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SAN FRANCISCO BAY SEDIMENT QUALITY SURVEY AND ANALYSES

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EXECUTIVE SUMMARY

1.) Most stations within South and Central San Francisco Bay and San Pablo Bay show evidence of either recent sediment erosion, redistribution, or deposition. The distribution of these sedimentological features is related to the location of protected inlets and embayments, shoals, and channels.

2.) Organically-enriched sites were identified for each portion of the Bay on the basis of low REMOTS® Organism-Sediment Indices (indicative of shallow apparent Redox Potential Discontinuity depths coupled with low order successional infaunal assemblages), high Clostridium perfringens counts, and high total organic carbon values. Stations in Redwood Creek (70), Oakland Inner Harbor (32), and in southwest San Pablo Bay off Petaluma River (4) represent the poorest benthic habitat quality as defined by this combination of parameters. If hypoxia occurs on a seasonal basis, we would expect the locations identified in Table 4-1 as stressed areas to be prime candidates for the onset of this phenomena. Station 27, located in Sante Fe Channel in Richmond Inner Harbor, is included in this ranking, but it is unique in terms of the apparent source of impacts.

3.) Using the same key parameters as above, stations located in San Pablo Bay north of Wilson Point (18), in the central bay off Brooks Island (19), and in the south bay off Candlestick Point (38) were identified as having the highest benthic habitat quality. In addition, stations were grouped using an unweighted average linkage clustering routine. The resulting clusters confirm the differences between the four "worst" and three "best" stations identified above. We recommend that NOAA consider locating long-term monitoring stations at some or all of these 7 stations.

4.) The contoured densities of C. perfringens allows identification of accumulations of sewage effluent and also allows estimations of dispersion patterns of this effluent. The contoured REMOTS® Organism Sediment Index values allow identification of physical disturbance gradients as well as sites of organic enrichment.

5.) All dissolved oxygen values were found to be within the aerobic range. The water column was either weakly stratified or unstratified at all stations. Future dissolved oxygen monitoring should only be done during those parts of the year when water temperatures are highest and the water column is the most stratified.

6.) We feel that REMOTS® imaging has an important role to play in the National Status and Trends Program and recommend its use for both reconnaissance mapping and permanent station monitoring. The major attribute of REMOTS® is that it rapidly provides in-situ information on processes and conditions that are critical for interpreting data acquired by other sampling techniques and the Sediment Quality Triad.

I. INTRODUCTION

NOAA's Status and Trends program was designed to monitor the environmental quality of many parts of the nation's coastal and estuarine zones; the program's main emphasis to date has involved chemical analyses of samples of sediment, fish and bivalves. A recent development has been the evaluation of various additional tests to determine the biological significance of the contamination identified by the ongoing chemical analyses. As part of this additional testing, NOAA has authorized 15 sediment samples from the San Francisco Bay area to be tested for toxicity using five different types of bioassays. All of these chemical and bioassay techniques are intended to assess the effects of toxic chemicals. In order to augment these tests, NOAA has expressed interest in adding other monitoring techniques which can rapidly assess sediment textural properties, the effect of nutrient over-enrichment, associated bottom water hypoxia, and responses of infaunal benthos to these variables. These new techniques are intended to augment and compliment the evaluation of sediment quality as measured by traditional chemical and bioassay methods.

In order to provide NOAA with rapid information on these additional assessments, SAIC performed a REMOTS® sediment-profile camera survey at 69 stations in San Francisco Bay from 3 to 9 February 1987. Additional samples were taken at each station to provide ancillary information about sediment grain-size (percent fines), sediment total organic carbon (TOC) and total organic nitrogen (TON), densities of Clostridium perfringens spores, and water column temperature, salinity and dissolved oxygen; these data were obtained to assist in the interpretation of sediment quality as determined from analysis of the REMOTS® images.

The key to interpreting REMOTS® images is to deduce dynamics from imaged structures. The designation of different areas in San Francisco Bay as "stressed" was based on both physical and biological evidence from the REMOTS® images. In some cases, stresses were related to scouring and erosion of bottom currents or deposition of organically-enriched material; other images showed evidence of biological disturbance from predation or foraging activities, or a combination of the above. The main objective of this survey was to map gradients in sediment characteristics related to both natural and anthropogenic processes. The data used to map these gradients were also used to identify areas which are experiencing eutrophication and potential hypoxia. REMOTS® parameters are capable of identifying both physically disturbed and organically-enriched areas, but the technique cannot uniquely identify the major source of the labile organic matter causing high sediment-oxygen demand. For this reason, densities of *C. perfringens* spores were obtained in order to identify sewage-derived organic matter.

II. METHODS

2.1 Data Acquisition

Field operations were conducted in San Francisco Bay from the vessel PROPHECY from 3 through 9 February 1987. Of the seventy stations specified in Task Order 1050, a single station (35) could not be occupied because the access was blocked by a unmanned drawbridge. Station locations were designated by the NOAA to provide reconnaissance data on the wide range of benthic environments which are present in San Francisco Bay. These environments include shallow fine-grained areas, deep fine-grained and coarse-grained high energy channel habitats, active and inactive disposal sites, creeks and river mouths, and ports and inner harbors.

2.1.1 Navigation and Data Logging

Navigational control of the survey vessel during this project was provided by the SAIC Integrated Navigation and Data Acquisition System (INDAS). This particular system consisted of a Northstar 6000 LORAN-C receiver interfaced to a Hewlett Packard Series 200 model 20 microcomputer. While providing positive control of the survey vessel through steering commands and a visual plot of the ship's position in relation to the station location which are relayed to the helmsman through a video display, the system also records the ship's position both on paper and magnetic disk either continuously or in response to specific events. This makes the return to the same sampling station at a future time quite simple. LORAN-C was chosen as the positioning system in this project, because it is a totally self-contained, passive system, requires no shoreside personnel to tend transponders, and is thus more cost-effective. The drawback to using LORAN-C is that the system is inherently less accurate in geodetic positioning than other systems. The LORAN-C lines of position (LOP) which are drawn on most nautical charts are theoretical in nature and are typically calculated by computer. They are corrected for commonly known sources of error, such as over-land transmission paths and secondary phase corrections; this results in a positioning system with an accuracy on the order of + 100 meters. While navigating offshore, errors of this magnitude may be acceptable. However, when sampling close inshore at stations located less than 100 to 500 meters apart, it is highly desirable to obtain positioning with somewhat greater accuracy. Therefore, a calibration procedure was utilized during this project which resulted in a much more accurate LORAN-C positioning system than is usually possible. In order to calibrate LORAN-C, it is necessary to position the LORAN-C receiver at a location whose position is known with a high degree of certainty. With the resulting calibration factors applied to the incoming LORAN-C coordinates, the ship's geodetic position may be calculated to an accuracy of ± 20 meters.

In the San Francisco Bay region, the theoretical LORAN-C coordinates for several U.S. Geodetic Survey benchmarks were calculated using the SAIC INDAS software. The geodetic position of these marks were obtained from the U.S. Corps of Engineers Survey Group (Sausalito, CA). The calculated coordinates were compared to the actual coordinates observed on the LORAN-C receiver when placed at each of these marks and calibration factors for various portions of the bay system were calculated. The location and name of each benchmark recovered during the pre-cruise calibration procedure are listed below:

Location	Benchmark Name
Redwood City	Station #8
San Mateo	Point San Mateo #2
San Bruno	Point San Bruno
Treasure Island	Towell #5
Vallejo	Semple
San Quinten	Quinton
Point Pinole	Point Pinole

In this sampling program, INDAS was used to record positional information for all samples obtained (e.g. each REMOTS® replicate, hydrographic cast, and sediment sample).

2.1.2 REMOTS® Images and Dissolved Oxygen Measurements

REMOTS® sediment-profile images were taken using a modified Benthos Model 3731 Sediment-Profile camera (Benthos Inc. North Falmouth, MA; Figure 2-1). The camera consists of a wedge-shaped prism with a plexiglass face plate; light is provided by an internal strobe. The back of the prism has a mirror mounted at a 45 degree angle to reflect the profile of the sediment-water interface up to the camera, which is mounted horizontally on the top of the prism. The prism is filled with distilled water, and because the object to be photographed is directly against the face plate, turbidity of the ambient seawater is never a limiting factor. The camera prism is mounted on an assembly that can be moved up and down by producing tension or slack on the winch wire. As the camera is lowered, tension on the winch wire keeps the prism in the up position. The support frame hits the bottom first, leaving the area to be photographed directly under the prism undisturbed.

Once the camera's frame touches the bottom, the scientist on deck constantly maintains sufficient slack in the winch wire to compensate for any movement of the surface vessel due to winds or currents; this insures that the REMOTS® frame is not moved or disturbed in any way while the camera is taking a picture. If for any reason sufficient slack on the winch wire cannot be maintained while the camera is on the bottom, it is readily apparent on deck; the camera is retrieved and another image is taken. This insures that any physical disturbance of the sediment detected in a REMOTS® image is not an artifact caused by the instrument itself. This slack on the winch wire also allows the prism to vertically cut the seafloor. The rate of fall of the optical prism into the bottom is controlled by an adjustable "passive" hydraulic piston. This allows the optical prism to enter the bottom at approximately 6 cm/sec. This slow fall rate insures that the descending prism does not impact the bottom at a high rate and therefore minimizes disturbance of the sediment-water interface. The bottom edge of the optical prism (shaped like an inverted periscope) consists of a blade which cuts a vertical profile of the bottom. The prism is driven several centimeters into the seafloor by the weight of the assembly. The camera trigger is tripped on impact with the bottom, activating a 13-second time delay on the shutter release; this gives the prism a chance to obtain maximum penetration before a photo is taken. As the camera is raised to a height of about ten feet from the bottom, a wiper blade automatically cleans off any sediment adhering to the prism faceplate; the film is automatically advanced by a motor drive, the strobes are recharged, and the camera can be lowered for another replicate image.

The REMOTS® camera was fitted with a Yellow Springs Instrument (YSI) dissolved oxygen (DO) probe (Figure 2-1) to allow DO measurements to be made 1 cm above the seafloor as each replicate image was obtained. During deployment, the DO data were recorded directly from the YSI meter in the deck box. This configuration was also used to obtain water column DO measurements by lowering the camera at specified intervals during the first deployment at each station. Between stations, the probe was removed from the camera mount and recalibrated using the Air Calibration Technique (YSI, 1982). Because the salinity at each station was not known at the time of DO probe deployment, all DO readings were taken with the YSI unit set for freshwater. In the laboratory, these DO values were corrected for the actual salinity at each station and depth obtained by the conductivity, temperature, and depth (CTD) cast. This correction procedure is described in section 2.2.

2.1.3 CTD and Depth Measurements

A STD-12 Applied Microsystems CTD was used to obtain conductivity and temperature profiles as a function of depth at each station. This instrument was lowered to within 1 meter of the seafloor. At the end of each field day, the data from this internally-recording unit was retrieved using an HP-85 microcomputer. A Standard Communications Horizon Model DS-2 digital depth sounder was used to record the depth at each sample location.

2.1.4 Sediment Samples (Total Organic Carbon, Total Organic Nitrogen, percent fines, and Clostridium)

At each station, an alcohol-rinsed Ponar grab was deployed to obtain the required sediment samples; care was taken to obtained an undisturbed sample, and the grab was discarded if surface disturbance was apparent. The top cm of one half of the grab was sampled using an alcohol-rinsed and flamed spatula and the sediment was placed in autoclaved opaque bottle for later *Clostridium* spore enumeration. The top cm of the other half of the grab was sampled and placed in a plastic bag for later analyses of TOC, TON, and percent fines. All sediment samples were stored on ice and shipped to the laboratory immediately after completion of the field work.

2.2 Data Analysis

2.2.1 REMOTS® Image Analysis

REMOTS® 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 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 22 different variables for each REMOTS® image obtained. Before all measurements from each REMOTS® image are stored on disk, a summary display is made on the screen so the operator can verify if the values stored in memory for each variable are within expected range; if anomalous values are detected, software options allow remeasurement before storage on disk. All computer data disks are backed-up by redundant copies at the end of each analytical day. All data stored on disks are printed out on data sheets for editing by the principal investigator and as a hard-copy backup of the data stored on disk; a separate data sheet is generated for each REMOTS® image. All data sheets are edited and verified by a senior-level scientist before being approved for final data synthesis, statistical analyses, and interpretation.

Disk storage of all REMOTS® parameters allows any variable of interest to be compiled, sorted, graphed, or compared statistically. In addition, the REMOTS® analysis files are merged with the INDAS positional data. This allows any REMOTS® parameters to be plotted (and contoured, if warranted) on base maps of the survey area.

A full discussion of the specific measurement techniques for the REMOTS® parameters indicated on the data sheets is presented in Appendix I; a finalized data sheet for each REMOTS® image analyzed in this survey is provided in Appendix II. The interpretive rationale for several of the more important REMOTS® measurements are outlined below.

Apparent Redox Potential Discontinuity (RPD) Depth

Oxic 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 sulphidic sediments below this oxygenated layer are 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 be one to three mm thick (Rhoads, 1974). This depth is related to the rate of supply of molecular oxygen (by Fickian 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 (SOD), 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 most cases, the depth of the actual Eh=0 horizon will be 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). Significant (i.e. 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 best used to document changes (or gradients) which develop over a seasonal or yearly cycle related to water temperature effects on bioturbation rates, seasonal hypoxia, SOD, and infaunal recruitment.

