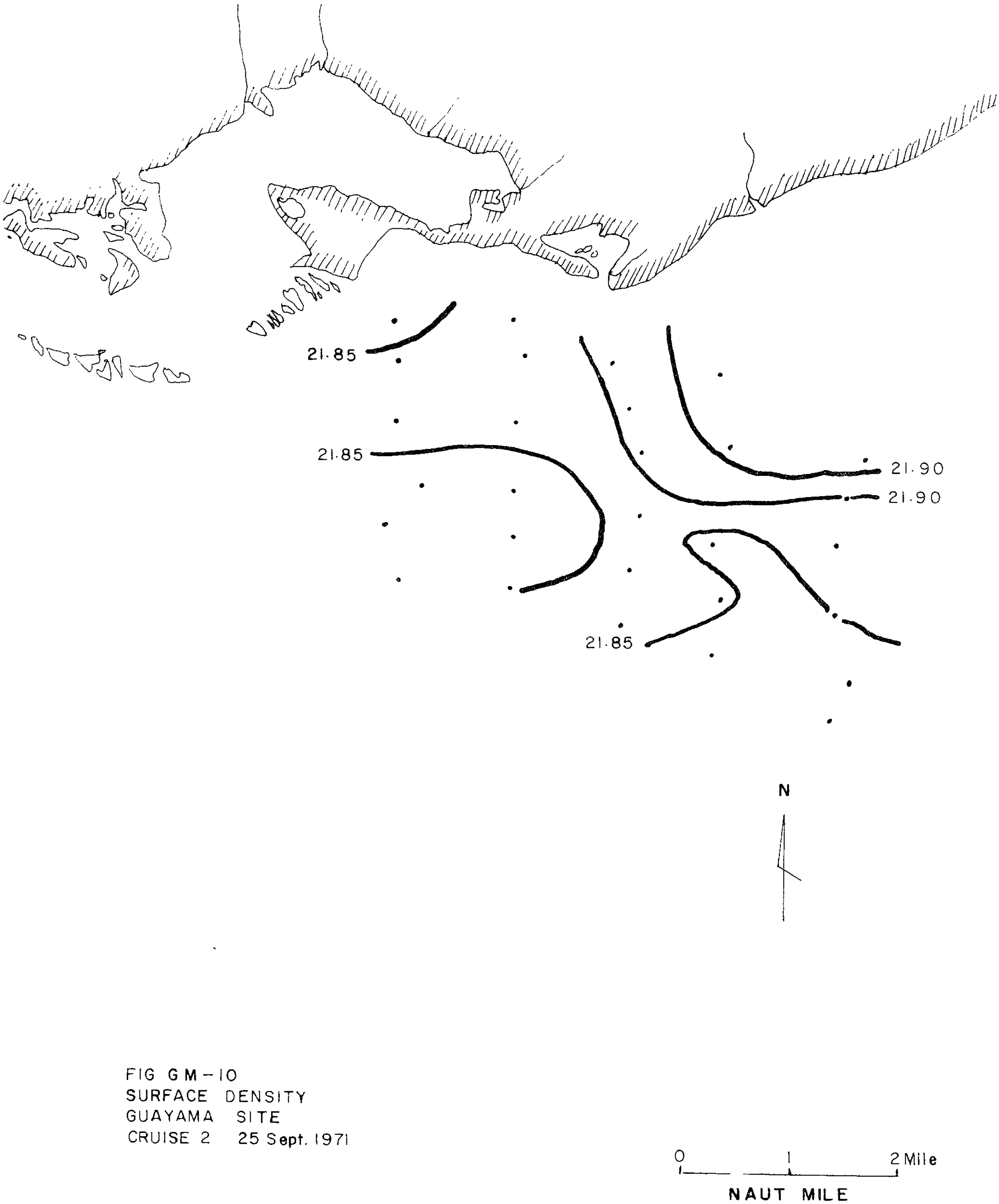


FIG GM-10
SURFACE DENSITY
GUAYAMA SITE
CRUISE 2 25 Sept. 1971

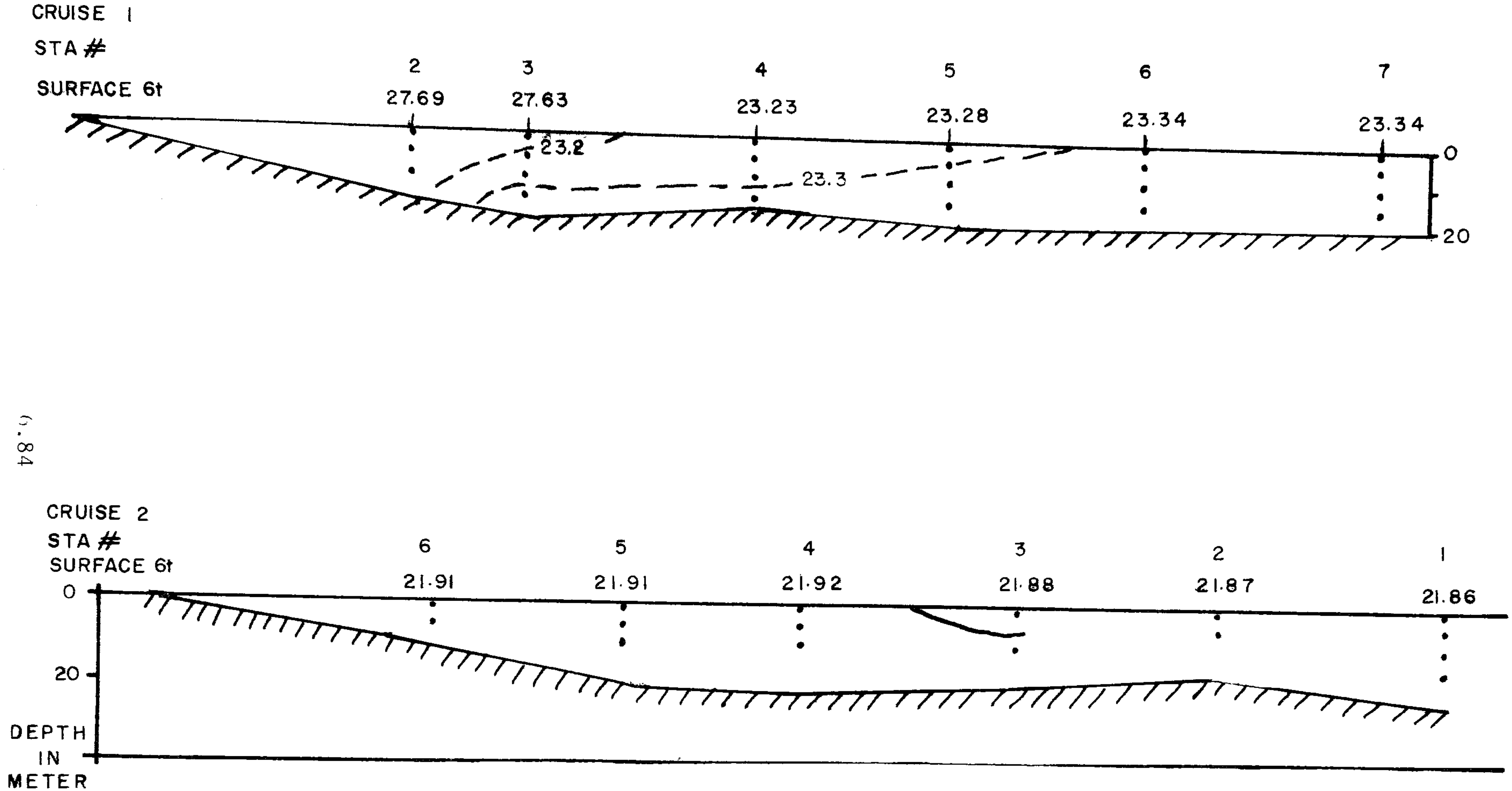
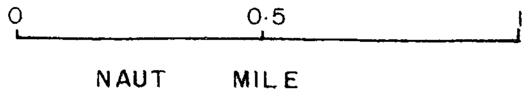


FIG GM-11
DENSITY
CENTRAL SECTION
GUAYAMA SITE
CRUISE 1 25, 26 MAY 1971
CRUISE 2 23 SEPT 1971



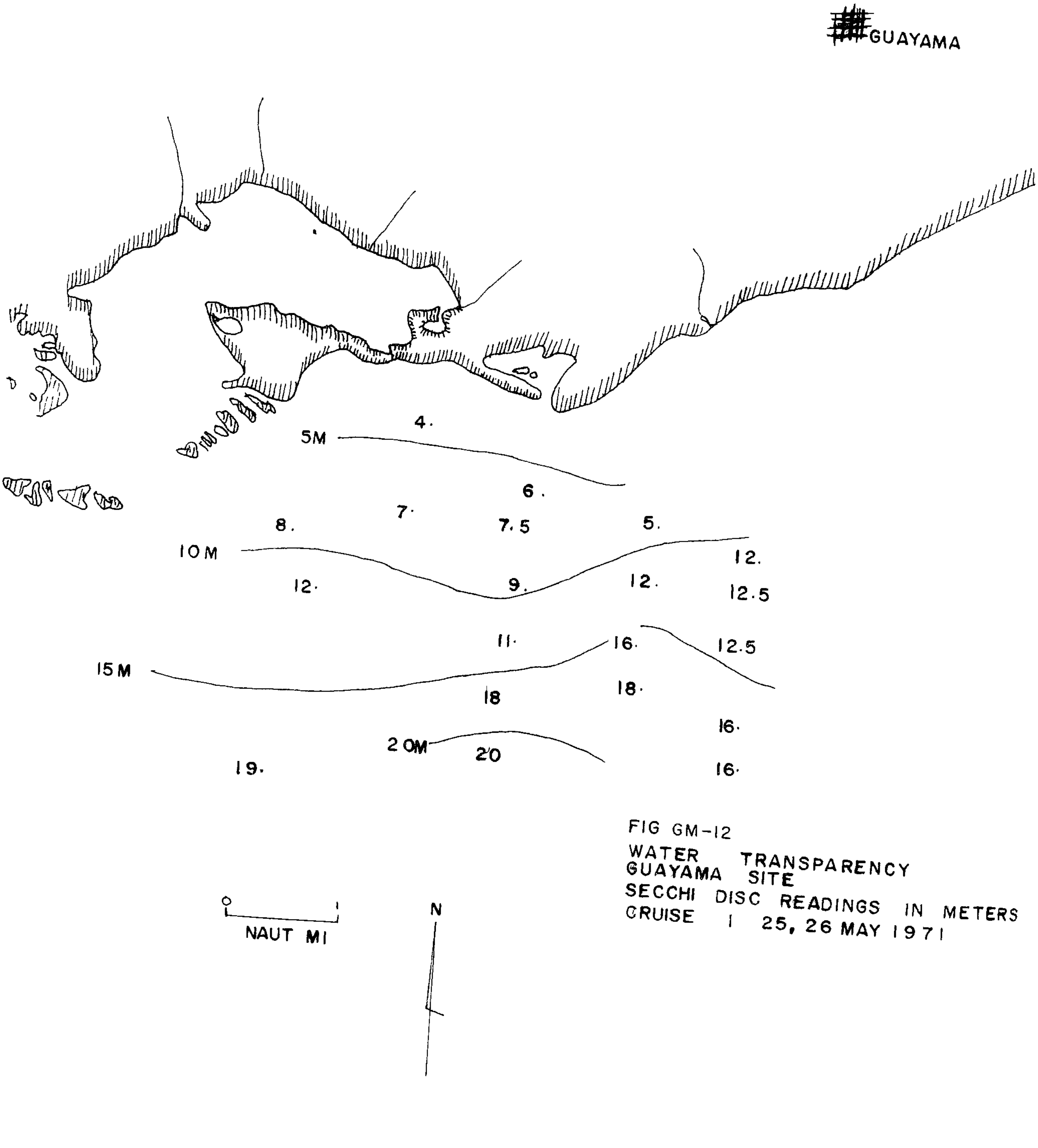


FIG GM-12
WATER TRANSPARENCY
GUAYAMA SITE
SECCHI DISC READINGS IN METERS
CRUISE 1 25, 26 MAY 1971

Ponce

Description of Study Area

The city of Ponce, with a population of 114,000, is the second largest city in the Commonwealth. Ponce is located 2 miles inland from the port, which is called Playa de Ponce.

Bahía de Ponce, situated on the south coast of Puerto Rico, is located at latitude 17°58' and longitude 66°37'. The bay is the most important commercial harbor on the south coast and one of the three leading ports of the island. The prevailing tides at Ponce Bay are diurnal, with a range of up to about 1.1 feet.

Prevailing winds in the area are from the easterly quadrant throughout the year. Close to shore, diurnal effects due to sunlight heating the land tend to produce onshore winds during the daytime and offshore winds at night. The harbor itself is protected from the prevailing easterly trade winds by Punta Peñoncillo and Cayo Gata with their surrounding reefs, but it is exposed southward. It is reasonable to expect that the prevailing westerly set of the ocean currents off the southern coast of the island would be modified by local conditions closer to shore.

Untreated domestic sewage enters the bay through two separate outfalls with a total flow of approximately 9.4 MGD (1). The Hostos outfall is submerged, extending 200 meters from shore while the Pampanos outfall, one foot above the water surface, discharges about 250 meters from the shoreline. It has been observed that sewage is quickly blown onshore by the prevailing winds (1), and that the receiving waters are unable to assimilate and disperse the pollutants (2). It has been estimated that the raw sewage being discharged into Ponce Bay is at present contributing about 19,400 pounds of BOD_5 daily (1) to the receiving waters.

There is also considerable industrial activity in the area adjacent to Bahía de Ponce. At the Ralston-Purina Tuna Fish Packing Plant about 150 tons of tuna fish per day are processed, with the resultant discharge of wastes rich in proteins, oils, fish meat, bones, and other organic constituents into Ponce harbor. The Ponce Tanning Corporation and the Municipal Slaughterhouse also discharge all liquid and solid wastes into the bay. Other sources of pollution include several textile and commercial establishments located in the area of Playa de Ponce.

Pollutants also enter Bahía de Ponce from two major river watersheds. The Río Matilde discharges just west of Punta Peñoncillo. The Río Portugués is another river which courses through Ponce, although it is on rare occasions that the river flow is sufficient to reach the ocean.

Hydrodynamics

Current studies prior to the present surveys were carried out at Ponce in 1969 (2), using drifting floats. It was found during this study that the surface currents have a net flow to the NE at speeds of 12 to 40 cm/sec, and, during two night observations, the floats were found to drift towards the SW. Similar results are reported by Rafael A. Domenech (1), as quoted from a survey report by P.R.A.S.A.

The studies at Ponce Bay followed procedures similar to those used at the other sites, but Cruise 3 was omitted for this area. In Figure P-1 the station locations for the study are given. The results obtained with the Ekman-Merz meter during the first cruise are shown in Figure P-2, and tabular data is included in Appendix G. For surface waters the results were similar to those obtained during previous studies. However, there was a shear present as indicated by a net movement to the SE at a depth of 8 to 9 meters. As can be seen from Figure P-2, the shear occurred at 0926 hours, one hour after low tide. A clock-wise reversal began at 1450, resulting finally in a flow in the same direction as the surface water. Again as at other sites, a bimodal pattern prevailed with the exception of two observations out of a total of 42. The speed varied from 9.9 cm/sec with the first early morning observation (0633), to above 30 cm/sec in mid-afternoon, for surface waters. Slightly lower values were recorded at a depth of 9 meters.

As at the other sites, both an in-situ recording current meter and drogues were used at Ponce to measure currents during Cruise 2. It was at Ponce, however, that it was discovered that the recently borrowed recording current meter had not been functioning properly. Subsequent attempts to correct the malfunction of this particular recording meter proved unsuccessful, and the questionable results obtained with this meter during Cruise 2 were discarded.

Drogue data from Cruise 2 is shown in Figure P-3, and tabular data is given in Appendix G. Again a shear is evident in Figure P-3, were flow was observed to be toward the east for the deeper drogue. All observations were made during flood tide. The deeper (5m) drogue was seen to veer toward the west at around 1310 hours, which, according to the Tide Tables (3), was half-way through the flood tide cycle. It has so far been impossible to establish any clear tide pattern influence on the currents at Ponce, as well as at other areas on the south coast. The Tide Tables were used to determine times of high and low tide. The reference station for this area of the south coast is Galveston, Texas, for which corrections of -6:30 hours for high tide and -12:00 hours for low tide are indicated. Though the Tide Tables do state that in cases where tides are listed as chiefly diurnal, as at Ponce, the computed times "are intended primarily for predicting the higher high and lower low waters," the results are nevertheless rather odd at certain times. It is felt that a more reliable source of tide data must be obtained if the tidal influence upon currents on the south coast is to be understood. At this writing it is expected that a recording tide guage will shortly be made available for use by the Oceanographic Project, and that results obtained with this instrument together with further current data will be published in the near future.

It has been concluded from an evaluation of the data obtained for Ponce that the prevailing flow of surface waters is shoreward in a NW direction, whereas the deeper water oscillates from NW to SE with no clearly-defined tidal relation. This, however, is not necessarily a representative pattern as continuous data for a considerably longer period will be required to obtain a more representative picture of the overall current pattern for the area.

Hydrographic Data

Hydrographic station locations are shown in Figure P-4. The hydrographic station data is given in tabular form in Appendix G, and water density values computed from these results are shown in Figures P-5 through P-8. The discolored waters of the inner bay are approximately 1°C warmer than the surface waters found outside the bay, and further along the coast to the east. A small horizontal gradient exists with the most turbid inshore water being a few tenths of a degree warmer than the slightly less turbid off-shore water. Temperatures at five meters are not significantly different from those at the surface.

Surface salinity values average about 0.2 percent less than the values at Guayama. Again, a slight horizontal gradient exists, the inshore water being slightly less saline (about 0.1-0.2 percent) than that offshore. The surface density, given as sigma-t in Figures P-5 and P-6, shows a similar pattern. It averages about 0.4 sigma-t units less dense than the surface water at Guayama, and a horizontal change of about 0.3 sigma-t units is present with the offshore waters being the more dense.

Profiles of temperature, salinity, and sigma-t along sections within the inner bay are not definitely structured. The density profile for the section running offshore along the western side of the survey area for Cruise 1 is shown in Figure P-7, whereas for Cruise 2 the offshore section along the eastern side has been shown in Figure P-8. As is apparent from the data in these figures, no significant density contrasts are present in the inshore area. Thus, within the inner bay no amount of mixing and dilution is expected to prevent the waste plume from rising to the surface of the bay where it now is. It is only at the outer stations where strong temperature, salinity, and resulting density gradients are found.

Water Quality

Water quality data was collected in the Ponce area during both cruises. Results are given in Appendix G. Secchi disk readings varied between 1.5 and 9 meters, with the bulk of the observations being between 1.5 and 3 meters (Figure P-9). These values are indicative of turbid water. However, the silica and phosphorus readings were low (0-0.1 mg/l and 0.00 to 0.01 mg/l respectively), indicating that there was a low level of nutrients present in this area.

On the second cruise Secchi depths were a little deeper, indicating less turbidity (Figure P-10). Readings varied from 2 to 24 meters, the majority being between 2 and 4 meters. The dissolved oxygen concentration varied between 6.07 and 7.19 mg/l, close to saturation. Coliform MPN levels were low (between 50 and 90/100 ml), as were silica and phosphorus concentrations (0.03 to 0.10 mg/l and 0.013 to 0.031 mg/l respectively).

