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Narragansett Bay Estuary Program

NARRAGANSETT BAY

SEDIMENT QUALITY SURVEY

AUGUST 1988

FINAL REPORT

14 April 1989

SAIC Report No. SAIC-89/7553&220

Submitted to:
The Narragansett Bay Project
291 Promenade Street
Providence, RI 02908-5767

REPORT #NBP-89-23

Submitted by:
Drs. Joseph Germano and Donald Rhoads
Science Applications International Corporation
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EXECUTIVE SUMMARY

Excessive organic enrichment of bottom sediments as a result of anthropogenic inputs, particularly sewage effluent, has been identified as a critical water quality problem in coastal embayments throughout the world. Because the seafloor is a long term "integrator" of organic enrichment, monitoring of benthic conditions can provide valuable information about overall trends related to water quality degradation. The present investigation of sediment and water quality in Narragansett Bay was sponsored by the Narragansett Bay Project. During the period 15 to 19 August 1988, SAIC performed a synoptic reconnaissance survey to assess benthic habitat and water quality and define benthic disturbance gradients throughout Narragansett Bay using three complimentary techniques: REMOTS® sediment-profile photography, dissolved oxygen measurements, and measurements of the densities of *Clostridium perfringens* spores (a human fecal indicator) in the sediment.

Only five stations had near-bottom dissolved oxygen concentrations below 3 mg/ℓ (defined as either hypoxic, dysaerobic, or anoxic). Four of these stations were located in the upper Providence River Reach, and the fifth was station SB-6 in Greenwich Bay. All other stations were found to have near-bottom dissolved oxygen concentrations in the aerobic range (i.e., above 3 mg/ℓ).

The highest oxygen values (greater than 10 mg/ℓ) were measured in Apponaug Cove and were attributed to high rates of benthic photosynthesis within this shallow embayment.

The REMOTS® sediment-profile photographic survey identified six areas of recent benthic disturbance related to excessive organic enrichment: the Providence River Reach, Greenwich Bay, Allen Harbor, the Potowomut River, the Taunton River mouth and an area southwest of Prudence Island. The largest area of enrichment was located within the Providence River Reach. Stations in this area exhibited shallow redox-potential discontinuity (RPD) depths, high apparent sediment oxygen demand, low-order benthic successional stages, and, at one station, sedimentary methane gas. The relatively low near-bottom dissolved oxygen concentrations measured at several stations in this area reinforced the REMOTS® interpretations of degraded habitats.

The REMOTS® photographs also indicated low benthic habitat quality in a topographic depression southwest of Prudence Island. Although this site is far removed from a point source of organic enrichment, it appears to be a sediment focusing area for fine-grained organic matter. This focusing may be related to the low kinetic depression, or an eddy may be located over this area.

Elevated counts of Clostridium perfringens spores were found at some of the same stations identified as having low habitat quality based on analysis of the REMOTS® images. The highest spore counts were found at the two uppermost stations in the Providence River Reach, and elevated values also were encountered at other stations in this area. The proximity of several sewage treatment plant and combined sewer overflow outfalls in the relatively narrow Providence River Reach most likely accounts for these high values. High spore counts and low OSI values in Greenwich Cove also were apparently related to the proximity of a sewage outfall. A gradient in increasing spore counts was seen in Mount Hope Bay approaching the mouth of the Taunton River, and the low kinetic sediment-focusing area to the southwest of Prudence Island also exhibited high spore densities. Other spore "hotspots" existed off of Wickford and Newport, south and west of Bristol, and at a single station in the lower East Passage.

Several stations exhibiting poor benthic habitat quality in the REMOTS® images did not have high sediment spore counts. This included all of Greenwich Bay and its associated coves and harbors, with the exception of Greenwich Cove and a single station located near a marina in Warwick Cove. Such results suggest organic enrichment from a source, or sources, other than sewage.

Overall, the most degraded habitat sampled was the upper Providence River Reach. This area exhibited low near-bottom dissolved oxygen levels, high Clostridium spore counts and low sediment quality as determined by REMOTS® sediment-profile photography. The combination of techniques employed in this investigation provided a way to separate sewage effects from other possible sources of benthic organic enrichment, such as industrial effluent, surface run-off, sediment focusing, or accumulation of plant detritus. Based primarily on the REMOTS® results, but also considering spatial gradients in spore counts and dissolved oxygen, four "critical boundaries" were identified in the Bay. These boundaries mark steep gradients between stressed versus relatively healthy bottom areas. One of these boundaries was located at the southern edge of the Providence River Reach, another at the mouth of Greenwich Bay, a third at the mouth of the Taunton River, and a fourth at the southwest edge of Prudence Island. Future monitoring of stations located on either side of these boundaries should allow detection of long-term changes in benthic enrichment of the Bay bottom.

1.0 INTRODUCTION

Excessive organic enrichment has been identified as a critical, pollutant-related water quality problem in coastal embayments such as Narragansett Bay. Anthropogenic inputs, particularly nutrient-rich sewage effluent, are known to increase the oxygen demand of water and sediments directly through organic loading or indirectly by stimulating the production of plants which eventually decompose. Such processes can result in severe ecological disturbance, compromising the commercial and recreational value of once-productive waters by reducing available habitat and by killing important benthic and pelagic species.

Organic enrichment of coastal waters has manifestations in both the water column and the seafloor. In the past, a great deal of emphasis has been given to the water column as an indicator of eutrophication. Dense plankton blooms, high nitrogen turnover and low dissolved oxygen levels are examples of water column phenomena typically linked to over-enrichment, but such events can be transient and short-lived and may occur only during the latest stages of habitat degradation. The intensive sampling programs required to document such phenomena often are narrowly-focused and fail to address long-term monitoring objectives.

The seafloor is a better long term "integrator" of organic enrichment than the water column. The integrated information can be in the form of shallow redox potential discontinuity depths, sulfitic or methanogenic sediments, and/or aberrant or retrograde benthic community successional patterns. Such characteristics typify areas of the seafloor that are accumulating labile organic matter at a rate that exceeds its utilization by heterotrophs. In the case of direct sewage inputs, a high sediment inventory of spore-forming enteric bacteria might also be expected.

The benthic habitat quality of the seafloor can be compromised without any apparent negative effects in the overlying water column, particularly in the early-to-intermediate stages of enrichment. For this reason, monitoring of benthic conditions can provide more valuable information about overall trends related to water quality degradation. During the period 15 to 19 August 1988, a synoptic reconnaissance survey of Narragansett Bay was performed to assess both benthic habitat and water quality using three complimentary techniques: REMOTS® sediment-profile photography, dissolved oxygen measurements, and measurements of Clostridium perfringens spore concentrations in the sediment. The collected data are used to identify enrichment "hot-spots" and to direct possible future biological and chemical studies. This synoptic survey also serves as a baseline and can be used to design an efficient future monitoring protocol.

The REMOTS® sediment-profile camera system, combined with computer image analysis, is capable of rapidly mapping large areas of the seafloor for the purpose of identifying gradients in both physical and biological conditions. The overall objective of the August REMOTS® survey of Narragansett Bay was to provide "quick-look" synoptic mapping of benthic disturbance gradients. An attempt was made to relate the observed gradients to organic enrichment, and determine the probable source of such enrichment. Of particular interest were those enriched areas having hypoxic (less than 3.0 mg/ℓ oxvgen) or anoxic (less than 0.1 mg/ℓ oxygen) near-bottom water and/or where sedimentary sulfides or methane gas were located near the sediment surface.

To document hypoxic or anoxic conditions, near-bottom dissolved oxygen concentrations were measured at each station occupied in the REMOTS® survey. The relationship between the instantaneous dissolved oxygen values and the time-integrated sediment record, as imaged with REMOTS®, has proven very insightful in recent years in surveys of Long Island Sound (SAIC 1987a, 1988). The combined techniques allow areas of the seafloor which represent <u>in situ</u> benthic oxygen sinks to be distinguished from areas having "exported" hypoxic or anoxic water.

While the REMOTS® system is capable of identifying enriched benthic areas, it usually cannot uniquely identify the source of the enrichment. For this reason, sediment counts of spores of the human enteric bacterium _Clostridium perfringens_ were included as an independent indicator of organic loading linked to sewage effluent discharges into Narragansett Bay. The endospores produced by _C. perfringens_ are highly resistant to die-off during wastewater disinfection and/or residence in terrestrial and aquatic environments (Cabelli, 1977). Levels of _C. perfringens_ spores in bottom sediments therefore provide a time-integrated record of fecal inputs into an estuary like Narragansett Bay. The period of time represented depends on the depth of the _C. perfringens_ sample removed from the sediment and the deposition rate of fecal particulates from the water column. Spatial as well as temporal changes in _Clostridium_ spore levels in the sediments reflect changes in the input and the particle size distribution of fecal particulates as affected by hydrographic conditions. The major source of _C. perfringens_ is municipal wastewater inputs, although stormwater discharges and direct fecal contamination also will contribute to increased levels of this "conservative" indicator in bottom sediments.

The combined techniques (sediment-profile photography, dissolved oxygen measurement and _Clostridium perfringens_ spore enumeration) have been used previously to identify sites and sources of chronic and/or seasonal organic loading and near-bottom hypoxia in both San Francisco Bay (SAIC, 1987b) and Long Island Sound (EG&G, 1987; SAIC, 1987a, 1988). A major objective of the present survey was to evaluate the use of these combined techniques to evaluate the effects of organic loading in Narragansett Bay. In addition, the results from selected stations were compared to earlier REMOTS® surveys conducted in 1975-76 to assess long-term changes in benthic habitat quality (as reflected in REMOTS® images by the depth of the apparent redox potential discontinuity and the infaunal successional stage).

2.0 METHODS

2.1 Selection of Station Locations

A total of 56 sampling stations were occupied during the five day period 15 to 19 August 1988. Stations were located throughout Narragansett Bay, Mount Hope Bay and the Sakonnet River (Figure 2-1). Many station locations were selected by the Narragansett Bay Project to coincide with those occupied in previous studies of sediment and/or water quality (see below). Stations were not deliberately located adjacent to sewage or other outfalls; the purpose of this sediment quality survey was to define bay-wide trends in benthic habitat quality rather than to focus on known point sources of enrichment. Most of the sampling was conducted aboard the 65-foot M/V BEAVERTAIL; however, a shallow draft skiff also was used to sample stations located in various coves and harbors. The latitude/longitude and depth of each station was recorded during the field operations (Table 2-1).

A station prefix of "SB" identifies stations previously occupied during the SINBADD Cruises in 1985-86 as part of the Narragansett Bay Water Quality Survey sponsored by the Narragansett Bay Project (Pilson and Hunt, 1988). A "C" prefix represents sediment core stations sampled from 1986 thru 1988 in an ongoing study by Dr. John King (University of Rhode Island), also sponsored by the Narragansett Bay Project. The prefix "R" indicates stations occupied in previous sediment-profile imaging surveys in 1975 and 1976 (Myers and Phelps, 1978). Stations occupied in various shallow coves and embayments are prefixed as follows: AH = Allen Harbor, AC = Apponaug Cove, WC = Warwick Cove, GC = Greenwich Cove, PR = Potowomut River. Station MF (Mussel Farm) was located in an area where rafts used for mussel culture had been deployed on the west side of Aquidneck Island. The remainder of the stations are designated with a single number; the positions of these "floater" stations were chosen by SAIC to maximize coverage of the Bay.

For purposes of data presentation and comparison, the stations sampled in this survey were grouped into three subsets (Table 2-2). Stations were placed into one of the three groups, ("Shallow Embayments," "Providence River Reach," or "Open Bay") based on similarities in geographic location and hydrodynamic regime.

2.2 Navigation

Primary navigational control of the survey vessel during field operations was provided by the SAIC Integrated Navigation and Data Acquisition System (INDAS). This system uses a Del Norte 540 Microwave Trisponder navigation system interfaced to a Hewlett Packard Series 200 model 20 microcomputer, providing accuracy for the survey vessel of ± 2-3 meters (Morton and Jones, 1985). The INDAS system provides positive vessel control through steering commands and a visual plot of the ship's position in relation to the station location which is relayed to the helmsman through a CRT display.

A minimum of two shore-based microwave antennas (trisponders), in line-of-sight positions, are required for operating the Del Norte navigation system. For the present survey, the trisponders were moved as needed as the survey vessel progressed to the various parts of the Bay. At each shore base, the trisponders were located over benchmarks or landmarks for which accurate horizontal control data were available.

At some stations, the INDAS precision navigation system could not be used because appropriate shore bases were either unavailable or inaccessible. In these instances, calibrated Loran C was used for navigation, providing an absolute accuracy of ± 100 meters and allowing stations to be re-occupied with a precision of ± 50 meters. The final locations of the shallow water stations in the various coves and harbors were determined in the field. An attempt was made to locate one station near the mouth, one near the head and one in the middle of each of these shallow embayments. The position of each of these stations was determined by sighting landmarks on the shoreline using a hand-held compass. These stations probably could be re-occupied with a precision similar to the calibrated Loran C (± 50 meters).

2.3 REMOTS® Sediment-Profile Photography

2.3.1 Field Procedures

REMOTS® (Remote Ecological Monitoring Of The Seafloor) is a formal and standardized technique for sediment-profile imaging and analysis (Rhoads and Germano, 1982). A Benthos Model 3731 Sediment Profile Camera was used in this study (Benthos, Inc., North Falmouth, MA; Figure 2-2). The camera is designed to obtain in-situ profile images of the top 15-20 cm of sediment.

Functioning like an inverted periscope, the camera consists of a wedge-shaped prism with a front face plate and a back mirror mounted at a 45 degree angle to reflect the profile of the sediment-water interface up to the camera (Figure 2-2). The camera is mounted horizontally on top of the prism. The prism assembly is moved up and down by producing tension or slack on the winch wire. Tension on the wire keeps the prism in the up position. The camera frame normally is lowered to the seafloor at a rate of about 1 meter/sec. When the frame settles onto the bottom, slack on the winch wire allows the prism to vertically penetrate the seafloor. A passive hydraulic piston ensures that the prism enters the bottom slowly (ca. 6 cm/sec) and does not disturb the sediment-water interface. On impact with the bottom, a trigger activates a 13-second time delay on the shutter release; once the prism comes to rest in the sediment, a photo is taken. Because the sediment photographed is directly against the face plate, turbidity of the ambient seawater does not affect image quality. When the camera is raised, a wiper blade cleans off the faceplate; the film is advanced by a motor drive, the strobe is recharged, and the camera can be lowered for another image.

In the present study, the camera was lowered repeatedly at each station in an attempt to obtain at least five replicate photographs for analysis.

3.1 Sedimentary Parameters

The dominant major modal grain-size for the Shallow Embayment, Providence River Reach, and Open Bay stations was greater than 4 phi (Figures 3-1 and 3-2). The upper bay, harbors, coves, and Providence River were largely silt-clay bottoms except at the mouth of Warwick Cove (station WC-3) and Potowomut River (station 4), where very fine to medium sand was present. In the Providence River Reach, station 6 consisted of a patchy distribution of medium, fine, and very fine sands and a molluscan shell-lag deposit (Figure 3-3). This station is located near a navigation channel where prop and bow wash and/or confined tidal flow keep the bottom free of fine-grained sediment. The lower Bay consisted of sandy bottoms mixed with minor modes of gravel and shell. Very fine sand was found in the lower reaches of West Passage (stations 1, SB-9, and SB-21). A fine sand bottom was present in the East Passage (Station SB-16). Station SB-20 at the lower end of the Sakonnet River and Station SB-22 outside the Bay consisted of fine rippled sands (Figure 3-4).

Because the number of weights on the camera was changed frequently to maximize prism penetration both between and within stations, it is of limited value to compare prism penetration depths among the replicates to determine relative sediment compactness. Generally, however, those stations where the mean communication); methods for extract filtration and plating were those of Bisson and Cabelli (1979) and Emerson and Cabelli (1982). A detailed description of these methods and the quality control procedure employed in the analyses are given in Appendix I.

3.0 RESULTS

Five replicate REMOTS® images suitable for analysis were obtained at 34 of the 56 stations. Only four out of the five attempted replicates could be analyzed at the following stations: 5, R-6, SB-2, WC-1, SB-6, SB-16, MF, SB-13, C-3, SB-19, SB-22, SB-7, 4, C-5, and C-6. Only three replicates were usable at stations SB-20, SB-8, 1, SB-5 and 7, two were analyzed at SB-18 and one was analyzed at SB-1. Images were not analyzed mainly because the camera prism did not penetrate the bottom or because movement of the boat caused the camera to be pulled out just before a photo was taken. In some of the photos which were analyzed, not all of the various REMOTS® parameters could be measured. The most common example of this was when camera prism penetration was limited yet sufficient enough to yield data on grain-size and boundary roughness, but the mean apparent RPD depth and infaunal successional stage could not be determined. For this reason, the sample size varies among the different REMOTS® parameters mapped and discussed in the following sections.

Phytoplankton and benthic plant respiration may produce dissolved oxygen minima during the early morning hours. To measure these minima would have required a measurement program separate from the one employed. All of our measurements were made during daylight hours. Therefore, our dissolved oxygen measurements may be conservative in terms of identifying the total population of stations that experience hypoxic, dysaerobic or anoxic conditions during some part of the day.

2.5 *Clostridium perfringens* Spore Collection and Analysis

One undisturbed surface sediment sample for determination of the concentration of *Clostridium perfringens* spores was collected at each station using a 1/25 m^2 Van Veen grab sampler. Three subsamples were taken from the upper 1-2 cm of the grab using a sterilized spatula (alcohol rinsed and ignited between samples); these replicate sediment subsamples were then placed in opaque, sterilized bottles and frozen immediately for later analysis.

Laboratory analyses for *Clostridium perfringens* spore enumeration were performed by Biological Analytical Laboratories, Inc. of North Kingstown, RI. The unpublished sodium metaphosphate method was used for spore extraction (Bisson and Cabelli, personal deployment. Dissolved oxygen measurements were read directly from the digital meter on deck; these readings were recorded when the instrument had stabilized (usually within one minute after the camera had reached the bottom).

At approximately half of the stations sampled, a Niskin bottle was used to obtain a water sample within one meter of the bottom. Two 125-ml subsamples were drawn from the Niskin bottle following retrieval, and the dissolved oxygen concentration in each replicate was determined immediately onboard the research vessel using a modification of the standard Winkler titration method (Strickland and Parsons, 1972; Parsons et al., 1984).

The temperature, pressure and salinity probes on the STD-12 were calibrated by the manufacturer. The YSI meter was calibrated using the air calibration technique specified by the manufacturer. The near-bottom dissolved oxygen concentrations determined by Winkler titration were used to calibrate the Rexnord probe. For those stations where both Winkler titrations and Rexnord probe measurements were performed, the Winkler dissolved oxygen values were regressed against the raw voltages measured near the bottom with the Rexnord probe. The resulting regression equation was used to convert the Rexnord probe voltages to dissolved oxygen concentration in mg/ℓ.

2.3.2 REMOTS® Image Analysis

Measurements of all physical parameters and some biological parameters are measured directly from the film negatives using a video digitizer and computer image analysis system. Negatives are used for analysis instead of positive prints in order to avoid changes in image density that can accompany the printing of a positive image. The image analysis system can discriminate up to 256 different gray scales, so subtle features can accurately be digitized and measured. Proprietary SAIC software allows the measurement and storage of data on 21 different variables for each REMOTS® image obtained. All data stored on disks are printed out on data sheets for editing by a senior-level scientist before being approved for final data synthesis, statistical analyses, and interpretation; a separate data sheet is generated for each REMOTS® image (Figure 2-3). Automatic disk storage of all parameters measured allows data from any variables of interest to be compiled, sorted, displayed graphically, contoured, or compared statistically. In addition, the integration of the REMOTS® analysis software with the INDAS system allows any REMOTS® measurement to be plotted (and if desired contoured) on a basemap of the survey area.

Specific measurement techniques for the REMOTS® parameters indicated in Figure 2-3 are presented in the sections that follow.

Sediment Type Determination

The sediment grain-size major mode and range are visually estimated from the photographs by overlaying a grain-size comparator which is at the same scale. This comparator was prepared by photographing a series of Udden-Wentworth size classes (equal to or less than coarse silt up to granule and larger sizes) through the REMOTS® camera. Seven grain-size classes are on this comparator: > 4 phi, 4-3 phi, 3-2 phi, 2-1 phi, 1-0 phi, 0-(-)1 phi, < -1 phi. The lower limit of optical resolution of the photographic system is about 62 microns, allowing recognition of grain sizes equal to or greater than coarse silt. The accuracy of this method has been documented by comparing REMOTS® estimates with grain-size statistics determined from laboratory sieve analyses.

Prism Penetration Depth

The REMOTS® prism penetration depth is determined by measuring both the largest and smallest linear distance between the sediment-water interface and the bottom of the film frame. The REMOTS® analysis software automatically averages these maximum and minimum values to determine the average penetration depth. All three values (maximum, minimum, and average penetration depth) are included on the data sheets. Prism penetration is potentially a noteworthy parameter; if the number of weights used in the camera is held constant throughout a survey, the camera functions as a static-load penetrometer. Comparative penetration values from sites of similar grain-size give an indication of the relative sediment water content.

Surface Boundary Roughness

Surface boundary roughness is determined by measuring the vertical distance (parallel to the film border) between the highest and lowest points of the sediment-water interface. In addition, the origin of this small-scale topographic relief is indicated when it is evident (physical or biogenic). In sandy sediments, boundary roughness can be a measure of sand wave height. On silt-clay bottoms, boundary roughness values often reflect biogenic features such as fecal mounds or surface burrows.

Mud Clasts

When fine-grained, cohesive sediments are disturbed, either by physical bottom scour or faunal activity (e.g., decapod foraging), intact clumps of sediment are often scattered about the seafloor. These mud clasts can be seen at the sediment-water interface in REMOTS® images. During analysis, the number of clasts is counted, the diameter of a typical clast is measured, and their oxidation state is assessed. Depending on their place of origin and the depth of disturbance of the sediment column, mud clasts can be reduced or oxidized (in REMOTS® images, the oxidation state is apparent from their reflectance value; see RPD section below). Also, once at the sediment-water interface, these sediment clumps are subject to bottom-water oxygen levels and bottom currents. Based on laboratory microcosm observations of reduced sediments placed within an aerobic environment, oxidation of reduced surface layers to depths of one to two millimeters by diffusion alone is quite rapid, occurring within 6-12 hours (Germano, 1983). Consequently, the detection of reduced mud clasts in an obviously aerobic setting suggests a recent origin. The size and shape of mud clasts, e.g. angular versus rounded, is also considered. Mud clasts may be moved about and broken by bottom currents and/or animals (macro- or meiofauna; Germano, 1983). Over time, large angular clasts become small and rounded. Overall, the abundance, distribution, oxidation state, and appearance of mud clasts are used to make inferences about the recent pattern of seafloor disturbance in an area.

Apparent Redox Potential Discontinuity (RPD) Depth

Aerobic near-surface marine sediments have a higher reflectance value relative to underlying hypoxic or anoxic sediments. This is readily apparent in REMOTS® images and is due to the fact that oxidized surface sediment contains particles coated with ferric hydroxide (an olive color when associated with particles), while the reduced sediments below this oxygenated layer are darker, generally grey to black. The boundary between the colored ferric hydroxide surface sediment and underlying grey to black sediment is called the apparent redox potential discontinuity (abbreviated as the RPD).

The depth of the apparent RPD in the sediment column is an important time-integrator of dissolved oxygen conditions within sediment pore waters. In the absence of bioturbating organisms, this high reflectance layer (in muds) will typically reach a maximum of two mm thick (Rhoads, 1974). This depth is related to the rate of supply of molecular oxygen by diffusion into the bottom, and the consumption of that oxygen by the sediment and associated microflora. In sediments which have very high sediment-oxygen demand, the sediment may lack a high reflectance layer even when the overlying water column is aerobic.

In the presence of bioturbating macrofauna, the thickness of the high reflectance layer may be several centimeters thick. The relationship between the thickness of this high reflectance layer and the presence or absence of free molecular oxygen (poise) in the associated pore waters must be made with caution. The boundary (or horizon) which separates the positive Eh region of the sediment column from the underlying negative Eh region is called the Redox Potential Discontinuity or RPD. The exact location of this Eh=0 potential can only be accurately determined with microelectrodes; hence the relationship between the change in optical reflectance, as imaged with the REMOTS® camera, and the actual RPD can only be determined by making the appropriate _in situ_ Eh measurements. For this reason, we describe the optical reflectance boundary, as imaged, as the "apparent" RPD and it is mapped as a mean value. In general, the depth of the actual Eh=0 horizon will be either equal or slightly shallower than the depth of the optical reflectance boundary. This is because bioturbating organisms can mix ferric hydroxide-coated particles downward into the bottom below the Eh=0 horizon. As a result, the _apparent_ mean RPD depth can be used as an estimate of the depth of pore water exchange, usually through pore water irrigation (bioturbation).

The depression of the apparent RPD within the sediment is relatively slow in organic-rich muds (on the order of 200 to 300 micrometers per day), therefore this parameter has a long time constant (Germano and Rhoads, 1984). The rebound in the apparent RPD is also slow (Germano, 1983). Measurable changes in the apparent RPD depth using the REMOTS® optical technique can be detected over periods of one or two months. This parameter is effectively used to document changes (or gradients) which develop over a seasonal or yearly cycle related to water temperature effects on bioturbation rates, seasonal hypoxia, sediment oxygen demand, and infaunal recruitment. In repeated sediment-profile surveys of ocean disposal sites throughout the New England region performed under the DAMOS program for the U.S. Army Corps of Engineers, New England Division, SAIC has repeatedly documented a drastic reduction in apparent RPD depths at disposal sites immediately after dredged material dumping followed by a progressive post-disposal apparent RPD deepening (barring further disposal activity). Consequently, time series RPD measurements can be a critical diagnostic element in monitoring the degree of recolonization in an area by the ambient benthos.

Another important characteristic of the apparent RPD is the contrast in reflectance values at this boundary. This contrast is related to the interactions among the degree of organic-loading and bioturbational activity in the sediment, and the levels of bottom-water dissolved oxygen in an area. High inputs of labile organic material increase sediment oxygen demand, and subsequently sulfate reduction rates (and the abundance of sulfide end-products). This results in more highly reduced (lower-reflectance) sediments at depth and higher RPD contrasts. In a region of generally low RPD contrasts, images with high RPD contrasts indicate localized sites of relatively high past inputs of organic-rich material (e.g., dredged material).

Sedimentary Methane

At extreme levels of organic-loading, pore-water sulfate is depleted, and methanogenesis occurs. The process of methanogenesis is detected by the appearance of methane bubbles in the sediment column. These gas-filled voids are readily discernable in REMOTS® images because of their irregular, generally circular aspect and glassy texture (due to the reflection of the strobe off the gas). If present, the number and total areal coverage of all methane gas pockets is measured.

Infaunal Successional Stage

The mapping of successional stages, as employed in this project, is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor perturbation (e.g., passage of a storm, dredged material deposition, hypoxia). This theory states that primary succession results in "the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance. These invertebrates interact with sediment in specific ways. Because functional types are the biological units of interest..., our definition does not demand a sequential appearance of particular invertebrate species or genera" (Rhoads and Boyer, 1982). This theory is formally developed in Rhoads and Germano (1982) and Rhoads and Boyer (1982).

The term disturbance is used here to define natural processes, such as seafloor erosion, changes in seafloor chemistry, foraging disturbances which cause major reorganization of the resident benthos, or anthropogenic impacts, such as dredged material or sewage sludge dumping, thermal effluent from power plants, pollution impacts from industrial discharge, etc. An important aspect of using this successional approach to interpret benthic monitoring results is relating organism-sediment relationships to the dynamical aspects of end-member seres (i.e., Stage I, II or III seres as defined in the following paragraphs). This involves deducing dynamics from structure, a technique pioneered by R. G. Johnson (1972) for marine soft-bottom habitats. The application of this approach to benthic monitoring requires <u>in-situ</u> measurements of salient structural features of organism-sediment relationships as imaged through REMOTS® technology.

Pioneering assemblages (Stage I assemblages) usually consist of dense aggregations of near-surface living, tube-dwelling polychaetes; alternately, the opportunistic mactrid bivalve <u>Mulinia</u> may colonize initially in dense aggregations after a disturbance (Rhoads and Germano, 1982, Santos and Simon, 1980a). These functional types are usually associated with a shallow redox boundary; bioturbation depths are shallow, particularly in the earliest stages of colonization. In the absence of further disturbance, these early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this "infaunalization" process is designated arbitrarily as a Stage II sere. Typical Stage II species are shallow dwelling bivalves or, as is common in Long Island Sound, tubicolous amphipods. In studies of hypoxia-induced benthic defaunation events in Tampa Bay, Florida, ampeliscid amphipods appeared as the second temporal dominant in two of the four recolonization cycles (Santos and Simon, 1980a and 1980b).

Stage III taxa, in turn, represent high-order successional stages typically found in low disturbance regimes. These invertebrates are infaunal, and many feed at depth in a head-down orientation. The localized feeding activity results in distinctive excavations called feeding voids. Diagnostic features of these feeding structures include: a generally semicircular shape with a flat bottom and arched roof, and a distinct granulometric change in the sediment particles overlying the floor of the structure. This relatively coarse-grained material represents particles rejected by the head-down deposit-feeder. These deep-dwelling infaunal taxa preferentially ingest the finer sediment particles. Other subsurface structures, such as burrows or methane gas bubbles, do not exhibit these characteristics. The bioturbational activities of these deposit-feeders are responsible for aerating the sediment and causing the redox horizon to be located several centimeters below the sediment-water interface. In the retrograde transition of Stage III to Stage I, it is sometimes possible to recognize the presence of relict (i.e. collapsed and inactive) feeding voids.

These end-member stages (Stages I and III) are easily recognized in REMOTS® images by the presence of dense assemblages of near-surface polychaetes and/or the presence of subsurface feeding voids; both types of assemblages may be present in the same image. More information on REMOTS® image interpretation can be found in Rhoads and Germano (1982 and 1986).

REMOTS® Organism-Sediment Index

A multi-parameter REMOTS® Organism-Sediment Index (OSI) has been constructed to characterize habitat quality. Habitat quality is defined relative to two end-member standards. The lowest value is given to those bottoms which have low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment (see Rhoads and Germano (1982, 1986) for REMOTS® criteria for these conditions). The REMOTS® Organism-Sediment Index for such a condition is minus 10. At the other end of the scale, an aerobic bottom with a deeply depressed RPD, evidence of a mature macrofaunal assemblage, and no apparent methane gas bubbles at depth will have a REMOTS® Organism-Sediment Index value of plus 11.

The REMOTS® Organism-Sediment Index is arrived at by summing the subset indices shown in Table 2-3.

The Organism-Sediment Index is calculated automatically by our software after completion of all measurements from each negative. We have found this index to be an excellent parameter for mapping disturbance gradients in an area and documenting ecosystem recovery after disturbance (Germano and Rhoads, 1984; Revelas et al., 1987).

The OSI can change seasonally. This is related to changing mean apparent RPD depths resulting from temperature control of bioturbation rates and sediment oxygen demand. Also, the successional status of a station may change over the course of a season related to recruitment and mortality patterns or the disturbance history of the bottom. The sub-annual change in successional status is, in our experience, limited to Stage I (polychaete-dominated) and Stage II (amphipod-dominated) seres. Stage III seres tend to be maintained over periods of several years unless they are eliminated by increased organic loading, extended periods of hypoxia, or buried with thick layers of dredged material. The recovery of Stage III seres following abatement of such events may take several years (Rhoads and Germano, 1982). In our experience, stations which have low OSI values (≤ +6) tend to have greater temporal and spatial variation in benthic habitat quality than stations which have higher OSI values.

2.4 Salinity, Temperature and Dissolved Oxygen Measurements

Vertical depth profiles of temperature and salinity were measured with an Applied Microsystems CTD probe (Model STD-12) attached to the REMOTS® camera. The STD-12 was mounted vertically on the REMOTS® camera such that its sensors were located approximately 40 cm from the sediment surface when the camera base was resting on the bottom. In this configuration, vertical hydrographic profiles were obtained at each station during REMOTS® image acquisition. Only the measurements made during ascent of the CTD (after the maximum sensor equilibration time) were used for plotting.

The accuracies of the STD-12 are ± 0.01° C for temperature, ± 0.01 ppt for salinity and ± 0.05 dBar for pressure (depth). The instrument is capable of sampling up to 8 scans per second and can store up to 7648 scans in 56K of internal RAM. Prior to commencing the field operations, the STD-12 was set to internally log data at 1 second intervals. Commands were sent to and data read from the instrument with a Compaq Portable II microcomputer via an RS-232 interface. The data were downloaded to the microcomputer during REMOTS® film changes and stored on floppy disks for later analysis.

A vertical profile of dissolved oxygen concentration was obtained at each station using a Rexnord Instruments Model 66 polarigraphic probe attached to the CTD. This probe utilizes a platinum-lead galvanic couple with a potassium-iodide electrolyte. The probe was mounted horizontally on the camera base frame such that its membrane was located between 6 to 9 cm above the sediment surface when the camera was resting on the bottom, depending on how deeply the frame settled into the sediment. At least two minutes were required per station for the camera to be raised slightly off the bottom and re-lowered five times; the camera rested on the bottom for at least 20 seconds for each replicate photograph. The near-bottom dissolved oxygen concentration taken as most accurate was the one measured just before retrieval of the camera to the surface (i.e., after the fifth replicate to insure the maximum equilibration time for the Rexnord probe).

A Yellow Springs Instruments (YSI) Model 58 digital dissolved oxygen meter equipped with a YSI Model 5739 probe and YSI Model 5795A submersible stirrer also was used as a "back-up" instrument to make measurements of near-bottom dissolved oxygen concentrations at most stations. A 0.5 mil membrane was used on the YSI probe to guarantee rapid sensor response and therefore minimize bottom equilibration time. The YSI probe and stirrer were mounted on the camera frame such that the sensor was located approximately 10 to 15 cm above the sediment surface during deployment. Dissolved oxygen measurements were read directly from the digital meter on deck; these readings were recorded when the instrument had stabilized (usually within one minute after the camera had reached the bottom).

At approximately half of the stations sampled, a Niskin bottle was used to obtain a water sample within one meter of the bottom. Two 125-ml subsamples were drawn from the Niskin bottle following retrieval, and the dissolved oxygen concentration in each replicate was determined immediately onboard the research vessel using a modification of the standard Winkler titration method (Strickland and Parsons, 1972; Parsons et al., 1984).

The temperature, pressure and salinity probes on the STD-12 were calibrated by the manufacturer. The YSI meter was calibrated using the air calibration technique specified by the manufacturer. The near-bottom dissolved oxygen concentrations determined by Winkler titration were used to calibrate the Rexnord probe. For those stations where both Winkler titrations and Rexnord probe measurements were performed, the Winkler dissolved oxygen values were regressed against the raw voltages measured near the bottom with the Rexnord probe. The resulting regression equation was used to convert the Rexnord probe voltages to dissolved oxygen concentration in mg/ℓ.

Phytoplankton and benthic plant respiration may produce dissolved oxygen minima during the early morning hours. To measure these minima would have required a measurement program separate from the one employed. All of our measurements were made during daylight hours. Therefore, our dissolved oxygen measurements may be conservative in terms of identifying the total population of stations that experience hypoxic, dysaerobic or anoxic conditions during some part of the day.

2.5 *Clostridium perfringens* Spore Collection and Analysis

One undisturbed surface sediment sample for determination of the concentration of *Clostridium perfringens* spores was collected at each station using a 1/25 m^2 Van Veen grab sampler. Three subsamples were taken from the upper 1-2 cm of the grab using a sterilized spatula (alcohol rinsed and ignited between samples); these replicate sediment subsamples were then placed in opaque, sterilized bottles and frozen immediately for later analysis.

Laboratory analyses for *Clostridium perfringens* spore enumeration were performed by Biological Analytical Laboratories, Inc. of North Kingstown, RI. The unpublished sodium metaphosphate method was used for spore extraction (Bisson and Cabelli, personal communication); methods for extract filtration and plating were those of Bisson and Cabelli (1979) and Emerson and Cabelli (1982). A detailed description of these methods and the quality control procedure employed in the analyses are given in Appendix I.

3.0 RESULTS

Five replicate REMOTS® images suitable for analysis were obtained at 34 of the 56 stations. Only four out of the five attempted replicates could be analyzed at the following stations: 5, R-6, SB-2, WC-1, SB-6, SB-16, MF, SB-13, C-3, SB-19, SB-22, SB-7, 4, C-5, and C-6. Only three replicates were usable at stations SB-20, SB-8, 1, SB-5 and 7, two were analyzed at SB-18 and one was analyzed at SB-1. Images were not analyzed mainly because the camera prism did not penetrate the bottom or because movement of the boat caused the camera to be pulled out just before a photo was taken. In some of the photos which were analyzed, not all of the various REMOTS® parameters could be measured. The most common example of this was when camera prism penetration was limited yet sufficient enough to yield data on grain-size and boundary roughness, but the mean apparent RPD depth and infaunal successional stage could not be determined. For this reason, the sample size varies among the different REMOTS® parameters mapped and discussed in the following sections.

3.1 Sedimentary Parameters

The dominant major modal grain-size for the Shallow Embayment, Providence River Reach, and Open Bay stations was greater than 4 phi (Figures 3-1 and 3-2). The upper bay, harbors, coves, and Providence River were largely silt-clay bottoms except at the mouth of Warwick Cove (station WC-3) and Potowomut River (station 4), where very fine to medium sand was present. In the Providence River Reach, station 6 consisted of a patchy distribution of medium, fine, and very fine sands and a molluscan shell-lag deposit (Figure 3-3). This station is located near a navigation channel where prop and bow wash and/or confined tidal flow keep the bottom free of fine-grained sediment. The lower Bay consisted of sandy bottoms mixed with minor modes of gravel and shell. Very fine sand was found in the lower reaches of West Passage (stations 1, SB-9, and SB-21). A fine sand bottom was present in the East Passage (Station SB-16). Station SB-20 at the lower end of the Sakonnet River and Station SB-22 outside the Bay consisted of fine rippled sands (Figure 3-4).

Because the number of weights on the camera was changed frequently to maximize prism penetration both between and within stations, it is of limited value to compare prism penetration depths among the replicates to determine relative sediment compactness. Generally, however, those stations where the mean depth of prism penetration into the bottom was less than 5 cm (stations 1, SB-15, SB-16, SB-22, SB-20, WC-3, 6, AH-3, and SB-4) represent compact medium to fine sands and very fine sands mixed with silt-clay (e.g., Figures 3-3 and 3-4). The compactness of the bottom at these stations may have been due either to the relative absence of bioturbation or the presence of large shell fragments which impeded penetration by the optical prism. Most of the low penetration stations were located near navigation channels in the Providence River (e.g.. stations SB-4 and 6) or near the mouths of harbors (e.g., stations WC-3 and AH-3). The compactness of Stations 1, SB-16, SB-22 and SB-20 in the lower Bay generally reflected higher wave and current energy regimes as manifested in rippled sands and shell lag deposits (Figure 3-4).

The frequency distribution of small-scale surface boundary roughness values for the Open Bay and Providence River Reach stations both had major modes at the 0.6 to 1.0 cm class interval, while the Small Embayment boundary roughness frequency distribution had a major mode at the 1.0 to 1.4 cm class interval (Figure 3-5). Most of the boundary roughness was attributed to biogenic features. Physical bedforms (ripples) accounted for this relief at Station 4 in the upper bay and at Stations SB-20 and SB-9 in the lower Bay (see Figure 3-4).

3.2 Salinity, Temperature and Near-Bottom Dissolved Oxygen

Vertical profiles of temperature, salinity and dissolved oxygen at individual stations are presented in Appendix II; concentrations for all three parameters varied both vertically through the water column and geographically throughout the bay. Maximum temperatures around 27°C were recorded near the surface at station SB-1 in the Providence River and at several Small Embayment stations. A minimum temperature of 11°C was recorded near the bottom at station SB-21. The lowest salinity of 16 ppt occurred at station SB-1; elsewhere, salinities generally ranged between 25 and 30 ppt. Overall, temperatures decreased and salinities increased moving from north to south down the Bay. The water column was stratified at most of the deeper stations, with warmer, less saline water overlying colder, denser water at depth. At stations exhibiting stratification, dissolved oxygen concentrations usually decreased from 2 to 4 mg/ℓ going from the surface to the bottom.

Near-bottom dissolved oxygen concentrations determined by Winkler titration, the YSI probe, and/or the Rexnord probe were tabulated for each station (Table 2-1). The YSI probe could not be used as a back-up instrument on the fourth and fifth days of the survey, because the instrument cable was severed by the boat's propeller and could not be replaced at sea. Dissolved oxygen measurements were not obtained at four stations with the Rexnord probe because low battery power caused the CTD datalogger to fail. The range in dissolved oxygen concentrations using these three different methods was less than 2 mg/ℓ at the majority of stations. At stations where the range exceeded 2 mg/ℓ, the Winkler values were almost always higher than the values obtained using either of the polarigraphic probes. We attribute the generally higher Winkler values to the fact that the water samples were taken approximately 1 meter above the bottom, while the polarigraphic probes measured dissolved oxygen within 15 cm of the bed. It is possible that sediment oxygen consumption resulted in a gradient of decreasing dissolved oxygen concentrations approaching the sediment-water interface. The anomalously high Rexnord probe value at station WC-1 is difficult to explain. For the purpose of data interpretation in this study, the dissolved oxygen concentrations determined by Winkler titration were relied upon as the most accurate. At stations where Winkler titrations were not performed, the Rexnord probe value (calibrated by the field Winkler values) was used.

When the Winkler titration or Rexnord probe values were mapped (Figure 3-6), hypoxic, dysaerobic or anoxic parts of the bay system were identified (Table 3-1 gives the dissolved oxygen ranges which define these categories). Only five stations (SB-1, SB-2, R-6, SB-4 and SB-6) were found to fall within these "critical" low-oxygen categories. Stations SB-1, SB-2, SB-4 and R-6 were located within the Providence River Reach; station SB-6 was located in the center of Greenwich Bay. The anoxic to dysaerobic dissolved oxygen values at Station SB-2 were the lowest measured in the survey, while the concentrations measured at the other four stations all fell within the hypoxic range. The highest dissolved oxygen values (greater than 10 mg/l) were recorded at the mouth and head (Stations AC-1 and AC-3) of Apponaug Cove in shallow water. This could have been due to high benthic primary productivity at the time of sampling. Much lower values might have been observed had these measurements been made at night or in the early morning hours, when near-bottom dissolved oxygen is consumed as a result of benthic respiration.

3.3 Depth of the Apparent RPD

Based on the results of numerous past REMOTS® surveys, apparent RPD depths less than 3 cm are considered indicative of chronically-stressed benthic habitats or those which have experienced recent disturbance (e.g., erosion, dredged material disposal, hypoxia, demersal predator foraging, etc.). The Providence River Reach and areas in and adjacent to Greenwich Bay, including Warwick Cove, Apponaug Cove, Greenwich Cove, Potowomut River and Allen Harbor, had extremely shallow mean apparent RPD depths (Figure 3-7). Other areas of shallow apparent RPD depths were located at station 3 outside of Wickford Harbor, at the north end of Conanicut Island (Station R-1), and at two of the three stations located within a topographic depression just southwest of Prudence Island (stations SB-7 and SB-14; Figure 3-8). Station SB-15 off Newport and station SB-12 near the head of East Passage also had shallow RPD depths.

Stations in the lower Bay such as SB-16 and SB-20 apparently had shallow RPD depths because of the absence of burrowing by infaunal organisms. Reworking of the bottom at these two stations probably is due to the migration of bedforms rather than biogenic advection. Maintenance of the apparent RPD depth near the sediment surface (i.e., less than 3 cm) usually results from high sediment oxygen demand and/or a limited supply of dissolved oxygen. This supply may be limiting because of inefficient irrigation of pore waters by bioturbating infauna or the absolute concentration of dissolved oxygen in the overlying water may be low. These two factors can act in concert to produce shallow RPD depths.

The inset on Figure 3-7 shows the frequency distributions of mean apparent RPD depths for the Open Bay stations (overall mean RPD = 3.44 cm), Providence River Reach stations (mean = 1.04 cm), and Shallow Embayment stations (mean = 0.50 cm). The RPD depths at the Open Bay stations were significantly deeper than those at both the Providence River Reach and Small Embayment stations (Kruskal-Wallis test, $p < 0.001$).

3.4 Benthic Successional Stage

The highest grade successional sere (Stage III) was encountered most frequently at the Open Bay stations (Figure 3-9). Stage III seres consist of head-down deposit-feeding infauna or burrowing megafauna, evidenced by the presence of sub-surface burrows or feeding voids (Figure 3-10). Intermediate seres (Stage II) were present at five Open Bay stations (SB-21, R-2, R-2A, C-6, and SB-22) and were a subdominant component at the Shallow Embayment stations. These Stage II seres consisted largely of dense populations of tubicolous amphipods (probably <u>Ampelisca</u> sp., Figure 3-11). No Stage II seres were observed in the Providence River Reach. Stage I seres, characterized by small, surface-dwelling capitellid and spionid polychaetes, dominated the Providence River Reach and Small Embayment stations (Figure 3-12).

The highest frequency of azoic stations (as deduced from the REMOTS® images) was encountered in Greenwich Cove. These azoic (with respect to macrofauna) stations showed evidence of bacterial mats at the sediment surface (Figure 3-13). Greenwich Bay, Warwick Cove, Apponaug Cove, Greenwich Cove, Potowomut River and Allen

Harbor were dominated by azoic, Stage I, and Stage II seres (see Figures 3-11 and 3-12). These coves and harbors had the highest concentration of low order infaunal seres. A strong clinal gradient in seres was observed along the Mount Hope Bay transect extending from stations 7 and SB-18 (Stage III) to station C-6 (a mixture of Stage II and III) to station SB-17 at the mouth of the Taunton River, which was dominated by Stage I (Figure 3-14). In the mid bay region, stations SB-7 and C-5 were dominated by Stage I seres. These two stations were located within a local topographic depression on the southwest side of Prudence Island. Stage I seres also dominated at station MF, located at a former mussel farm on the west side of Aquidneck Island near the Middletown/Portsmouth town line. The presence of Stage I seres at Station SB-9 at the mouth of West Passage probably was related to physical disturbance rather than organic enrichment. Similarly, the dominance of Stage II seres at Station SB-22 may be related to seasonal physical disturbance and the presence of a sandy substratum which attracts the amphipod <u>Ampelisca</u> sp., the Stage II dominant at this station.

3.5 Organism-Sediment Index

SAIC's extensive past experience mapping the Organism-Sediment Index (OSI) in regions surveyed with REMOTS® has shown that values less than +6 characterize areas of the bottom which have experienced disturbance in the form of physical erosion, deposition or organic enrichment. Typically, the identification of specific causes requires further analysis of the images, which may, for example, show evidence of storm lag deposits, ripples, or the appearance of low reflectance sediment (high sulphide inventory) overlying high reflectance sediment (low sulphide inventory). Low OSI values can also be indicative of low dissolved oxygen conditions or toxic chemical inputs. These conditions may or may not be manifested in imaged structures or reflectance properties. Negative OSI values are especially important because they identify habitats which are severely compromised in terms of supporting a productive and diverse assemblage of benthic macrofauna.

Low OSI values (i.e., less than +6) were concentrated within the Providence River Reach, Greenwich Bay and associated coves and harbors (including Potowomut River and Allen Harbor) and within a local depression west of Prudence Island (Figure 3-15). Within the Providence River Reach, negative values were found south of the Providence sewage treatment plant (STP) and combined sewer overflow (CSO) outfall (stations SB-3, R-5 and R-6). The lowest values among the Small Embayment stations were found in Greenwich Cove (all three stations), where station GC-1 had the lowest mean OSI value (negative 4.8) recorded in the survey. Stations AC-1 and AC-2 in Apponaug Cove and station PR-1 in Potowomut River also had negative OSI values.

The depressed OSI values southwest of Prudence Island were associated with the topographic depression which apparently represents a low kinetic depositional area for organic matter. This may explain why OSI values at stations SB-7, C-5 and SB-14 in this area were near or below +6.

Station SB-17 near the mouth of the Taunton River had a mean OSI value slightly above +6, but the transect gradient in Mount Hope Bay clearly indicated a progressive degradation in benthic conditions as the mouth of the river was approached. For this reason, it might be inferred that low benthic habitat conditions existed immediately upriver from station SB-17. Station SB-9 in the entrance to West Passage appears to be the only station where a depressed OSI value (+5.4) can be attributed to physical instability of the bottom rather than organic enrichment.

All the mean OSI values at the Open Bay stations were positive and distributed with a major mode between +9 and +10 and an overall mean of +8.5 (Figure 3-15). The Providence River Reach station values were more widely distributed, ranging between the -5 and +7 class intervals. The frequency distribution of mean OSI values at the Small Embayment stations ranged between the -5 and +6 class intervals (Figure 3-15). The mean OSI values for the Open Bay stations were significantly higher than those for the other two station subgroups (Kruskal-Wallis test, $p < 0.001$), while the

Providence River Reach and Small Embayment station values were not significantly different (Mann-Whitney U-test, p = 0.121).

3.6 Density of Clostridium perfringens Spores

The concentration of C. perfringens spores in each replicate subsample at each station is reported in tabular form in Appendix III. We have arbitrarily chosen spore densities of ≥ 100 CFU's (colony forming units) to identify sediments clearly receiving sewage inputs. This value was chosen to allow a reasonable degree of resolution for contouring and thereby delimit boundaries; most of the values in the Bay were greater than 100 CFU's (Figure 3-16). Gradients in the observed C. perfringens spore counts generally were consistent with the known distribution of point sources of both sanitary wastewater inputs and combined sewer overflows (Figure 3-17). The highest spore concentrations were found in the Providence River north of Sabin Point; stations SB-1 and SB-2 north of the Providence sewage treatment plant had the highest concentrations measured in the survey. Spore concentrations decreased with increasing distance down river to Conimicut Point. High values in the station cluster SB-3, R-6 and R-5 may reflect wastewater discharges from the East Providence STP and those from the Pawtuxet River.

There was no discernible decrease in spore concentrations in upper Narragansett Bay from Conimicut Point south to the northern tip of Prudence Island. Spore levels at station R-4 were considerably higher than those at stations 5 and SB-4, as well as adjacent stations 6 and SB-10. The coarse sediment texture observed at station 6 suggests that scour prevents the accumulation of fine organic materials and associated spores. Station R-4 may be located in a low kinetic area where fines accumulate, resulting in the observed high concentration of spores. This low kinetic energy regime may be related to bottom topography or to the pattern of currents in the area.