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 sulphate reduction rates (and the abundance of sulphide end-products). This results in more highly reduced (lower-reflectance) sediments at depth and higher RPD contrasts.

Infaunal Successional Stage

The mapping of successional stages is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor perturbation (Rhoads and Germano, 1982; Rhoads and Boyer, 1982). This theory states that primary succession results in "the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance." The term disturbance includes 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 effluents from power plants, pollution impacts from industrial discharge, etc.

The designation of successional status in REMOTS® images is based on the recognition of two end-member assemblages. Disturbed benthic environments are commonly associated with dense tube aggregations at or near the sediment surface. These appear as small hair-like tube projections at the sediment surface. They are usually spaced 10 or more per linear centimeter along the imaged sediment surface. These "enrichment" assemblages typically consist of spionid or capitellid polychaete populations and are mapped as Stage I seres. 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. These seres are identified as shallow-dwelling bivalves or tubicolous amphipods, such as those belonging to the genus Ampelisca. These may also be densely aggregated at the sediment surface. The other end-member infaunal assemblage (Stage III) is dominated by polychaetes which have larger body sizes, are less abundant, and feed head-down several centimeters below the surface (conveyor-belt species). These species are usually not imaged *per se*, but rather the feeding pockets or voids that develop around their head ends can be seen in profile images. Active voids are lenticular in shape and the bottoms of these are typically filled with coarse particles. Inactive voids may appear as "collapsed" or relic structures which are recognizable only by their lenticular shape and coarser grain-size. These infaunal stages are typically represented by maldanid or orbiniid polychaetes and are mapped as Stage III seres. They are typically present on those parts of the seafloor which do not experience severe frequent (i.e. several times a year) physical disturbance or organic enrichment. This trophic type is apparently adapted to sediments which are relatively "oligotrophic" (Rice and Rhoads, in press).

The pattern described above for primary succession, or the pattern of changes in benthic community functional types after a radical disturbance or the opening of a new patch in the physical environment for colonization, has been repeatedly documented in REMOTS® monitoring of severely disturbed areas such as dredged material disposal sites. However, it is also quite common when monitoring "ambient" seafloor areas to detect a combination of successional seres in the same image (e.g., a Stage I on Stage III, or Stage II on Stage III). This documents the process of secondary succession, which is usually the result of mild physical disturbances or biological interactions such as competition and predation. Secondary succession is the process of reestablishment of conditions similar to the original community after a temporary disturbance.

REMOTS® Organism-Sediment Index

A multi-parameter REMOTS® Organism-Sediment Index (OSI) has been constructed to characterize habitat quality. The REMOTS® Organism-Sediment Index is arrived at by summing the appropriate subset indices shown in Table 2-1. The lowest OSI value (-10) 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. 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. Past REMOTS® surveys have shown the OSI to be an excellent parameter for mapping disturbance gradients in an area and documenting ecosystem recovery after disturbance (see Germano and Rhoads, 1984).

2.2.2 CTD/DO Profiles

The salinity and temperature data were compiled as a function of depth in tabular form. The observed dissolved oxygen (uncorrected for salinity), $C_{T,0}$, and the corrected dissolved oxygen, $C_{T,S}$, for each depth is included in this table. The observed DO readings were corrected for salinity as follows (Eq. 1):

$$C_{T,S} = C_{T,0} + \Delta C_S \qquad \text{Eq. 1}$$

where, $\Delta C_S = \partial C \,/\, \partial S$ for constant temperature

The empirical relationship for dissolved oxygen with respect to temperature and salinity is expressed in Equation 2.

$$\text{Ln } C_{T,S} = A_1 + A_2/T - A_3/T^2 + A_4/T^3 - A_5/T4 - S \times [B_1 - B_2/T + B_3/T^2] \qquad \text{Eq. 2}$$

where, $C_{T,S}$ = Concentration of Dissolved Oxygen in mg/l, as a function of Temperature and Salinity.

T = Temperature in deg. kelvin,

S = Salinity in parts per thousand,

$A_1 = - 139.34411$

$A_2 = 1.575701 \times 10^5$

$A_3 = 6.642308 \times 10^7$

$A_4 = 1.243800 \times 10^{10}$

$A_5 = 8.621949 \times 10^{11}$

$B_1 = 0.017674$

$B_2 = 10.754$

$B_3 = 2140.7$

Therefore, the dissolved oxygen correction, ΔC_S, for salinity can be evaluated by taking the partial derivative of C with respect to S. The solution to this operation is shown in Equation 3.

$$\Delta C_S = \partial C \,/\, \partial S = - \mathbf{B} \times \mathbf{A} \times e^{-\mathbf{B}S} \qquad \text{Eq. 3}$$

where, $\mathbf{A} = e^{(A_1 + A_2 / T - A_3 / T + A_4 / T - A_5 / T)}$

$\mathbf{B} = B_1 - B_2 / T + B_3 / T$

So, for some condition (t,s),

$$\Delta C_s = - \mathbf{B} \times \mathbf{A} \times e^{-\mathbf{B}s} \times (s - 0)$$

and the corrected dissolved oxygen is:

$$C_{t,s} = C_{t,0} - \mathbf{B} \times \mathbf{A} \times s \times e^{-\mathbf{B}s} .$$

Based on the above calculations, dissolved oxygen as well as temperature, and salinity were tabulated and are presented in Appendix III. The five near-bottom (+1 cm) dissolved oxygen measurements from each station were averaged and incorporated into the above data set. Profiles for salinity, temperature, and dissolved oxygen as a function of depth at each station are also presented in Appendix III.

2.2.3 Sediment Samples (TOC, TON, percent fines, and *Clostridium*)

Under the direction of Dr. M. Pilson at the University of Rhode Island, the sediment samples were divided for analyses of percent fines as well as TOC (total organic carbon) and TON (total organic nitrogen). The weight percent of fine-grained ($\geq$ 4 phi units) sediments was determined by conventional wet sieve techniques; all sediment from an individual sample which passed through a 62-micron sieve was weighed and compared with the total weight of the original sample.

The TOC measurements were obtained using a Carlo Erba CHN Analyzer. All obvious carbonate fragments were removed from the samples before analysis. Although not called for in the original task, the total organic nitrogen (TON) content of the samples was also obtained. Both TOC and TON levels are reported and discussed.

Enumeration of *Clostridium perfringens* spores in the sediment samples was carried out at SAIC's La Jolla, CA laboratory. Dr. V. Cabelli of the University of Rhode Island performed quality assurance checks of this procedure. The methods used for spore extractions, extract filtration and plating are described fully in Bissen and Cabelli (1979) and Emerson and Cabelli (1982). The specific laboratory techniques used in this program are detailed in Appendix I. *Clostridium* spore counts for each station were tabulated and mapped.

III. RESULTS

3.1 REMOTS® Sediment-Profile Survey

The positions and designations of all stations occupied during this survey are shown in Figure 3-1; coordinates for each sampling station are presented in Table 3-1. The stations extend from the southern end of South San Francisco Bay to the northern end of San Pablo Bay (Mare Island). To facilitate data presentation and broad-scale geographic comparisons, this area has been divided into three sub regions: the South Bay, the Central Bay, and San Pablo Bay (Figure 3-1). Data sets from each of these regions are presented separately in the sections that follow.

3.1.1 The South Bay

Stations in South San Francisco Bay (stations 30 through 70, excluding 48-50) were occupied from 2-6 February 1987. REMOTS® images were obtained at all stations except number 35, which could not be occupied because of an unmanned drawbridge which blocked the access. At least five replicate images were taken at each station. However, all replicates were not suitable for image analysis due to inadequate prism penetration, preventing accurate measurement of apparent RPD depth or assessment of infaunal successional stage; only four replicates provided usable data at stations 32, 38, 46, 55, 60, 61, 65, and 67, and only three images were suitable for final analysis from station 58.

Physical/Sedimentary Characteristics of the South Bay

Station designations, the distribution of grain-size major modes and water depths in the South Bay are shown in Figure 3-2. This large shallow embayment consists predominately of silt-clay sediments ($\geq$ 4 phi) mixed with minor fractions of very fine to fine sands (4-2 phi). However, several stations, (37-40, 42, 53, 58, and 60) show large subordinate fractions of very fine to fine sand (Figure 3-3), and a single station, 61, is dominated by very fine sand (4-3 phi). Stations 37-40 are located in shallow water just south of the Port of San Francisco. Stations 61, 58, and 60 are located in shallow water (< 4 meters) in the eastern, central portion of the bay. Both articulated and disarticulated oyster shells are evident in this area (Figure 3-4). The presence of these shell banks prevented optimal penetration of the REMOTS® prism in some replicate images. The coarse sedimentary fractions evident in these shallow, relatively unprotected portions of the bay likely reflect the effects of wind wave resuspension of the bottom during storm events. Stations 42 and 53 are located in deeper water (> 8 meters) near the South Bay's main shipping channel. The coarse sediment fraction observed at these stations may represent a scour deposit resulting from high tidal currents associated with the channel environment.

A benthic "process" map of the South Bay is shown in Figure 3-5. A process map shows the distribution of features which can be used to make inferences about kinetic regimes. Mud clasts are evident at all but six stations in the South Bay; these clasts represent cohesive chunks of seafloor which have been eroded from the bottom. The clasts vary widely in size, shape, and apparent oxidation state (Figure 3-6). This heterogeneity indicates both spatial and temporal variability in the processes which produced the clasts. Other imaged features which suggest frequent bottom disturbance include both shell lag layers (areas where fine-grained sediment is removed by bottom currents, leaving a "lag" layer of shell fragments) which serve to armor the bottom (Figure 3-7) or conversely fine-grained depositional layers. Shell lag deposits and shell hash are restricted to the central portion (trending north to south) of the bay. This distribution may reflect the distribution of active or relic shellfish beds.

Recently deposited sediment layers are evident at 14 stations (Figure 3-8). The distribution and thickness of these depositional layers are shown in Figure 3-5. With the exception of station 57, these deposits are restricted to relatively shallow-water and/or sheltered regions of the South Bay. In some cases, these sedimentary layers are darker than the underlying bottom (Figure 3-9); this suggests that the freshly deposited material is organically-enriched relative to the ambient bottom. These depositional layers most likely represent sediments carried into the Bay during recent winter storms. According to Krone (1979), this winter-introduced material settles first in the upper bays and is subsequently redistributed by waves generated by strong spring and summer onshore winds. Based on these REMOTS® results, recent sediment inputs are generally accumulating in sheltered regions where wind waves and/or tidal currents lack the energy to keep material in suspension. The presence of this allochthonous material may have critical implications for the interpretation of both biological and chemical benthic data from San Francisco Bay. This seasonal sedimentological cycle may be an important structuring mechanism for the bay's benthic communities. Moreover, the coupling of biological and chemical benthic characteristics may vary significantly in space and time depending on the timing and intensity of depositional events. These issues will be discussed further in section V of this report.

Based on the distribution of surface disturbance and depositional features, it is possible to map the kinetic gradients which existed in the South Bay during the survey period (Figure 3-5). As indicated above, most of the bay is a relatively high kinetic region. The deeper channel habitats appear scoured by high tidal flows, while the broad shallow stretches are likely affected by wind wave-generated disturbances. Depositional layers are apparently accumulating where these forces are weakened due to the local physiography. These relatively low kinetic areas include the far southern end of the Bay (the mouth of Coyote Creek), Redwood Creek, shallow areas off Coyote and Sierra Points, the region surrounding San Bruno Shoal (i.e. the area bounded by stations 59 and 57), Oakland Inner Harbor, and among the piers of the Port of San Francisco.

The frequency distribution of surface boundary roughness values (small-scale topographic relief measured at the sediment-water interface) in the South Bay is shown in Figure 3-10. The distribution of roughness values is right skewed with a major mode of 0.8 cm. This value reflects the frequent small-scale bottom disturbance that occurs throughout the region. Although most of the boundary roughness appears to be produced by physical factors, biogenic roughness elements are also present (Figure 3-11).

It is noteworthy that replicates from two stations (47 and 70) show distinct low-reflectance (sulphidic ?) layers at depth in the sediment column (Figure 3-12); these layers are mapped tentatively as dredged material in Figure 3-5. These low-reflectance layers appear to represent a past input of organic-rich sediments. Both stations lie in or near navigation channels; these layers may be related to past channel maintenance dredging activity.