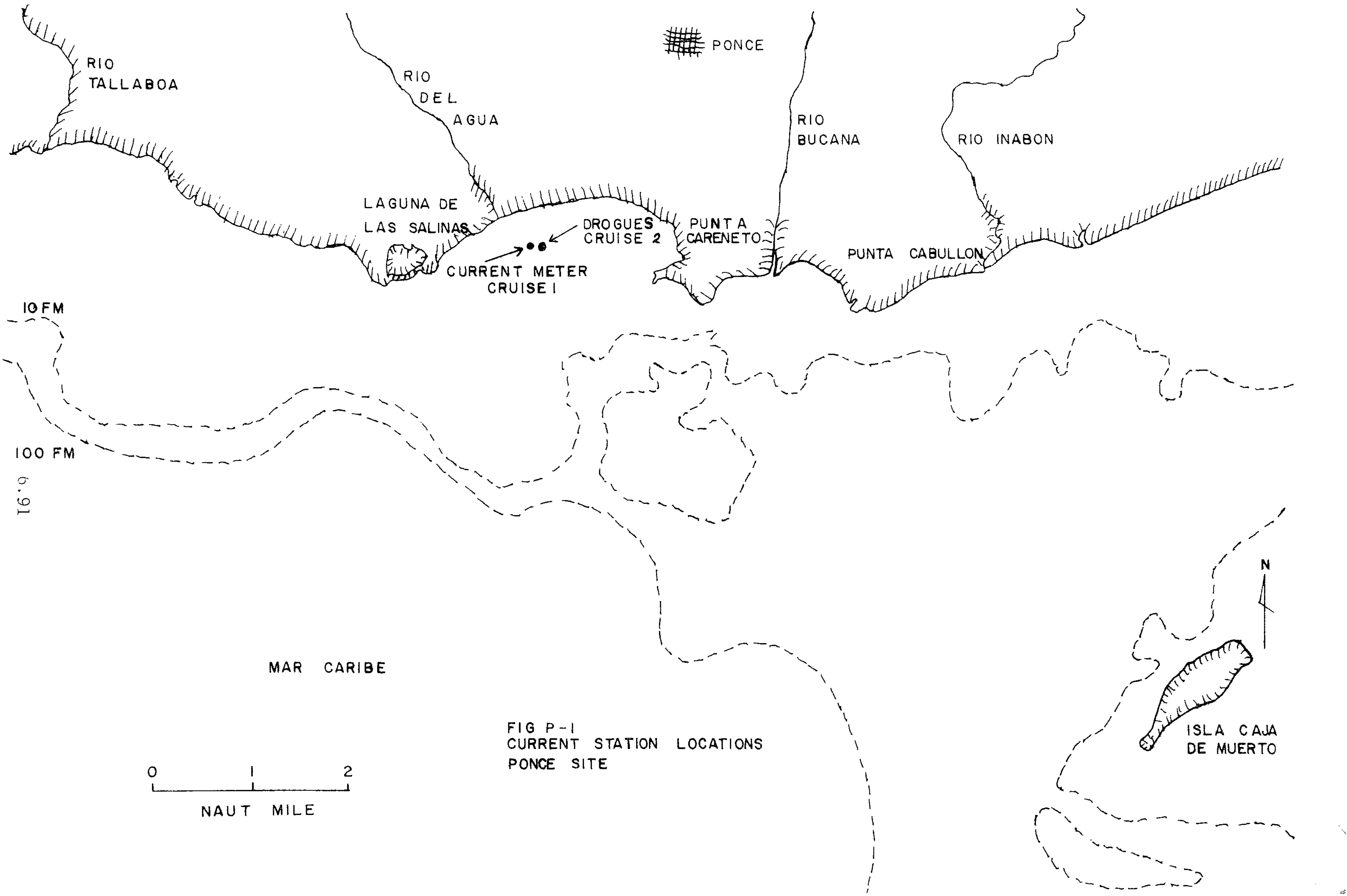


FIG P-1
CURRENT STATION LOCATIONS
PONCE SITE

16.9

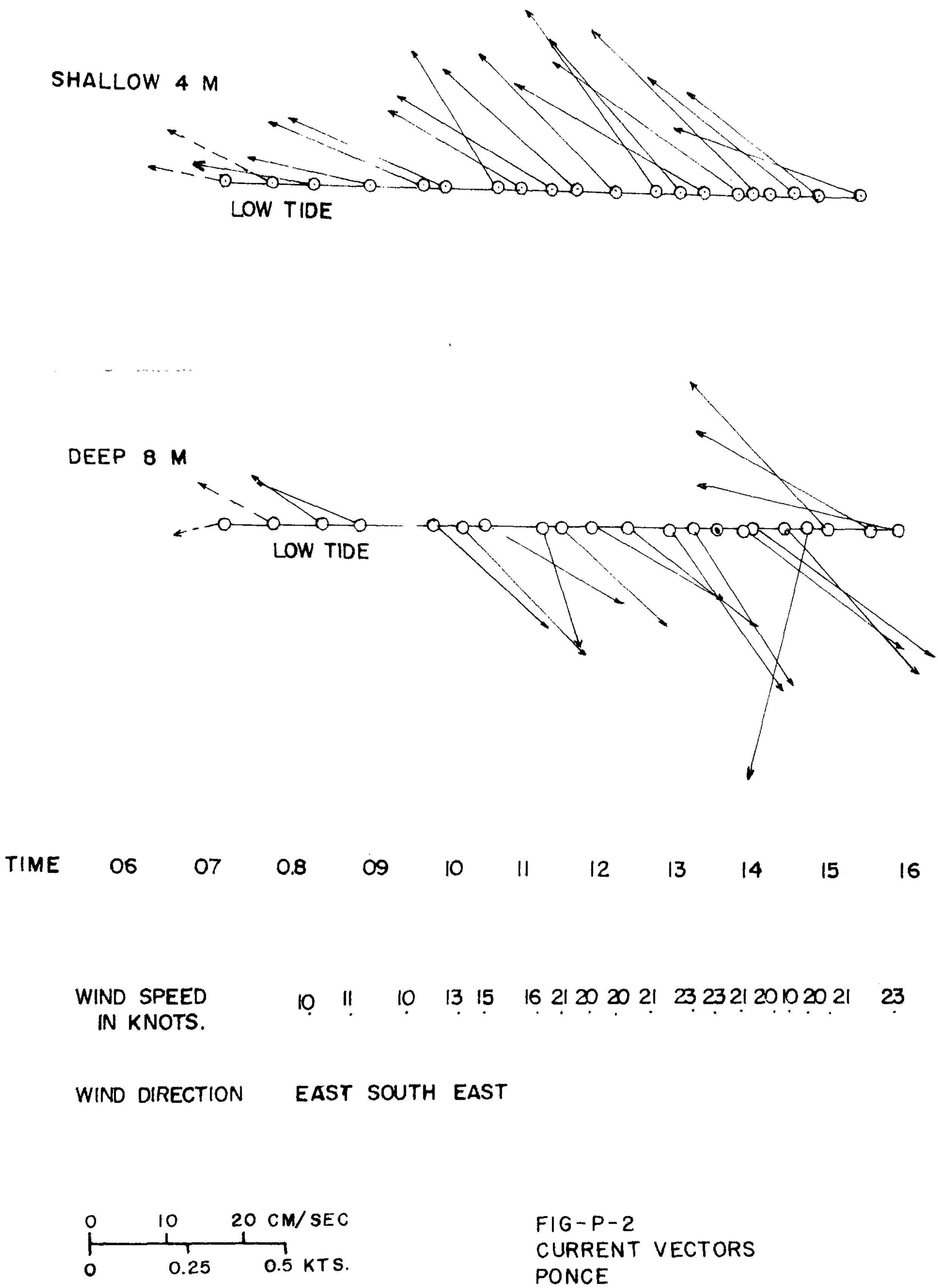


FIG-P-2
CURRENT VECTORS
PONCE
CRUISE I JUNE 4 1971
LOW TIDE 0827

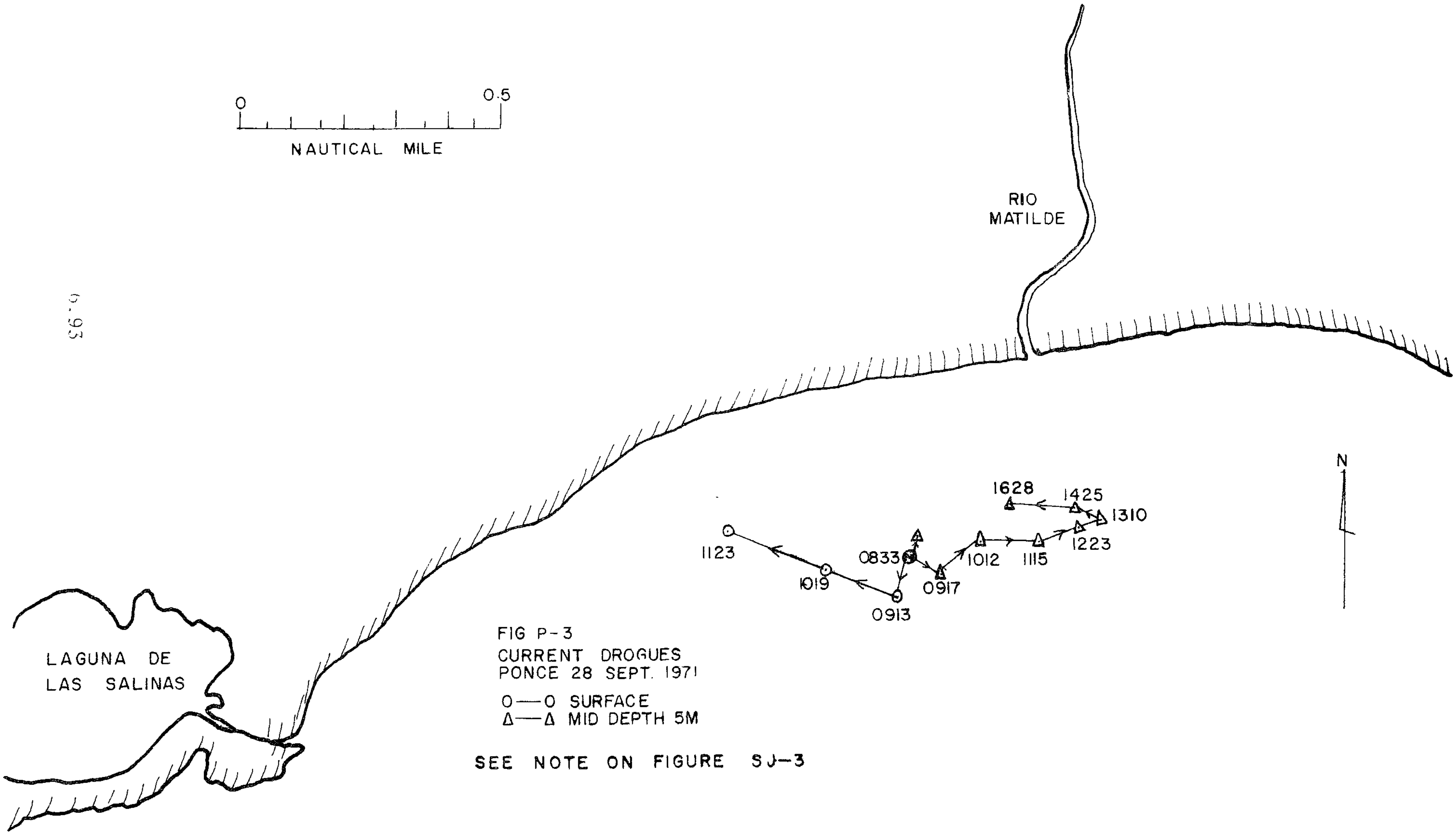


FIG P-3
CURRENT DROGUES
PONCE 28 SEPT. 1971

SEE NOTE ON FIGURE SJ-3

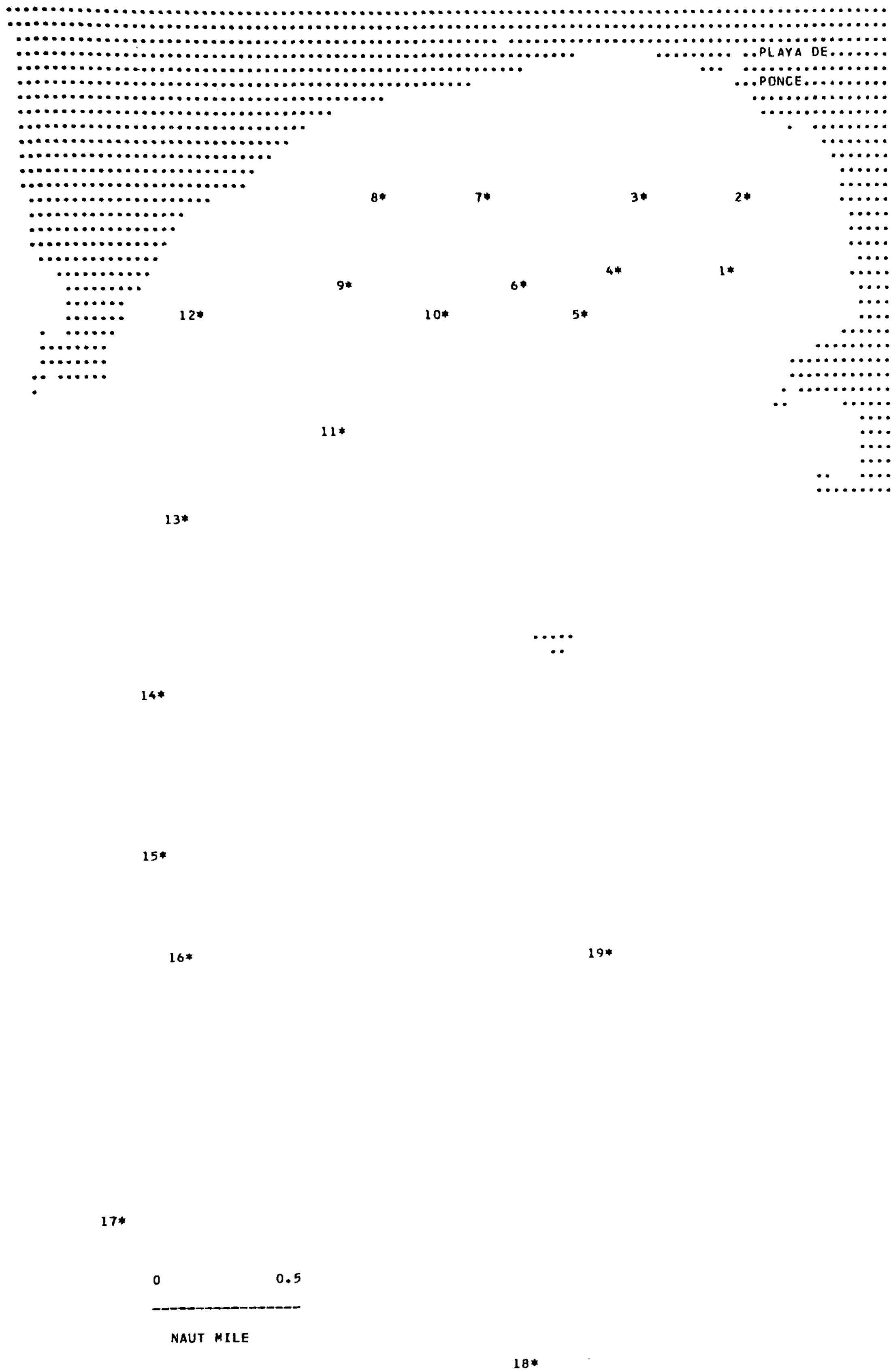


Figure P-4a
HYDROGRAPHIC STATION LOCATIONS
PONCE
CRUISE 1   3 JUNE 1974

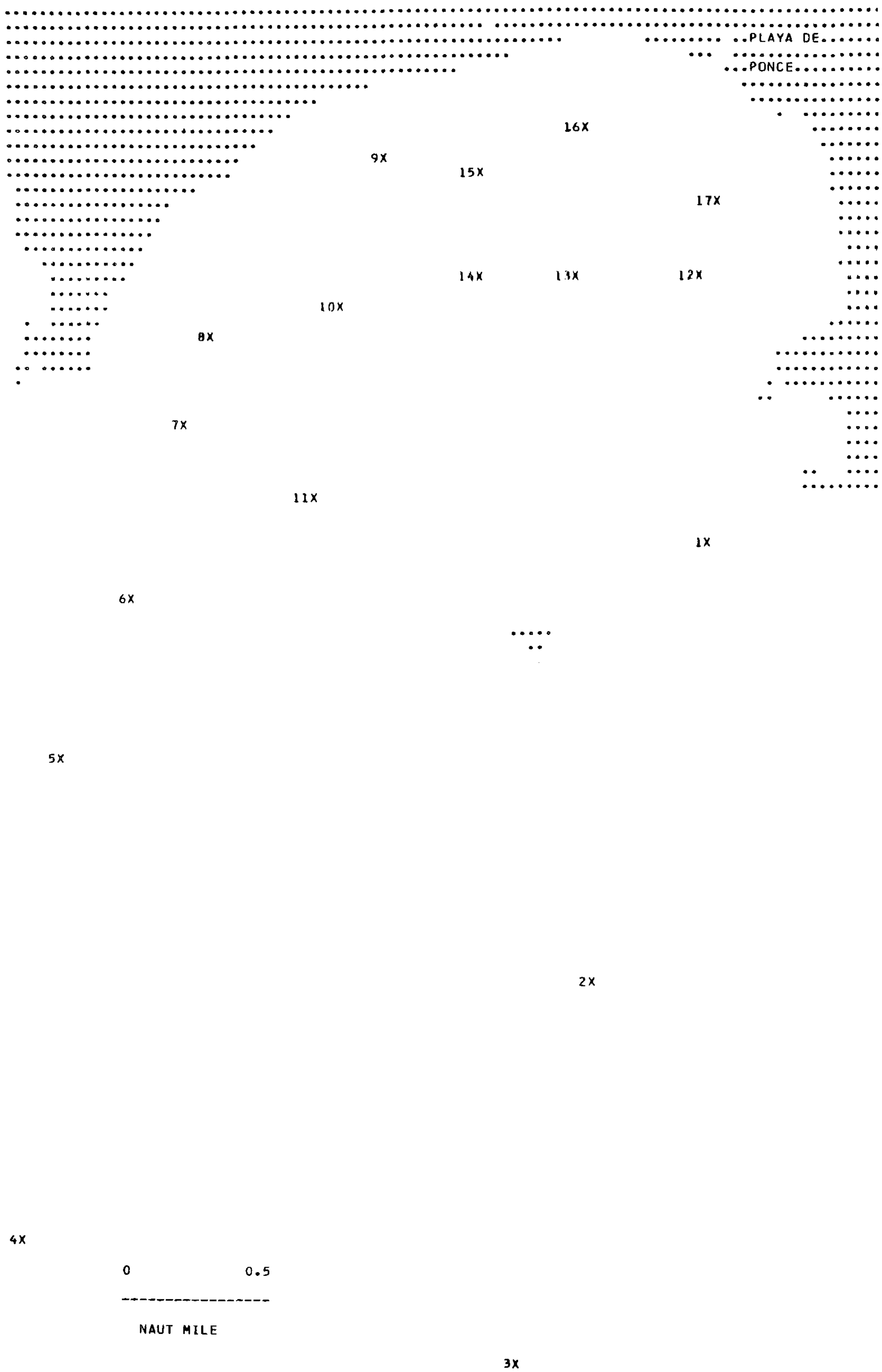


Figure P-4b
HYDROGRAPHIC STATION LOCATIONS
PONCE
CRUISE 2 27 SEPTEMBER 1971

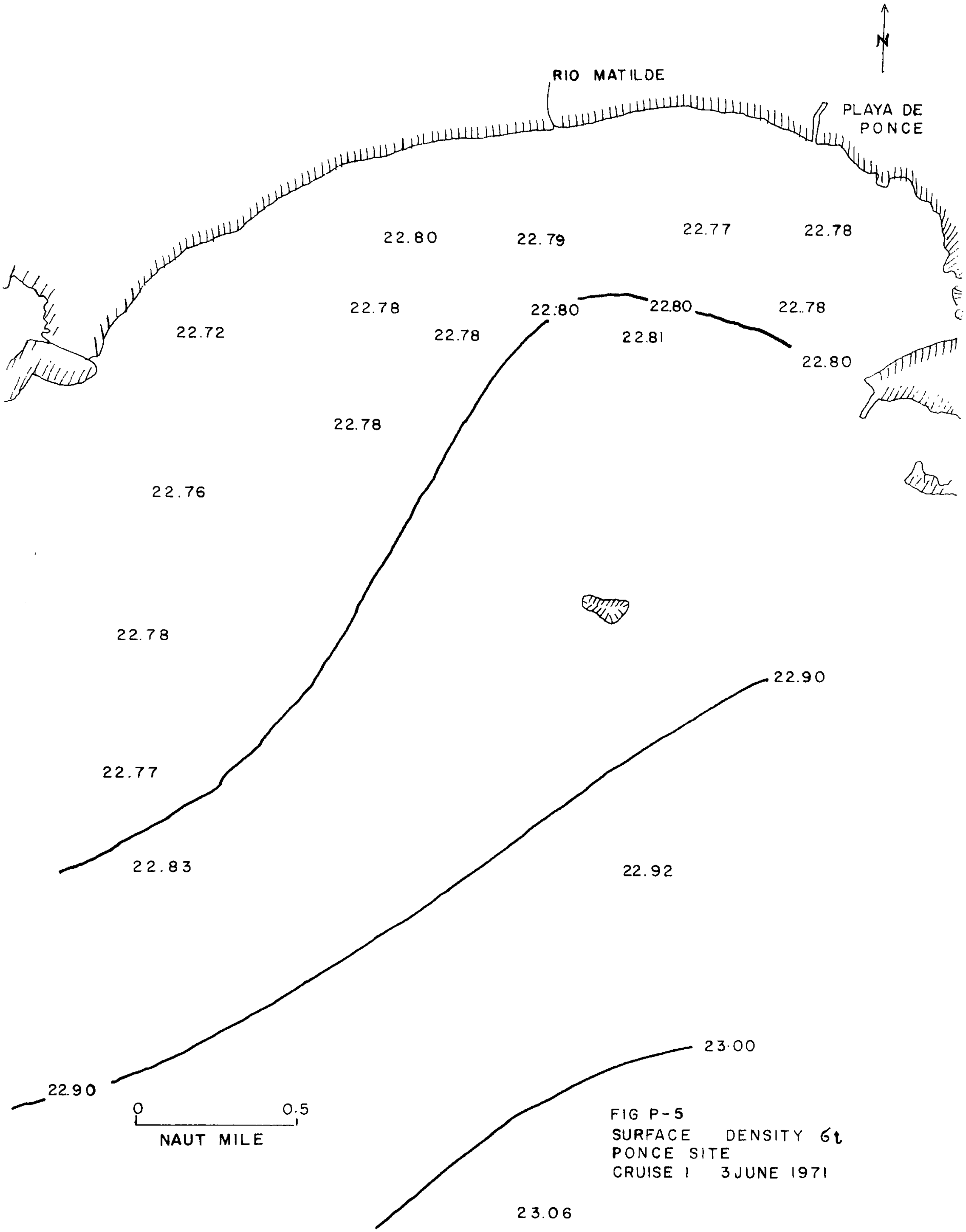


FIG P-5
SURFACE DENSITY σt
PONCE SITE
CRUISE 1 3 JUNE 1971

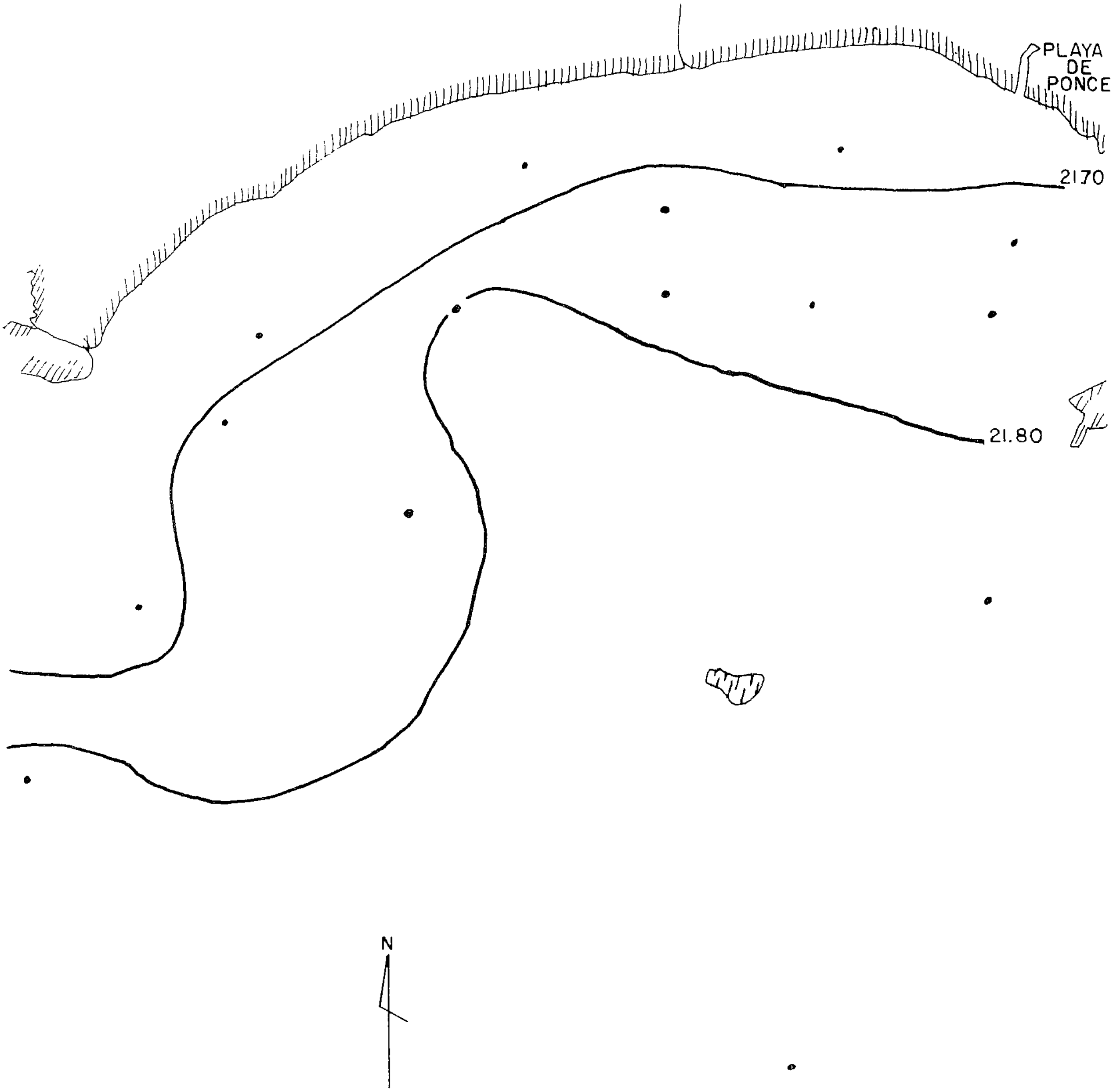
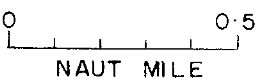


FIG P—6
SURFACE DENSITY σt
PONCE SITE
CRUISE 2, 27 September 1971



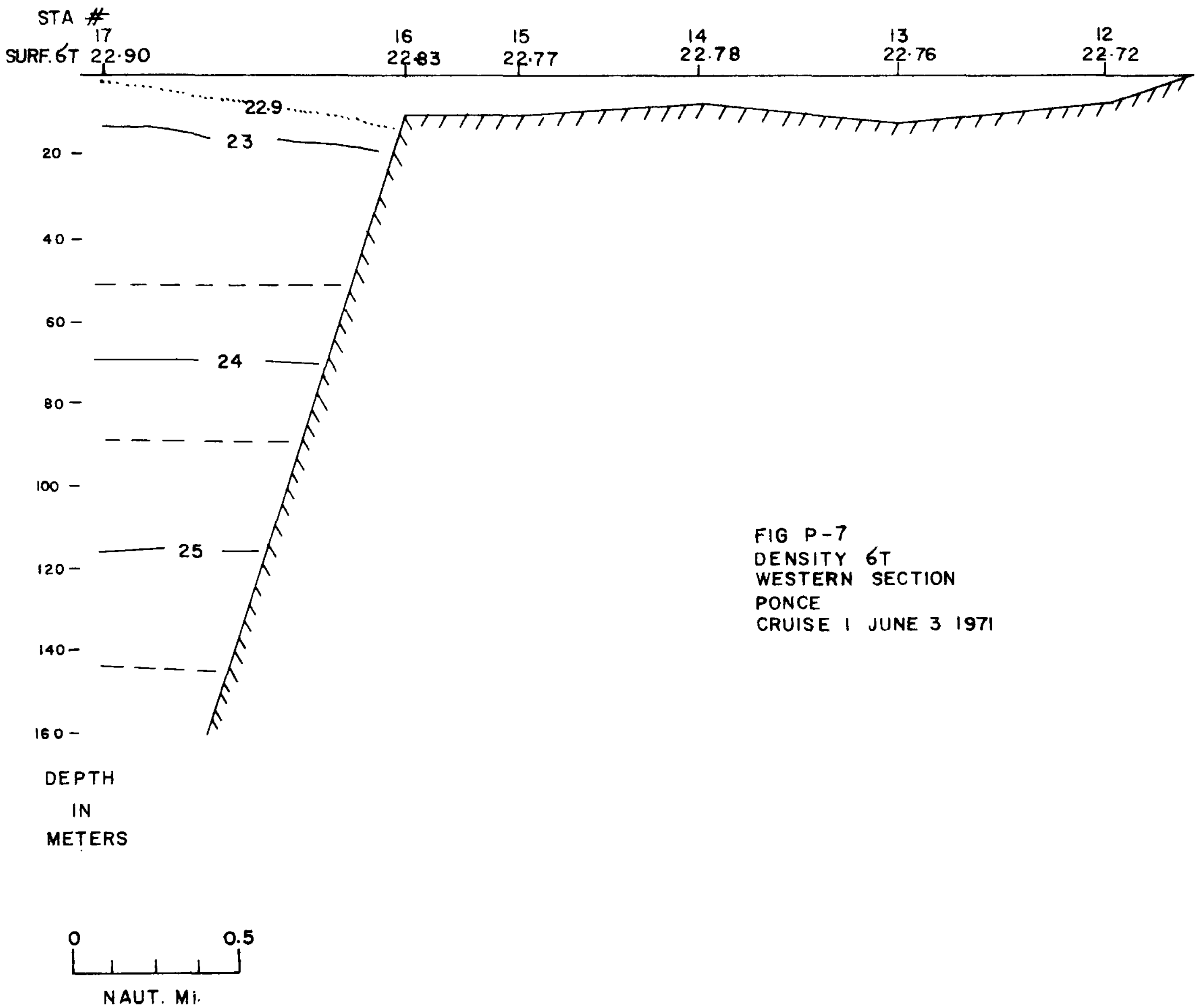


FIG P-7
DENSITY 6T
WESTERN SECTION
PONCE
CRUISE 1 JUNE 3 1971

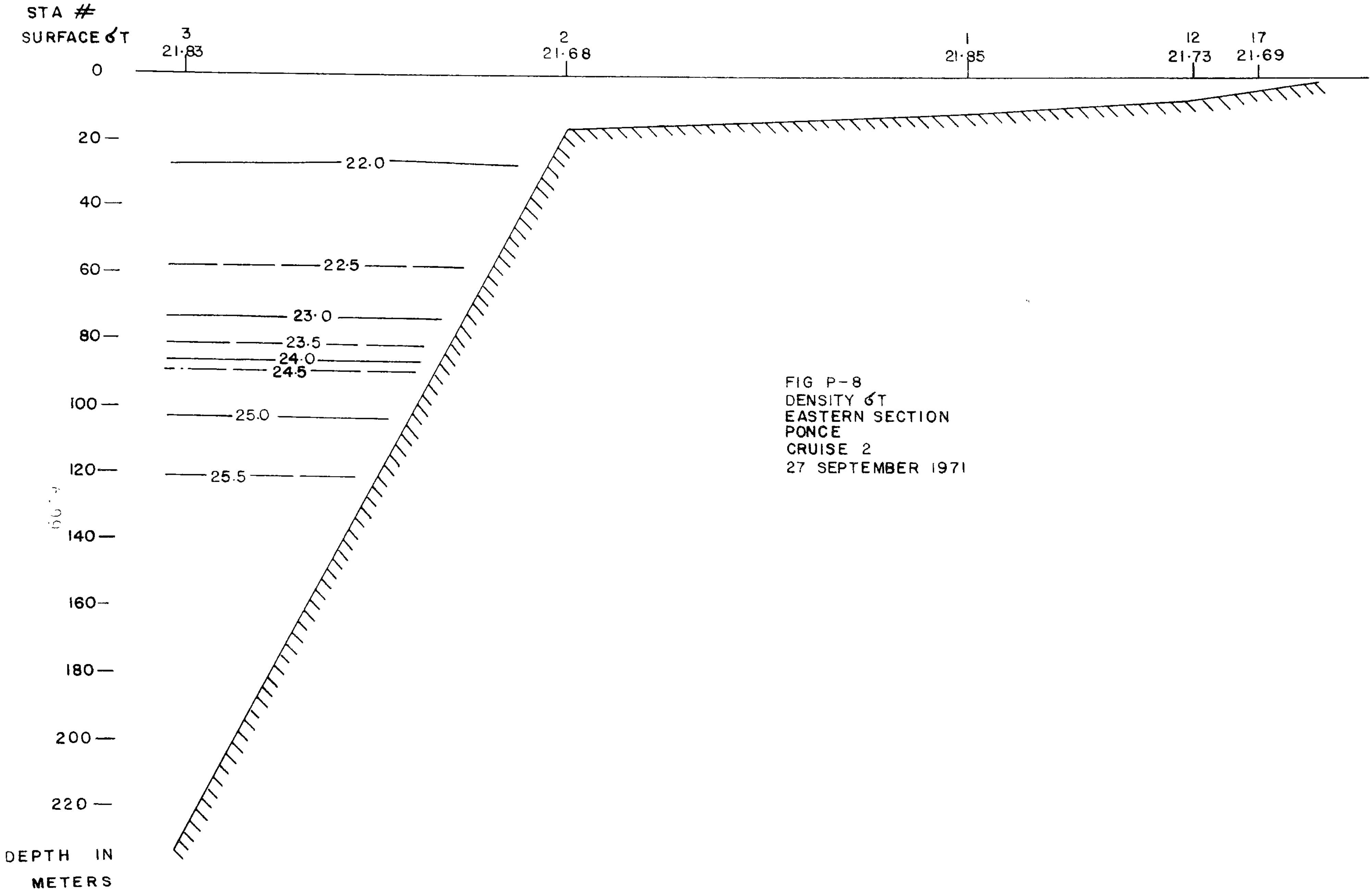


FIG P-8
DENSITY σT
EASTERN SECTION
PONCE
CRUISE 2
27 SEPTEMBER 1971

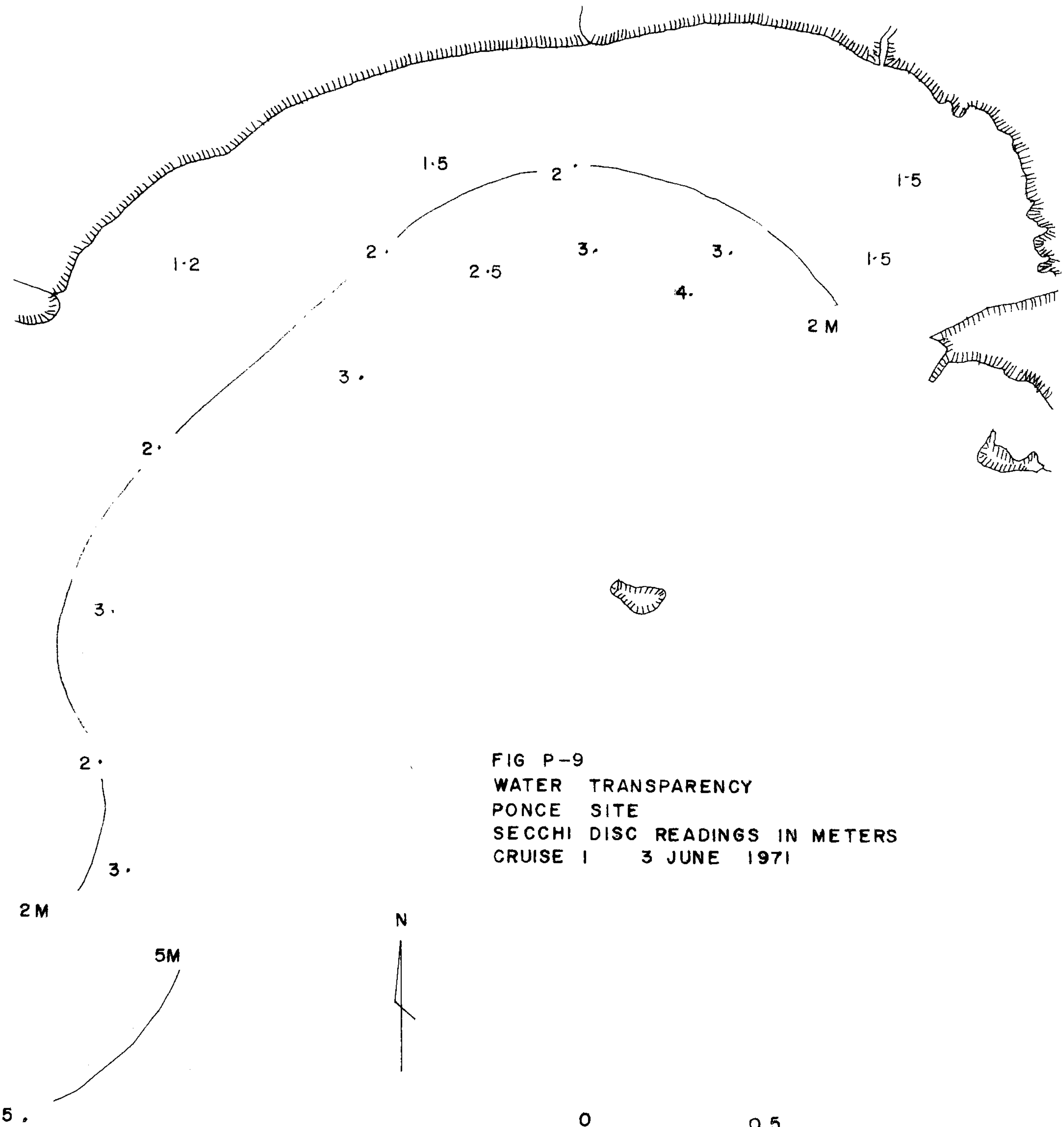


FIG P-9
WATER TRANSPARENCY
PONCE SITE
SECCHI DISC READINGS IN METERS
CRUISE I 3 JUNE 1971

0 0.5
NAUT MI

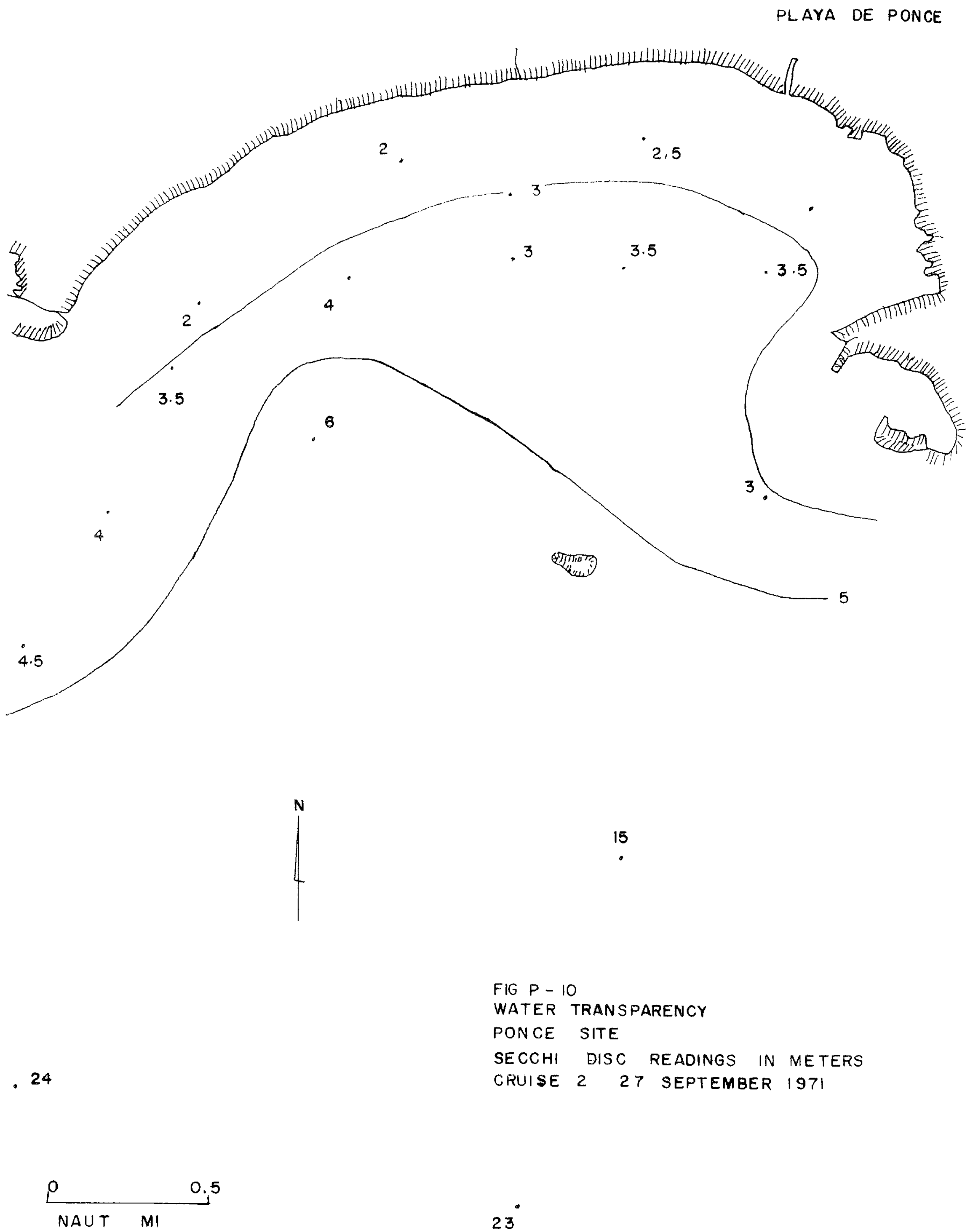


FIG P - 10
WATER TRANSPARENCY
PONCE SITE
SECCHI DISC READINGS IN METERS
CRUISE 2 27 SEPTEMBER 1971

GUAYANILLA

Description of Study Area

The Guayanilla-Yauco area is situated on the south coast of Puerto Rico, about one-third of the length of the island from the western end. The area receives freshwater inflows from Río Yauco and Río Guayanilla. The river basins include portions of the rainy west central mountains, the semi-arid southern foothills, and the dry southern coastal lowlands. Major industries in the area include sugar processing mills at Central San Francisco and Rufina (though the mill at Rufina is reported to have stopped operating in 1968), and large petrochemical refineries. There are also light manufacturing industries located mostly in Yauco. Commercial fishing and dairy farming are carried out on a small scale in the area. Of the three disposal sites studied on the south coast of Puerto Rico, namely Guayama, Ponce, and Guayanilla, the water is deeper than 50 meters within two miles offshore of the proposed treatment plant only at Guayanilla.

Hydrodynamics

Three current surveys were carried out at Guayanilla in the vicinity of the submerged canyon that approaches the coast just east of Punta Ventana. Station locations for each survey are shown in Figure Gn-1. An Ekman-Merz current meter was used during Cruise 1, drogues during Cruise 2, and the three relatively recently acquired in-situ recording current meters during Cruise 3.

As happened with the Ekman-Merz meter at other sites on the south coast, many of the measurements made with this instrument at Guayanilla during

Cruise 1 showed bi-modal currents. Average speeds were similar at the three depths at which readings were taken, being 0.38, 0.34, and 0.35 knots at depths of 4, 12, and 24 meters respectively. There was no apparent correlation between velocity and the presence or absence of bi-modal currents. As has been done in other cases involving bi-modal readings, both the single mode and bi-modal (if present) directions are given in tabular form in Appendix H. Single mode vectors are plotted in Figure GN-2. Like other sites on the south coast, the tides at Guanica, some ten miles west of Guayanilla, are listed in the Tide Tables as being chiefly diurnal, and Galveston, Texas, is the reference station for which time and height corrections are given. As stated elsewhere in this report, verification of tide predictions for locations on the south coast computed from the values given in the Tide Tables is to be desired. It is with this reservation that the times of high and low water at Guanica, as computed from the Tide Tables, are used in what follows as an approximation of the times of high and low water in the region of Guayanilla.

The observations covered the last 5.5 hours of the falling tide and the first 4 hours of the rising tide. This was a period of spring tides, with a predicted range of one foot, so tidal effects may be expected to have been at a maximum. Low tide was at 1252. As can be seen in Figure Gn-2, the current underwent a marked change in direction at each level but at quite different times, with a strong shear developing between depths of 4 and 12 meters at around 1045. The wind was steadily from the ESE throughout the observation period with velocities starting at nine knots and increasing to 18 knots. It could be speculated that as the wind increased in strength it began to move the surface water inshore, and as this built up, a compensatory current developed below the surface to relieve the pressure. This, however, does not explain the curious shift to the north which occurred only in the deeper (24 meters) water between 1430 and 1540. Figure Gn-3 is another presentation of the same data, where the length of each vector is proportional to the actual resultant net flow at each depth over the entire period of observation, and the numerical average speed regardless of direction is also given for each depth (see Appendix B).

During Cruise 2 drogues were used at depths of 1 and 5 meters. Results, as shown in Figure Gn-4, show average speeds of 0.22 and 0.09 knots for the shallower and deeper drogues, respectively, with a general northwesterly movement, approaching shore obliquely (see Appendix H). Unfortunately, no drogues were used at depths greater than five meters because of the likelihood of deeper drogues running aground. Thus, it is not known whether the shear which had previously been observed at depths between 4 and 12 meters was again present.

Guayanilla was the last site occupied during Cruise 3 prior to the writing of this report. The three Hydro Products model 502 in-situ recording current meters were used. One meter was placed close to Punta Ventana in 7.5 fathoms of water, with the sensor at a depth of slightly under 7 fathoms. The two other meters were placed a few feet from one another in precisely 25 fathoms of water, with one sensor at 6.5 fathoms and the other at 17 fathoms, about 1.25 miles SE of Punta Ventana. These station locations are shown in Figure GN-1. A series of developments, including rough seas, mechanical difficulties with the vessel, and finally failure of the pop-up marker buoys to surface at the outer station, caused a delay in retrieval of the two deeper instruments until February 8 when they were recovered by divers in approximately 35 fathoms of water. The ocean bottom in this immediate vicinity drops from a depth of approximately 19 fathoms to 150 fathoms within a horizontal distance of about 550 meters, and the anchors of the current meters had slipped 10 fathoms down the side of the "hill", making it impossible for the marker buoys to reach the surface. What had been intended as the outer shallow instrument had dropped to 17 fathoms, the depth intended for the outer deep meter. The other instrument, retrieved at a depth of about 27 fathoms, failed to record any data because of a minor malfunction in the chart paper transport mechanism of the Rustrak recorder.

Graphs of results obtained with the inner shallow and what ended up as the outer deep meter are shown in Figure Gn-5. Comparison of directional variations at the outer deep meter with predicted times of high and low water seems to indicate a tendency for the current to flow towards the west near times of low tide, and for a north-easterly flow to occur near times of high tide. In general, the registered speeds were low, rarely reaching 0.3 knot at either station. There was no noticeable correlation between tides and either current direction or current speed at the inner shallow station. Tabulated data is given in Appendix H.

Results of an analysis of the data are illustrated in Figure Gn-6.

Here the length of each vector is proportional to the total quantity of water which flowed in each indicated direction, and the resultant (labeled R in the figure) shows the magnitude and direction of the net total flow over the entire period of observation. Average speed (labeled $\bar{v}$) of current in each direction is given, and the percent of total time during which flow was in the indicated direction is also given. It is to be noted that these average speeds are not the same as the numerical average speeds given in resultant net flow diagrams, such as Figure Gn-3, illustrating results of a similar analysis of data from the Ekman-Merz current meter used during Cruise 1. In the case of the Ekman-Merz data analysis only resultant vectors are shown and the average speeds given are simply numerical averages without regard to direction. The corresponding numerical average speed values for the in-situ recording meters at Guayanilla are 0.19 knot for the inner shallow meter, and 0.13 knot for the outer deep meter. A more detailed description of the methods of analysis employed here is given in Appendix B.

As is clear from Figure Gn-6, the current at the outer station at Guayanilla flowed either towards the north-east or south-west for nearly 60 percent of the total period of observation. It is also apparent from the figure that no such reversal occurred at the inner station. Unfortunately, it was again impossible to determine whether the shear between shallow and deeper water which was observed during Cruise 1 was present at the outer station during Cruise 3.

Perhaps it is worth emphasizing that the information displayed in

Figures Gn-5 and Gn-6 represents a summary of virtually continuous data acquisition at two stations over a period of 118 hours, and is therefore much more significant than data collected over a period of only a few hours. The conclusions which an investigator might draw from observations made at the outer station at Guayanilla during the daylight hours of January 29th, for example, would differ markedly from conclusions he might arrive at from similar observations on January 31st, as can be seen at a glance in Figure Gn-5.

Most of the near-shore current studies along the coasts of Puerto Rico have been of very brief duration. The comparatively long-term current measurements made at Guayanilla during Cruise 3 covered a period of about one-sixth of a lunar month, starting at about the time of full moon and spring tides on Jauary 30. It is hoped that in the future it will be possible to collect data over a full lunar month, and simultaneously to obtain tidal and meteorological data, which is perhaps a reasonable minimum for a realistic evaluation of the current structure in a given area.

Hydrographic Data

Hydrographic station locations at the Guayanilla site are shown in Figure Gn-7. Data obtained at these stations during Cruise 1 and 2 is given in tabular form in Appendix H. The inner part of Bahía de Guayanilla is roughly one degree warmer than the water outside the bay at all levels. Flushing of the bay must be extremely limited for this gradient to be maintained. A tongue of relatively cool water appears to coincide with the depression in the bottom just east of Punta Ventana, indicating that cooler offshore water flows shoreward along the depression. The surface salinity pattern similarly shows a tongue of more saline offshore water coinciding with the bathymetric depression. Salinity values in the inner bay are higher than those immediately outside. It may be that this area of limited flushing acts as an evaporation basin, thus raising the surface salinity. Horizontal patterns of salinity at depths of 5, 10, and 30 meters are more or less similar to the pattern at the surface, with only slight salinity changes at any given depth. Horizontal density gradients are also generally slight, as can be seen for surface waters in Figures Gn-8 and Gn-9. Density profiles are shown in Figures Gn-10 and Gn-11. As can be seen from these figures, density changes from the surface to a depth of 50 meters were found to be less than about 0.5 sigma-t units during both cruises.

Water Quality Data

The data collected for a water quality survey of the Guayanilla area is given in tabular form in Appendix H. Secchi disc readings showed very low water transparency values, as is illustrated in Figures Gn-12, Gn-13, indicating extreme turbidity.

During Cruise 1 measured silica and phosphorus levels were very low, varying from 0.0 to 0.2 mg/l for silica and from 0.00 to 0.02 mg/l for phosphorus. Dissolved oxygen concentrations varied between 5.29 and 7.00 mg/l, with values around 6.5 mg/l being typical for most of the area. Silica concentrations were found to be a little higher, and phosphorus values a little lower, during Cruise 2. Coliform MPN values varied between 20 and 250/100 ml at four stations where measurements were carried out.