The concentration of spores at station R-3 was considerably higher than those at stations 6 and SB-10 to the north and station C-1 to the west. The distribution of spore densities in this passage suggests that stations R-3, SB-11 and SB-12 are located within depositional areas for sediments and spores moving down the Providence and, to a lesser extent, Warren Rivers into the northern end of East Passage. Station SB-12 had the highest spore levels observed in East Passage. The relatively small volume of discharge from the Bristol STP or STP's along the west side of Portsmouth could account in part for this high spore concentration, but the volume of such discharges is probably small compared to the loads of both organic detritus and associated spores moving down the Bay from the Providence River. Within Mount Hope Bay, a gradient in spore concentrations extended from station C-3 to SB-17, with levels generally increasing toward the mouth of the Taunton River. This clearly reflects the influence of the Fall River STP outfall in this location.

It is difficult to determine the significance of the small sewage sources along the west shore of Portsmouth to the elevated C. perfringens counts at station SB-13. The C. perfringens concentrations in the narrows connecting East and West Passage south of Prudence Island (stations SB-14, C-5, SB-7, and R-1) are somewhat higher than those in the West Passage but lower than at station SB-13. This gradient may reflect the net movement of water from southeast to northwest through this channel. The apparent depositional basin in the region of stations SB-14, C-5 and SB-7 were also identified from the REMOTS® data (shallow mean apparent RPD depths, low-order successional stages, and low OSI values). Such a low kinetic area could serve to accumulate spores moving to the northwest through this passage. Spore counts decreased progressively moving south from station SB-13 to SB-21 in Rhode Island Sound, suggesting that the Newport and Jamestown effluent is being diluted by exchange with open Sound waters.

Spore concentrations in the Sakonnet River were low (i.e., background) and near the sensitivity limits for this microbial assay method. This suggests that the influence of the Taunton River regarding spore contamination to the upper Sakonnet

River (station SB-19) is minimal through the constricted passage between the Sakonnet and Mount Hope Bay. This further suggests that lateral inputs into the Sakonnet River from either the east or west shore do not have a marked effect on spore levels.

In the Greenwich Bay area, the highest spore counts were encountered in Greenwich Cove, especially at station GC-2. This is clearly related to this station's proximity to the outfall of the Greenwich STP. The only other station with elevated spore counts in this area was station WC-1, located near a marina. The mainstem of West Passage had spore values which were marginally above the 100 CFU values used for identifying fecal inputs. A local elevation in spores at stations 2 and 3 could be related to the proximity of the Quonset Point STP. The lower part of West Passage (below the northern end of Conanicut Island) was particularly low in spore counts. This is attributed to high flushing and exchange with open Sound water; this interpretation is supported by the coarse nature of the substratum at stations 1 and SB-9, as imaged with the REMOTS® camera.

3.7 **Benthic Process Map**

The distribution of sediment types, physical and biogenic bedforms, mean apparent RPD depths, dissolved oxygen and C. perfringens spores provides information about bottom and near-bottom processes. Inferences about sources and sinks for fine-grained sediment and associated spores can be deduced from mapped gradients in these parameters. Figure 3-18 is an interpretive map showing the distribution of high and low kinetic regions and areas of accumulation of spores and fine-grained sediment. Apparent net transport directions for spores also are shown. In addition, areas of high apparent sediment oxygen demand are mapped based on the presence of sulfitic sediment at, or near, the sediment surface.

As might be expected, fine-grained sediments appear to be associated with major depositional and low kinetic areas within the Bay system. The upper reaches of the Providence River are a major focusing site (i.e., a far-field site of concentration) for C. perfringens spores and labile organic matter. Sediments near or in contact with the overlying water column in this area exhibited low optical reflectance, suggesting high apparent sediment oxygen demand. The instantaneous measurements of dissolved oxygen near the bottom also suggested that these sediments had high apparent oxygen demand; all of the stations north of and including station SB-4 had hypoxic bottom water (except station SB-3).

An eddy has been proposed as one possible explanation for the high fecal spore counts at Station R-4. In spite of these high counts, bottom dissolved oxygen was found to be relatively high, and the mean apparent RPD depth was greater 3 cm. Greenwich Bay and its appended coves and harbors are other likely sites for the accumulation of labile organic matter. High apparent sediment oxygen demand was associated with all stations except at the mouth of Warwick Cove (WC-3) and outer Apponaug Cove (AC-3). The source of the organic loading clearly was fecal inputs in the case of Greenwich Cove and in the inner most region of Warwick Cove (WC-1). However, the relatively low C. perfringens counts at the balance of the stations in this complex suggest sources other than sewage inputs may be a factor. This is also true for stations AH-1 and AH-2 in Allen Harbor, where fecal spore counts were very low yet REMOTS® images suggested organic enrichment. Alternative sources for organic matter are adjacent marshes or industrial inputs.

Gradients in C. perfringens spores suggest that both spores and sediments from the Providence River move southeast through the passage between Prudence Island and the Bristol shore. Further, Station SB-12 appears to be a significant collecting site for these spores. This is supported by the anomalously thin (1.75 cm) mean apparent RPD at this station, while surrounding stations exhibited deep biological mixing zones.

A second gradient in spores extended from the mouth of the Taunton River to station SB-18. This same transect showed a marked clinal gradient in successional seres (Figures 3-9 and 3-14), which supports the inference about the riverine source of organic loading. A third gradient in spore densities occurred from station SB-12 around the southwest corner of Prudence Island. The focusing mechanism in this area appears to be a low kinetic depression. High spore counts at Station R-1 may also reflect an apparent transport direction from east to west in this passage. Other weak gradients extended off Quonset in the region of stations 3 to 2 and off Newport at stations C-2 to SB-15.

Many stations in the lower reaches of both the East and West Passage showed evidence of bottom sediment transport. This supports an interpretation of high water exchange and flushing in the lower Bay and further explains why no strong focusing sites or "hot spots" with high *C. perfringens* spore concentrations were identified in this region.

3.8 Ranking of Benthic Habitat Quality

The three independently-derived parameters (REMOTS® OSI values, fecal spore counts, and near-bottom dissolved oxygen measurements) can help to identify and rank eutrophic benthic habitats in Narragansett Bay. The first two parameters can be used as time-integrators of organic loading. The REMOTS® OSI is useful for identifying enrichment gradients, but it cannot be used to uniquely resolve the source(s) of the enrichment. The *C. perfringens* counts uniquely identify fecal sewage inputs. Used in combination, it is possible to identify enrichment by sewage (high spore counts) versus non-sewage enrichment (low OSI values with low spore counts). The presence of high spore counts does not necessarily mean that a point source is nearby. Sewage-associated material can be transported far from its point of introduction and be concentrated in distant parts of an estuary or embayment. Such far-field sites of concentration (i.e., focusing sites) are usually associated with low-kinetic energy and topographic depressions.

The instantaneous dissolved oxygen data are transient measurements which must be interpreted with caution. Low dissolved oxygen values in the water column can be an indicator of sediment enrichment only in its late stages when near-bottom oxygen demand is so high that it affects the overlying water column; similarly, low values merely may reflect the nadir of a temporal variation in water column levels which are not consistently low enough to adversely affect the infaunal community.

One can group stations by their similarity with respect to the two parameters which are the time-integrated measurements of sediment quality (OSI values and C. perfringens spore counts). Figure 3-19 shows a 2-dimensional scatter plot of the stations with respect to these two variables, and Figure 3-20 shows these same data represented by a dendrogram produced by average linkage clustering (Systat Software, Systat, Inc., Evanston, IL). The two stations which clearly are segregated from the entire sample with low habitat quality probably due to sewage input are SB-1 and SB-

2 (Figure 3-19); Stations PR-1 and AH-1 at the other corner of the graph represent habitats degraded by organic inputs other than sewage-derived material. The ranking of the remaining clusters in terms of habitat quality are indicated in Figure 3-20; the one drawback to this agglomerative classification is that both variables are given equal weight. Stations with high OSI values yet relatively high spore counts indicate areas where sewage-derived organic loading is occurring; however, one cannot unequivocally classify these stations as "degraded", for the indigenous community is obviously metabolizing the organic inputs at a rate sufficient to prevent the system from becoming eutrophic.

One can also consider dissolved oxygen data when ranking stations. Those areas of the bay that had low OSI values (less than +6), high C. perfringens spore counts (greater than 100 CFU's), and low near-bottom dissolved oxygen concentrations (less than 3 mg/ℓ) represent those benthic habitats where sewage-derived excess organic loading has had the most adverse effects (Figure 3-21). Stations which were at the opposite end of the range for these three variables represent the highest quality benthic habitats. Table 3-2 gives the ranking of different station groupings based on the mapped patterns in Figure 3-21. Station Group A are those which had OSI values greater than +6, fecal spore counts less than 100 CFU's, and aerobic bottom water (> 3 mg/ℓ dissolved oxygen), while Group B represents stations with OSI values less than +6. Stations with fecal spore counts greater than 100 CFU's are listed in Group C, while Group D represents stations with OSI values less than +6 and fecal spore counts greater than 100 CFU's. Group E represents stations with OSI values less than +6 and hypoxic (or less) bottom water. Representing the most degraded areas, Group F includes all those stations where OSI values were less than +6, fecal spore counts were greater than 100 CFU's, and bottom water was found to be hypoxic or anoxic.

Using this qualitative ranking technique, the highest and lowest quality (i.e., "end-member") conditions can easily be recognized. Those stations in group A represent locations which all fall above the critical values described above and therefore had the highest quality benthic ranking. All these stations are located in the lower Bay system, except station SB-10 which is located in a high kinetic area in the lower Providence River Reach (Figure 3-18). Group F, limited to the upper reaches of the Providence River, represents that part of the Bay system which had the lowest benthic habitat quality.

The remaining stations in Groups B, C, D and E represent intermediate conditions; however, it is difficult to justify unequivocally their positions relative to one another. Hypoxic bottom water is considered an important negative habitat quality, for it can adversely effect not only infauna but also demersal fish and mobile megafauna. Group B stations are all located in small coves and harbors, except station C-1 in the upper Bay and SB-9, a high kinetic station in the lower Bay. Group C is comprised of stations located primarily in the middle Bay, ranging from the lower Providence River Reach and Mount Hope Bay to areas off Newport in the lower Bay. Group D stations are located in the Providence River Reach, small coves and harbors, and the focusing site adjacent to the southwest corner of Prudence Island. Group E in Greenwich Bay was defined to identify stations with low OSI values and hypoxic water. Although only one station qualified for this group (SB-6), it was still considered noteworthy. Stations with low OSI values and high fecal spore counts were placed in Group D, the third-most degraded position. Most of the Small Embayment stations, which had shallow mean apparent RPD depths (high apparent sediment oxygen demand), fall within this cluster. Many of these stations might have shown lower dissolved oxygen in bottom waters if the measurements had been made in the early morning hours. One can argue that the position of stations within groups B and C relative to one another is somewhat arbitrary, but the presence of fecal spores (Group C) was weighted more in the ranking of habitat quality than merely low OSI values (low OSI values can be caused by events and processes uncoupled from anthropogenic sources).

4.0 DISCUSSION

The highest and lowest quality benthic stations in Narragansett Bay have been identified by evaluating values of the mapped parameters and by a non-weighted clustering technique. These two approaches are based on three parameters: the REMOTS® OSI, dissolved oxygen, and fecal spore counts. Both techniques identified a subset of the most degraded and least degraded stations. Ranking of stations between these two end members is more difficult because of the subjective aspect of evaluating the relative importance of the three parameters for characterizing benthic "health".

Six major areas of organic enrichment of the bottom were identified from mapping those parts of the Bay floor where the REMOTS® Organism-Sediment Index (OSI) was less than +6. This critical threshold value has been chosen based on extensive mapping experience with this parameter in New England coastal waters. The six major areas of enrichment in Narragansett Bay were located within the Providence River Reach, Greenwich Bay (and associated coves and harbors), the Potowomut River, Allen Harbor, the mouth of the Taunton River, and in an area located along the southwest side of Prudence Island (Figure 3-21). The most severely disturbed sites (zero or negative OSI values) were located in the region of the mouth of the Pawtuxet River, all three stations in Greenwich

Cove, two Apponaug Cove stations, and one station in the Potowomut River.

The imaged biological characteristics of these six enriched areas indicated that they were dominated by small tubicolous polychaete species known to inhabit organically-enriched bottoms. These were probably Stage I spionid and/or capitellid polychaetes (see Figure 3-12). In addition, perimeter areas near the most enriched sites tended to support dense populations of Stage II tubicolous amphipods (Ampelisca sp.). A gradient of successional seres from Stage III to II-III to I was found to extend from Mount Hope Bay to the mouth of the Taunton River.

The most biologically-stressed area was Greenwich Cove, where all three stations were apparently devoid of macrofauna (azoic), as evidenced by the lack of organisms or feeding structures in the replicate REMOTS® images. Surface mats of anaerobic bacteria (and associated nematodes) were imaged in both Greenwich Cove and Apponaug Cove (Figure 3-13). Most Open Bay stations were dominated by mixed assemblages of Stage I and III seres, representing the highest quality benthic habitats.

At the time of sampling, near-bottom hypoxic/dysaerobic water was limited to four stations within the upper Providence Reach and one station within Greenwich Bay. Instantaneous measurement of near-bottom dissolved oxygen can be a poor predictor of benthic enrichment for several reasons. First, measurements are usually taken during daylight hours when high benthic primary productivity may produce high partial pressures of dissolved oxygen near the bottom. This may explain the supersaturated conditions measured in Apponaug Cove in the late afternoon. Conversely, measurements made during the early morning hours (the period of plant respiration) can result in much lower measured oxygen values. Also, hypoxic water may outwell from areas of high respiration and overlie sediments having low oxygen demand. Similarly, aerobic water may be advected over bottom sediments with high oxygen demand, but the supply of oxygen may exceed consumption so that no depression of oxygen concentrations is measured. The dynamics of the water column and the non-conservative nature of dissolved oxygen in seawater makes this variable very difficult to use as the primary parameter for characterizing long-term benthic habitat quality. Measurements of dissolved oxygen are best used to evaluate the most advanced stages of eutrophication when estuaries, or parts of estuaries, become seasonally stratified (e.g., Chesapeake Bay and Long Island Sound). The REMOTS® OSI parameter and the inventory of _C. perfringens_ spores are better time-integrators of benthic enrichment than dissolved oxygen, particularly in the early to intermediate stages of enrichment.

Concentrations of _C. perfringens_ spores in excess of 100 CFU's per gram of wet sediment have been used to identify significant sewage inputs. The station locations were not selected to document effects of specific sewage outfalls but rather to identify focusing sites for sewage in harbors and the open Bay. With the exception of five stations, areas where the REMOTS® OSI values were less than +6 also had high spore counts. A marked gradient in spore counts extended from the upper Providence River (high counts) into the upper Bay (lower counts). Similarly, another gradient in counts extended from the mouth of the Taunton River (high counts) into Mount Hope Bay (lower counts). Smaller scale gradients were observed off the mouth of the Potowomut River extending southward into the West Passage, with values increasing away from the river mouth in this case. This may be related to higher kinetic conditions near the mouth of the river (coarse-grained sediment and rippled bottom) preventing the accumulation of spores. Spores entrained in the water column may be deposited in the axis of the West Passage some 5 kilometers away from the harbor mouth.

The presence of an eddy or low kinetic depression may explain high spore counts at the southwest edge of Prudence Island. No local point source for these spores exists in this area. This location apparently represents a far-field focusing site for spores and labile organic matter, possibly moving westward from East Passage. Other local spore "hot spots" were located within Greenwich Cove, off Wickford, and off Newport.

Allen Harbor, Apponaug Cove, the Potowomut River, and Warwick Cove all exhibited OSI values less +6. However, with the exception of station 1 in Warwick Cove, all these sites showed relatively low spore counts. This suggests that the source of organic enrichment in these embayments may be from sources other than sewage. The combination of the REMOTS® OSI and Clostridium spore counts has been used in San Francisco Bay to identify enrichment from sewage versus other sources such as industrial inputs, natural marsh or grass bed inputs, or non-point run-off (SAIC, 1987b). This has proven to be an effective combination of techniques to rapidly "screen" harbors for source inputs. Continued use of these techniques has been recommended by the National Oceanic and Atmospheric Administration (Long and Buchman, 1989).

To help document long-term changes in benthic habitat quality, the results of the present survey were compared with those from an earlier sediment-profile survey conducted in Narragansett Bay in October, 1975. This earlier work was done at six stations running from the Providence Reach down to the northern tip of Conanicut Island (Myers and Phelps, 1978). The station numbers ran consecutively from 1 to 6, corresponding to stations R-1 to R-6 in the present survey.

The initial survey was supported by measurements of sediment trace metals, benthic biology, sediment nutrient fluxes, and grain-size. The Myers and Phelps 1978 report summary indicated that gradients in sediment quality inferred from the profile imaging were supported by these independent measurements. Before the sediment profile image data from the 1975 survey are compared with the 1988 REMOTS® survey, some limitations need to be considered. First, the 1975 data set was acquired using an early prototype of the sediment profile camera. Because the optical prism of the earlier model exerted a vertical force that was much less than the Benthos camera used in the 1988 survey, differences in camera prism penetration depth cannot be compared between surveys. Also, the 1975 work was done before the successional paradigm and the Organism-Sediment Index (OSI) were devised. Nevertheless, the 1975 data have been re-interpreted in light of current methods of image interpretation by Dr. D. C. Rhoads to insure comparability in interpretation. There are also seasonal differences in the two data sets which must be considered. The present survey was conducted in August, when water temperatures in the bay were at or near their maximum, while the 1975 data were collected in October, when seasonal cooling would affect the benthic community.

Between the two sampling periods, there were obvious differences in the mean apparent RPD at Stations R-3, R-5 and R-6

1975 and June 1976 were not observed in 1988. These apparent differences strongly suggest that the benthic habitat quality at Stations R-5 and R-6 in the Providence River Reach may have declined over the last decade relative to the apparent increase in SOD. Likewise, the apparent disappearance of amphipod populations from Stations R-3 and R-4 may also reflect a general decline in benthic habitat conditions over this time span.

A major advantage of the REMOTS® mapping technique is that it allows for the design of the most efficient monitoring plans for detecting subsequent changes in estuarine benthic systems. Based on the results of the August 1988 "reconnaissance" survey, we propose a revised sampling program for long-term monitoring of Narragansett Bay based on "critical boundaries" (Figure 4-4). These critical boundaries separate high quality benthic habitats from organically-enriched areas. One of these boundaries was located at the southern edge of the Providence River Reach, another at the mouth of Greenwich Bay, a third at the mouth of the Taunton River, and a fourth at the southwest edge of Prudence Island. If these boundaries move toward the axis of the Bay or down the Bay in the future, it would be an indication that enrichment from marginal areas was encroaching into the open Bay system. If, however, the critical boundaries move closer to the shore or up the bay, it would be an indication that the enrichment problem was improving.

(Figure 4-1); the 1988 RPD values for these three stations appear to be much lower than in 1975. The appearance of sulfitic sediment near the sediment surface suggests a high sediment oxygen demand at stations R-5 and R-6 in August 1988.

The gradient in infaunal successional seres apparently has changed only with respect to Stations R-3 and R-4 (Figure 4-2). Tubicolous amphipods (Stage II seres) were present at both of these stations in 1975, but they were not imaged in 1988.

Mean Organism-Sediment Index values calculated for each of the 1975 stations were compared with those of 1988 (Figure 4-3). A major conclusion drawn in the earlier work was that the area between Stations R-4 and R-5 marked a steep gradient in benthic habitat quality. Stations R-1 thru R-4 represented relatively high benthic habitat quality while Stations R-5 and R-6 represented low habitat quality. The 1988 data also indicated that the bottom between these two stations represents a strong gradient in sediment quality. However, the 1988 OSI values for Stations R-5 and R-6 are much lower due to shallower apparent RPD depths.

In summary, the major differences between the 1975 and 1988 data sets is that Stations R-5 and R-6 had no apparent RPD within the sediment column in 1988 while the mean apparent RPD depth in 1975 was over 2 cm deep at these stations. Further, the Stage II amphipods imaged at Stations R-3 and R-4 in both October

The proposed future sampling plan illustrated in Figure 4-4 focuses on long-term monitoring of critical boundaries at the expense of monitoring within areas known to be either degraded or clean. Thus, sampling is avoided both in the lower Bay and the Sakonnet River, which appeared to be relatively pristine, as well as in the upper Providence River and Small Embayments, which appeared to be chronically-enriched. Based on key management issues, this revised survey design can be expanded to include specific critical "hotspots" within known degraded areas to document, for example, the effects of upgrading particular sewage treatment plants or marina facilities. The proposed matrix consists of 40 stations, including 21 of the stations occupied in the present survey. Nineteen new stations have been located to better define the critical boundaries during future monitoring efforts.

5.0 SUMMARY AND CONCLUSIONS

The purpose of this synoptic reconnaissance survey was to define gradients in benthic habitat quality in Narragansett Bay using three complimentary techniques. The dominant sediment type at most of the 56 stations occupied was organic silt-clay muds (greater than 4 phi major modal grain-size). Very fine to fine sands were limited to the mouth of the Bay in the West and East

Passages, lower Sakonnet River and Rhode Island Sound. The mouths of Warwick Cove, Potowomut River, Allen Harbor, and station 6 in the lower Providence River Reach also were characterized by sands.

At the time of sampling, only five stations had near-bottom dissolved oxygen concentrations below 3 mg/ℓ (hypoxic, dysaerobic, or anoxic). Four of these stations were located in the upper Providence River Reach, and the fifth was station SB-6 in Greenwich Bay. All other stations were found to have dissolved oxygen concentrations above 3 mg/ℓ. Additional low oxygen stations might have been identified if the measurements had been made in the early morning hours. The highest values (greater than 10 mg/ℓ) were measured in Apponaug Cove and were attributed to high rates of benthic photosynthesis within this shallow embayment.

Based on extensive past experience with the REMOTS® Organism-Sediment Index (OSI) in New England waters, values less than +6 imply recent benthic disturbance by physical activity or organic enrichment. Six areas in the Bay were found to have OSI values less than +6: the Providence River Reach, Greenwich Bay, Allen Harbor, the Potowomut River, the Taunton River mouth and an area southwest of Prudence Island. In all six areas, the low OSI values were attributed to excessive organic loading of the bottom. The largest area of enrichment was located within the Providence River Reach (stations SB-1, SB-2, SB-3, R-6, R-5, SB-4, 5, C-1 and

R-3). Of these nine stations, three had negative values (stations SB-3, R-5 and R-6). These low values were related to shallow mean apparent RPD depths (high sediment oxygen demand), low-order successional stages, and, at station R-6, sedimentary methane gas. Relatively low dissolved oxygen concentrations measured in the water overlying the bottom at these three stations reinforced the REMOTS® OSI interpretations of degraded habitats.

Station SB-9, located at the mouth of West Passage, also had an OSI less than +6. This was attributed to physical disturbance. Low OSI values also were found southwest of Prudence Island in a topographic depression (stations SB-14, C-5, SB-17). Although this site is far removed from a point source of organic enrichment, it appears to be a sediment focusing area for fine-grained organic matter. This focusing may be related to the low kinetic depression, or an eddy may be located over this area.

Six of the REMOTS® stations from the present survey were also sampled thirteen years ago (October 1975) using a sediment-profile camera. Stations R-1 thru R-6 were compared between these two time periods. No significant changes in REMOTS® parameters were detected at lower Bay stations R-1 and R-2. The depth of the apparent RPD was zero at stations R-5 and R-6 in the Providence River Reach in 1988, compared to RPD depths of over 2 cm in October 1975. In addition, Providence River Reach stations R-3 and R-4 had dense populations of tubicolous amphipods in 1975; no amphipods were detected at these stations (or other stations within the Reach) in 1988. These changes suggest, but do not prove, that benthic habitat conditions may have become degraded at these Providence River Reach stations over the 13 year period. This interpretation is severely limited by the small sample size and lack of seasonal sampling. The major difficulty in making the comparison was that the 1975 data were acquired in October when cooling and turnover of the water column may have resulted in improved benthic habitat conditions relative to August.

Elevated counts of <u>Clostridium</u> <u>perfringens</u> spores (greater than 100 colony forming units (CFU's) per gram wet weight of sediment) were found at some of the same stations identified as having low REMOTS® OSI values. Highest spore counts were found at stations SB-1 and SB-2 (values over 2000 CFU's/gm). Elevated values also were encountered at stations SB-3, R-5 and R-6. The proximity of several sewage treatment plant and combined sewer overflow outfalls in the relatively narrow Providence River Reach most likely accounts for these high values. High spore counts and low OSI values in Greenwich Cove also were apparently related to the proximity of a sewage outfall. A gradient in increasing spore counts also was seen in Mount Hope Bay approaching the mouth of the Taunton River. The low kinetic sediment-focusing area to the southwest of Prudence Island also exhibited high spore densities. Other spore "hotspots" existed near Wickford, off Newport, at station SB-12, and at station SB-16 in the lower East Passage.

Several stations that had low OSI values did not have high spore counts. This included all of Greenwich Bay and its associated coves and harbors with the exception of Greenwich Cove as noted above and station WC-1, located near a marina in Warwick Cove; these data indicate organic enrichment from a source, or sources, other than sewage. Some stations were found to have elevated spore counts, yet OSI values were also high. This situation suggests that, although sewage may be reaching such a bottom, the sedimentation rate of labile organic matter is balanced by its "combustion" as a result of benthic ecosystem metabolic processes. The benthic ecosystem of Narragansett Bay has an assimilative capacity and an ability to metabolically "burn-off" inputs of labile organic matter. A key future research topic, which has management implications, is to determine the critical sedimentation rate of labile organic matter that can compromise this balance and cause more of the system to become eutrophic.

Results of our reconnaissance monitoring using REMOTS®, near-bottom dissolved oxygen measurements, and enumeration of _C. perfringens_ spores has allowed identification of benthic enrichment gradients. No single parameter is adequate for this task, but the combination of approaches provides insight into sources and sinks and allows ranking of benthic stations according to habitat quality. The most degraded habitats were those which had low dissolved oxygen (less than 3 mg/ℓ), low OSI values (less than +6), and high Clostridium spore counts (greater than 100 CFU's/gm). The highest benthic quality was attributed to those stations where mean values for these three variables were at the opposite end of these ranges. Six classes of stations were recognized based on combinations of critical values for the three parameters; station rank-orders were arranged from least to most degraded.

Instantaneous measurements of dissolved oxygen are the poorest indicator of benthic habitat quality. These instantaneous measurements do not provide good information about temporal/spatial variance. Sediment enrichment must be in an advanced state of degradation before such conditions are manifested in hypoxic bottom water. The REMOTS® data and C. perfringens spore counts are better time-integrators of benthic enrichment than dissolved oxygen, particularly in the early to intermediate stages of enrichment. This combination of REMOTS® and spore density mapping is a very cost-effective way to "screen" harbors to separate sewage effects from other sources of enrichment and/or degradation such as industrial effluent, surface run-off, sediment focusing, or accumulation of plant detritus. Further "ground-truth" sampling usually would be required to definitely identify such non-sewage sources of benthic disturbance.

Based primarily on the REMOTS® OSI, but also considering spatial gradients in spore counts and dissolved oxygen, four "critical boundaries" were identified in the Bay. These boundaries mark steep gradients between bottoms which were stressed primarily as a result of organic over-enrichment versus relatively healthy bottoms. Future monitoring of stations located on either side of these boundaries should allow detection of long-term changes in benthic enrichment of the Bay bottom. If these boundaries move toward the center of the Bay, it would suggest that benthic habitat conditions are being progressively degraded. If the boundaries contract toward shore, it may indicate that benthic conditions are improving.

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Table 2-1

Stations occupied in the REMOTS® survey of Narragansett Bay, 15-19 August 1988. See text for descriptions of station name abbreviations. All dissolved oxygen concentrations are in mg/ℓ; WINK = average Winkler titration value (n = 2 replicates), YSI = YSI meter value, REXN = Rexnord probe value.

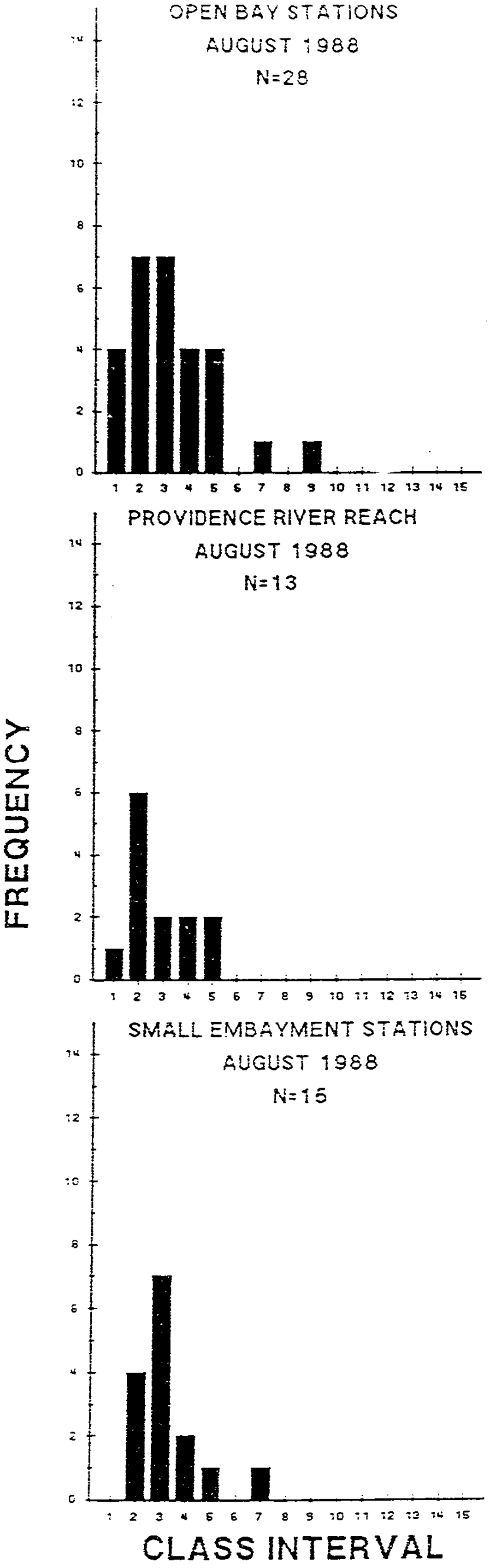
STATION	APPROXIMATE COORDINATES LAT/LONG	DATE OCCUPPIED	DEPTH IN FT	DISSOLVED OXYGEN		
				WINK	YSI	REXN
SB-8	41°33.495N 71°23.500W	08/15/88	38	8.5	4.2	4.5
2	41°33.617N 71°24.450W	08/15/88	26	6.7	4.1	----
3	41°34.283N 71°25.767W	08/15/88	16	4.1	4.8	6.2
R-1	41°34.917N 71°22.283W	08/15/88	22	5.5	4.4	4.3
SB-14	41°34.995N 71°20.365W	08/15/88	44	4.2	4.6	4.0
C-5	41°35.220N 71°20.416W	08/15/88	45	4.2	4.2	3.4
SB-7	41°37.785N 71°21.925W	08/15/88	21	4.0	3.4	3.9
R-2	41°38.000N 71°22.833W	08/15/88	22	3.8	2.5	3.1
R-2A	41°38.000N 71°23.750W	08/15/88	20	6.8	6.9	7.6
4	41°39.925N 71°23.173W	08/15/88	34	6.2	6.8	7.1
SB-5	41°39.955N 71°21.185W	08/16/88	24	4.6	4.0	4.1
C-1	41°41.417N 71°20.867W	08/16/88	25	----	3.8	3.9
R-4	41°40.533N 71°19.500W	08/16/88	23	4.9	5.1	4.5
R-3	41°41.702N 71°18.586W	08/16/88	23	----	4.7	4.8
SB-10	41°41.235N 71°18.335W	08/16/99	23	6.3	4.8	4.6
5	41°42.350N 71°19.700W	08/16/88	23	----	5.4	5.7
6	41°42.341N 71°19.704W	08/16/88	20	3.3	5.2	4.0
SB-4	41°43.290N 71°20.920W	08/16/88	55	----	2.8	2.6
R-5	41°43.667N 71°22.050W	08/16/88	21	4.2	2.5	3.0

	Sample Collection				Sample	Spores per gram of
Lab No.	Date	Time	Station	Replicate	Weight	sediment (wet weight)
70	8/19	1035	SB-9	2	0.71	85
71				1	0.42	48
72				3	0.59	34
73	8/16	1435	SB-2	1	0.49	3400
74				2	0.73	2500
75				3	0.48	3600
76	8/16	1410	SB-3	2	0.77	545
77				3	0.57	561
78				1	0.45	200
79	8/18	1430	7	2	0.48	63
80				3	0.58	259
81				1	0.58	414
82	8/16	1345	R-6	2	0.48	500
83				1	0.48	125
84				3	0.63	48
85	8/18	1810	SB-20	2	0.56	<18
86				1	0.81	<12
87				3	0.79	<12
88	8/16	1255	SB-4	2	0.48	375
89				1	0.82	37
90				3	0.79	152
91	8/18	1150	C-3	1	0.48	125
92				2	0.66	136
93				3	0.78	384
94	8/17	1532	WC-1	3	0.40	125
95				2	0.51	137
96				1	0.45	67
97	8/16	1000	C-1	2	0.48	<63
98				3	0.62	97
99				1	0.53	113
100	8/17	1155	AH-1	3	0.46	<22
101				1	0.55	22
102				2	0.52	12
103	8/16	1125	SB-10	2	0.42	<71
104				1	0.52	58
105				3	0.74	73

Lab No.	Sample Collection Date	Time	Station	Replicate	Sample Weight	Spores per gram of sediment (wet weight)
106	8/16	1315	R-5	1	0.47	574
107				2	0.50	480
108				3	0.86	348
109	8/16	1020	R-4	3	0.61	472
110				1	0.61	334
111				2	0.69	409
112	8/17	1655	GC-3	3	0.69	278
113				1	0.95	297
114				2	0.69	165
115	8/16	1115	R-3	3	0.75	360
116				1	1.11	541
117				2	0.59	336
118	8/18	1000	C-2	1	0.70	394
119				2	0.60	330
120				3	0.73	510
121	8/18	1320	SB-11	2	0.62	368
122				3	0.72	542
123				1	0.99	442
124	8/19	0955	SB-21	3	0.70	86
125				2	0.60	120
126				1	0.68	79
127	8/17	1630	SB-6	2	0.55	120
128				3	0.74	24
129				1	0.69	9
130	8/17	1504	WC-2	2	0.61	39
131				1	0.80	83
132				3	0.81	52
133	8/17	1440	WC-3	3	0.69	26
134				1	0.96	13
135				2	0.50	108
136	8/17	1210	AH-2	1	0.72	17
137				3	0.65	83
138				2	0.69	43
139	8/18	1100	SB-13	3	0.56	514
140				2	1.10	709
141				1	0.41	307

	Sample Collection				Sample Weight	Spores per gram of sediment (wet weight)
Lab No.	Date	Time	Station	Replicate		
142	8/18	0850	SB-16	3	0.71	101
143				2	0.85	120
144				1	0.77	234
145	8/18	1345	SB-12	1	0.71	1183
146				2	0.99	727
147				3	1.15	913
148	8/18	0935	SB-15	1	1.35	258
149				2	0.62	194
150				3	1.00	270
151	8/18	1920	SB-22	1	0.70	34
152				2	0.91	53
153				3	0.60	30
154	0/18	1335	PR-1	3	0.63	29
155				2	0.93	10
156				1	0.62	29
157	8/17	1200	AH-3	3	0.66	55
158				1	0.62	68
159				2	0.91	20
160	8/17	1347	PR-2	2	0.70	111
161				3	0.48	113
162				1	0.60	80

Figure 3-4. Rippled sand bottom (an example of physically-induced surface boundary roughness) at station SB-20 near the mouth of the Sakonnet River. A lag deposit consisting of numerous small shell fragments is visible at the sediment surface. Note also the shallow penetration of the camera prism in this type of bottom. Scale of image = 1X.



SMALL-SCALE SURFACE BOUNDARY ROUGHNESS

CLASS INTERVAL	RANGE OF VALUES (CM)
1	0.0 - 0.6
2	0.6 - 1.0
3	1.0 - 1.4
4	1.4 - 1.8
5	1.8 - 2.2
6	2.2 - 2.6
7	2.6 - 3.0
8	3.0 - 3.4
9	3.4 - 3.8
10	3.8 - 4.2
11	4.2 - 4.6
12	4.6 - 5.0
13	5.0 - 5.4
14	5.4 - 5.8
15	5.8 - 6.2
16	6.2 - 6.6
17	6.6 - 7.0
18	7.0 - 7.4
19	7.4 - 7.8
20	7.8 - 8.2

Figure 3-5. Frequency distributions of average small-scale surface boundary roughness values for each of the three station subsets.

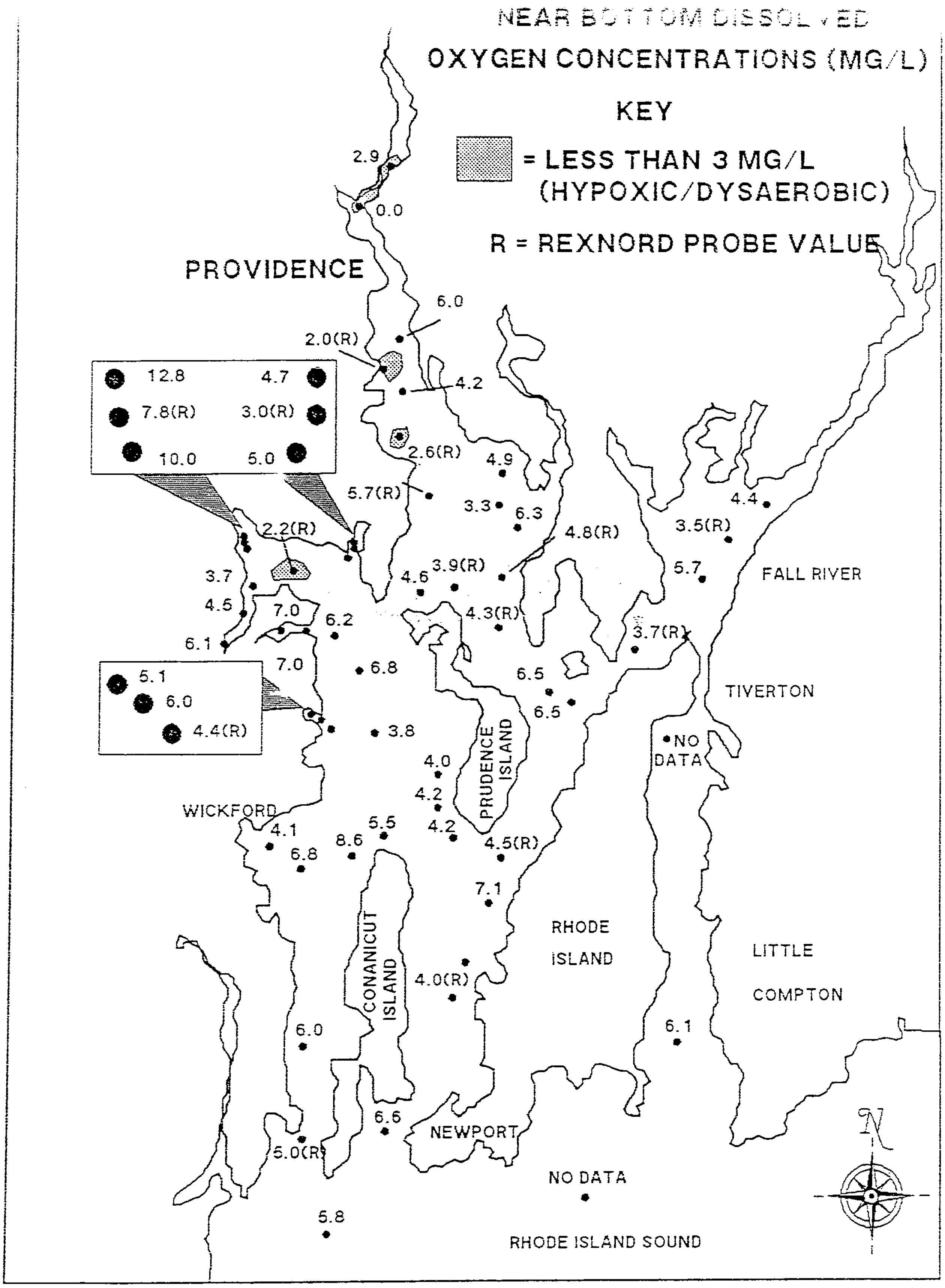


Figure 3-6. Dissolved oxygen concentrations (in mg/ℓ) measured within one meter of the bottom at Narragansett Bay REMOTS® stations, August 1988. The majority of the mapped values are average concentrations determined by replicate Winkler titrations. At stations where Winkler titrations were not performed, the Rexnord (R) polarigraphic probe values are reported.

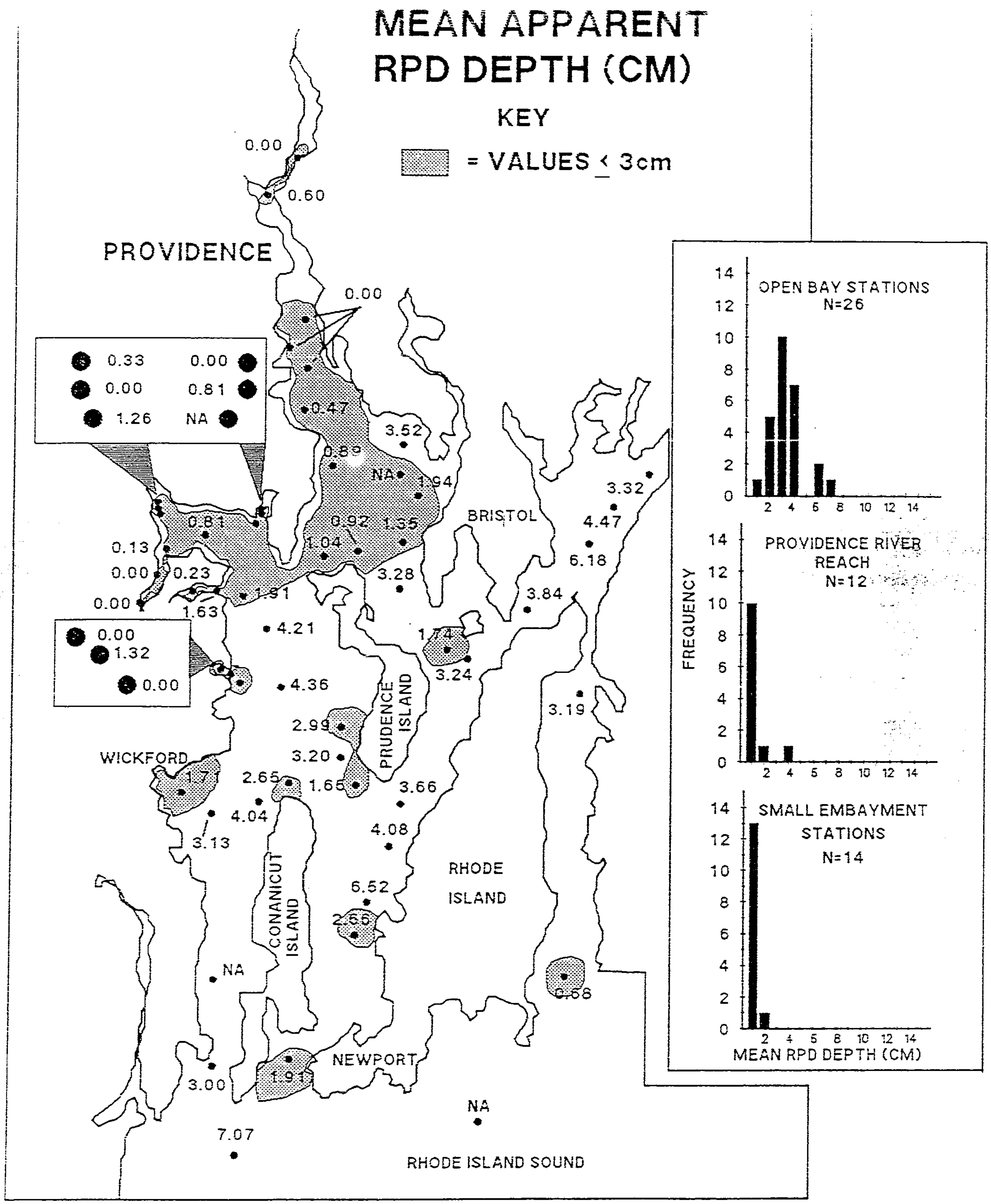
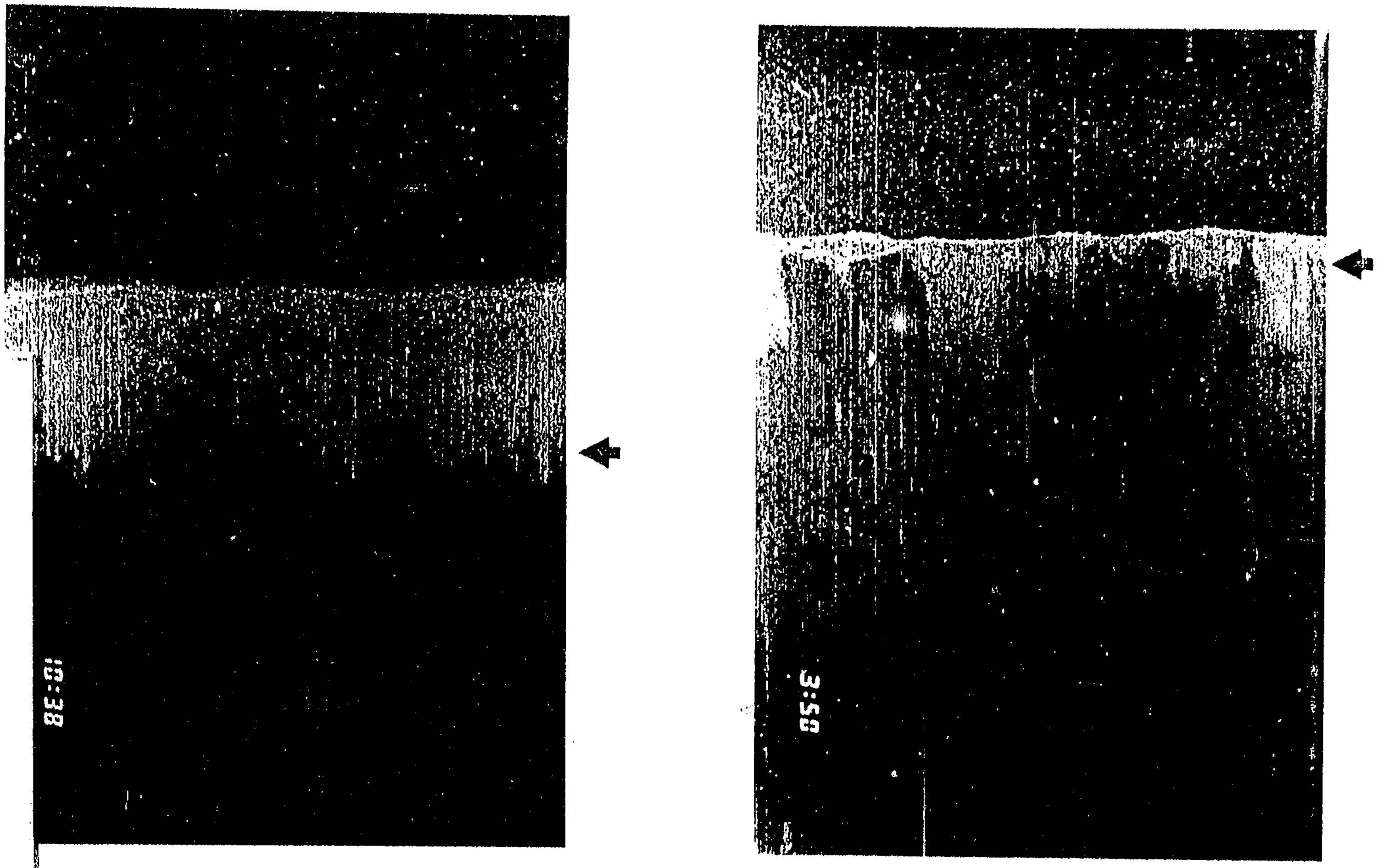


Figure 3-7. Mean apparent RPD depths (in centimeters) at the Narragansett Bay REMOTS® stations, August 1988. Frequency distributions of these values for each of the station subsets are illustrated (inset). NA indicates that the RPD measurement was not available due to inadequate prism penetration.



Poor Quality Original

Figure 3-8. Two REMOTS® images which help to illustrate the contrast between a relativel deep, well-developed RPD at station MF (left image) versus a relativel shallow RPD at station SB-14 (right image). The RPD is measured from the sediment surface to the point where there is a distinct change in the optica reflectance of the sediment (arrows). The RPD measured 4.1 centimeters i the left image and 1.4 centimeters in the right image. Approximate scale o both images = 0.5X.