A map of the mean apparent RPD depths, averaged by station, is given in Figure 3-13. Stations where mean RPD depths average less than 3.00 cm are delimited. These stations include those at the mouth of Coyote Creek, upstream in Redwood Creek, off Coyote Point, in Oakland Inner Harbor, and in the Port of San Francisco. Five stations in the central South Bay (stations 53, 54, 56, 60, and 63) also exhibit relatively low RPD values. Several of the areas exhibiting shallow RPD depths show apparently high sediment oxygen demand sediments (SOD) at or near the sediment-water interface (Figure 3-14). The presence of high SOD sediments is inferred from high reflectance contrast across the apparent RPD (Redox Potential Discontinuity) boundary. Potentially high SOD sediments are located close to the sediment surface in the mouth of Coyote Creek, in Redwood Creek, in inner Oakland Harbor, and in the Port of San Francisco. Near-bottom dissolved oxygen readings obtained from these sites are not anomalously low (see Appendix III). However, if hypoxic conditions exist in South San Francisco Bay on a seasonal or longer-term frequency, then these locations are the most likely sites for the onset of this oxygen depletion. The three central bay areas which exhibit shallow RPD depths lack low-reflectance sediments at depth. These sites also show evidence of physical disturbance (i.e. mud clasts, shell lag deposits, eroded tube mats). It is likely that the shallow RPD depths at these sites are due to physical disturbance of the bottom, e.g. stripping away of oxidized surface sediments.

The stations in the central portions of the South Bay which exhibit recent depositional layers (57, 59, and 63) also do not show high SOD sediments at depth. This indicates that labile organic matter is not accumulating at these sites. This may reflect the ability of the local benthic communities to prevent this build-up by keeping the sediment column in an advected state (combined with high bottom water flushing rates) or more likely indicates that net deposition of organic-rich sediments does not occur in these areas due to scour from wind-generated waves.

The RPD frequency distribution is included in Figure 3-15. Most of the South Bay exhibits relatively deep RPD values. The mean RPD depth for all replicates is 3.58 + 1.93 cm. The observed apparent RPD depths directly reflect the depth to which bioturbating infauna are reworking bottom sediments. At some South Bay stations (45, 44, 65, 70, 56, 36, and 55), there is notable within-station heterogeneity among the replicate RPD values. For example, at station 55, RPD values range from 1.40 cm to 5.23 cm. This within-station variation indicates small-scale patchiness in the distribution of relatively large bioturbating infauna and/or disturbance factors. Overall, across most of the South Bay, the top 3-6 cm of the seafloor is reworked and irrigated by the activities of the infaunal community.

Biological Characteristics of the South Bay

The mapped distribution of successional stages in the South Bay is shown in Figure 3-16. Head-down deposit feeders (Stage III infauna) are observed in much of the region. These relatively deep-dwelling infauna are detected by the presence of feeding voids at depth in the sediment (Figure 3-17). Although widespread (47% of all replicates), individual Stage III organisms appear to be relatively small in size, and the Stage III assemblages appear to be low in abundance. This inference is based on the low density and small size of the feeding pockets in many images (Figure 3-18). The predominate Stage III organism in the South Bay is likely the maldanid polychaete, Asychis elongata (Nichols, 1979; Nichols and Thompson, 1985). Large cylindrical tubes, assumed to be the caudal ends of this tube-dwelling species, can be seen at the surface in some images (Figure 3-19). Many stations exhibiting these Stage III infauna also show abundant small, surface dwelling polychaetes at or near the interface, classified in REMOTS® images as Stage I organisms (Figure 3-20). Component Stage I species are most likely Streblospio benedicti, Heteromastus filiformis, and Polydora spp. (Nichols and Thompson, 1985).

Four areas in the South Bay, stations 30 and 31 (Inner Oakland Harbor), station 34 (Port of San Francisco), stations 69 and 70 (Redwood Creek), and stations 66 and 67 (the mouth of Coyote Creek) appear to lack Stage III forms (Figure 3-21). These regions are evidently "stressed" or disturbed at a frequency which excludes the longer-lived Stage III taxa. Each of these areas is associated with apparently high SOD sediments, and may experience oxygen depletion during the warmer portions of the year.

Tubicolous amphipods, tentatively identified as Ampelisca abdita (Figure 3-22) are evident at several stations scattered throughout the South Bay. High densities of A. abdita have been reported from San Francisco Bay in several previous studies (see Nichols, 1979 for review). In some of the REMOTS® images, these amphipods are densely aggregated (> 4 per linear centimeter; see Figures 3-11 and 3-24). At several locations, these tube mats appear to be physically disturbed (Figures 3-23 and 3-24). This suggests that local physical and/or biogenic disturbance factors strongly influence the distribution of the amphipod beds (Figure 3-24). These amphipod assemblages have been designated as Stage II seres in Figure 3-16. This designation is based on our work in Long Island Sound, where this assemblage may appear several months after disturbance, typically following the acme of Stage I colonizers. During primary succession, the order of appearance of colonizing benthos can be predicted on the basis of generation time and degree of opportunism displayed by a particular taxon. Many polychaetes are typically the first to colonize an area (e.g., Dauer and Simon, 1976; McCall, 1977; Rhoads et al., 1978; Santos and Simon, 1980). Amphipods appear to be more selective in their settlement patterns and are very sensitive to low oxygen conditions; they can appear as faunal dominants after the initial zenith of opportunistic polychaetes occurs. This particular successional pattern commonly occurs in northeast estuaries and was also documented in Tampa Bay, Florida by Santos and Simon (1980). Their study of four annual defaunation cycles caused by periodic hypoxia in Tampa Bay showed two of the four cycles having Ampelisca appear as the second temporal dominant in the recolonization process, supporting our designation of these assemblages as Stage II seres.

In San Francisco Bay, Nichols (1985) has noted an annual cycle in Ampelisca abundance with peak population levels consistently occurring in the fall (October). Nichols suggests that this annual pattern reflects the fact that Ampelisca has two generations each year: a small overwintering generation comprised of juveniles and subadults that mature in spring, and the spring generation that matures rapidly and produces the autumn generation. The REMOTS® data from this survey indicate that the amphipod tube mats are widespread, but unevenly distributed throughout much of the South Bay. This taxon is present at a single site characterized by apparently high SOD sediments (station 66; Figures 3-13 and 3-25). Excluding this site, tube-dwelling amphipods do not occur in any area identified above as a "stressed" environment.

The frequency distribution of Organism-Sediment Index (OSI) values is given in Figure 3-26. The distribution is polymodal, with values ranging from -2 to +11. This range in values reflects the range in habitat quality observed in the South Bay. The majority of values range from +7 to +11 and indicate that much of the bay represents a relatively "healthy" benthic environment. Although frequently physically disturbed, most of the surveyed area does not appear to be anthropogenically stressed. The OSI values less than or equal to +6 are found largely in the bordering regions characterized by high SOD sediments, shallow RPD depths, and low-order infaunal successional status. REMOTS® surveys from other coastal regions (e.g. Long Island Sound, Chesapeake Bay, the Bay of Fundy, Puget Sound, and the Florida and Louisiana Coast) have shown that OSI values less than 7 suggest a "stressed" benthic environment. The areas in South San Francisco Bay which exhibit low OSI values (i.e. less than 7) are restricted in areal extent (Figure 3-27). The distribution of low values in urbanized ports and harbors and adjacent to creek and river mouths illustrates the influence of anthropogenic factors (i.e. industrial, agricultural, and urban activity).

3.1.2 Central Bay

Fourteen stations in the Central Bay region were occupied from 7-9 February 1987. Five REMOTS® images were obtained at all Central Bay stations; only four replicate images were suitable for analysis from stations 23, 25, and 26.

Station designation, water depth (m) and grain-size major mode at stations in the Central Bay region are shown in Figure 3-28. The major grain-size mode is $\geq$ 4 phi (silt-clay) at all stations except station 49, which is a rippled sand consisting of intercalations of both mud and fine sand (Figure 3-29). This station apparently lies within a sand-mud transition zone. This transition is associated with the boundaries of the Alcatraz Dredged Material Disposal Site.

Figure 3-30 is a benthic process map of the Central Bay. Excluding the three stations adjacent to Alcatraz Island, the area is similar to the South Bay. Mud clasts are present at all stations except station 49. The widespread distribution of these mud clasts suggests that they are formed from processes which are operating on a broad scale. Biological erosion is usually local in its effects. In some cases, the clasts appear to represent recent local erosion (Figure 3-31). Alternately, some clasts appear to have been transported as part of an erosion/sedimentation event (Figure 3-32). Shell lag deposits are evident only at station 48 and this shell hash likely represents dredged material (Figure 3-33). The lack of shell debris in the Central Bay most likely indicates the lack of extensive indigenous shellfish beds.

Five stations (23, 25, 26, 27, 28) show the presence of newly deposited sedimentary layers consisting of either finely dispersed sediment (Figure 3-34) or layers of mud clasts (Figure 3-32). As in the South Bay, this allochthonous material appears to be accumulating in relatively sheltered, nearshore areas.

Stations 48 and 50 show "exotic" sediment which represents material disposed at the Alcatraz Disposal Site (Figure 3-33). From July 1986 through February 1987, SAIC performed monthly surveys at this site to assess the influence of various disposal techniques on the dispersal of dredged material; this monitoring included extensive REMOTS® surveys of the area. Stations 48 and 50 lie within an area subjected to frequent disposal activity. Station 49 is located on the western flank of the site, a region of ambient, mobile sand waves intermixed with clumps of cohesive sediment being dispersed from the area.

Taken as a whole, the Central Bay region has high mean boundary roughness (1.60 cm) relative to both the southern (1.33 cm) and northern bay (1.38 cm) regions (see Figure 3-10). The origin of these roughness elements in the central bay is overwhelmingly from physical processes, both natural and anthropogenic (i.e. dredged material disposal). The features mapped in Figure 3-30 indicate that many areas in the central bay have experienced redistribution of surface sediments in the recent past.

The frequency distribution of mean apparent RPD values for the Central Bay stations is included in Figure 3-15. The distribution is right skewed, with most values less than 3 cm. The average RPD depth for all Central Bay replicates is 2.92 $\pm$ 2.09 cm; this compares to average RPD depths of of 3.58 $\pm$ 1.93 and 3.07 $\pm$ 1.65 cm for the South Bay and San Pablo Bay stations, respectively. These generally lower apparent RPD depths are caused by both surface erosion (stripping away of the oxidized surface sediment as discussed above) and areas of seafloor which exhibit apparent high sediment oxygen demand (stations 26, 27, 24, 29, and 50). Figure 3-35 shows the mapped distribution of mean apparent RPD depth and the distribution of high SOD sediment. Stations 29 and 27, located just outside Oakland Outer Harbor and Richmond Harbor respectively, show the presence of sulphidic sediment at the sediment-water interface (Figure 3-36). This apparently high SOD was not reflected in the bottom dissolved oxygen measurements at these sites (Appendix II). However, Richmond and Oakland Harbors are potential candidates for the onset of oxygen depletion as water temperatures increase. In addition, Station 20 contains dark algal material associated with the sediment, and this station may be a candidate for high SOD as this material decays (Figure 3-37).

Biological Characteristics of the Central Bay

The mapped distribution of infaunal successional stages at Central Bay stations is shown in Figure 3-38. Subsurface deposit feeders (Stage III taxa) are widespread in the region. Only the inner Richmond Harbor region lacks evidence of subsurface infauna. This inner harbor region is apparently organically-enriched as manifested in high SOD sediments and depressed RPD depths. The Stage III designations for the outer Oakland Harbor site (station 28) are equivocal. The feeding voids present in images from this site were small and indistinct (Figure 3-39); this suggests the presence of a recently stressed or poorly developed Stage III community. Stage III taxa are also sparse at the three stations in or near the Alcatraz Disposal Site. This survey and SAIC's recent work at Alcatraz for the San Francisco District of the Army Corps of Engineers show the area to be severely affected by ongoing and extensive dredged material disposal.

Tube-dwelling amphipods (probably Ampelisca abdita) are distinctly evident at a single shallow station (19) in the Central Bay. This Stage II assemblage overlies Stage III infauna and appears to be biogenically disturbed. Figure 3-40 shows the tube mat being ripped up by the large burrow of an infaunal organism. This type of biotic disturbance, as well as physical factors, may be limiting the distribution and density of Ampelisca beds in this portion of the bay.

The mapped distribution of Organism-Sediment Index values in the Central Bay is shown in Figure 3-41, and the associated frequency distribution is included in Figure 3-26. The inner Richmond harbor site exhibits the lowest OSI values; this reflects both the shallow RPD depths and the low-order successional stages. The Alcatraz disposal site stations and outer Oakland Harbor also show relatively low OSI values. The remainder of the Central Bay exhibits relatively high OSI values. Heterogeneity in replicate OSI values from a single station directly reflects patchiness in the distribution of Stage III infauna. A slight increase in OSI values is evident between the nearshore (20, 22, 24) and offshore (19, 21, 23) stations off the Berkeley marina. This appears to be a result of greater patchiness in the distribution of Stage III infauna nearshore.

Overall, the Central Bay region exhibits a wide range of benthic habitats. This reflects a mosaic of disturbance factors including natural physical and biogenic processes, dredged material disposal, and inputs of organic-rich and contaminated material.

3.1.3 San Pablo Bay

Eighteen stations in San Pablo Bay were occupied on 8 and 9 February 1987. Two stations in San Pablo Bay (10, 11) could not be sampled with the REMOTS® camera because of extremely strong tidal currents. In addition, a number of stations located near the central channel consisted of cobbles, well-sorted sands and/or over-consolidated mud bottoms which were only shallowly penetrated by the REMOTS® prism. As a result, despite repeated attempts at several of these stations, only four replicate images were suitable for analysis from stations 7 and 15, three replicates from stations 3, 5, 6 and 13, two replicates from stations 8 and 14, and only a single image was available from station 16.