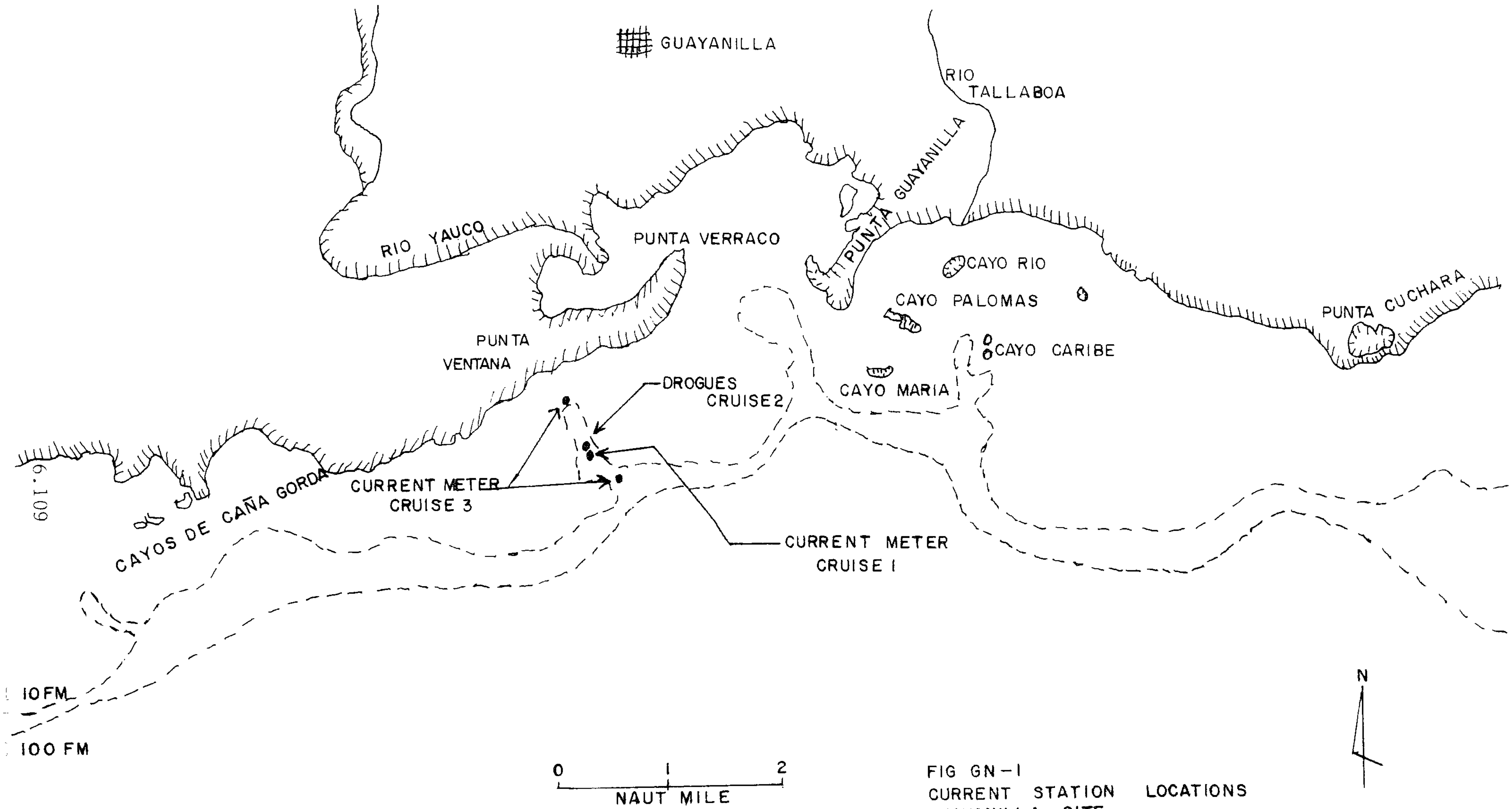


FIG GN-1
CURRENT STATION LOCATIONS
GUAYANILLA SITE

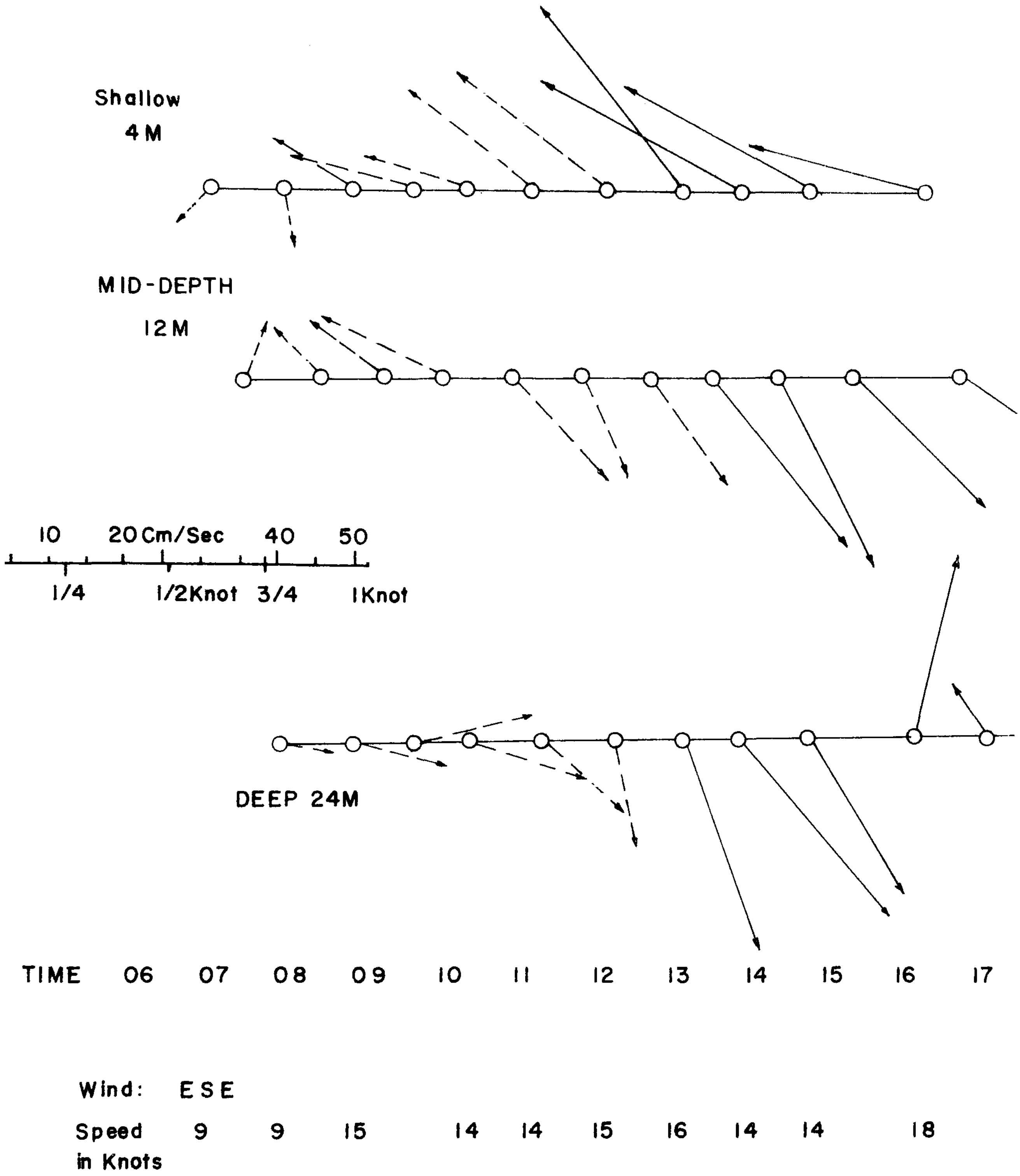


FIG GN-2
CURRENT VECTORS
GUAYANILLA
CRUISE I — 10 JUNE 1971

HIGH TIDE 9 JUNE 2303
LOW TIDE 10 JUNE 1252
HIGH TIDE 10 JUNE 2351
WATER DEPTH 33 M.

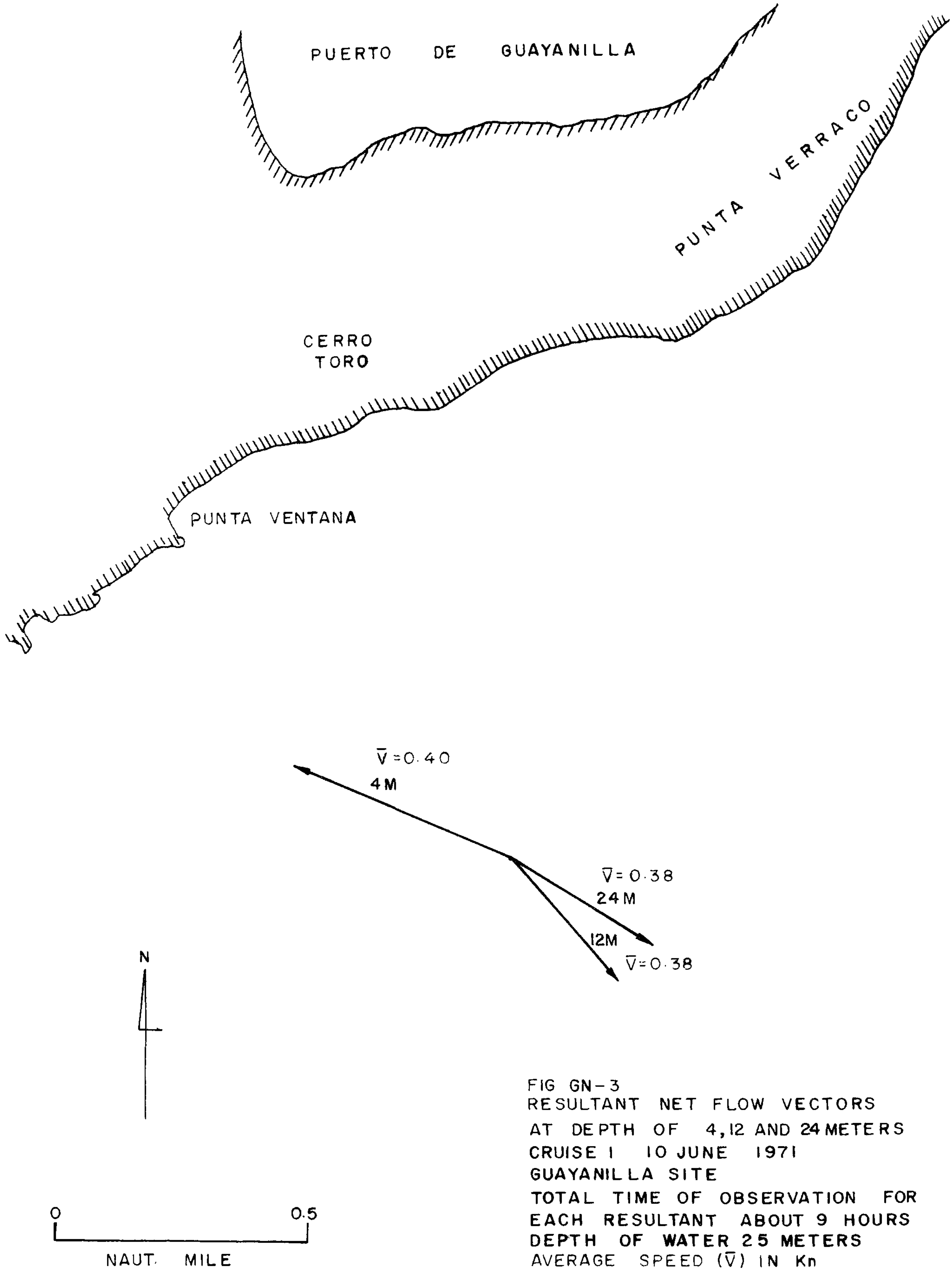


FIG GN-3
RESULTANT NET FLOW VECTORS
AT DEPTH OF 4,12 AND 24 METERS
CRUISE I 10 JUNE 1971
GUAYANILLA SITE
TOTAL TIME OF OBSERVATION FOR EACH RESULTANT ABOUT 9 HOURS
DEPTH OF WATER 25 METERS
AVERAGE SPEED ($\bar{V}$) IN Kn

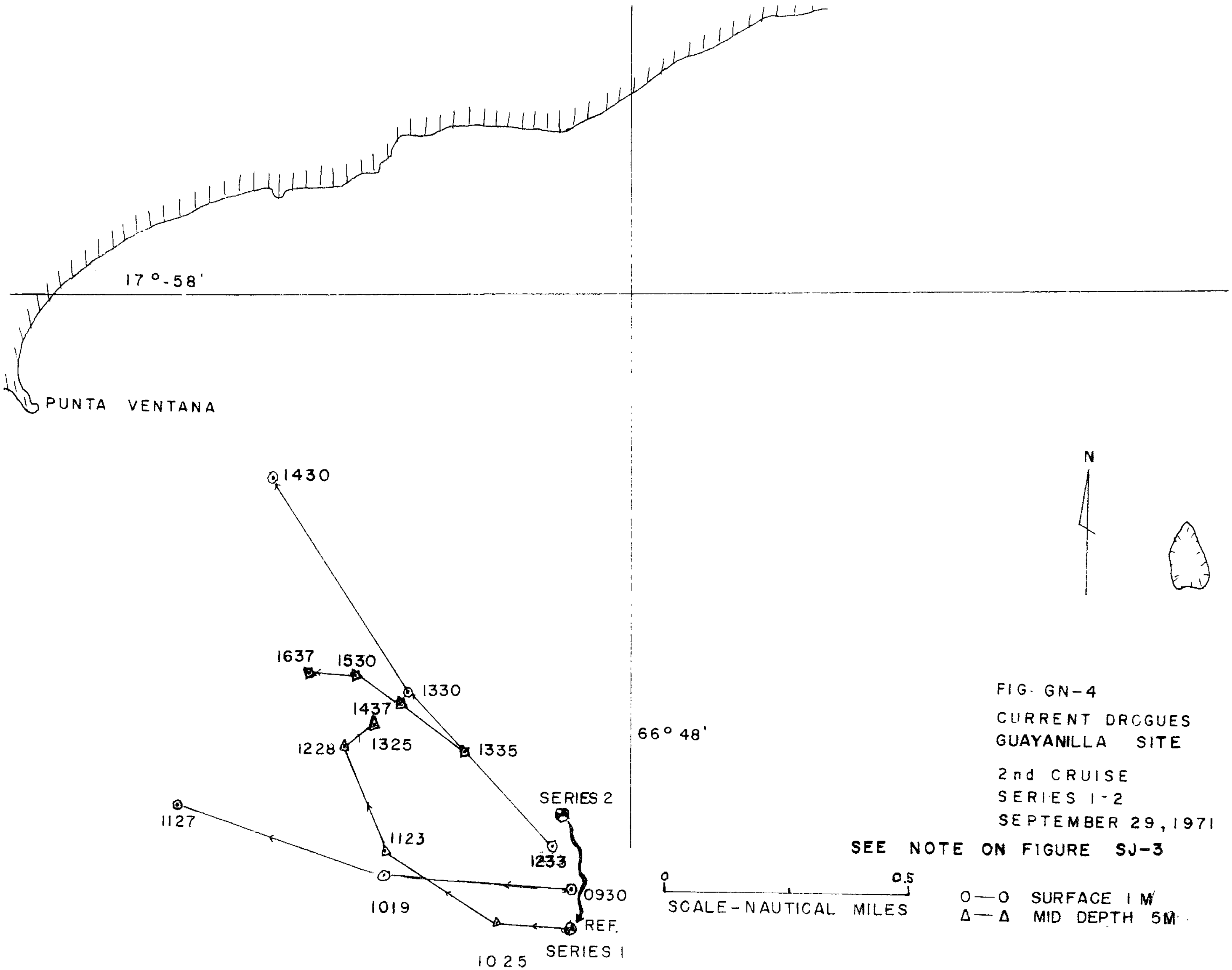


FIG. GN-4
CURRENT DROGUES
GUAYANILLA SITE
2nd CRUISE
SERIES 1-2
SEPTEMBER 29, 1971

PAGE NOT

AVAILABLE

DIGITALLY

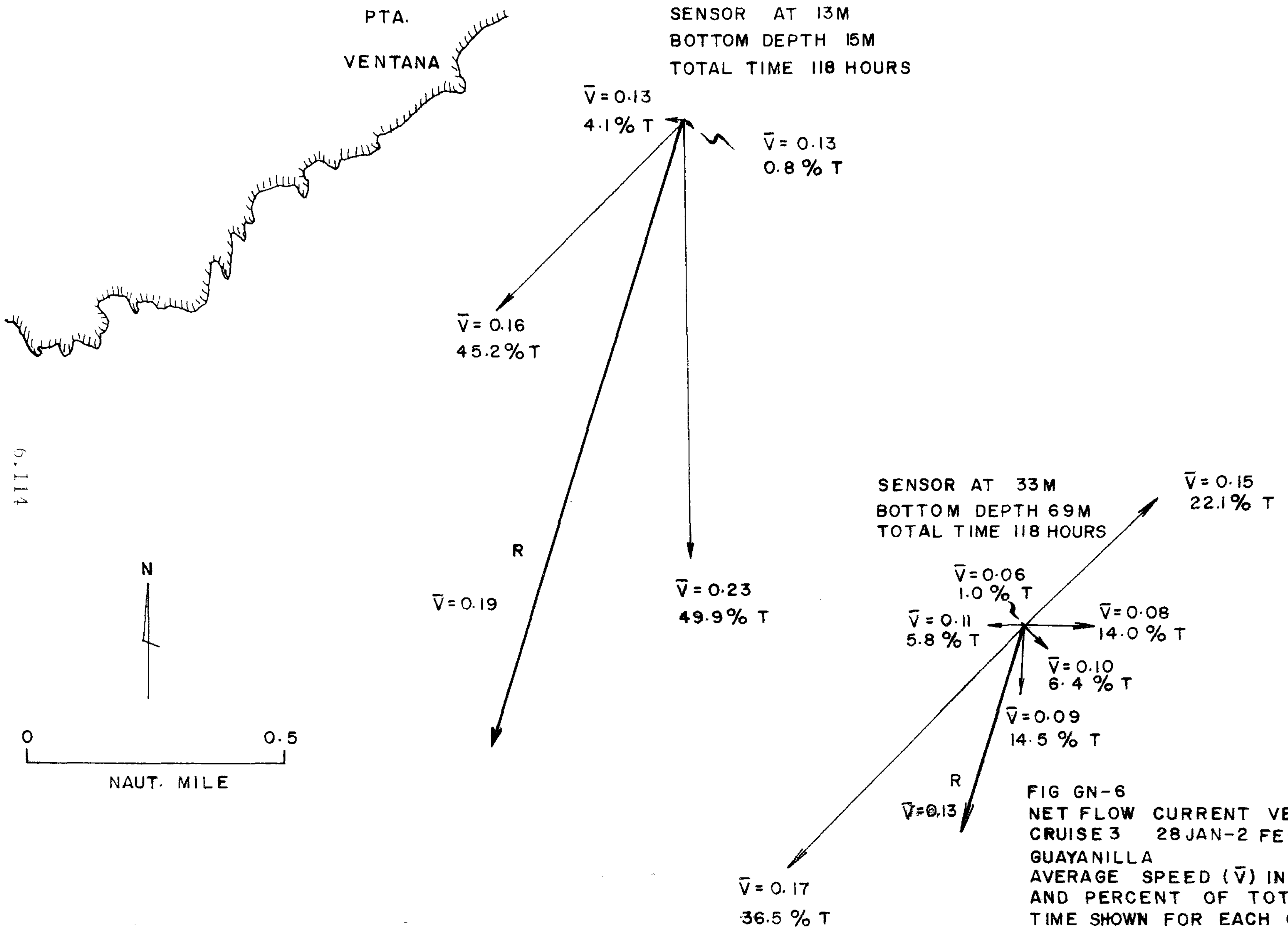


FIG GN-6
NET FLOW CURRENT VECTORS
CRUISE 3 28 JAN-2 FEB 1972
GUAYANILLA
AVERAGE SPEED (V̄) IN Kn
AND PERCENT OF TOTAL
TIME SHOWN FOR EACH OCTANT

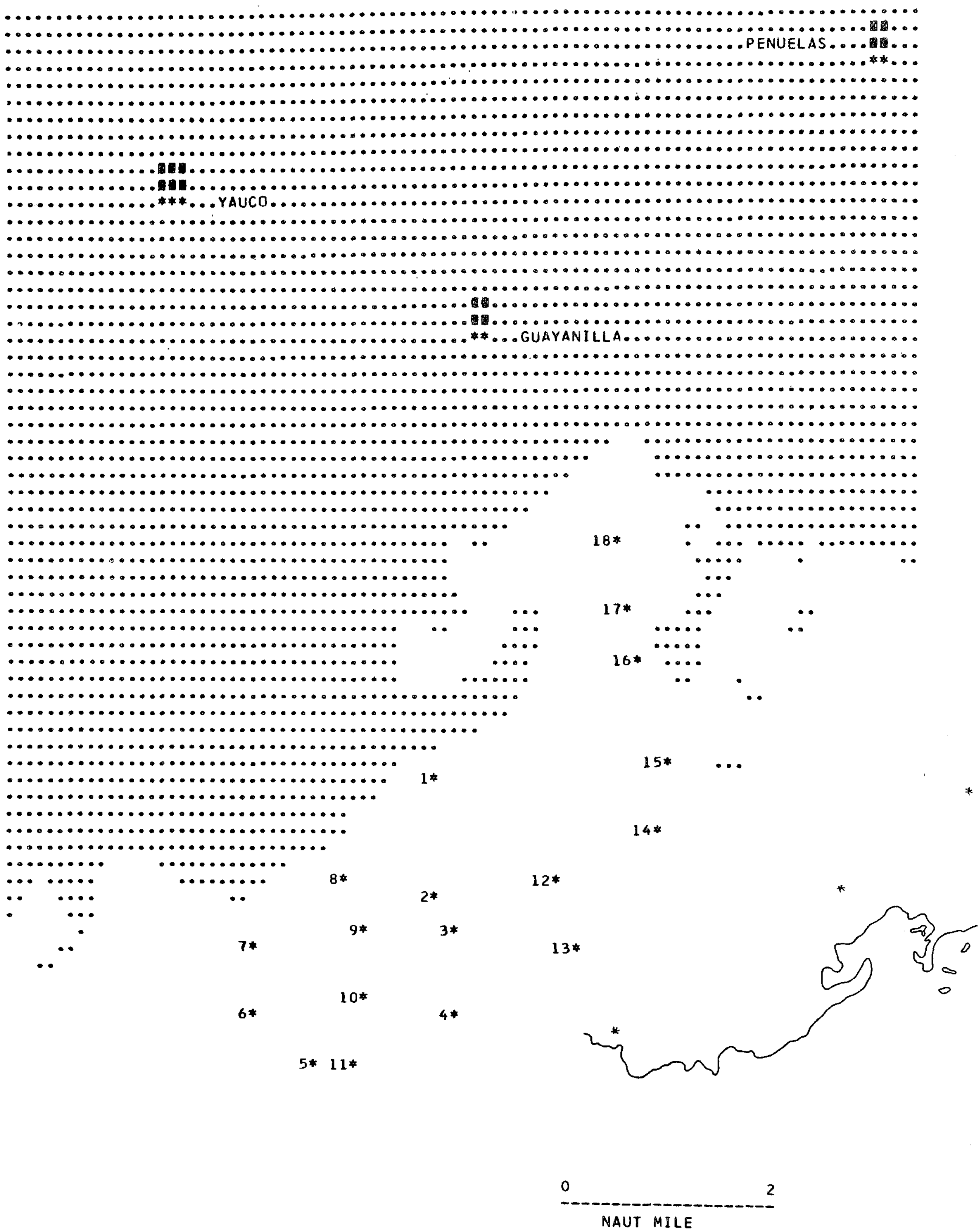


Figure GN-7a
HYDROGRAPHIC STATION LOCATIONS
GUAYANILLA
CRUISE 1 9, 10 JUNE 1971

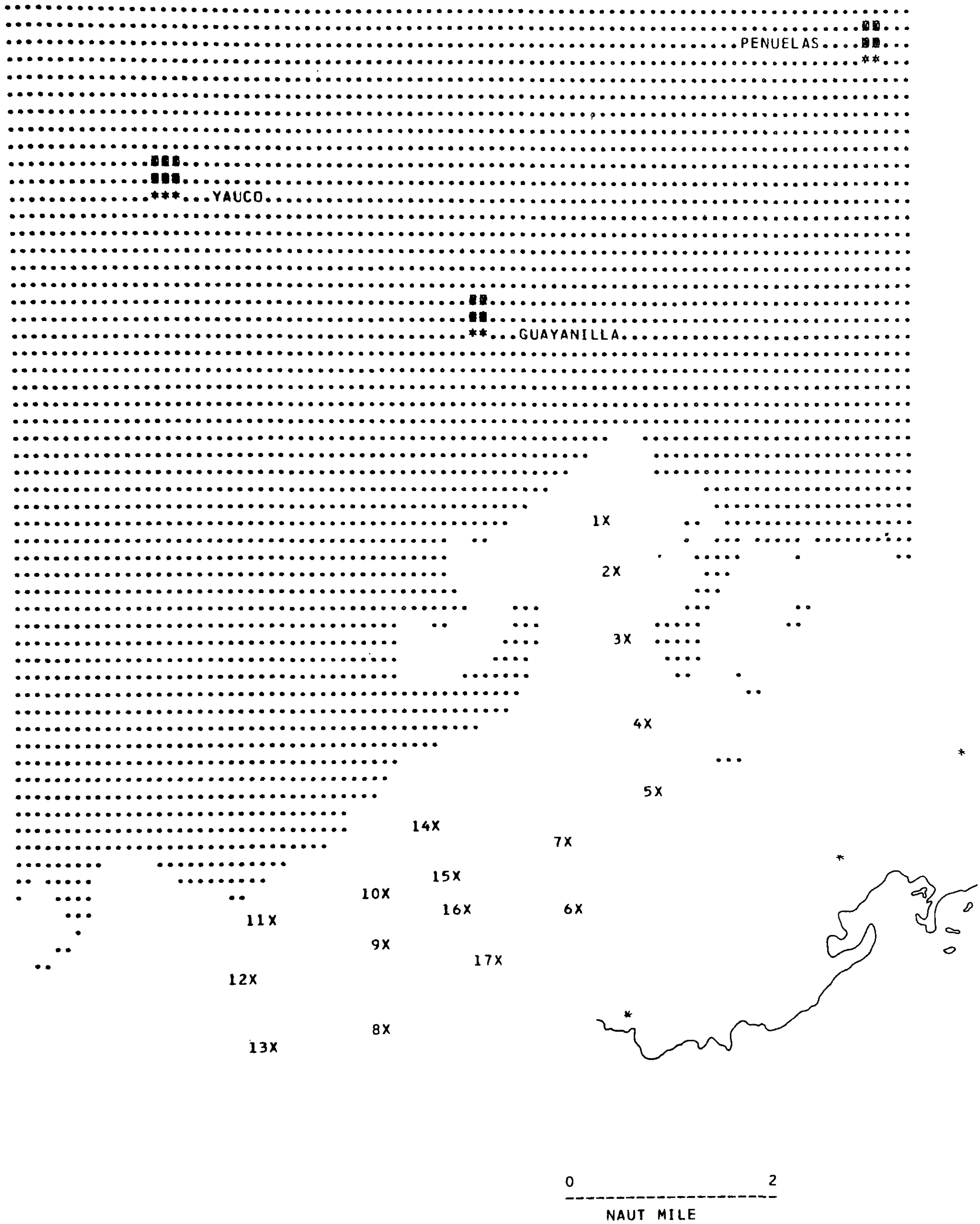


Figure GN-7b
HYDROGRAPHIC STATION LOCATIONS
GUAYANILLA
CRUISE 2   4 OCTOBER 1971

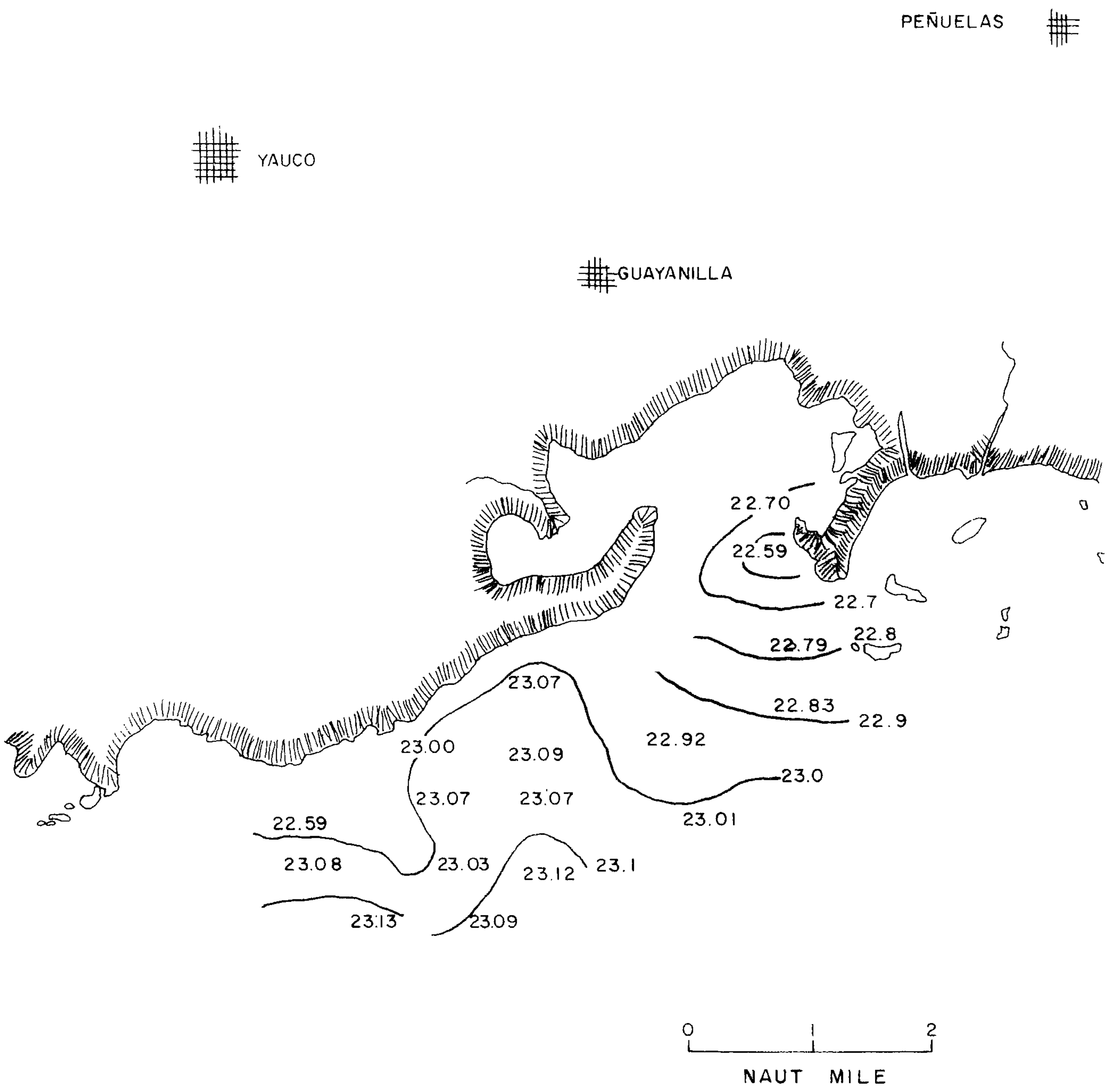


FIG GN-8

SURFACE DENSITY
GUAYANILLA SITE
CRUISE 1 9 JUNE 1971.