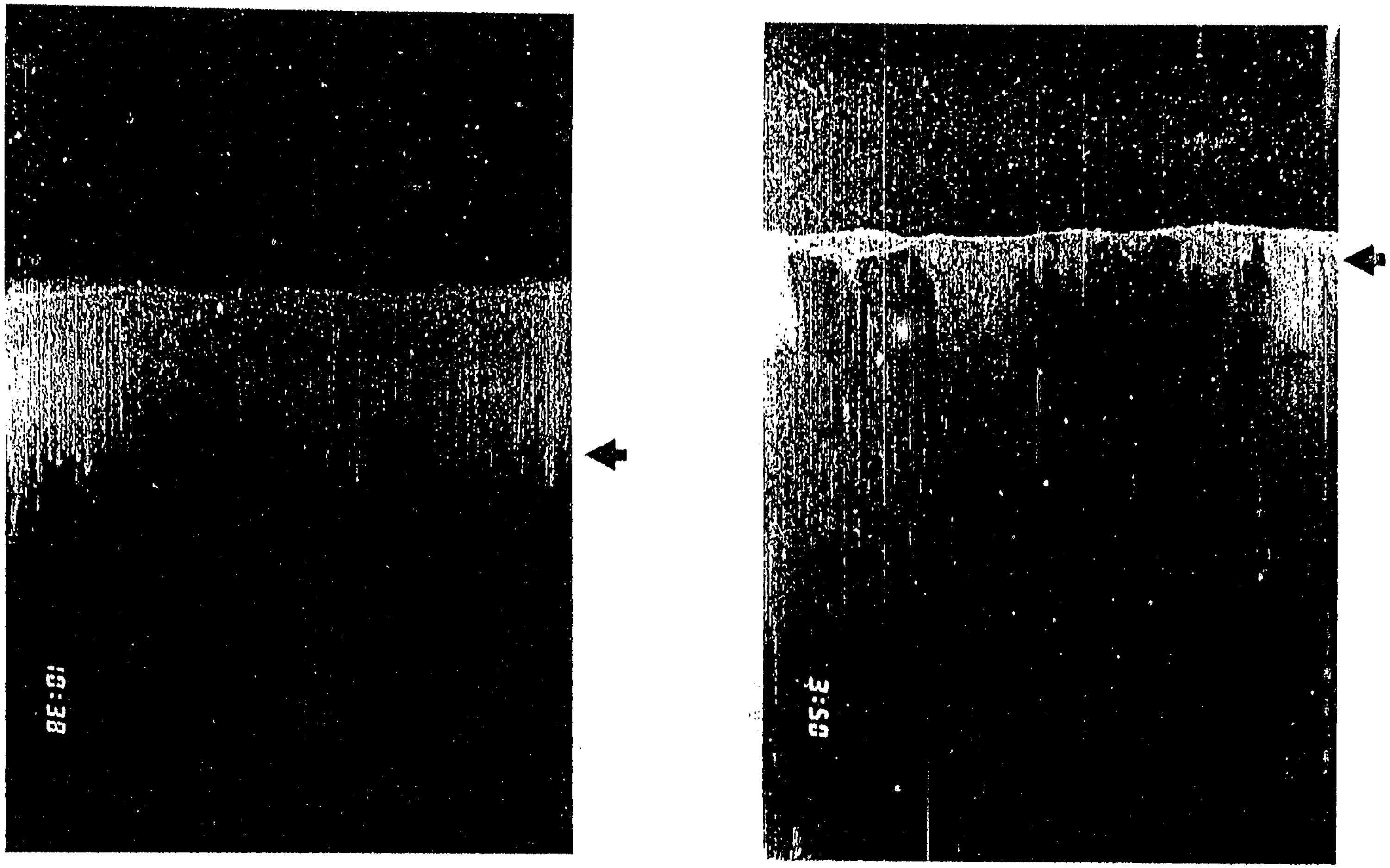


Figure 3-8. Two REMOTS® images which help to illustrate the contrast between a relativel deep, well-developed RPD at station MF (left image) versus a relativel shallow RPD at station SB-14 (right image). The RPD is measured from the sediment surface to the point where there is a distinct change in the optica reflectance of the sediment (arrows). The RPD measured 4.1 centimeters i the left image and 1.4 centimeters in the right image. Approximate scale o both images = 0.5X.

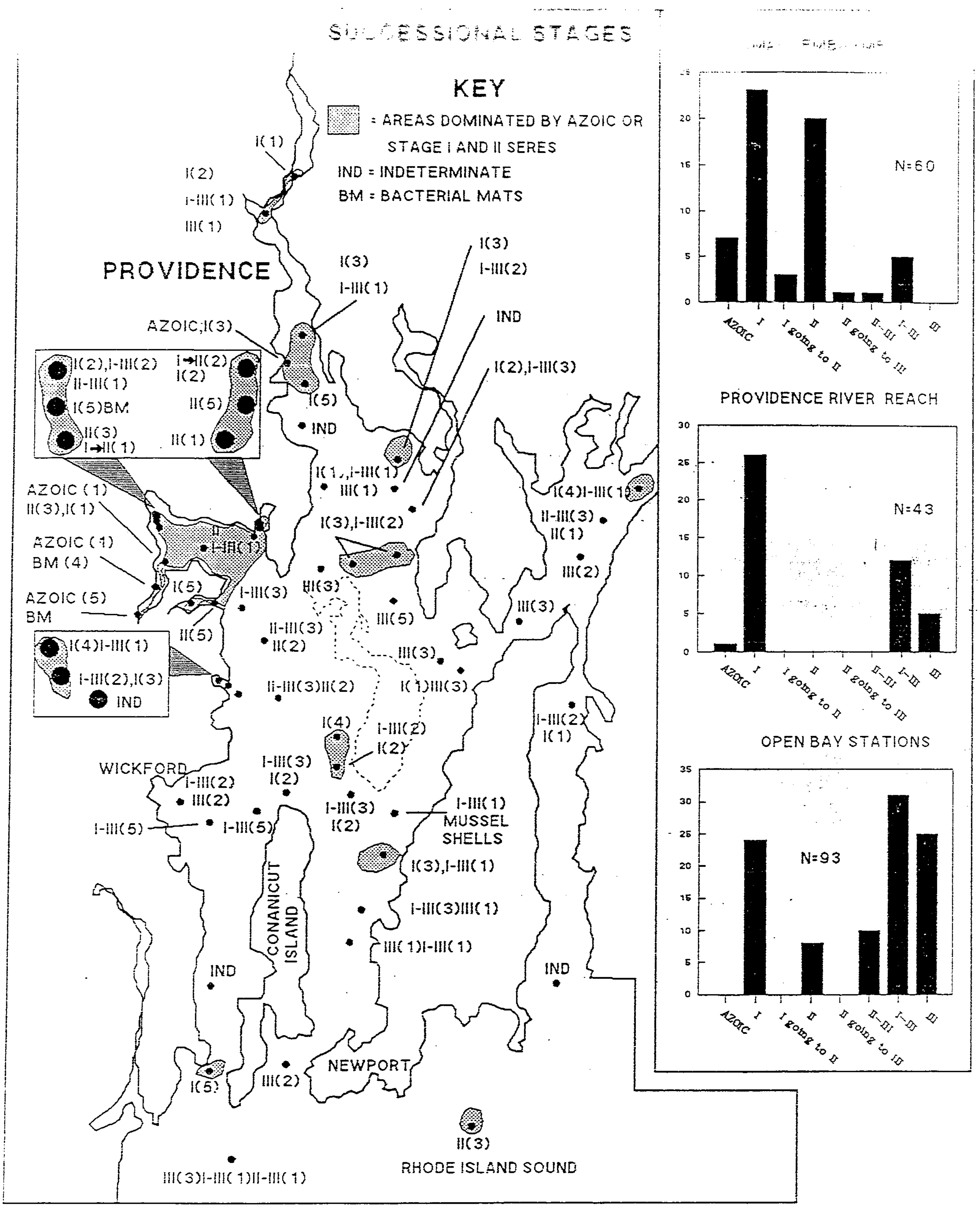


Figure 3-9. Infaunal successional stages observed at the Narragansett Bay REMOTS® stations in August 1988. The number in parentheses indicates the number of replicate images exhibiting a particular successional stage at each station. The frequency distributions of successional stages for all replicates in the three station subgroups are

Poor Quality Original

Figure 3-10. The REMOTS® image on the left shows a series of subsurface burrows at station 7, while the image on the right shows feeding voids (arrows) at station 5. Both images were given a Stage III successional designation. Approximate scale = 0.5X.

Figure 3-10. The REMOTS® image on the left shows a series of subsurface burrows at station 7, while the image on the right shows feeding voids (arrows) at station 5. Both images were given a Stage III successional designation. Approximate scale = 0.5X.

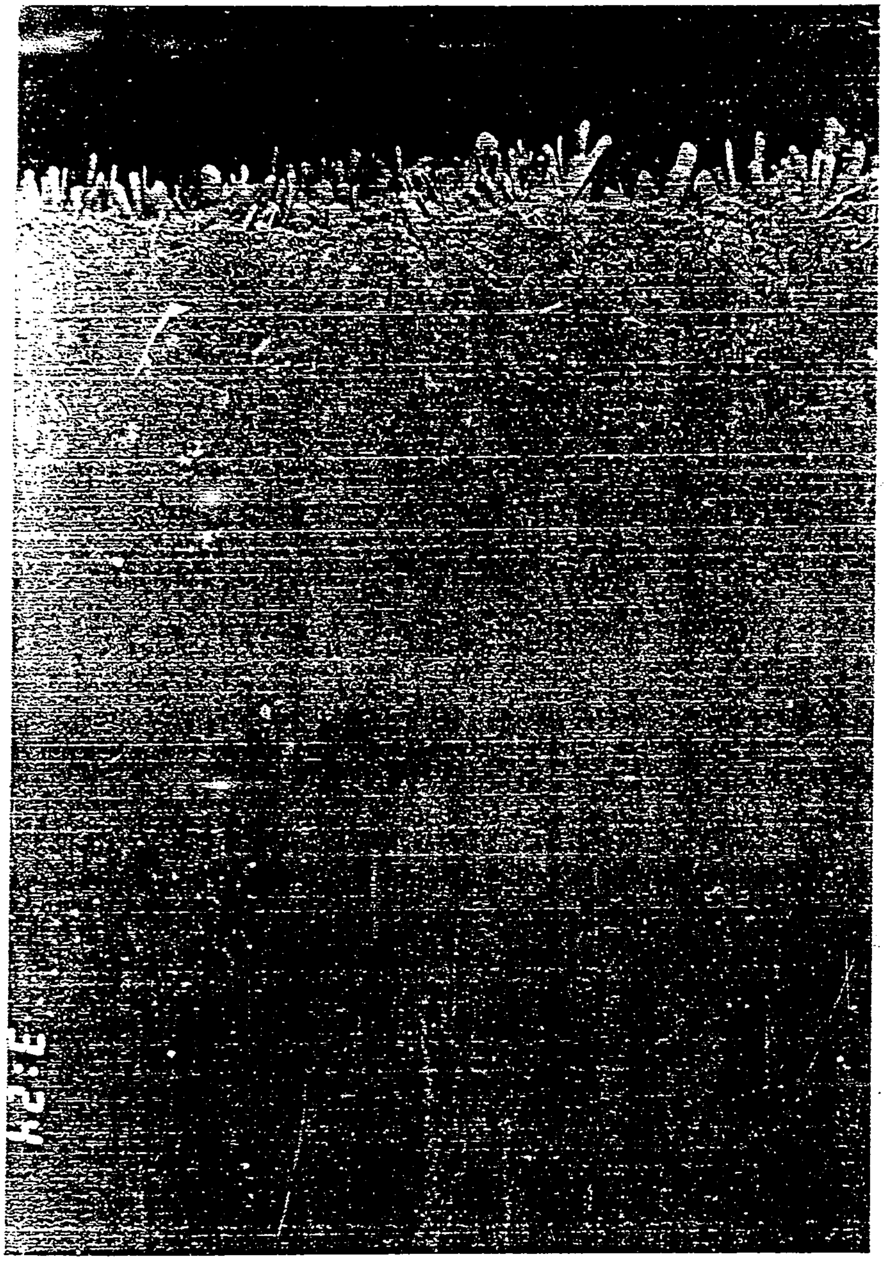


Figure 3-11. REMOTS® i [illegible] a dense
assemblag [illegible] sediment
surface. [illegible]

Poor Quality Original

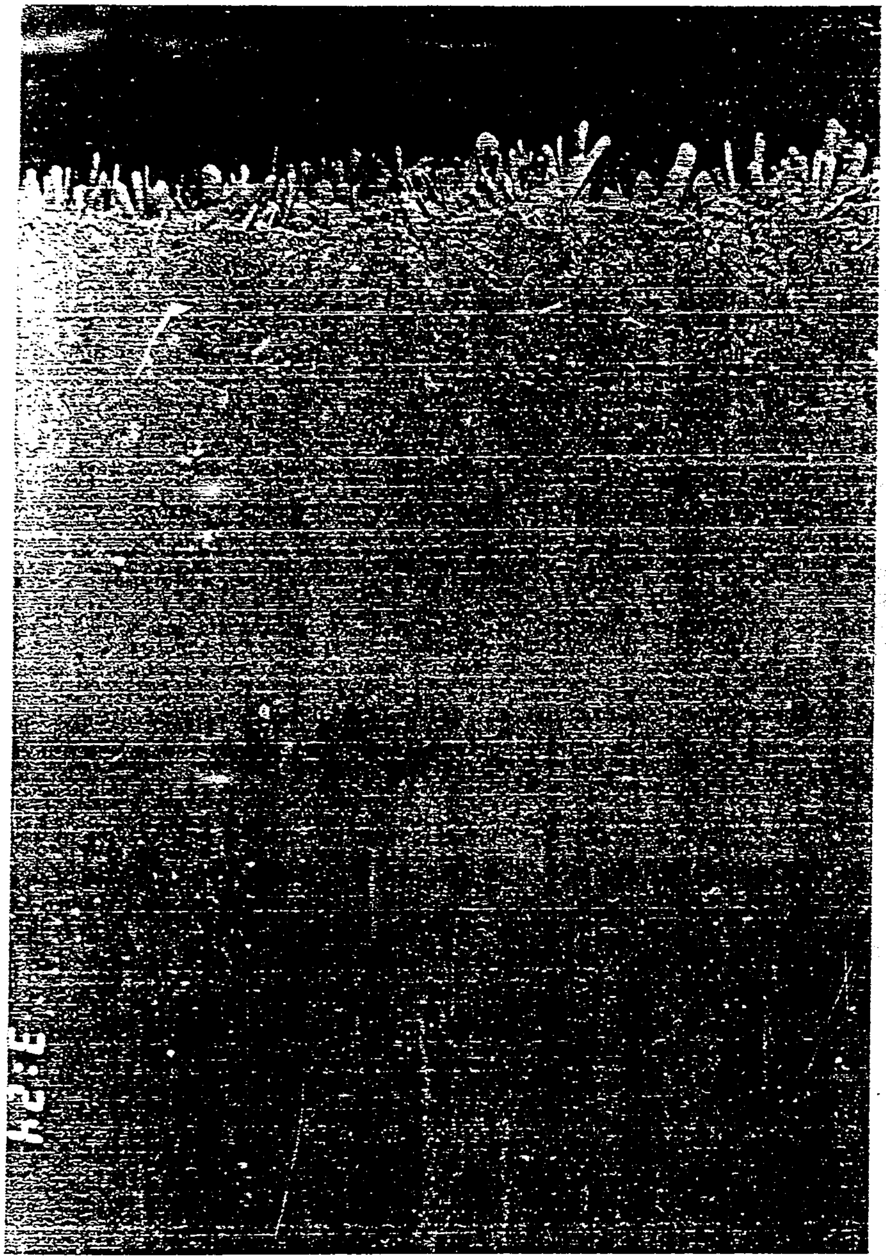


Figure 3-11. REMOTS® image from station C-6 illustrating a dense assemblage of amphipod tubes at the sediment surface. Scale = 1X.

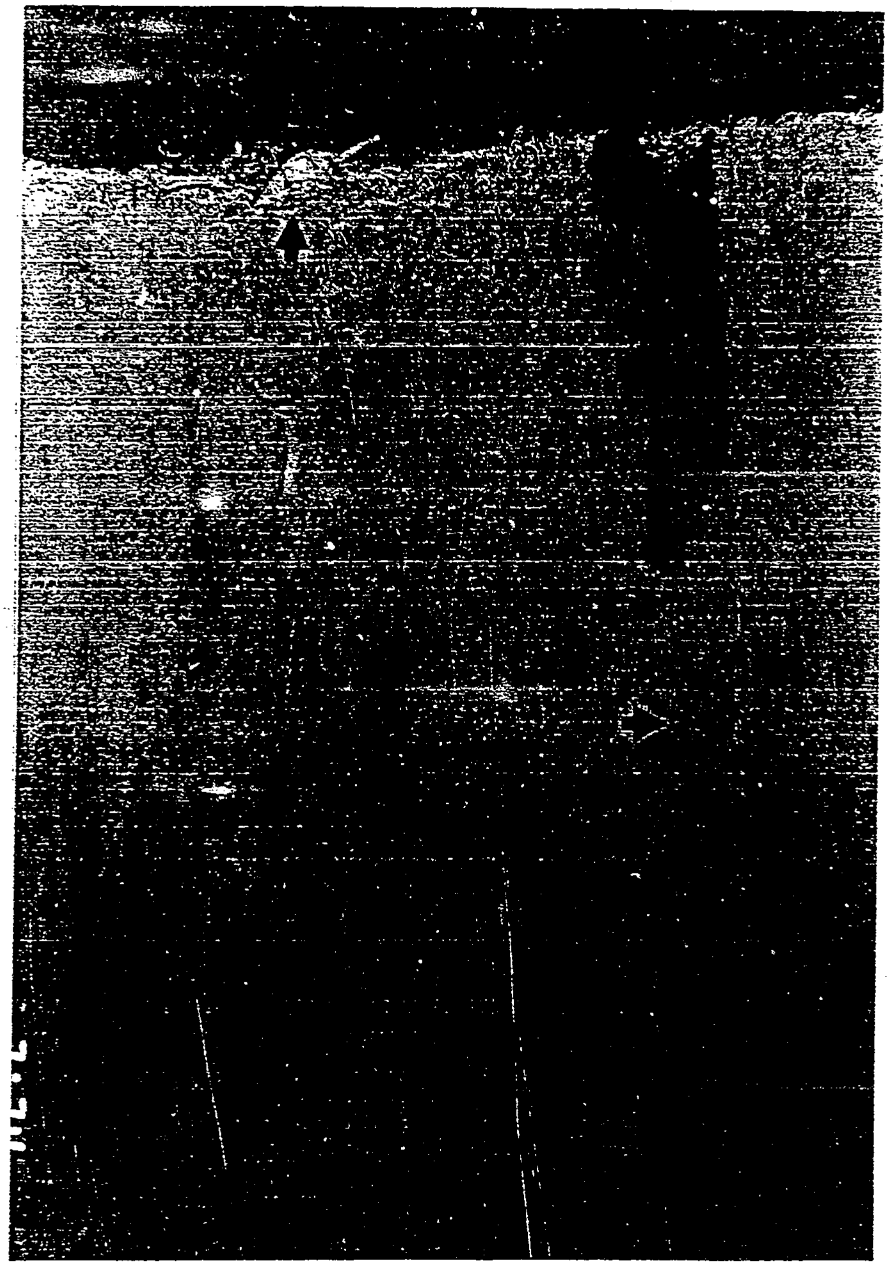


Figure 3-12. A dense assemblage of small, tubicolous Stage I polychaetes and a gastropod (top arrow) are visible at the sediment surface in this REMOTS® image from station SB-17. The presence of a small feeding void at depth (bottom arrow) gives this image a Stage I on III successional designation. Scale of image = 1X.

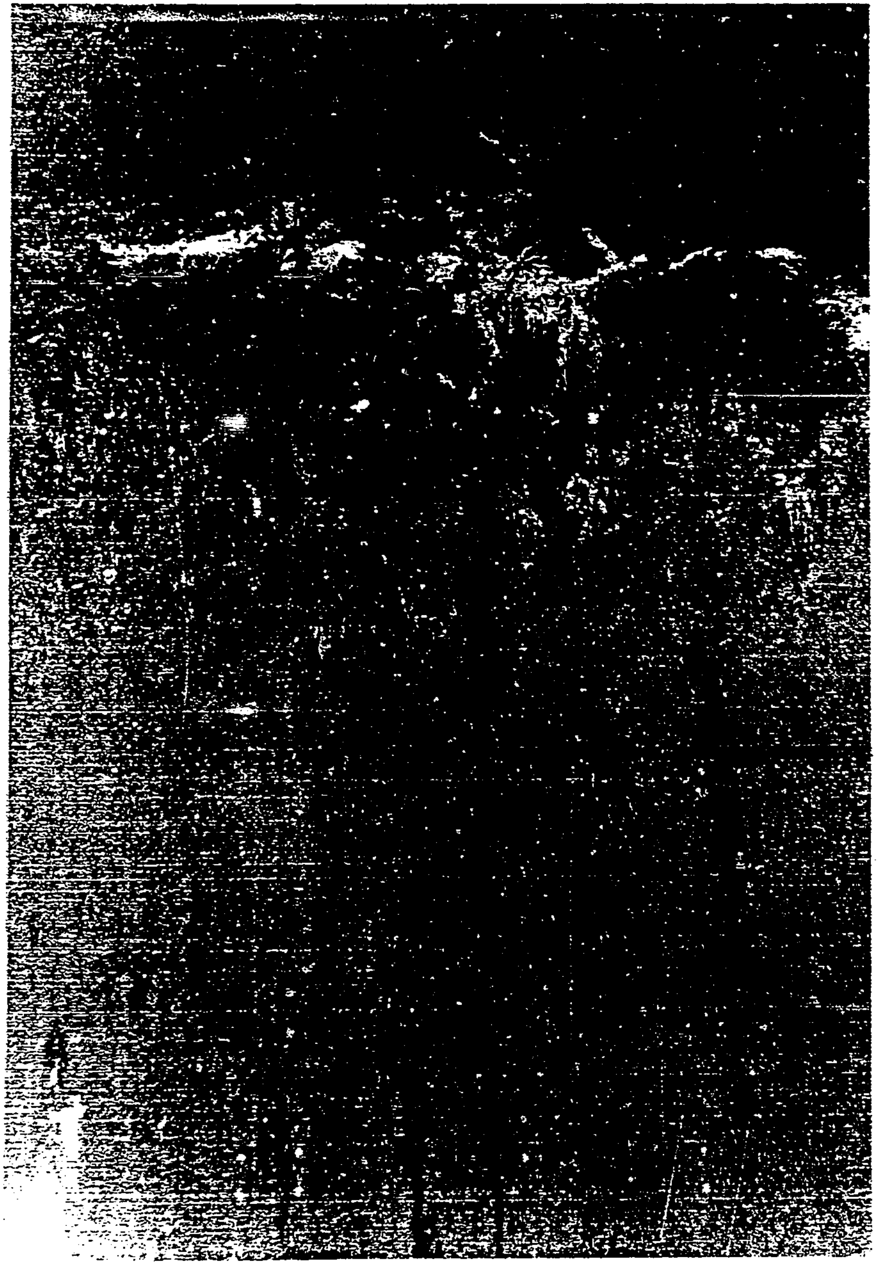


Figure 3-13. REMOTS® image from station GC-2 in Greenwich Cove showing high reflectance (i.e., very light colored) patches of bacteria on the surface of highly-reduced, low reflectance sediment. Scale = 1X.

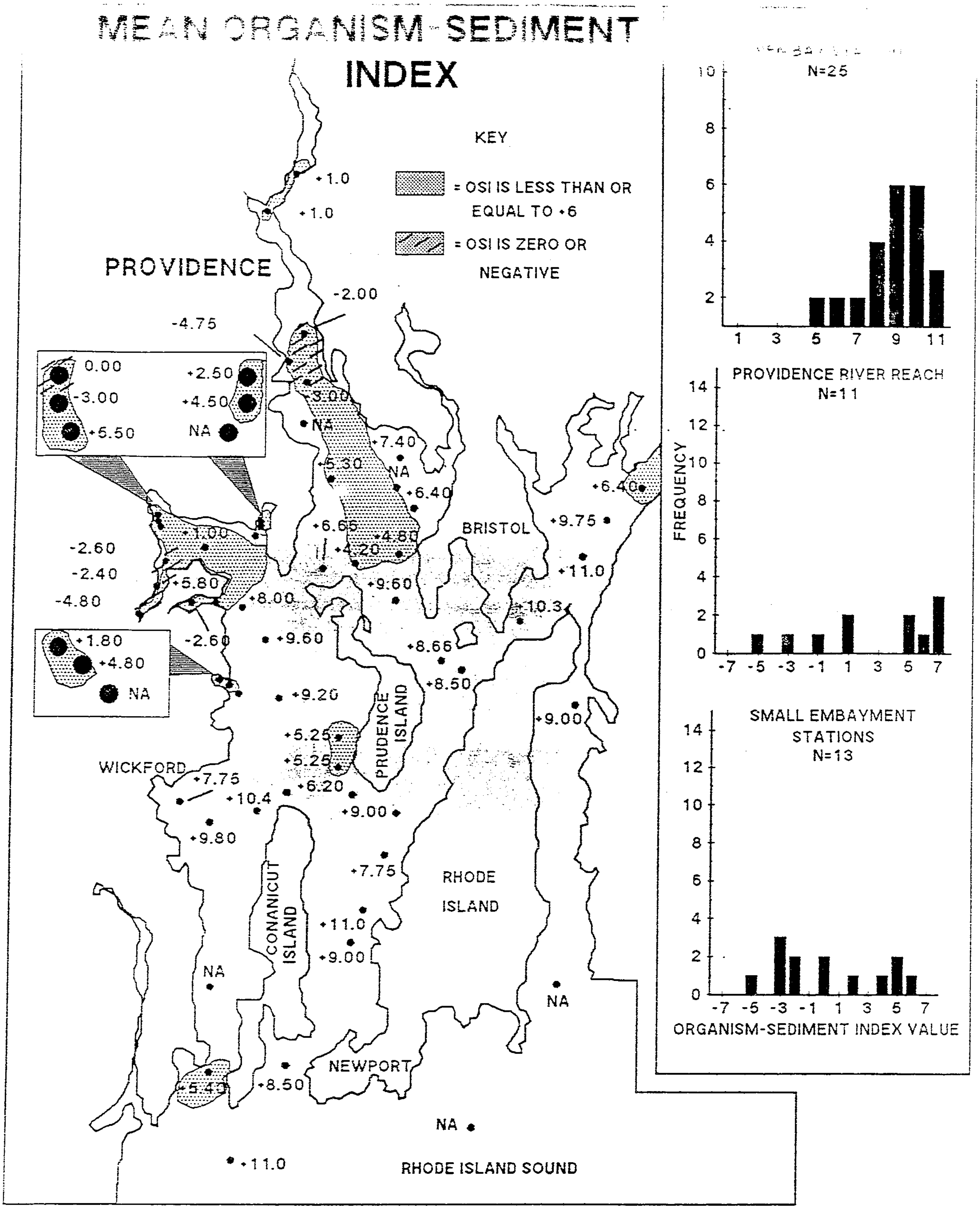


Figure 3-15. Mean Organism-Sediment Index (OSI) values calculated for the Narragansett Bay REMOTS® stations occupied in August 1988. NA (not applicable) indicates the OSI could not be calculated because inadequate prism penetration prevented the successional stage or RPD from being determined. The inset shows the frequency distributions of these values for each of the three station subsets.

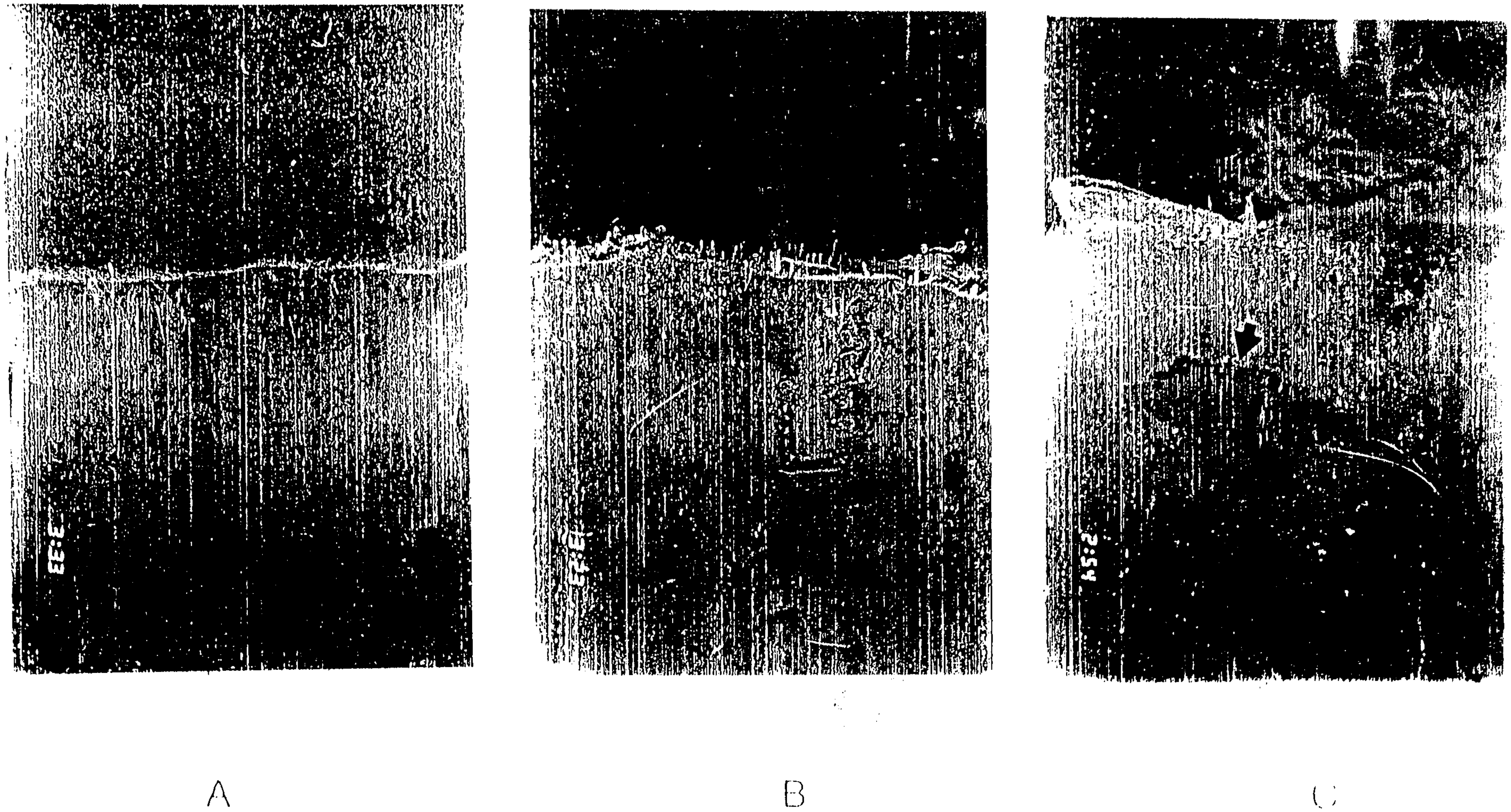


Figure 3-14. Three REMOTS® images illustrating a clinal gradient in successional seres along a transect in Mount Hope Bay. Image A shows a Stage I assemblage at station SB-17, image B from station C-6 illustrates a Stage II on III successional stage, and image C shows a partly-obscured Stage III feeding void (arrow) at station SB-18. Approximate scale of images = 0.5X.

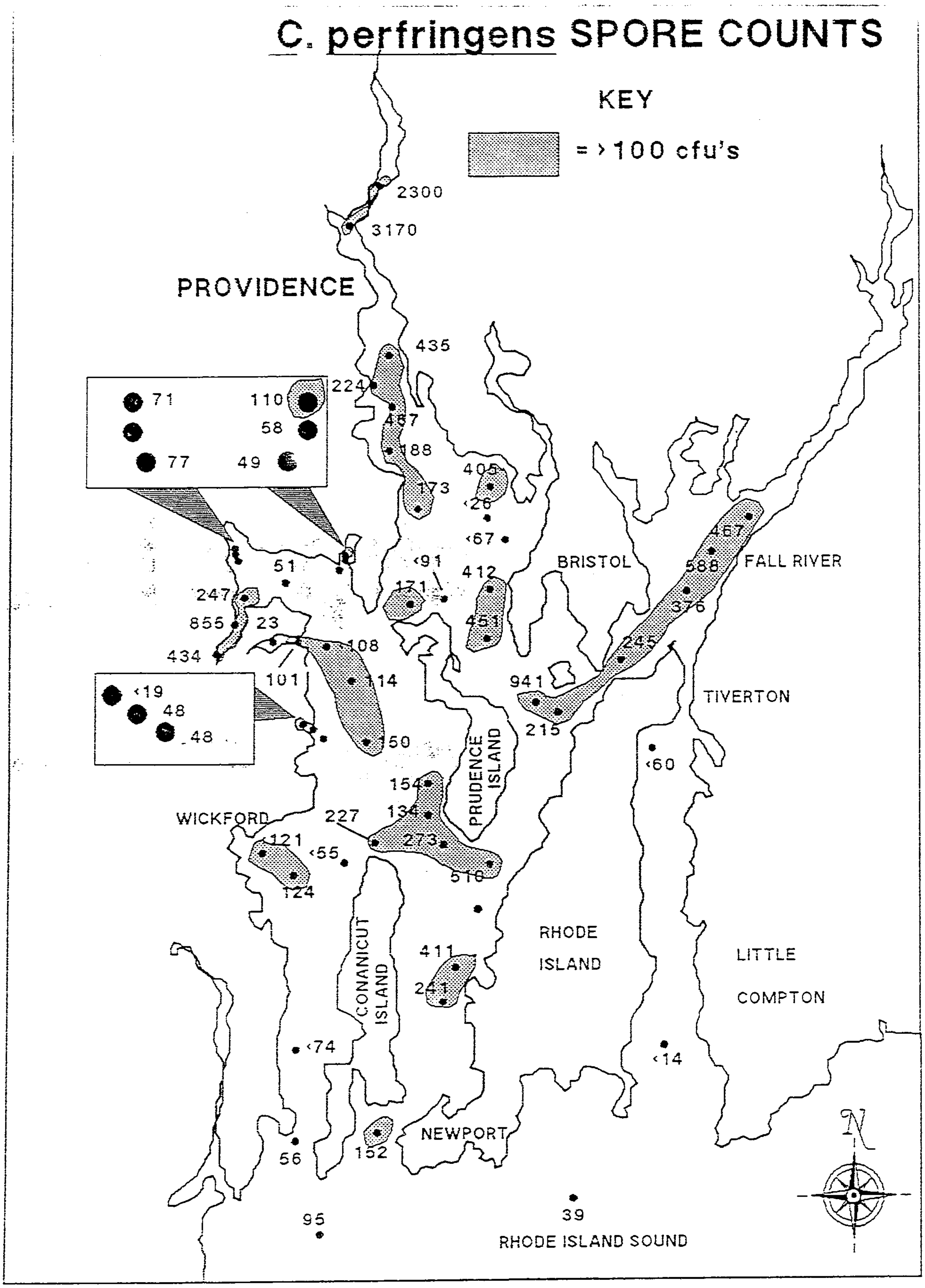
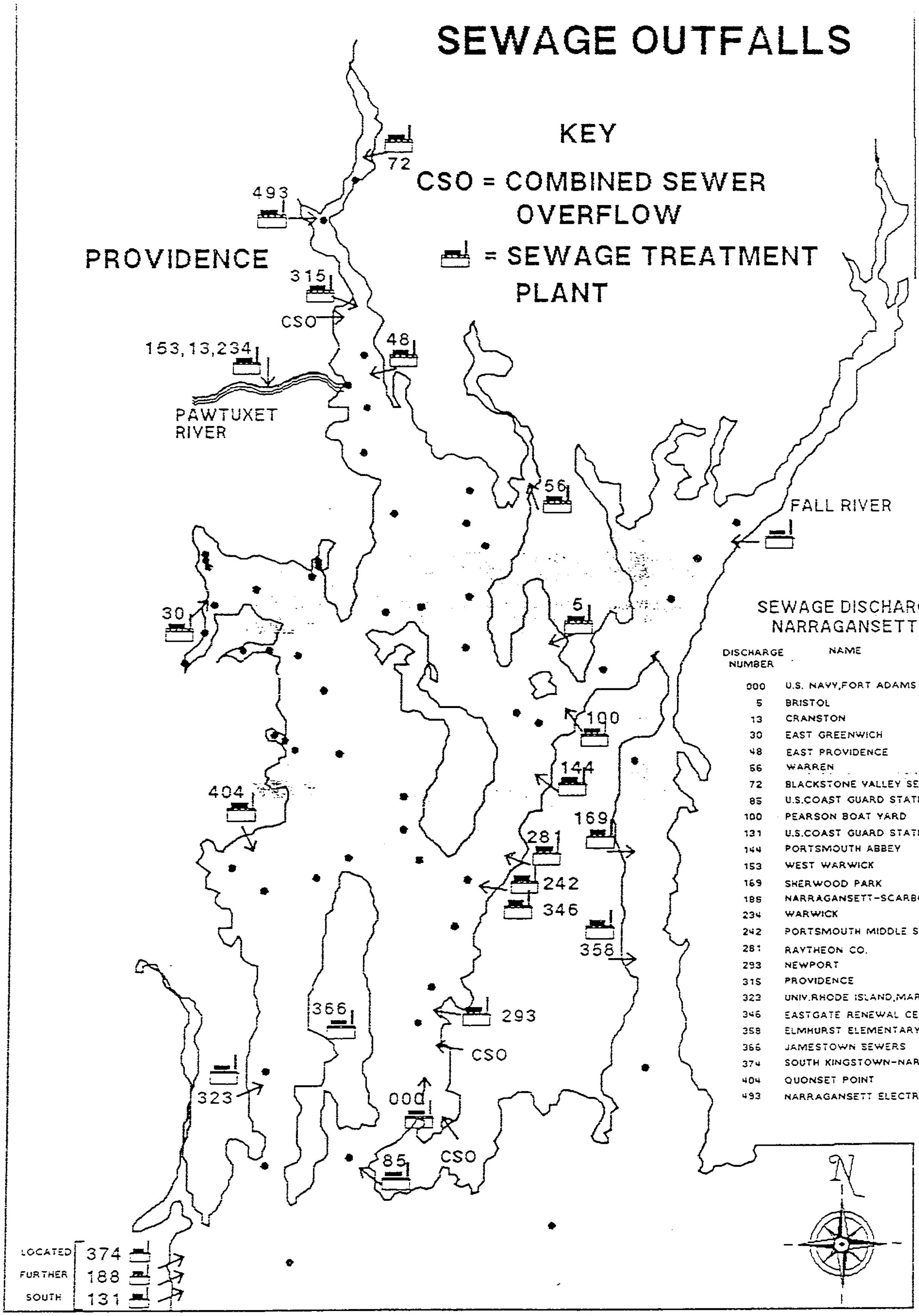


Figure 3-16. *Clostridium perfringens* spore counts at Narragansett Bay REMOTS® stations, August 1988. The spore counts are expressed as Colony Forming Units (CFU's) per gram wet weight of sediment.



SEWAGE DISCHARGES TO NARRAGANSETT BAY

DISCHARGE NUMBER	NAME
000	U.S. NAVY,FORT ADAMS
5	BRISTOL
13	CRANSTON
30	EAST GREENWICH
48	EAST PROVIDENCE
56	WARREN
72	BLACKSTONE VALLEY SEWER DIST.
85	U.S.COAST GUARD STATION,CASTLE HILL
100	PEARSON BOAT YARD
131	U.S.COAST GUARD STATION,PT. JUDITH
144	PORTSMOUTH ABBEY
153	WEST WARWICK
169	SHERWOOD PARK
185	NARRAGANSETT-SCARBOROUGH HILLS
234	WARWICK
242	PORTSMOUTH MIDDLE SCHOOL
281	RAYTHEON CO.
293	NEWPORT
315	PROVIDENCE
323	UNIV.RHODE ISLAND,MARINE CAMPUS
346	EASTGATE RENEWAL CENTER
358	ELMHURST ELEMENTARY SCHOOL
366	JAMESTOWN SEWERS
374	SOUTH KINGSTOWN-NARRAGANSETT
404	QUONSET POINT
493	NARRAGANSETT ELECTRIC CO.

Figure 3-17. Locations and designations of outfalls for sewage treatment plants (STP's) and combined sewer overflows (CSO's) in Narragansett Bay.

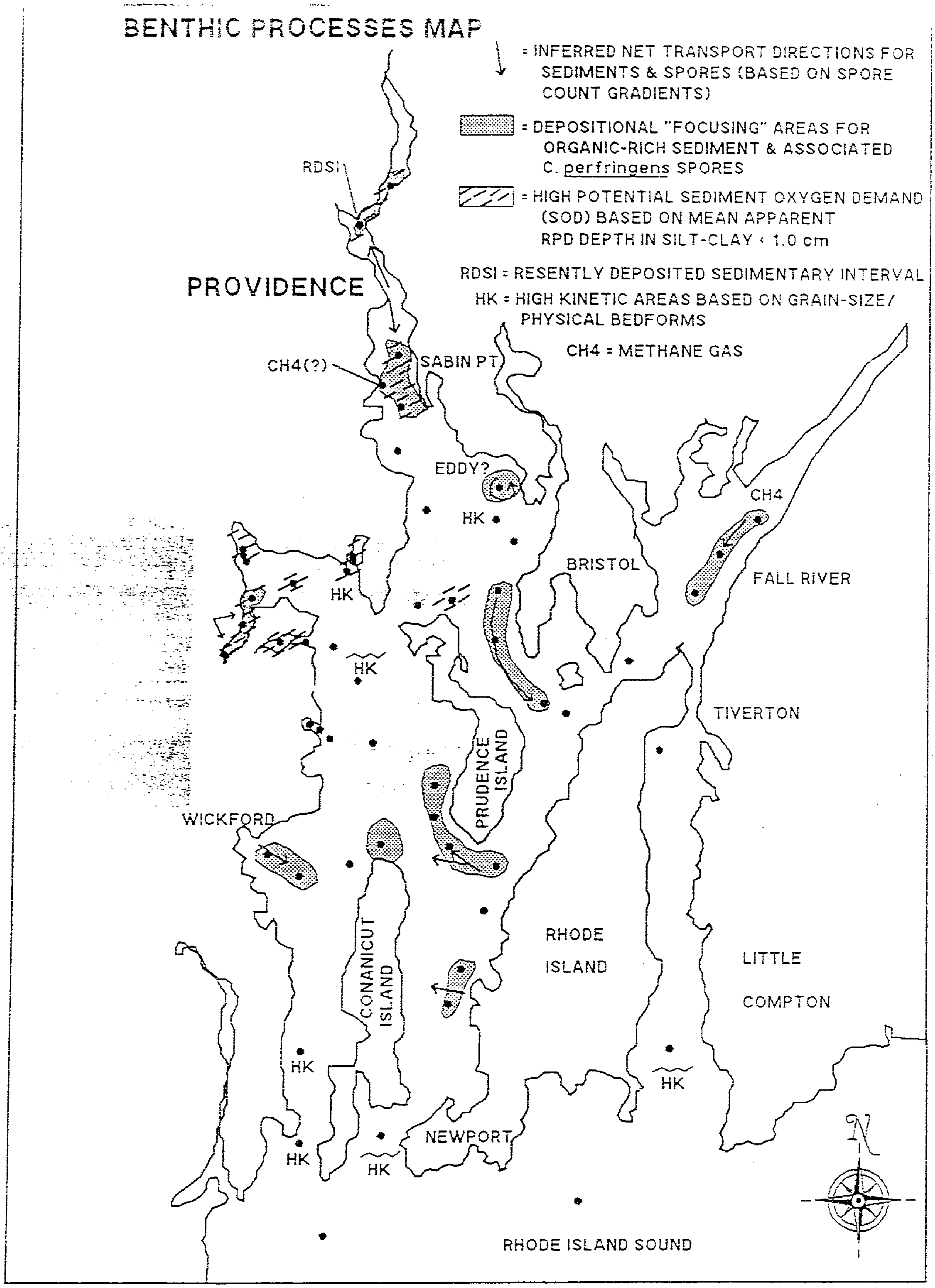


Figure 3-18. Benthic "processes" map for the Narragansett Bay REMOTS® stations occupied in August 1988.

Scatter Plot of Narragansett Bay Stations:

REMOTS OSI Values vs. C. perfringens Counts

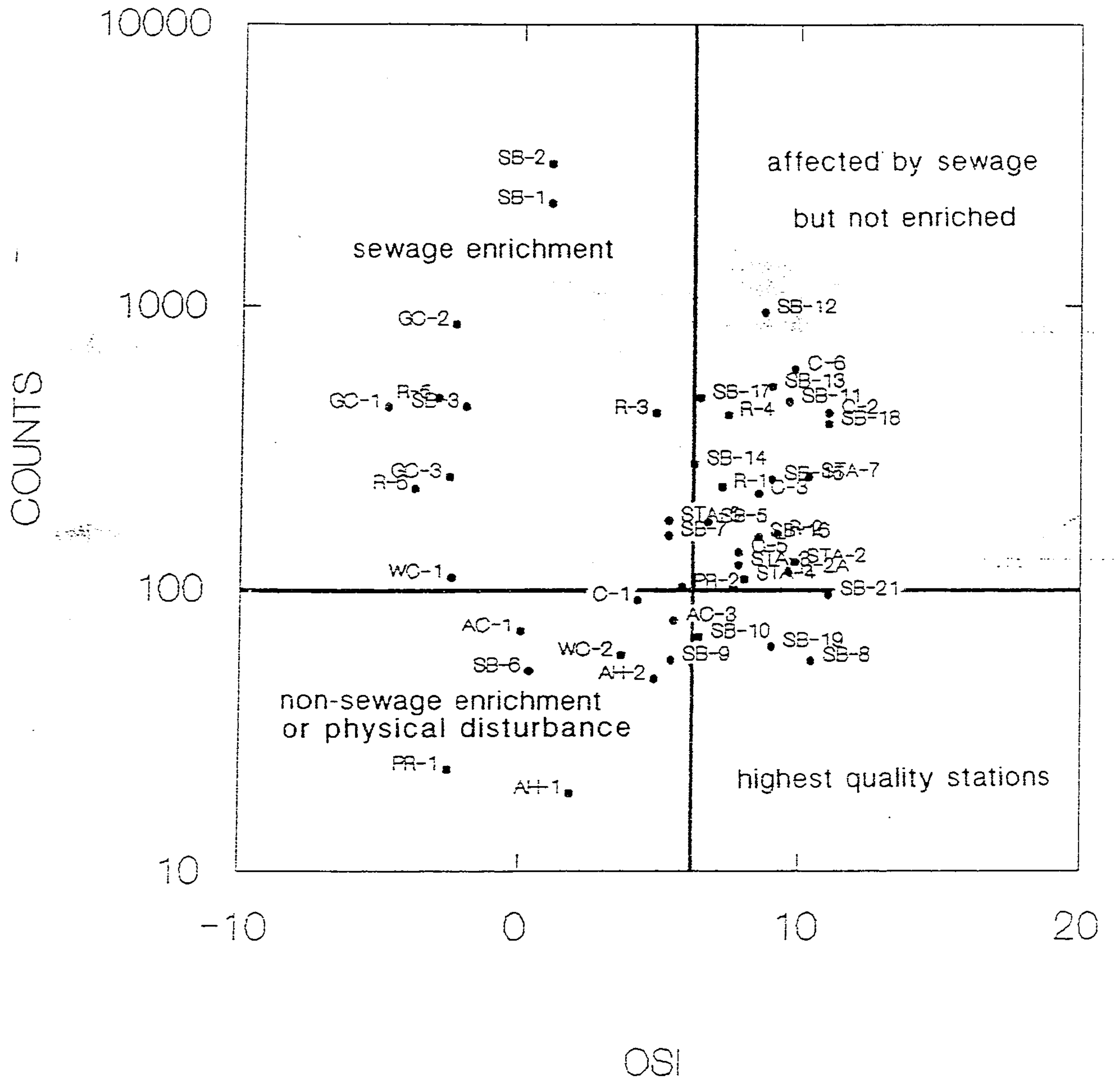


Figure 3-19. Two-dimensional scatter plot of station locations based on REMOTS® OSI values and C. perfringens spore counts.