The distribution of station designations, station depths and grain-size major modes in San Pablo Bay is shown in Figure 3-42. Sandy sediments are much more widespread in San Pablo Bay than in the Central and South San Francisco Bay areas. These sands are generally associated with the relatively deep central channel of the bay. The broad shallow northern flank of San Pablo is characterized by silt-clay sediments, while the stations south of the channel exhibit mixtures of sand and silt-clay sediments.

The benthic process map for San Pablo Bay is given in Figure 3-43. Five stations (1, 2, 4, 5, and 6) exhibit biogenically reworked silt-clay sediments and have mud clasts at the sediment-water interface indicating recent seafloor disturbance. The presence of clasts at the shallower stations is most likely related to physical disturbance caused by wind waves. At the deeper silt-clay sites (behind Mare Island), physical disturbance, related to currents, bow waves and prop wash, as well as biogenic factors may be important. Consolidated silt-clay sediments and well-sorted sands are observed in and near the main channel of San Pablo Bay (Figure 3-44). Extremely high current flow is known to exist in this embayment. Large bedforms (sand waves) are evident at many of the sandy stations (Figure 3-45). Where sands are not predominate in the channel region, extremely consolidated (relic ?) silt-clay sediments are present. This over-consolidated material resembles sediments imaged with REMOTS® at the Alcatraz Disposal Site. At station 16, the over-consolidated material is exhibited in extremely low reflectance at depth (Figure 3-46). This station is located just east of a disposal area. The apparently high SOD sediment may represent allocthonous material introduced by disposal activity. Pre- and post-disposal REMOTS® surveys at the Alcatraz Disposal Site have shown that while near-surface fluidized dredged material is rapidly dispersed when placed in a dynamic environment, underlying cohesive silt-clay sediment clumps are extremely consolidated and resistant to erosion. This "weathered" dredged material exhibits a distinct "smooth and lumpy" surface texture similar to that observed at station 16 in San Pablo Bay.

Although fine-grained sediments dominate the shallow stations south of the channel (17, 18), there is a significant subordinate sand mode at these sites. At station 13, a burrowed mottled sand-mud texture is evident (Figure 3-47). This texture is probably the result of periodic (e.g. storm-related ?) inputs of different sized material coupled with subsequent incomplete biogenic mixing of particles. More distinctly stratified sand/mud transitions, as seen at station 9 (Figure 3-48), probably represent longer-term (e.g seasonal) variations in local kinetic regimes resulting in alternating sand and silt-clay deposition. A final facies type present in San Pablo Bay is cobble/epifaunal-dominated bottom at station 3. The coarse texture at this high energy site prevented adequate REMOTS® prism penetration.

The frequency distribution of surface boundary roughness values from San Pablo Bay is included in Figure 3-10. The distribution is bimodal with peaks centered at 0.8 cm, representing the fine-grained bottom, and at 2.0 cm, representing rippled sandy channel bottom.

Overall, San Pablo Bay represents a very dynamic benthic habitat. Excluding the deep muddy sites behind Mare Island (station 1 and 2) and shallow muddy stations north of the channel (4, 5, 6), the region is characterized by temporally-varying patterns of bottom scour, bedload transport, and sedimentation of both sands and fine-grained sediments. As with the areas in the Central and especially the South Bay showing seasonal deposition, many of the benthic environments in San Pablo Bay show sedimentological features which indicate that physical and biogenic processes vary markedly in time. It may be critical to identify the spatial and temporal patterns of environmental change in these areas before an accurate "characterization" can be made.

The mapped distribution of apparent mean RPD values averaged by station in San Pablo Bay is shown in Figure 3-49, and the associated frequency distribution is included in Figure 3-15. Where prism penetration was minimal, the apparent RPD depth could not be determined. Only three stations (1, 18, and 12) exhibit average RPD depths greater than 3.0 cm. In general, these relatively shallow average RPD values appear to be due to physical disturbance factors (i.e. erosion of oxidized surface sediments and mechanical disturbance of the benthic community). A single station, 16, shows an extremely shallow RPD and high SOD sediments near the sediment-water interface. As indicated above, this low-reflectance material may represent disposed dredged material. Given the dynamic character of the areas of San Pablo surveyed in this study, it seems unlikely that low oxygen conditions would develop in the bay. Although some organically-enriched material is present, current and wind wave action throughout the year probably preclude the development of hypoxic conditions in the region.

Biological Characteristics of San Pablo Bay

The mapped distribution of infaunal successional stages is shown in Figure 3-50. At several stations in or near the central channel characterized by rippled, well-sorted sands or over-consolidated muds, successional stage could not be determined due to limited REMOTS® prism penetration. At other stations in the central channel, surface-dwelling tubicolous polychaetes (Stage I infauna) dominate. At stations located in the shallower portions of the bay and behind Mare Island, deep-dwelling head-down deposit feeders (Stage III) are prevalent. The exclusion of these forms in the channel environment is likely due to extremely high current velocities. Perhaps the most striking biological feature of the San Pablo Bay region is the widespread distribution of tube-dwelling amphipods (Figure 3-51). Excluding station 2, these organisms (identified as Stage II assemblages on the successional stage map) are present at all stations which exhibit Stage III infauna. Interestingly, these mats occur in a variety of bottom facies types. For example, tube mats are prevalent in the deep silt-clay bottom facies behind Mare Island, in the shallow mud bottom north of the channel, and in the sand and mud mixtures south of the channel (Figure 3-52). In most cases, the mats are similar in appearance and are tentatively identified as Ampelisca abdita. The tubes evident at station 13, however, are distinctly smaller in appearance (see Figure 3-47). This may represent a juvenile cohort or another tube-dwelling gammarid. This difference may be associated with the difference in bottom type at this station (muddy sand versus silt-clay).

The amphipod tube mats appear "disturbed" at two stations (1 and 4). At Station 1, this "disturbance" is an artifact caused by surface sediment collapse while the camera prism penetrated the bottom (Figure 3-51). This collapsed 2-3 cm layer is evident in four of the five replicates from Station 1 and appears to represent recently accreted fine-grained material around the individual amphipod tubes. The presence of the tube mat may be enhancing the deposition of sediments being transported down the Napa River. Also, given the observed tube density, biodeposits of amphipod fecal material probably are accumulating rapidly at the site. This matrix of tubes, fecal material, and fine-grained sediments comprises the top few centimeters of the bottom. The action of the prism caused this layer to slump, and the boundary with the underlying more-consolidated bottom is evident in the images (Figure 3-51). At station 4, all five replicates show evidence of physical disturbance. The tube mats appear to have been mechanically ripped up (Figure 3-53). This relatively shallow, unprotected site is likely subjected to strong physical forces produced by wind waves. The other amphipod assemblages observed throughout San Pablo Bay appear to be relatively intact.

The calculated Organism-Sediment Index values are mapped in Figure 3-54. OSI values are indeterminate wherever the RPD depth or the successional stage cannot be determined. The lowest OSI values are located at the northeast end of the main channel (stations 8, 16). These depressed values reflect both shallow RPD values and the lack of high-order successional infauna. The high SOD sediments at station 16 suggest that in addition to the extreme physical disturbance factors present at this station, anthropogenic influences (i.e. disposal activity) may be important. For the most part, the remainder of San Pablo Bay exhibits intermediate OSI values (e.g. +7). The frequency distribution of these values is included in Figure 3-27. This relatively even distribution reflects an environment broadly affected by strong physical disturbance factors.

3.2 Sediment Samples

Surface sediment samples for <u>Clostridium</u> spore counts, total organic carbon (TOC) analysis, and percent fines determination were obtained using a Ponar grab at 68 of the 69 stations occupied in San Francisco Bay. Despite repeated attempts at station 11, a grab sample could not be obtained due to extremely high current velocities.

3.2.1 <u>Distribution of Fine-Grained Sediments</u>

The percentage of fine-grained sediments ($\geq$ 4 phi) at each station, as determined by wet sieving, is shown in Figures 3-55 through 3-57. Areas comprised of less than 50 percent fines are delimited for each region of the bay. Table 3-2 compares the wet sieved sediment results with the REMOTS® grain-size major mode data. Stations for which the two techniques do not agree are indicated by an asterisk. These discrepancies are discussed below.

Overall, fine-grained sediments dominate the regions surveyed. In the South Bay (Figure 3-55), four of the six stations (42, 46, 56, 62) which show fine-grained fractions of 41% or lower are located in or near the main South Bay channel. The channel environment is apparently subject to higher current velocities and/or bottom scour. Based on the REMOTS® analysis, stations 46, 56, and 62 are dominated by fines, although a large subordinate sand fraction is apparent (see Figure 3-7). The fact that all three of these stations are adjacent to the channel suggests that this bottom habitat is heterogeneous in terms of the distribution of fines. The two other relatively coarse-grained stations (60 and 61) are located in a shallow, shell bank area east of the main channel. Excluding the three stations discussed above, the REMOTS® major modal grain-size designations and sieve analysis results agree for all stations in the South Bay.

In the Central Bay (Figure 3-56), silt-clay fractions comprise greater than 50% (by weight) of the sediments at all sites, except for station 49. Station 49 is located on the rippled sand bottom which surrounds the Alcatraz Disposal Site (see Figure 3-29). The REMOTS® grain-size data agrees with wet sieve results for all stations in the Central Bay (Table 3-1).

In San Pablo Bay, coarse-grained material dominates the channel environment (stations 8, 16, 14, 13, 12, 10 and 9), while fines dominate the areas north and south of the channel and behind Mare Island (Figure 3-57). Three stations (3, 12, 16) show discrepancies between the two techniques (Table 3-1). At station 3, the grab sample was taken much closer to the actual station location (adjacent to several pilings), than the REMOTS® images. The camera could not be safely deployed where the Ponar grab was taken. This spatial difference may account for the difference in observed grain-size. At station 16, only a single REMOTS® replicate was obtained which consisted of overconsolidated silt-clay (see Figure 3-46). Coarse-grained sediments are apparently also present in this high kinetic region. Station 12, located in the channel, consists of patchy sand lenses in a silt-clay matrix. Depending on the exact location of the grab sample relative to the five replicate REMOTS® images, different proportions of sand and silt-clay could have been sampled.

3.2.2 Total Organic Carbon (TOC), Total Organic Nitrogen (TON)

The mapped distribution of total organic particulate carbon (TOC) and total organic particulate nitrogen (TON) at each station in San Francisco Bay is given is Figures 3-58 through 3-60. Although not specified in Task Order 1050, TON measurements were generated during the TOC analysis; these values are included on the maps and discussed where they provide useful information concerning the nature of the organic matter.

In the South Bay, five areas show relatively high levels (> 15 mg C/g) of TOC: inner Oakland Harbor (stations 30-33), around the port of San Francisco (station 34), Redwood Creek (stations 68-70), the mouth of Coyote Creek (stations 66 and 67), and a broad area in the east, central bay (stations 52, 58, and 60-62; see Figure 3-58). Excluding the central region, all these areas are associated with potential sources of organic loading, both natural and anthropogenic. The high TOC values in the middle to east side of the South Bay reflect the presence of shellfish beds (see Figure 3-4). Although all obvious carbonate fragments are removed from the sediment samples in the laboratory before processing, there is no satisfactory way to completely eliminate the contribution of carbonate fragments to the final carbon value. This shell material results in anomalously high TOC values. Unlike the other TOC-rich areas, the TON values at these stations do not increase proportionally with TOC values; high C/N ratios further support this inference. The TOC values in the South Bay range from 4.23 to 28.77 mgC/g (mean value of 14.99 ± 4.61 mgC/g). Station 42 exhibits an atypically low TOC value. This station is characterized by relatively coarse-grained sediments and likely represents a scoured, non-depositional channel area.

TOC values in the Central Bay region are less variable and generally lower than the values in the South Bay (Figure 3-59). TOC values range from 2.40 to 16.52 mgC/g, with a mean value of 12.40 ± 3.24 mgC/g. Highest TOC vales are found at the Alcatraz Disposal Site, in Richmond Harbor, and in outer Oakland Harbor. These areas are also associated with relatively high TON values. This pattern represents the influence of anthropogenic factors (i.e. dredged material disposal, urban and industrial activity). The sharp gradient in TOC/TON values between station 49 and 50 at the Alcatraz Disposal Site represents the boundary between the active disposal area and the surrounding "clean" sand bottom.

TOC and TON values in San Pablo Bay are much more variable than values observed in the Central or South Bay (Figure 3-60). The San Pablo TOC values range from 0.52 to 16.67 mgC/g, with a mean value of 8.82 ± 6.10 mgC/g. This large standard deviation reflects the two major benthic facies: the scoured channel versus the depositional, shallow regions. The highest TOC/TON values occur in the silt-clay facies behind Mare Island and south of the channel near Pinole Point. Relatively high values also occur in the shallow area north of the channel. This pattern may reflect the deposition of both natural and anthropogenic organic material. Low TOC and TON values are evident in or near the channel. Marked accumulation of fine-grained organic material apparently does not occur in this dynamic channel environment.