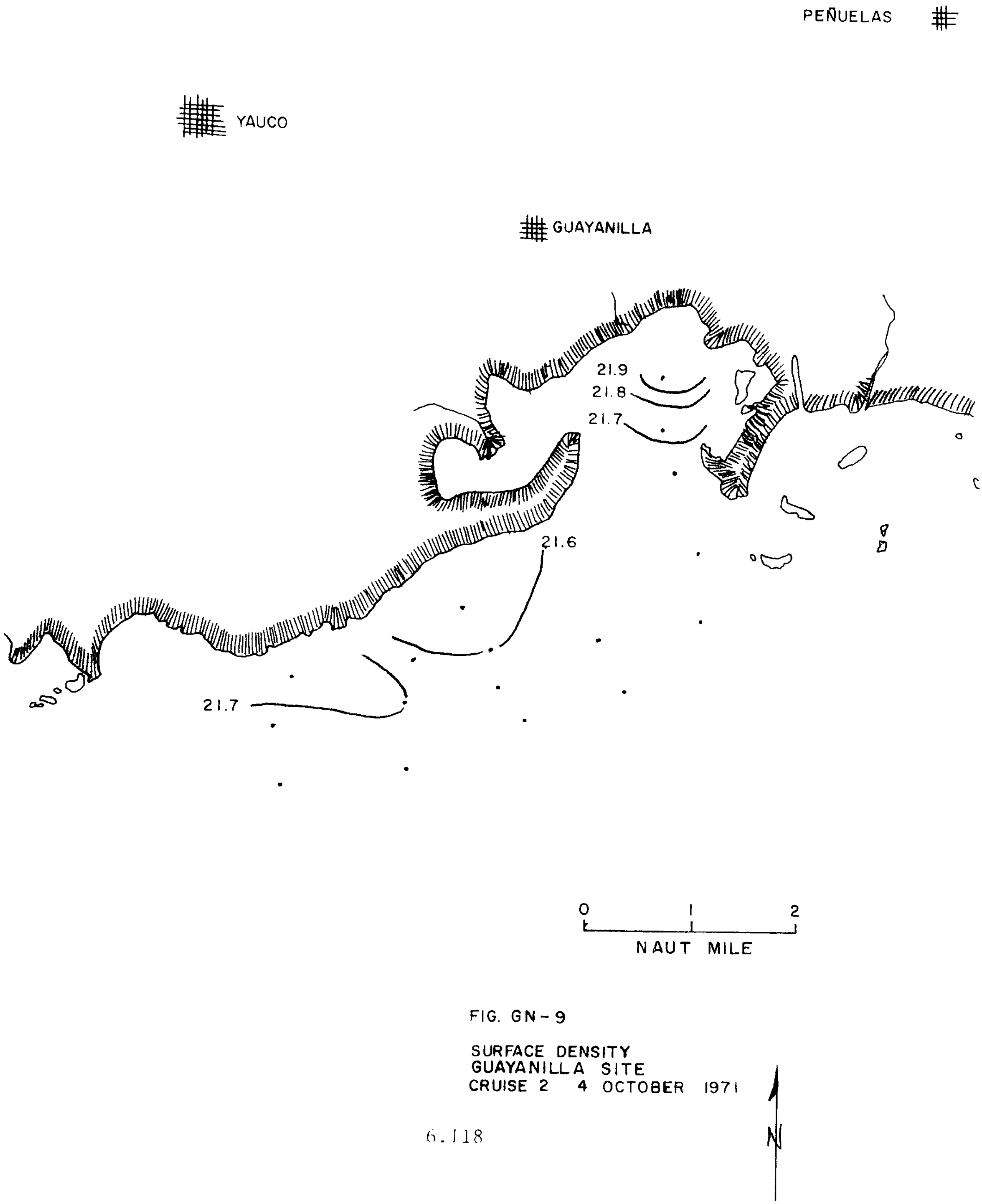


FIG. GN-9

SURFACE DENSITY
GUAYANILLA SITE
CRUISE 2 4 OCTOBER 1971

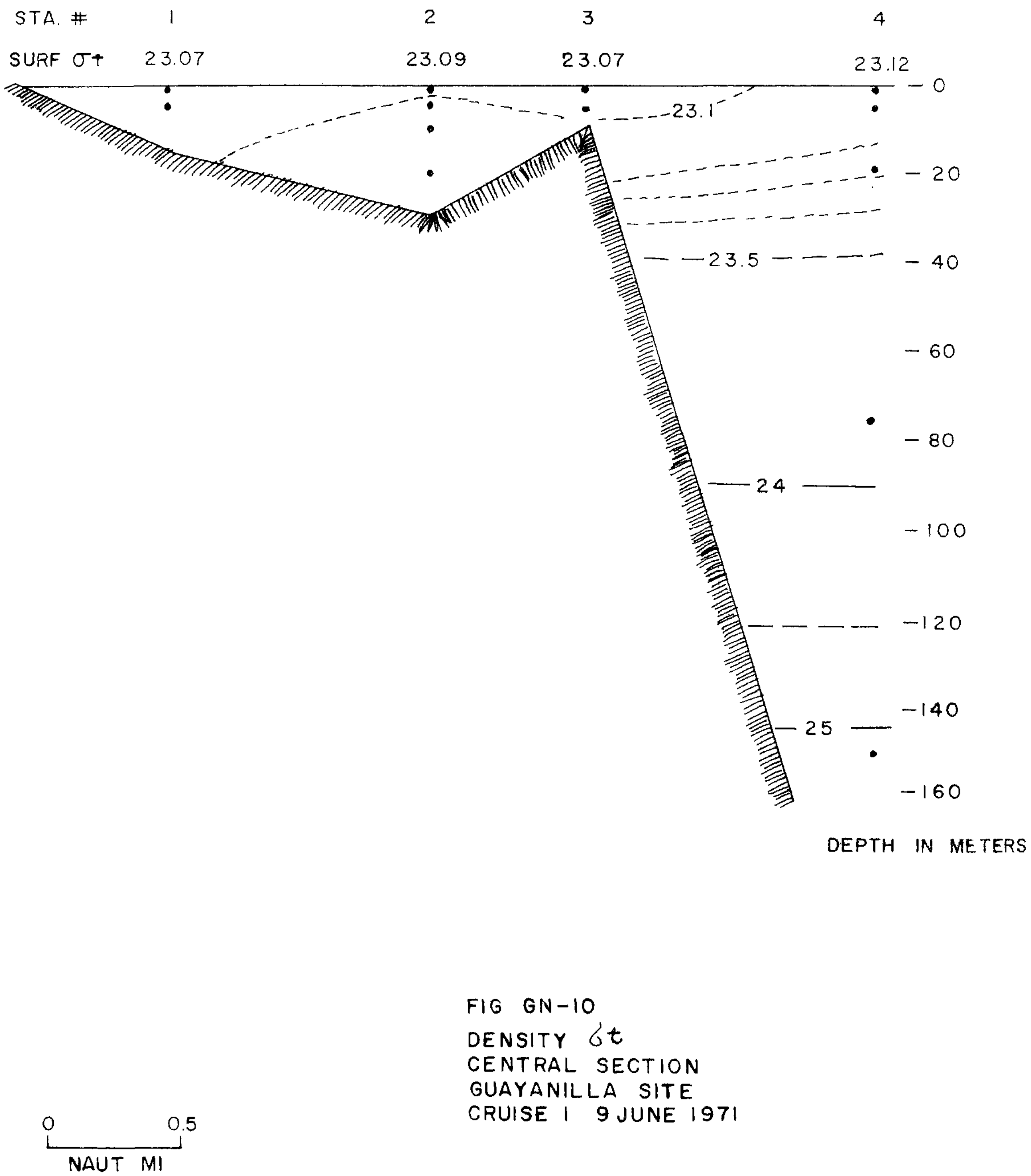


FIG GN-10
DENSITY σt
CENTRAL SECTION
GUAYANILLA SITE
CRUISE I 9 JUNE 1971

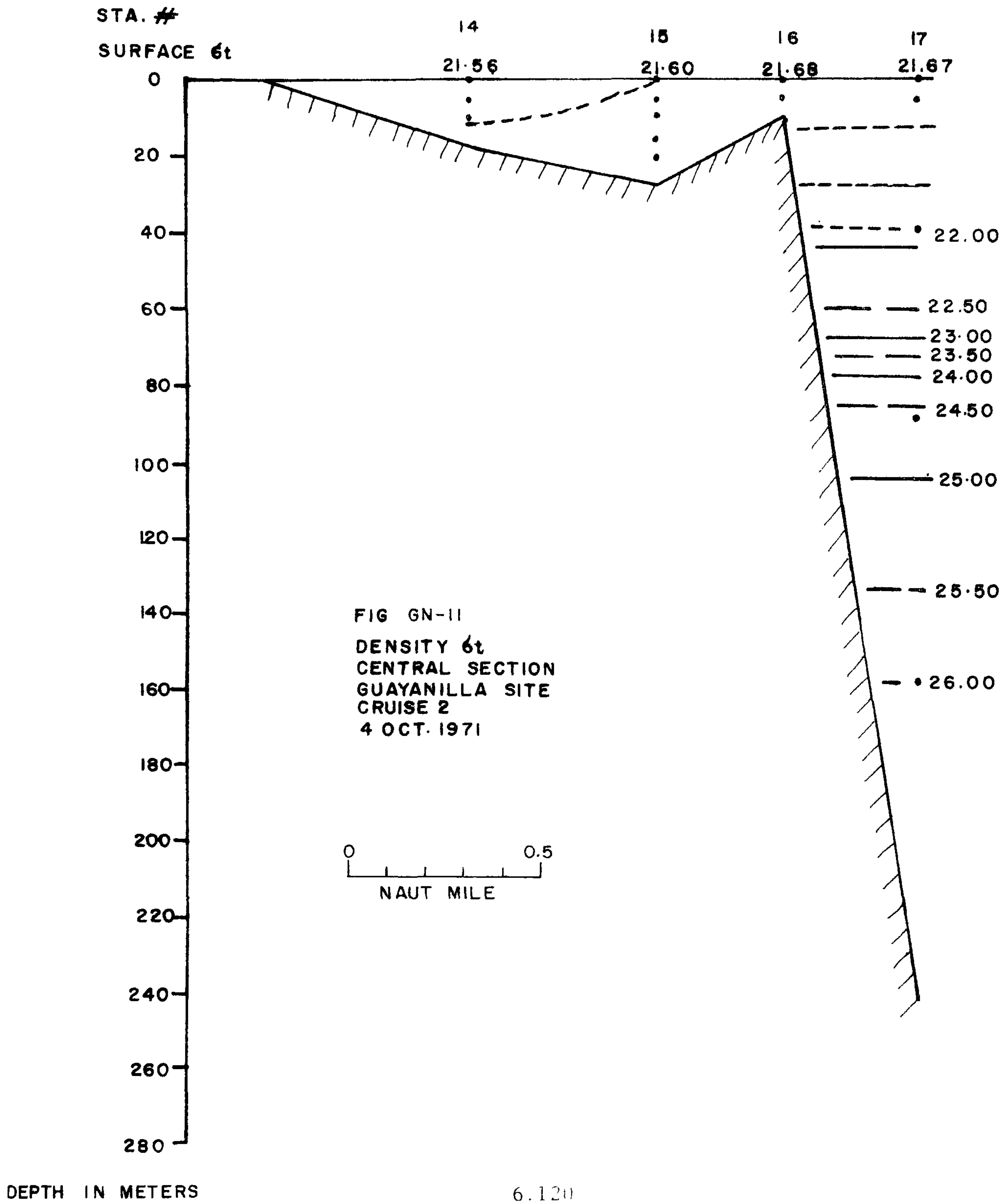


FIG GN-11
DENSITY σt
CENTRAL SECTION
GUAYANILLA SITE
CRUISE 2
4 OCT. 1971

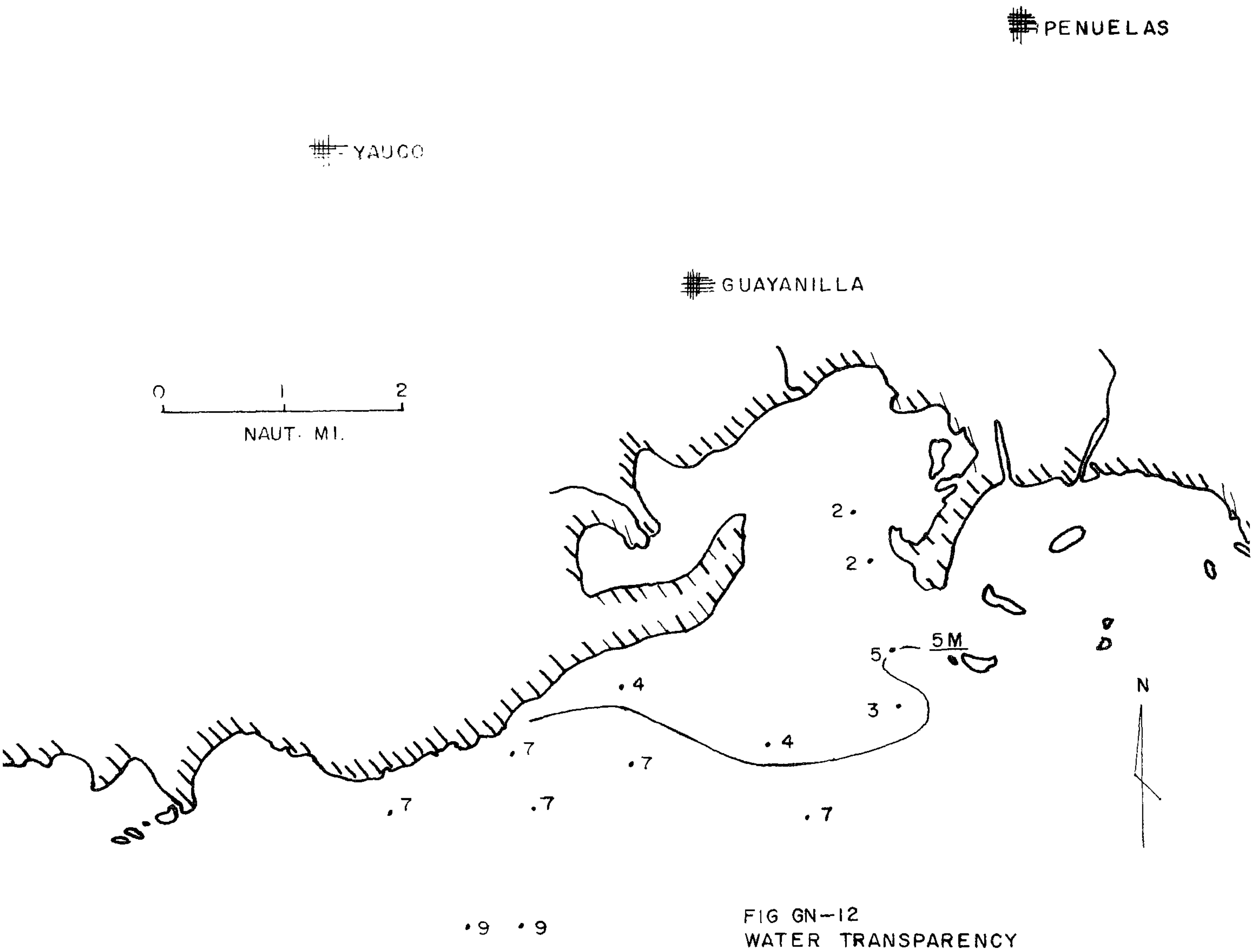


FIG GN-12
WATER TRANSPARENCY
GUAYANILLA SITE
SECCHI DISC READINGS IN METERS
CRUISE 1 9 JUNE 1971

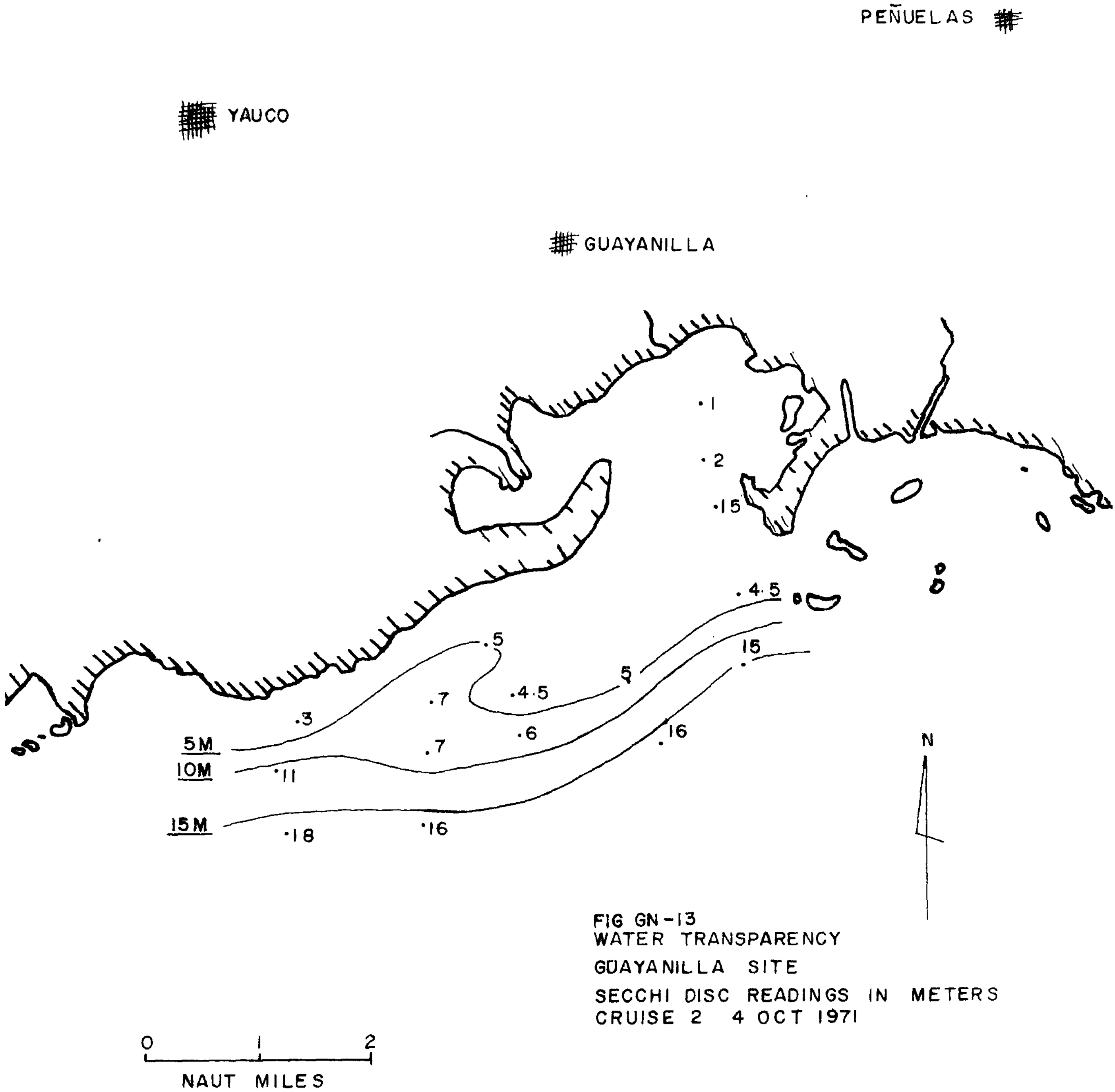


FIG GN-13
WATER TRANSPARENCY
GUAYANILLA SITE
SECCHI DISC READINGS IN METERS
CRUISE 2 4 OCT 1971

Mayaguez

Description of Study Area

Mayaguez Bay, one of the three leading ports of Puerto Rico, is located approximately in the middle of the west coast of the island. Depths in the northern part of the bay run to 60 ft, but the southern part is mostly shoal. The bay extends from Punta Guanajibo in the south to Punta Algarrobo located one mile northeast of the shipping terminal. The freshwater contribution to Mayaguez Bay is almost entirely from the Rio Guanajibo in the south and the Rio Yaguez in the north. At times there is no discharge from the Rio Yaguez (1).

A recent survey conducted by the Aqueduct and Sewer Authority indicated that there are 161 industries in Mayaguez, 115 of which discharge wastewater into the sanitary sewage systems of the city (1). Industrial wastes reach Mayaguez Bay directly and indirectly via the Yaguez and Guanajibo Rivers. Industries discharging wastes directly into the bay are centered in the area north of the Government Wharf (2). These include three tuna canning plants and a cattlefeed producing plant. The Rio Guanajibo brings into the bay the wastes from Central Eureka and the effluents from a number of industries located in the Mayaguez Free Trade Zone (2). The Yaguez River picks up the wastes from India Brewery and from a number of small industrial plants as it passes through Mayaguez, and finally discharges them into the bay.

Mayaguez has a population of 86,000. Approximately 43% of the population is connected to sewers feeding a submerged, 48-inch, open-ended outfall which discharges approximately 3000 feet from shore into about 20 feet of water. An estimated 3.74 million gallons of untreated sewage is discharged into Mayaguez Bay daily through this pipe.

Hydrodynamic Data

The Mayaguez area is characterized by a wind pattern which is different from that of other regions of the island (3). The sea breeze acts in an almost opposite direction from that of the easterly trades, lessening the strength of the trades and frequently becoming dominant, resulting in an on-shore westerly wind. This is an area of well developed tidal currents. The Tidal Current Tables (4) show that at a place 1.5 miles west of Punta Ostiones (which is roughly 8 miles south along the coast from Mayaguez) the flood tide produces a southward flowing current with an average speed of 1 knot. The ebb tide produces a northward flowing current with an average speed of 0.9 knot. Previous current studies by Muñoz, Nazario, et al (2) describe a reversing cycle with a period of 5.75 hours and an average speed of 0.38 knot. The usual path of the current is parallel to shore, according to results of this study. However most of these observations were made in a limited period of time and the way the data is presented does not provide the information required for any further analysis. Guzman (1) made a study of currents between Punta Guanajibo and the mouth of Río de Añasco. His drogue data showed an offshore/on-shore flow pattern. Guzman made a more extensive study with in-situ current meters. Station locations for this study are given in Figure M-1. Direct on-shore current flows were observed for 17.2 percent of the time. A reversing cycle with a period of about 2.5 hours was observed. Another current study was carried out by Colón (5) using in-situ current meters. Figure M-1 also shows the station location for this study. Tidal effects were apparent, but the current during flood tide was towards the northeast and to the southwest during ebb, which is roughly opposite from the corresponding directions given in the Tidal Current Tables for the area near Punta Ostiones.

Two current surveys were carried out at Mayaguez by the Oceanographic Project. Station locations are given in Figure M-1. The results of the current studies are given in Figures M-2 through M-4, and in Appendix I. Measurements were made at depths of 4, 12, and 24 meters with an Ekman-Merz current meter during Cruise 1. Figure M-2 shows velocity vectors giving the result of each individual measurement, while Figure M-3 illustrates the direction of the resultant net flow at each depth together with the numerical value of average speed (regardless of direction) at that depth (see Appendix B).

Results of the drogue studies carried out during Cruise 2 are illustrated in Figure M-4. As can be seen from the figure, the general pattern of flow is roughly parallel to shore, with a slow trend towards shore. The highest speeds measured with the drogues were considerably higher than maximum values obtained with the Ekman-Merz meter during Cruise 1. This may well be due to the fact that Cruise 1 measurements were made close to the time of neap tides, while the Cruise 2 measurements were made near the time of spring tides. The drogue results agree roughly with predictions from the Tidal Currents Tables, which predict southerly currents off Punta Ostiones during flood tide, and northerly currents during the ebb.

Hydrographic Data

Locations of the hydrographic stations are shown in Figure M-5. Temperature and salinity data is given in Appendix I. A slightly cooler ban of water is present inshore along the coast of Bahía de Añasco extending at least as far as Punta Cadena. This may represent a minor upwelling brought about by local winds pushing a thin surface layer offshore and bringing up deeper slightly cooler water close to shore. The greatest range of surface temperature over the entire survey area was slightly more than half a degree. Surface salinity values were fairly constant over the study area during both cruises, though changes of 1-2% were observed to have occurred during the time interval between the two studies. The U.S. Geological Study has indicated an interest in documenting the presence of freshwater springs erupting from the ocean floor on the west coast of Puerto Rico. No evidence of such springs was found during these two studies at Mayaguez. Surface density contours, computed from measured values of temperature and salinity, are shown in Figures M-6 and M-7. Density profiles are shown in Figures M-8 and M-9.

<u>Water Quality</u>

Water quality in the Mayaguez area was surveyed during Cruises 1 and 2. Data obtained during these cruises is presented in Appendix I. Only five Secchi disc readings were taken during the first cruise, after which the disc was lost. These readings varied between 6 and 79 meters. Dissolved oxygen concentrations varied between 4.29 and 5.17 mg/l. BOD concentrations and coliform MPN levels were determined from samples taken at selected stations. BOD levels ranged from 0.00 to 1.37 mg/l, and coliform MPN levels were from 0 to 576/100 ml. Levels of silica and phosphorus were low, both varying between 0.0 and 0.1 mg/l.

During Cruise 2, Secchi disc readings were from 8 to 23 meters. Silica and phosphorus levels were low, ranging from 0.04 to 0.33 mg/l and 0.007 to 0.019 mg/l, respectively. Coliform MPN levels were slightly lower than values observed during Cruise 1, varying from 0 to 240/100 ml.

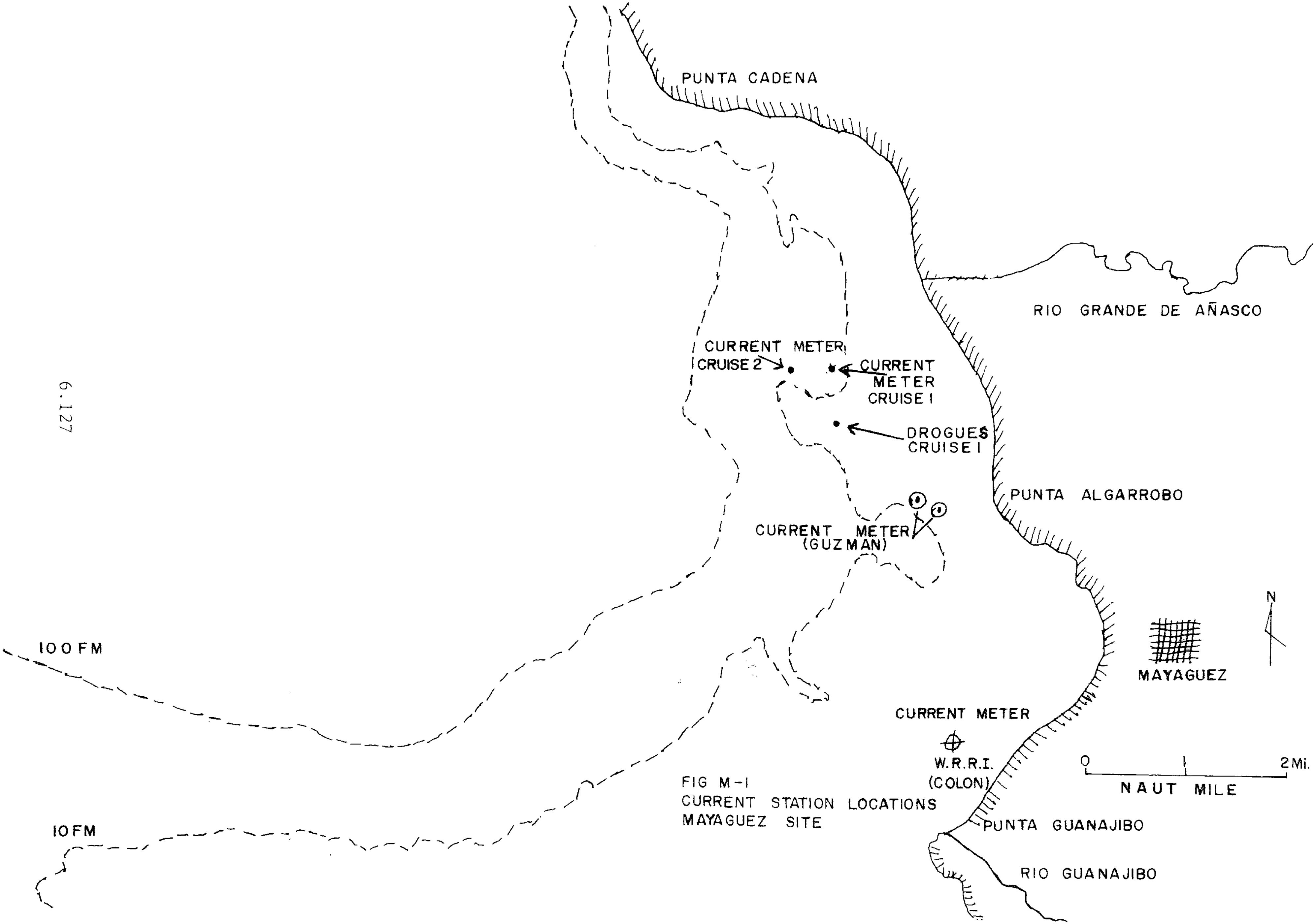
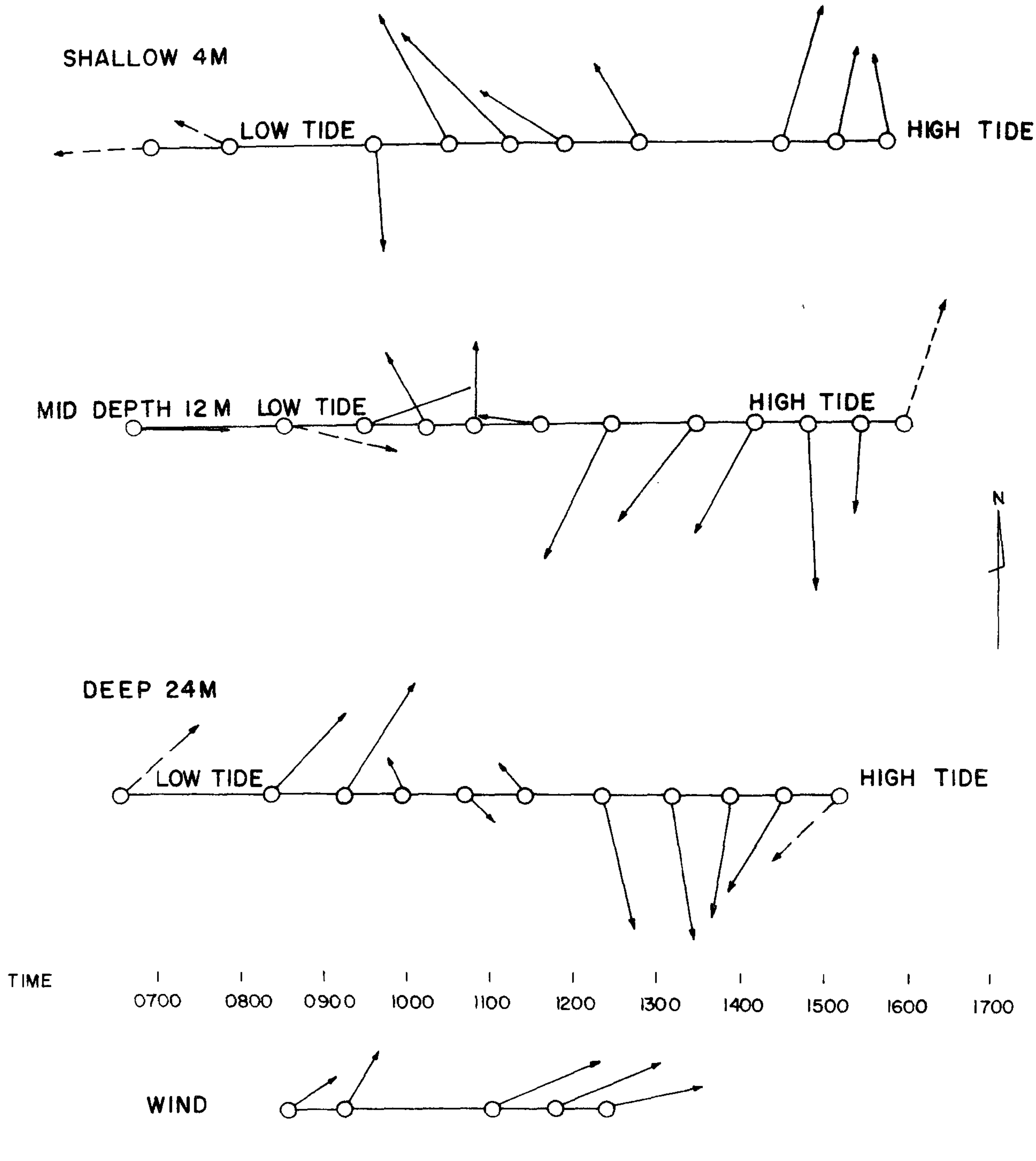


FIG M-1
CURRENT STATION LOCATIONS
MAYAGUEZ SITE



RISING TIDE
FALLING TIDE

0 10 20 30 40 CM/SEC

FIG M-2
CURRENT VECTORS
MAYAGUEZ
CRUISE I 17 JUNE 1971
WATER DEPTH 20 M
LOW TIDE 0918
HIGH TIDE 1616

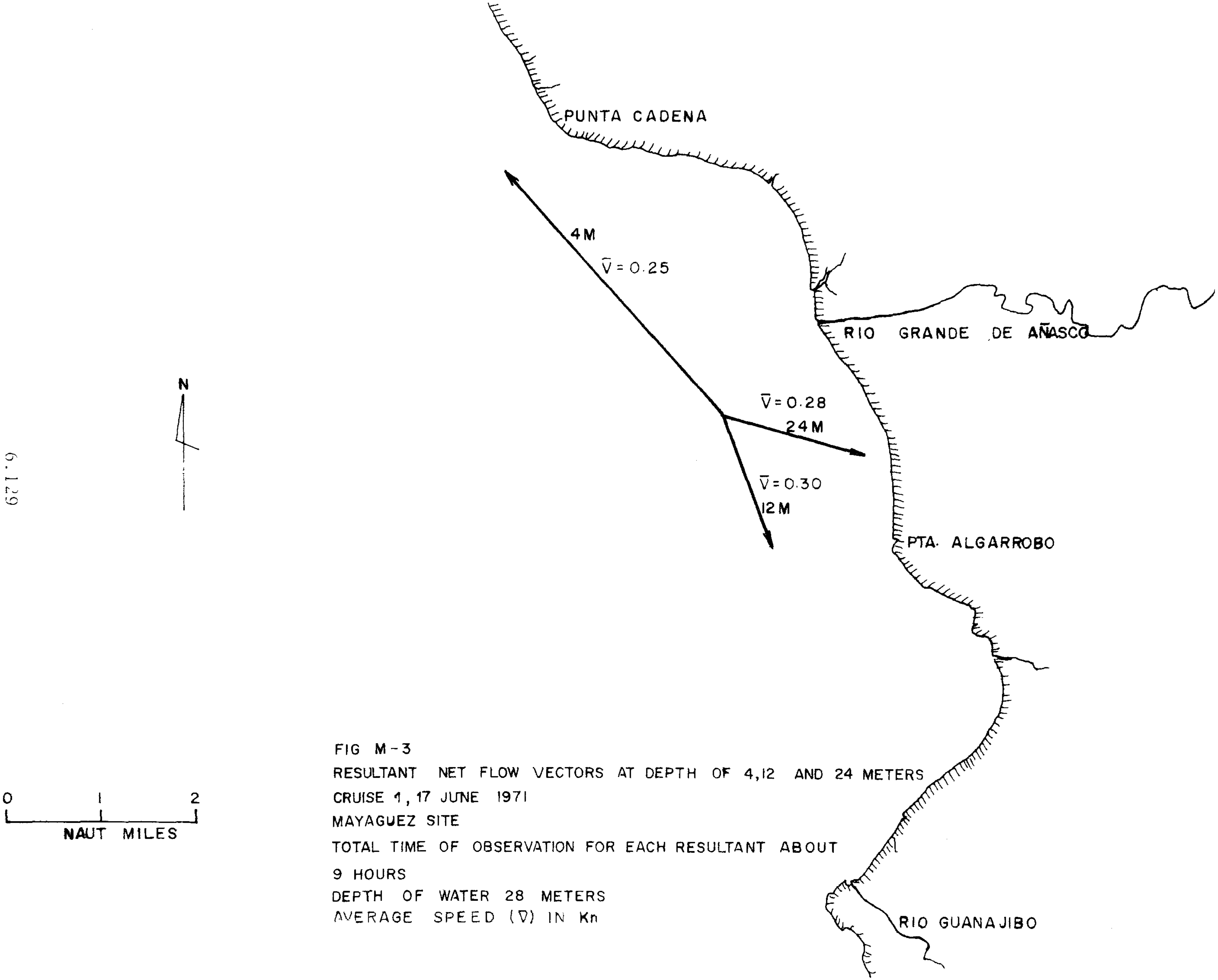


FIG M-3
RESULTANT NET FLOW VECTORS AT DEPTH OF 4,12 AND 24 METERS
CRUISE 1, 17 JUNE 1971
MAYAGUEZ SITE
TOTAL TIME OF OBSERVATION FOR EACH RESULTANT ABOUT
9 HOURS
DEPTH OF WATER 28 METERS
AVERAGE SPEED ($\bar{V}$) IN Kn