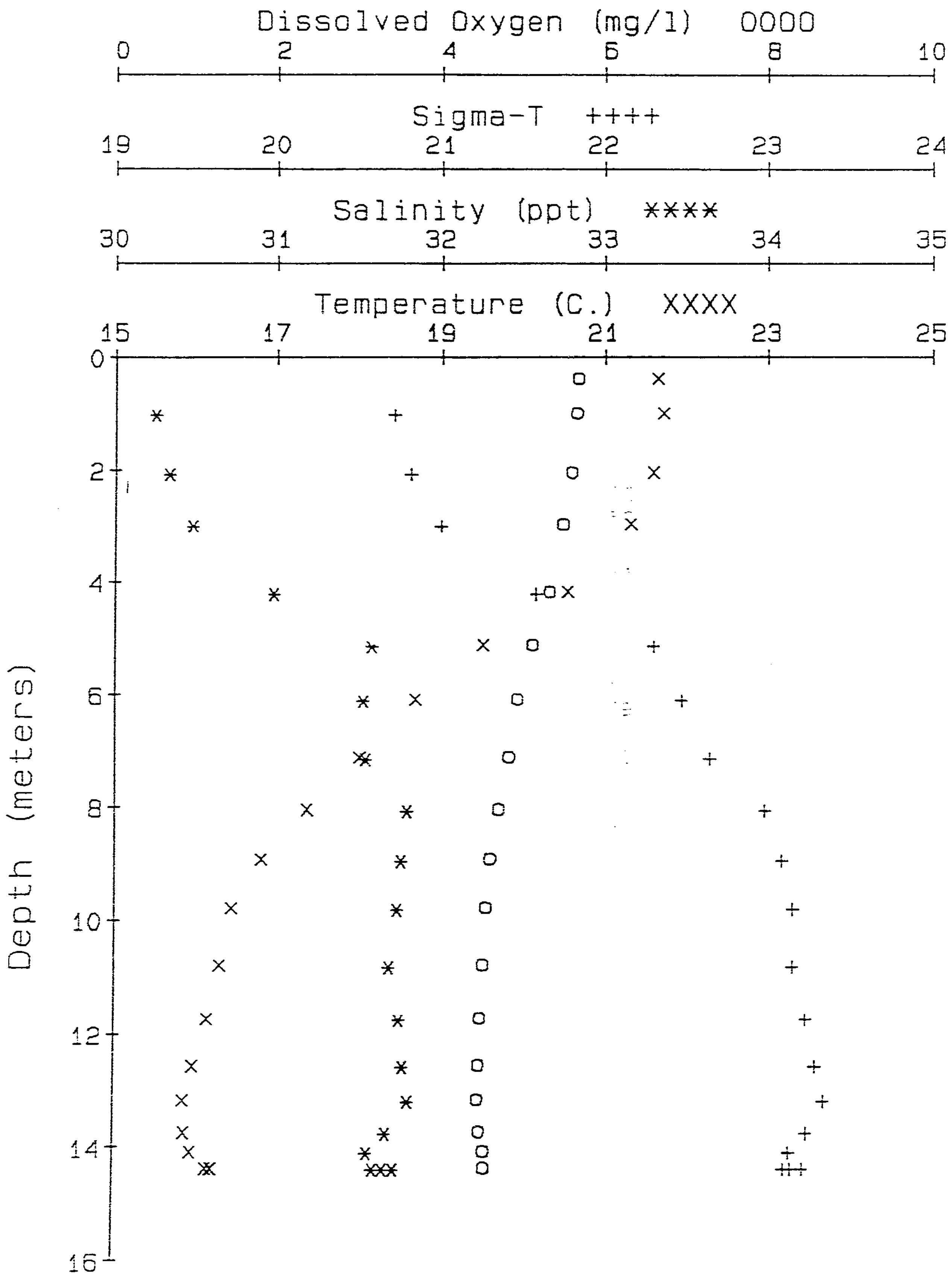
Lab No.	Sample Collection Date	Time	Station	Replicate	Sample Weight	Spores per gram of sediment (wet weight)
34	8/15	1800	4	2	0.48	125
35				3	0.41	146
36				1	0.58	<52
37	8/16	0945	SB-5	1	0.62	194
38				3	0.62	97
39				2	0.54	222
40	8/17	1015	GC-2	1	0.47	957
41				2	0.52	808
42				3	0.45	800
43	8/17	1000	GC-1	2	0.58	621
44				3	0.45	400
45				1	0.64	281
46	8/18	1520	C-6	1	0.47	638
47				2	0.48	688
48				3	0.41	439
49	8/18	1450	SB-18	1	0.64	516
50				3	0.61	393
51				2	0.41	220
52	8/18	1725	SB-19	3	0.50	<60
53				1	0.58	<52
54				2	0.40	<75
55	8/15	1511	R-1	2	0.52	462
56				1	0.57	158
57				3	0.49	61
58	8/18	1530	SB-17	1	0.41	293
59				2	0.43	907
60				3	0.45	200
61	8/16	1158	5	1	0.51	235
62				2	0.54	111
63				3	0.52	173
64	8/17	1800	AC-3	2	0.60	50
65				3	0.58	52
66				1	0.70	129
67	8/17	1300	AC-1	2	0.40	117
68				1	0.52	26
69				3	0.58	69

APPENDIX III

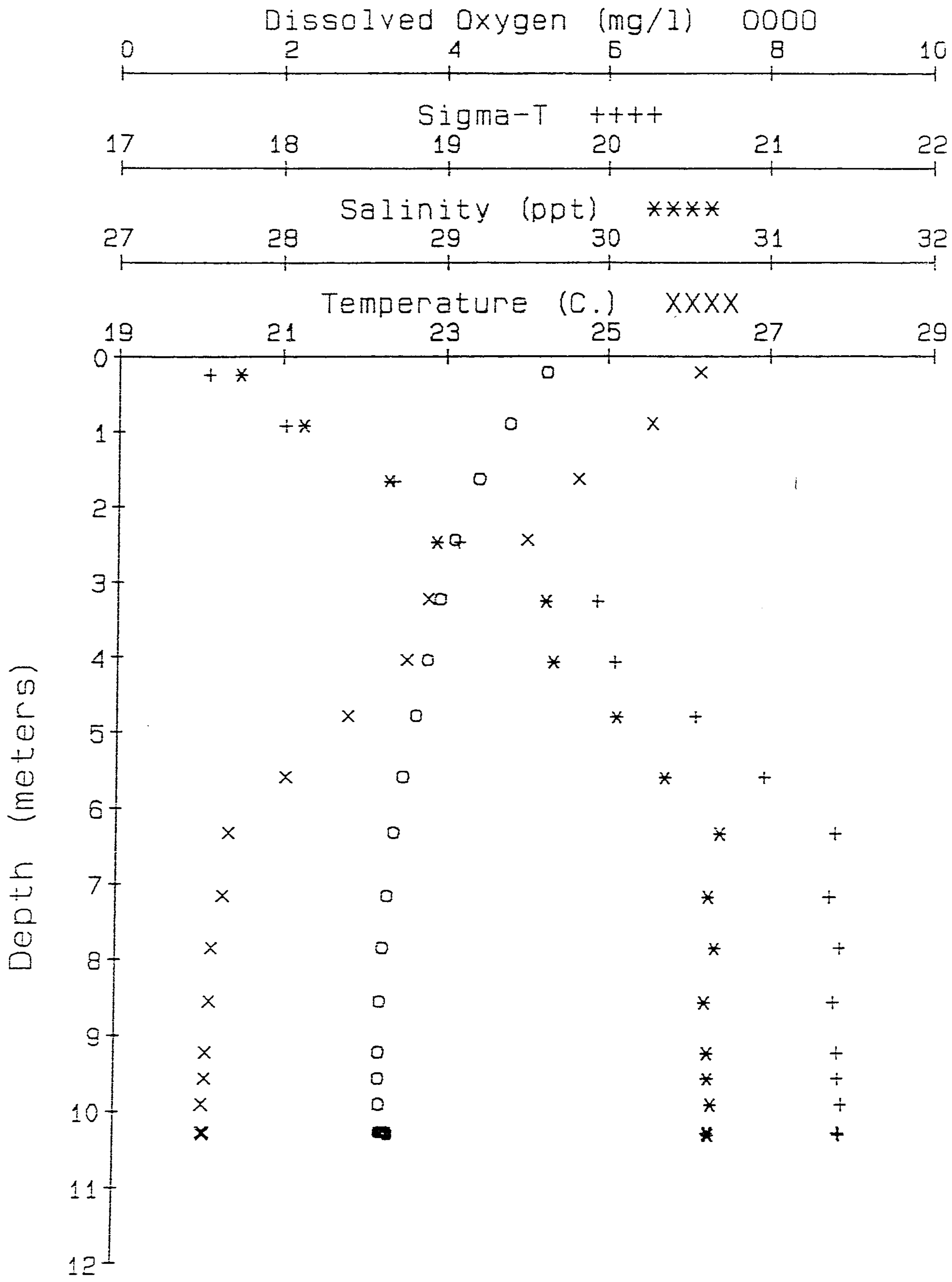
Results of analyses for *C. perfringens* spores in sediment samples collected during the August 1988 REMOTS survey of Narragansett Bay (n = 3 replicates per sample).

	Sample Collection				Sample	Spores per gram of
Lab No.	Date	Time	Station	Replicate	Weight	sediment (wet weight)
1	8/15	1600	SB-14	2	0.51	117
2				3	0.62	290
3				1	0.51	411
4	8/15	1655	SB-7	3	0.50	180
5				2	0.54	222
6				1	0.51	59
7	8/15	1717	R-2	2	0.49	184
8				3	0.51	59
9				1	0.58	207
10	8/19	1215	SB-8	1	0.60	50
11				3	0.51	59
12				2	0.53	<57
13	8/19	1130	1	3	0.51	118
14				2	0.65	<46
15				1	0.51	<59
16	8/16	1215	6	1	0.58	17
17				2	0.49	41
18				3	0.47	<21
19	8/16	1515	SB-1	3	0.52	2000
20				1	0.51	2200
21				2	0.52	2700
22	8/15	1444	3	1	0.52	<58
23				3	0.49	244
24				2	0.50	<60
25	8/15	1357	2	1	0.50	120
26				3	0.61	98
27				2	0.59	153
28	8/15	1612	C-5	2	0.54	167
29				3	0.52	115
30				1	0.50	120
31	8/15	1740	R-2A	2	0.77	117
32				3	0.52	115
33				1	0.54	111

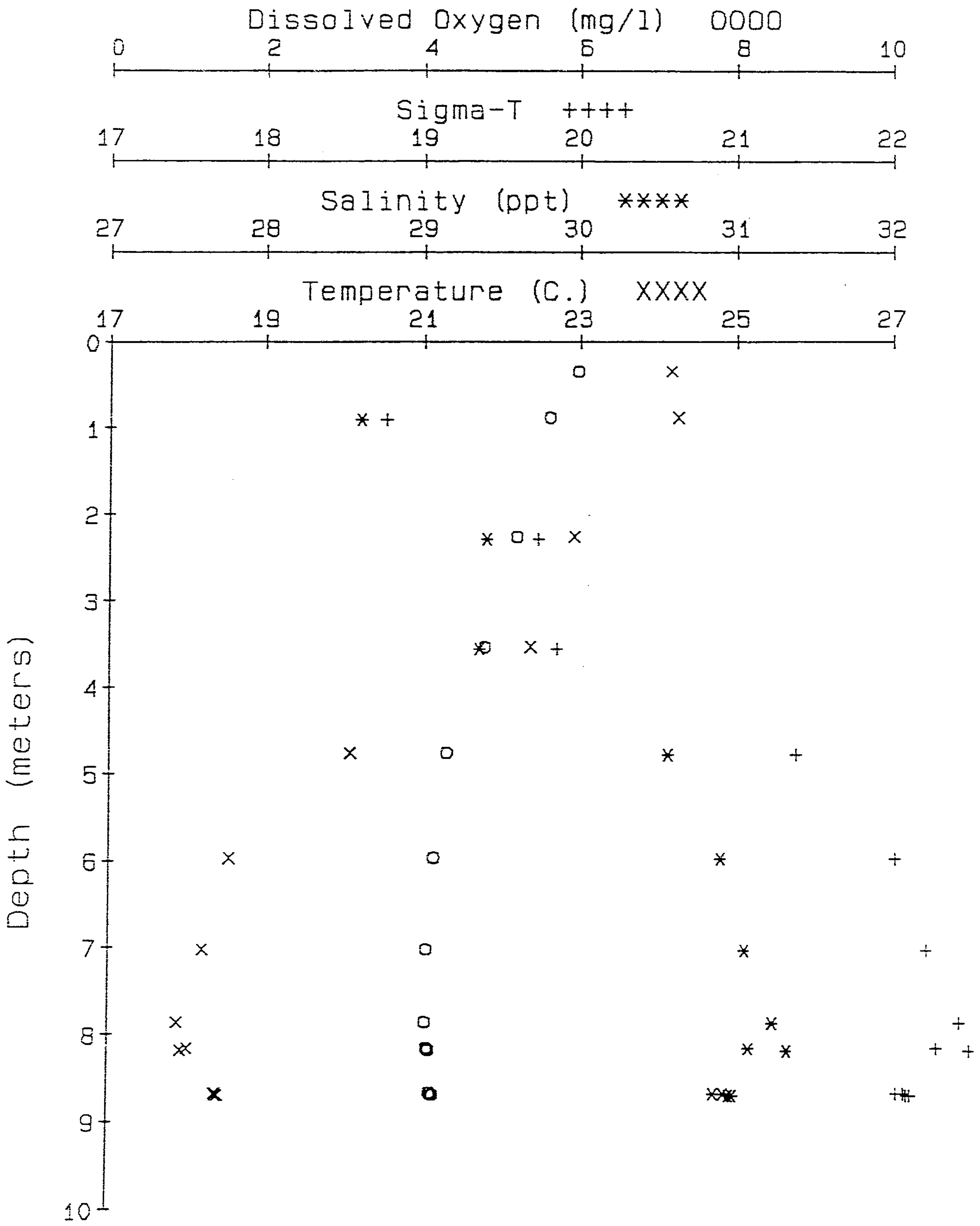
Station MF


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
19
20
21
22
23
24
Salinity (ppt) ****
30
31
32
33
34
35
Temperature (C.) XXXX
15
17
19
21
23
25
Depth (meters)
0
2
4
6
8
10
12
14
16

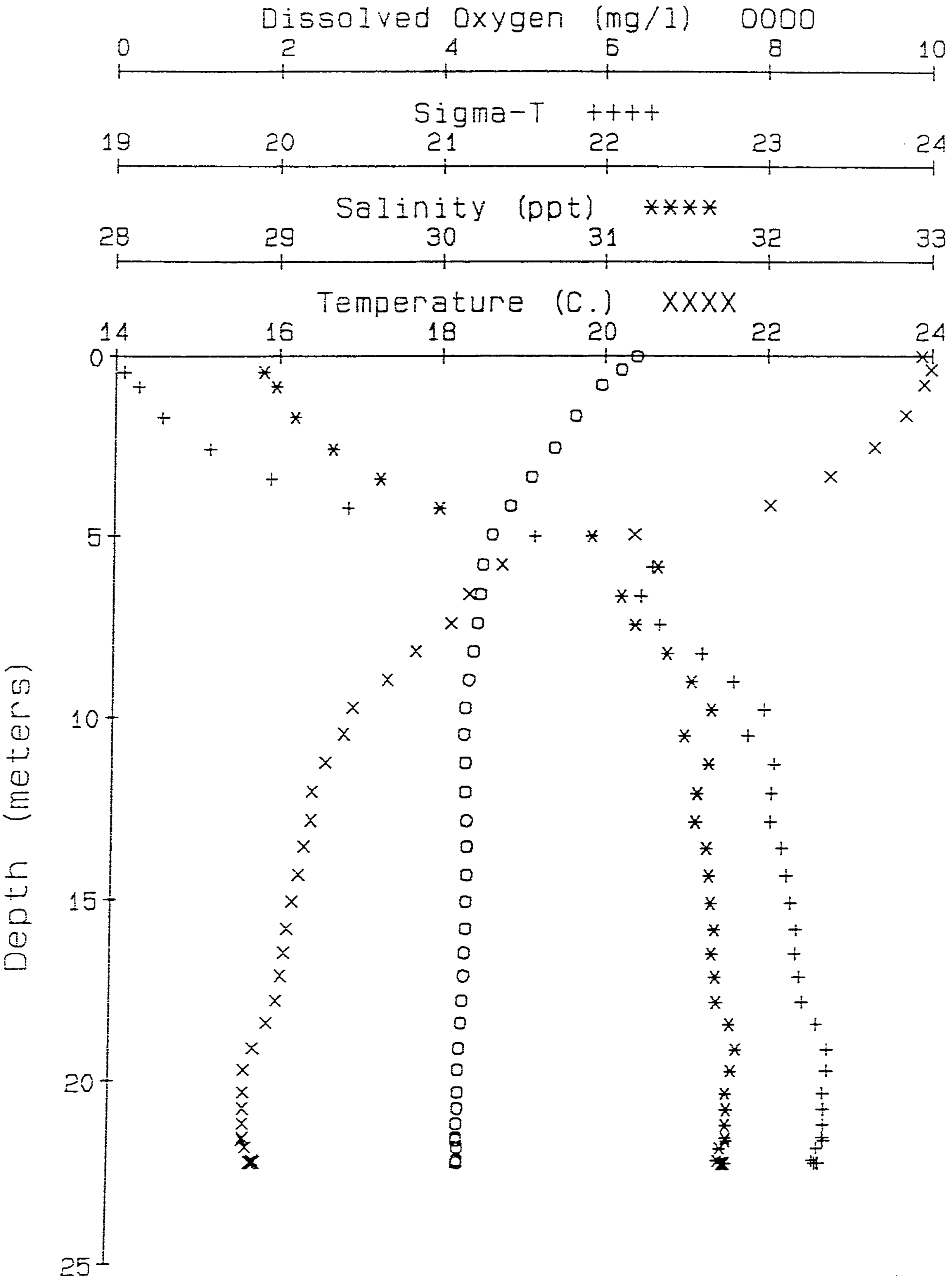
Station Sb17



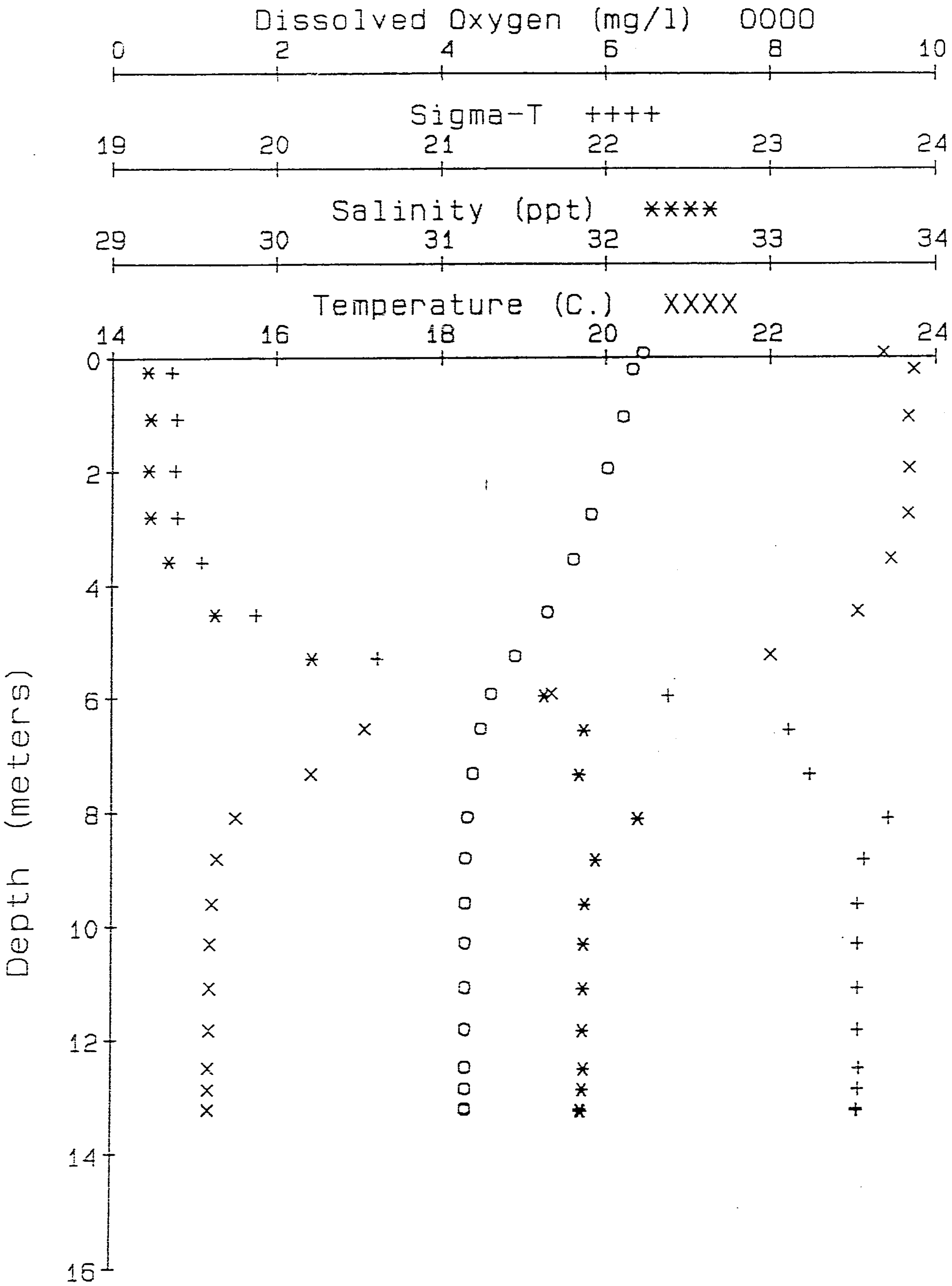
Station SB18



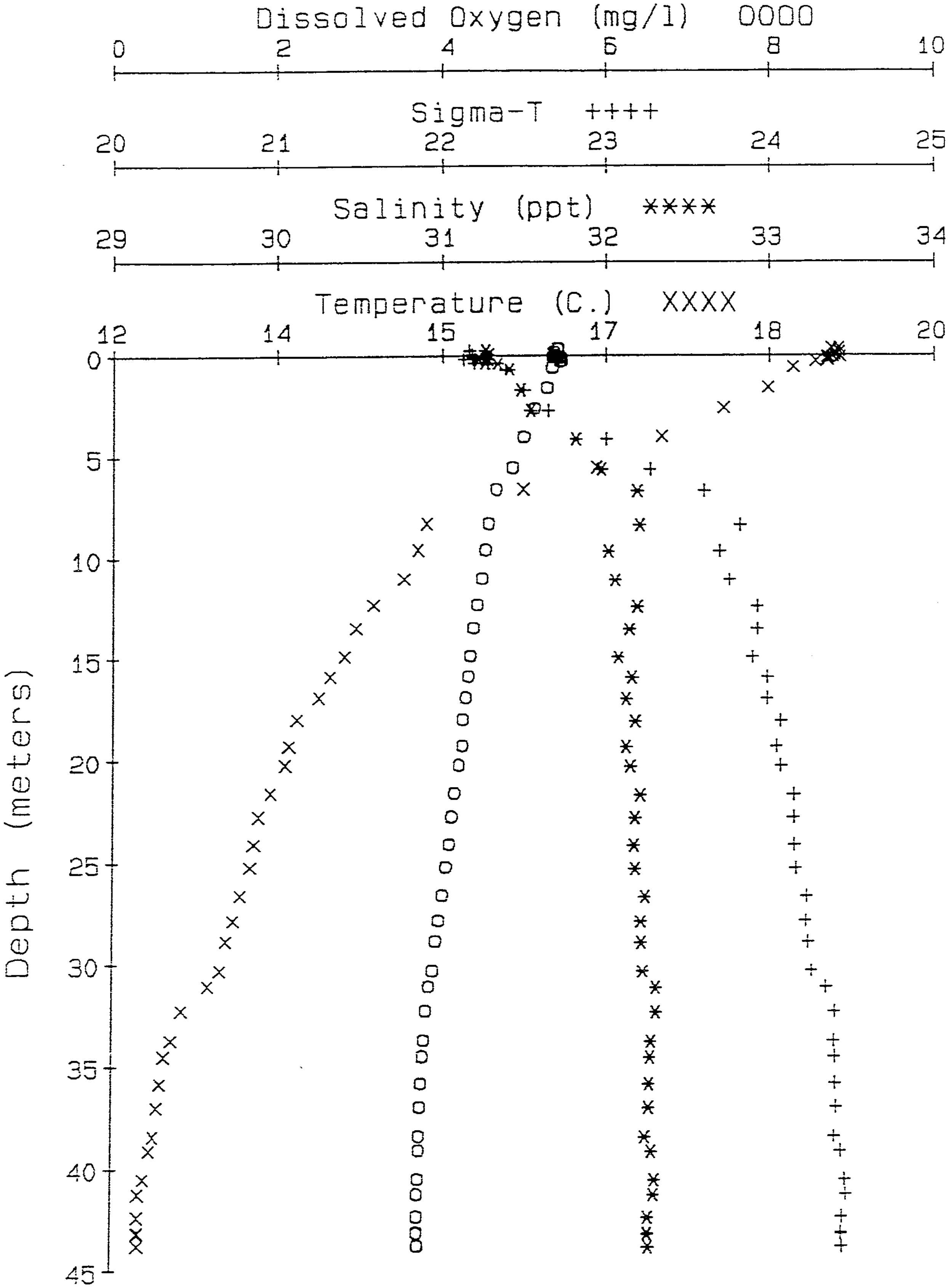
Station SB12

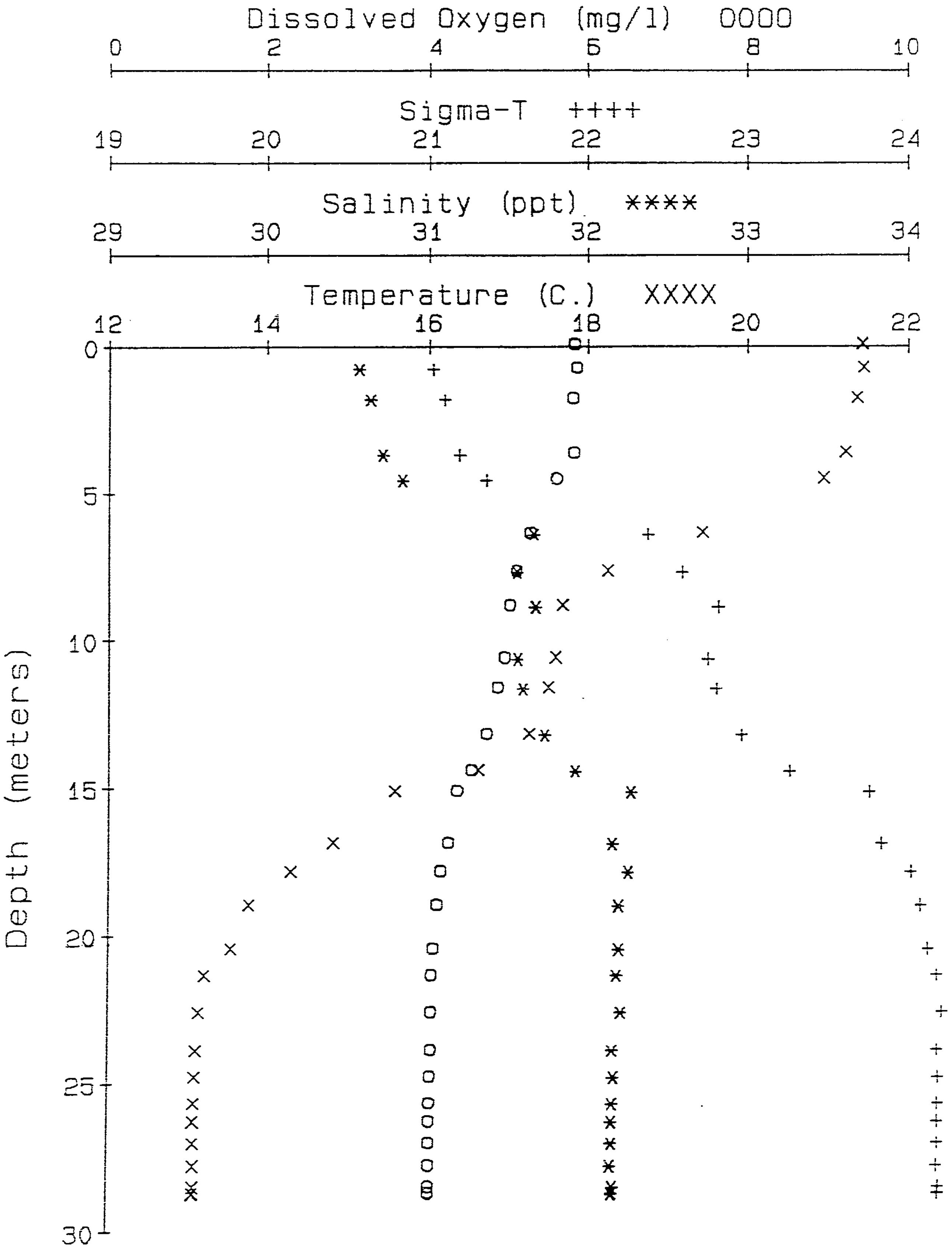


Station SB11



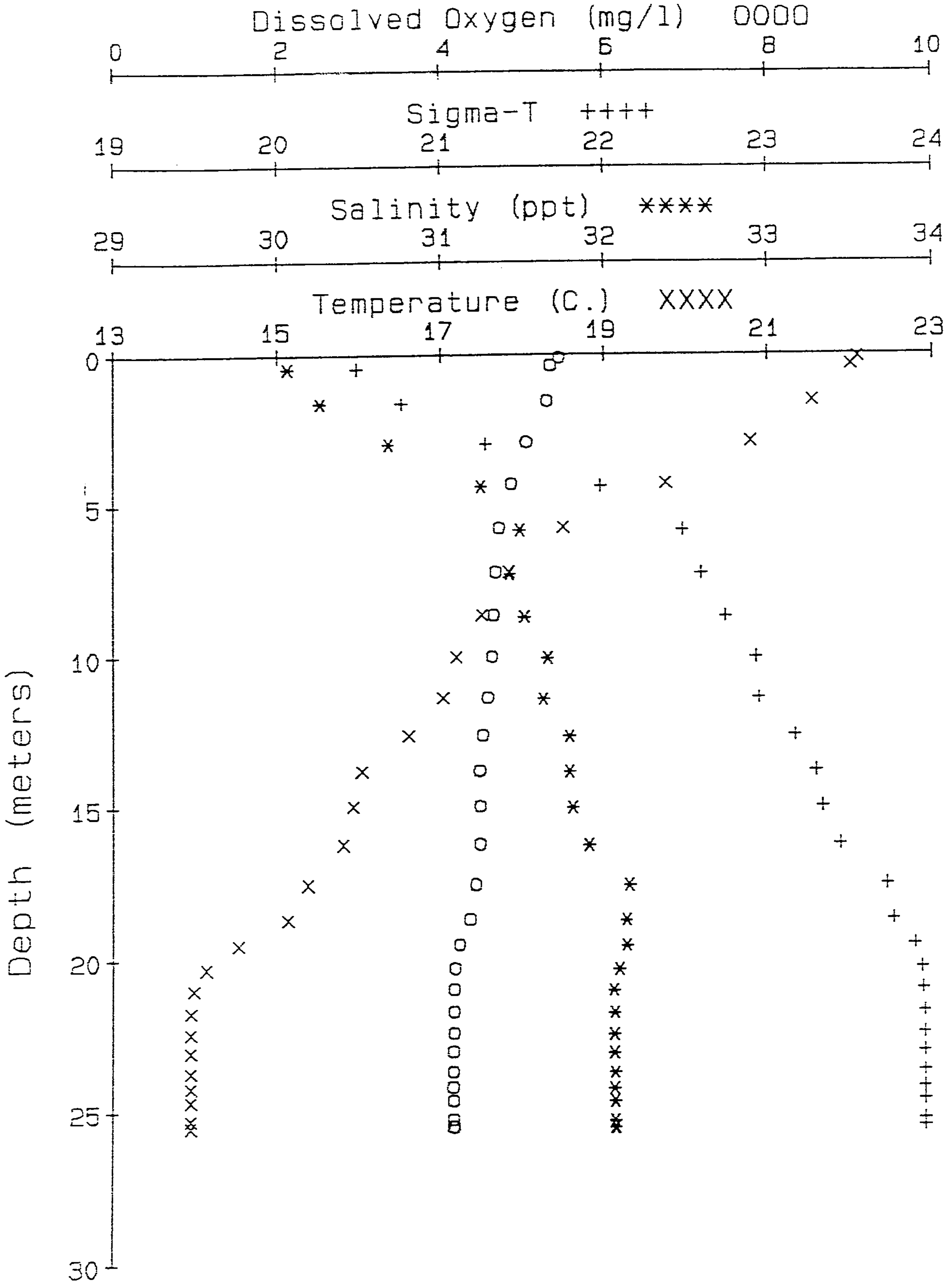
Station SB16



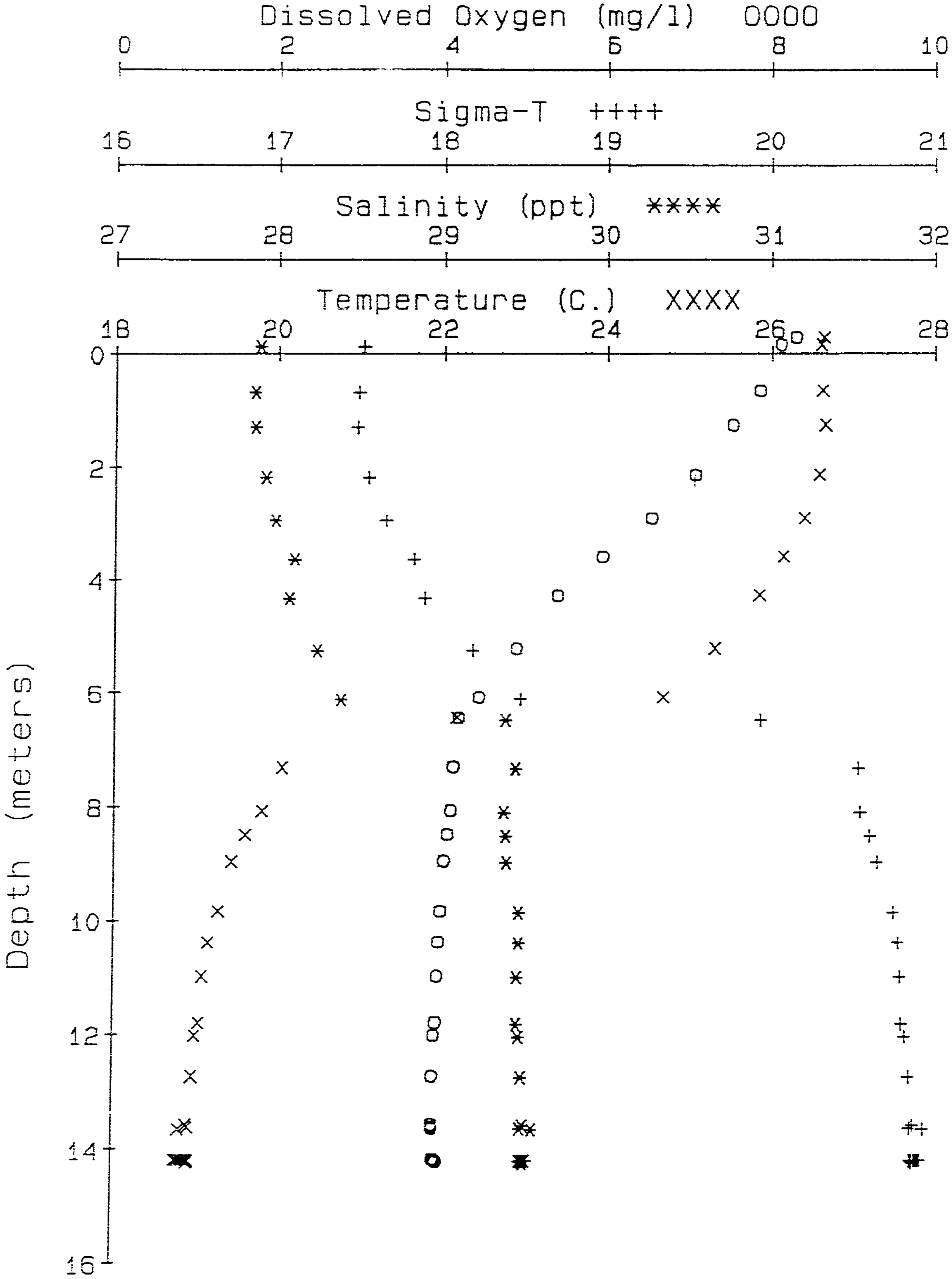


Station SB15

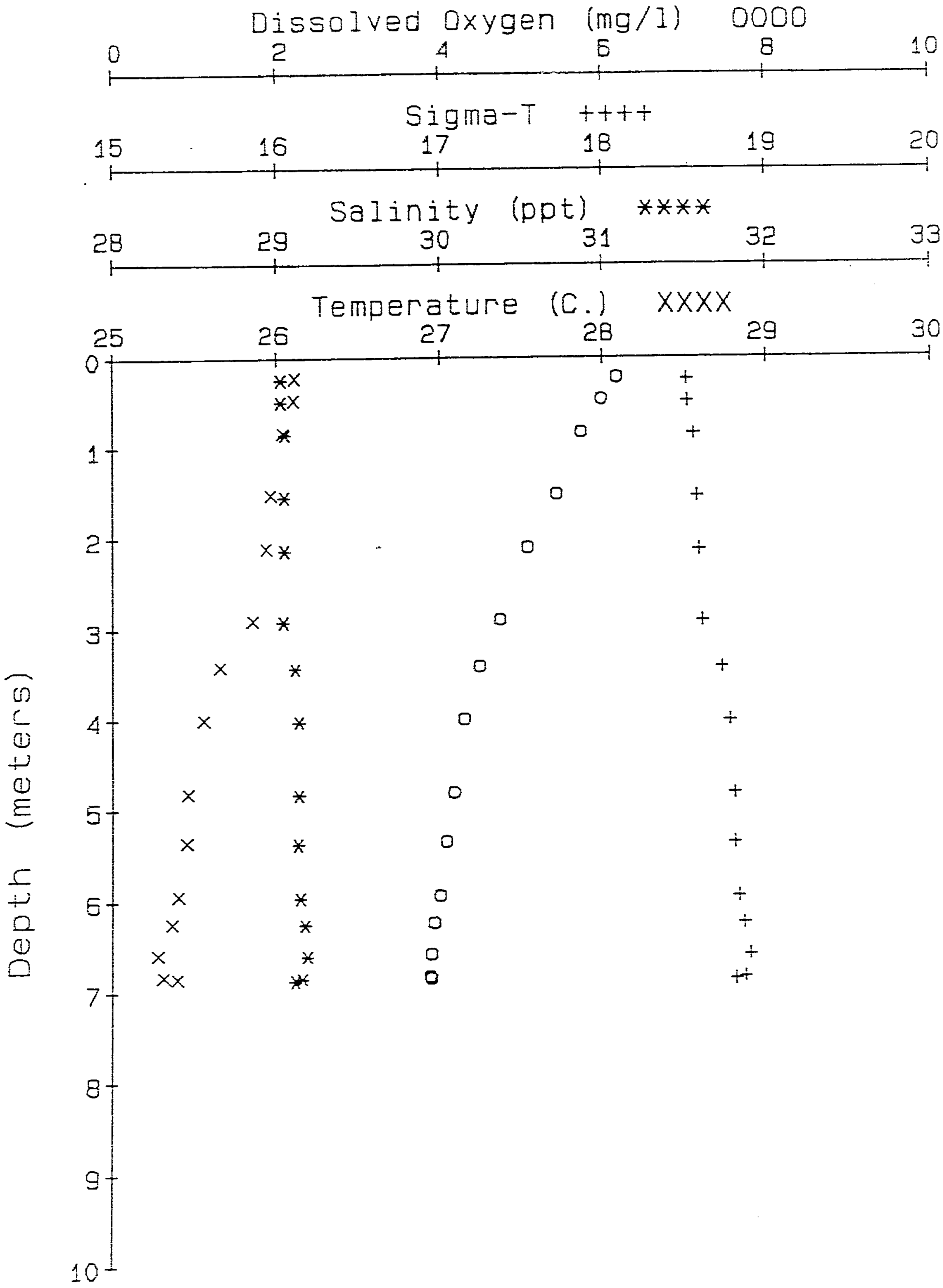
Station S513



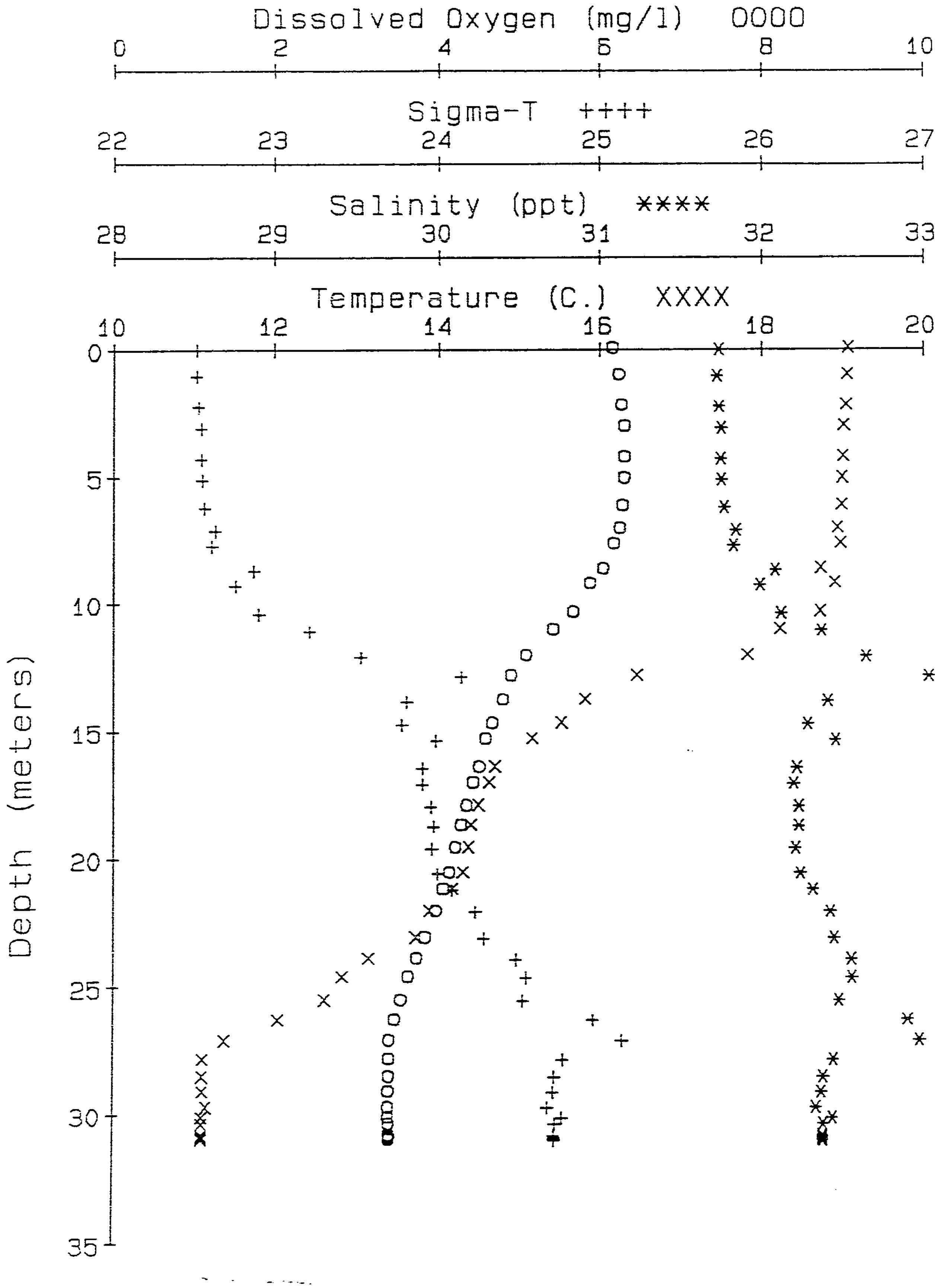
Station SB14



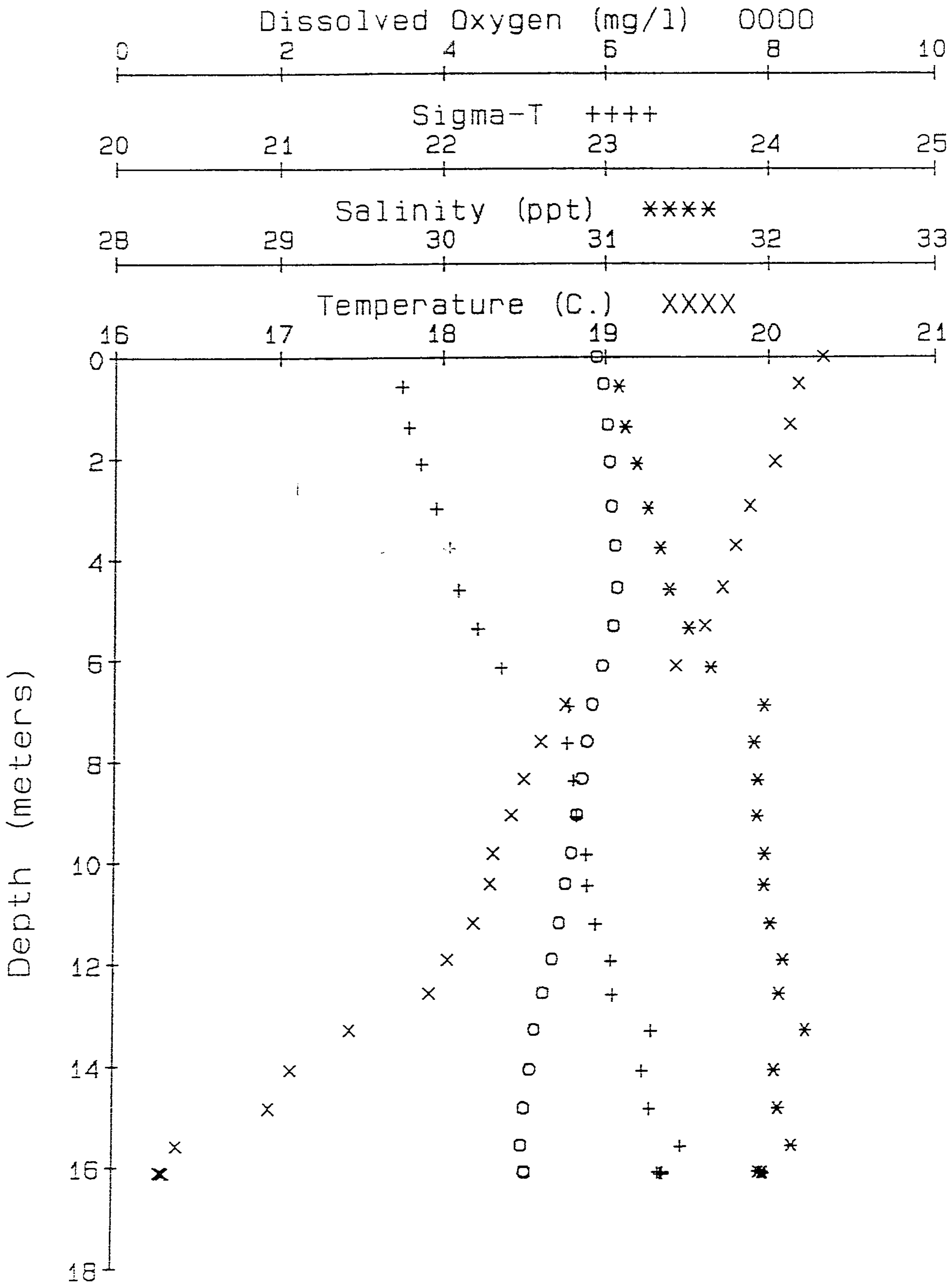
Station SB7

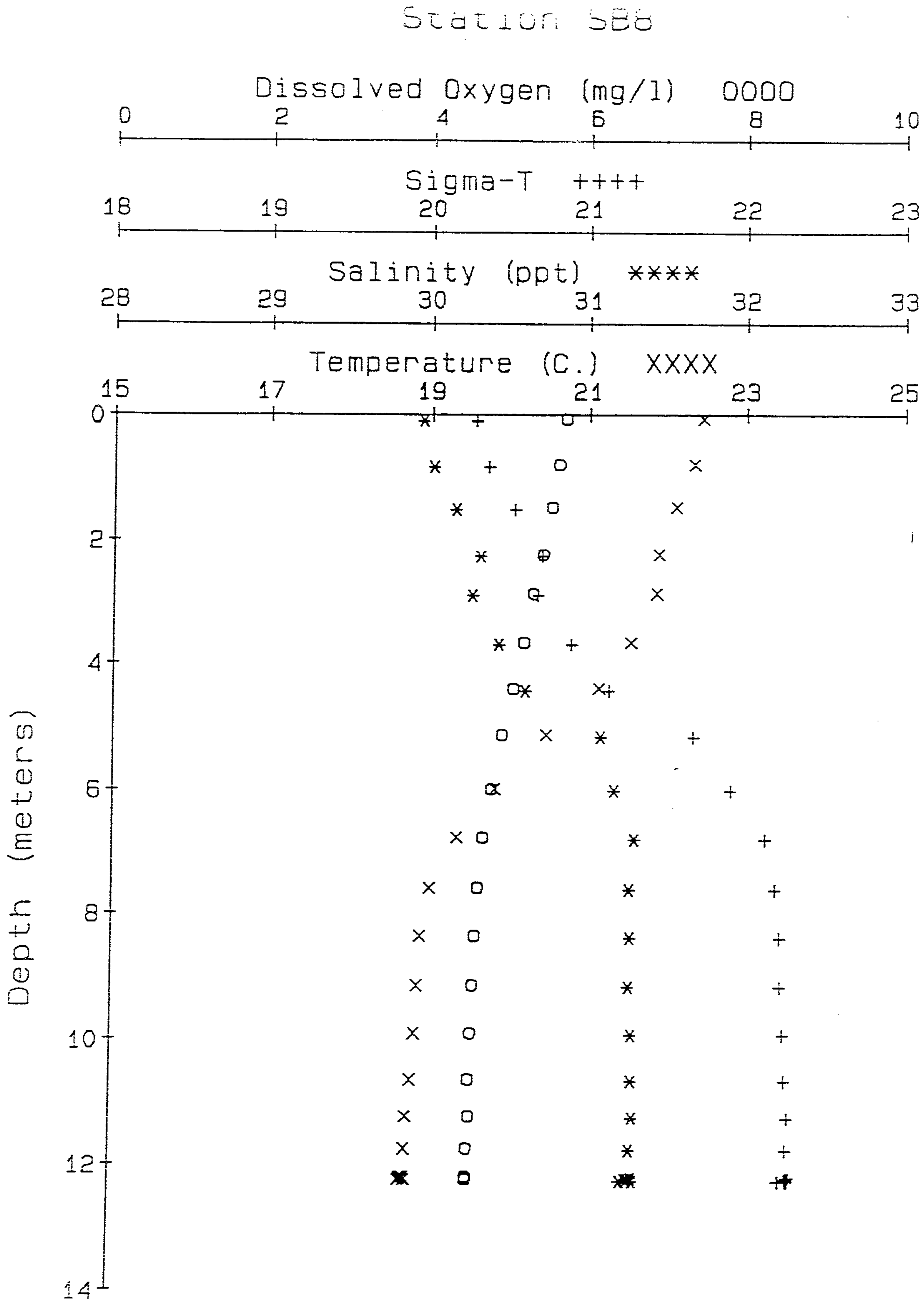

Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station SB21



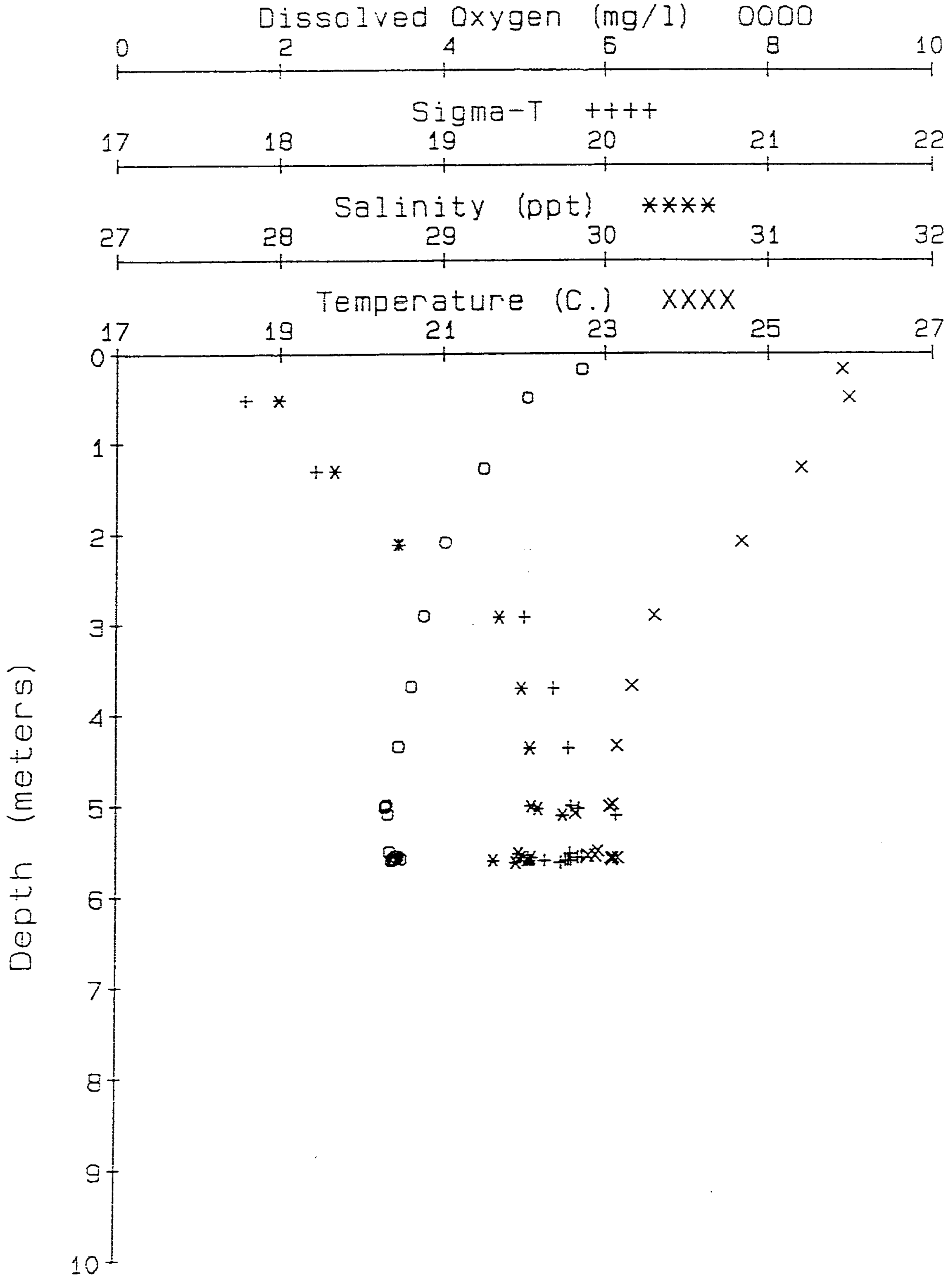
Station SB9


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
20
21
22
23
24
25
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
16
17
18
19
20
21
Depth (meters)
0
2
4
6
8
10
12
14
16
18