3.2.3 Clostridium perfringens Distribution

Figure 3-61 shows the mapped distribution of the *Clostridium* spores at stations in the South Bay. *C. perfringens* counts of < 25/gm represent background concentrations for "clean" habitats based on past work (Cabelli, pers. comm.). High spore counts (1000 or greater) are observed in Redwood Creek, at the mouth of Coyote Creek, around the port of San Francisco, in inner Oakland Harbor, along the western shore south of San Francisco and in a large swath which extends from southeastern San Francisco into the bay toward station 47. The distribution of spores likely reflects both point sources of sewage and redistribution patterns of sewage-associated sediment in the bay. For example, the value of 21,000 spores estimated for station 33 in Oakland Harbor indicates a very local, high input of material. Similarly, station 70 in Redwood Creek (4,469 spores) probably is close to a source of sewage effluent. Other relatively high values around the margins of the bay may indicate less significant or more widely spread point sources. The swath of high values extending into the bay from San Francisco may reveal the long-term deposition pattern of sediment-associated sewage contaminants in that part of the bay. Clostridium spores are long-lived and their dispersal and accumulation is associated with the movement of fine-grained sediments. The observed distribution suggests that, over time, sedimentary material is accumulating in the region from station 51 south through station 47. The presence of San Bruno shoal in the center of this area (between station 59 and 57) may be influencing this apparent long-term depositional pattern.

The distribution of Clostridium spores in the Central Bay shows accumulations of sewage-derived material in inner Oakland Harbor and near Treasure Island (Figure 3-62). High values are also evident in the sediments deposited at the Alcatraz Disposal Site. Interestingly, Richmond Harbor, which exhibits high organic-loading and low REMOTS® Organism-Sediment Indices, shows relatively low numbers of Clostridium spores; this strongly suggests a non-sewage related stress factor. The lowest spore count for the Central Bay is found at station 49 (50 spores/g), the ambient sand bottom surrounding the Alcatraz Site.

In San Pablo Bay, the Clostridium distribution (Figure 3-63) reflects the distribution of fine-grained sediments and kinetic gradients (Figure 3-44). Relatively high values are evident behind Mare Island, and in the silt-clay areas surrounding the main channel. The value of 2,240 spores/g at station 1 suggests the presence of a nearby sewer outfall. The relatively high values north and south of the channel may indicate sources both on the north side of the bay and northeast of Pinole Point. Alternately, the pattern may reflect long-term circulation and depositional patterns of sediments entering San Pablo Bay. While several of the channel stations show intermediate Clostridium values, a number of stations (7, 15, 10, 9) show extremely low spore abundance (i.e. < 25 spores/g). These values are typical of offshore oceanic environments (Cabelli, pers. comm.). This pattern apparently reflects the extreme near-bottom high energy regime characteristic of this channel habitat.

3.3 Water Column Properties

Tabulated data of dissolved oxygen (DO), salinity (S), and temperature (T) at each station along with measurement date and time are presented in Appendix III; the plotted profiles of these data are presented in Appendix IV. CTD/DO data were obtained at all stations except for stations 35 and 48; station 35 was not occupied due to blocked access by an unmanned drawbridge, and field operations were aborted at station 48 (the last station sampled on the final day of field operations) by captain's orders after all electronics failed on the research vessel.

The water column during the period of measurement was either weakly stratified or non-stratified with many stations being isothermal and isohaline. All stations were fully aerobic. The threshold value of DO for hypoxic conditions is 4 ppm. Values above 4 ppm are not limiting to most aerophilic marine organisms. The bottom-most dissolved oxygen measurement (+ 1 cm above the interface) was the same value as measured higher in the water column at most stations. Those stations which showed a slight decrease in the +1 cm DO value remained within the aerobic range. These results are expected given the cool water temperatures, high tidal exchange, current velocities, and wind-mixing associated with the period of measurement.

IV. DISCUSSION

The purpose of this survey was to map gradients in sediment and benthic habitat quality in San Francisco Bay and to compare these results with ancillary measurements (C. perfringens spore enumeration, sediment TOC, TON, grain-size analyses, and water column CTD/DO measurements). Stations can be ranked by comparing data taken from the REMOTS® images with the independent measurements made on C. perfringens counts, TOC and TON, and near-bottom dissolved oxygen. This allows identification of the most severely disturbed and least disturbed sites in the Bay as determined with the above measures.

Tables 4-1 and 4-2 give the results of this analysis for each of the three segments of the Bay. It is important to note that the initial choice or ranking of stations in these two tables is dictated by the REMOTS® "summary" parameter, the Organism-Sediment Index (OSI) value. Based on our experience over the past seven years with REMOTS® mapping of urban estuaries and dredged material disposal sites on both the east and west coasts, recently disturbed areas have OSI values of 7 or less, while areas not subject to frequent stress have OSI values between 9 to 11. To identify the most severely stressed stations in the present survey (Table 4-1), only those with mean OSI values of < 7 were chosen. To identify the least disturbed areas (Table 4-2), only stations with mean OSI values of > 10 were chosen.

South Bay:

Thirteen stations in this region were selected initially on the basis of low OSI values; stations 70 and 32 were designated as representing the most severely stressed stations after consideration of all relevant ancillary measurements (low OSI values, high C. perfringens counts, and TOC values approaching 2% by weight). None of the stations on a bay-wide basis can be ranked on near-bottom dissolved oxygen at this time of year, because all values were aerobic (> 4 mg/l). One speculation for the apparent low sediment quality at station 70 (Redwood Creek) may be related to eutrophication by sewage and inputs of marsh detritus. Station 32, located in the inner part of Oakland Harbor, could possibly be stressed by sewage and/or industrial waste (?).

Five stations also were selected initially on the basis of high OSI values as representing relatively unstressed habitats (Table 4-2). Of these, Station 38 is the least stressed on the basis of its high OSI, relatively low C. perfringens count, and its TOC value of 1.2 % (by wt.).

Central Bay:

Four stations were selected on the basis of low OSI values as severely stressed (Table 4-1). The Alcatraz area is affected by dredged material disposal activities. Station 27 in Richmond Harbor was chosen as the most stressed area based mainly on its low OSI value, even though the C. perfringens counts are relatively low compared to the other three stations. The highest quality station appears to be Station 19 (Table 4-2).

San Pablo Bay:

Three stations have low OSI's (Table 4-1); stations 8 and 16 have the lowest OSI values and are located near each other in a region which may contain disposed materials, relic overconsolidated sediment, and is experiencing severe natural bottom scour. Station 4, located in southwest San Pablo Bay, is also a candidate for the most stressed station based on high C. perfringens counts and high TOC value. Station 18 was chosen as the least stressed station based on its high OSI and relatively low C. perfringens counts (Table 4-2).

There are a wide variety of potential factors contributing to the low OSI values noted for the above stations. For example, sewage and storm water outfalls are prevalent in the urban San Francisco and Oakland areas, while at the southern end of the bay, both anthropogenic inputs as well as high detrital inputs from bordering wetlands and creeks may be important. Compared with a number of east-coast urban estuaries surveyed with REMOTS® technology (e.g., Boston Harbor, New Haven Harbor, Clinton Harbor, Bridgeport Harbor, Providence Harbor, Norfolk Harbor, Hillsborough Bay), San Francisco Bay shows a relatively small percentage of its overall area (given the stations surveyed in this study) negatively affected by anthropogenic inputs.

In summary, this habitat and sediment ranking exercise has identified 7 stations in the Bay which represent extremes in sediment and habitat quality as ranked on REMOTS® OSI values, C. perfringens counts, and TOC. The most stressed stations are: 70 and 32 (South Bay), 27 (Central Bay), and 4 (San Pablo Bay). The least affected stations appear to be Stations 38 (South Bay), 19 (Central Bay), and 18 (San Pablo Bay). These seven stations are good candidates as permanent "core" stations for long-term monitoring of status and trends in the Bay using the techniques described here, the Sediment Quality Triad, or other techniques.

In order to compare areas in a more objective manner based on both REMOTS® parameters and Clostridium counts, an unweighted group average clustering technique was employed using the mean OSI values and C. perfringens counts (Figure 4-1). Six station groupings can be recognized. Station 27, Richmond Harbor, (Group

I) stands alone. As described above, the major stress factor at this station is apparently some anthropogenic input other than sewage accumulation; both OSI values and C. perfringens spore counts are low. At the next cluster level, group 1aa, 1ab, and 1b contain all of the stations that were identified above as having low sediment and habitat quality. Group 2b contains all of the stations which we identified above as being relatively unstressed. The distribution of these clustered stations groups (at the 1 versus 2 level) is shown in Figure 4-2. It can be seen that all the areas independently identified as disturbed in Table 4-1 are also separated by the clustering routine.

Given the quick data acquisition and return possible with REMOTS® technology and its ability to document hypoxic and eutrophic effects during the late summer period of maximum water stratification, a valuable data base could be compiled to document seasonal changes at the seventy stations designated for the present survey. At a minimum, all stations sampled during this survey should be re-occupied during the late summer to compare with these winter measurements. To choose the most parsimonious sampling strategy based on these results, a reduced REMOTS® sampling matrix for monitoring the status and trends of sediment quality parameters in San Francisco Bay can also be selected. All of the major sediment quality gradients could be monitored with sediment profile photography at the approximately 30 stations indicated in Figure 4-2. Periodic monitoring of these sites would allow environmental changes in these areas of the bay to be determined rapidly. Stations located on or near the Alcatraz Disposal Site have not been included; because of the continual stress resulting from disposal activities, this is not a good location to document long-term changes in the status and trends of the Bay. However, once an offshore disposal site for dredged material from the San Francisco Bay region is established and disposal activities cease at the Alcatraz site, stations in and around this area should be established to document the long-term recovery process.

V. RECOMMENDATIONS

Sediment profile imaging has been used historically (since 1979) and most effectively in benthic monitoring programs in two major applications. The first consists of reconnaissance mapping (similar to this present survey of San Francisco Bay) to quickly and efficiently map regional or bay-wide gradients in benthic processes and sediment-habitat quality. In most cases, this is done prior to selecting a subset of stations for permanent or long-term sampling with traditional oceanographic sampling techniques (typically using grabs or box-cores). Once the most parsimonious grab-sampling station matrix has been established, REMOTS® can continue to be used in a reconnaissance mode to fill-in information on gradients between these permanent stations and/or to document seasonal changes between periods of sampling with these more traditional methods. This "second-phase" reconnaissance mapping is often done with a reduced REMOTS® sampling matrix, such as the 30 station matrix we have recommended for future monitoring of San Francisco Bay (Figure 4-2). For nearshore shallow areas, REMOTS® surveys ideally should be repeated to document variations due to seasonal effects; the present survey was conducted in the winter, and doubtless a different pattern would emerge if the survey had been done in the late summer when rates of infaunal bioturbation as well as chemical and biological oxygen demand are at their maximum. Until these seasonal effects are known, it is difficult to designate which "transitional" stations are useful as long-term monitoring stations. The reduced sampling matrix suggested in Figure 4-2 does not include many "transitional" stations for this very reason.

The second major application for REMOTS® technology has been to occupy permanent sampling stations (i.e. stations sampled with other techniques) to obtain <u>in-situ</u> information on benthic habitat conditions (mean apparent RPD depth, successional stage, Organism-Sediment Indices, deposition or erosion at the site, etc.) which, because of its functional perspective, can help interpret other types of measurements. For example, in this survey we have presented REMOTS® data on areas which have recently experienced bottom erosion or deposition of newly introduced sediment layers. These data should prove valuable in interpreting measured concentrations of sediment-associated pollutants or assessing processes which may have altered sediment grain-size or community structure.

The use of the summary REMOTS® OSI parameter together with the <u>C. perfringens</u> concentrations appears to have great promise in characterizing one aspect of sediment quality. In many cases, high <u>C. perfringens</u> concentrations appear to be associated with low OSI values. When this occurs, both techniques support a hypothesis of high organic loading from sewage effluents. The gradient in densities of C. perfringens can also used to indicate potential sources of sewage effluent. For example, the distribution of Clostridium spores in the central bay suggest that major sources of sewage input are located within inner Oakland Harbor and near Treasure Island. Valuable reconnaissance information can also be gained when these two parameters do not track one another closely. In one case (Station 27 - inner Richmond Harbor), the low OSI value reflected high organic loading, but the C. perfringens concentrations were low. This provided valuable insight into the nature of the organic loading source and strongly suggested a non-sewage source of enrichment. In this specific case, we hypothesize anthropogenic hydrocarbons from industrial contamination as the source of this loading; however, gas chromatographic/mass spectrometer analyses of sediments from this location would be needed to identify the compounds responsible for this organic enrichment. In eutrophication studies, it is also a problem to separate direct biological oxygen demand loading from sewage versus indirect loading from enhanced phytoplankton growth. The combination of REMOTS® mapping and C. perfringens counts may be one approach to this problem.

We expect that the REMOTS® data will also be correlated with some of the parameters that are part of the Sediment Quality Triad. In addition, the REMOTS® process maps will provide important in-situ information for interpreting these data. If the Sediment Quality Triad is intended to characterize contaminated sites and long-term site conditions, it is important to know about the seasonal sedimentation regimes at those selected Triad sites. For example, in San Francisco Bay, our February REMOTS® mapping has shown that most stations are associated with mud clasts (erosional products of cohesive sediments), and 21 stations show the presence of recently deposited sedimentary layers. Sediments in nearshore areas, on shoals, and in channels apparently experience resuspension and redistribution. The chemistry of sediment from these areas may therefore differ from the ambient underlying sediment. This phenomena should be considered when samples are evaluated for the trace metal and organic components of the Sediment Quality Triad. Triad stations located within these areas may be expected to show large temporal variance in these component measurements. REMOTS® mapping can be used to identify and characterize this kind of seasonal and spatial variability.