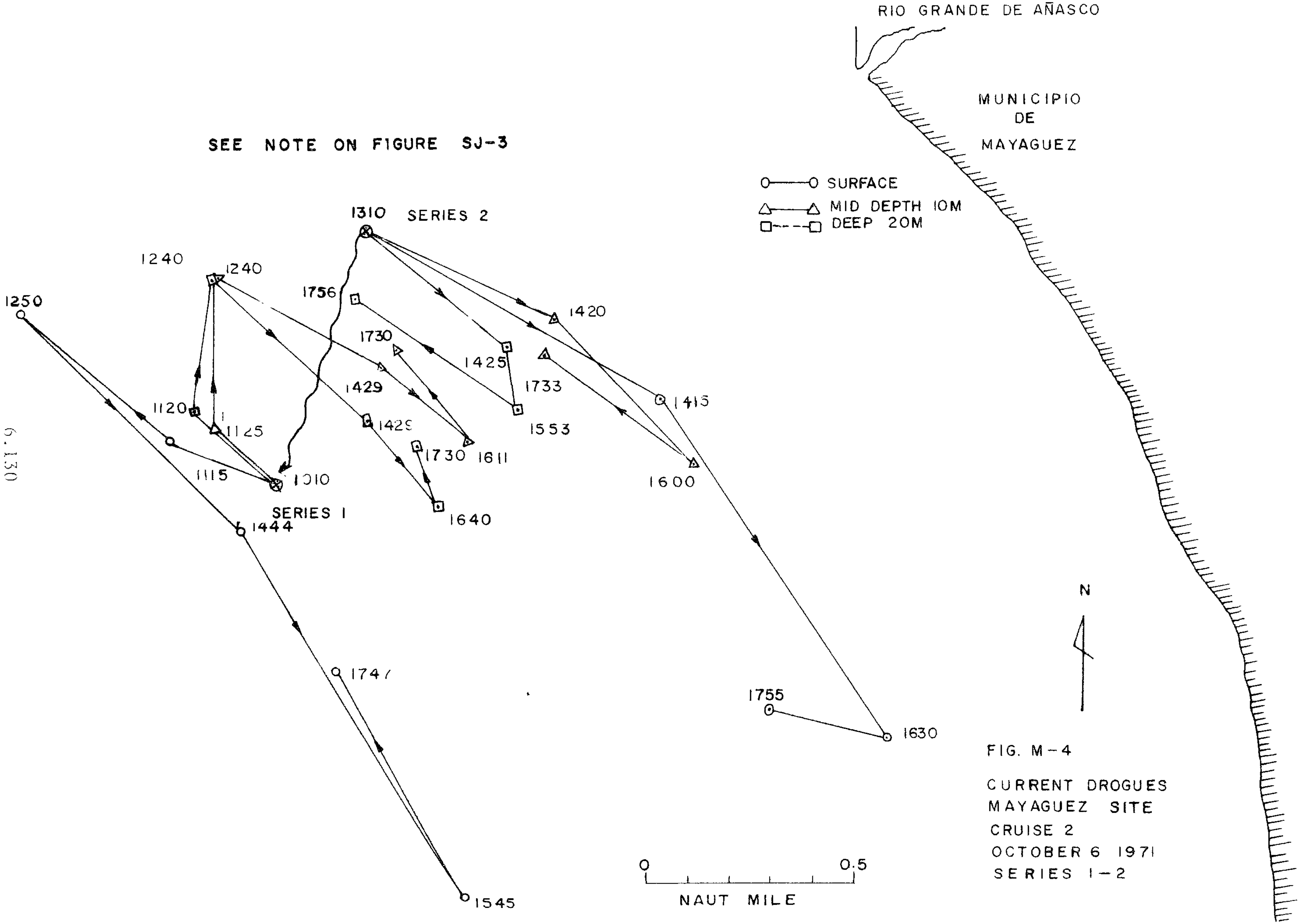


FIG. M-4
CURRENT DROGUES
MAYAGUEZ SITE
CRUISE 2
OCTOBER 6 1971
SERIES 1-2

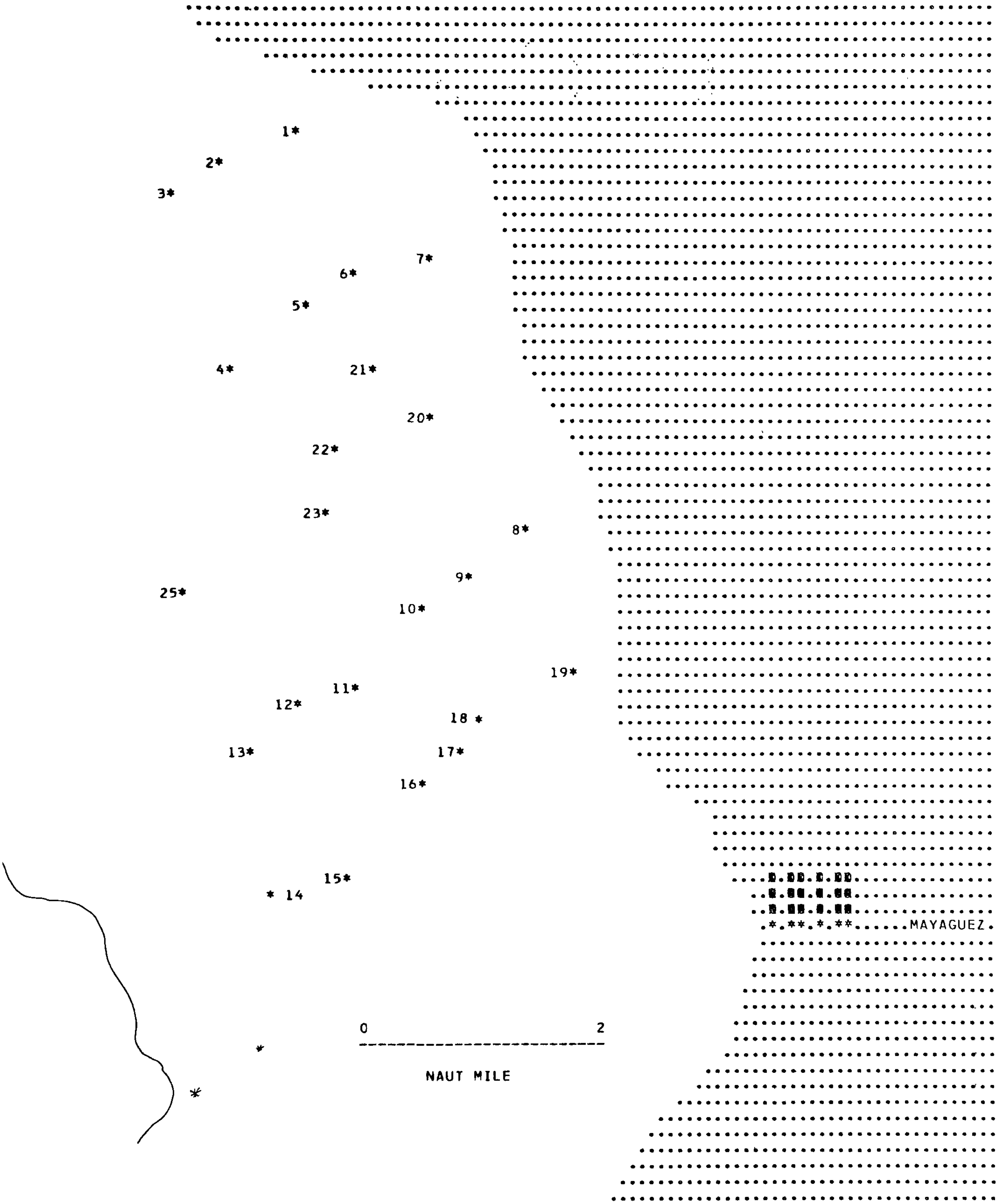


Figure M-5a
HYDROGRAPHIC STATION LOCATIONS
MAYAGUEZ
CRUISE 1 16, 17 JUNE 1971

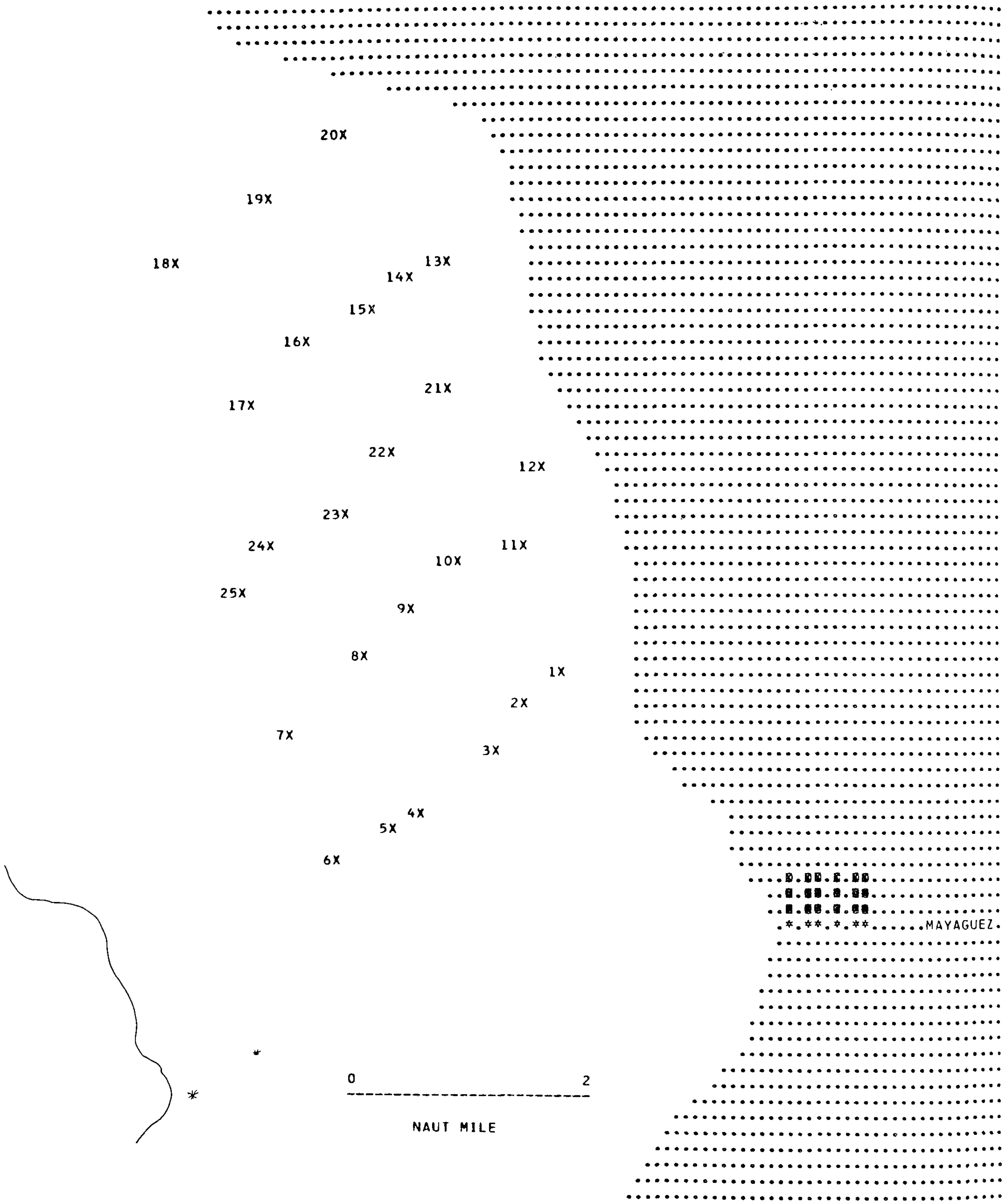


Figure M-5b
HYDROGRAPHIC STATION LOCATIONS
MAYAGUEZ
CRUISE 2   7 OCTOBER 1971

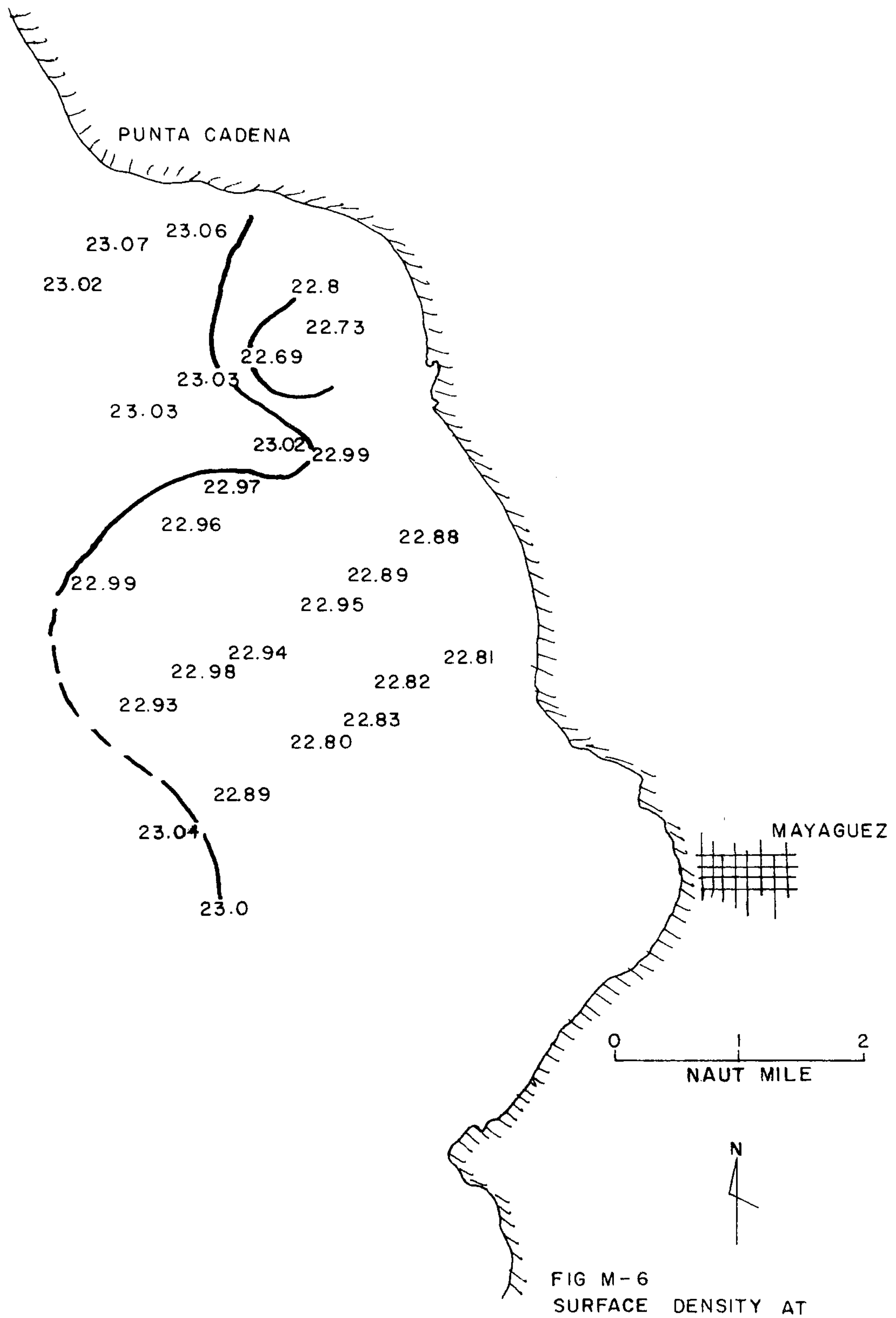


FIG M-6
SURFACE DENSITY AT
MAYAGUEZ SITE
CRUISE I 16 JUNE 1971

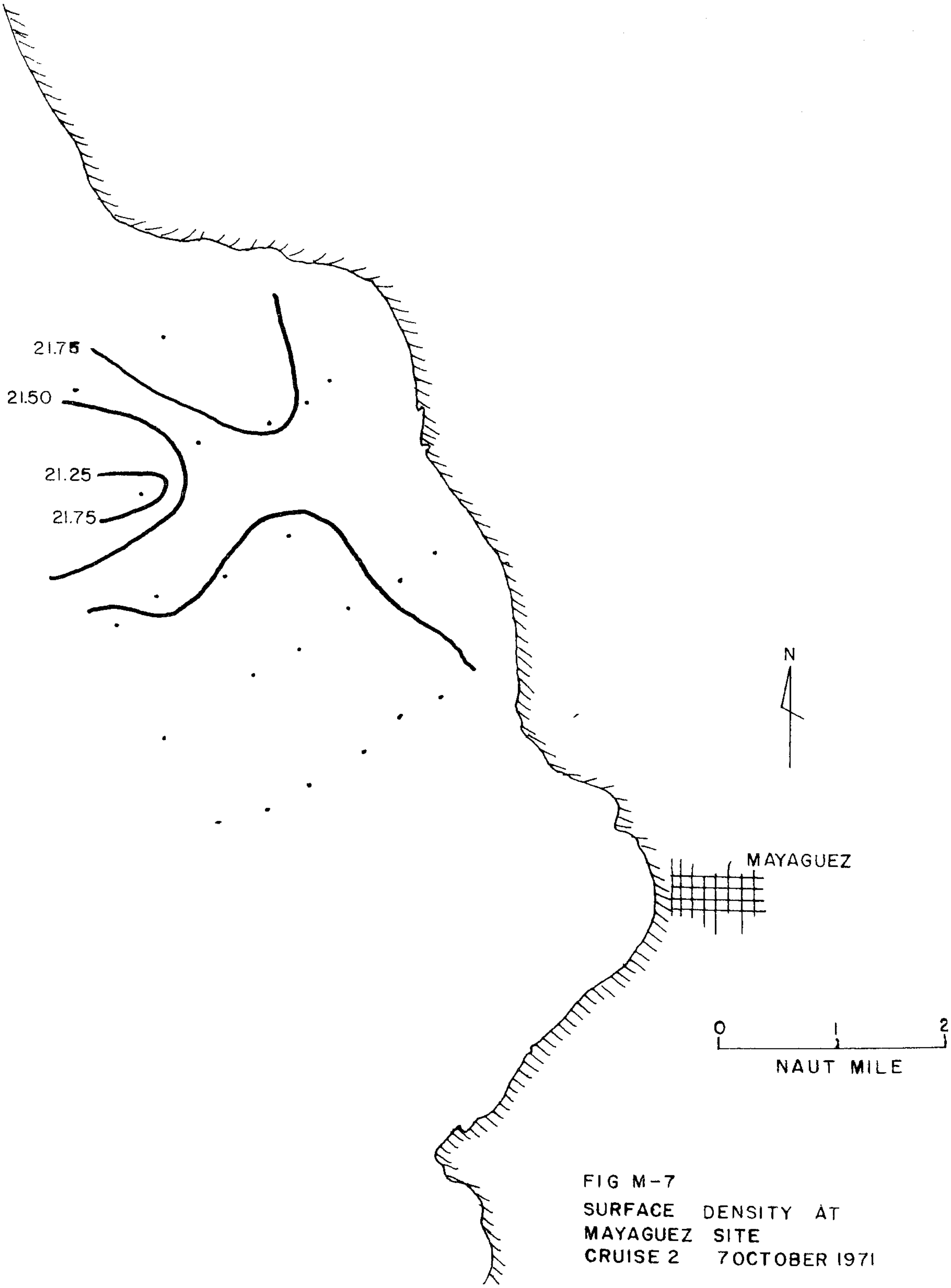


FIG M-7
SURFACE DENSITY AT
MAYAGUEZ SITE
CRUISE 2 7 OCTOBER 1971

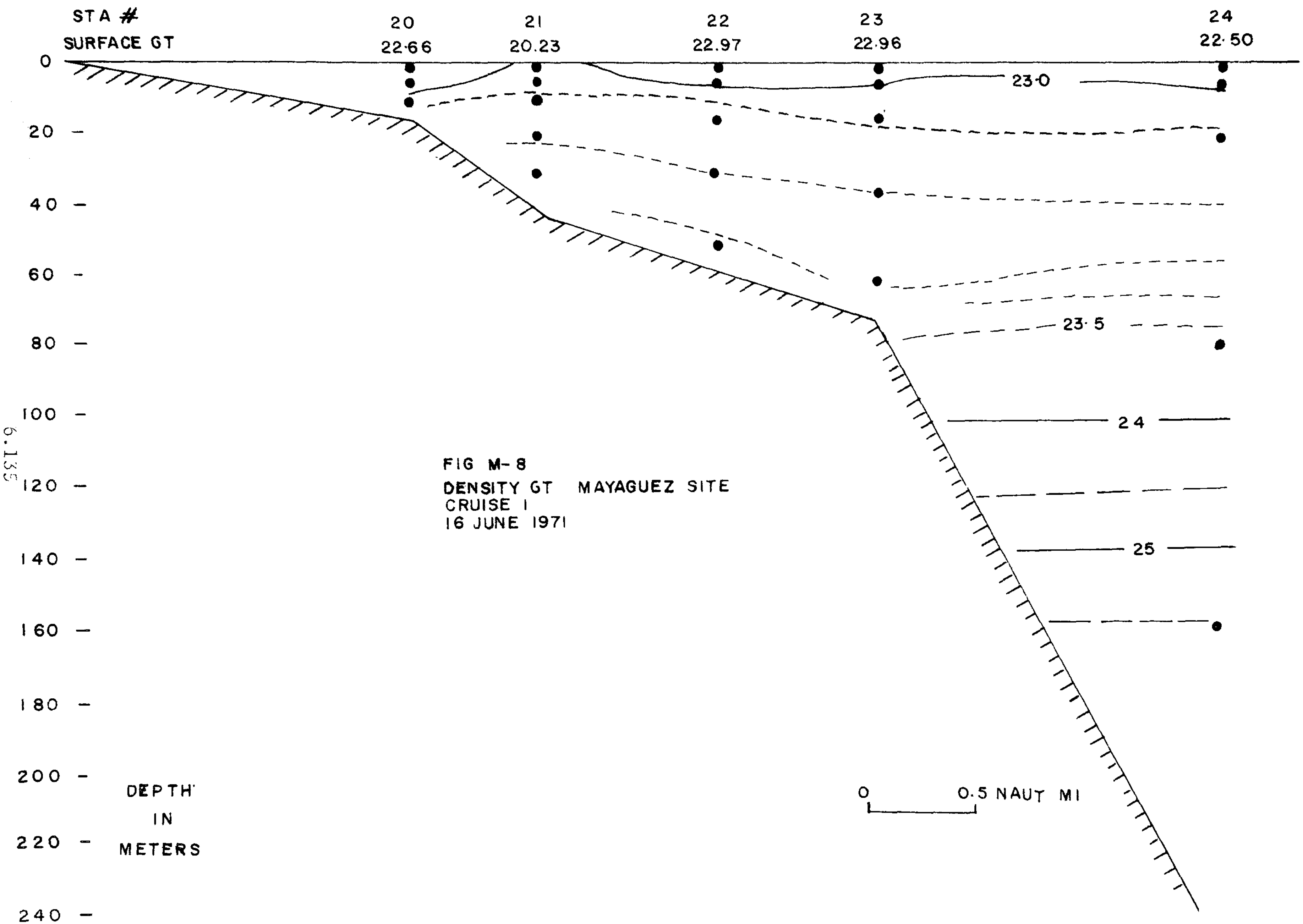


FIG M-8
DENSITY GT MAYAGUEZ SITE
CRUISE I
16 JUNE 1971

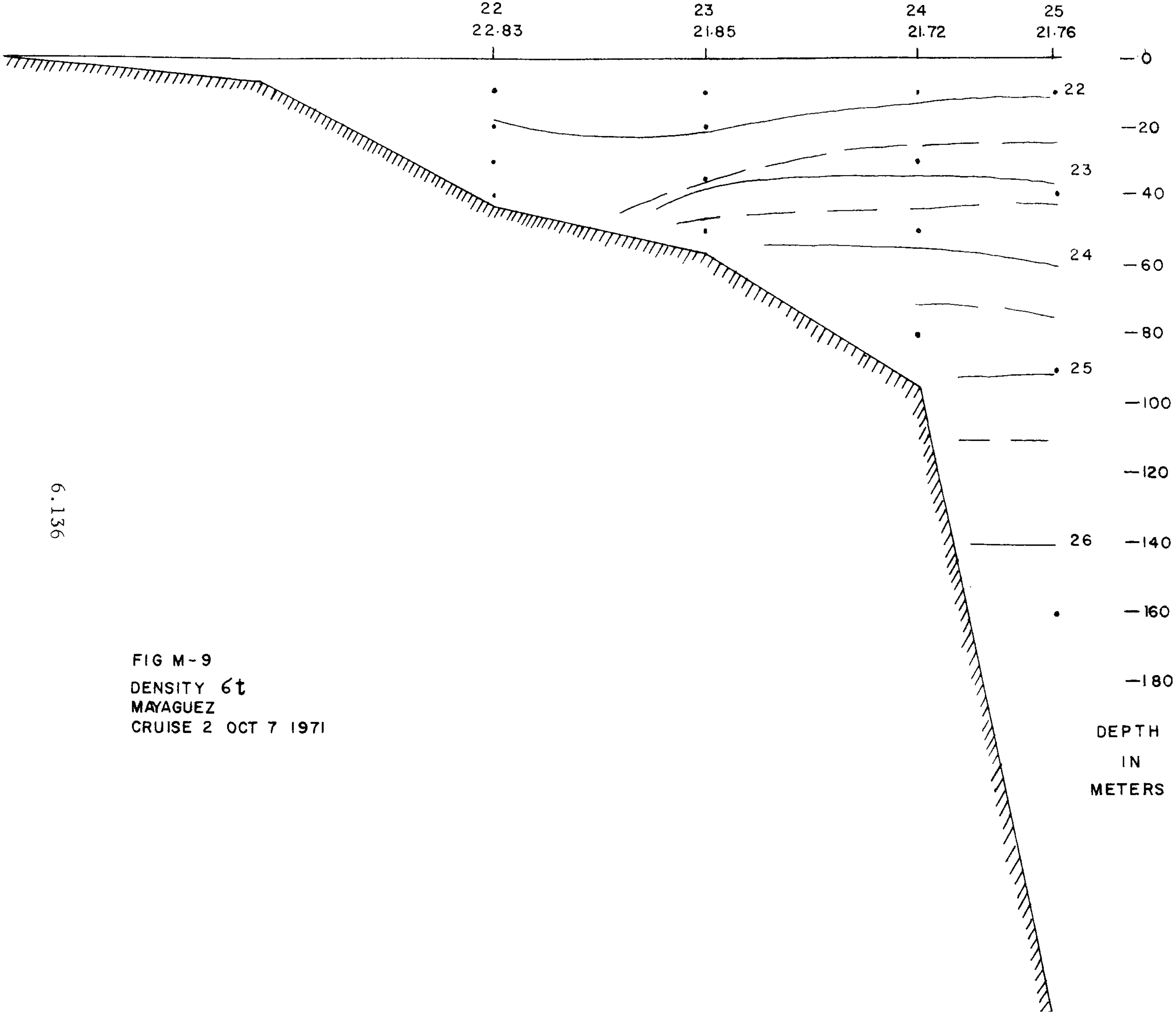


FIG M-9
DENSITY 6t
MAYAGUEZ
CRUISE 2 OCT 7 1971

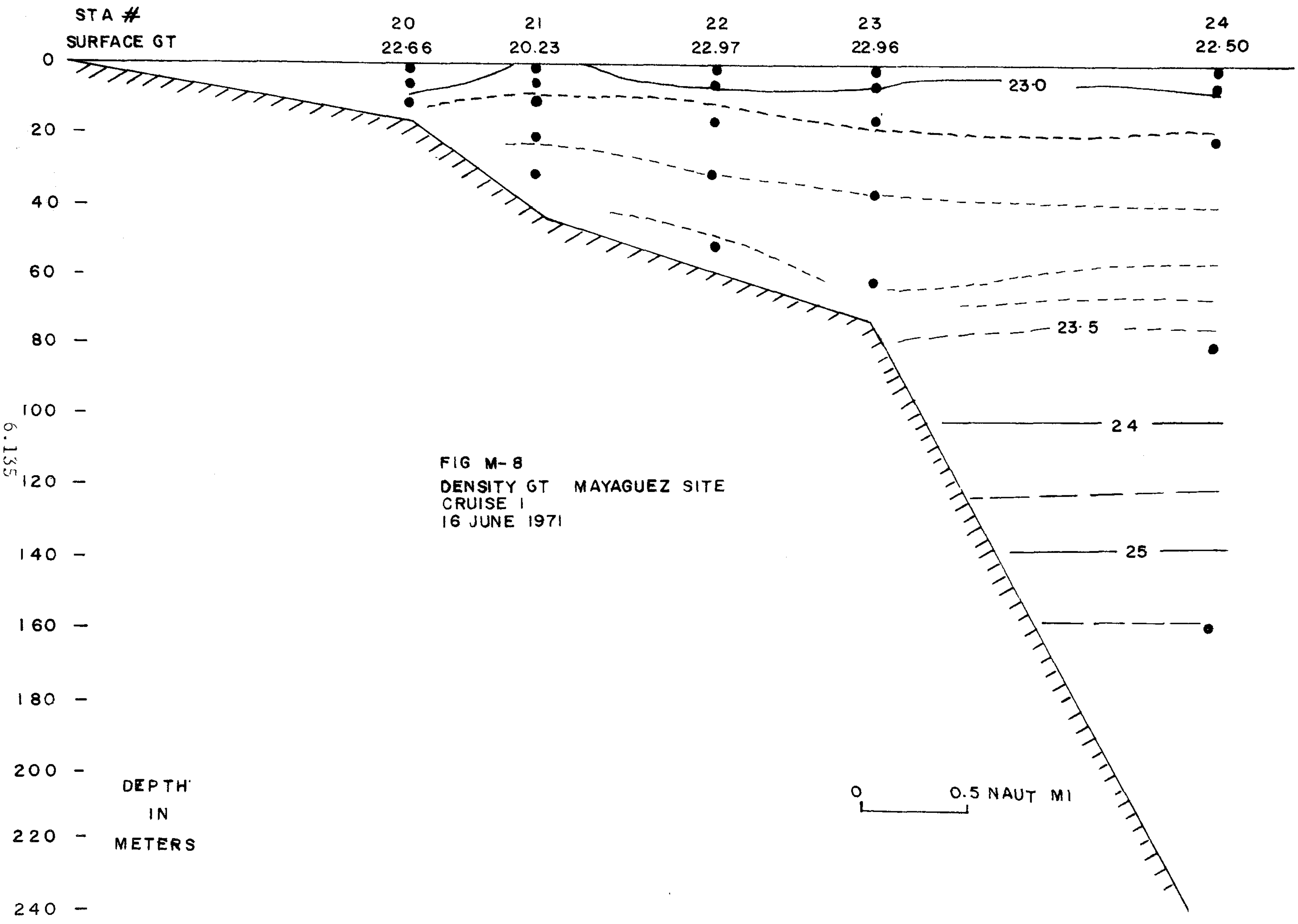


FIG M-8
DENSITY GT MAYAGUEZ SITE
CRUISE I
16 JUNE 1971

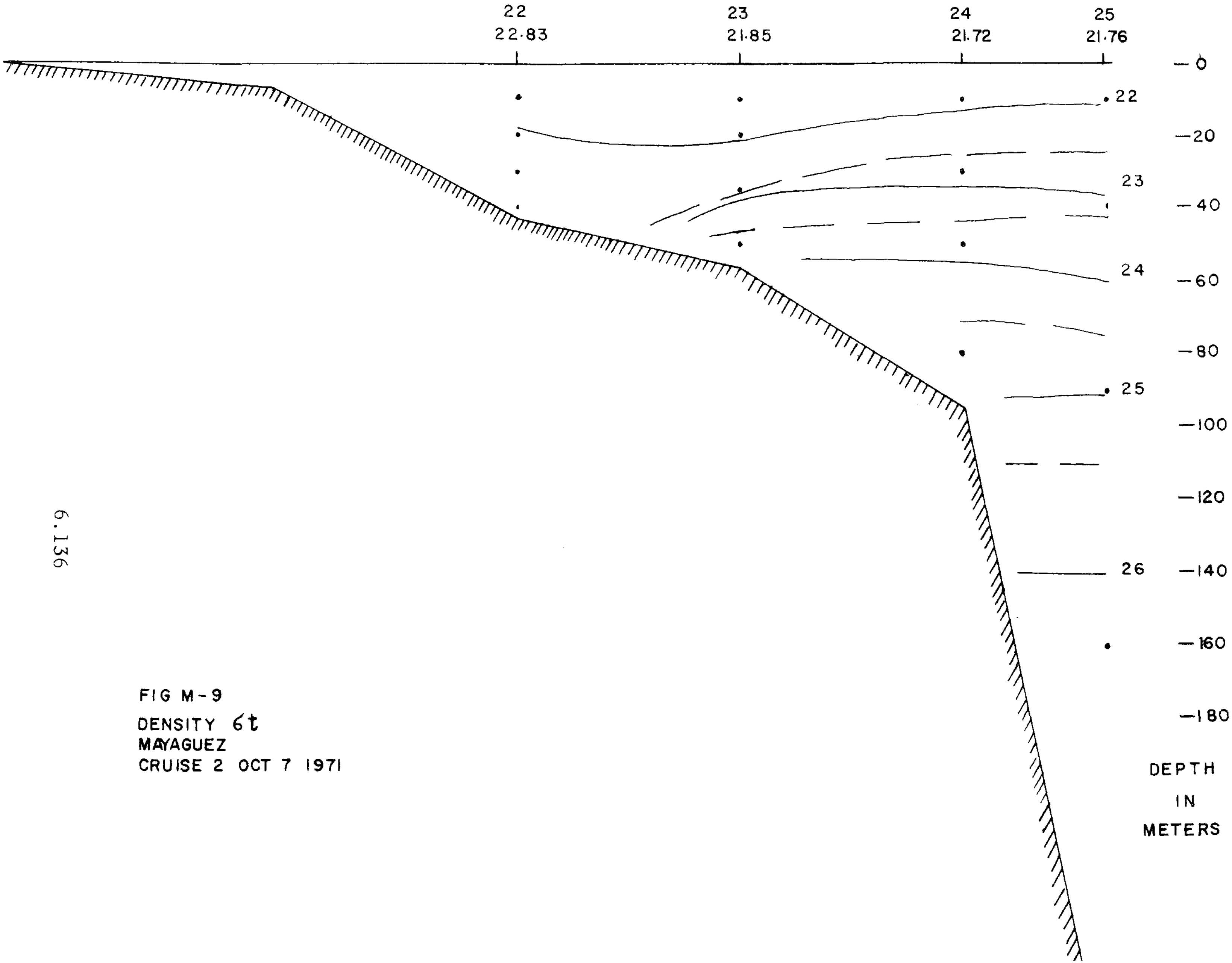


FIG M-9
DENSITY σ_t
MAYAGUEZ
CRUISE 2 OCT 7 1971

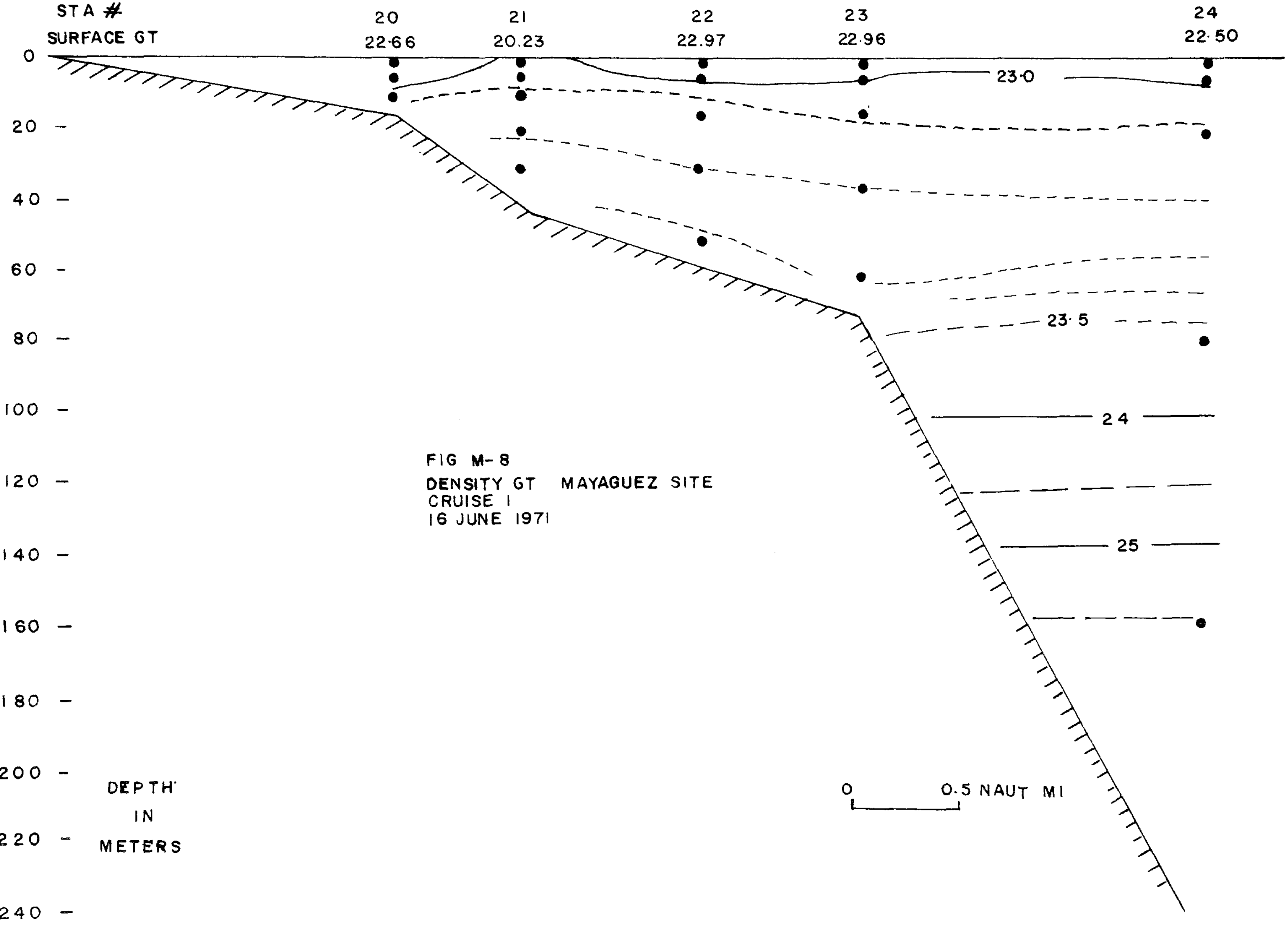


FIG M-8
DENSITY GT MAYAGUEZ SITE
CRUISE I
16 JUNE 1971

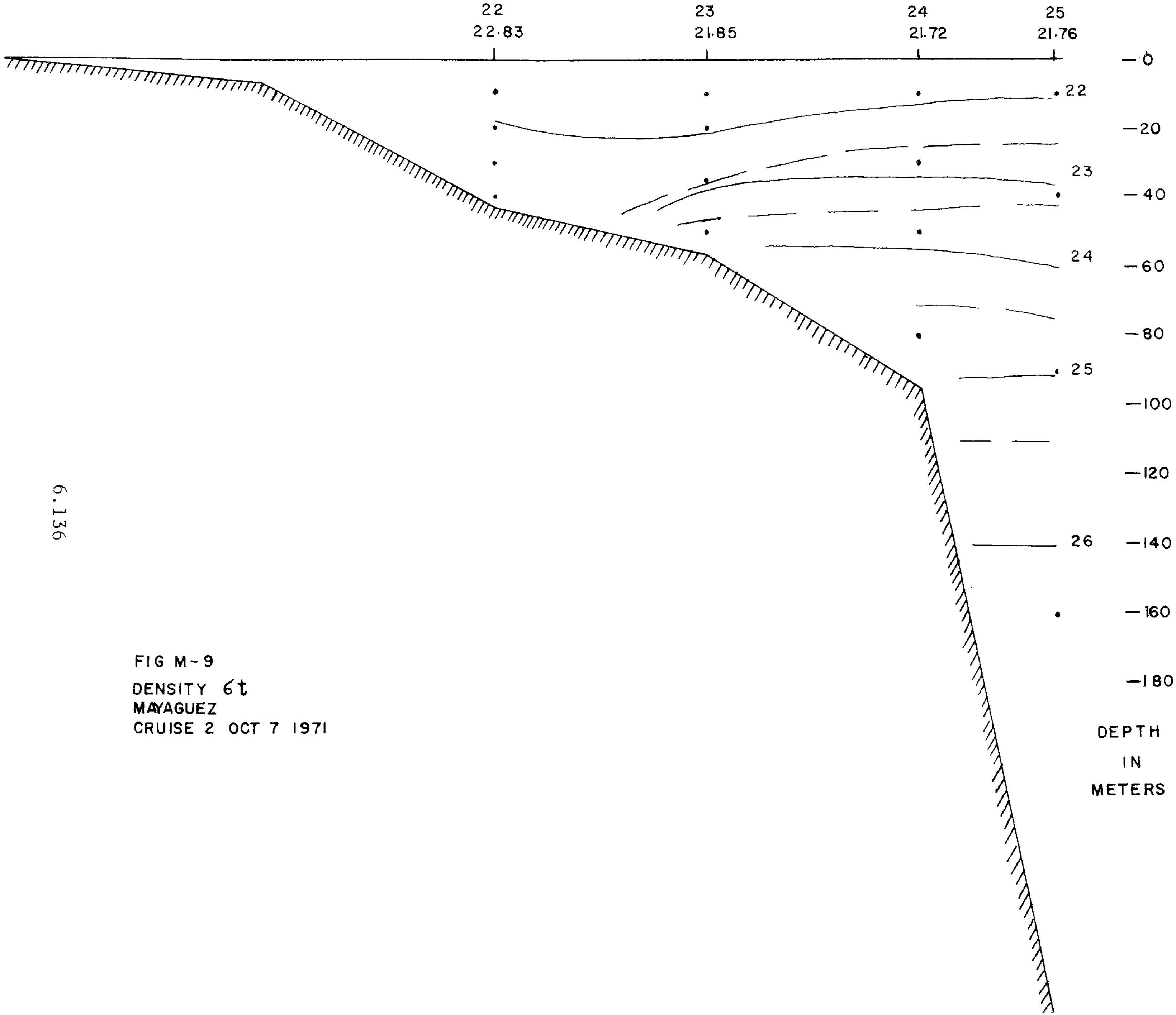


FIG M-9
DENSITY σt
MAYAGUEZ
CRUISE 2 OCT 7 1971

AGUADILLA

Description of Study Area

Aguadilla is situated near the northern extremity of the west coast of Puerto Rico, facing Mona Passage to the west. The central urban area occupies a narrow coastal zone bounded by Aguadilla Bay to the west and by mountains to the east. Aguadilla Bay extends from about seven miles northeast of Punta Higuero, the westernmost point of Puerto Rico, to Punta Borinquen, the northwest corner of the island. There are no coral reefs in the bay to dissipate wave action (1).

The Río Culebrinos drains into Aguadilla Bay just south of the city of Aguadilla, and is the only major stream discharging into the bay. Like so many of the rivers in Puerto Rico, the Culebrinos undergoes enormous changes of flow in short periods of time (3). Fifty percent of the time the flow amounts to 77.5 MGD or less. The river flow is less than 30 MGD about 10 percent of the time and is more than 90 MGD 10 percent of the time. A peak of 19,122 MGD was reached during a flood on the 27th of November 1968.

Rainstorms over the watershed introduce large amounts of silt laden water into the coastal waters. During periods of relative calm the less-dense waters of low salinity maintain their identity as distinct surface layers of high turbidity as far as eight miles from the mouth of the river. However, rapid mixing occurs near the mouth of the river during periods of high wave and breaker activity (2).

The large watershed drained by the Río Culebrinos includes the towns of Lares, San Sebastián, Moca and Aguada. From each of these towns the Río Culebrinos receives the effluent of municipal sewage treatment plants. The Central Plata sugar mill in San Sebastián uses river water in its operations and discharges both process wastes and cooling water directly to the river. The Central Coloso, 2.5 miles northeast of Aguada, also uses river water and discharges process wastes and cooling water to a swampy area from which most of the effluents eventually return to the river (2). Raw sewage also enters Aguadilla Bay from four short outfalls which extend about 30-50 feet into the bay. There are many breaks along the length of these pipes which result in the discharge of wastewaters to the surf-zone.

Hydrodynamics

The general westward flow of the North Equatorial Current has been identified by Lowman (5) as a factor creating a clockwise gyre in Aguadilla Bay. If this is indeed the case, then important seasonal changes caused by modifications of the far offshore general current patterns are to be expected. The Pilot Charts state that in March the prevailing current in Mona Passage is toward the northwest (from Caribbean Sea into Atlantic Ocean), while it is towards the southwest (from the Atlantic into the Caribbean) in June. Drogue studies carried out by Weston et al (6) showed a parallel-to-shore (SW or NE) flow, or offshore (westerly) flow at Aguadilla. In only a few cases was an onshore current observed. The clockwise gyral was present at times, but it was not always observable. On various occasions a flow apparently associated with tidal reversal was observed.

Two current surveys were carried out at Aguadilla by the Oceanographic Project. Station locations for the two cruises are shown in Figure Ag-1. Results obtained with the Ekman-Merz meter during the first cruise are shown in Figures Ag-2 and Ag-3, and further data is included in Appendix J. As may be seen in Figure Ag-2, results showed a reversal from SW to roughly NE during ebb tide. The maximum current speed occurred during the time of SW flow, at approximately the time of high tide, when it reached a speed of about 0.8 knot. The current pattern was very much the same from the surface to a depth of 24 meters during the entire nine hour period of observation. Calculated average speeds during this period were about 0.36 knot at the surface, 0.33 knot at a depth of 12 meters, and 0.30 knot at 24 meters. Figure Ag-3 shows the results of an analysis which gives an indication of relative amounts of flow at the three depths. The length of each resultant is proportional to the net flow (or transport) in the direction indicated. A discussion of the method used to compute these values is included in Appendix B.