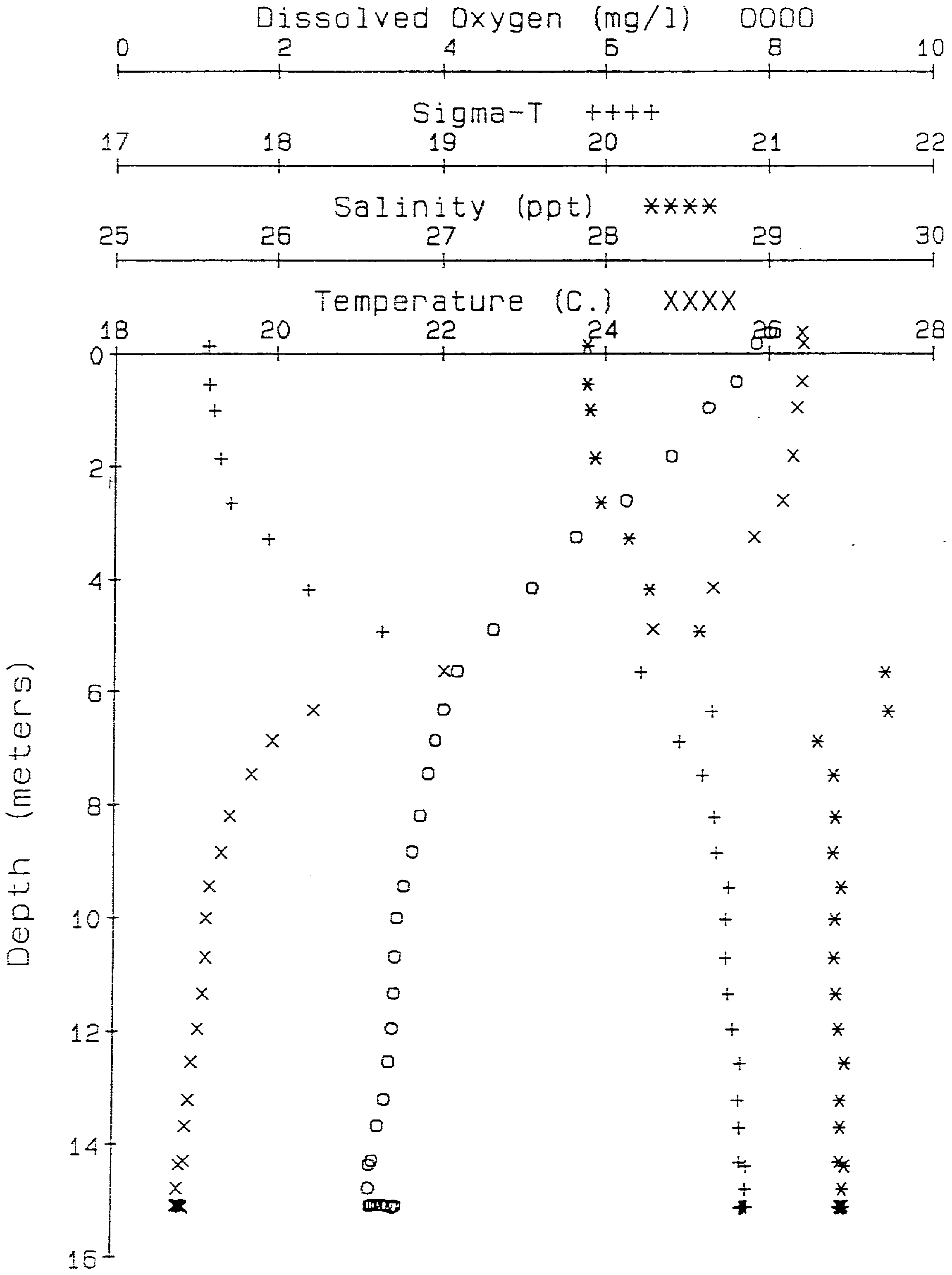


Station SB8
Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
18
19
20
21
22
23
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
15
17
19
21
23
25
Depth (meters)
0
2
4
6
8
10
12
14

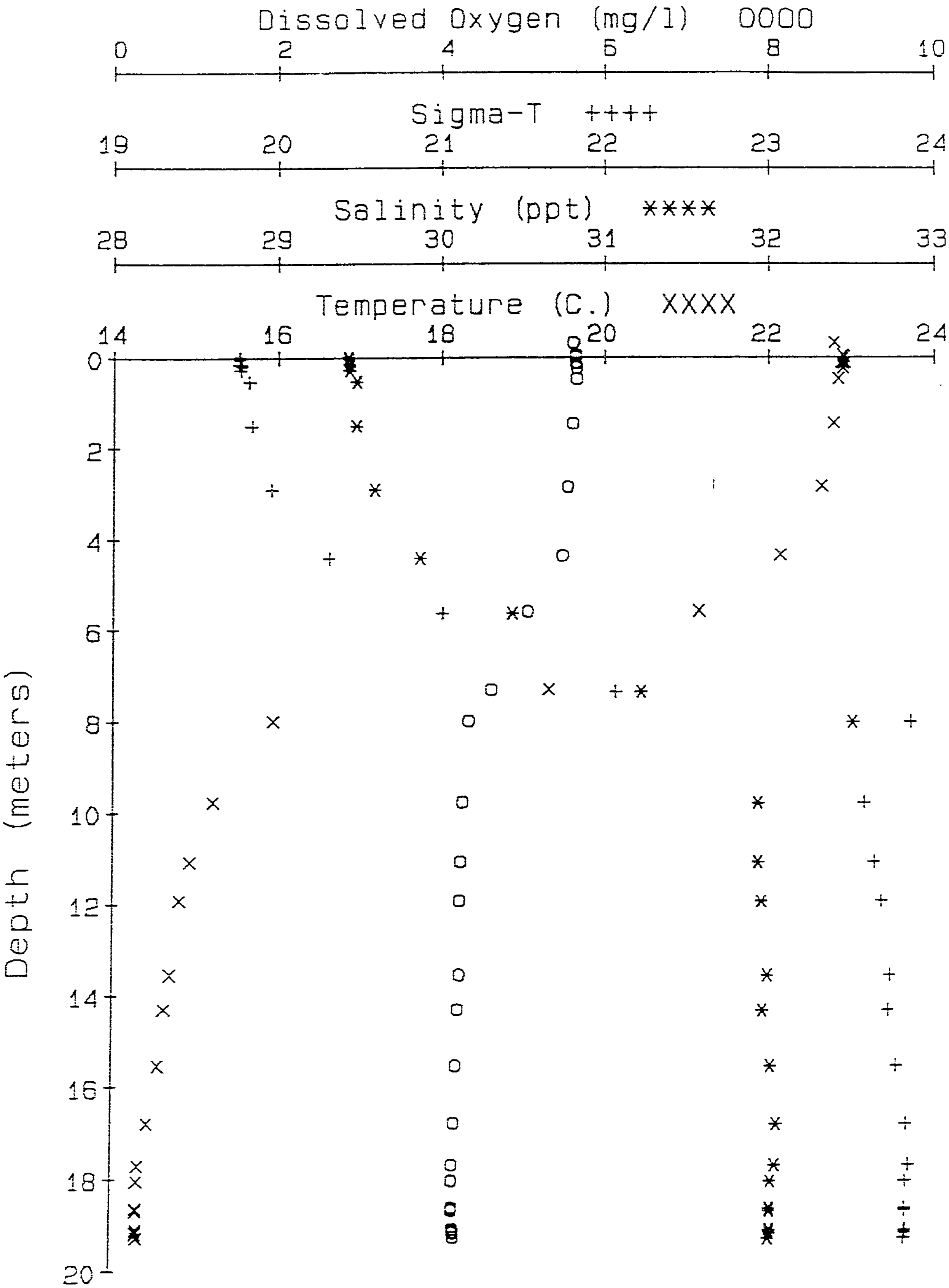
Station C-6


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
27
28
29
30
31
32
Temperature (C.) XXXX
17
19
21
23
25
27
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

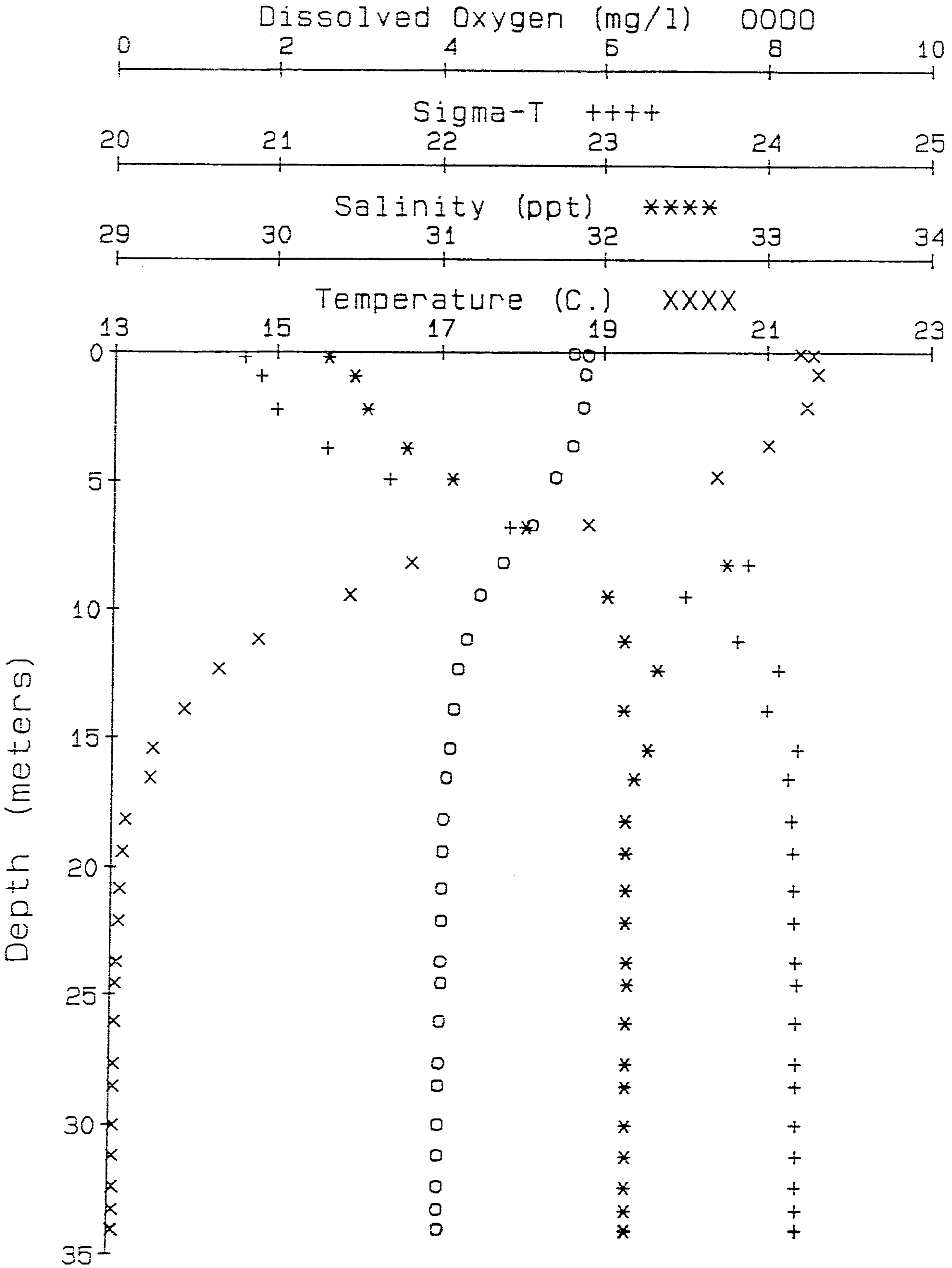
Station C-5


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
18
20
22
24
26
28
Depth (meters)
0
2
4
6
8
10
12
14
16

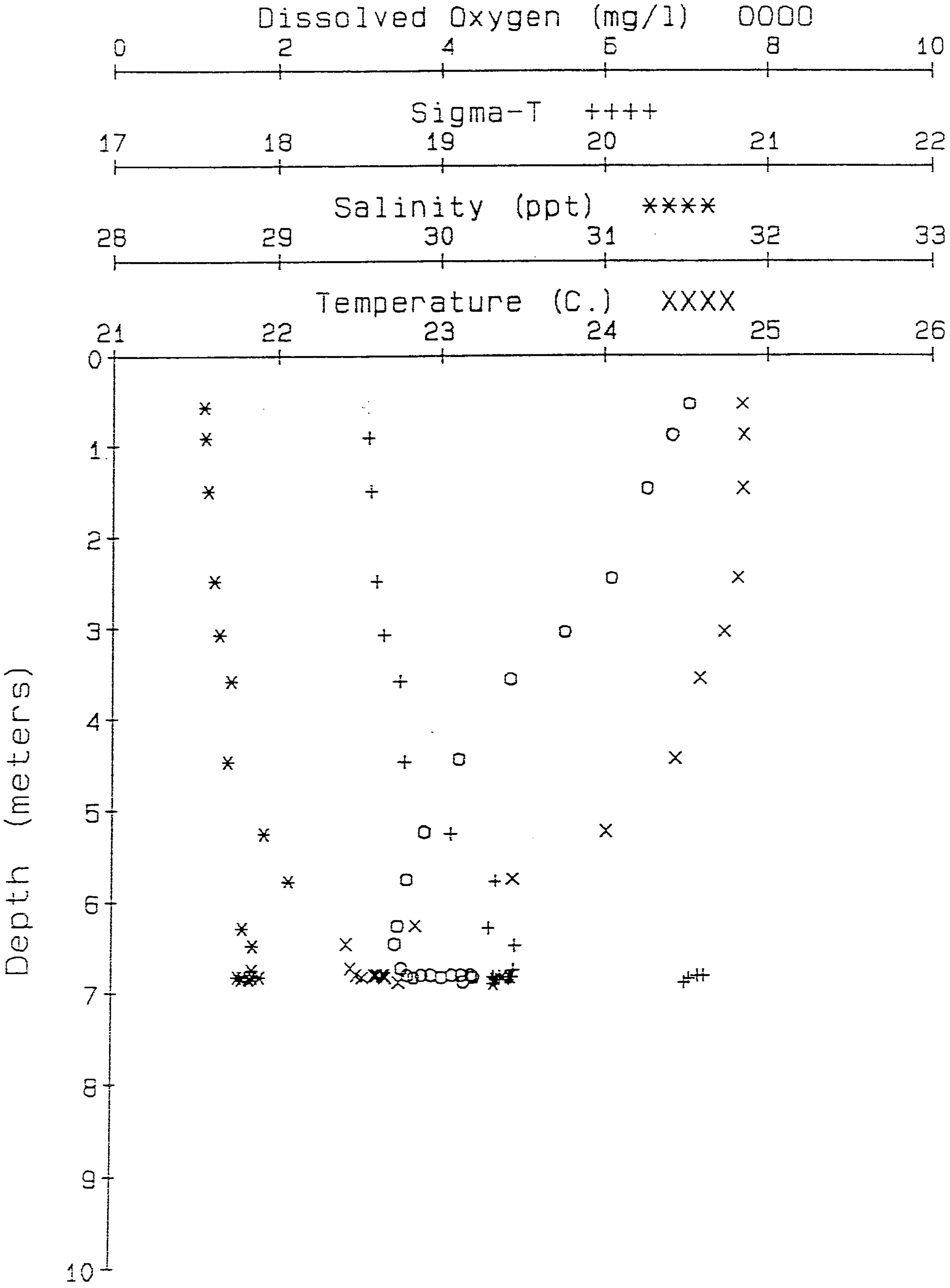
Station C-3


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
19
20
21
22
23
24
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
14
16
18
20
22
24
Depth (meters)
0
2
4
6
8
10
12
14
16
18
20

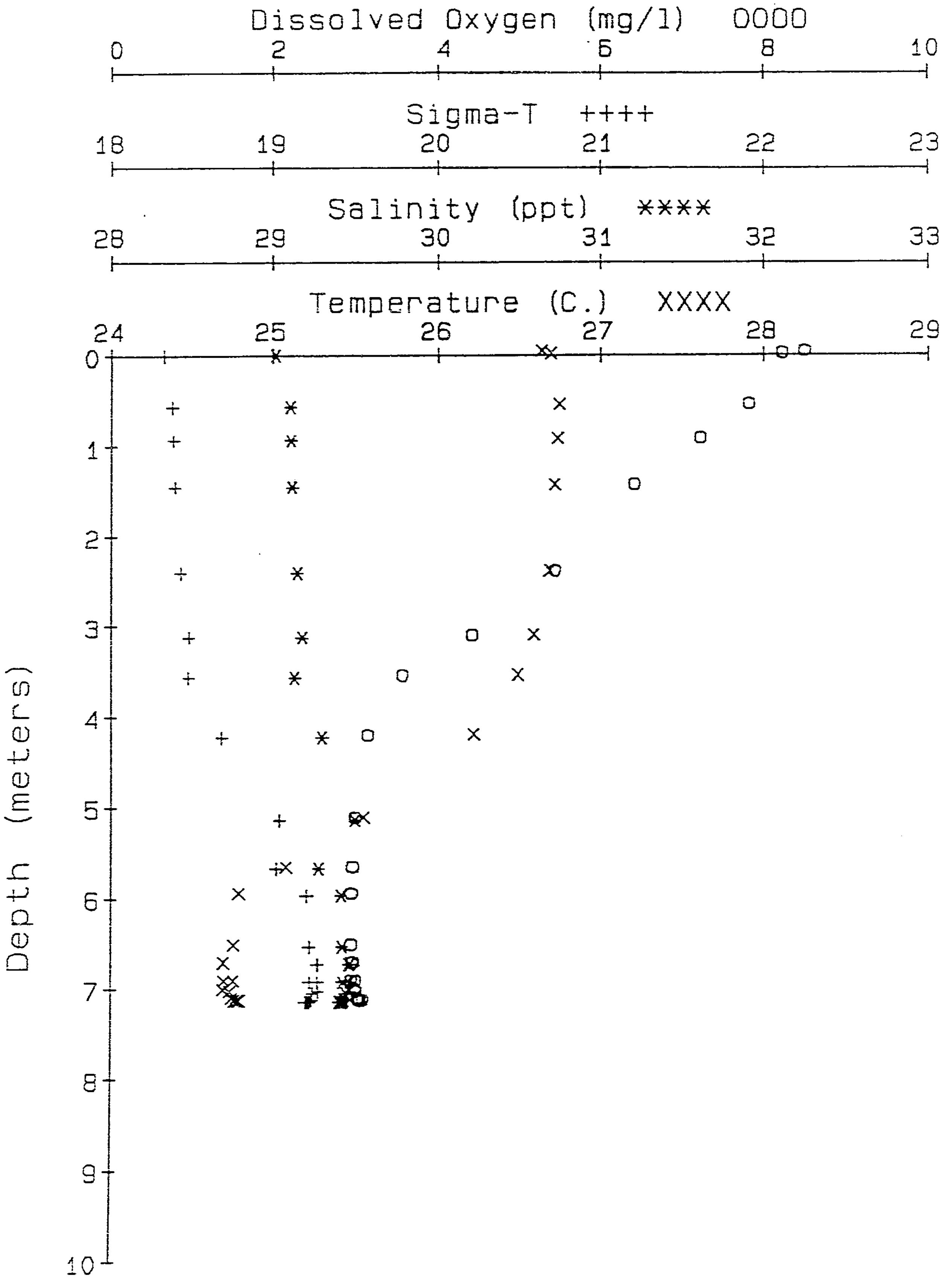
Station C-2


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
20
21
22
23
24
25
Salinity (ppt) ****
29
30
31
32
33
34
Temperature (C.) XXXX
13
15
17
19
21
23
Depth (meters)
0
5
10
15
20
25
30
35

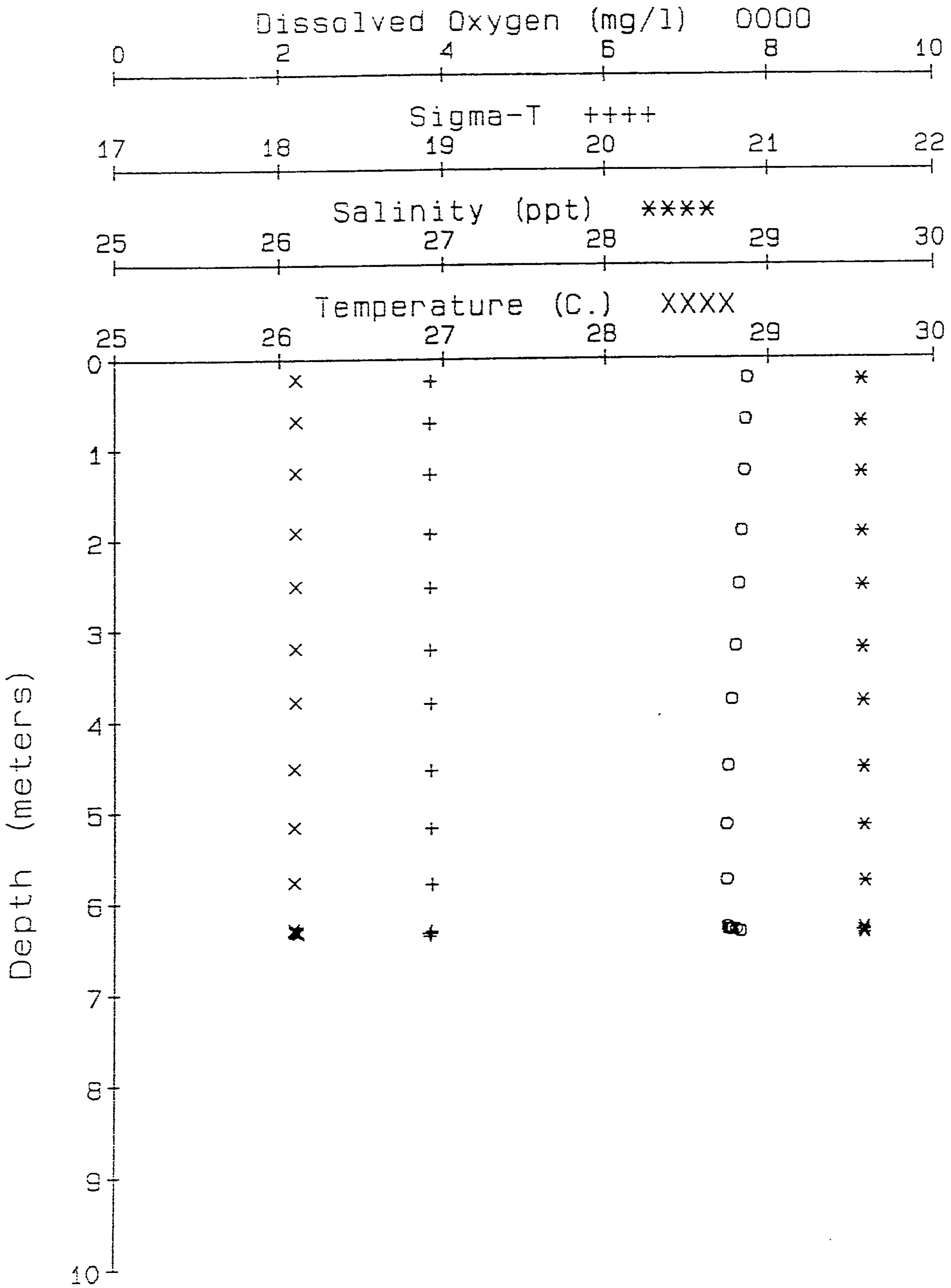
Station A1


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
21
22
23
24
25
26
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

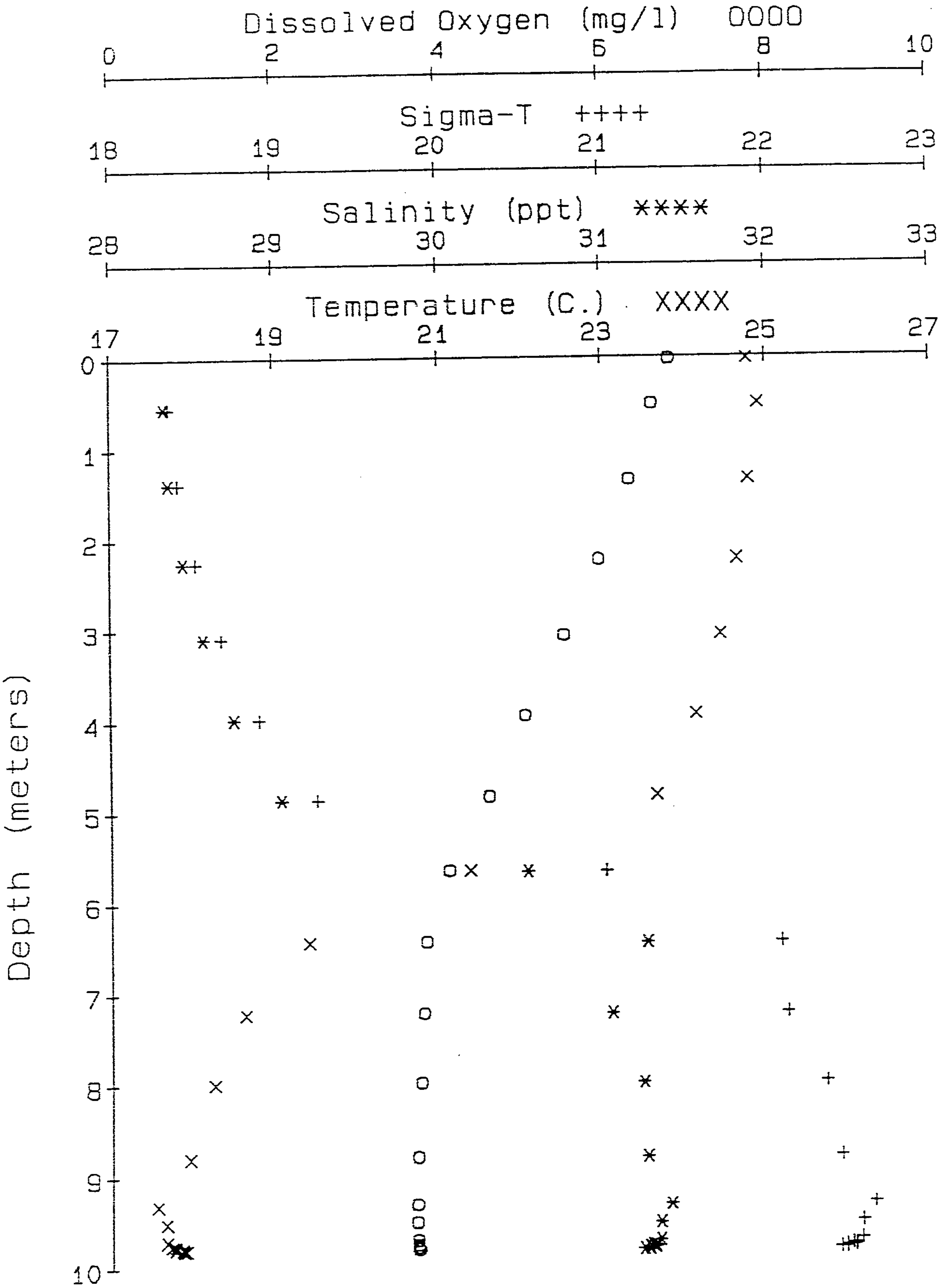
Station R2


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
18
19
20
21
22
23
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
24
25
26
27
28
29
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

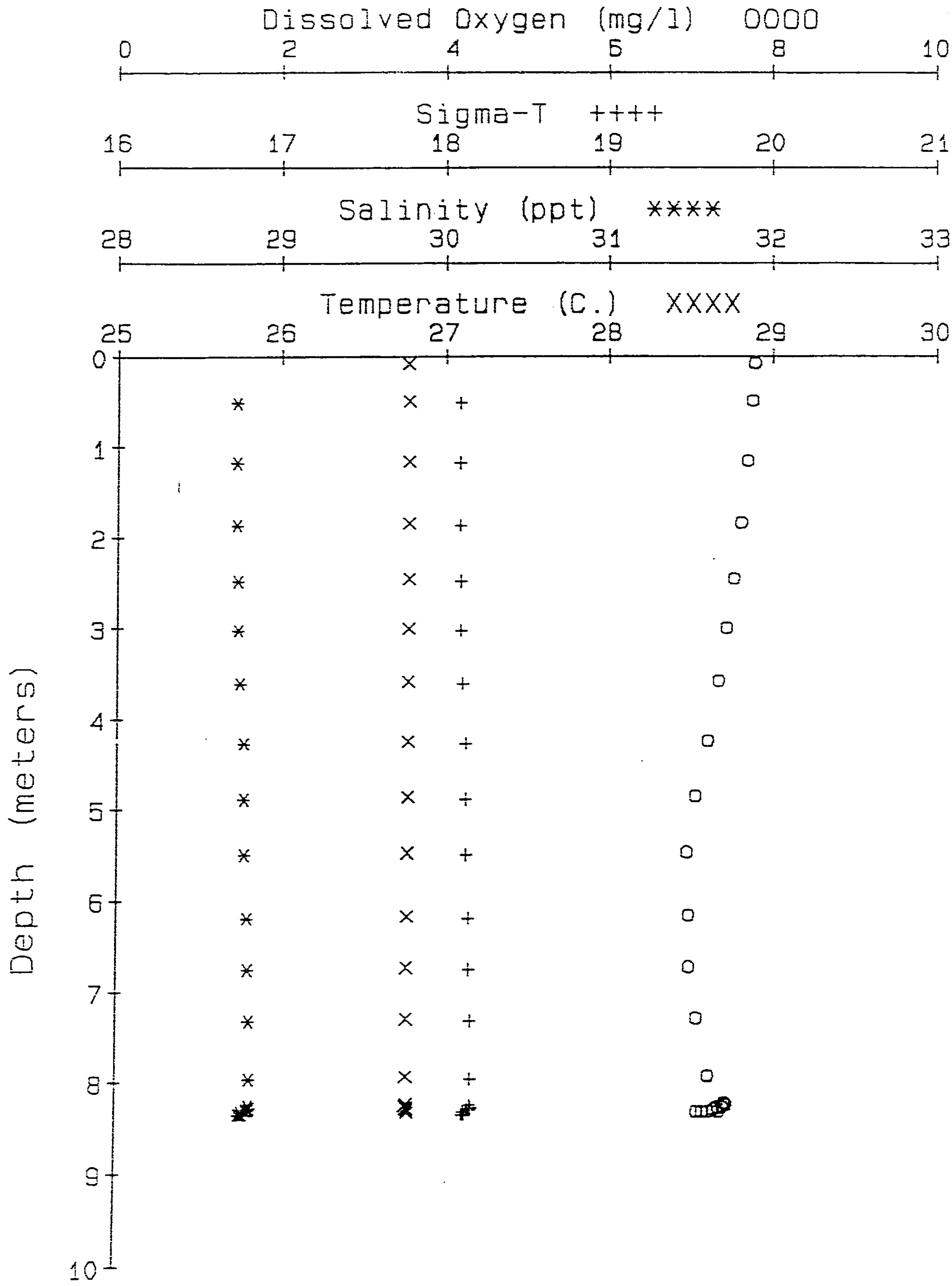
Station R2A


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

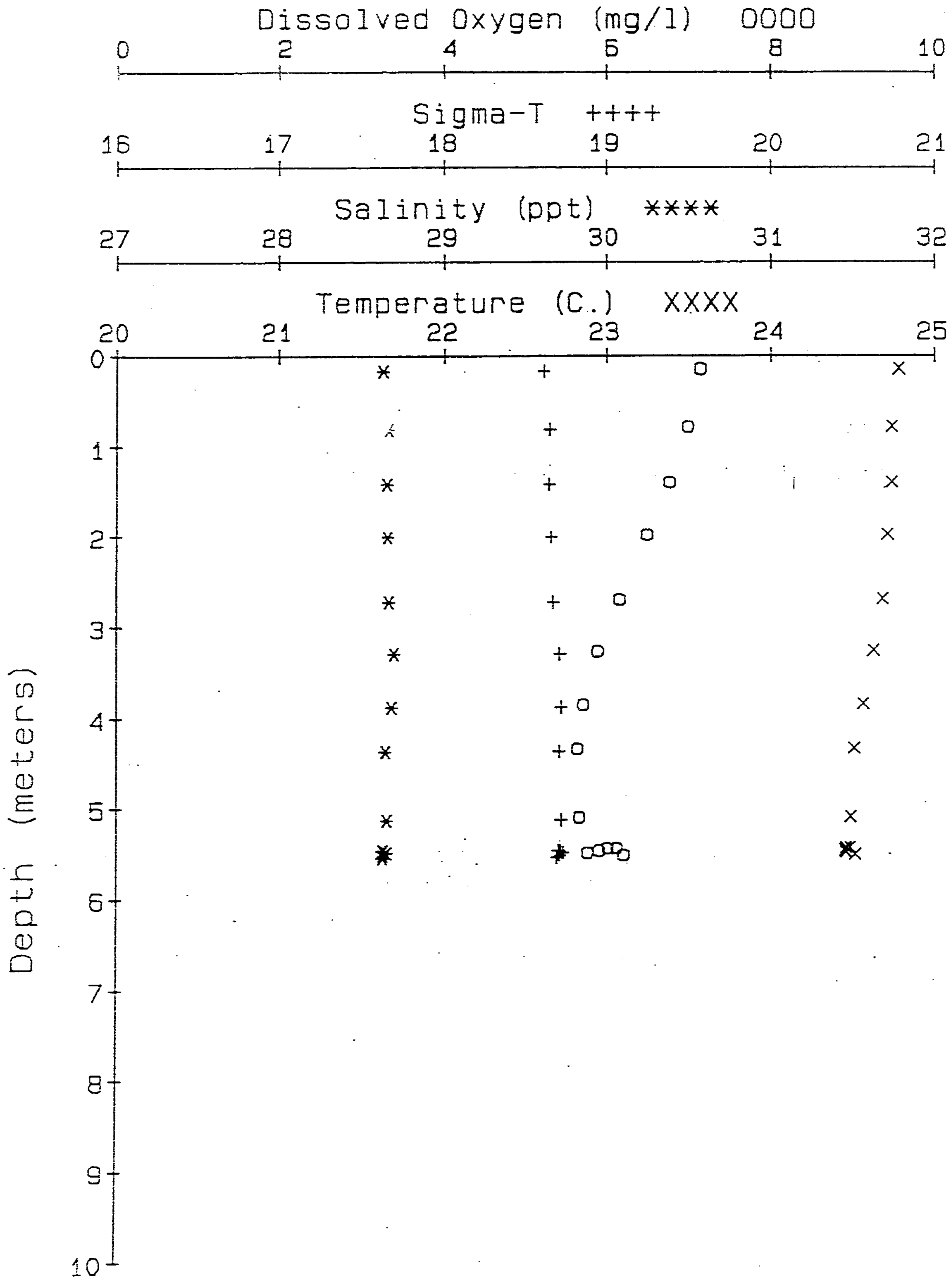
Station 7


Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
18
19
20
21
22
23
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
17
19
21
23
25
27
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

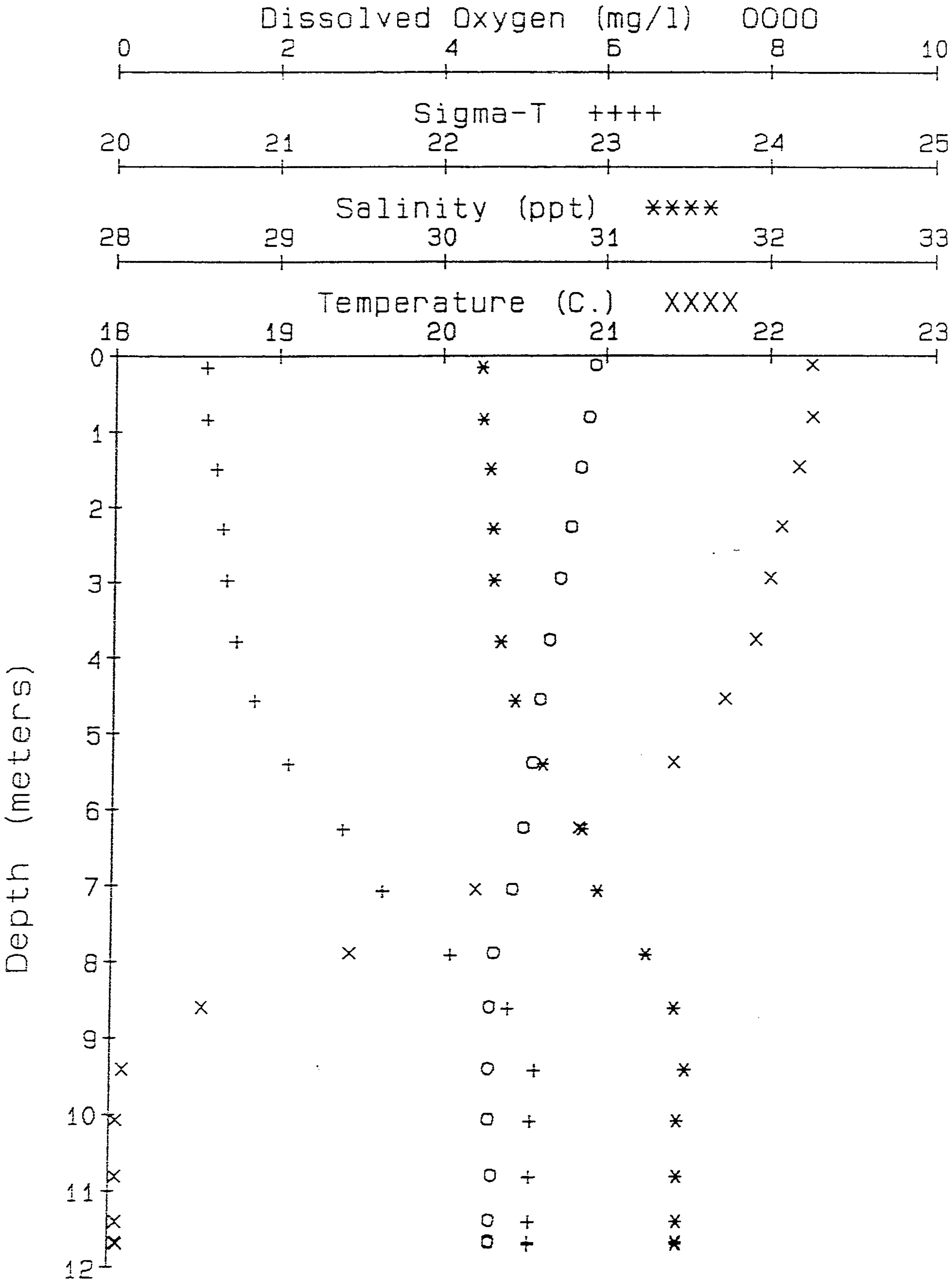
Station 4


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
16
17
18
19
20
21
Salinity (ppt) ****
28
29
30
31
32
33
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

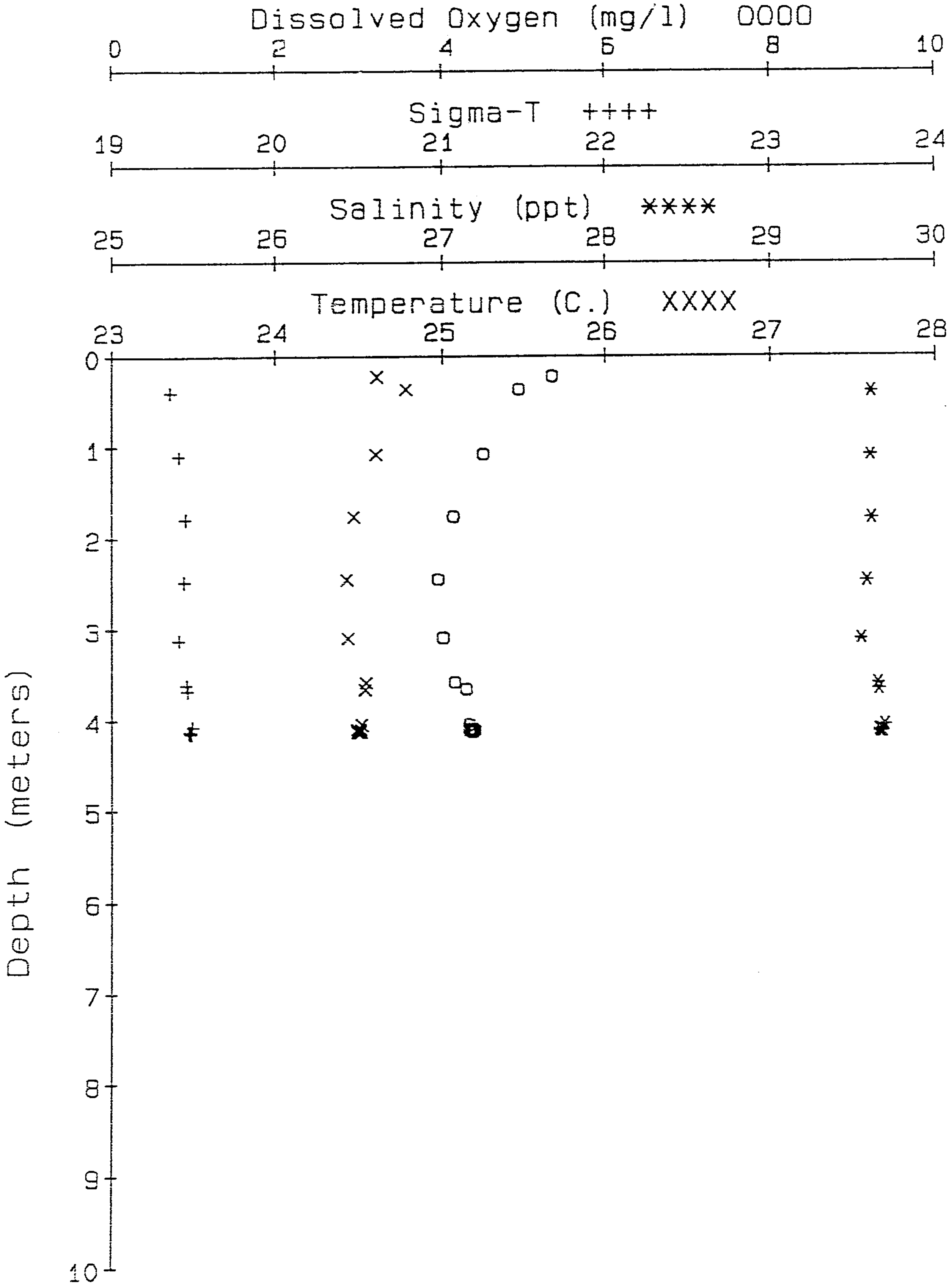
Station 3


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
16
17
18
19
20
21
Salinity (ppt) ****
27
28
29
30
31
32
Temperature (C.) XXXX
20
21
22
23
24
25
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

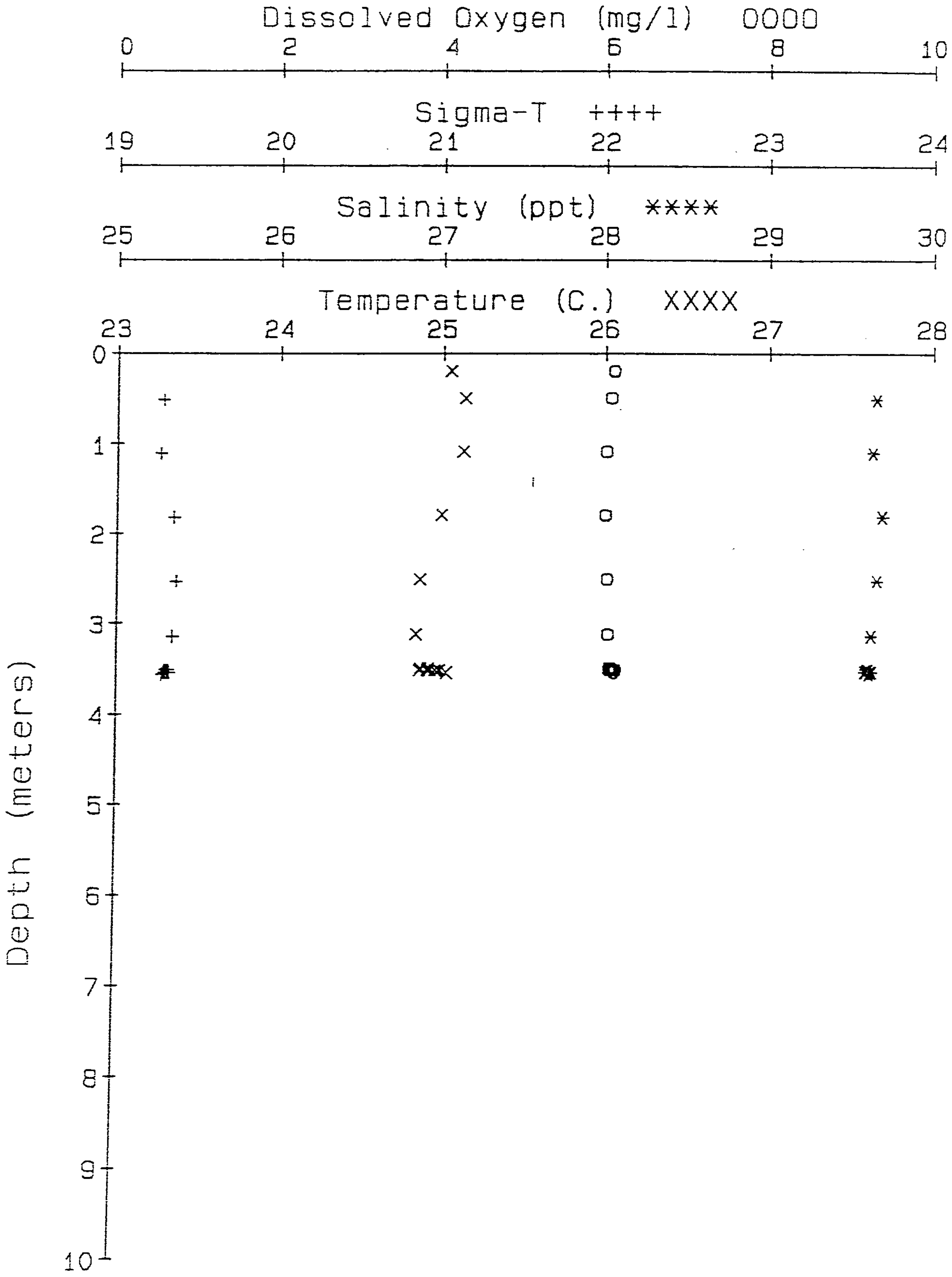
Station 1


Dissolved Oxygen (mg/l) 0000
0 2 4 6 8 10
Sigma-T ++++
20 21 22 23 24 25
Salinity (ppt) ****
28 29 30 31 32 33
Temperature (C.) XXXX
18 19 20 21 22 23
Depth (meters)
0 1 2 3 4 5 6 7 8 9 10 11 12