Patterns of sediment deposition and erosion vary greatly between the estuaries and embayments that are included in the National Status and Trends Program. One of the most striking aspects of the REMOTS® images from San Francisco Bay is the ubiquity of features indicative of near-surface disturbance. In contrast, REMOTS® mapping of Puget Sound in November 1985 showed that most of the bottom areas surveyed were located in low kinetic areas. The large depths and limited wind fetch apparently contribute to this condition. In Puget Sound, one may therefore expect less seasonal variance due to sediment remobilization than in San Francisco Bay. Long-term, seasonal REMOTS® monitoring of Long Island Sound has revealed an intermediate condition in bottom stability between that described here for San Francisco Bay and for Puget Sound. This in-situ coupling of biological, chemical, and geological information obtained with REMOTS® sediment-profile photography is not readily attained with other benthic sampling techniques.

For the above reasons, we can see great utility in using REMOTS® in both a reconnaissance mode and permanent station sampling mode in the Status and Trends Program. Once physical and biological disturbance gradients and benthic community patterns have been documented in an initial reconnaissance survey, long-term monitoring with this technology will reveal shifts in disturbance regimes (e.g., recent depositional inputs from allochthonous sources or plankton detritus, bed-load transport due to wind-generated storm waves, effects of near-bottom hypoxia) through measurements of surface boundary roughness, sediment grain-size major mode, and depth of the apparent RPD. The status of the benthic ecosystem and any trends toward recovery of areas initially identified as stressed (e.g., azoic or Stage I, low OSI values) can also be documented with long term REMOTS® monitoring. We would also recommend ancillary sediment sampling for TOC and Clostridium spore enumeration in combination with REMOTS® monitoring as a relatively rapid, inexpensive method to potential sources of organic enrichment. Near-bottom dissolved oxygen measurements are also critical for assessing the effects of benthic eutrophication and hypoxia; however, we recommend that these measurements of near-bottom dissolved oxygen be done only during the late summer, when the water is the warmest and the water column is the most stratified.

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Table 2-1. Calculation of the REMOTS® Organism-Sediment Index Value

CHOOSE ONE VALUE:

Mean RPD Depth	Index Value
0.00 cm	0
> 0 - 0.75 cm	1
0.76 - 1.50 cm	2
1.51 - 2.25 cm	3
2.26 - 3.00 cm	4
3.01 - 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 Present	-2
No/Low Dissolved Oxygen	-4

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

RANGE: -10 to +11

Table 3-1

San Francisco Sediment Quality Survey
Station Coordinates

Station Number	Latitude	Longitude
1	38 06.383N	122 16.250W
2	38 05.717N	122 15.500W
*3	38 04.190N	122 14.296W
*4	38 01.611N	122 25.415W
5	38 03.500N	122 23.583W
6	38 03.750N	122 21.250W
7	38 03.367N	122 18.283W
*8	38 03.835N	122 15.250W
9	37 57.000N	122 25.833W
10	37 59.167N	122 25.750W
*11	38 00.468N	122 24.918W
12	38 01.217N	122 23.167W
13	38 02.000N	122 21.667W
14	38 02.667N	122 20.000W
15	38 03.217N	122 18.083W
16	38 03.567N	122 15.667W
17	38 01.800N	122 20.167W
18	38 02.417N	122 18.000W
19	37 53.500N	122 22.750W
20	37 53.500N	122 20.500W
21	37 51.500N	122 22.500W
22	37 52.000N	122 20.000W
23	37 49.717N	122 21.250W
*24	37 49.716N	122 20.310W
25	37 54.271N	122 22.989W
26	37 54.333N	122 21.667W
27	37 55.000N	122 21.667W
28	37 49.117N	122 19.283W
29	37 48.867N	122 20.500W
30	37 48.167N	122 20.000W
31	37 47.483N	122 18.000W
32	37 47.117N	122 15.250W
33	37 47.117N	122 14.800W
34	37 44.867N	122 22.833W
35	37 44.867N	122 23.633W
36	37 44.167N	122 22.150W
37	37 44.150N	122 21.717W
38	37 42.367N	122 22.000W
39	37 41.667N	122 22.250W
40	37 40.500N	122 22.333W
41	37 39.250N	122 21.417W
*42	37 46.584N	122 21.000W
43	37 37.500N	122 20.000W
44	37 37.000N	122 19.000W
45	37 36.284N	122 18.633W

Table 3-1 (cont.)

Station Number	Latitude	Longitude
46	37 35.333N	122 15.333W
*47	37 36.321N	122 14.790W
*48	37 49.384N	122 25.250W
*49	37 49.384N	122 25.668W
*50	37 49.384N	122 25.467W
51	37 42.750N	122 18.250W
52	37 42.750N	122 16.000W
53	37 41.200N	122 19.283W
54	37 41.667N	122 17.917W
55	37 41.667N	122 16.500W
56	37 39.333N	122 19.000W
57	37 39.333N	122 16.500W
58	37 39.633N	122 14.167W
59	37 37.617N	122 17.250W
60	37 37.617N	122 14.500W
61	37 36.083N	122 13.083W
62	37 34.167N	122 13.000W
63	37 33.233N	122 11.167W
64	37 31.850N	122 09.583W
*65	37 30.255N	122 07.150W
66	37 30.167N	122 07.000W
*67	37 28.401N	122 04.000W
68	37 32.000N	122 11.500W
69	37 30.917N	122 12.417W
*70	37 30.401N	122 12.785W

*Station adjusted as per sheet received from E. Long of NOAA.

Table 3-2.

Comparison of REMOTS Grain-Size Designations and Wet Sieving Results.

Sediments were collected from the top 1 cm layer of a Ponar grab; REMOTS grain-size determinations were made from assessing the entire cross-section of the upper 15-20 cm of sediment. Fines are defined as sediment having a grain-size of ≥4 phi. When the percent fines is ≥50% and the <u>majority</u> of REMOTS replicates shows a major mode of ≥4 phi, the two methods are deemed in agreement.

Station No.	Percent Fines (By wet sieving)	REMOTS Grain Size Major Mode (phi units)
1	98.4	≥4 (5)
2	96.5	≥4 (5)
3*	55.6	2-1 (3)
4	95.4	≥4 (3)
5	95.9	≥4 (3)
6	93.2	≥4 (3)
7	5.5	3-2 (4)
8	<1	3-2 (1), ≥4 (1)
9	5.3	3-2 (5)
10	61.6	no data
12*	15.4	≥4 (5)
13	32.2	4-3 (3)
14	33.9	3-2 (2)
15	5.0	3-2 (4)
16*	13.8	≥4 (1)
17	92.7	≥4 (5)
18	62.7	≥4 (5)
19	95.6	≥4 (5)
20	75.9	≥4 (5)
21	79.7	≥4 (4), >4-3
22	88.7	≥4 (5)
23	90.8	≥4 (4)
24	95.3	≥4 (5)
25	96.3	≥4 (4)
26	97.9	≥4 (4)
27	94.8	≥4 (5)
28	97.1	≥4 (5)
29	93.3	≥4 (5)
30	98.7	≥4 (5)
31	50.5	≥4 (5)
32	98.2	≥4 (4)
33	97.0	≥4
34	96.7	≥4 (5)
36	99.2	≥4 (5)
37	86.9	≥4 (5)

Table 3-2 (cont.)

Station No.	Percent Fines	REMOTS Grain Size Major Mode (phi units)
38	83.4	≥4(4)
39	93.6	≥4(5)
40	86.2	≥4(4), >4-3
41	96.0	≥4(5)
42	28.5	>4-3(4), 3-2(1)
43	91.9	≥4(5)
44	84.3	≥4(5)
45	84.5	≥4(5)
46*	27.2	≥4(4)
47	94.5	≥4(5)
48	76.0	≥4(4), 3-2(1)
49	8.1	3-2(3), ≥4(2)
50	65.5	≥4(5)
51	87.8	≥4(5)
52	94.2	≥4(5)
53	62.3	≥4(4), 4-3(1)
54	89.1	≥4(5)
55	78.6	≥4(4)
56*	39.6	≥4(5)
57	84.8	≥4(5)
58	54.6	≥4(2), >4-3
59	96.9	≥4(5)
60	40.1	>4-3
61	38.3	4-3(3), ≥4
62*	41.2	≥4(5)
63	72.6	≥4(5)
64	83.3	≥4(5)
65	91.5	≥4(4)
66	83.8	≥4(5)
67	98.7	≥4(4)
68	98.3	≥4(5)
69	99.7	≥4(5)
70	95.6	≥4(5)

* Stations for which the two methods do not agree.

Table 4-1.

Comparison Of REMOTS OSI and RPD Data With Other Parameters
For Identification Of Ecologically "Stressed" Stations.

	REMOTS OSI $\bar{X} \leq 7$	REMOTS RPD $\bar{X}$	CLOSTRIDIUM (#/gm)	TOC/TON (mg/g)	DO ≤ 4 mg/l
South Bay					
Redwood Creek					
63	6.6	2.45	886	14.15/1.66	none
68	6.2	3.32	1080	15.23/1.89	none
69	7.0	6.04	2190	15.94/1.99	none
70*	3.0	2.00	4469	15.94/1.99	none
Coyote Creek					
66	4.8	1.21	491	15.65/1.64	none
67	5.3	2.11	1540	16.34/1.81	none
Port of S. Fran.					
34	4.6	2.20	1400	18.87/2.35	none
36	6.2	2.77	741	13.94/1.64	none
Inner Oakland Harbor					
30	7.0	5.57	2130	15.68/1.79	none
31	3.0	1.16	161	8.13/0.95	none
32*	7.0	2.17	5470	19.62/2.07	none
Off Coyote Pt.					
45	5.8	1.36	827	13.94/1.56	none
46	4.3	1.30	598	10.91/1.17	none

* Stations recommended for long-term status and trend monitoring in San Francisco Bay

Table 4-1 continued.

	REMOTS OSI $\bar{x} \leq 7$	REMOTS RPD $\bar{x}$	CLOSTRIDIUM (#/gm)	TOC/TON (mg/g)	DO ≤ 4 mg/l
Central Bay					
Richmond Harbor 27*	3.0	0.56	226	14.49/1.59	none
Alcatraz Disposal Site					
50	4.0	0.51	1070	12.35/1.31	none
48	5.0	1.50	2051	16.52/1.59	none
Outer Oakland Harbor 29	6.0	1.03	942	13.80/1.56	none
San Pablo					
8	2.0	2.19	151	8.25/0.59	none
16	3.0	0.84	261	1.87/0.33	none
4*	6.2	1.35	1530	13.71/1.34	none

* Stations recommended for long-term status and trend monitoring in San Francisco Bay

Table 4-2.

Comparison of REMOTS OSI and RPD Data with other parameters for Identification of Low-Disturbance Stations

	REMOTS OSI $\bar{x} \leq 7$	REMOTS RPD $\bar{x}$	CLOSTRIDIUM (#/gm)	TOC/TON (mg/g)	DO ≥ 4 mg/l
South Bay					
52	10.7	7.09	510	15.11/1.75	yes
57	11.0	4.41	1330	12.47/1.44	yes
58	10.5	4.02	409	18.36/1.66	yes
39	11.0	6.33	1160	13.02/1.49	yes
38	10.5	4.83	877	12.09/1.39	yes
Central Bay					
19*	10.2[1]	4.38	1250	13.13/1.57	yes
San Pablo					
18*	10.4[1]	5.37	666	13.80/1.08	yes

* Stations recommended for long-term status and trend monitoring in San Francisco Bay