Drogue results for Cruise 2 are shown in Figure Ag-4, and additional data is given in Appendix J. Most of the period of observation fell within the period of ebb tide. The flow indicated by the drogues was generally to the NE, veering towards the west after low tide. Speeds at all depths were slightly lower than the values obtained during Cruise 1. As explained elsewhere in this report, an in-situ recording current meter was used in addition to drogues during Cruise 2, but the results obtained with this instrument are considered unreliable and have therefore been omitted. In the particular case of Aguadilla, however, the recording current meter did yield results more-or-less in agreement with the drogue data, especially as regards current direction.

Judging from the data obtained during the two cruises, it appears that the water mass at Aguadilla behaves as a vertical unit, changing speed and direction approximately simultaneously from the surface to at least 20 meters. The current is usually (but not always) roughly parallel to the shoreline, with a tendency to flow towards the south-west during flood tide, and towards the north-east during ebb tide. Current speeds are sometimes relatively high. A summary of wind data obtained from Ramey Air Force Base covering the years from 1940 to 1967 is given in Appendix J. The wind is generally from the ENE, E, or ESE.

As Aguadilla Bay is protected from easterly winds, wind speeds are probably considerably lower in the bay than at Ramey. This view is supported by field measurements by Weston et al (6). Accordingly, wind is not likely to play an important role in the current structure at Aguadilla.

Hydrographics

The hydrographic station locations for Cruises 1 and 2 are presented in Figure Ag-5. Hydrographic data is given in Appendix J, and in Figures Ag-6 through Ag-9. The discharge from the Río Culebrinos causes the surface receiving water in the vicinity of the river mouth to be more than 0.5°C warmer than the rest of the bay. Due to the reversal of current flow in this bay with each tidal cycle, the direction of flow of the tongue of the river may vary. The temperature gradient in the upper layers is relatively weak. Surface salinity values (see Appendix J) indicate that the area of relatively fresh water west of the river mouth is attributable to river runoff. The change in salinity is about one part per thousand. Vertical salinity profiles are included in Appendix J. The salinity gradient in the upper layers is somewhat more pronounced than is the temperature gradient.

The horizontal density distribution in the surface waters at Aguadilla is shown in Figures Ag-6 and Ag-7. As would be expected, the areas of low salinity also show up as areas of low density. The density change is only about 0.4 sigma-t units from one to 30 meters of depth.

Although sizeable horizontal gradients, especially of salinity and sigma-t, appear at the surface, they quickly disappear at depth. As can be seen from the tabular data for Cruise 1 in Appendix J, throughout the area there was a variation of only 0.08 percent in salinity at 30 meters compared with 0.95 percent at the surface. Similarly, the sigma-t variation at 30 meters amounted to 0.10 compared with 0.93 at the surface. Thus, although the inshore stations show some indication of the presence of warm, less saline, river water at the surface, the waters of Aguadilla Bay are relatively homogeneous below the surface layer.

Water Quality

The assessment of water quality for this area included two cruises which measured Secchi disc depths, dissolved oxygen, coliforms, silica, and phosphorus. The data collected is presented in tabular form in Appendix J.

The main feature of the Secchi depths on the first cruise was the observation of the tongue of turbidity projecting into the ocean from Río Culebrinos as may be seen in Figure Ag-10. Many of the towns on the river dump wastes into this stream or its tributaries, and these materials are eventually transported in the stream to the ocean. The levels of silica were found to be 0.2 and 0.3 mg/l, while, surprisingly, no phosphorus was detected at the sampling stations. Coliform MPN levels varied from 1300 to 1600/100 ml range, reflecting the presence of adjacent waste water discharges. The dissolved oxygen concentration averaged about 5 mg/l.

On the second cruise, the Secchi readings showed an eastward shift of the end of the tongue of turbidity from the mouth of the Río Culebrinos, as seen from values given in Figure Ag-11. The dissolved oxygen concentrations varied from 6.34 to 8.85 mg/l, which is significantly higher than observed on the first cruise. Silica concentrations were between 0.08 and 0.64 mg/l, and phosphorus levels between 0.003 and 0.051 mg/l, i.e., greater than from the first cruise, and possibly due to seasonal variation in the phytoplonkton populations. The coliform MPN levels varied from 0 to 3,000/100 ml, showing a wide variation, the high counts being associated with the turbid plume of the Río Culebrinos.

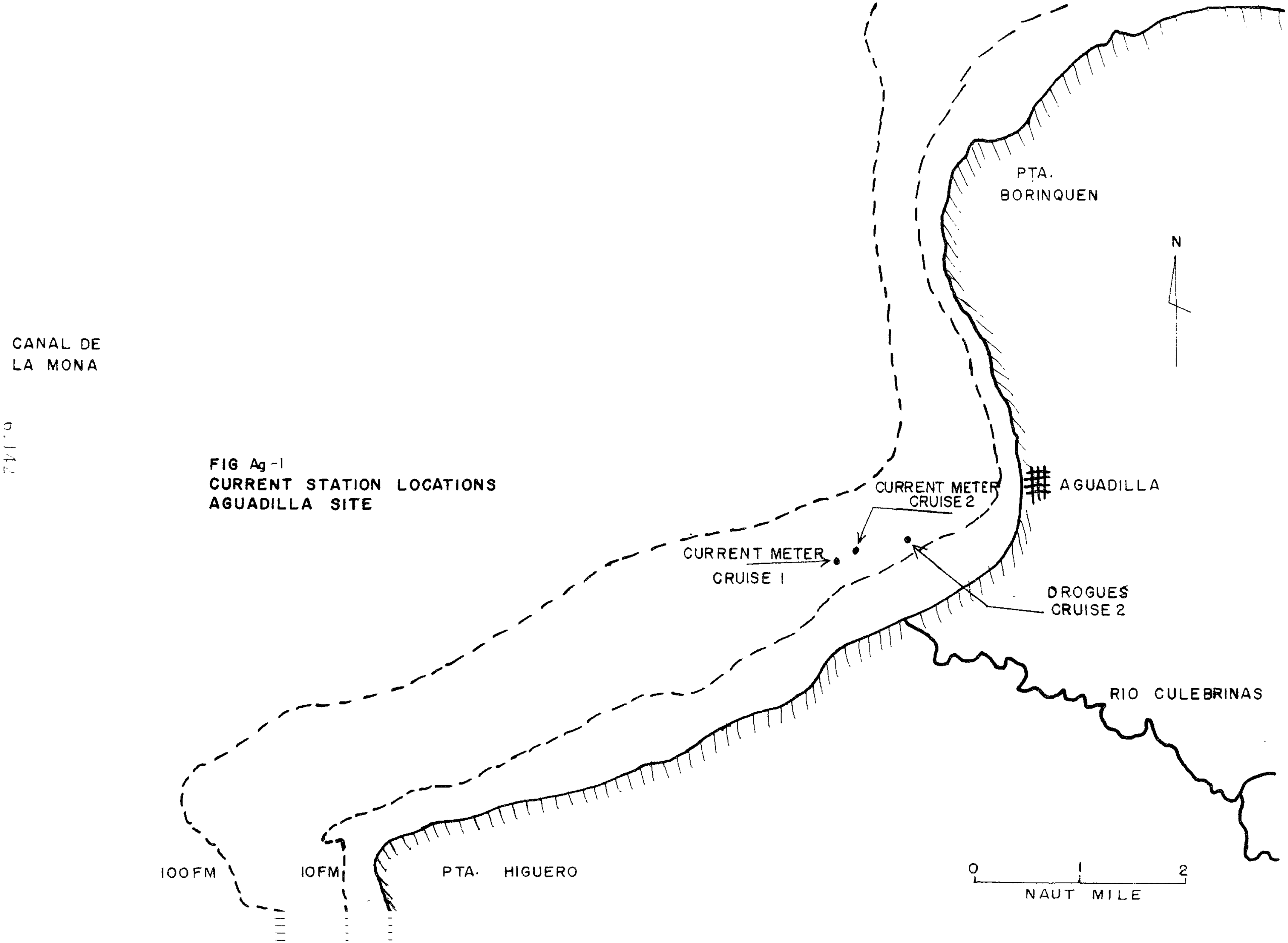


FIG Ag-1
CURRENT STATION LOCATIONS
AGUADILLA SITE

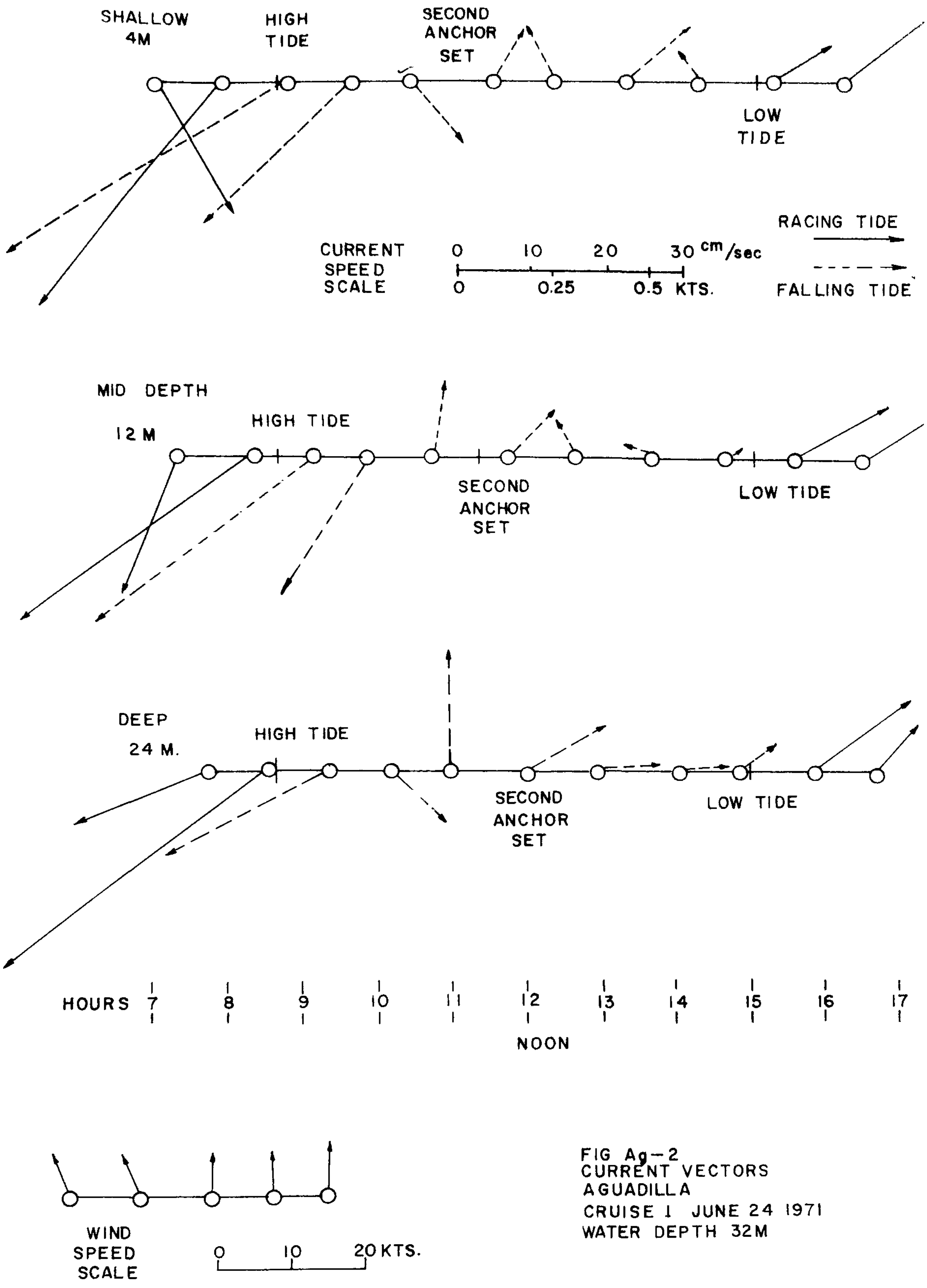


FIG Ag-2
CURRENT VECTORS
AGUADILLA
CRUISE 1 JUNE 24 1971
WATER DEPTH 32M

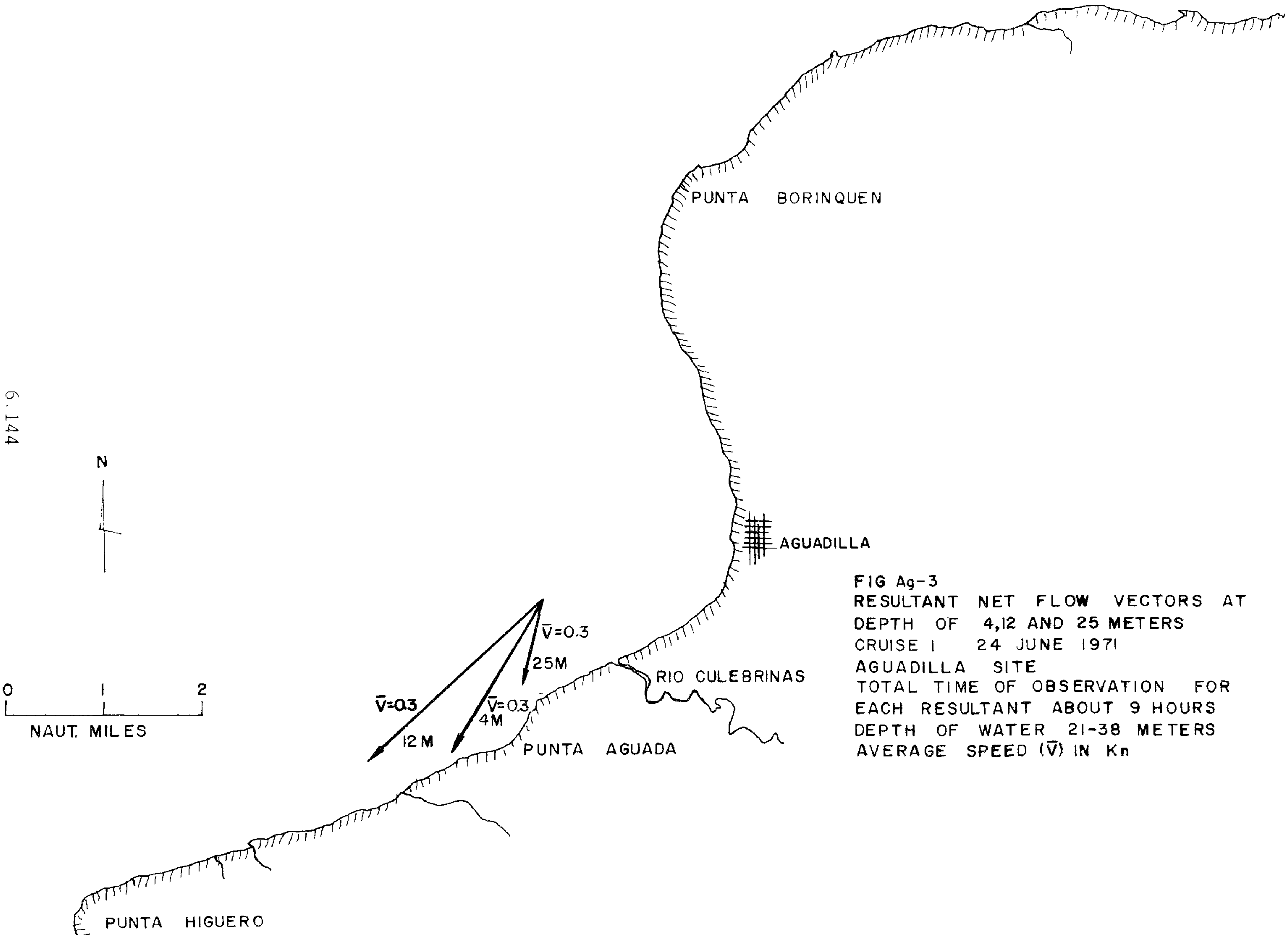


FIG Ag-3
RESULTANT NET FLOW VECTORS AT DEPTH OF 4,12 AND 25 METERS
CRUISE I 24 JUNE 1971
AGUADILLA SITE
TOTAL TIME OF OBSERVATION FOR EACH RESULTANT ABOUT 9 HOURS
DEPTH OF WATER 21-38 METERS
AVERAGE SPEED ($\bar{V}$) IN Kn