Station AH3

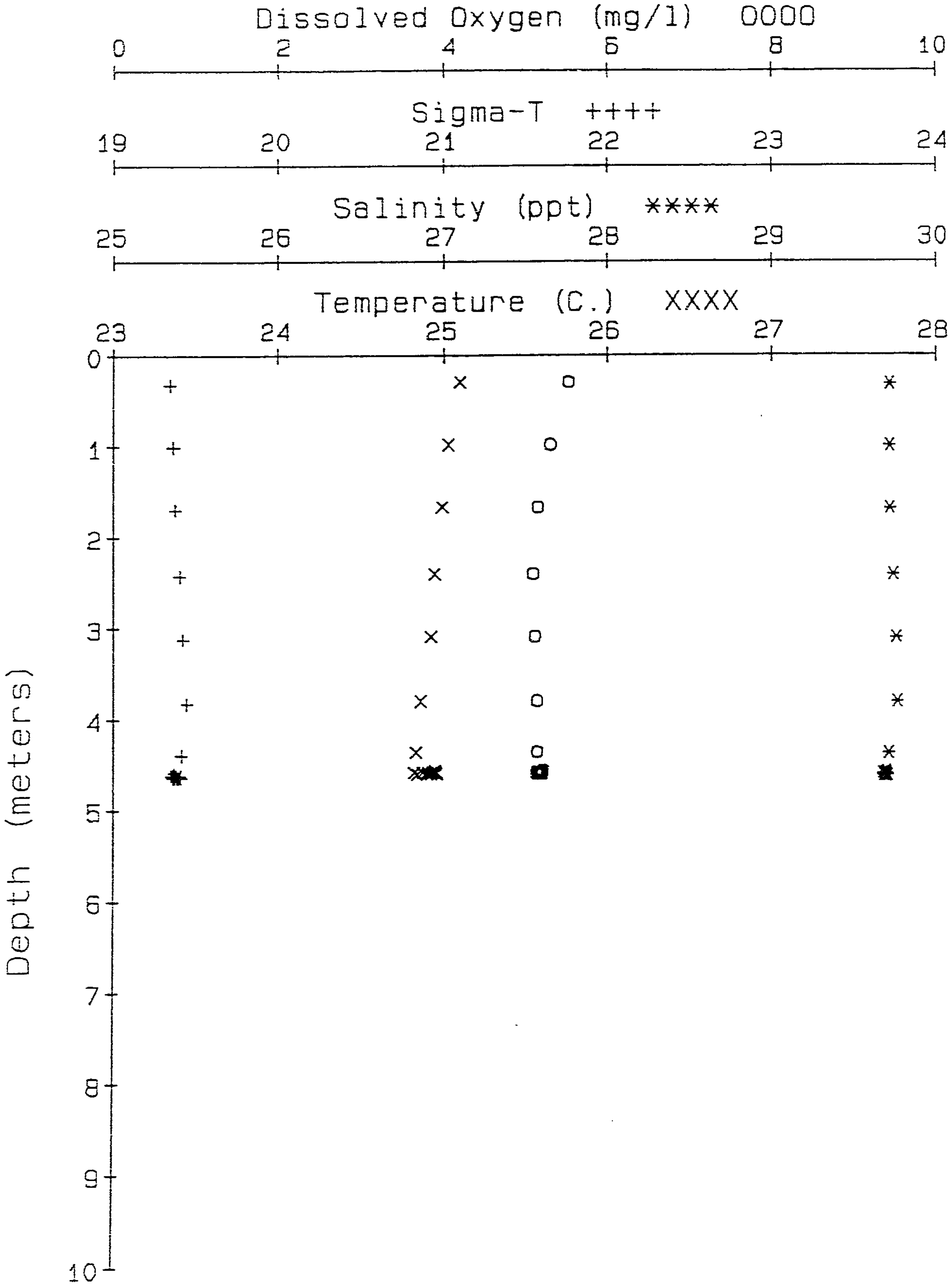

Dissolved Oxygen (mg/l) 0000
0 2 4 6 8 10
Sigma-T ++++
19 20 21 22 23 24
Salinity (ppt) ****
25 26 27 28 29 30
Temperature (C.) XXXX
23 24 25 26 27 28
Depth (meters)
0 1 2 3 4 5 6 7 8 9 10

Station AM2

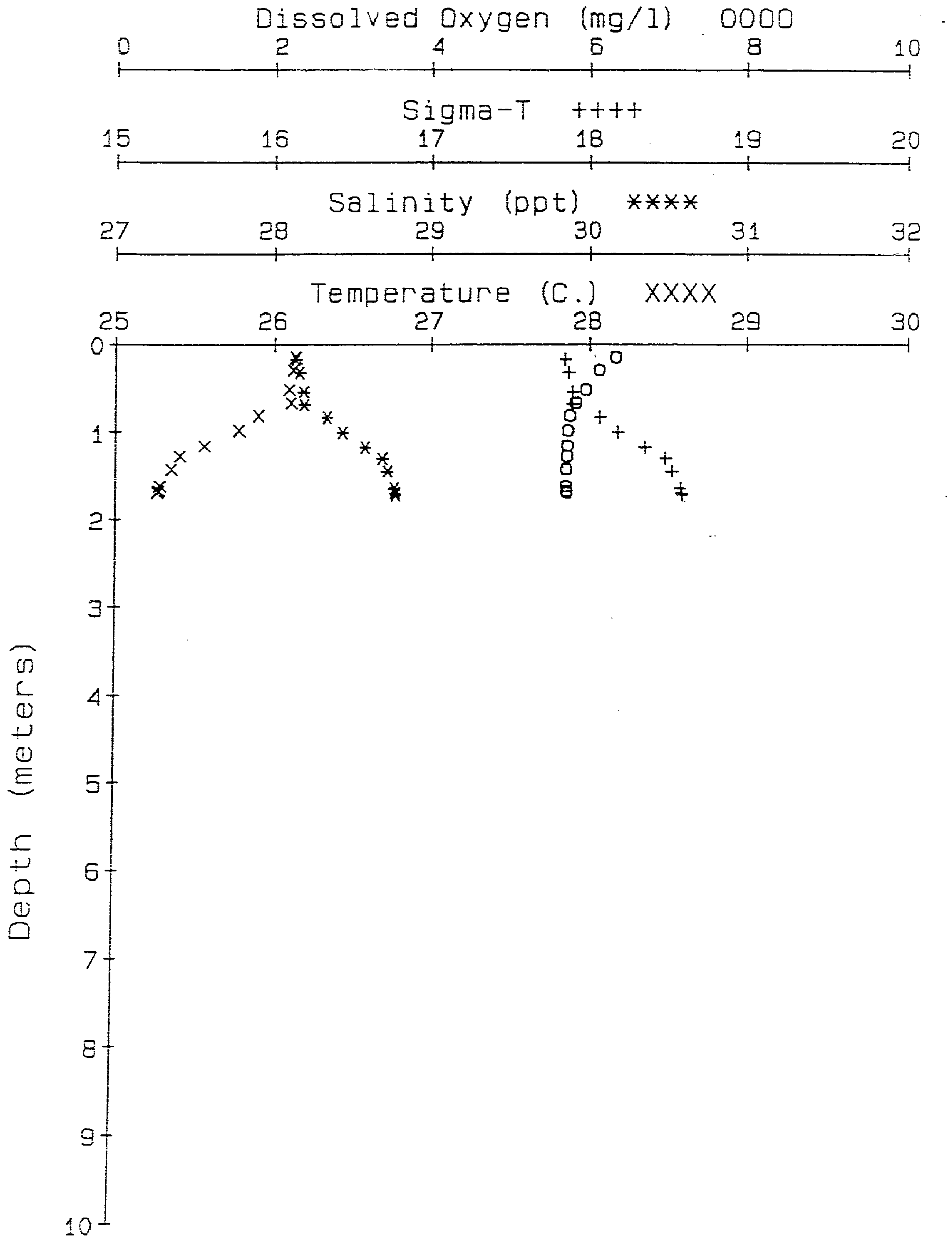


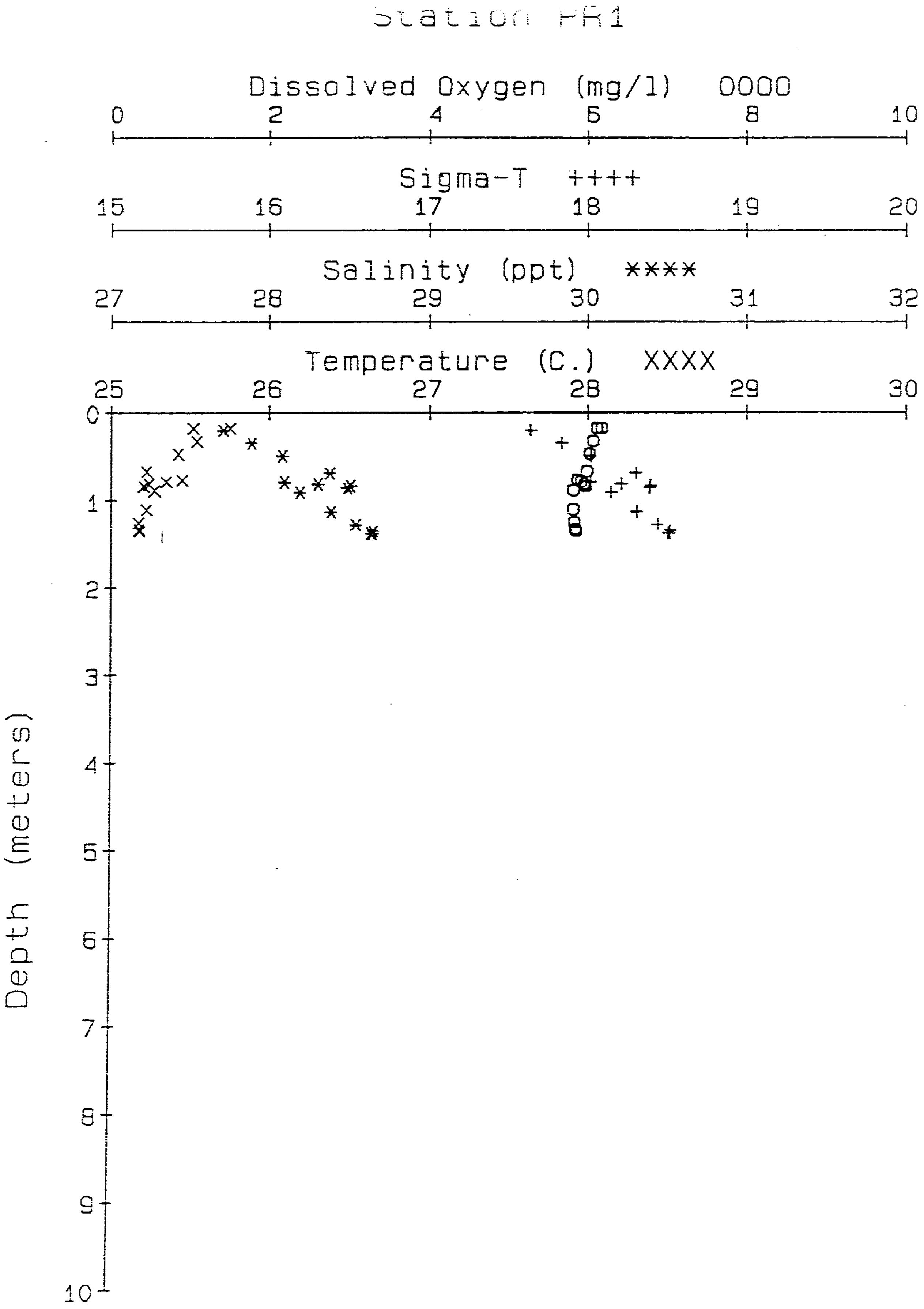
Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
19
20
21
22
23
24
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station AH1

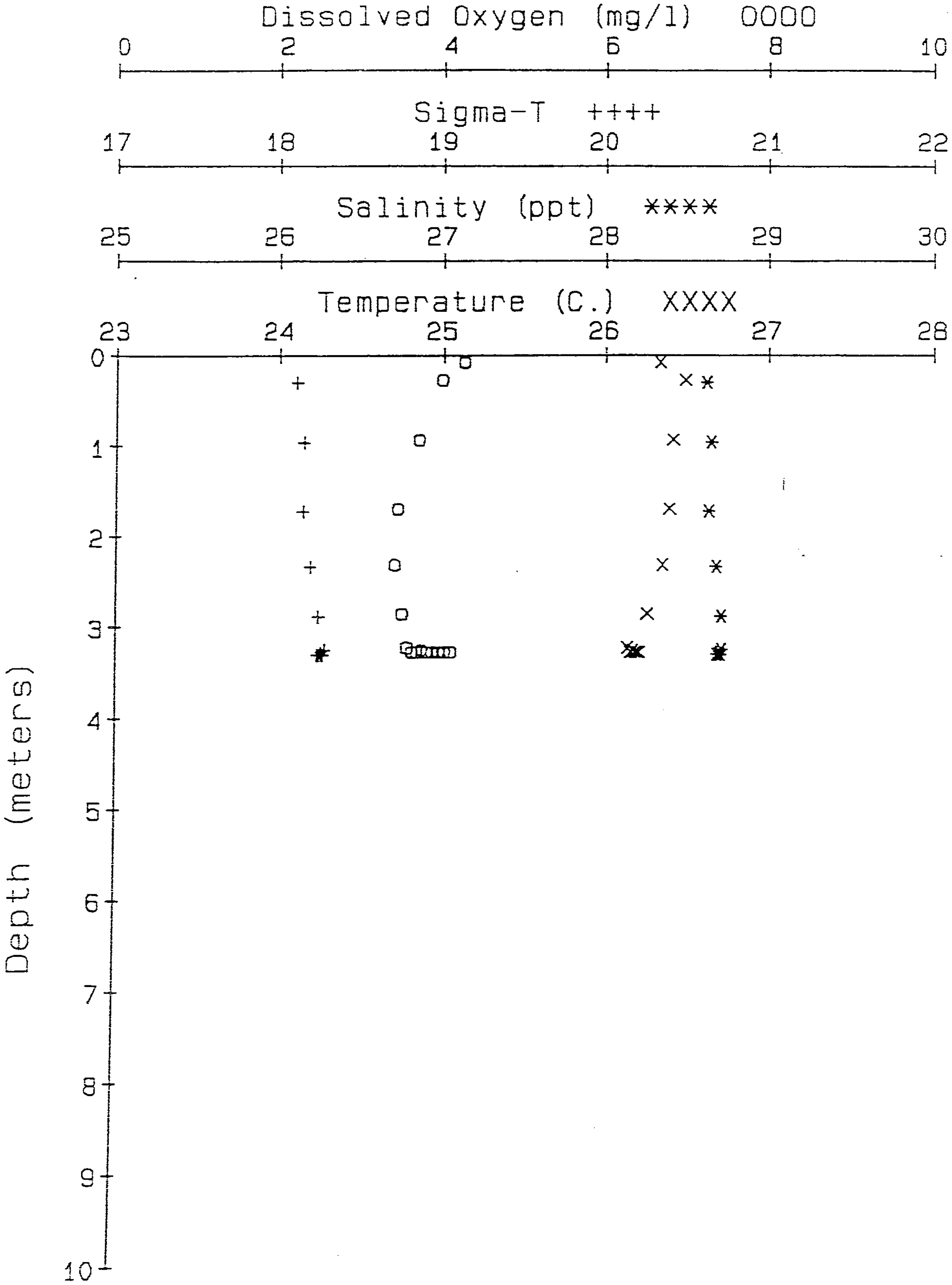

Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
19
20
21
22
23
24
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station #R2

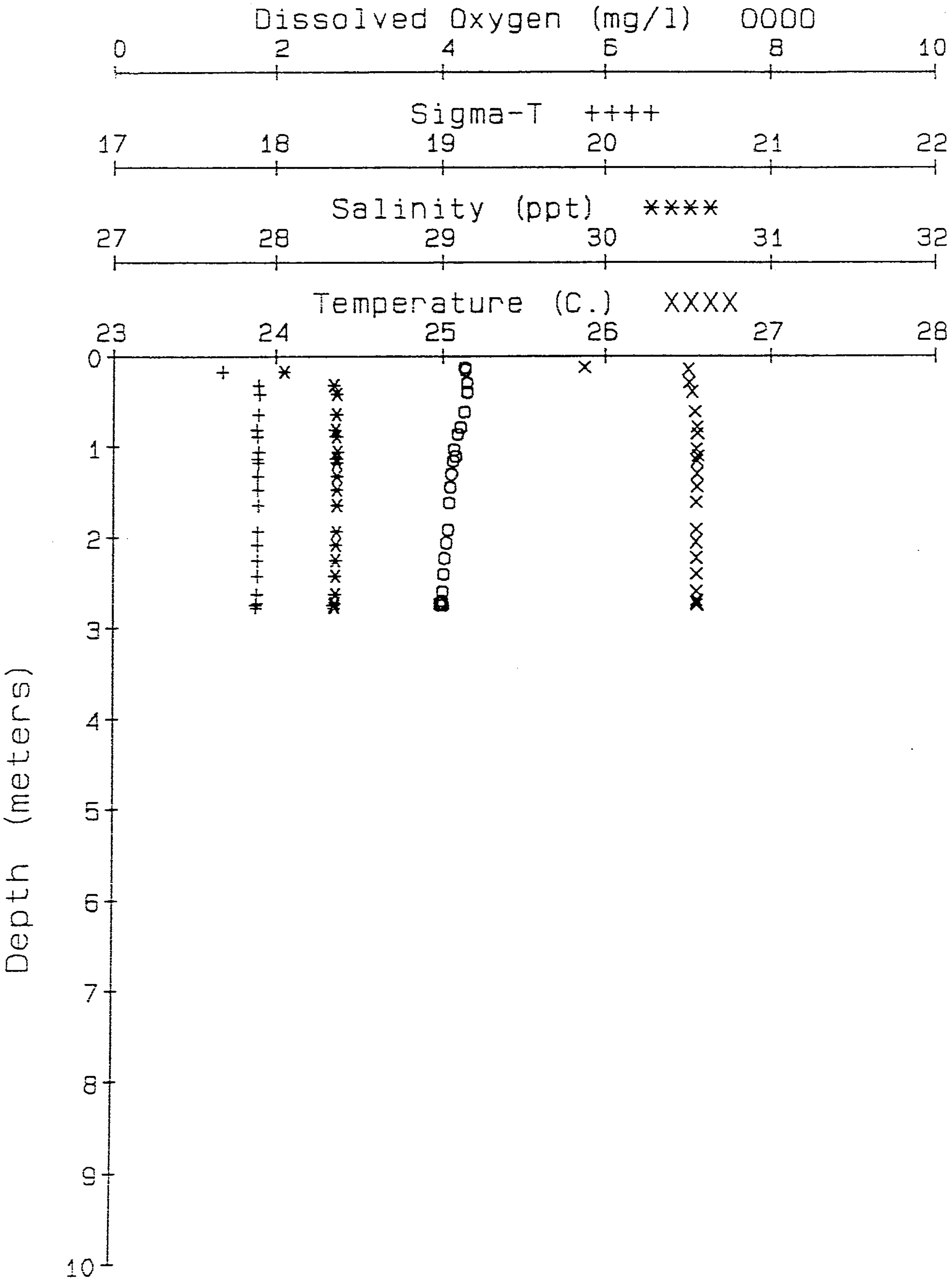

Dissolved Oxygen (mg/l) OOOO
0 2 4 6 8 10
Sigma-T ++++
15 16 17 18 19 20
Salinity (ppt) ****
27 28 29 30 31 32
Temperature (C.) XXXX
25 26 27 28 29 30
Depth (meters)
0 1 2 3 4 5 6 7 8 9 10


Station PR1
Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
27
28
29
30
31
32
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

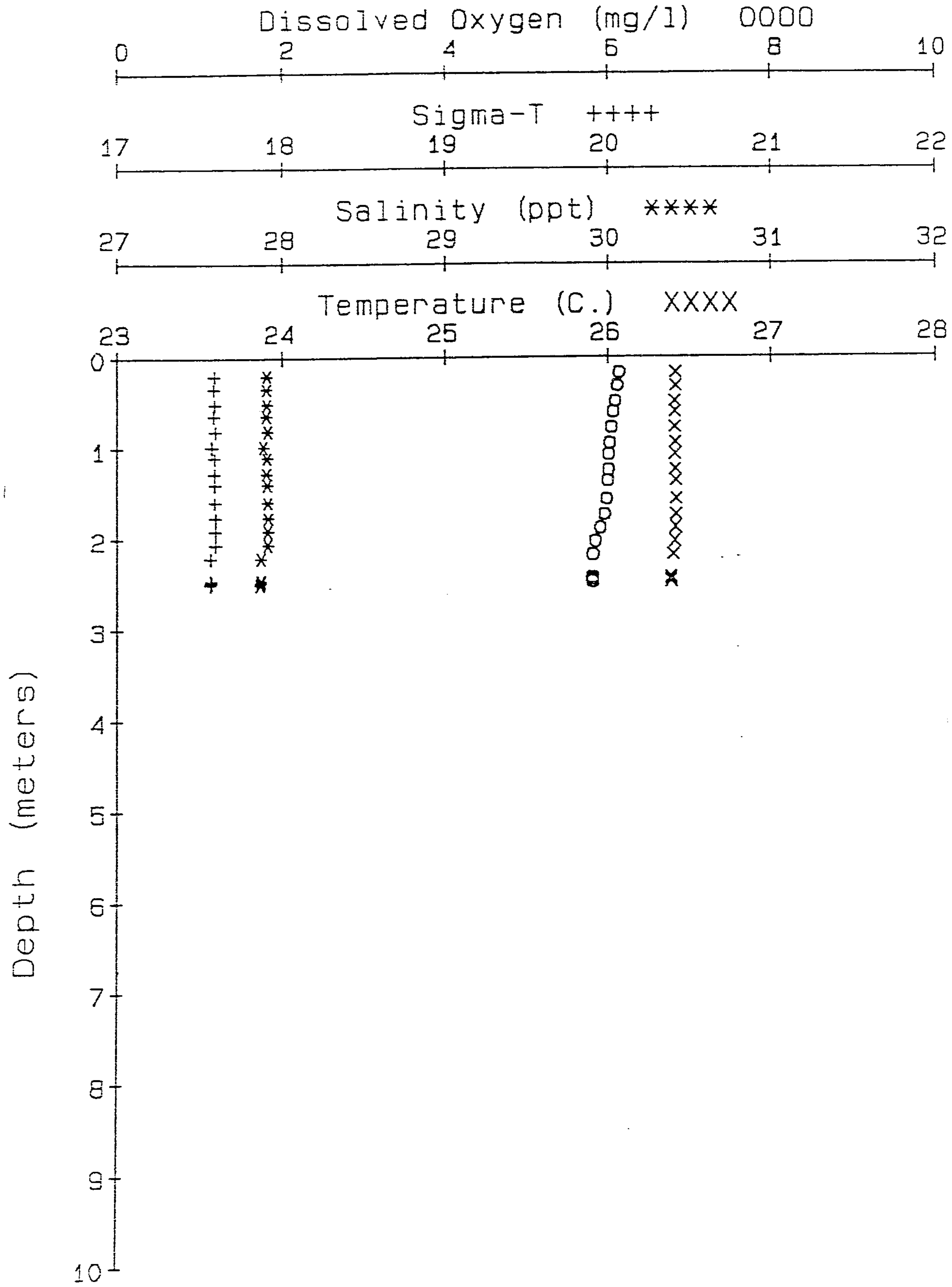
Station GC3


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

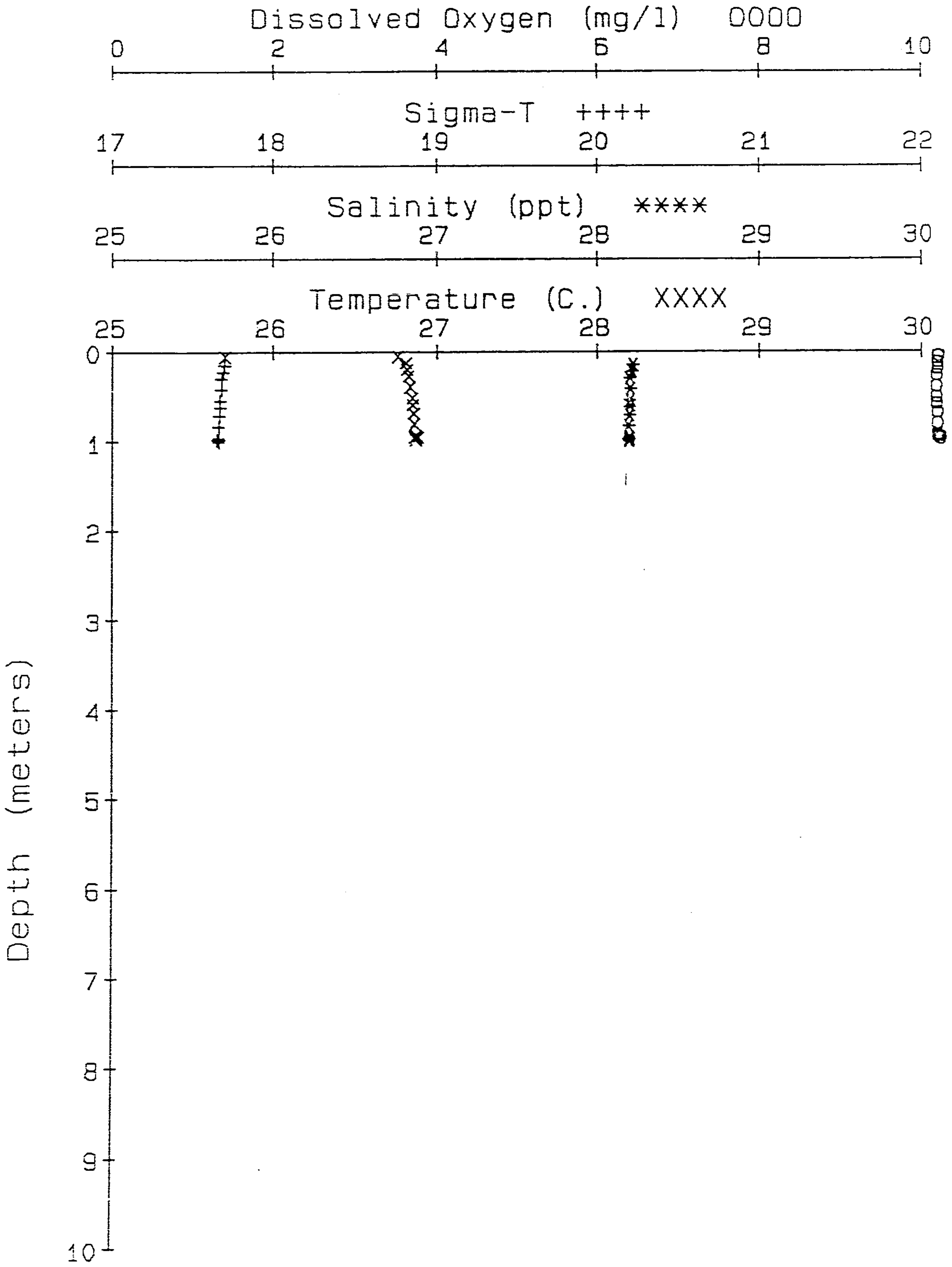
Station GU2


Dissolved Oxygen (mg/l) OOOO
0 2 4 6 8 10
Sigma-T ++++
17 18 19 20 21 22
Salinity (ppt) ****
27 28 29 30 31 32
Temperature (C.) XXXX
23 24 25 26 27 28
Depth (meters)
0 1 2 3 4 5 6 7 8 9 10

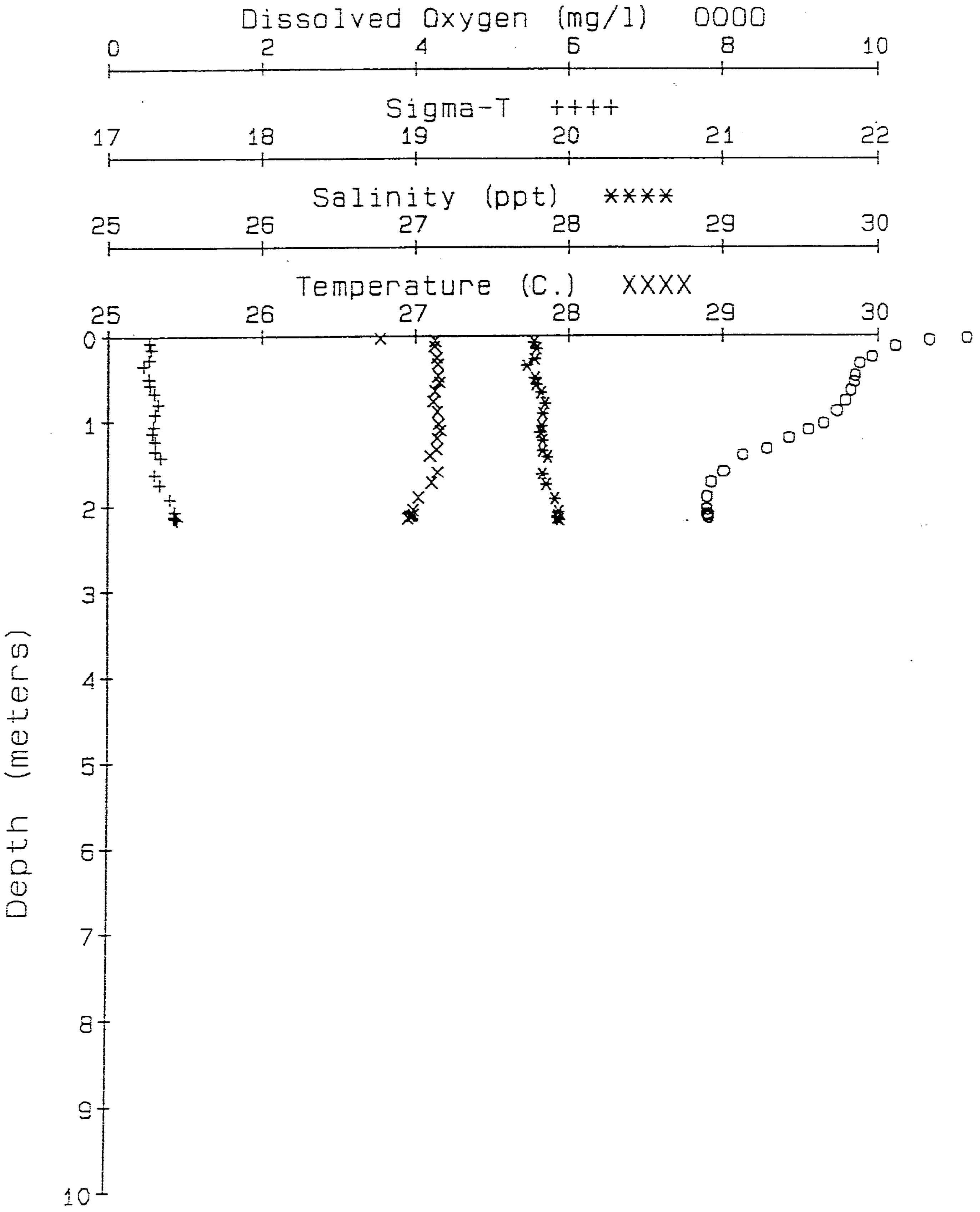
Station 001


Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
27
28
29
30
31
32
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

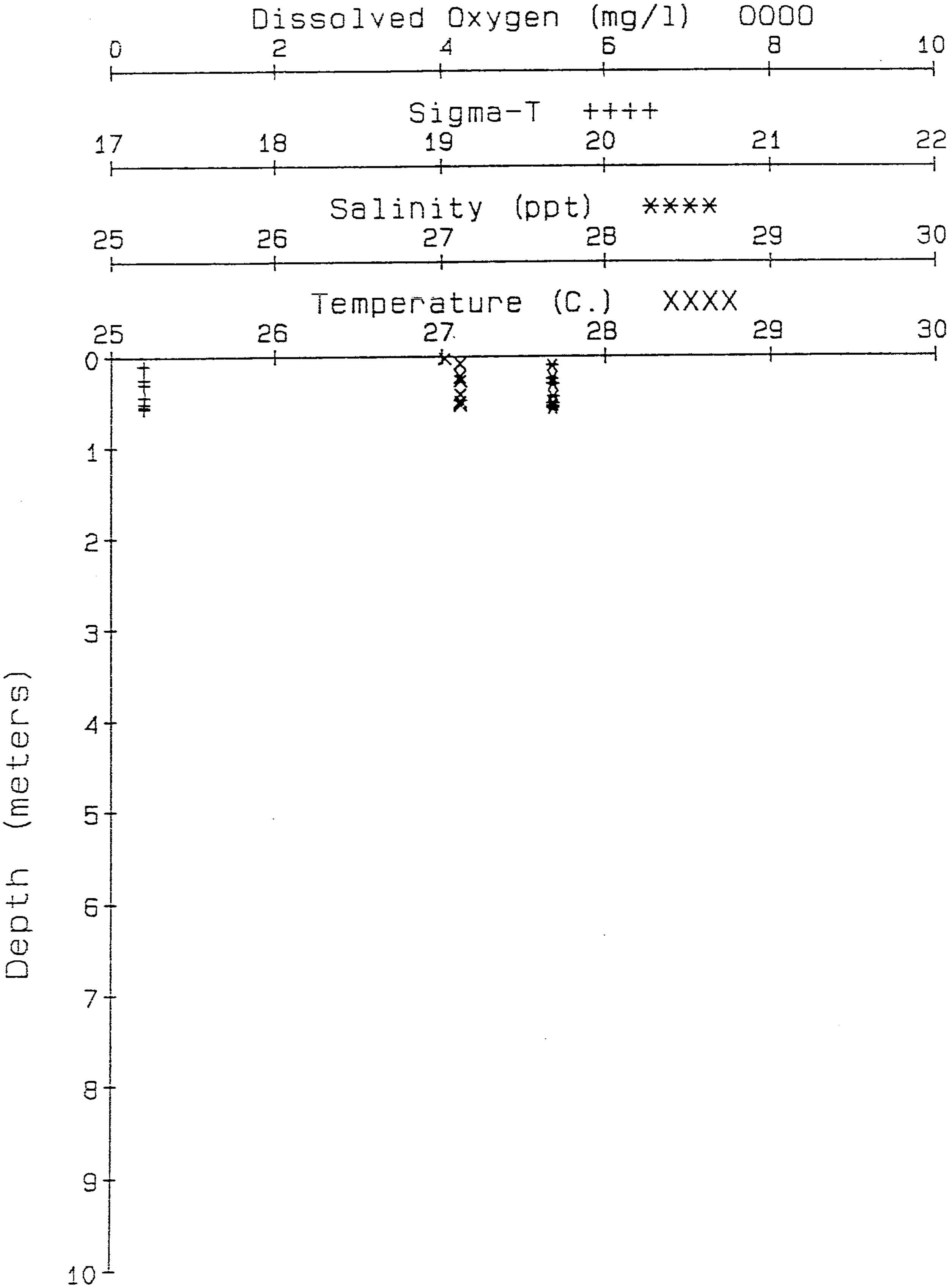
Station AC3


Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

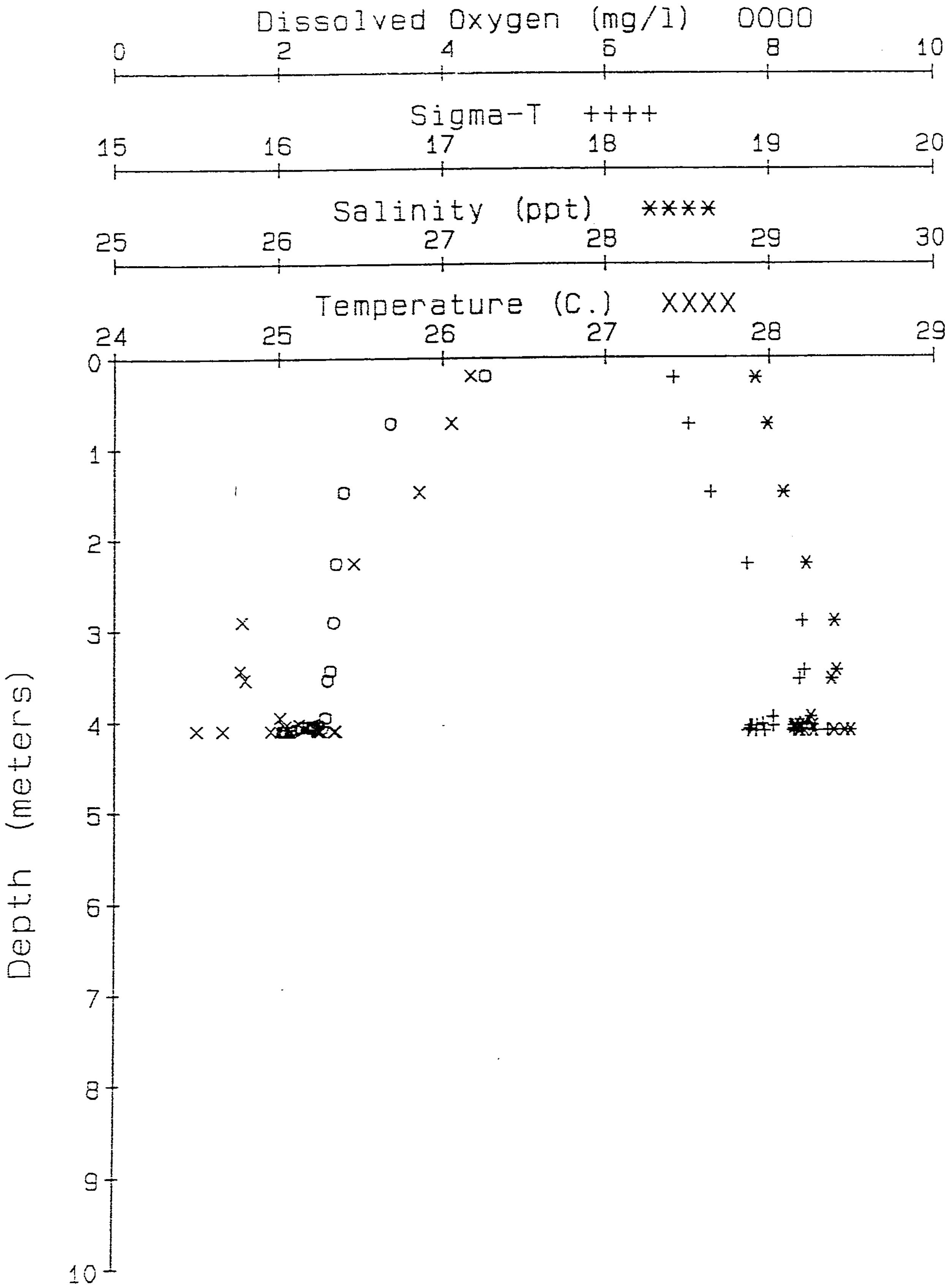
Station A02


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

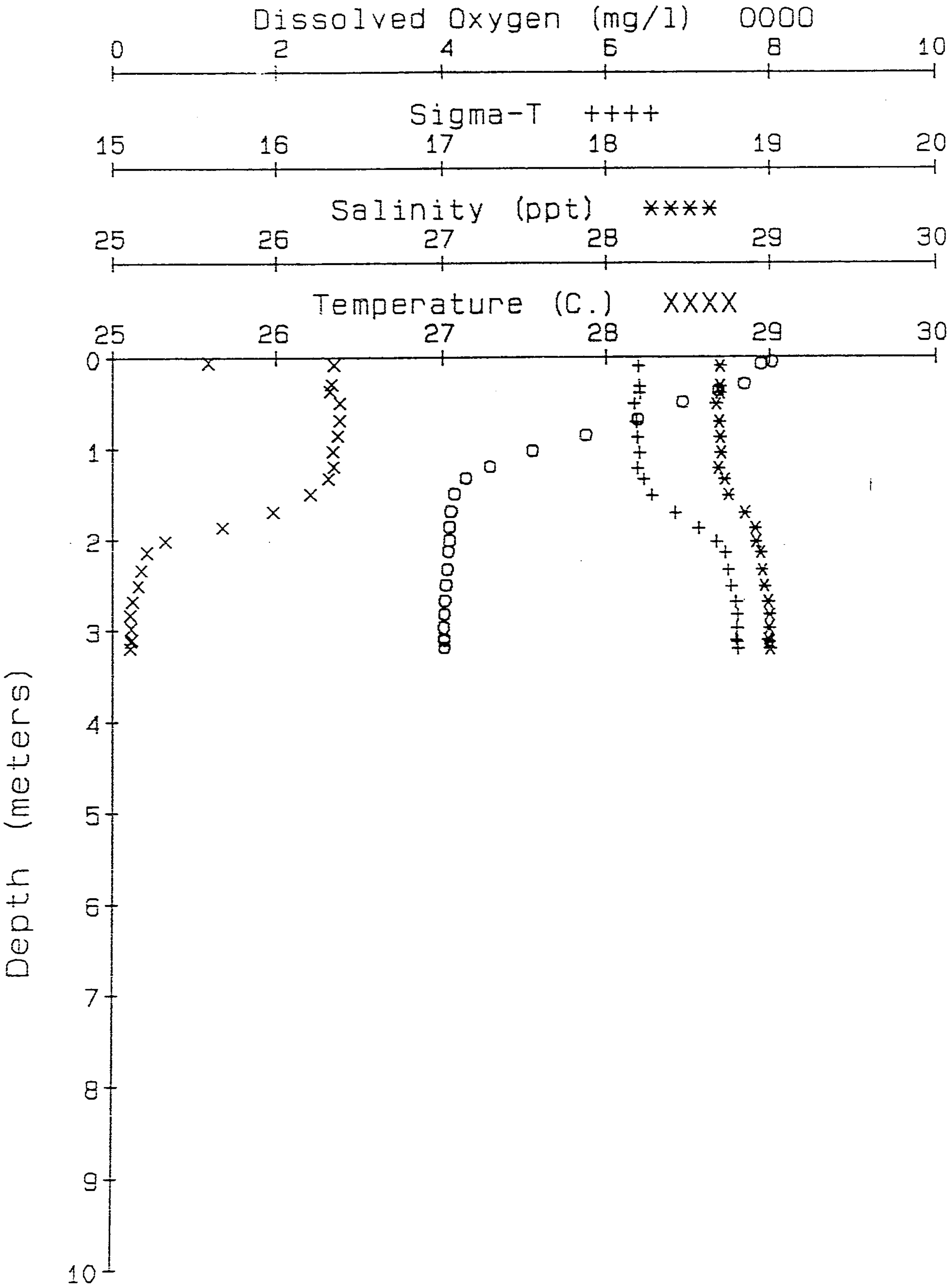
Station AC1


Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

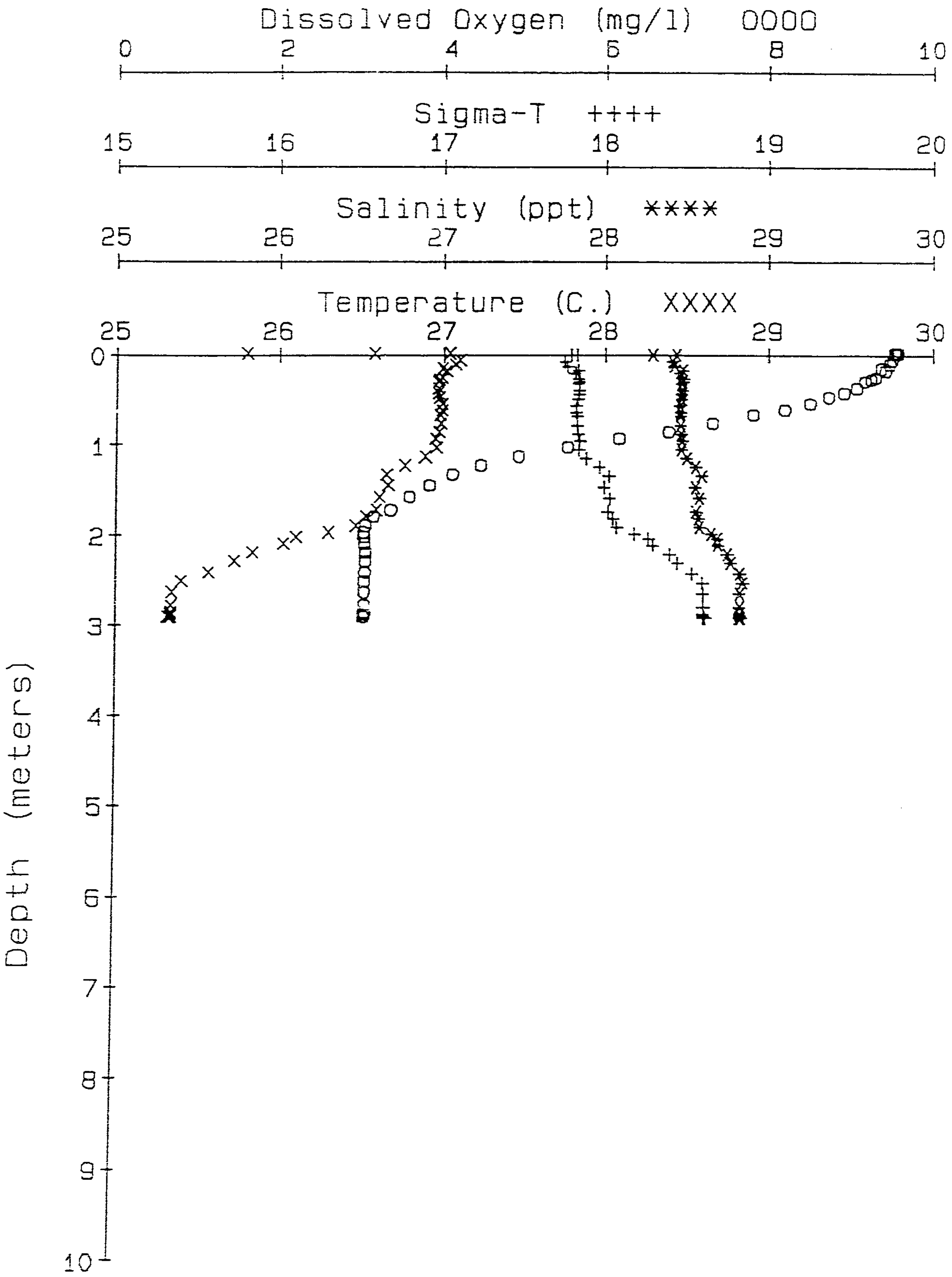
Station SB6


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
24
25
26
27
28
29
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

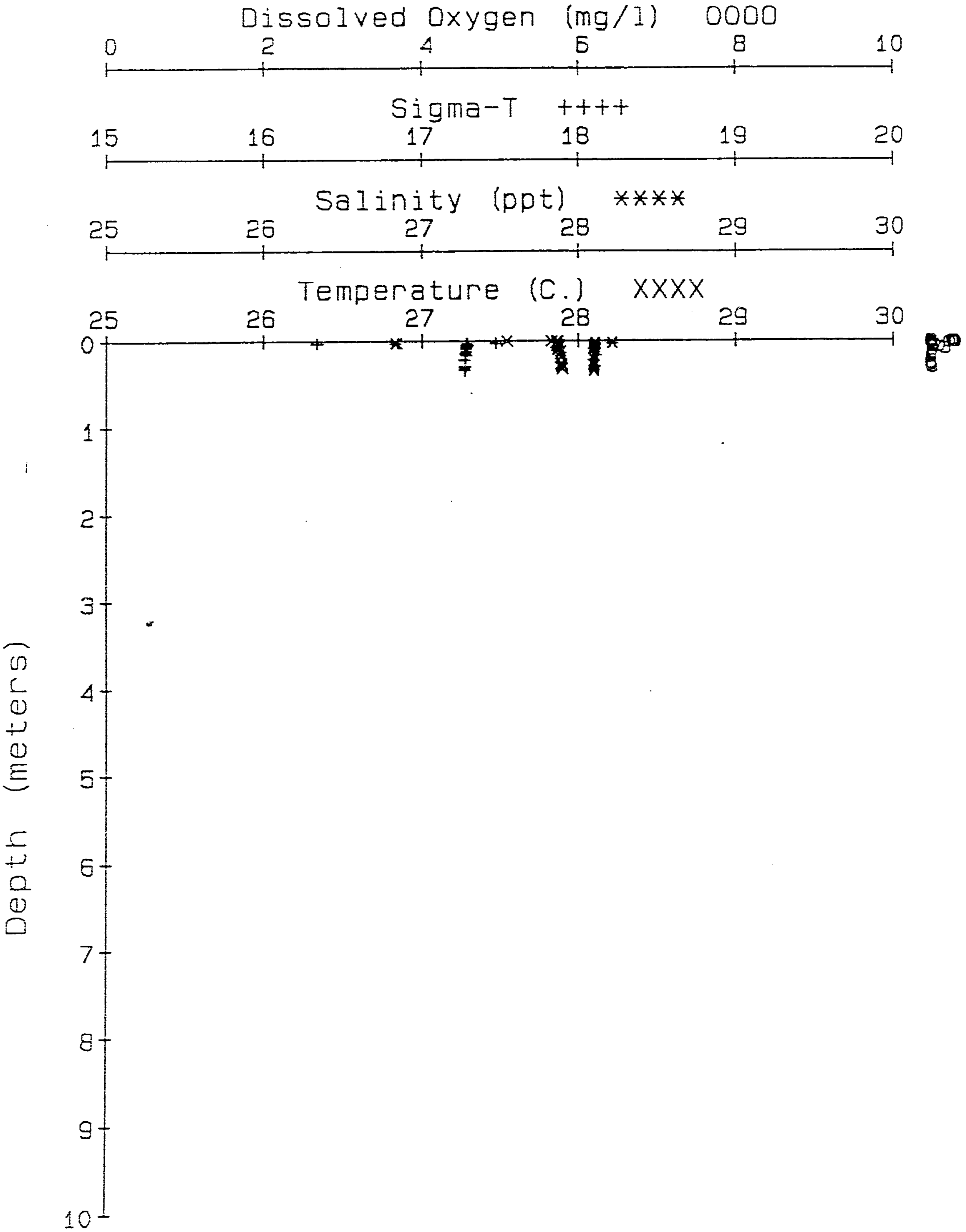
Station WC3


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ✱✱✱✱
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