1 These OSI were highest values in respective bays.

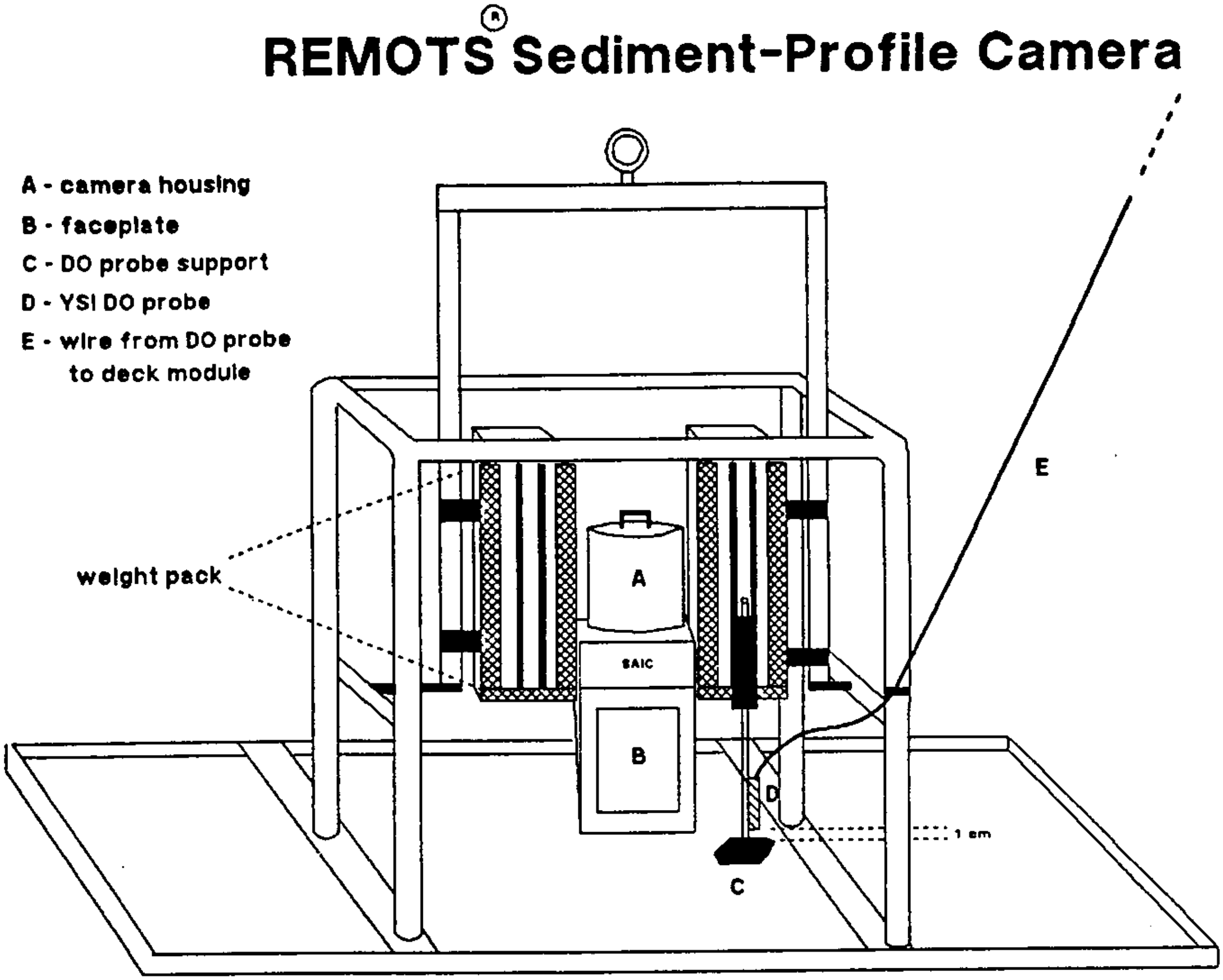

Figure 2-1. Benthos Model 3731 sediment-profile camera fitted with a YSI DO probe (D) for obtaining DO measurements one centimeter above the bottom. Instrument height is ca. 1.5 meters.

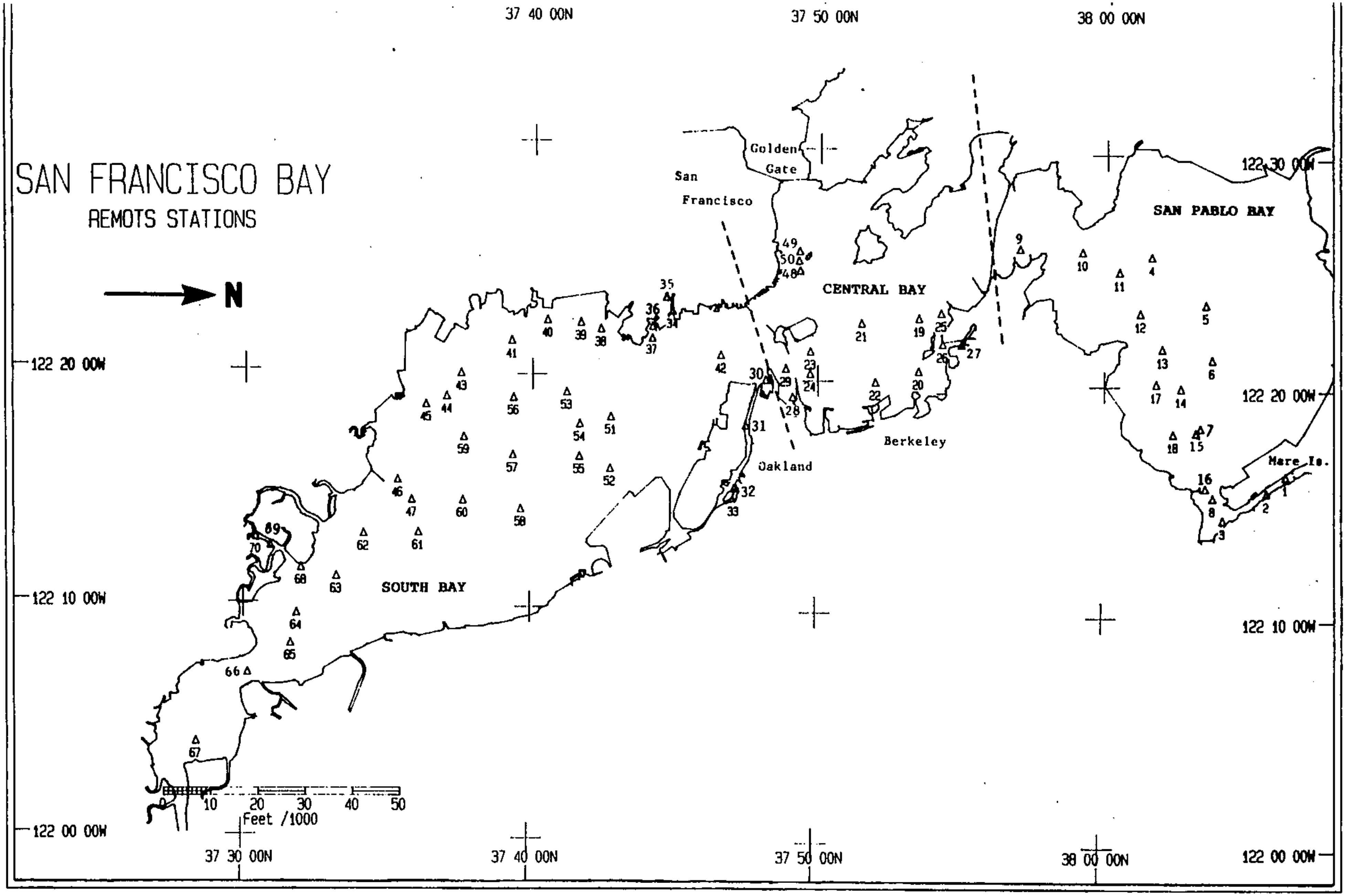

Figure 3-1. The positions and designations of all stations occupied during this survey.

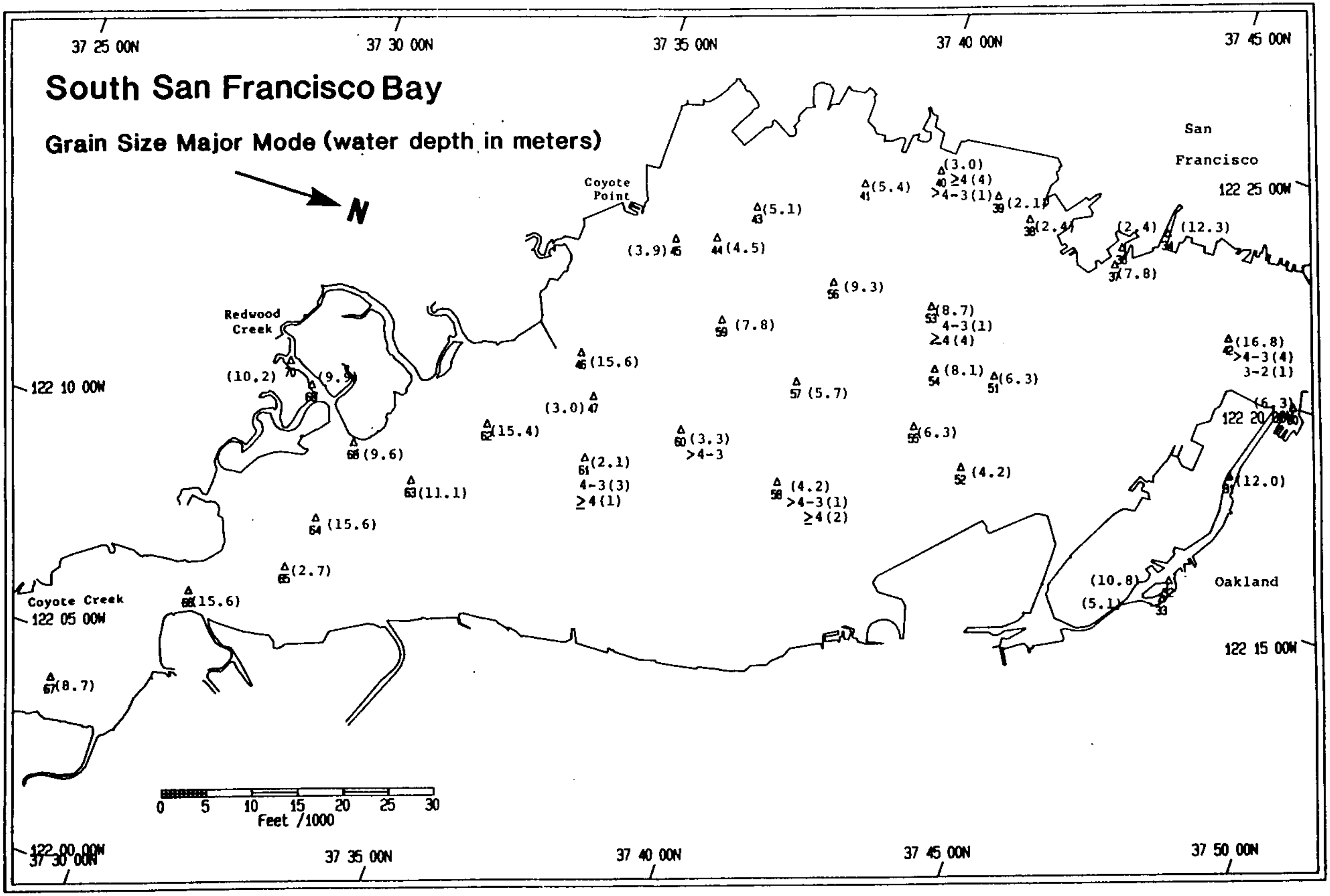

Figure 3-2. South Bay station names, water depth in meters (# in parentheses), and grain-size major mode in phi units, e.g. 4-3. Parenthetical numbering following phi range indicates number of replicate images with that value. All stations without assigned grain-size values exhibited only ≥4 phi major modes.

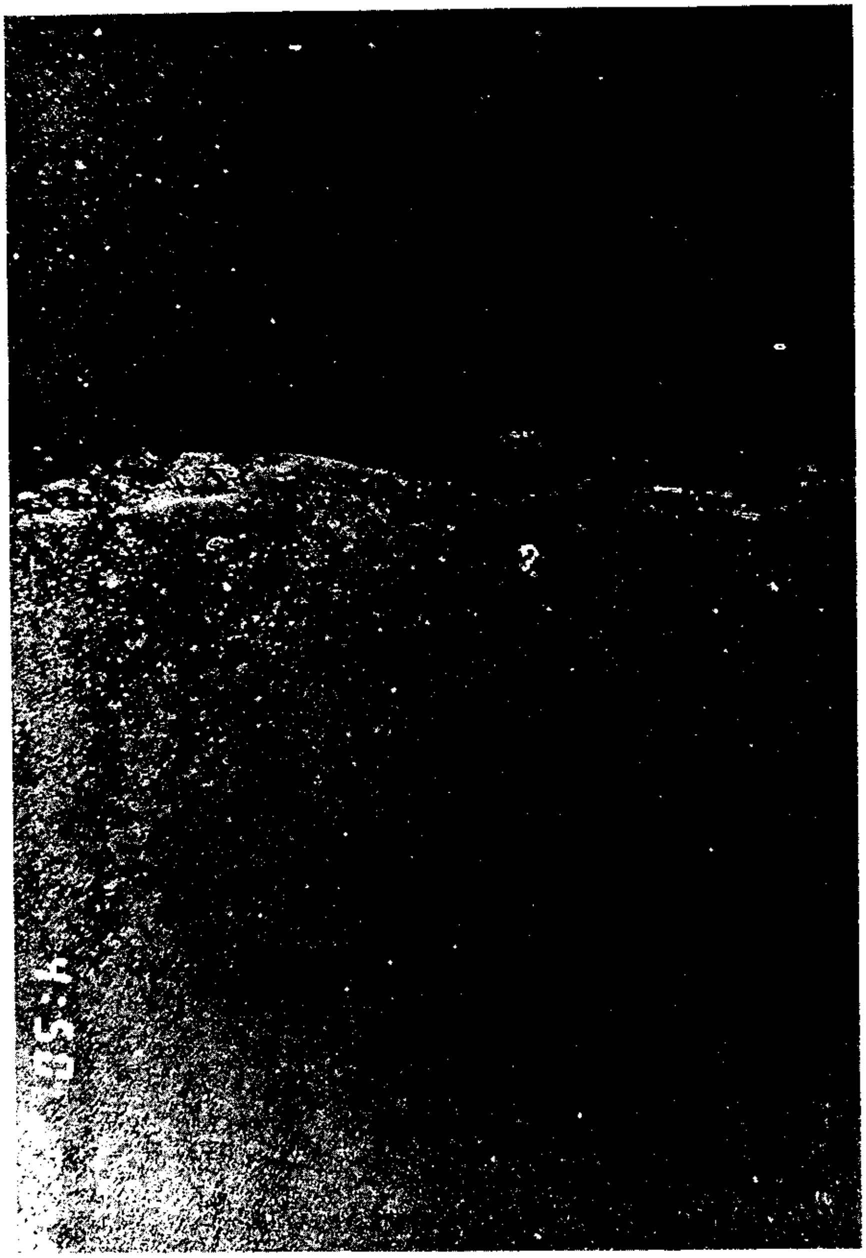

Figure 3-3. REMOTS image from station 42 showing a bimodal grain-size distribution consisting of a major mode of silt-clay and a subordinate sand mode. The fabric is mottled suggesting that bioturbation is responsible for the mixing of these two modes. Scale =1X.