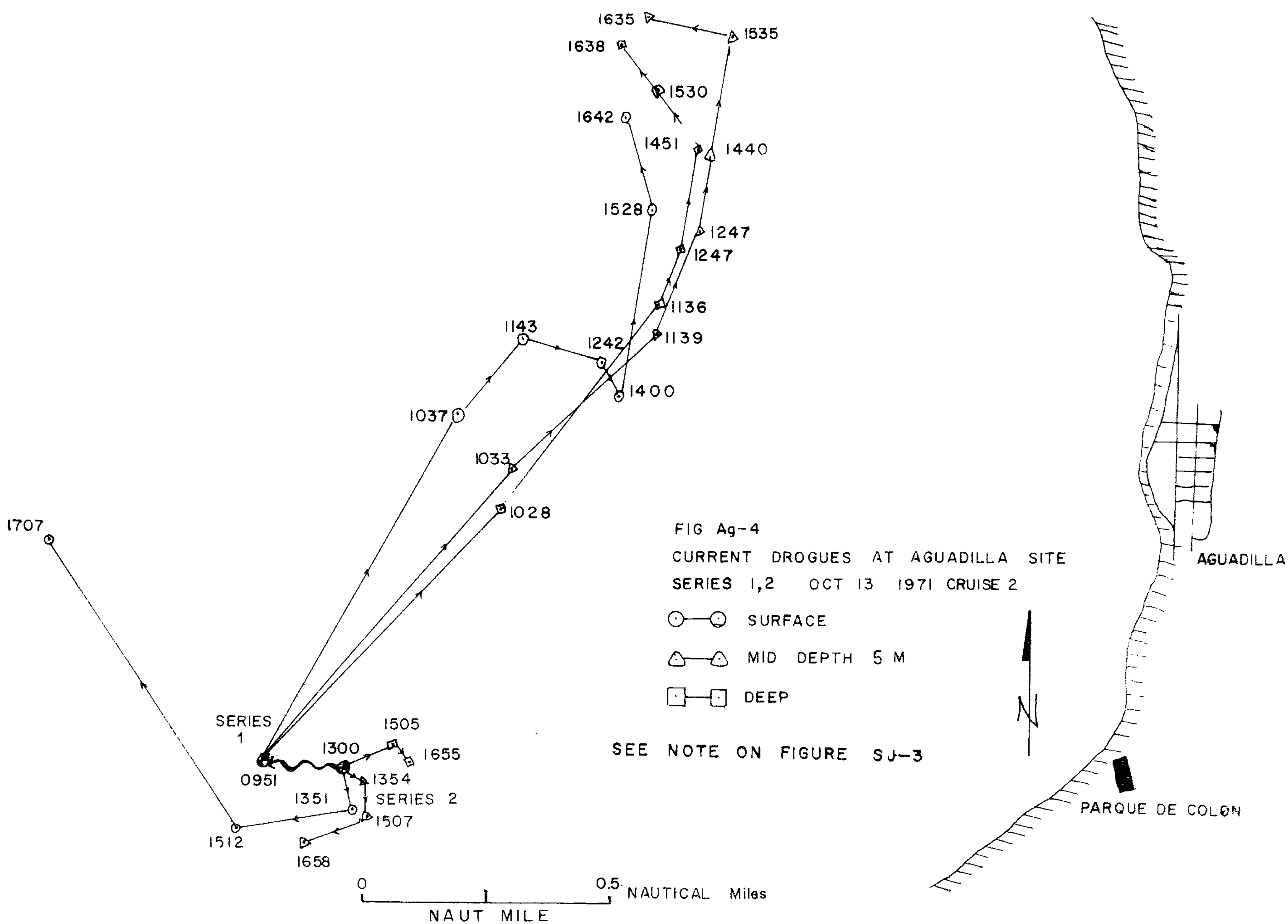


FIG Ag-4
CURRENT DROGUES AT AGUADILLA SITE
SERIES 1,2 OCT 13 1971 CRUISE 2

SEE NOTE ON FIGURE SJ-3

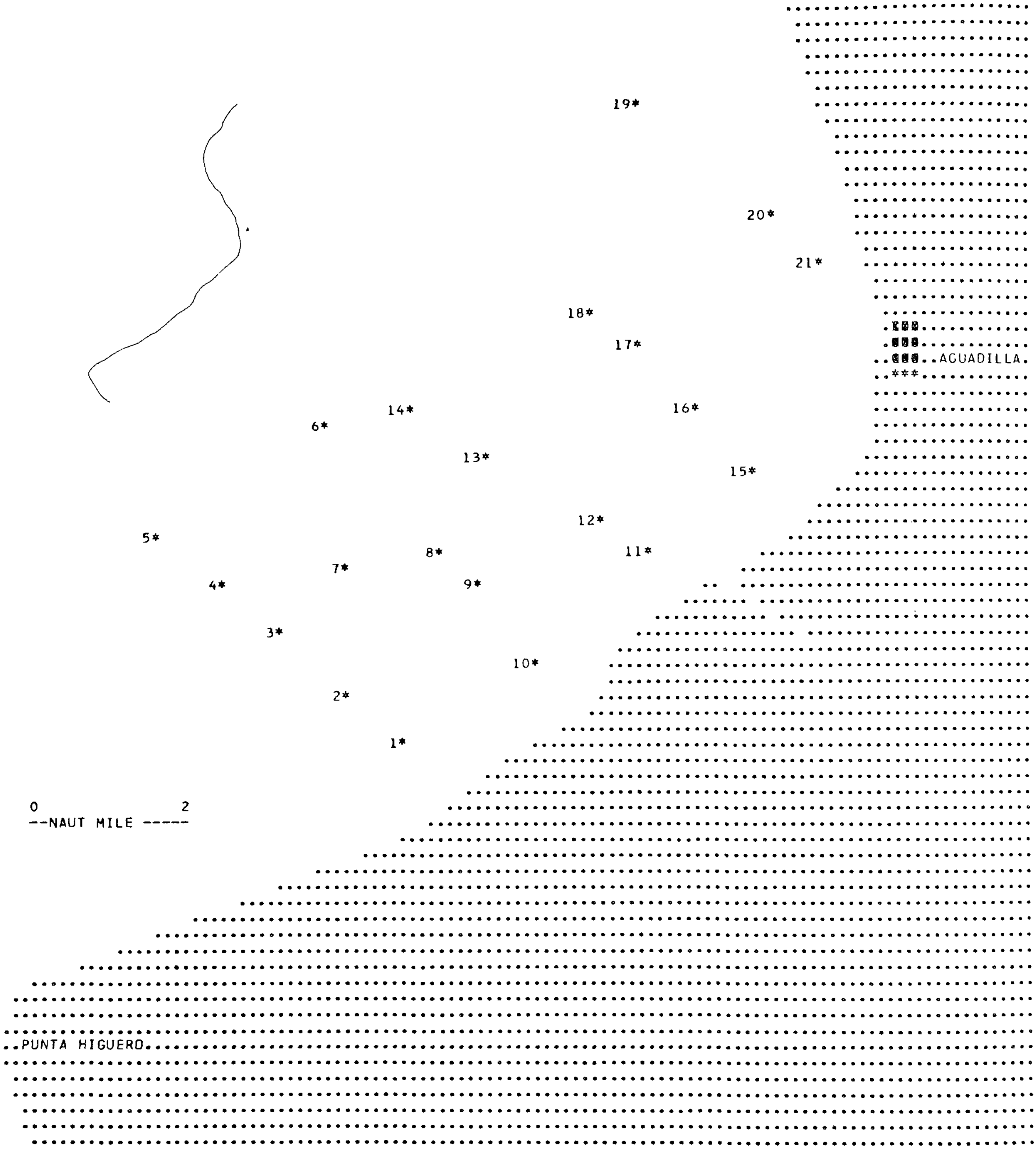


Figure AG-5a
HYDROGRAPHIC STATION LOCATIONS
AGUADILLA
CRUISE 1 23 JUNE 1971

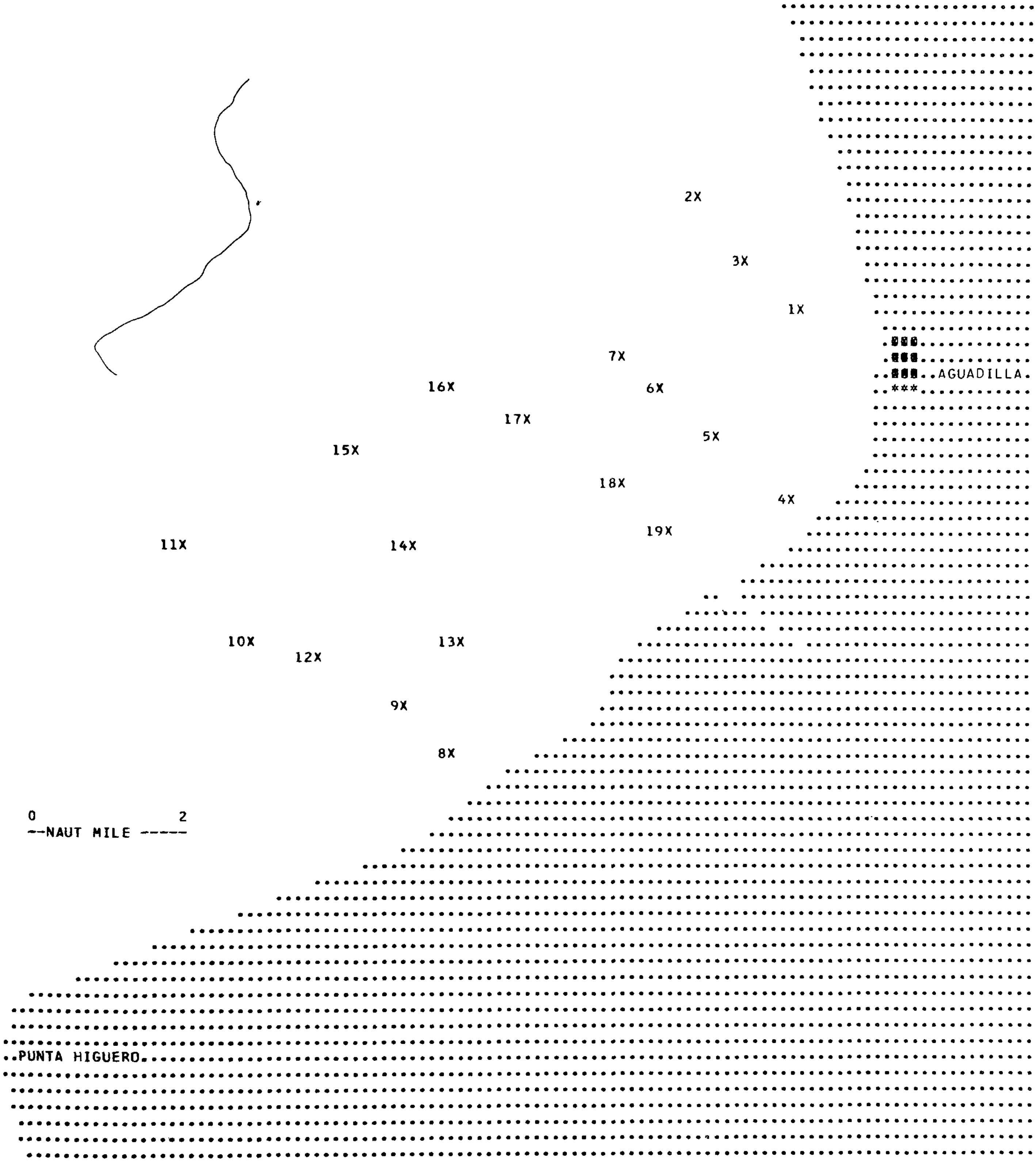


Figure AG-5b
HYDROGRAPHIC STATION LOCATIONS
AGUADILLA
CRUISE 2 14 OCTOBER 1971

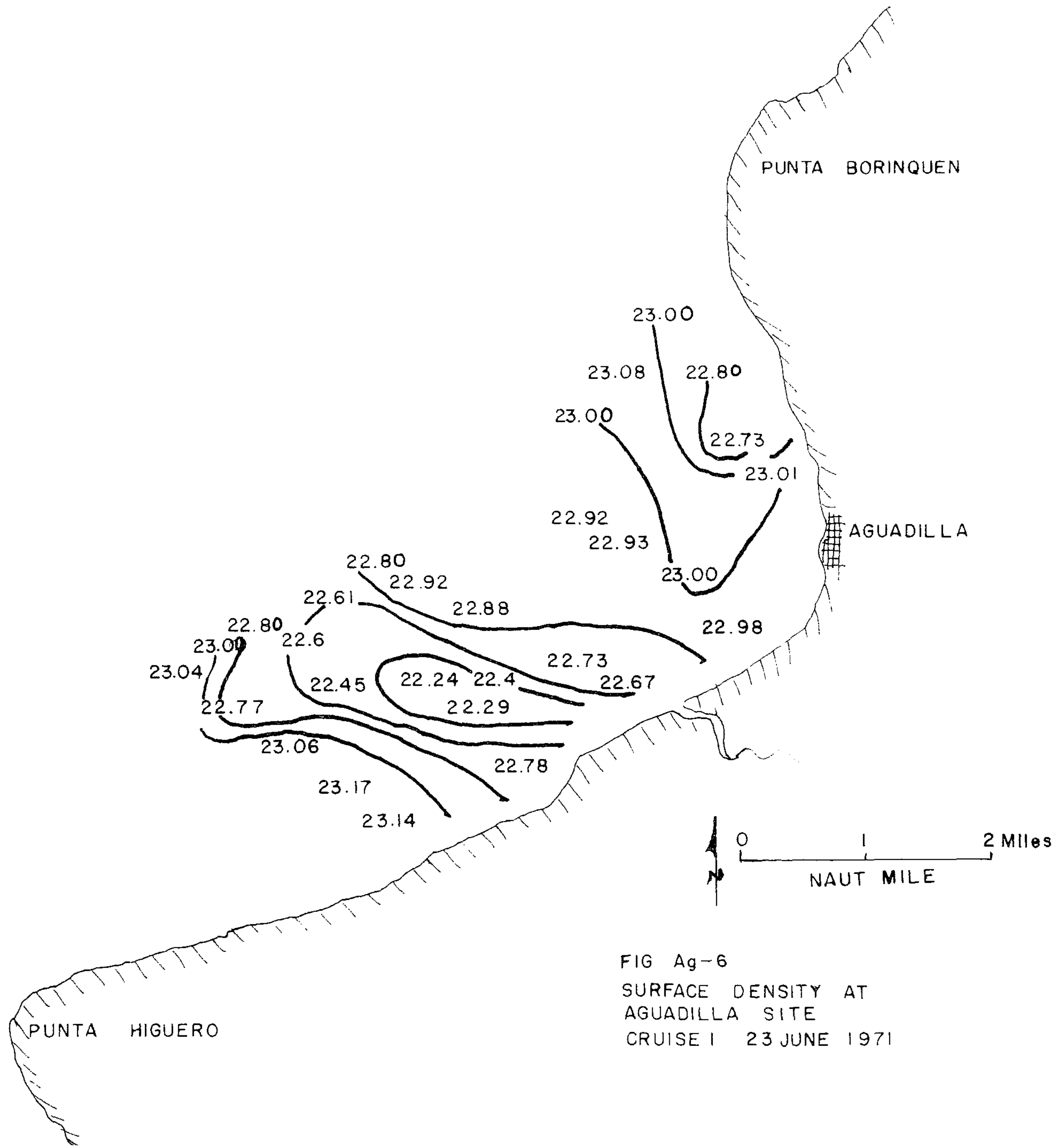


FIG Ag-6
SURFACE DENSITY AT
AGUADILLA SITE
CRUISE I 23 JUNE 1971

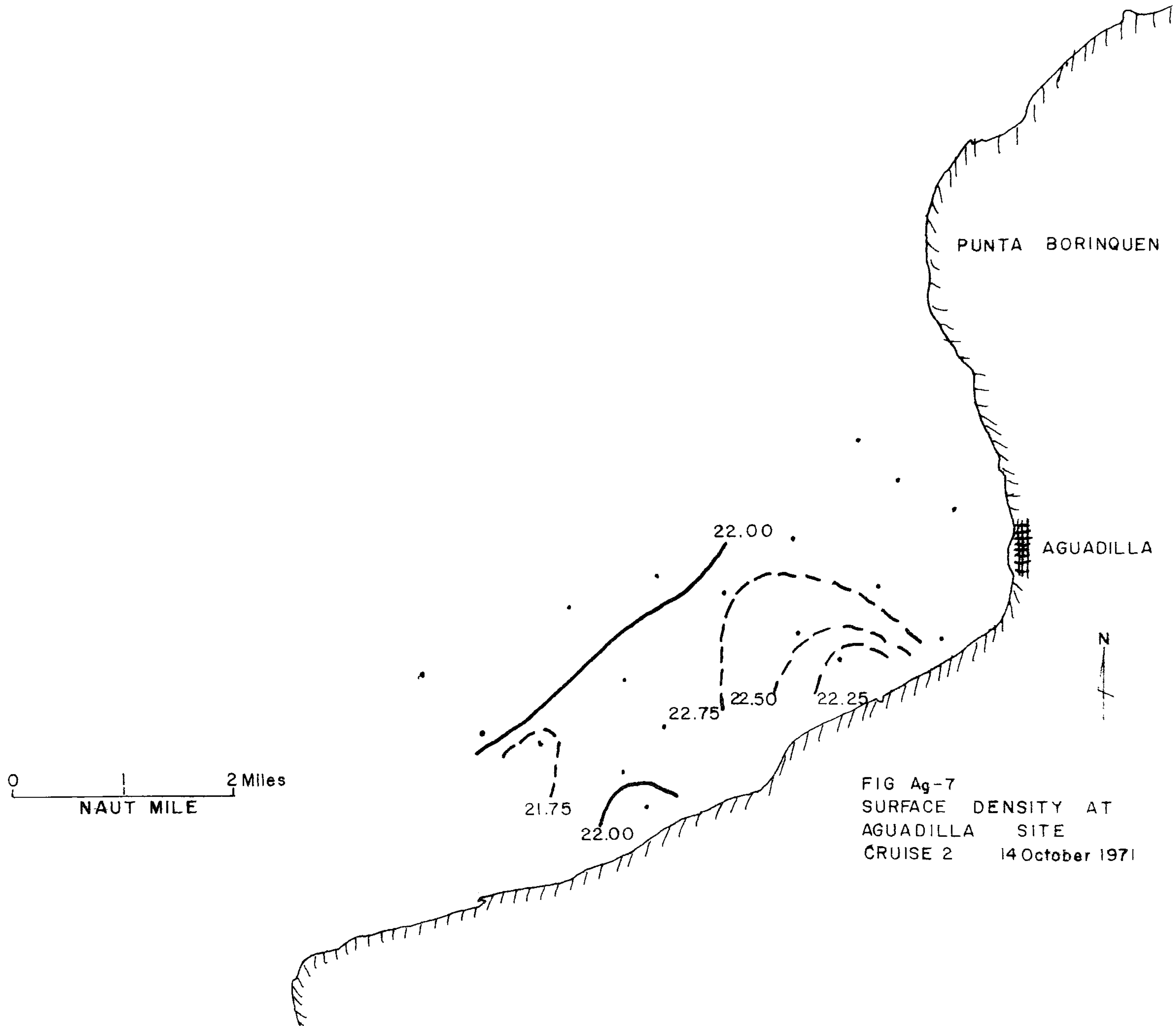


FIG Ag-7
SURFACE DENSITY AT
AGUADILLA SITE
CRUISE 2 14 October 1971

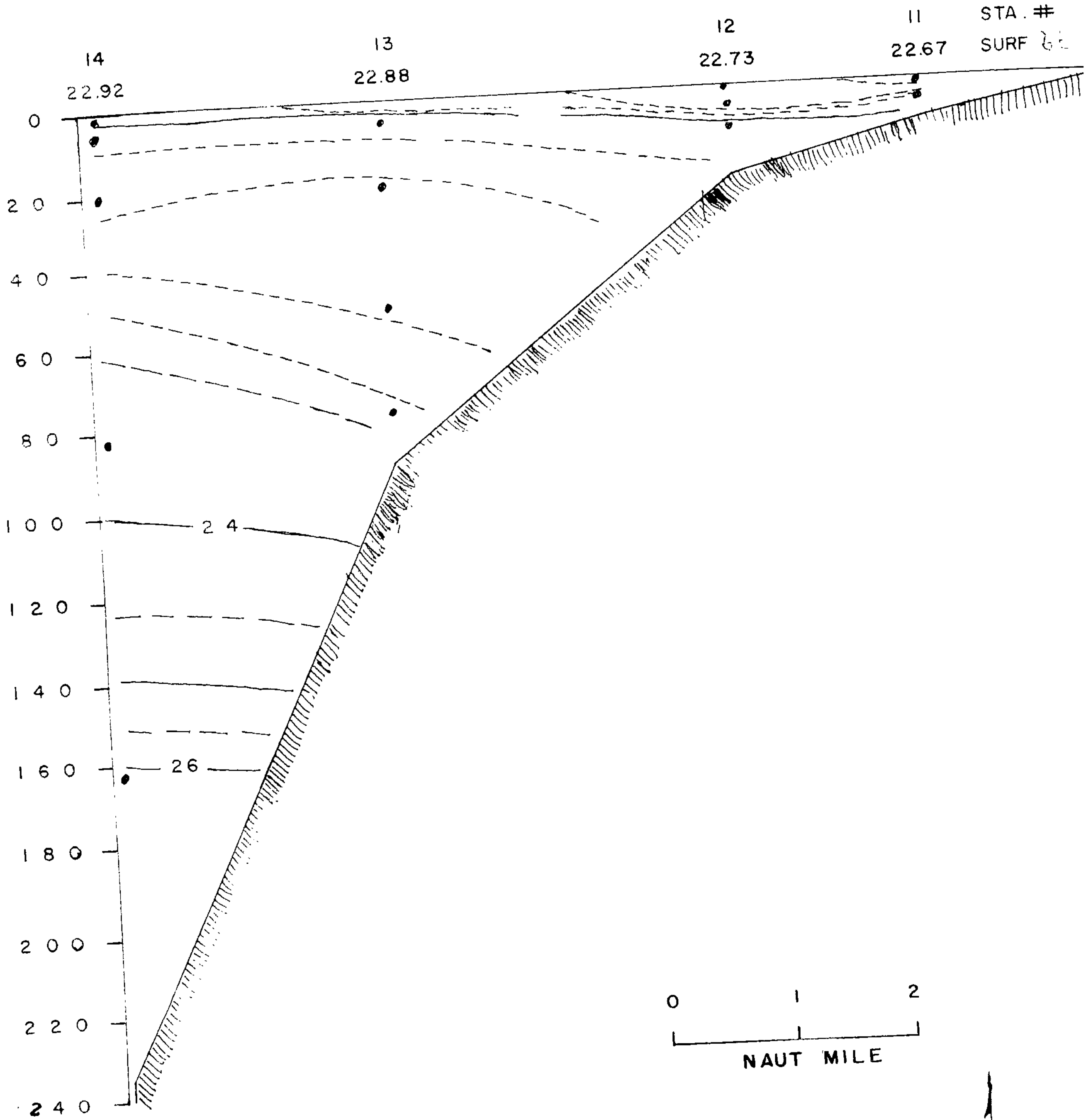


FIG Ag-8
DENSITY σt AGUADILLA SITE
CENTRAL SECTION
CRUISE 1 16 JUNE 1971

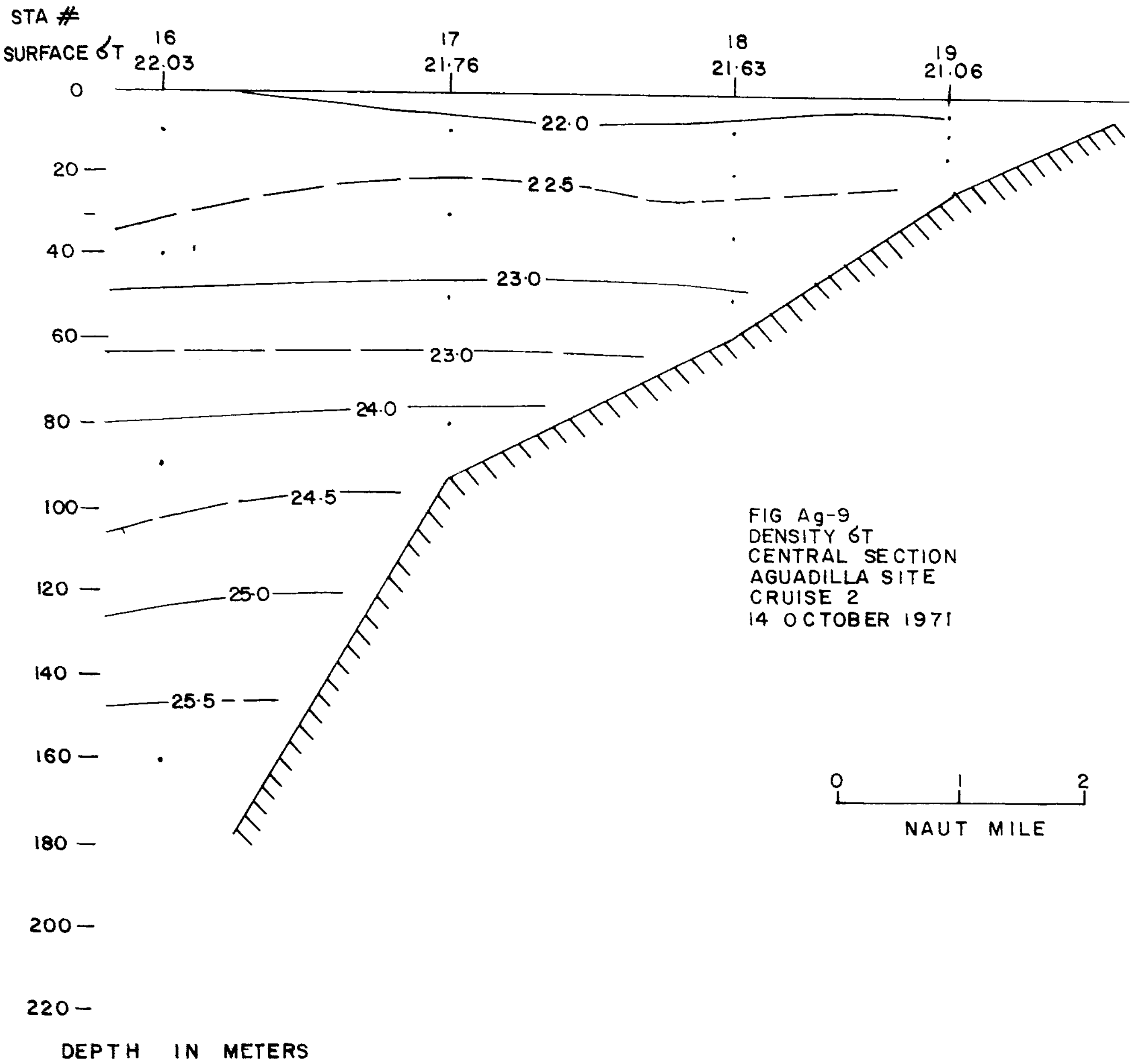


FIG Ag-9
DENSITY σT
CENTRAL SECTION
AGUADILLA SITE
CRUISE 2
14 OCTOBER 1971

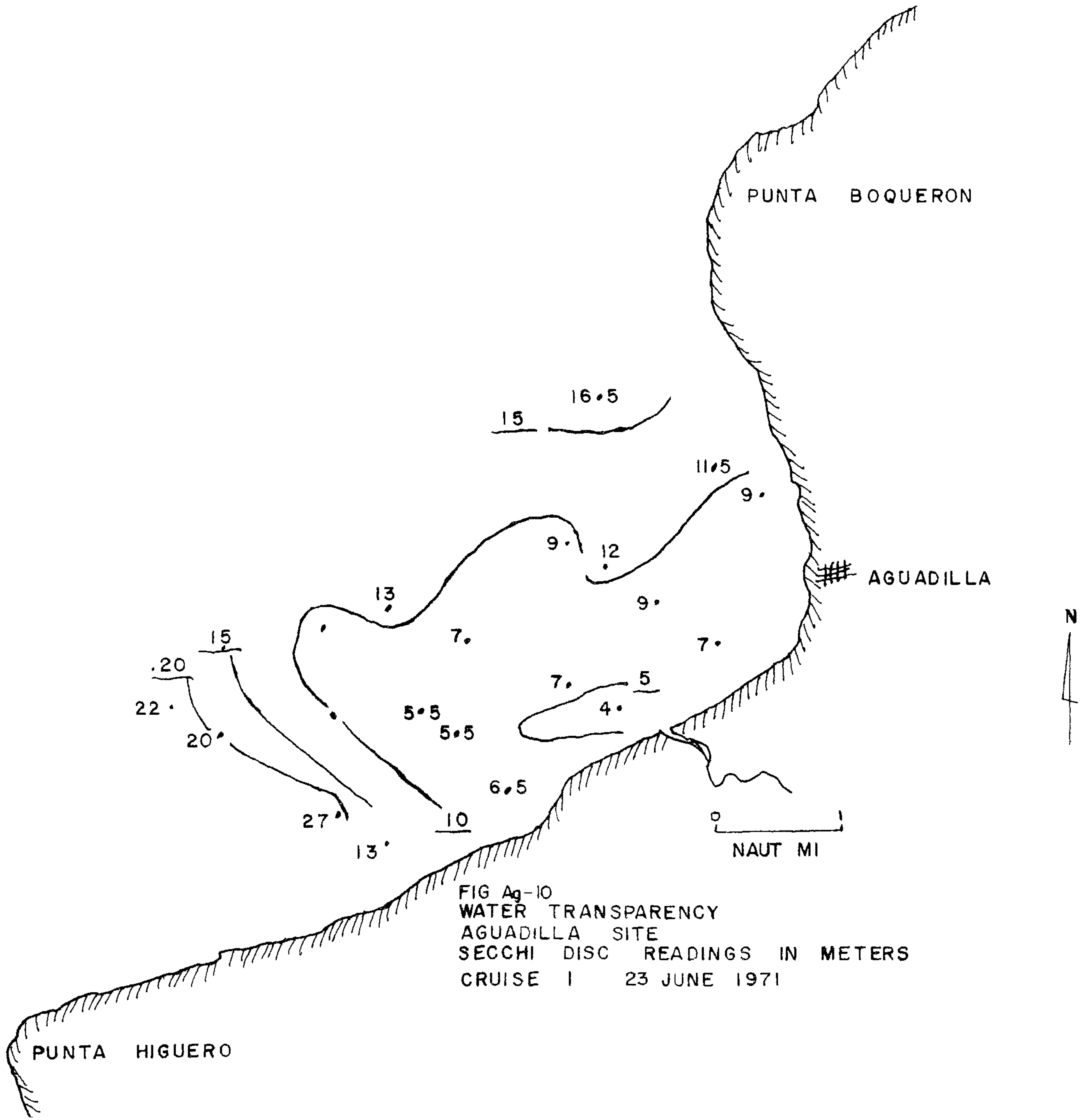


FIG Ag-10
WATER TRANSPARENCY
AGUADILLA SITE
SECCHI DISC READINGS IN METERS
CRUISE 1 23 JUNE 1971

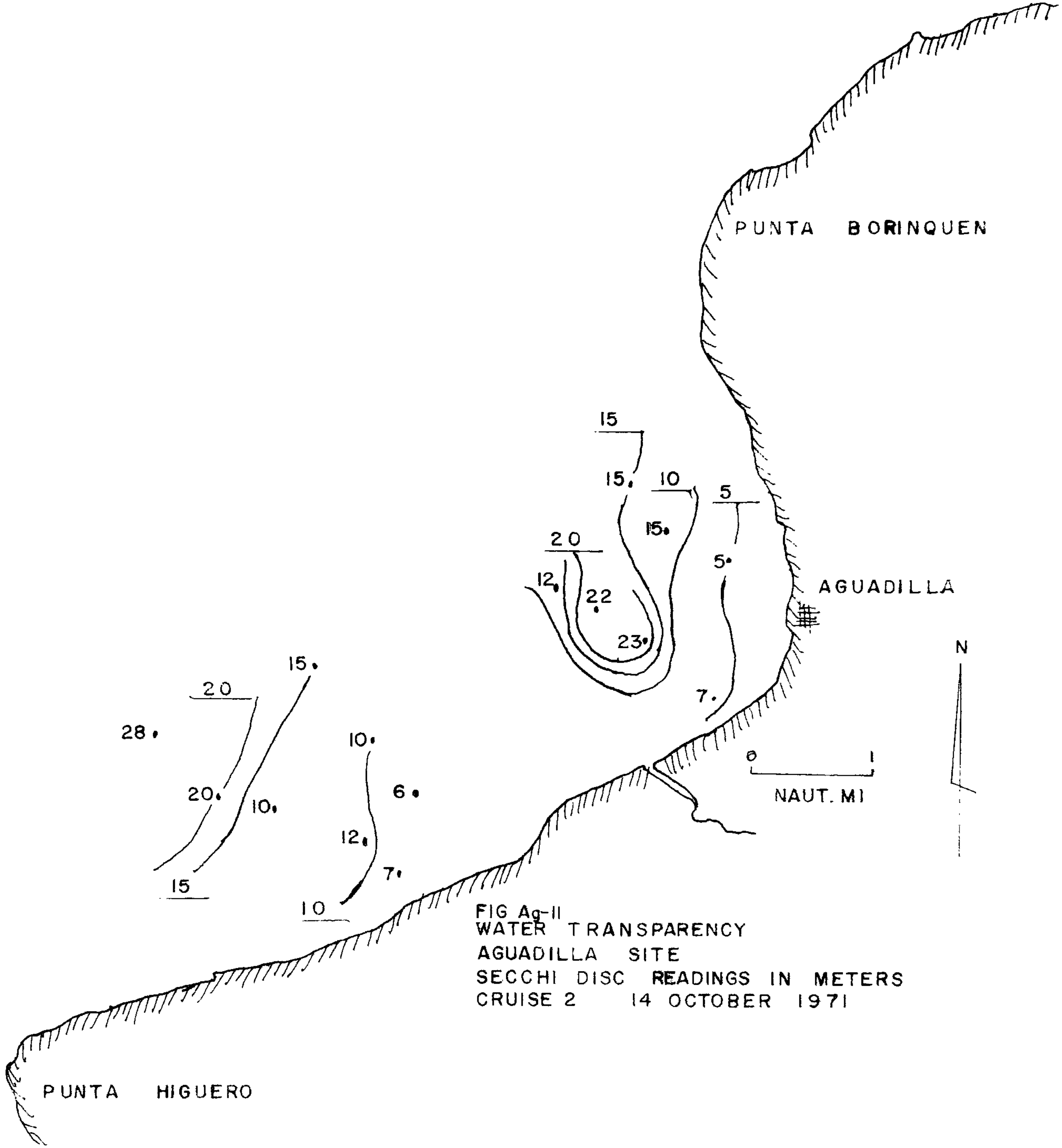


FIG Ag-II
WATER TRANSPARENCY
AGUADILLA SITE
SECCHI DISC READINGS IN METERS
CRUISE 2 14 OCTOBER 1971

ARECIBO/BARCELONETA

Description of Study Area

The Arecibo and Barceloneta disposal sites are located adjacent to each other on the exposed north coast of Puerto Rico and will be treated together in this discussion. At both sites, the Island shelf is generally about 1.5 miles wide to the 100 fathom contour. It appears that the main problem in getting a submarine outfall to deep water will not be the distance involved, but rather the steep slope of the bottom in these areas.

At each site, a major river has a pronounced effect on the water quality. At Arecibo, the Río Grande de Arecibo enters the ocean about one mile west of Punta Morillos. The Río Tanamá, a major tributary which originates in the mountains west of Utuado and empties into the Río Grande de Arecibo, is harnessed for hydro-power generation purposes and provides water for the city of Arecibo. At Barceloneta, the Río Grande de Manatí enters the ocean about two miles east of Punta Palmas Altas, in the vicinity of the proposed outfall site. A smaller river which enters the Río Grande de Manatí through a network of channels in the lowlying land adjacent to the shoreline enters the ocean about one mile west of Punta Palmas Altas.

An industrial park has been established adjacent to Barceloneta, and other firms are reported to have commitments to build in the area (1).

Hydrodynamics

Black, Veatch and Domenech conducted current studies for the Aqueduct and Sewer Authority at Barceloneta prior to the present study (1). Conclusions of the earlier study were that non-tidal currents flow parallel to the shoreline either in an easterly or westerly direction, and that on-shore currents may occur when the tide is turning, near the time of high or low water, with a speed unlikely to exceed 0.1 meter/sec.

The currents at Arecibo and Barceloneta are considered together in this report because of the proximity of the sites, and the similarity of geographical features. Station locations for Cruise 1 and Cruise 2 are shown in Figure Ar/B-1. Cruise 3 was interrupted on the south coast before the third circuit of the Island was completed, so no data was obtained at these sites during Cruise 3. At the present writing, there are plans for the completion of Cruise 3, with current measurements utilizing in-situ recording current meters to be made at Arecibo and Barceloneta, and results to be published at a later date. Drogue studies were carried out at each of these sites during Cruises 1 and 2, and concurrent observations were made with an in-situ recording current meter. Unfortunately, the instrument did not function properly and no Cruise 2 current meter data has been included in this report.

Station locations for the two cruises are shown in Figure Ar/B-1. Results of drogue studies made during Cruise 1 are shown in Figures Ar/B-2 and Ar/B-3 for Arecibo and Barceloneta, respectively. The initial path of the drogues at Arecibo was eastward, the path of the surface drogue shifting to the west at about 1050, whereas the path of the drogue at 10 meters shifted westward at around 1245. For the remainder of observations the drogue paths were westward. The shift in direction occurred at roughly the time of high tide. The average speed of the surface water movement was over 0.5 knots, which is a relatively high value for coastal areas. The current speed at 10 meters was slightly less (see Appendix K).

The drogue pattern for Barceloneta (one day after the drogue observations at Arecibo) was different from that of Arecibo. An initial drift to the west was observed with an eastward shift occurring at a period between low and high tide, and a shift back to the west occurring one or two hours after high tide. The average speed for the surface drogue was 0.4 knots. At both sites the eastward drift velocity of the surface waters was less than that observed at a depth of 10 meters, suggesting the existence of a wind effect on the surface flow. In both cases, the wind was from ENE, reaching speeds of 20 knots or more (Appendix K).

The drogue data for Arecibo during Cruise 2 indicated an onshore drift path throughout most of the observation period as can be seen in Figure Ar/B-4 The average surface velocity was 0.2 knots, which is considerably less than was observed during the previous survey (Appendix K).

The results of the current study at Barceloneta (which was carried out a day after the study at Arecibo) showed rather different results. The drogues indicated an eastward flow during the period of rising tide. Nearly two hours after high tide, a shift to the west was observed as shown in Figure Ar/B-5. The speed values were comparatively high, the average value for the surface being 0.56 knot (Appendix K). An evaluation of the wind data did not provide a basis for explaining the marked difference in speed and direction observed at Arecibo and Barceloneta, since on both occasions the wind velocity was low and from the NE or ENE (Appendix K).

The results of the present study were similar to those of Domenech, Black and Veatch (1). It was found that the current usually flows roughly parallel to the coastline with relatively high velocities for coastal waters. An onshore current is present on occasion. During ebb tide the flow is usually to the west, while during flood tide it is usually to the east. The eastward flow of surface waters was observed to have a lower velocity than deeper waters. This may well be due to the effect of NE winds on the surface waters. Caution must be used in making any broad generalization. The use of anchored current meters for periods of time up to a full lunar month will be required to provide a suitable data base for documenting the structure of these currents.

Hydrographic Data

Tables of hydrographic data for Arecibo and Barceloneta are given in Appendix K. Locations of the hydrographic stations are shown in Figure Ar/B-6. For the most part, the range of temperatures observed at the surface was very small, having a maximum differential of about 0.5°C. Similar conditions exist in the surface salinity, for which a maximum range of 1 percent was observed, and in the surface density for which a maximum change of 0.8 sigma-t units was observed. The range of values of temperature, salinity, and density is quite small for such a wide stretch of coastal water and is indicative of homogeneous surface waters (see Figures Ar/B-7, Ar/B-8).

Density (sigma-t) profiles for both of the areas are presented in Figures Ar/B-9 through Ar/B-12. In the deeper water (below 50 meters), the various isotherms, isohalines, and isopycnals are somewhat shallower at Arecibo than at Barceloneta. Above 50 meters no significant differences are noted between the two areas. Although temperature, salinity, and density values obtained on different days do vary somewhat, there is considerable uniformity in the values obtained during a single sampling event.

Water Quality

The Arecibo and Barceloneta areas were also considered together for water quality because of their adjacent coastal locations. Two cruises were made to evaluate and compare parameters. The data from these cruises is presented in tabular form in Appendix K.

The transparency of the water, as measured by Secchi disc readings, shows turbidity levels associated with the presence of runoff of the Río Grande de Arecibo and the Río Grande de Manatí (see Figures Ar/B-13, Ar/B-14). Stations were not placed in the eastern section, so the shape of the Río Grande de Mantí plume was not determined.

The dissolved oxygen concentrations varied from 4.24 to 4.51 mg/l for Arecibo and from 4.56 to 4.92 mg/l for Barceloneta, both representing approximately 90 percent saturation. The phosphorus and silica levels were both low (0-0.03 mg/l and 0-0.23 mg/l, respectively). The MPN coliform levels varied from 0 to 348/100 ml at Arecibo, and were not determined at Barceloneta. The BOD levels were not measured at Arecibo and varied from 0.06 to 0.71 mg/l at Barceloneta.

During Cruise 2, efforts were directed primarily at measurement of Secchi depths, dissolved oxygen levels, and coliform counts. The Secchi depths followed the same pattern as seen previously. Dissolved oxygen levels were higher during the second cruise (6.6-8.4 mg/l), reflecting the change in water temperature. Coliform levels varied from 0 to 50/100 ml at the stations where observations were made.