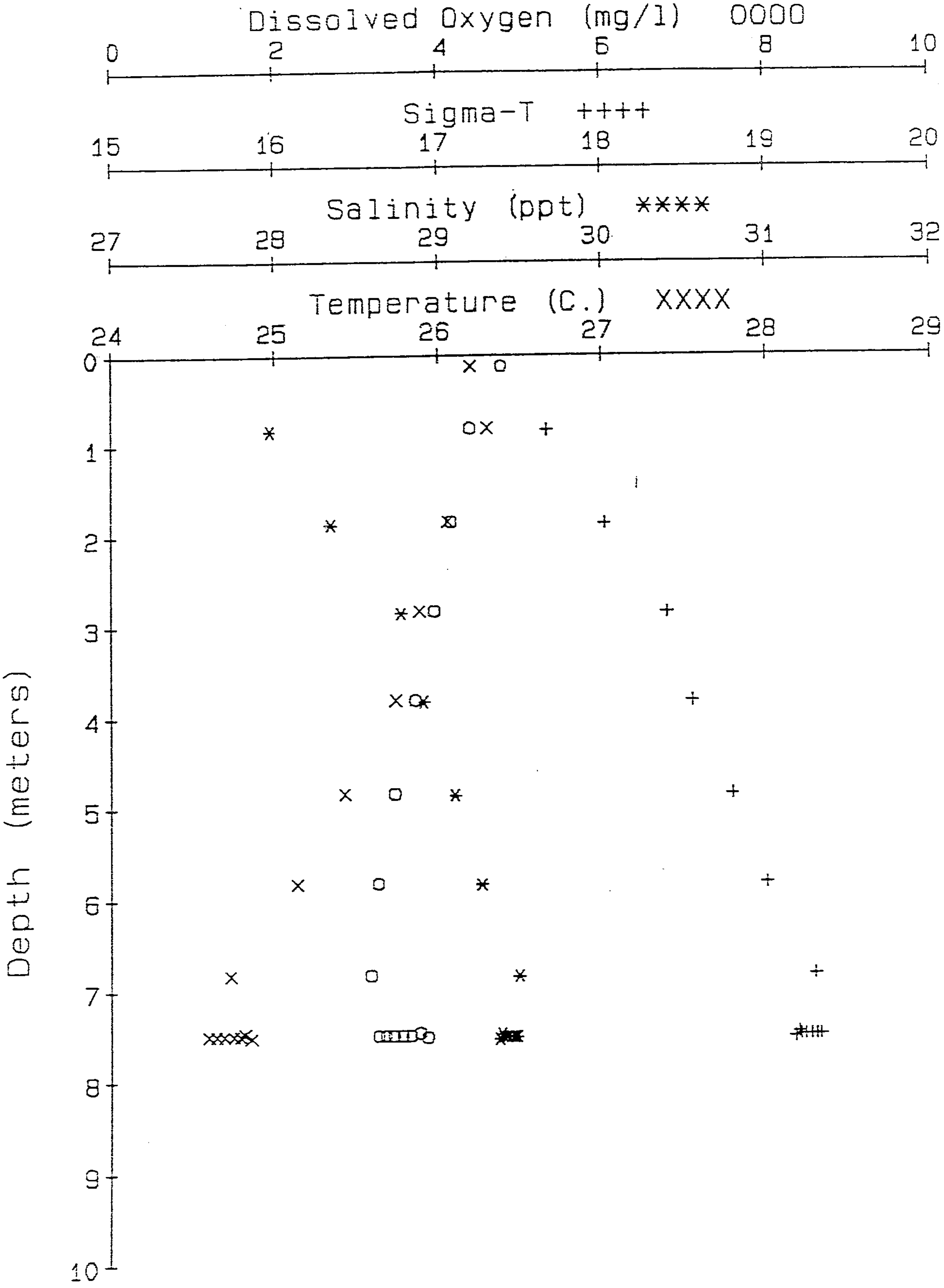
Station W02


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station WC1

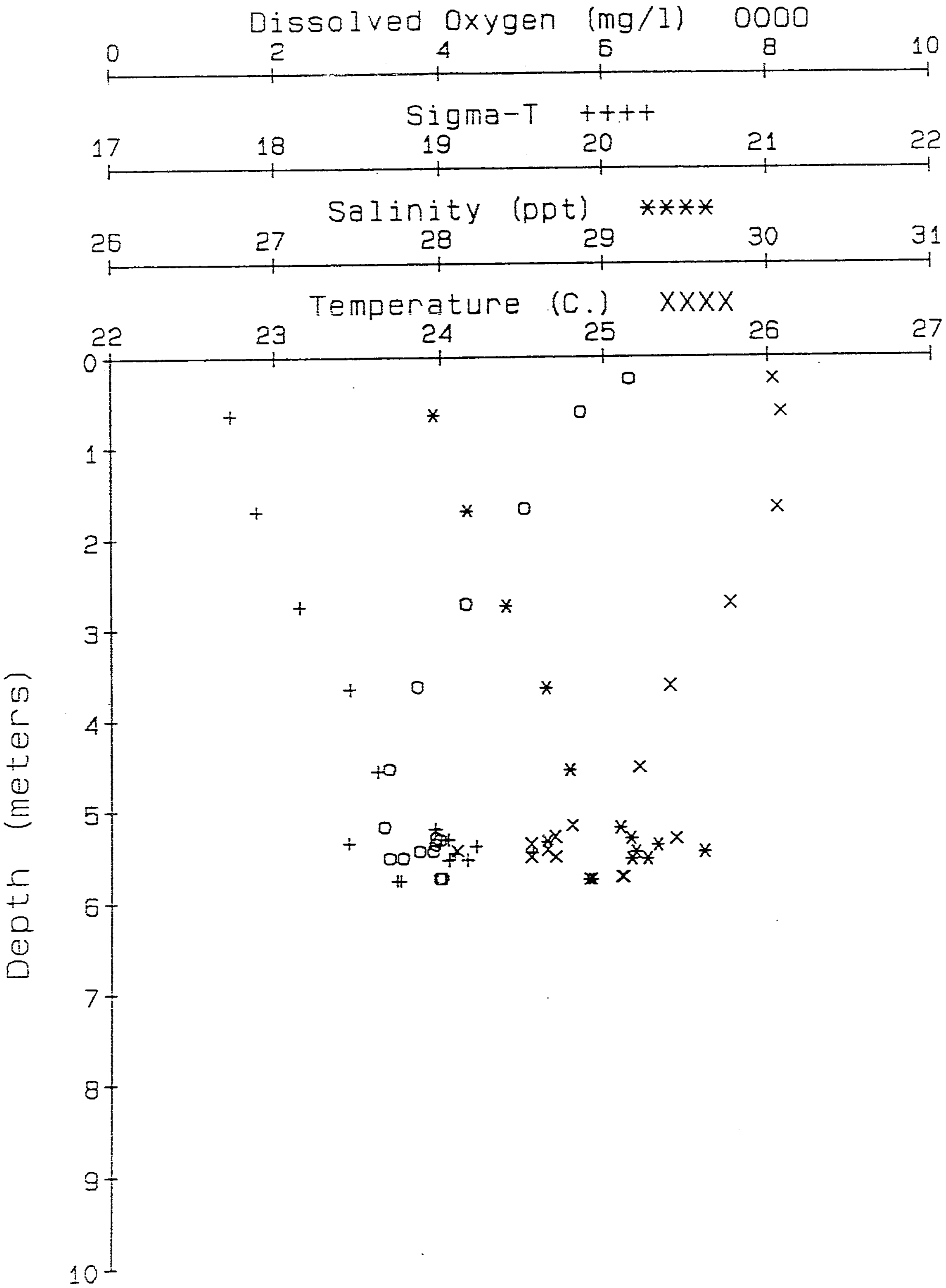

Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
25
26
27
28
29
30
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station C-1

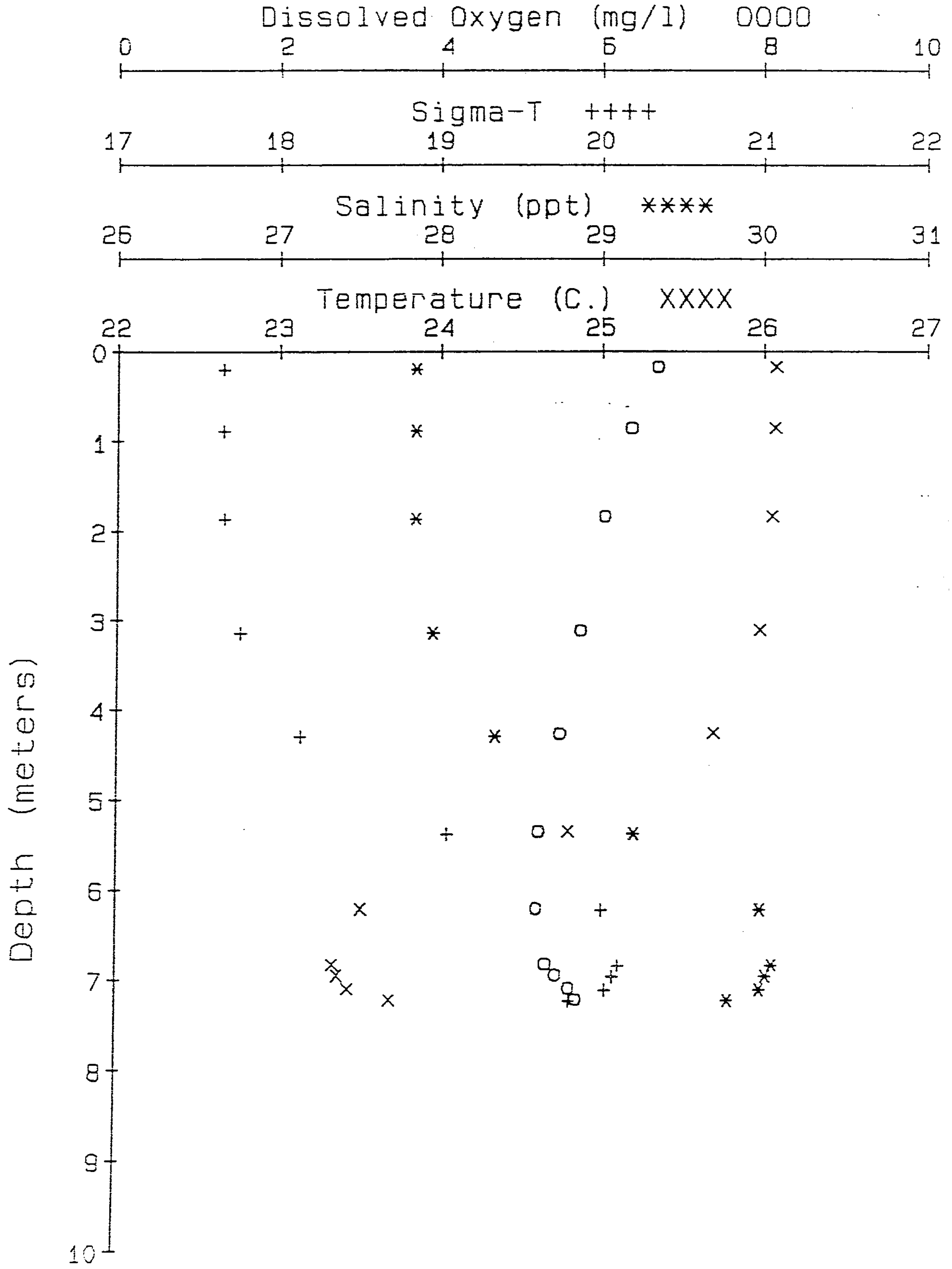


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
27
28
29
30
31
32
Temperature (C.) XXXX
24
25
26
27
28
29
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

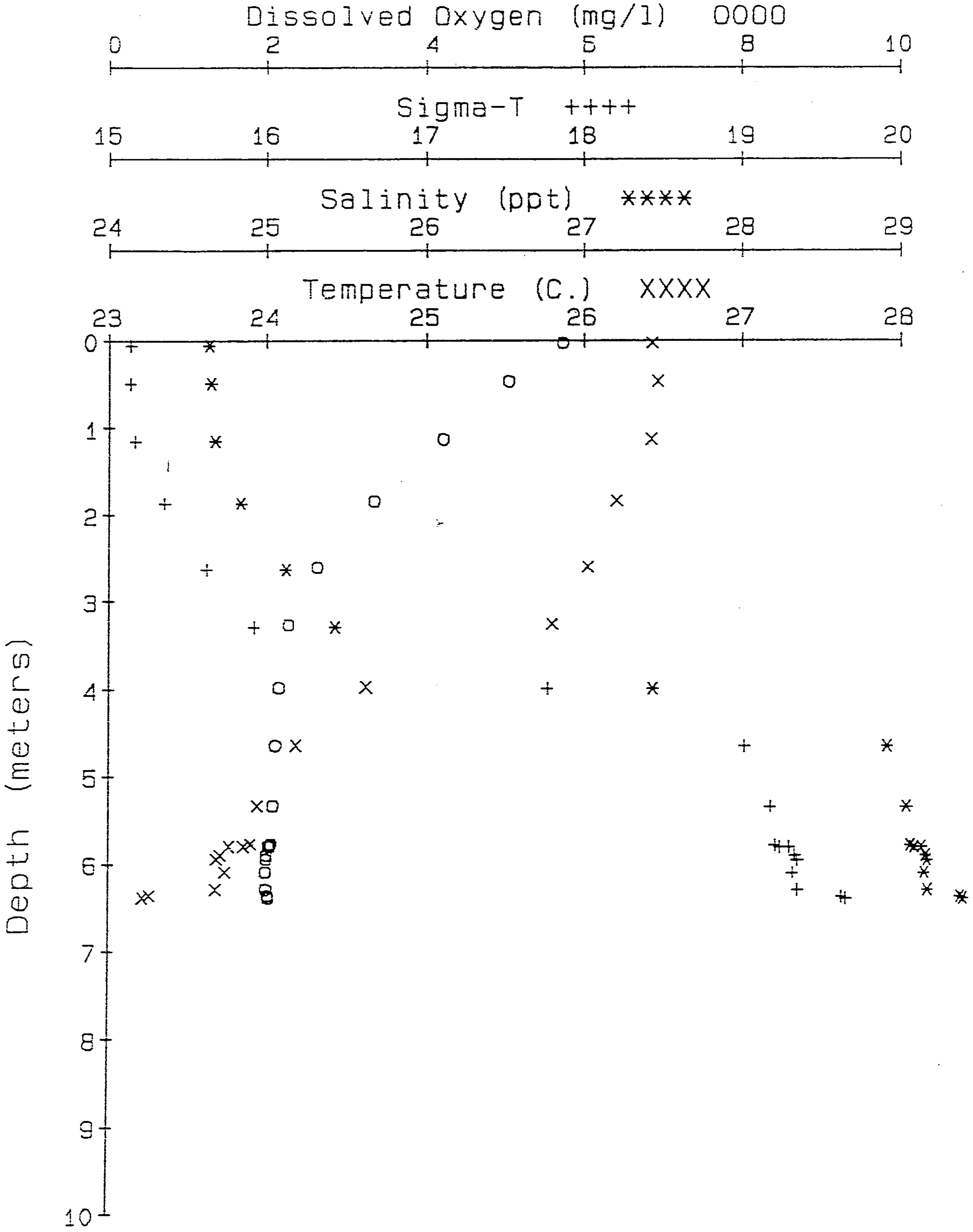
Station 5

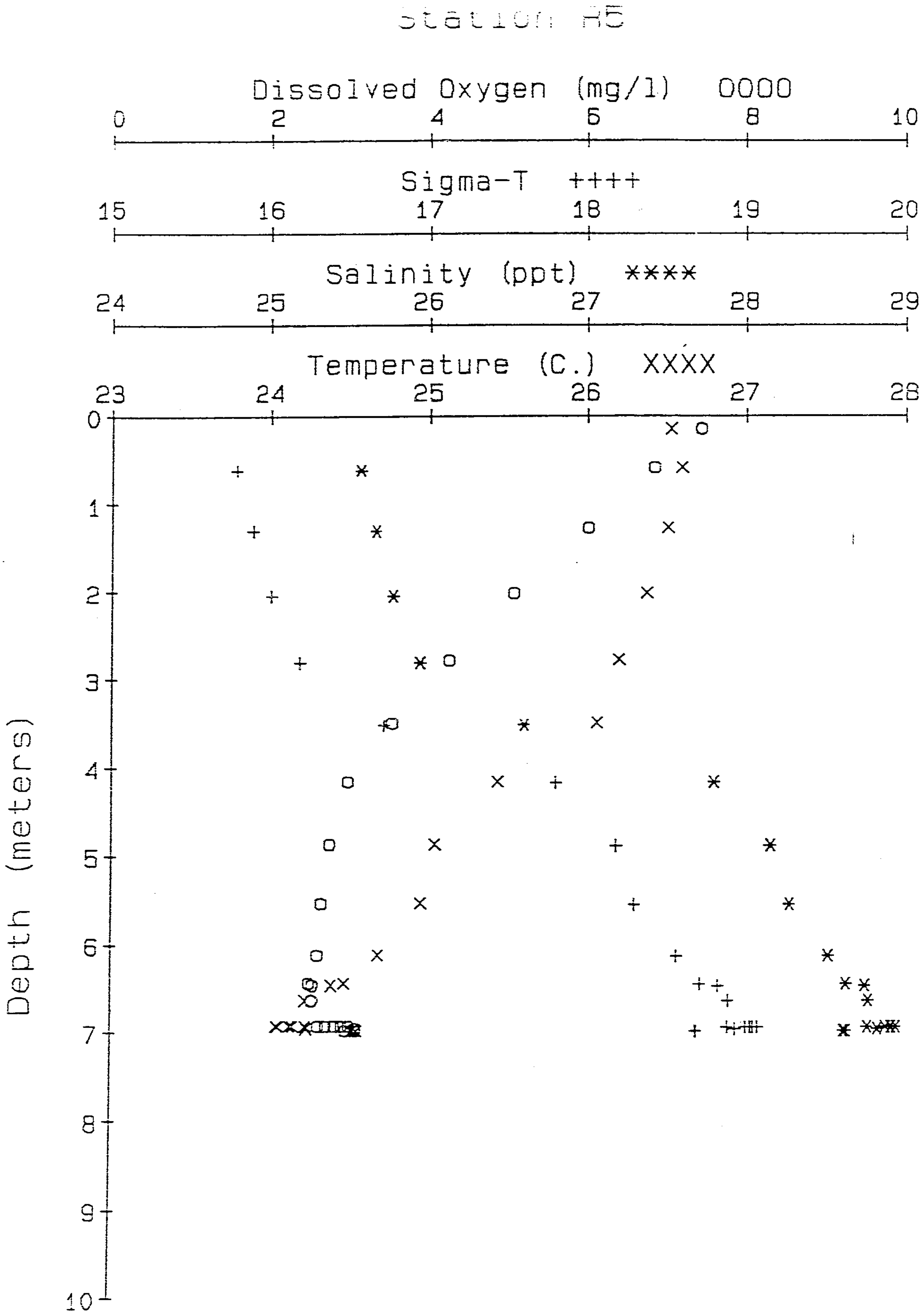

Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
26
27
28
29
30
31
Temperature (C.) XXXX
22
23
24
25
26
27
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station 5

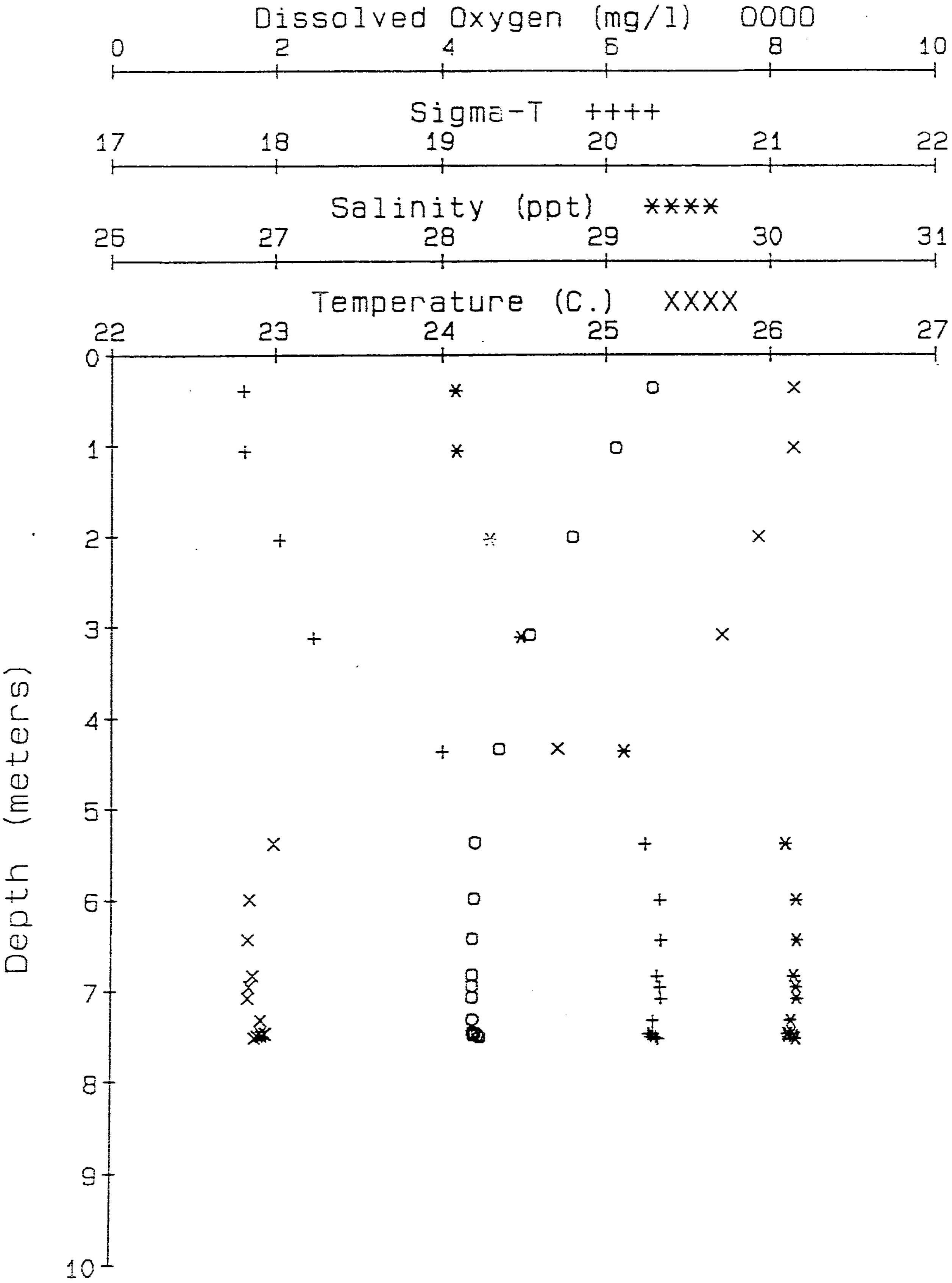

Dissolved Oxygen (mg/l) OOOO
0 2 4 6 8 10
Sigma-T ++++
17 18 19 20 21 22
Salinity (ppt) ****
26 27 28 29 30 31
Temperature (C.) XXXX
22 23 24 25 26 27
Depth (meters)
0 1 2 3 4 5 6 7 8 9 10

Station R6

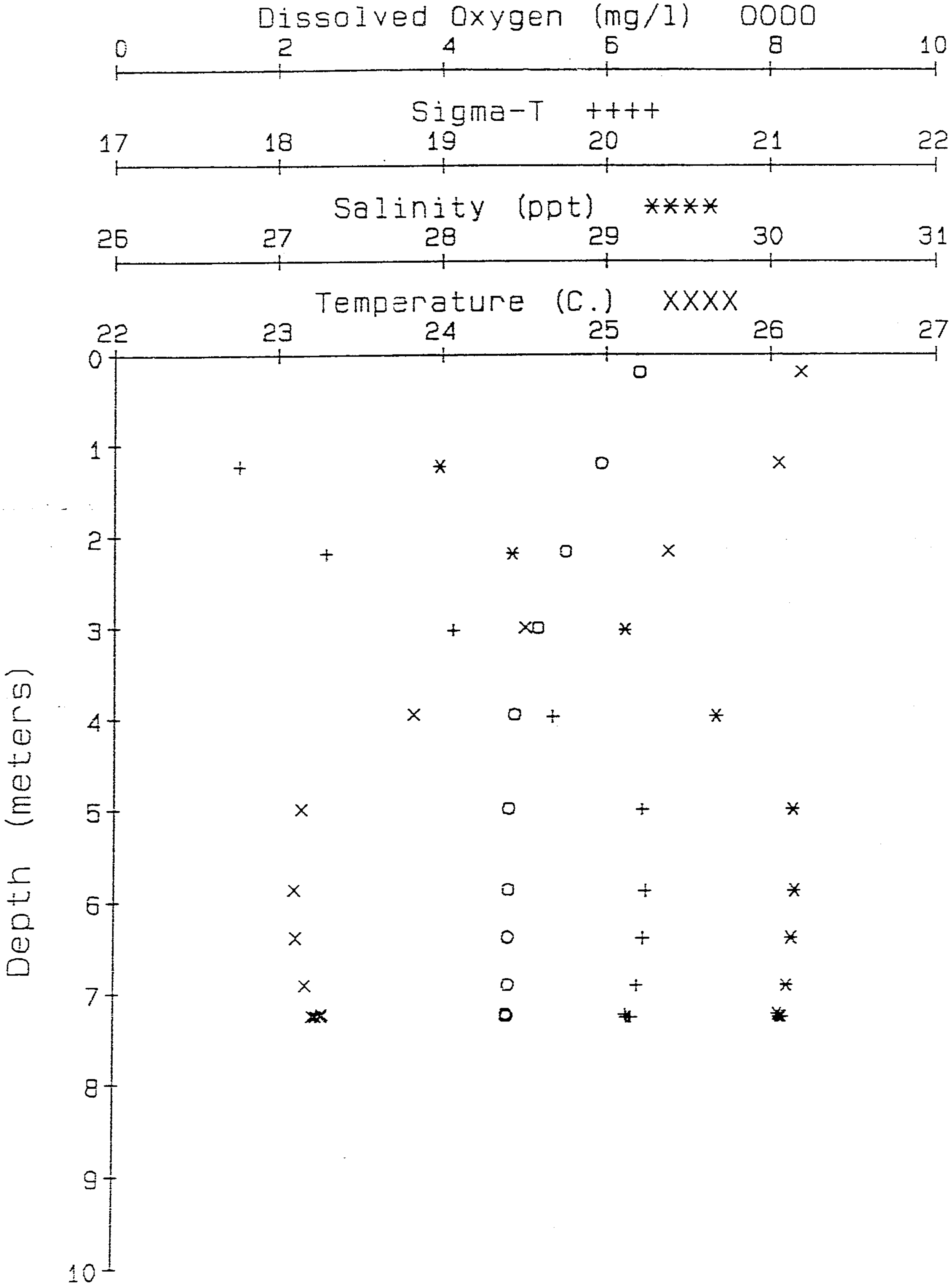

Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
24
25
26
27
28
29
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10


Station R5
Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
24
25
26
27
28
29
Temperature (C.) XXXX
23
24
25
26
27
28
0
1
2
3
4
5
6
7
8
9
10
Depth (meters)

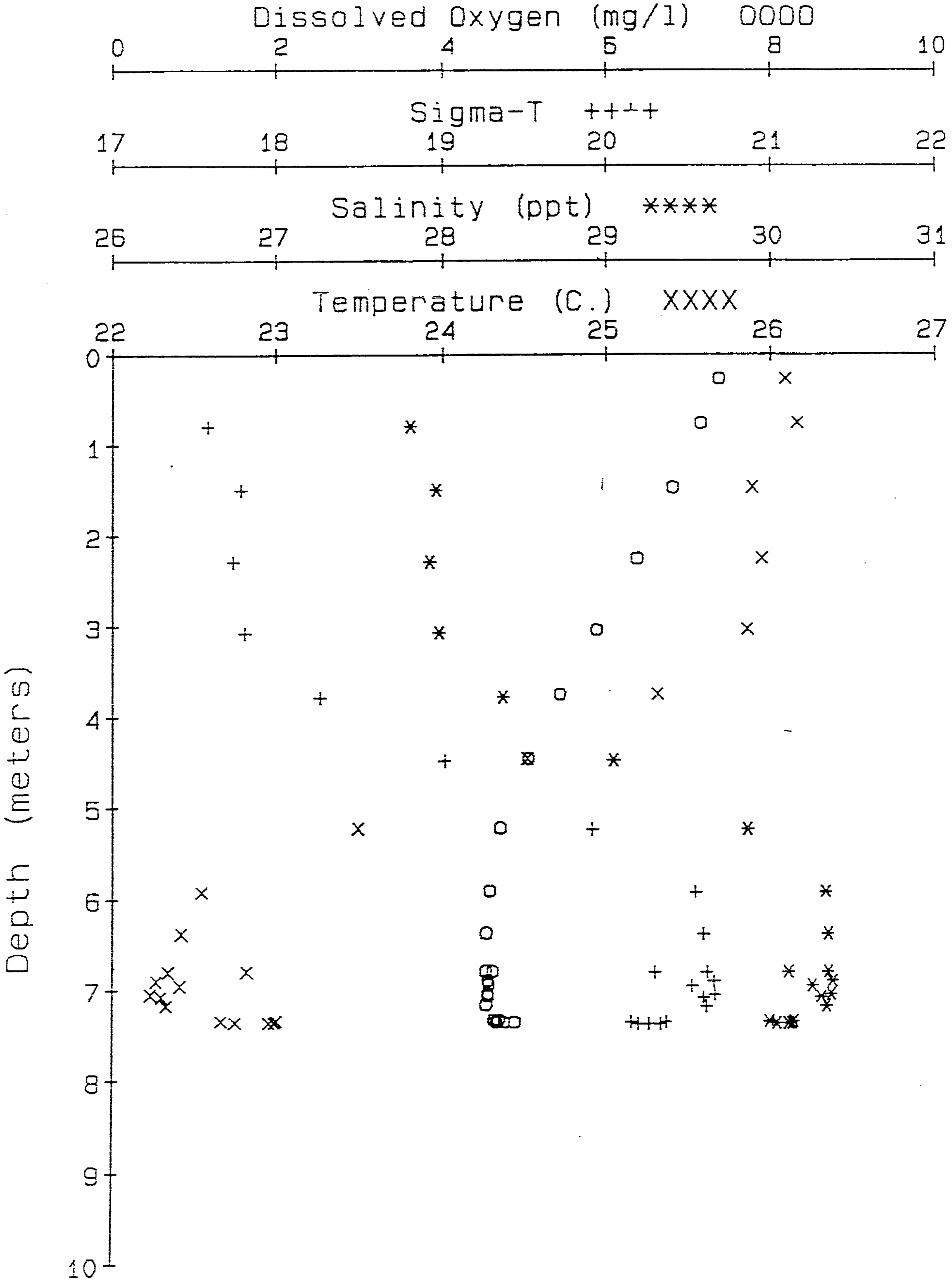
Station R4


Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
26
27
28
29
30
31
Temperature (C.) XXXX
22
23
24
25
26
27
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

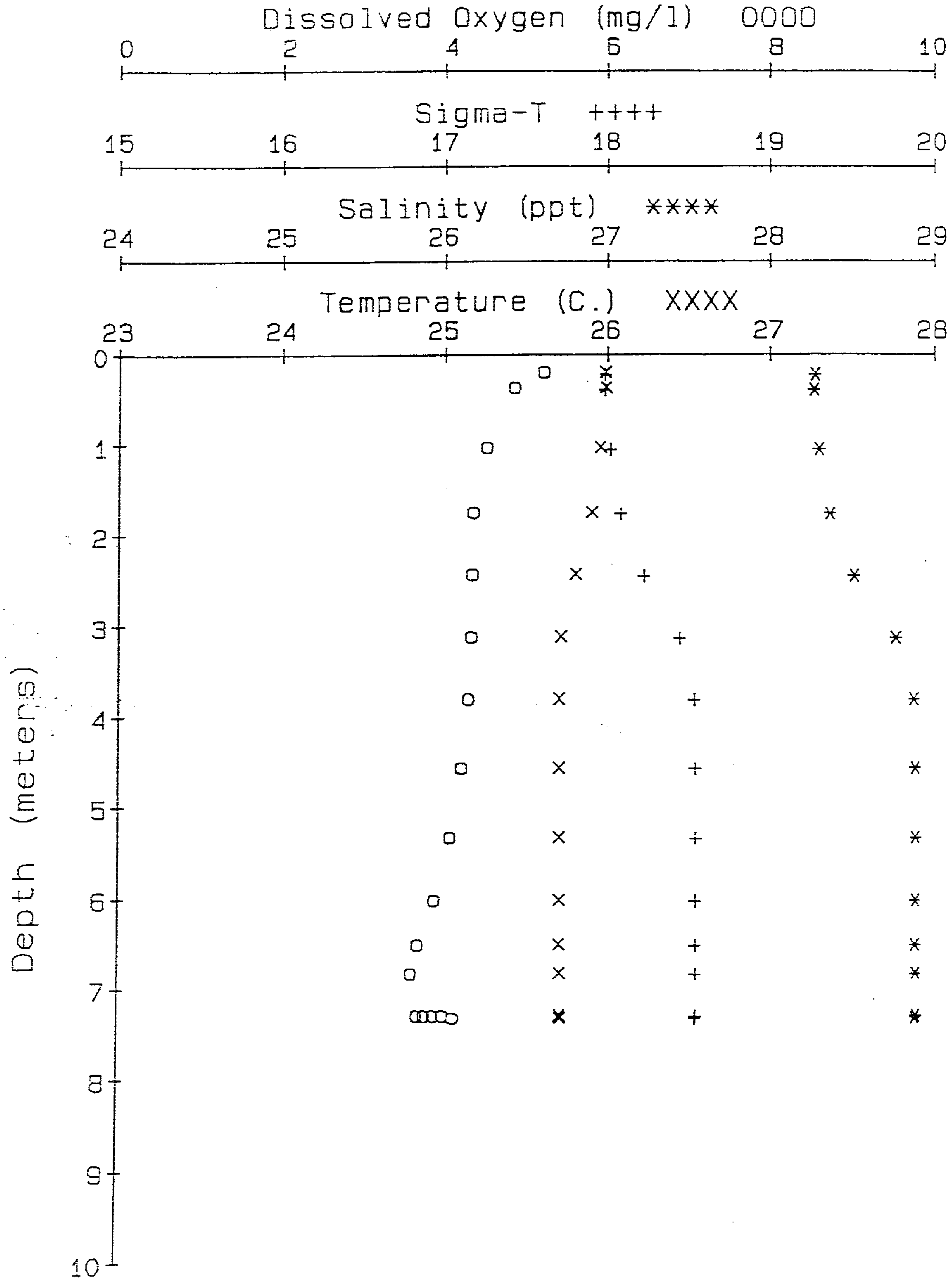
Station R3


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
17
18
19
20
21
22
Salinity (ppt) ****
26
27
28
29
30
31
Temperature (C.) XXXX
22
23
24
25
26
27
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

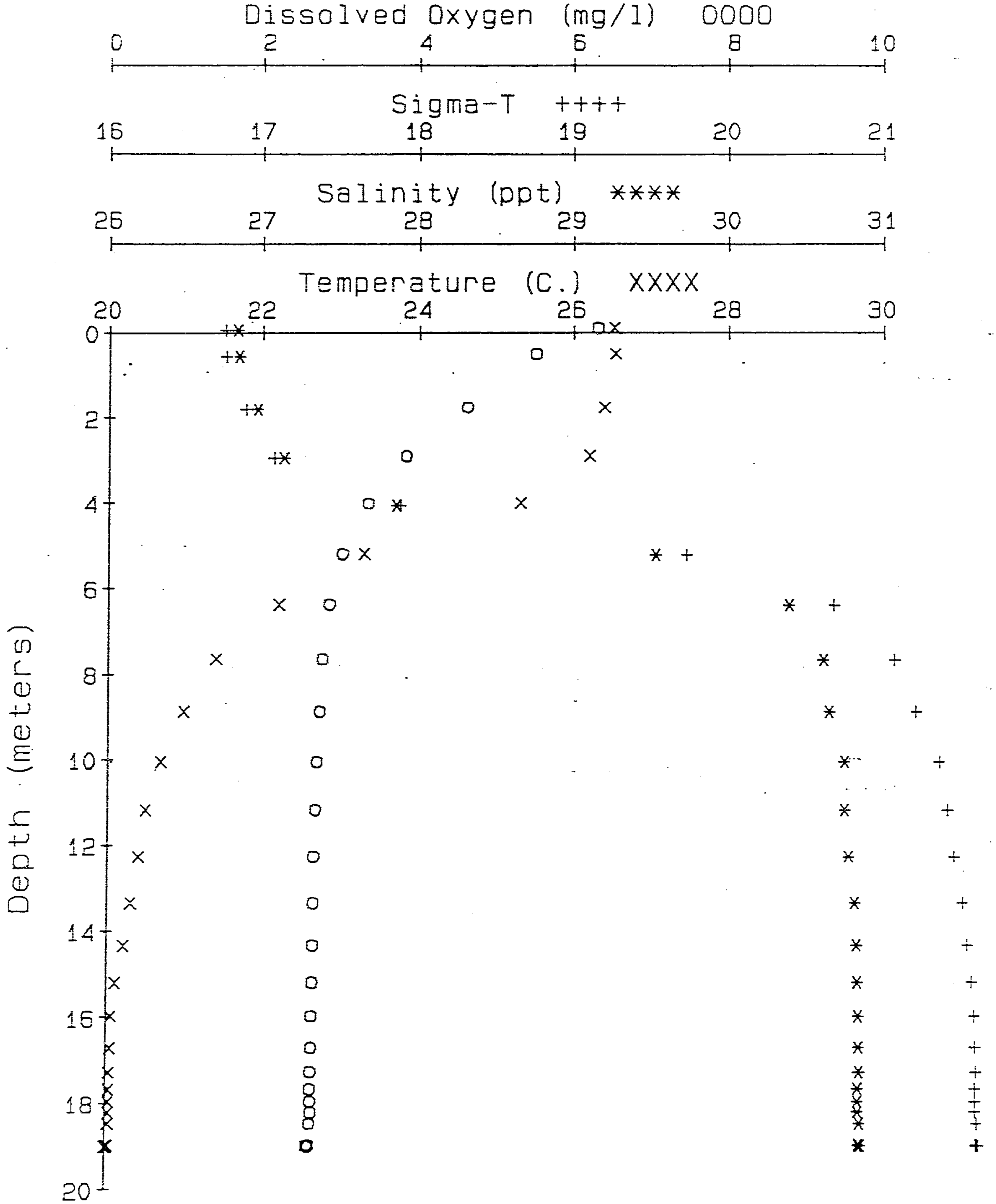
Station SB10



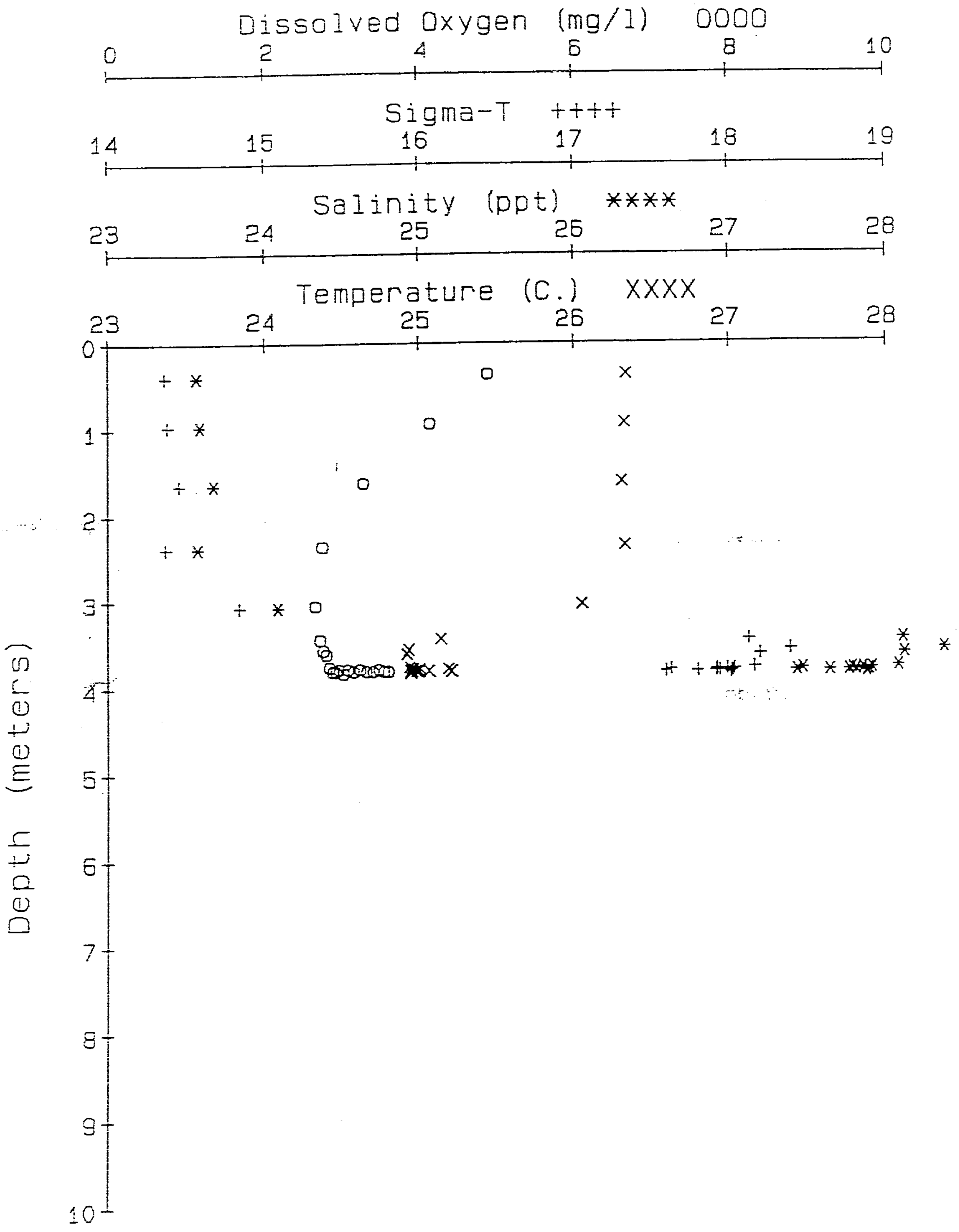
Station SB5


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
15
16
17
18
19
20
Salinity (ppt) ****
24
25
26
27
28
29
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

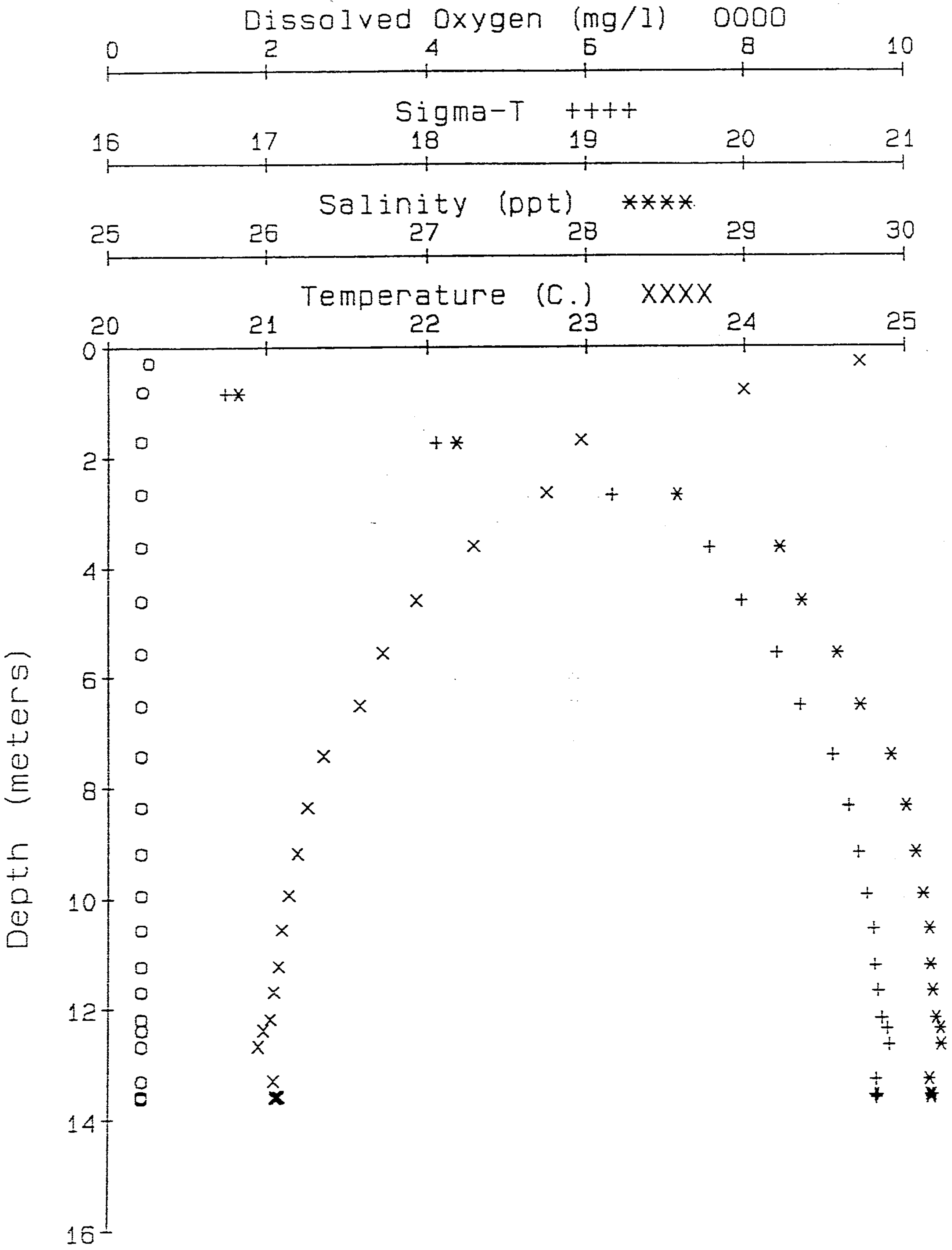
Station SB4


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
16
17
18
19
20
21
Salinity (ppt) ****
26
27
28
29
30
31
Temperature (C.) XXXX
20
22
24
26
28
30
Depth (meters)
0
2
4
6
8
10
12
14
16
18
20

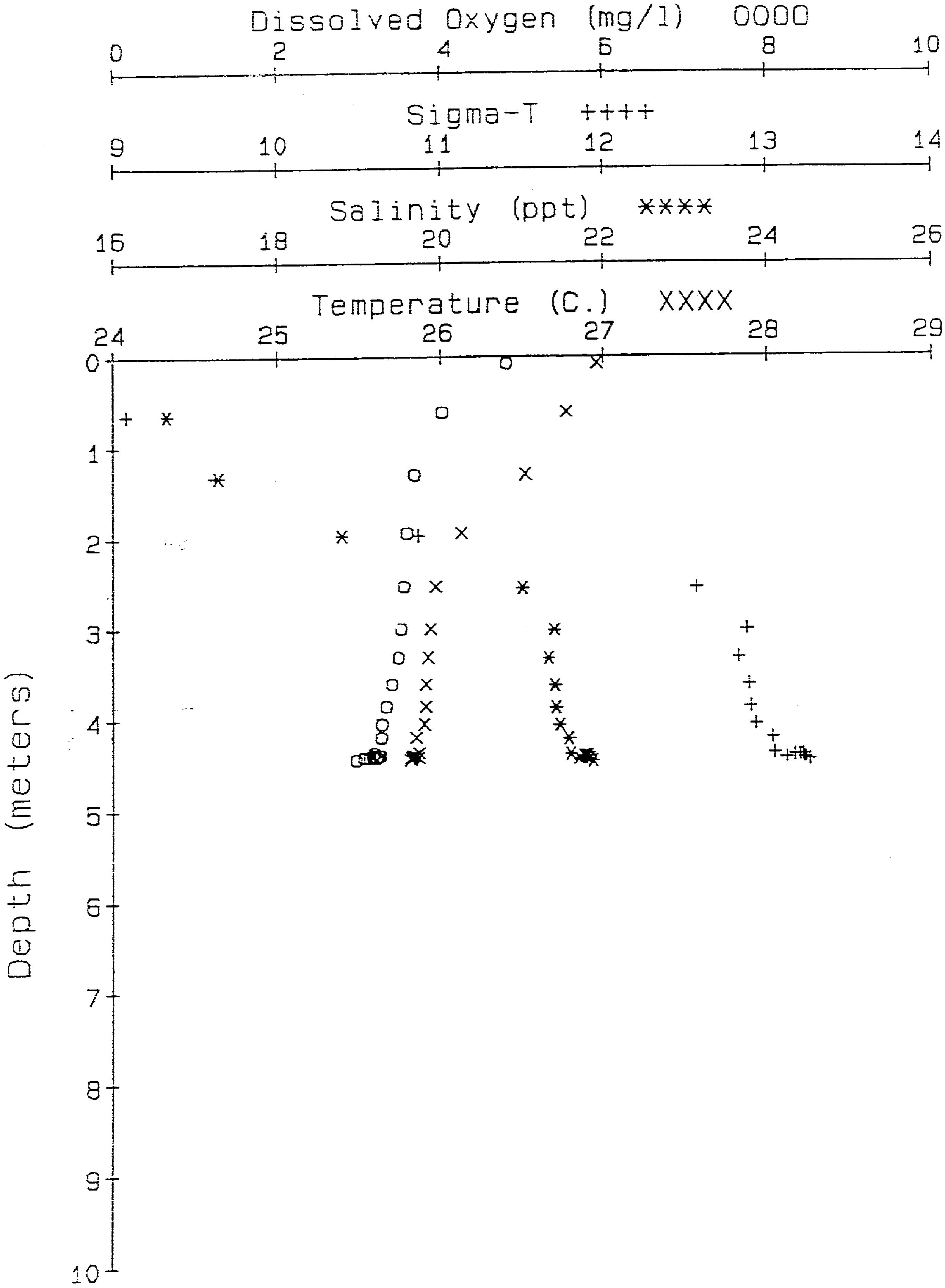
Station SB3


Dissolved Oxygen (mg/l) 0000
0
2
4
6
8
10
Sigma-T ++++
14
15
16
17
18
19
Salinity (ppt) ****
23
24
25
26
27
28
Temperature (C.) XXXX
23
24
25
26
27
28
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

Station SB2


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
16
17
18
19
20
21
Salinity (ppt) ****
25
26
27
28
29
30
Temperature (C.) XXXX
20
21
22
23
24
25
Depth (meters)
0
2
4
6
8
10
12
14
16

Station SB1


Dissolved Oxygen (mg/l) OOOO
0
2
4
6
8
10
Sigma-T ++++
9
10
11
12
13
14
Salinity (ppt) ****
16
18
20
22
24
26
Temperature (C.) XXXX
24
25
26
27
28
29
Depth (meters)
0
1
2
3
4
5
6
7
8
9
10

APPENDIX II

Vertical profiles of temperature, salinity, density (as sigma t) and dissolved oxygen at the Narragansett Bay REMOTS® stations, August 1988. Only the dissolved oxygen value measured at the bottom is valid; the other values obtained during ascent of the DO probe represent measurements taken before the instrument could equilibrate. The stations are grouped together and listed in the same order as they appear in Table 2-2.

5.) Calculations:

To calculate spores/gram sediment (wet weight), the following equation is used:

$$\frac{CE_T}{E_F S_E} \quad - \quad \text{spores/gram sediment}$$

where C - mean number of colonies counted (equals number of spores deposited on filter),

E_T - total extract volume, ml

E_F - volume extract filtered, ml, and

S_E - mass wet sediment extracted, gm.