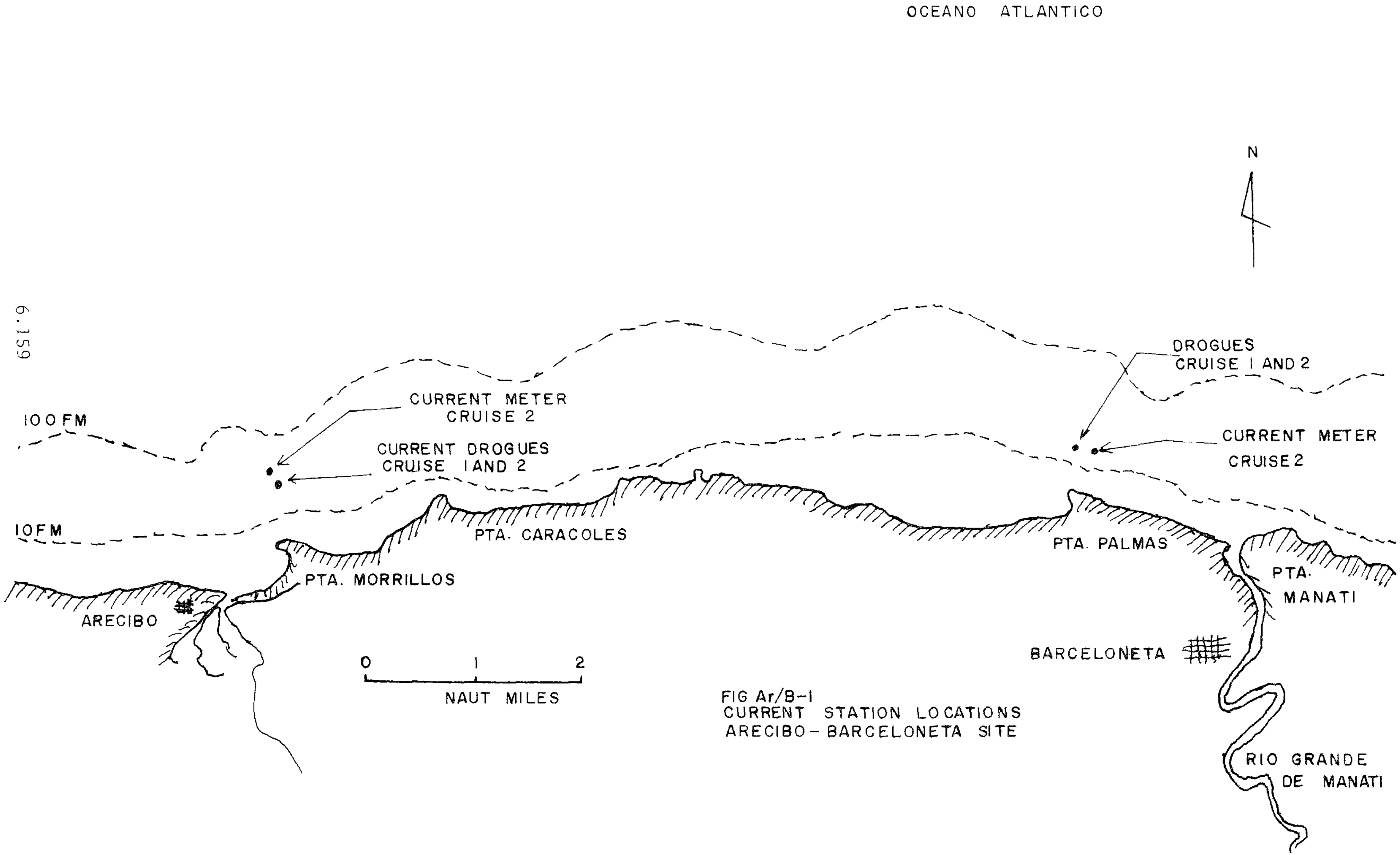


FIG Ar/B-1
CURRENT STATION LOCATIONS
ARECIBO-BARCELONETA SITE

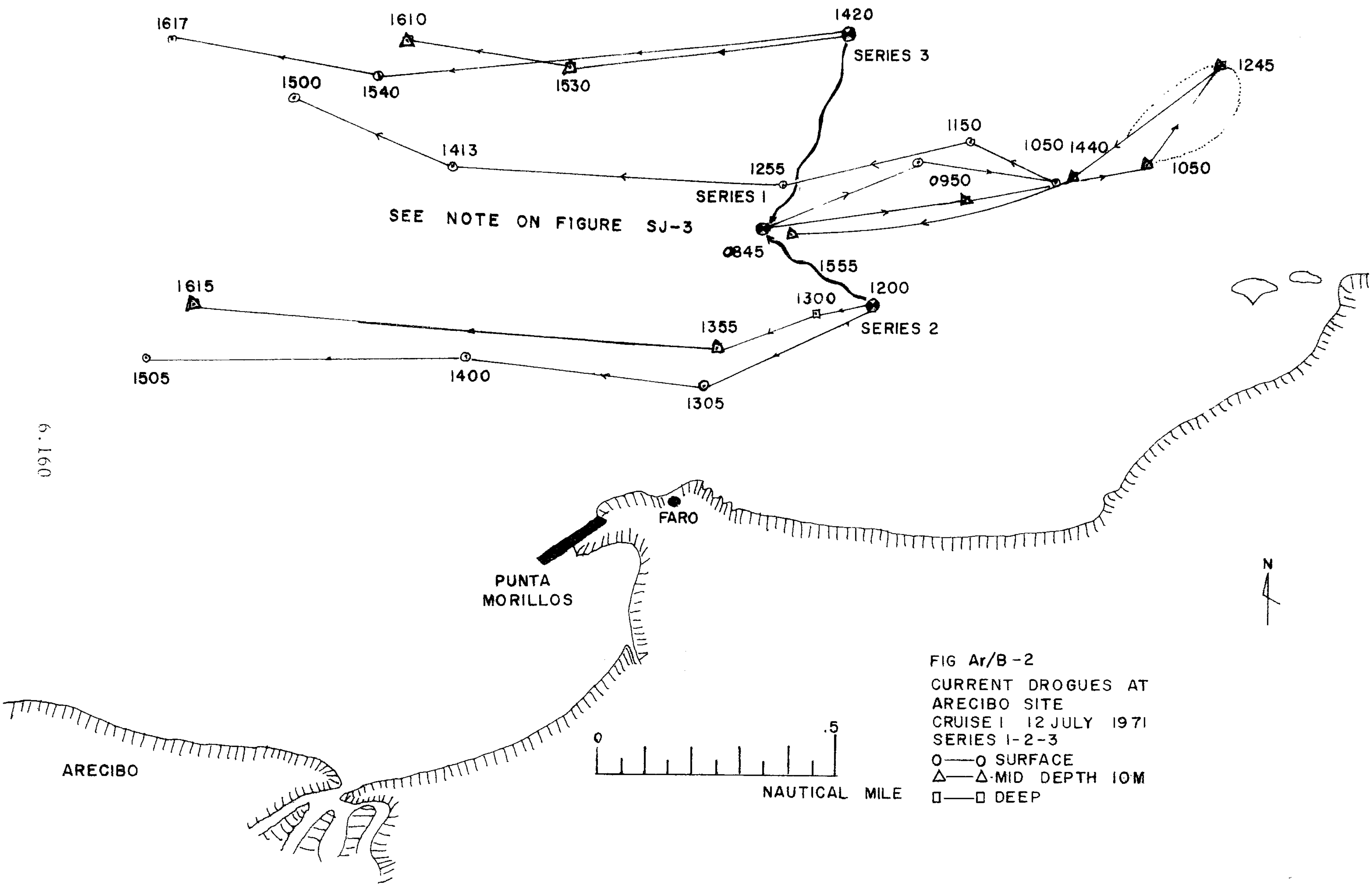


FIG Ar/B-2
CURRENT DROGUES AT ARECIBO SITE
CRUISE I 12 JULY 1971
SERIES 1-2-3

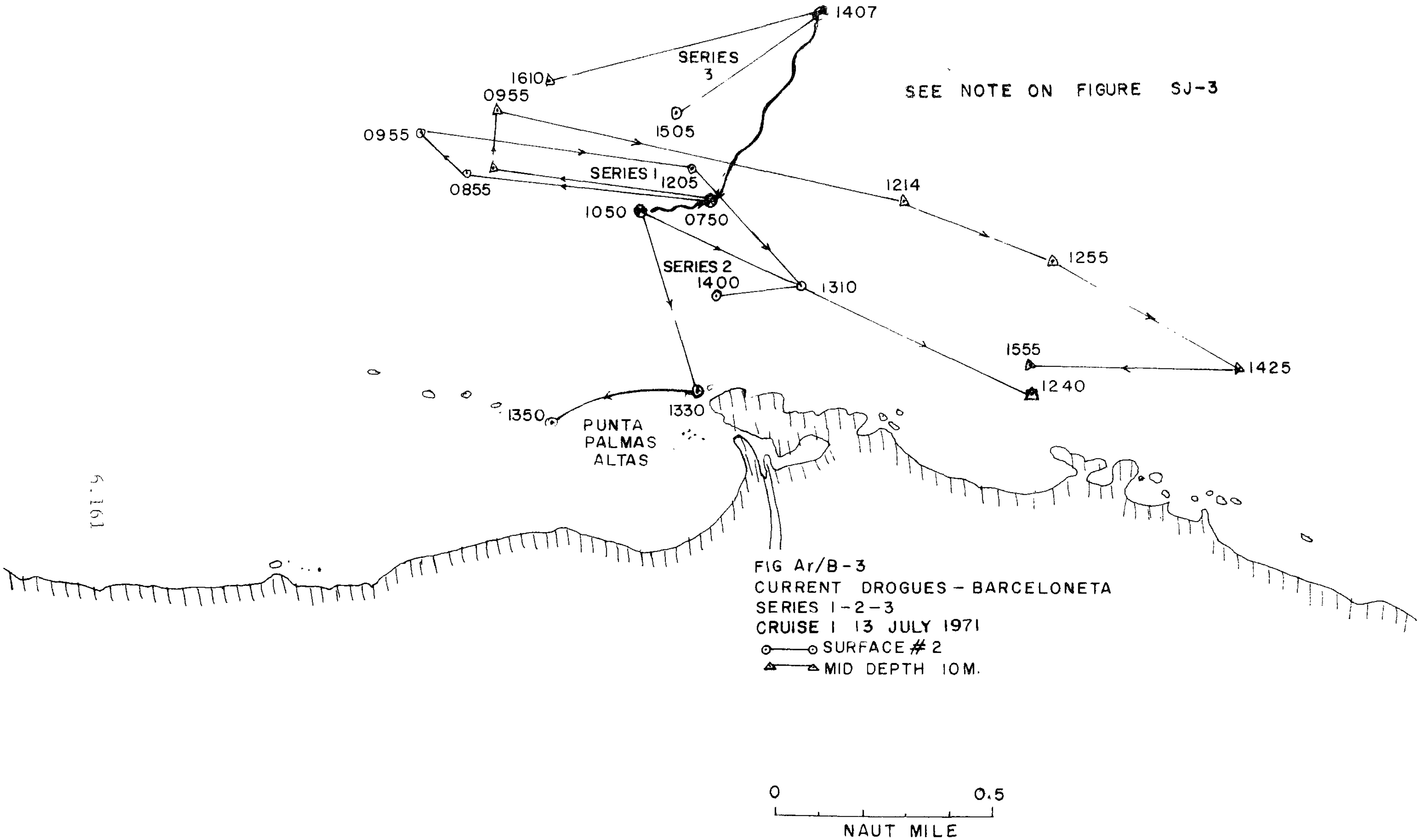


FIG Ar/B-3
CURRENT DROGUES - BARCELONETA
SERIES 1-2-3
CRUISE I 13 JULY 1971

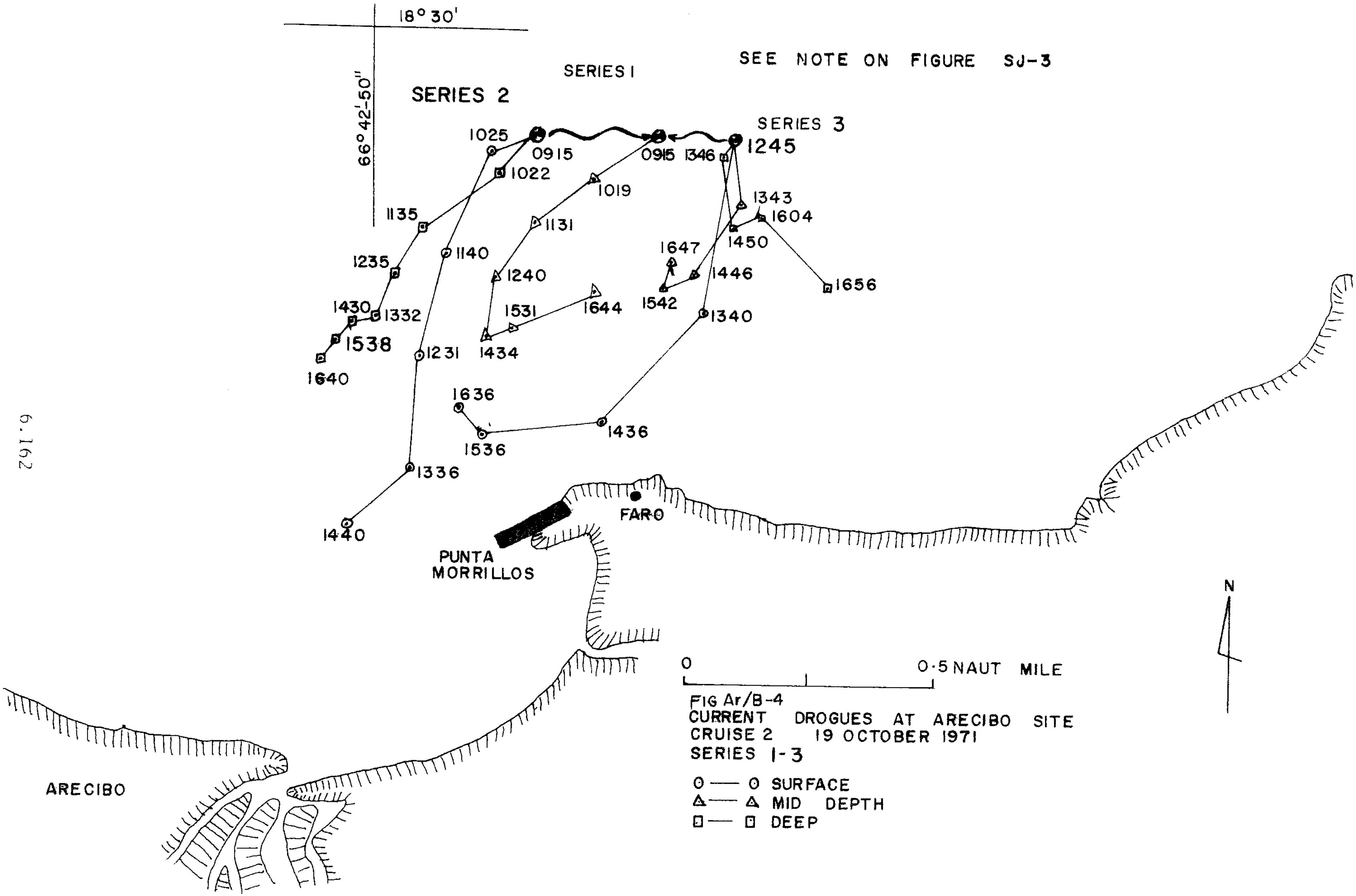


FIG Ar/B-4
CURRENT DROGUES AT ARECIBO SITE
CRUISE 2 19 OCTOBER 1971
SERIES 1-3

O —— O SURFACE
Δ —— Δ MID DEPTH
□ —— □ DEEP

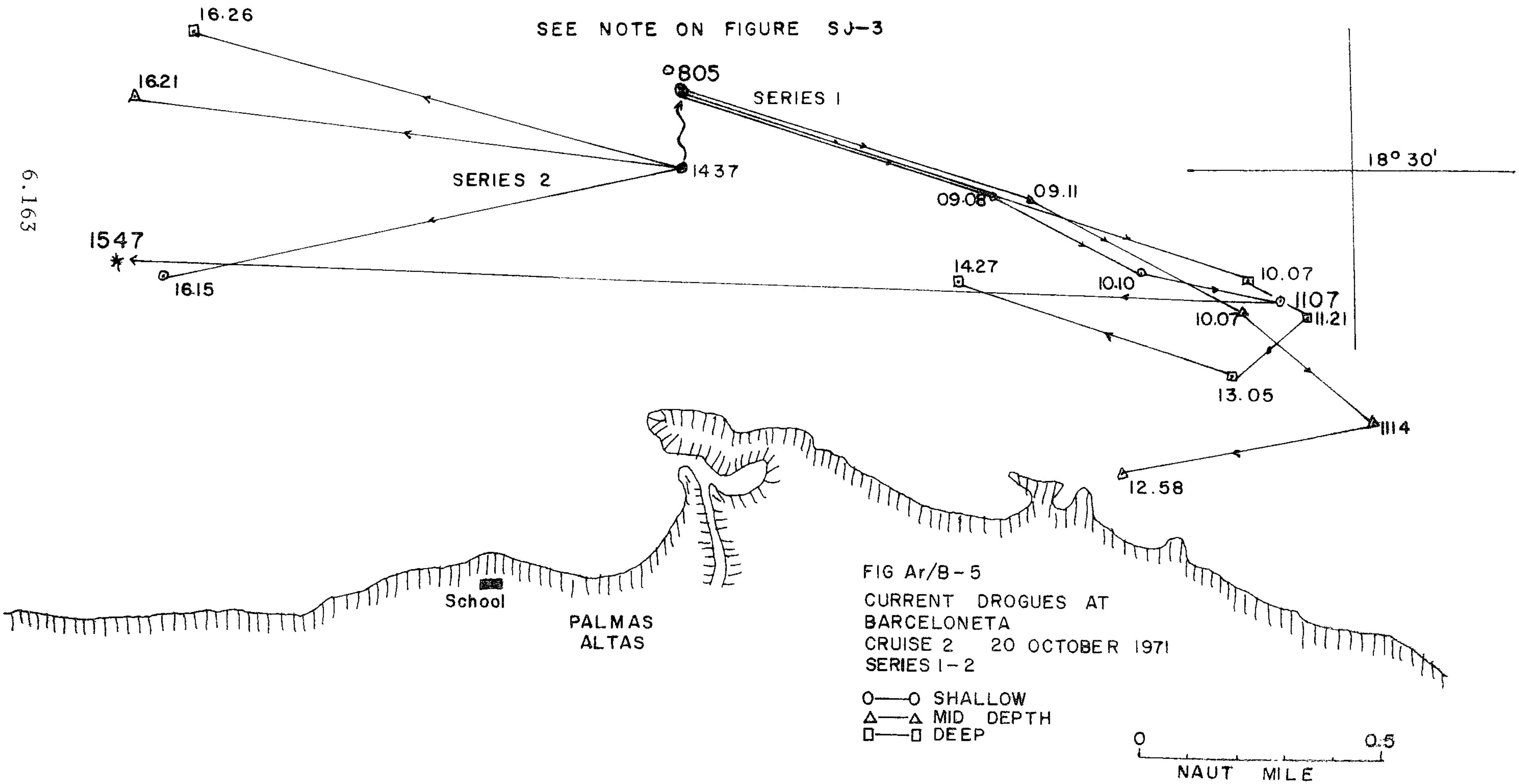


FIG Ar/B-5
CURRENT DROGUES AT
BARCELONETA
CRUISE 2 20 OCTOBER 1971
SERIES 1-2

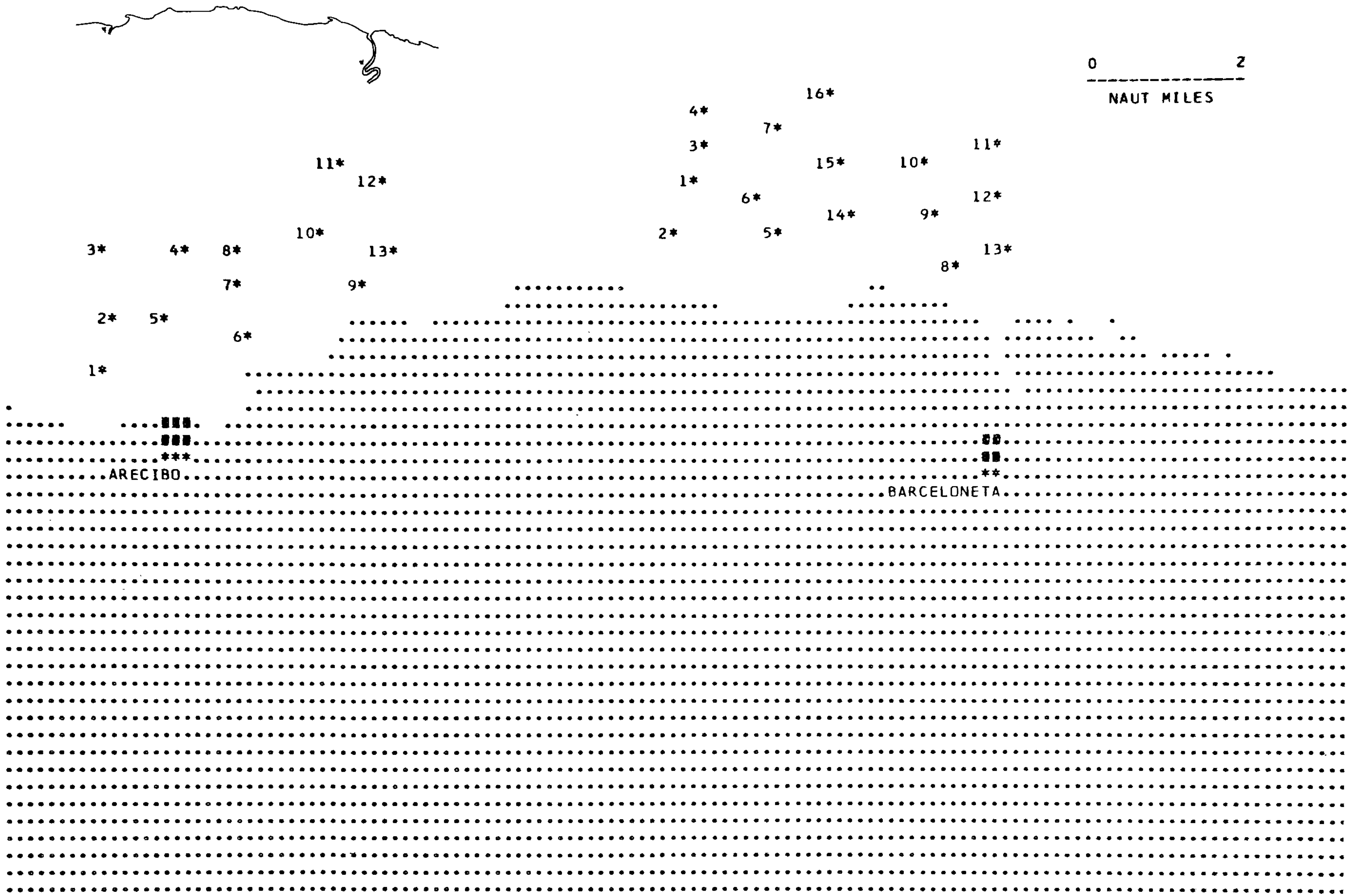


Figure Ar/B-6a
HYDROGRAPHIC STATION LOCATIONS
ARECIBO-BARCELONETA
CRUISE 1   7, 8 JULY 1971

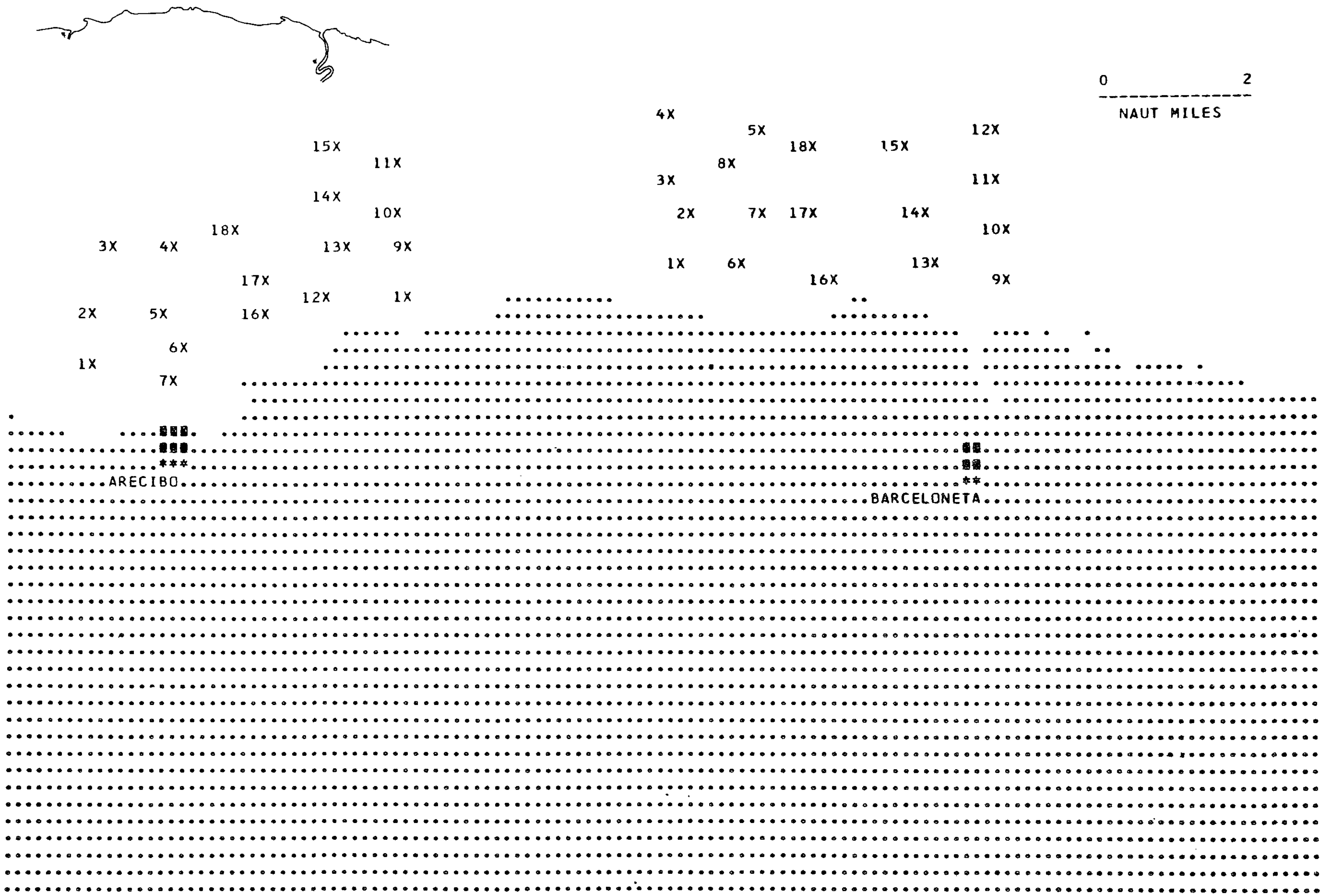


Figure Ar/B-6b
HYDROGRAPHIC STATION LOCATIONS
ARECIBO-BARCELONETA
CRUISE 2 21, 27 OCTOBER 1971

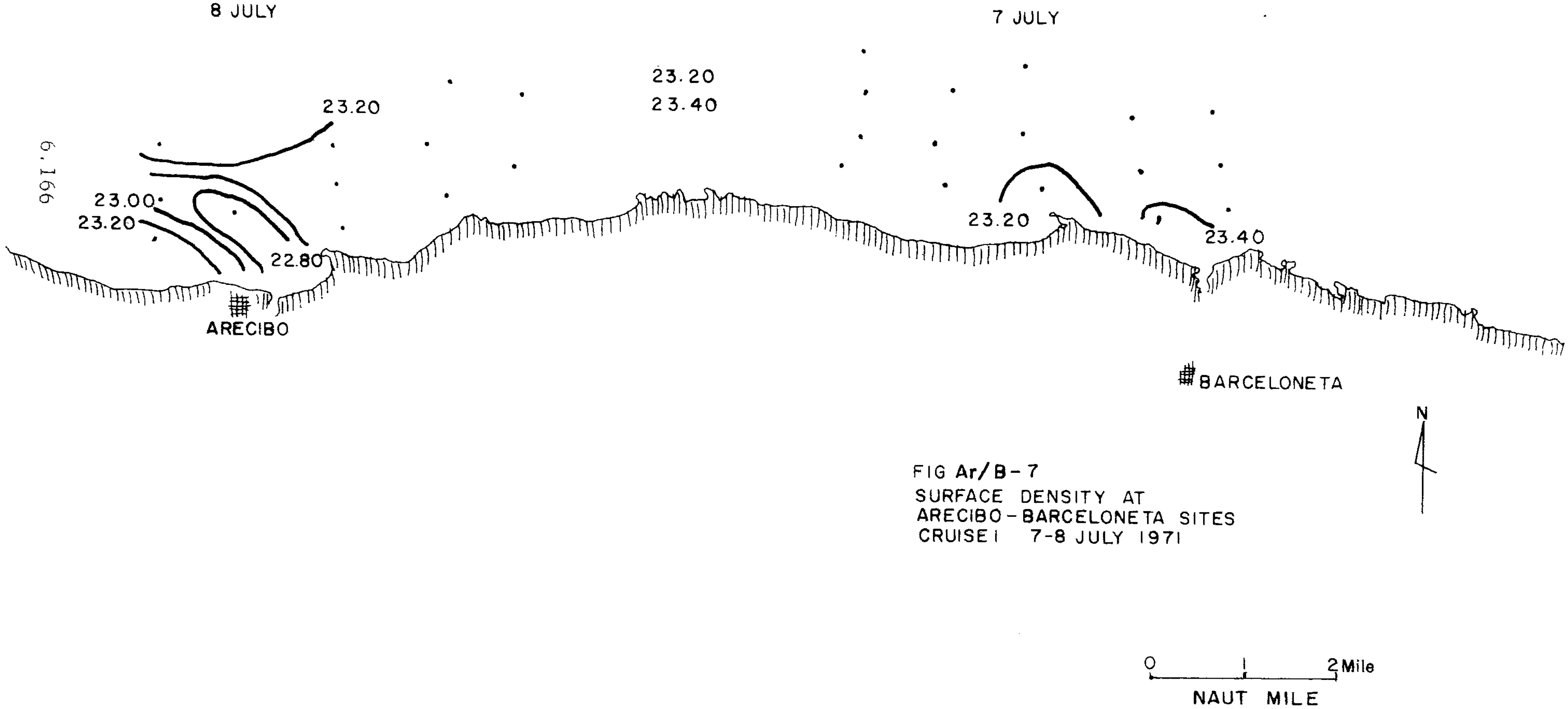


FIG Ar/B-7
SURFACE DENSITY AT
ARECIBO-BARCELONETA SITES
CRUISE I 7-8 JULY 1971

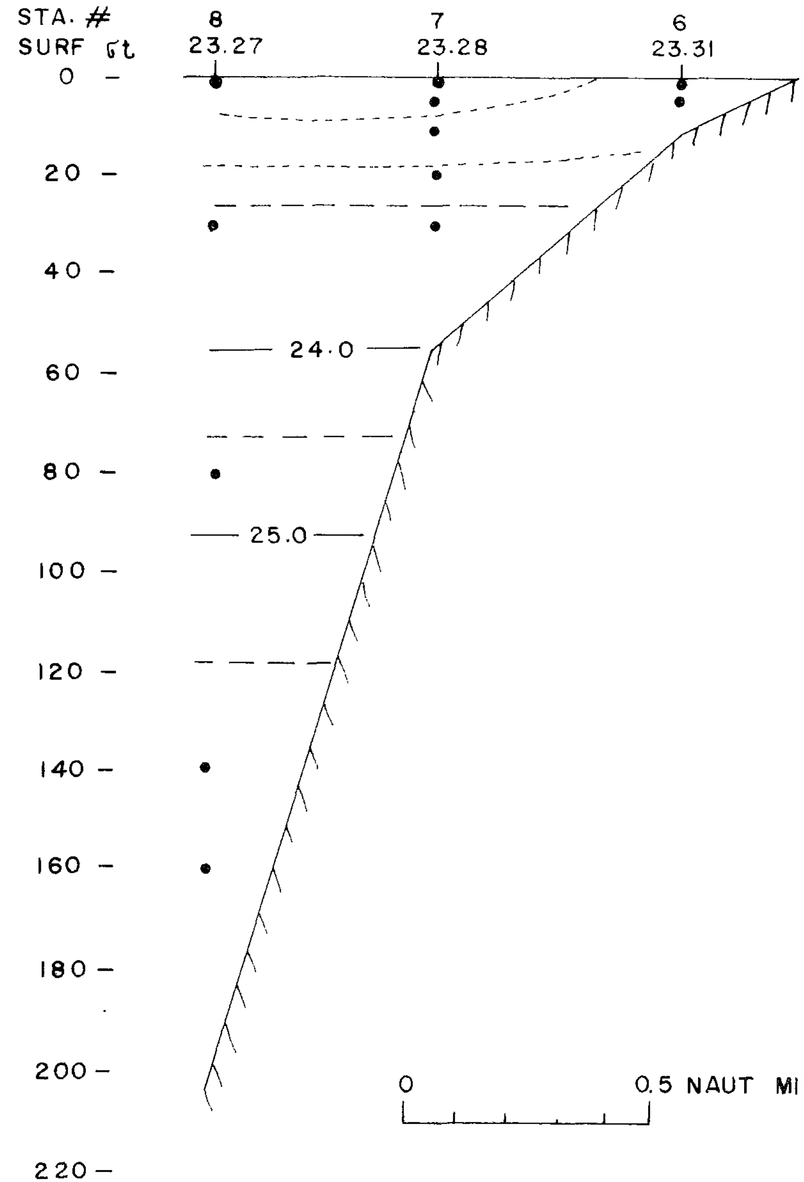


FIG Ar/B-9
DENSITY σt
CENTRAL SECTION
ARECIBO SITE
CRUISE 1
8 JULY 1971

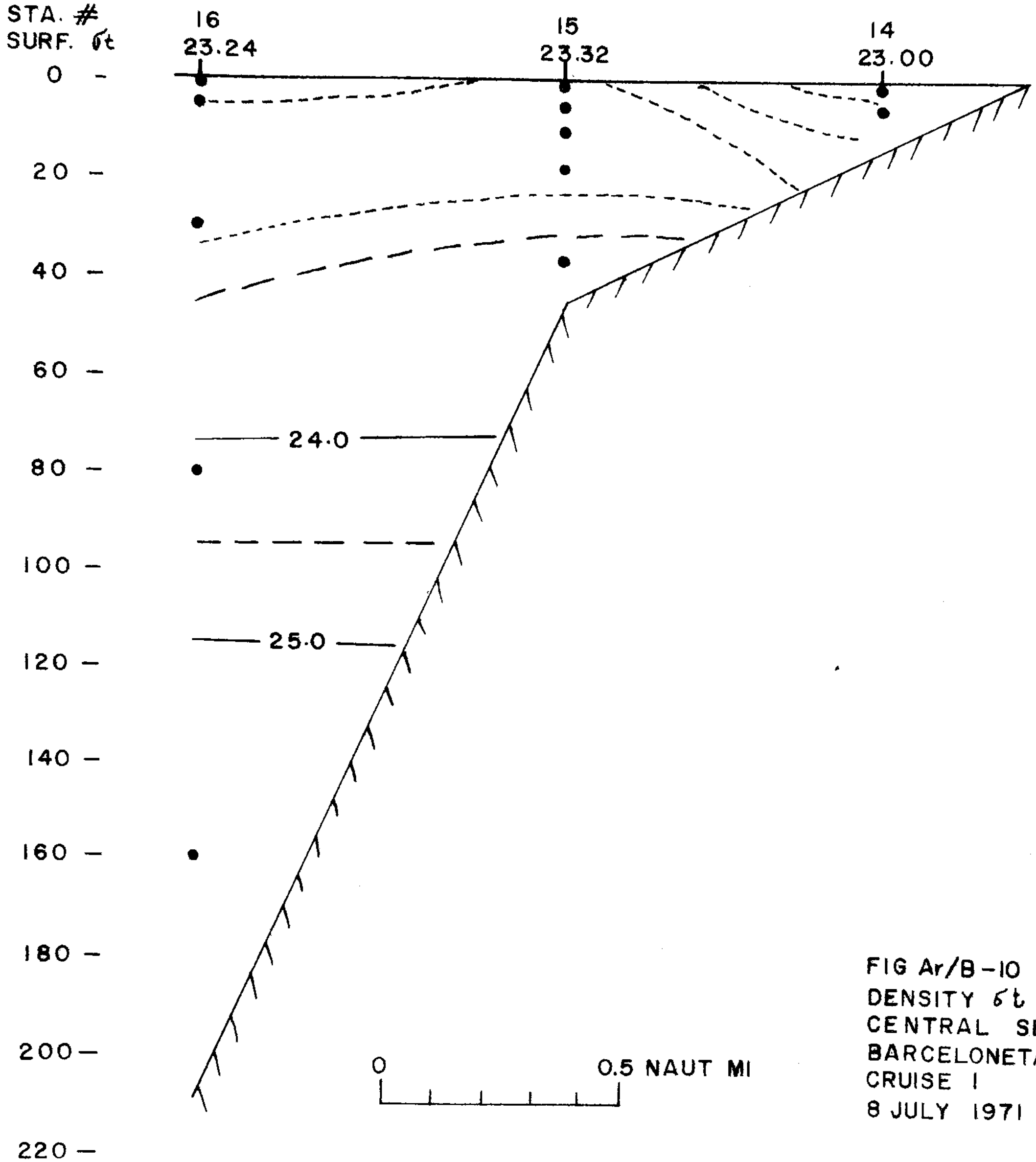


FIG Ar/B-10
DENSITY σt
CENTRAL SECTION
BARCELONETA SITE
CRUISE I
8 JULY 1971

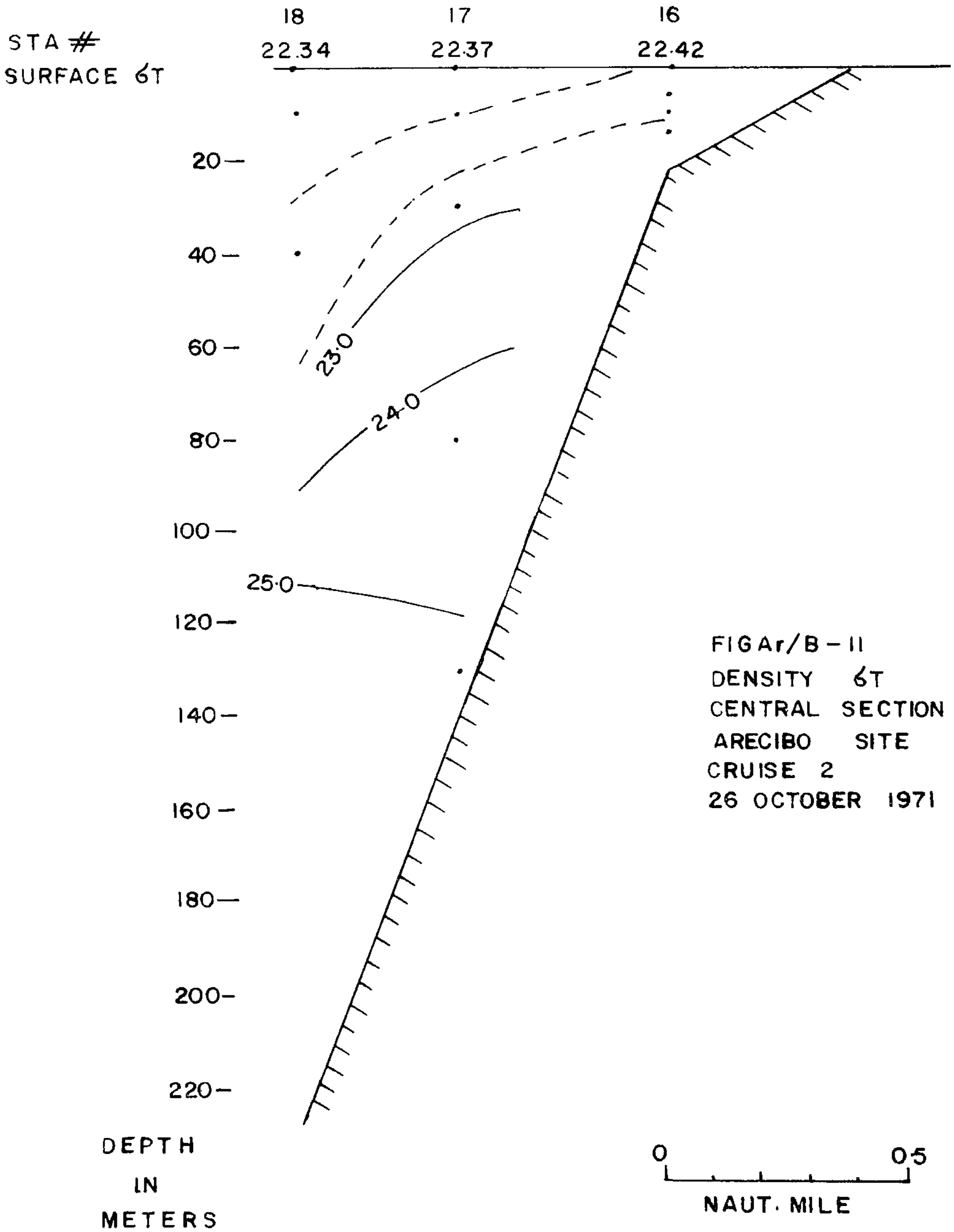


FIG Ar/B-11
DENSITY σT
CENTRAL SECTION
ARECIBO SITE
CRUISE 2
26 OCTOBER 1971

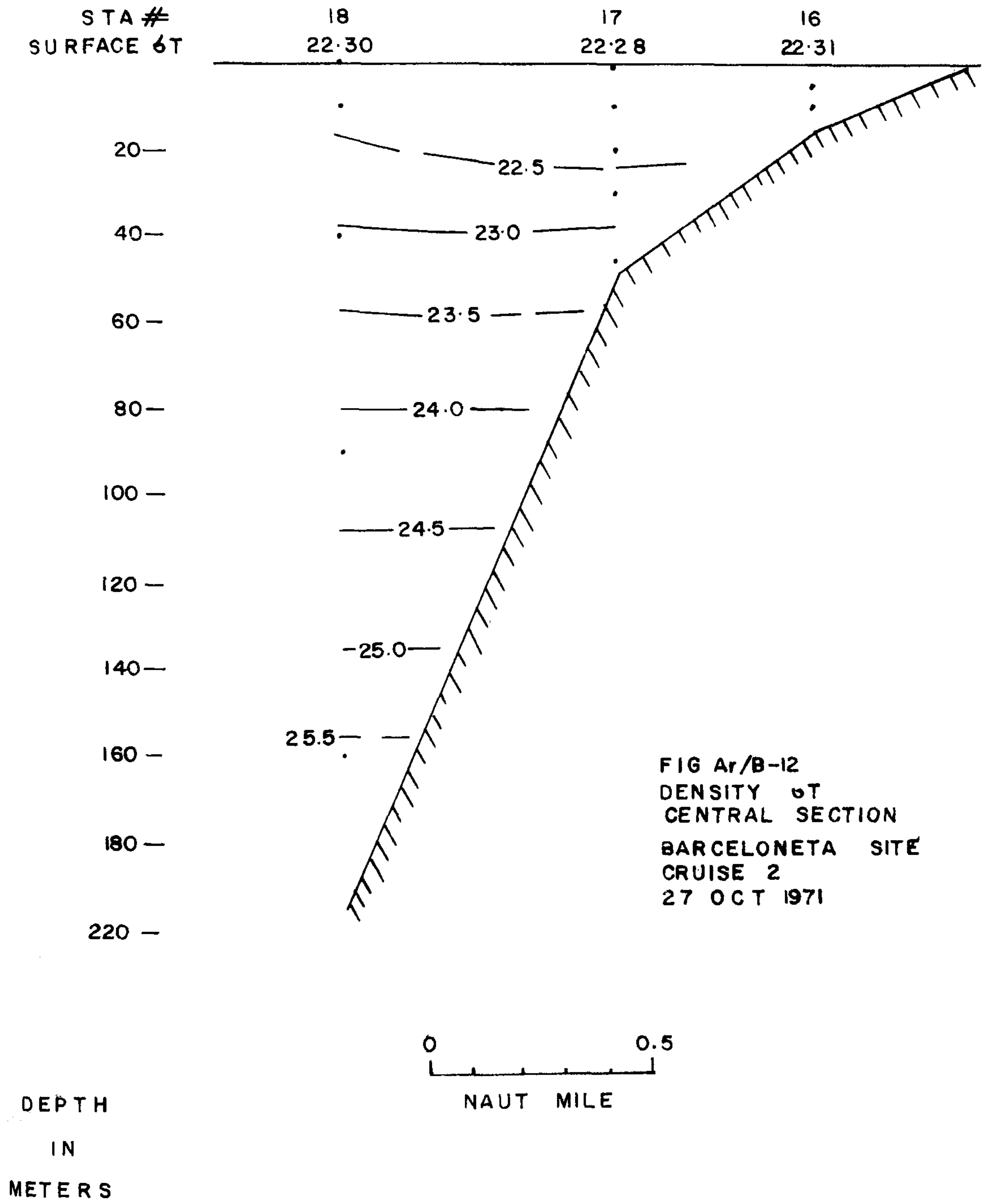


FIG Ar/B-12
DENSITY σT
CENTRAL SECTION
BARCELONETA SITE
CRUISE 2
27 OCT 1971

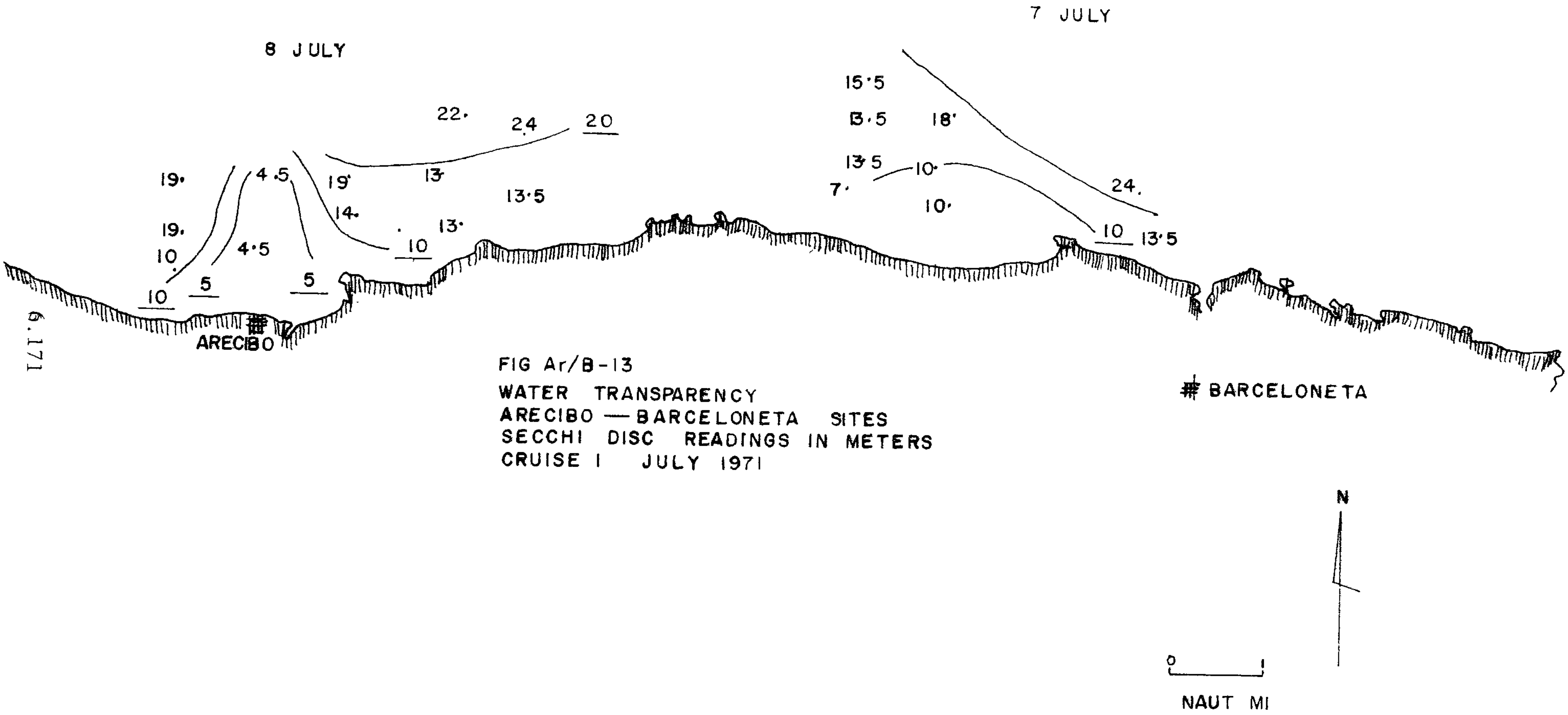


FIG Ar/B-13
WATER TRANSPARENCY
ARECIBO — BARCELONETA SITES
SECCHI DISC READINGS IN METERS
CRUISE I JULY 1971

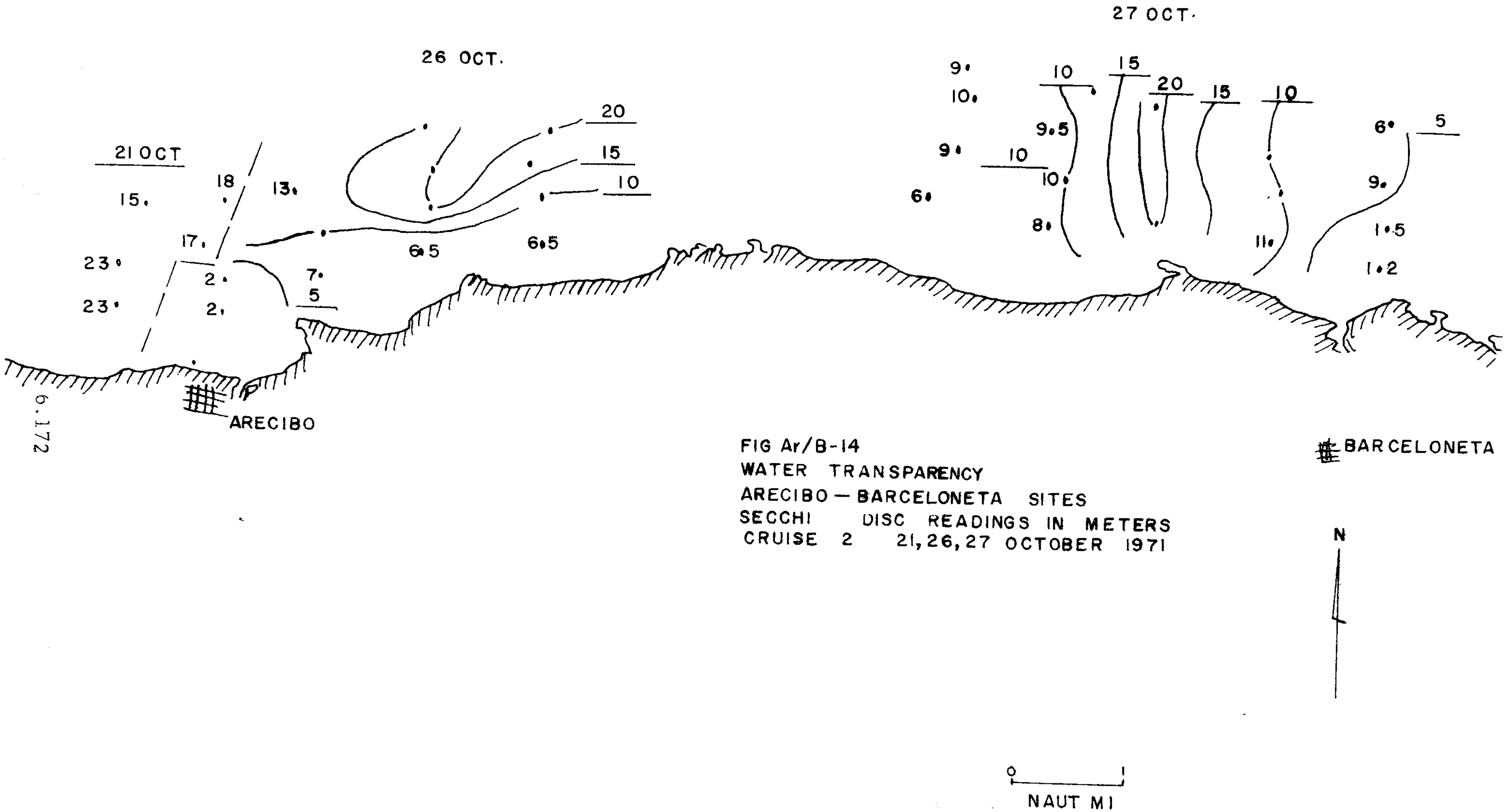


FIG Ar/B-14
WATER TRANSPARENCY
ARECIBO — BARCELONETA SITES
SECCHI DISC READINGS IN METERS
CRUISE 2 21, 26, 27 OCTOBER 1971