2.) mCP Medium Preparation

The mCP method utilizes a highly specialized medium (mCP medium) that selectively germinates Clostridium perfringens spores with the nearly complete exclusion of other marine microbes. The medium is prepared by adding the following ingredients (in grams per 90 ml) to distilled water: tryptose, 3.0; yeast extract, 2.0; sucrose, 0.5; L-cysteine hydrochloride, 0.1; $MgSO_4 \cdot 7H_2O$, 0.01; bromocresol purple, 0.0004; and agar, 1.5. The ingredients are dissolved and the pH is adjusted to 7.6. After autoclaving at 121°C for 15 minutes, the base medium is cooled to 50°C and the following ingredients are added: D-cycloserine, 40 mg; polymyxin-B sulfate, 2.5 mg; indoxyl-B-D-glucoside (IBDG), 30 mg dissolved in 8 ml sterile distilled water; phenolphthalein diphosphate, 2.0 ml of a filter-sterilized, 0.5% solution; and $FeCl_2$, 0.2 ml of a filter-sterilized, 4.5% solution. The mCP medium is then dispensed in 5 ml quantities with a Cornwall pipet into Falcon 1007 60x15mm sterile petri dishes and stored aerobically at 4°C.

3.) Extract Dilutions and Filtrations

The mCP filtration method consists of two steps. First, a probe is run on 1-log dilutions of sediment extract to single plates (1 dilution to 1 plate). After an 18-20 hr anaerobic incubation at 45°C, the plates are counted to determine the approximate dilution at which the optimum 20-80 colonies are observed. The second step is to run 1/2-log extract dilutions to replicate plates from replicate sediment splits.

4.) Plate Counting

The plates are counted after an 18-20 hr anaerobic incubation at 45°C. Counting is performed using the standard procedures outlined in the literature cited. In situ presumptive confirmation for the presence of C. perfringens is indicated by exhibition of sucrose fermentation, acid phosphatase production, gelatin hydrolysis, and negative glucosidase production in colonies counted on each filter. Ultimate confirmation may be determined based on the testing for the following characteristics: gram-positive rod; obligate anaerobe; non-motile; fermentation of lactose, mannose, and sucrose with gas production; non-fermentation of cellobiose, mannitol, and salicin; stormy milk fermentation; production of lecithinase, gelatinase, and acid phosphatase; and sulfite and nitrite reduction to H_2S and nitrate, respectively.

APPENDIX I

Laboratory Methods for Clostridium perfringens Spore Enumeration

The following procedures for enumeration of *Clostridium perfringens* spores are based in general on the published methods of Bisson and Cabelli (1979) and Emerson and Cabelli (1982). In the Narragansett Bay study, the sodium metaphosphate modification (J. W. Bisson and V. J. Cabelli, personal communication) of the extraction procedure detailed by Emerson and Cabelli (1982) was employed.

1.) Sediment Extractions

The details of the sodium metaphosphate method used to extract the spores from sediment particulates have not been published and, at the request of the developers of the method (Drs. J. W. Bisson and V. J. Cabelli), will not be presented. However, as a quality control test of this method, randomly selected samples also were examined using the Iron Milk-MPN method detailed in St. John *et al*. (1982). Table 1-1 gives the results of this comparison.

Table 1-1. Comparison of *C. perfringens* recoveries by the sodium metaphosphate extraction-mCP method versus the Iron Milk-MPN method, using randomly-selected samples.

Station	Replicate	C. perfringens/gm Ext-MF[a]	C. perfringens/gm MPN[b]
R-4	3	472	640
C-2	1	394	330
SB-21	3	86	49
SB-12	1	1180	1300
SB-22	1	34	23
PR-1	3	29	33

---

[a] metaphosphate extraction followed by mCP membrane filtration
[b] Iron Milk-MPN method

The counts obtained by the two methods were converted to logarithms and tested using the standard t-test for paired comparisons. The resulting t-value of 0.733 was less than the critical t-value of 2.571 (at $p = 0.05$), indicating no significant difference in spore enumeration between the two techniques.

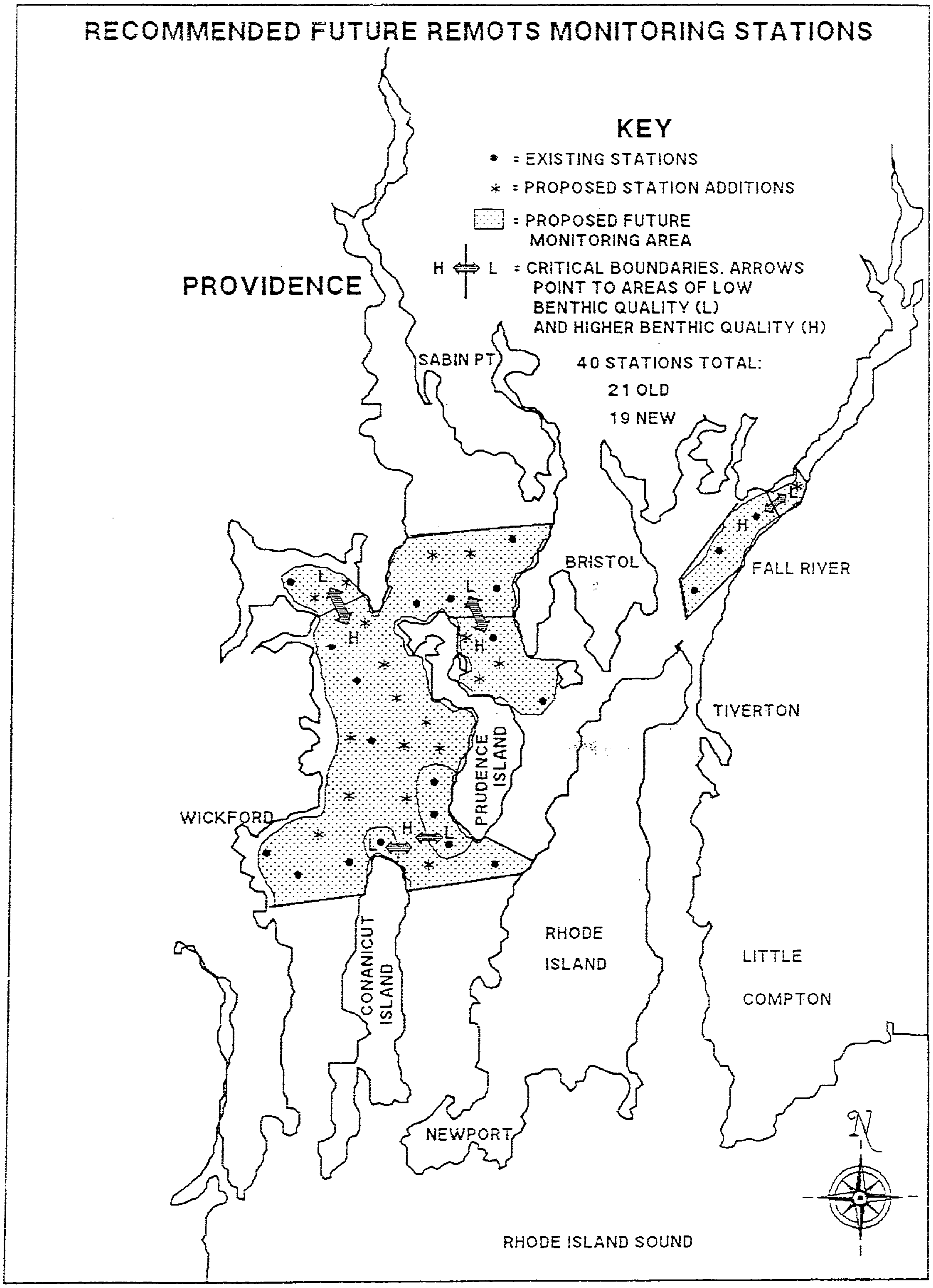


Figure 4-4. Recommended future REMOTS® monitoring stations in Narragansett Bay based on the results of the August 1988 reconnaissance survey.

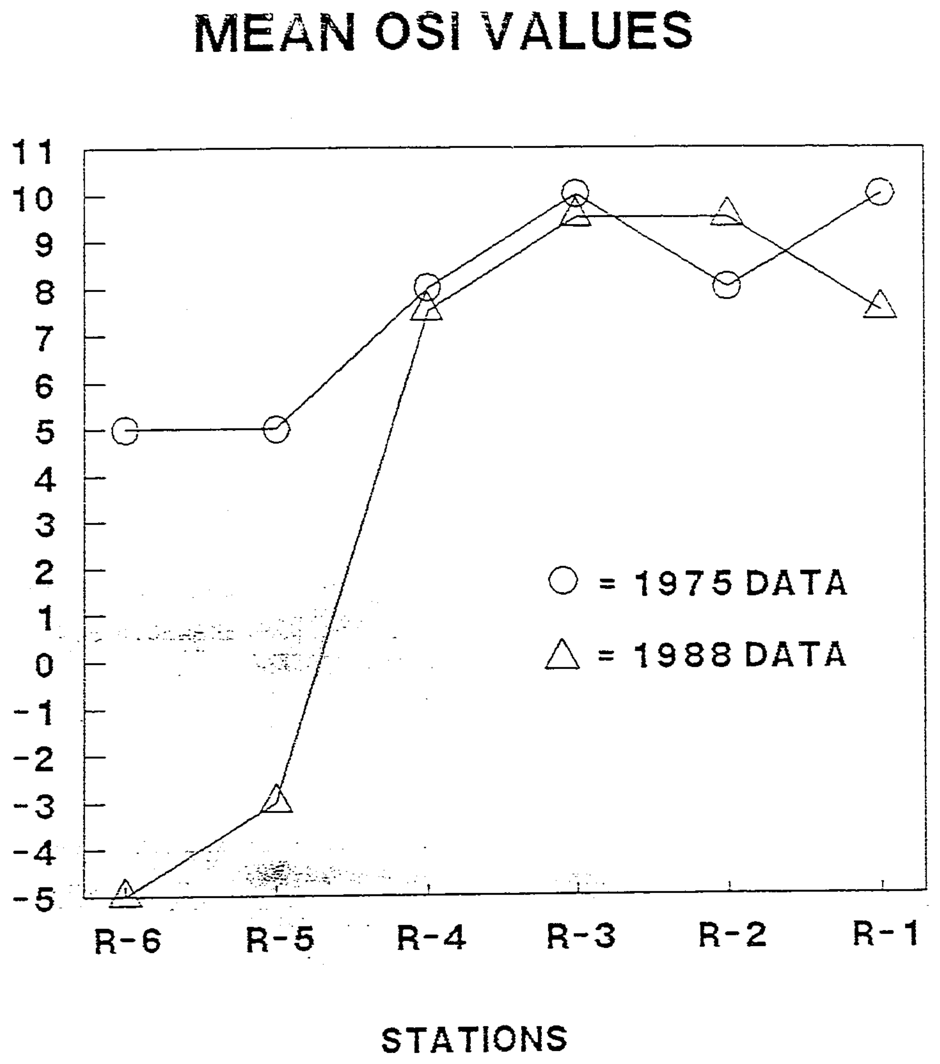


Figure 4-3. Mean OSI values at stations R-1 thru R-6 in 1975 and 1988.

Table 2-1, continued

DEPTH	COORDINATES LAT/LONG	DATE OCCUPPIED	DEPTH IN FT	DISSOLVED OXYGEN		
				WINK	YSI	REXN
R-6	41°44.900N 71°22.133W	08/16/88	20	----	1.6	2.2
SB-3	41°46.135N 71°22.175W	08/16/88	16	6.0	2.6	3.6
SB-2	41°48.545N 71°23.655W	08/16/88	41	0.0	0.2	0.4
SB-1	41°49.550N 71°23.000W	08/16/88	22	2.9	2.2	3.0
GC-1	41°39.166N 71°26.966W	08/17/88	7	6.1	5.3	5.8
GC-2	41°39.566N 71°26.616W	08/17/88	8	4.4	3.6	4.0
GC-3	41°39.916N 71°26.666W	08/17/88	12	----	3.3	4.1
AH-1	41°37.166N 71°24.850W	08/17/88	14	5.1	4.6	5.2
AH-2	41°37.416N 71°24.933W	08/17/88	12	6.0	6.0	6.1
AH-3	41°37.333N 71°24.700W	08/17/88	12	----	3.3	4.4
PR-1	41°39.116N 71°25.566W	08/17/88	3	7.0	5.8	5.9
PR-2	41°39.300N 71°25.883W	08/17/88	5	7.0	5.5	5.7
WC-1	41°41.750N 71°23.400W	08/17/88		4.7	1.4	10.5
WC-2	41°41.500N 71°23.500W	08/17/88	8	----	2.8	3.0
WC-3	41°41.150N 71°23.533W	08/17/88	9	5.1	4.0	4.0
SB-6	41°40.460N 71°25.230W	08/17/88	14	----	2.8	2.2
AC-1	41°41.666N 71°27.000W	08/17/88	1	12.8	13.4	13.7
AC-2	41°41.616N 71°26.866W	08/17/88	6	----	6.7	7.8
AC-3	41°41.383N 71°26.750W	08/17/88	2	10.0	10.1	10.2
SB-16	41°27.510N 71°22.305W	08/18/88	137	6.6	----	3.7
SB-15	41°30.530N 71°20.715W	08/18/88	90	----	----	4.0
C-2	41°31.500N 71°20.167W	08/18/88	109	7.1	----	4.0

Table 2-1, continued

DEPTH	COORDINATES	DATE	DEPTH	DISSOLVED OXYGEN		
	LAT/LONG	OCCUPPIED	IN FT	WINK	YSI	REXN
SB-13	41°35.434N 71°18.289W	08/18/88	70	----	----	4.1
C-3	41°37.250N 71°17.867W	08/18/88	60	6.5	----	4.2
SB-11	41°38.770N 71°18.410W	08/18/88	43	----	----	4.3
SB-12	41°37.914N 71°16.114W	08/18/88	70	6.5	----	4.2
7	41°39.316N 71°14.742W	08/18/88	31	----	----	3.7
SB-18	41°39.205N 71°14.109W	08/18/88	30	5.7	----	4.1
C-6	41°41.483N 71°12.038W	08/18/88	20	----	----	3.5
SB-17	41°40.790N 71°11.945W	08/18/88	35	4.4	----	3.3
SB-19	41°34.300N 71°13.120W	08/18/88	25	----	----	----
SB-20	41°29.395N 71°13.090W	08/18/88	38	6.1	----	----
SB-22	41°25.895N 71°16.535W	08/18/88	80	----	----	----
SB-21	41°24.855N 71°22.635W	08/19/88	100	5.9	----	3.4
SB-9	41°28.070N 71°24.305W	08/19/88	55	----	----	5.0
1	41°32.083N 71°24.158W	08/19/88	37	6.0	----	4.6

Table 2-2

Station subsets used for graphic presentation in this report.

Providence River Reach	Shallow Embayments	Open Bay
SB-1	WC-1,2,3	1, 2, 3, 4, 7
SB-2	SB-6	R-2A
SB-3	AC-1,2,3	R-2
SB-4	GC-1,2,3	R-1
SB-5	PR-1,2	C-2
SB-10	AH-1,2,3	C-3
R-3		C-5
R-4		C-6
R-5		SB-8
R-6		SB-9
5		SB-21
6		SB-7
C-1		SB-14
		SB-13
		SB-15
		SB-16
		SB-11
		SB-12
		SB-18
		SB-17
		SB-19
		SB-20
		SB-22
		MF

Table 2-3

Calculation of the REMOTS® Organism-Sediment Index value

CHOOSE ONE VALUE:

Mean RPD Depth	Index Value
0.00 cm	0
> 0 to 0.75 cm	1
0.76 to 1.50 cm	2
1.51 to 2.25 cm	3
2.26 to 3.00 cm	4
3.01 to 3.75 cm	5
> 3.75 cm	6

CHOOSE ONE VALUE:

Successional Stage	Index Value
Azoic	-4
Stage I	1
Stage I → II	2
Stage II	3
Stage II → III	4
Stage III	5
Stage I on III	5
Stage II on III	5

CHOOSE ONE OR BOTH IF APPROPRIATE:

Chemical Parameters	Index Value
Methane Gas Present	-2
No/Low Dissolved Oxygen**	-4

REMOTS® ORGANISM-SEDIMENT INDEX = Total of above subset indices

RANGE: -10 to +11

** Note: This is not based on the Winkler or polarigraphic electrode measurements. It is based on the imaged evidence of reduced, low reflectance (i.e., high oxygen demand) sediment at the sediment-water interface.

Table 3-1

Ecologically Important Dissolved Oxygen Ranges As Determined From Permanently Stratified Low-Oxygen Marine Basins (From Rhoads And Morse, 1971)

Dissolved Oxygen Range (mg/ℓ)	Facies
> 3.0	Aerobic
3.0 to 0.41	Hypoxic*
0.4 to 0.14	Dysaerobic
< 0.14	Anaerobic

* The hypoxic facies has been added to the Rhoads and Morse (1971) basin model by Dr. Barbara Welsh, University of Connecticut, to include responses of high metabolic rate demersal or benthic megafauna.

Table 3-2

Ranking of station clusters based on critical OSI values, sediment concentrations of C. perfringens spores, and near-bottom dissolved oxygen concentrations. Station ranking within each cluster is not intended; comparisons are to be made between clusters. Station attributes within each cluster are as follows:

A = OSI >+6, Spore count <100, D.O. >3 mg/ℓ
B = OSI <+6, Spore count <100, D.O. >3 mg/ℓ
C = OSI >+6, Spore count >100, D.O. >3 mg/ℓ
D = OSI <+6, Spore count >100, D.O. >3 mg/ℓ
E = OSI <+6, Spore count <100, D.O. <3 mg/ℓ
F = OSI <+6, Spore count >100, D.O. <3 mg/ℓ

These station groupings are mapped in Figure 3-21.

Least degraded<-->Most degraded

A	B	C	D	E	F
SB-10	C-1	R-4	SB-3	SB-6	SB-1
SB-8	SB-9	SB-5	R-5		SB-2
SB-21	PR-1	SB-11	5		R-6
SB-19	AH-1	4	R-3		
	AH-2	R-2A	GC-1		
	AC-1	R-2	GC-2		
1[*]	AC-2	3	GC-3		
SB-22[*]	AC-3	2	PR-2		
SB-20[*]	WC-2	R-1	SB-7		
		SB-13	C-5		
		C-2	SB-14		
		SB-15	WC-1		
		SB-16			
		SB-12			
		C-3			
		7			
		SB-18			
		C-6			
		SB-17			

---

[*] These stations lacked OSI values, but clearly represented least degraded habitat. Stations WC-3, AH-3, SB-4 and 6 were omitted because they lacked OSI values and could not otherwise be classified. Station MF was omitted because C. perfringens analyses were not performed there.

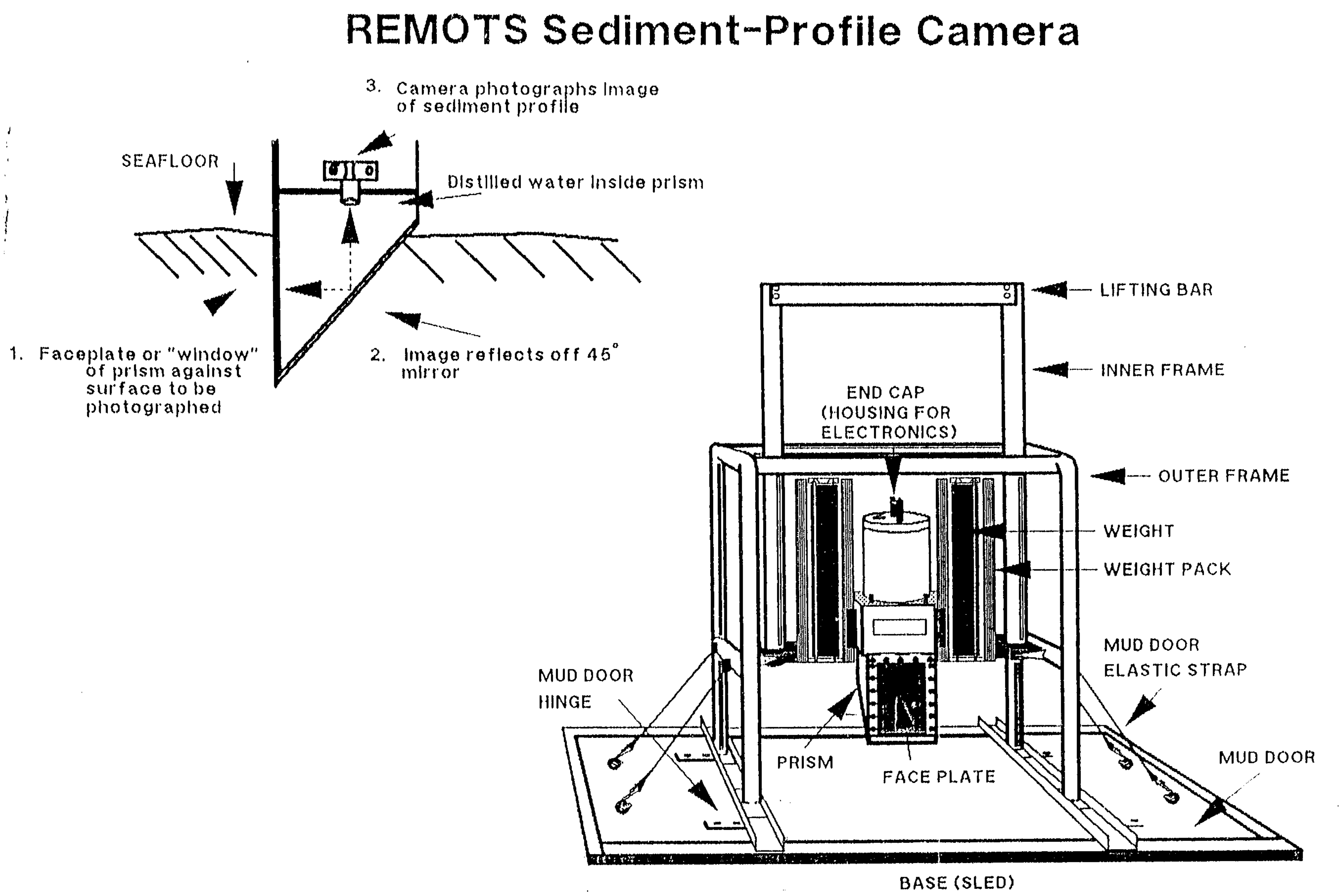


Figure 2-2. The Benthos Model 3731 sediment-profile camera used for REMOTS® image acquisition.

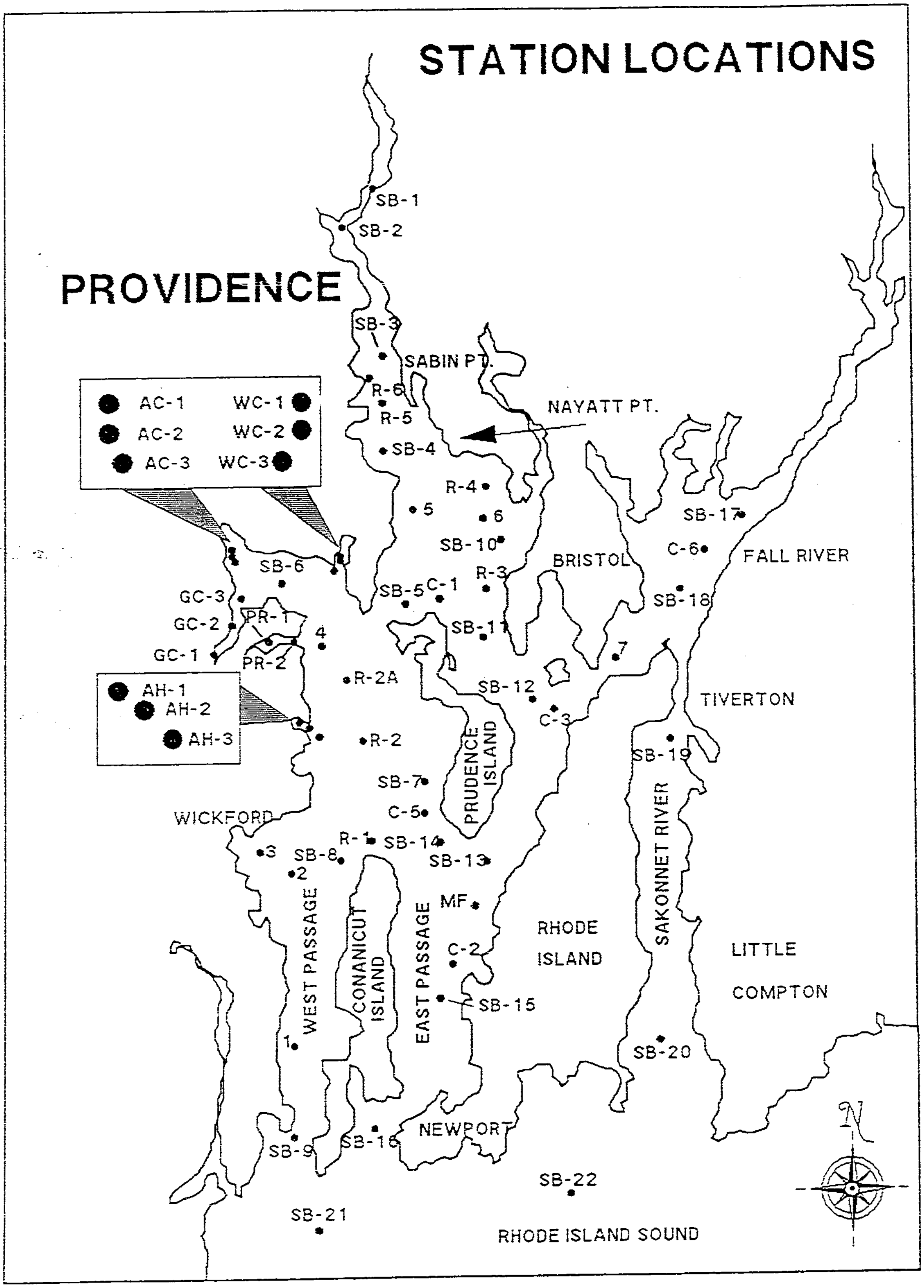


Figure 2-1. Map of stations occupied during the REMOTS® synoptic survey of Narragansett Bay, 15 to 19 August 1988. See the text for descriptions of the station name abbreviations. Warwick Cove (WC), Apponaug Cove (AC), and Allen Harbor (AH) stations are shown in the two enlarged panels.

```
                    REMOTS DATA SHEET
                  Science Applications


PROJECT: NARRAGANSETT BAY 8/88             STATION: SB-5/4
FIELD DATE: 8/16/88                                FRAME #: 4
Measurements By: ArG                     Time of Photo: 9.:39

                  Data Record #: 1

************* PHYSICAL - CHEMICAL PARAMETERS *************

1. Grain Size:
    Major Mode: ≥4 φ    Range: ≥4-3 φ

2. Total Prism Penetration Depth:
    Minimum: 16.42 cm.      Maximum: 17.91 cm.     Average: 17.17 cm.

3. Surface Boundary Roughness: 2.24 cm. ------ Biogenic

4. Mud Clasts
     # of Clasts: 0
     Average Diameter: 0 cm.            Status: NA

5. Mean Redox Depth: 1.39 cm.

6. Redox Rebound (former distance from sed. surface): Not Present
7. Methane Gas Pockets: Not Present
    Number: 0       Area: 0 sq. cm.
  Min. Range: 0 cm.   Max. Range: 0 cm.   Average Depth: 0 cm.

8. Low Dissolved Oxygen in Overlying Water: No
9. Dredged Material thickness (cm.): Not Present
10. Additional Measurement: 0 cm.        Label: NA

11. Comment: BHERM?LRG VD@SURF&@DPTH


******************** BIOLOGICAL PARAMETERS ********************

12. Epifauna: None Visible

13. Tube Density (#/linear cm.): 0
14. Tube Type: NA

15. Fecal Pellet layer:
  Min. Thickness: 0 cm.  Max. Thickness: 0 cm.  Average: 0 cm.

16. Microbial Aggregations Present?: 0
17. Feeding Voids --     Average Depth: 0 cm.
     Number: 0      Minimum Depth: 0 cm.      Maximum Depth: 0 cm.

18. Faunal Dominants:
19. Apparent Species Richness:
20. Successional Stage: STAGE 3

21. Organism-Sediment Index: 7
```

Figure 2-3. A representative REMOTS® data sheet.

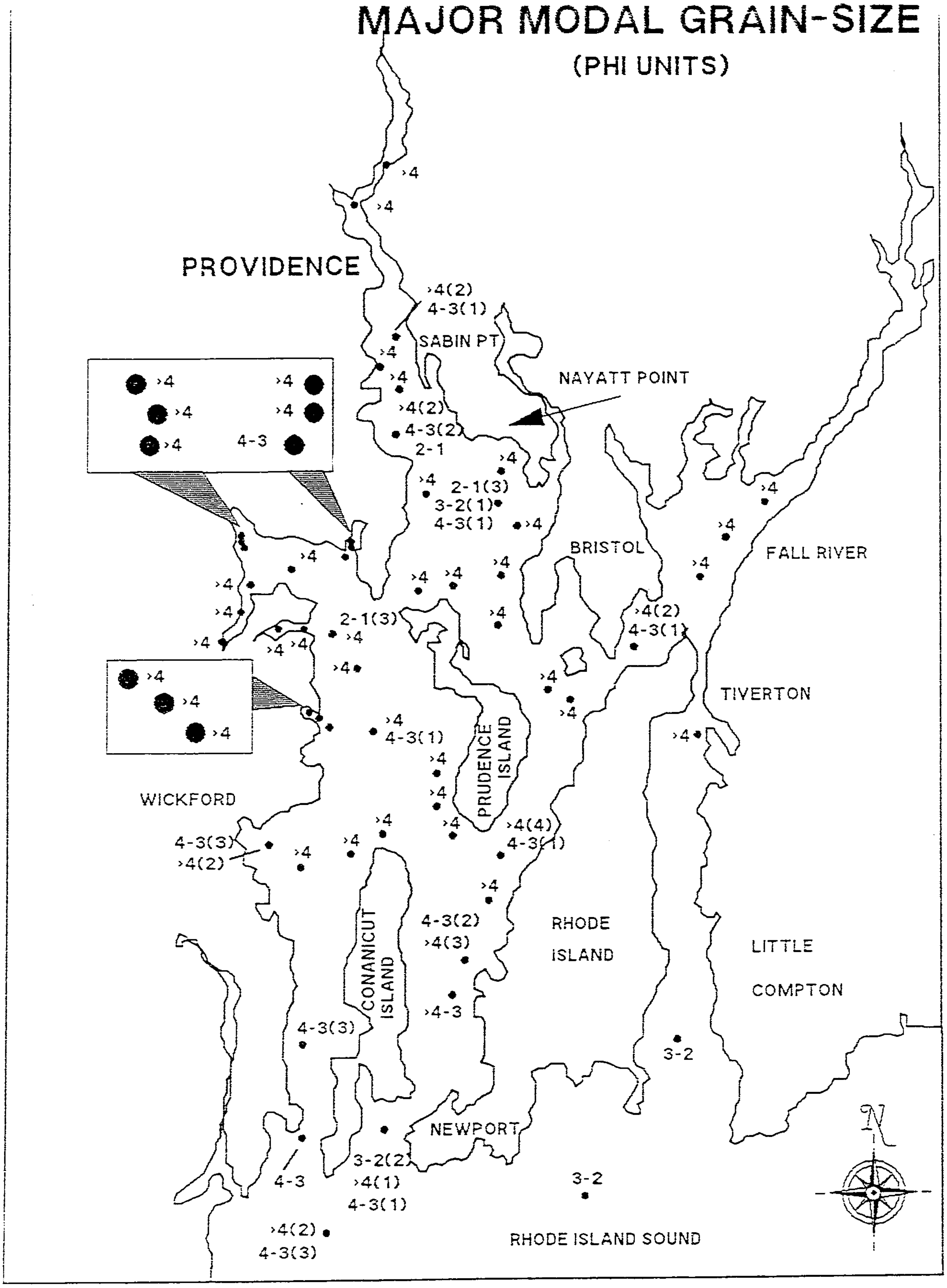


Figure 3-1. Map of sediment grain-size major mode (in phi units) at the Narragansett Bay REMOTS® stations, August 1988. At most stations, all of the replicate REMOTS® images showed the same grain-size major mode. At stations where this does not apply, the number in parentheses is the number of replicates

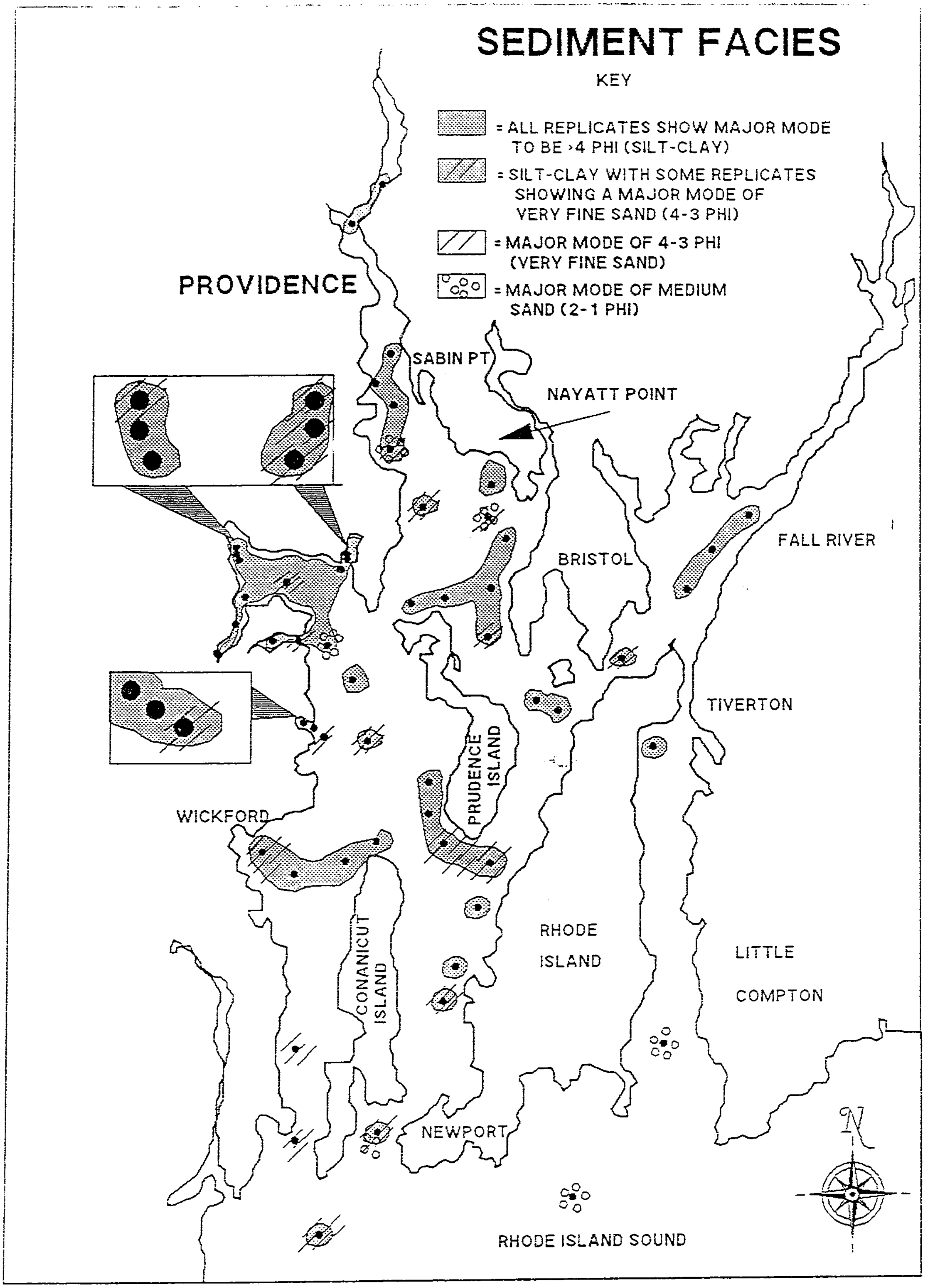


Figure 3-2. Map of sediment facies in Narragansett Bay based on the REMOTS® results depicted in Figure 3-1.

Figure 3-3. REMOTS® image from Providence River Reach station 6, showing a mixture of very fine to medium sand and numerous shells at the sediment surface. Scale of image = 1X.

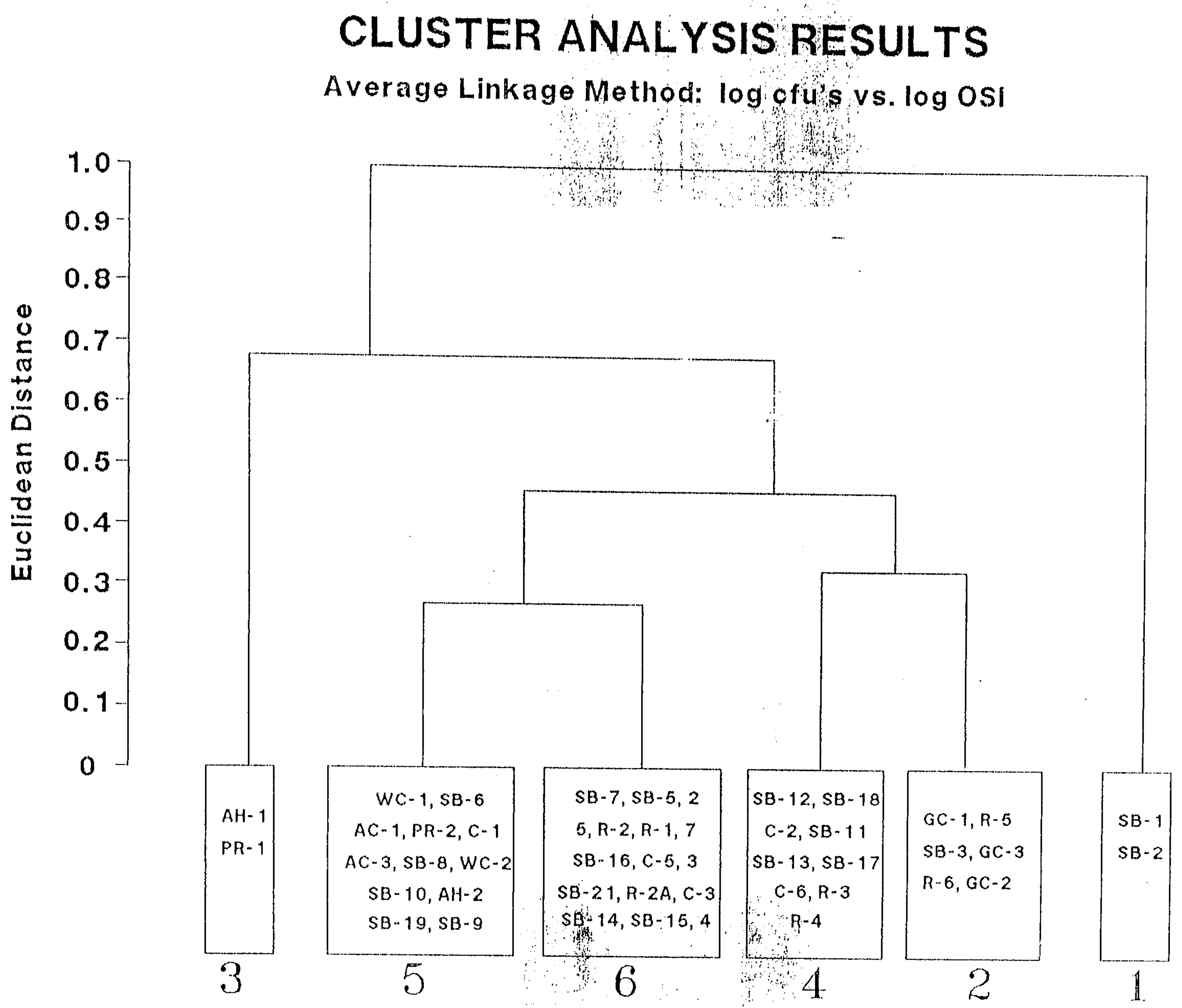


Figure 3-20. Dendrogram showing graphical results of aggolomerative clustering algorithm; data were log-transformed to remove effects due to scale differences. Groups are ranked numerically from most severely disturbed (1) to least disturbed (6).

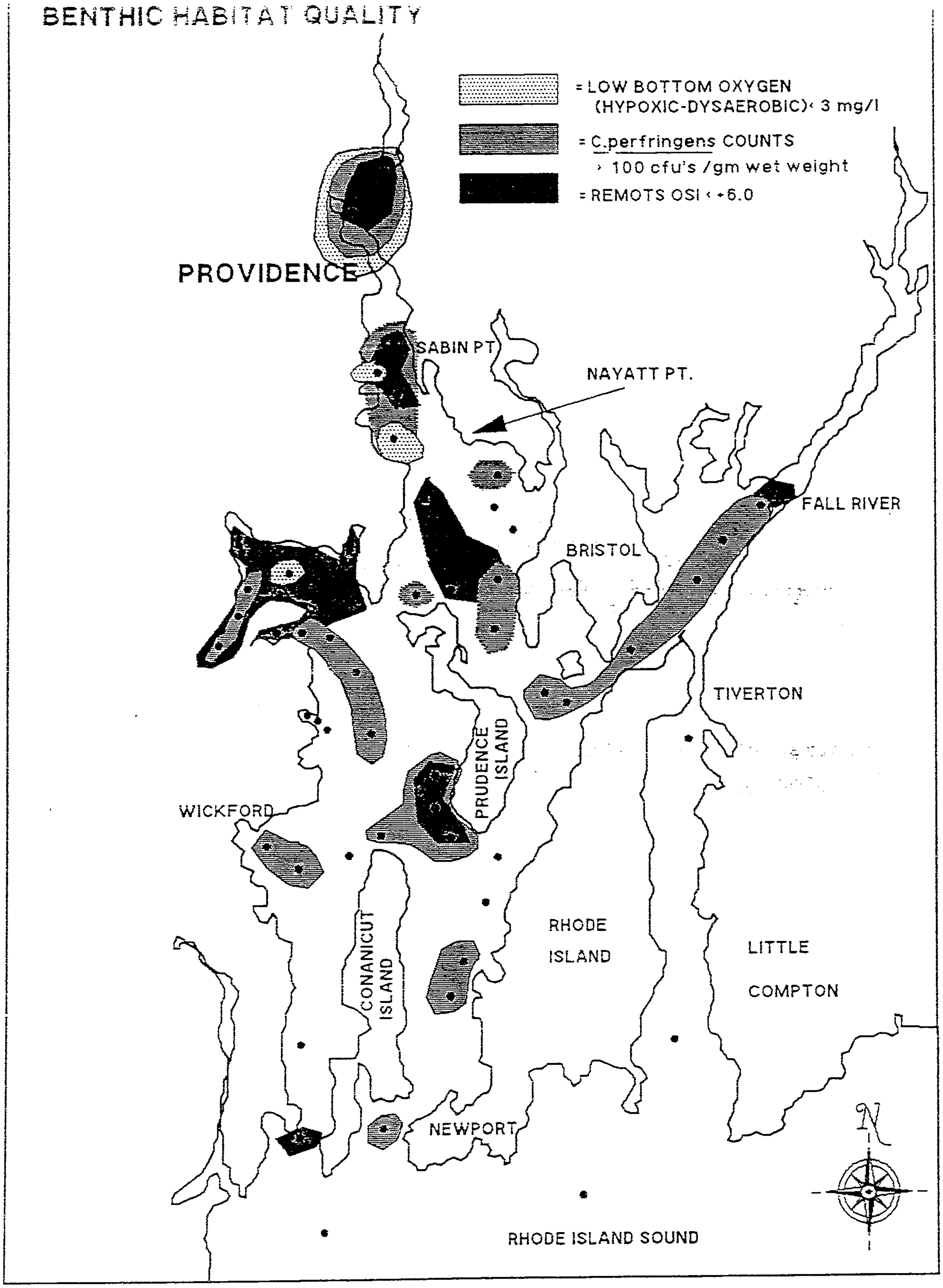


Figure 3-21. Map of benthic habitat quality based on the combination of the REMOTS® OSI values, *C. perfringens* spore counts and near-bottom dissolved oxygen concentrations at the Narragansett Bay REMOTS® stations occupied in August 1988 (see also Table 3-2).

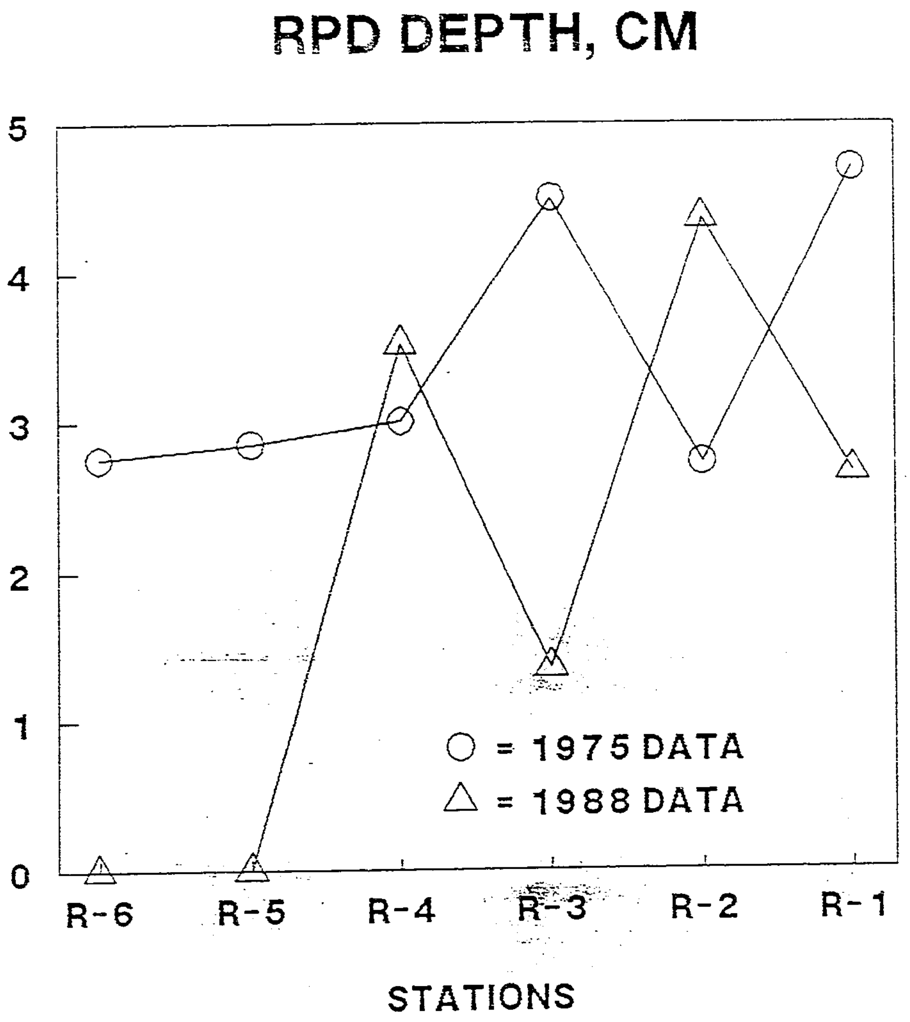


Figure 4-1. Mean apparent RPD depths (centimeters) measured at stations R-1 thru R-6 in 1975 and 1988.

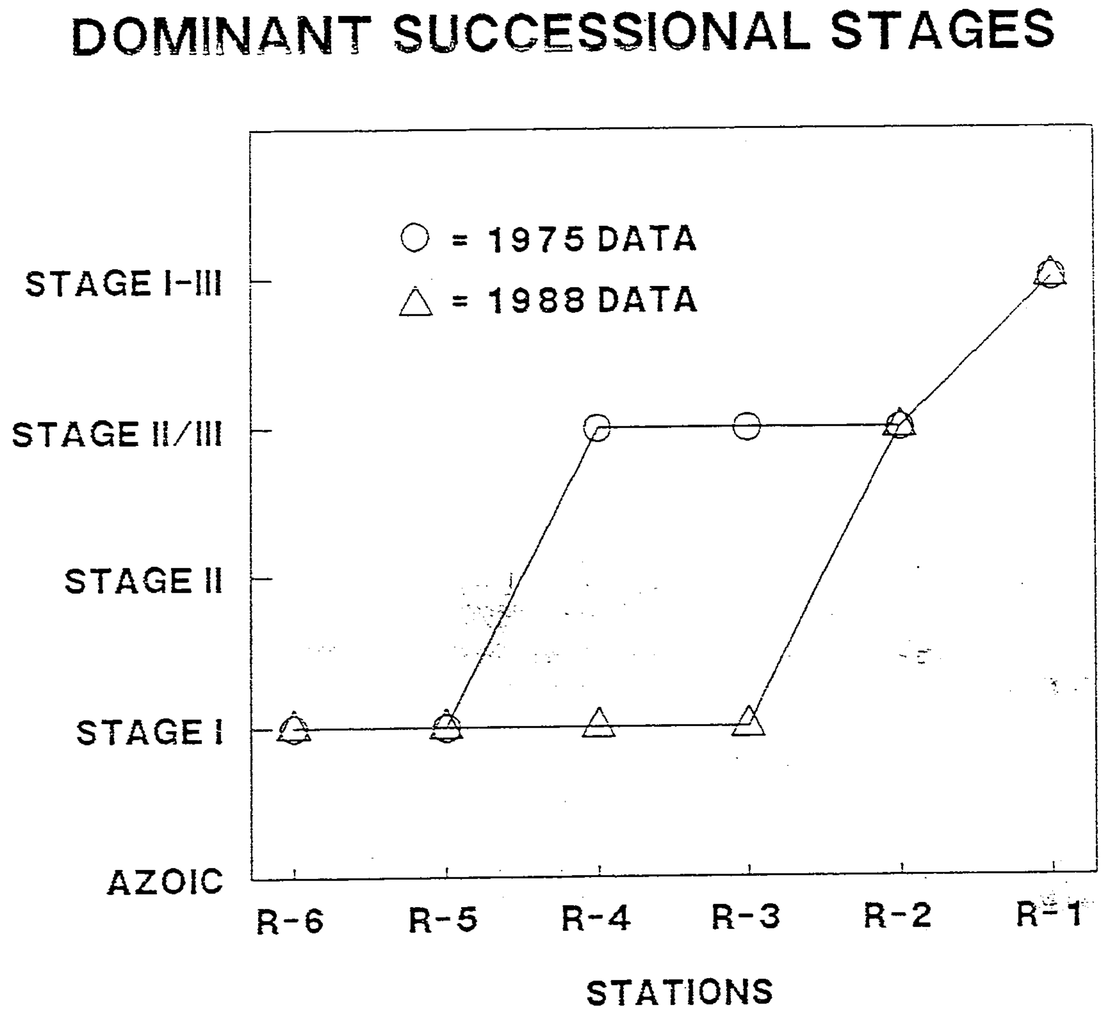


Figure 4-2. Dominant successional stages at stations R-1 thru R-6 in 1975 and 1988.