Figure 3-4. Oyster bioherm at Station 61. Articulated and disarticulated shells are mixed with fine-grained sediment. Scale =1X.

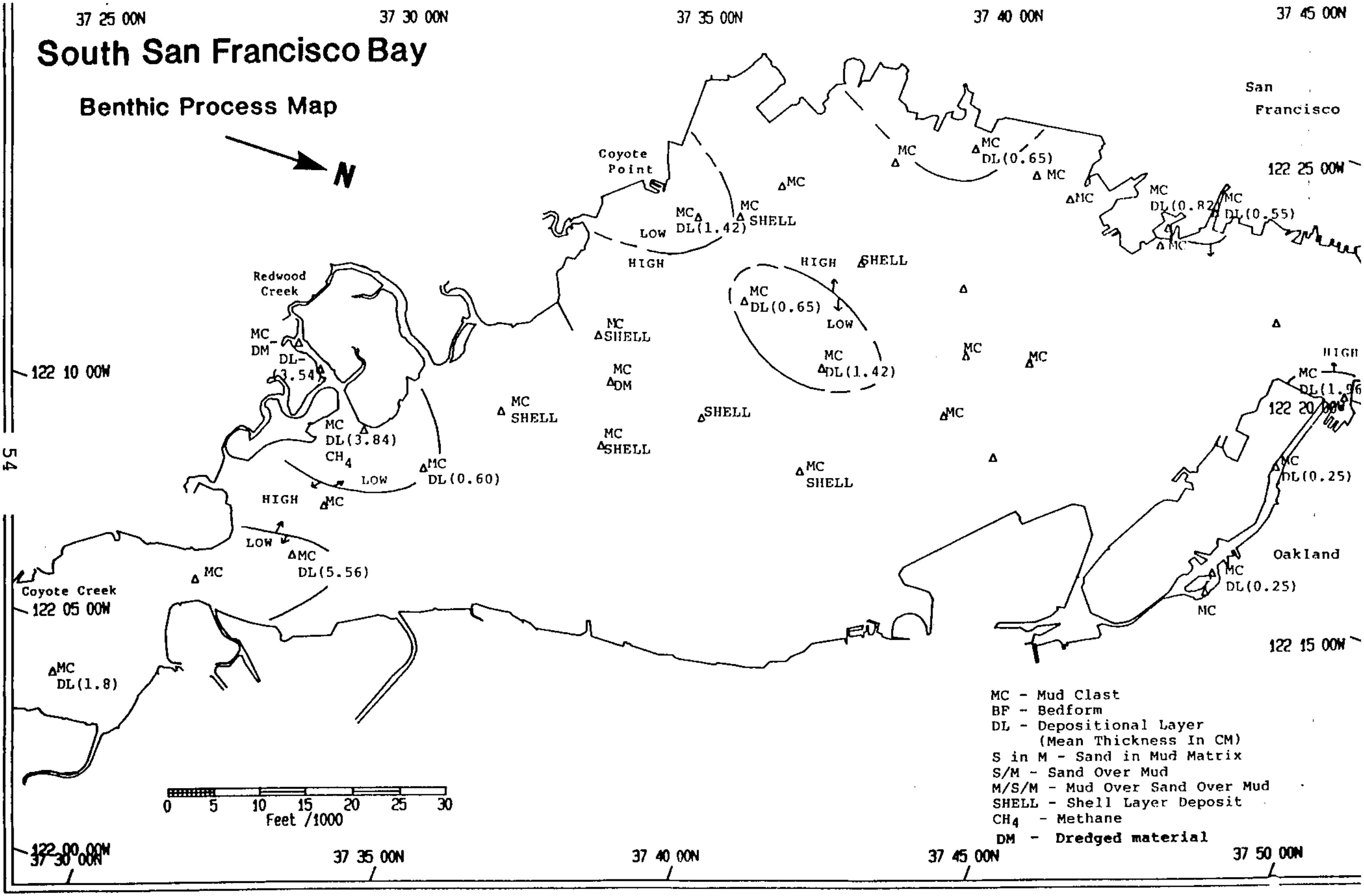

Figure 3-5a. A benthic process map of the South Bay. The contours separate low and high kinetic regions. Data is not mapped at stations 42, 52, and 53 because of the lack of distinguishable benthic process features in the REMOTS images from these stations. Station designations are provided in Figure 3-5b (following page).

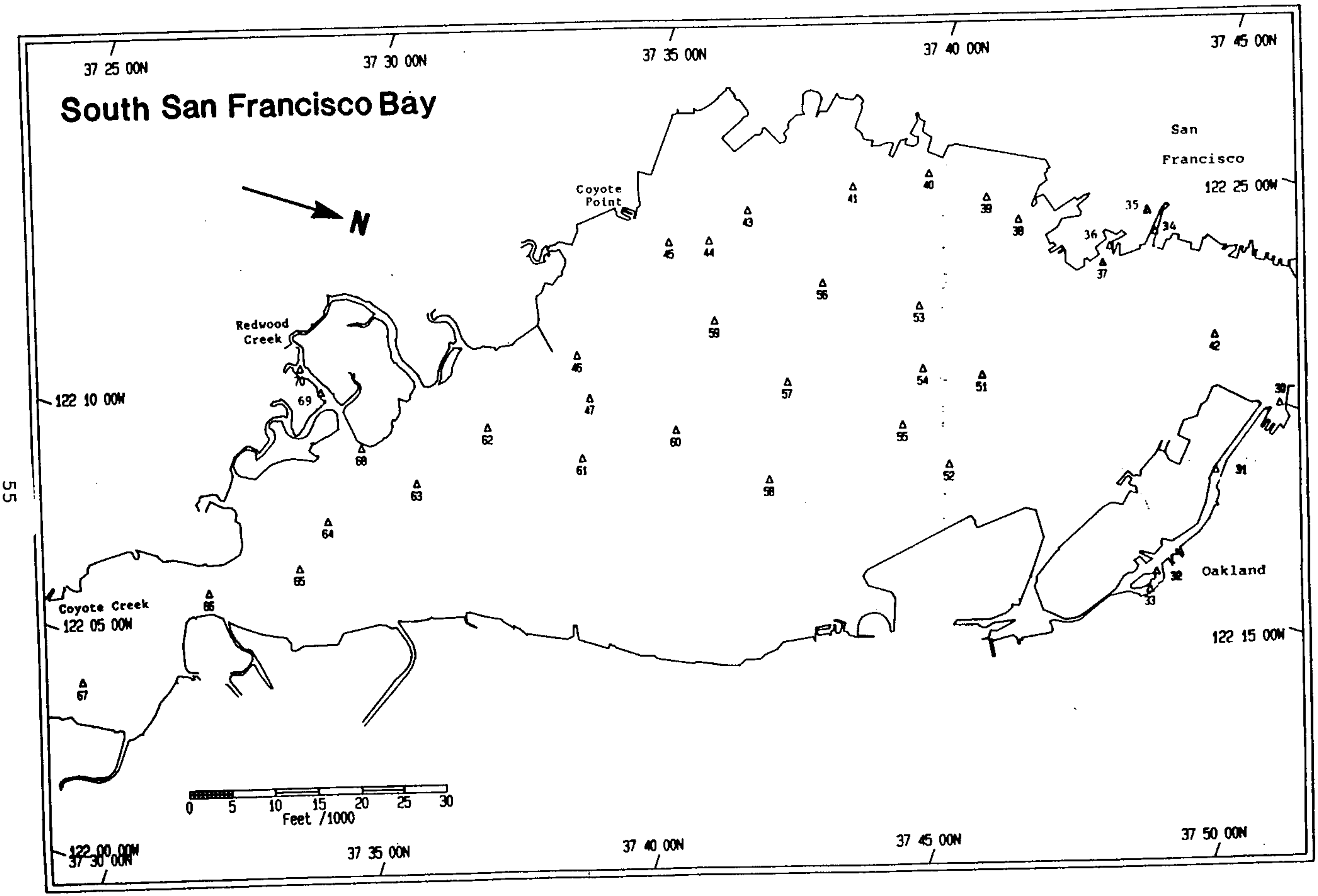

Figure 3-5b. Locations and designations of stations in South San Francisco Bay.

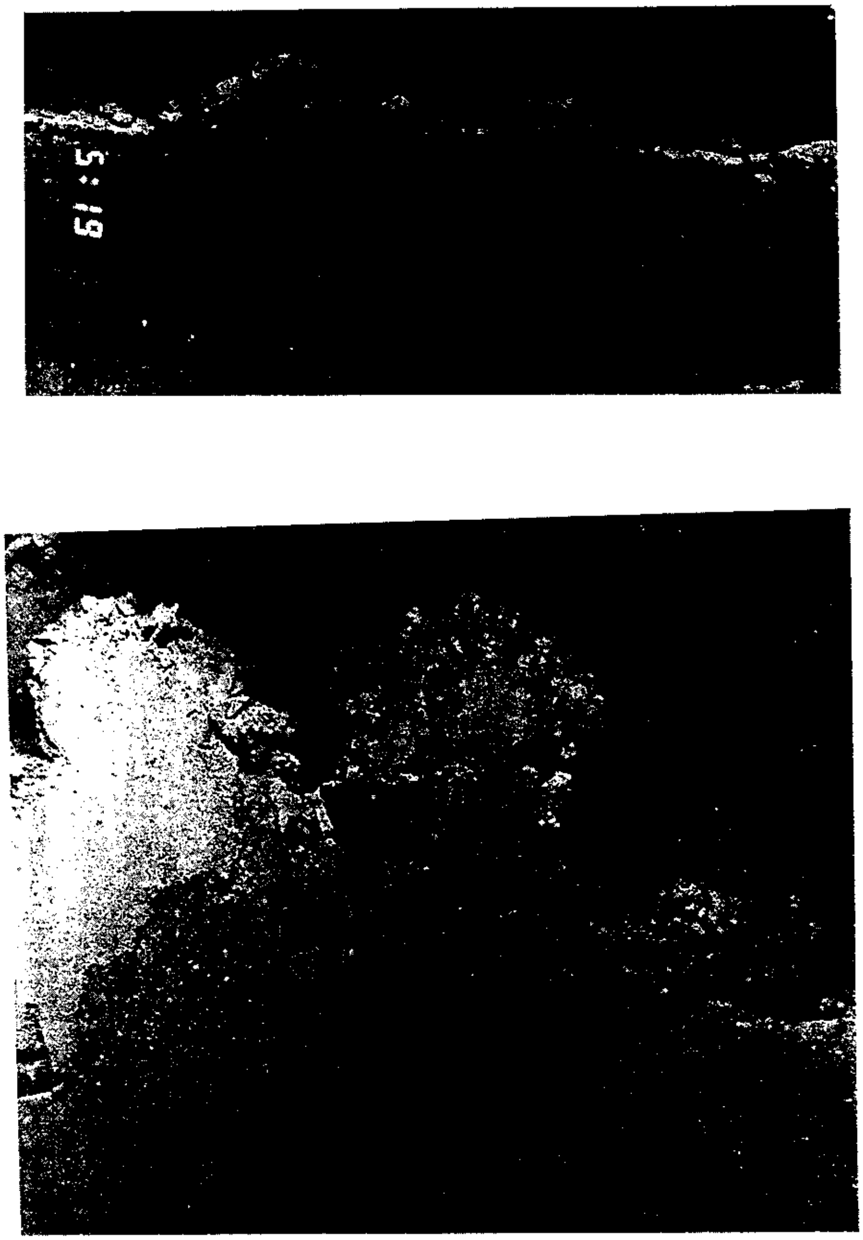

Figure 3-6. REMOTS images from stations 67 (top) and 41 (bottom) showing mud clasts of various size, degree of angularity (an indication of transport), and apparent oxidation state. Mud clasts characterize many of the San Francisco Bay sampling sites. Much of this eroded cohesive sediment is related to current scour but some of it may be related to burrow excavation. Scale: actual width of images = 15.2 cm.

Figure 3-7. Surface shell lag layer at Station 46 overlying a silt-clay and sandy sediment. This poor sorting suggests that this station experiences periodic surface erosion. Scale =1X.

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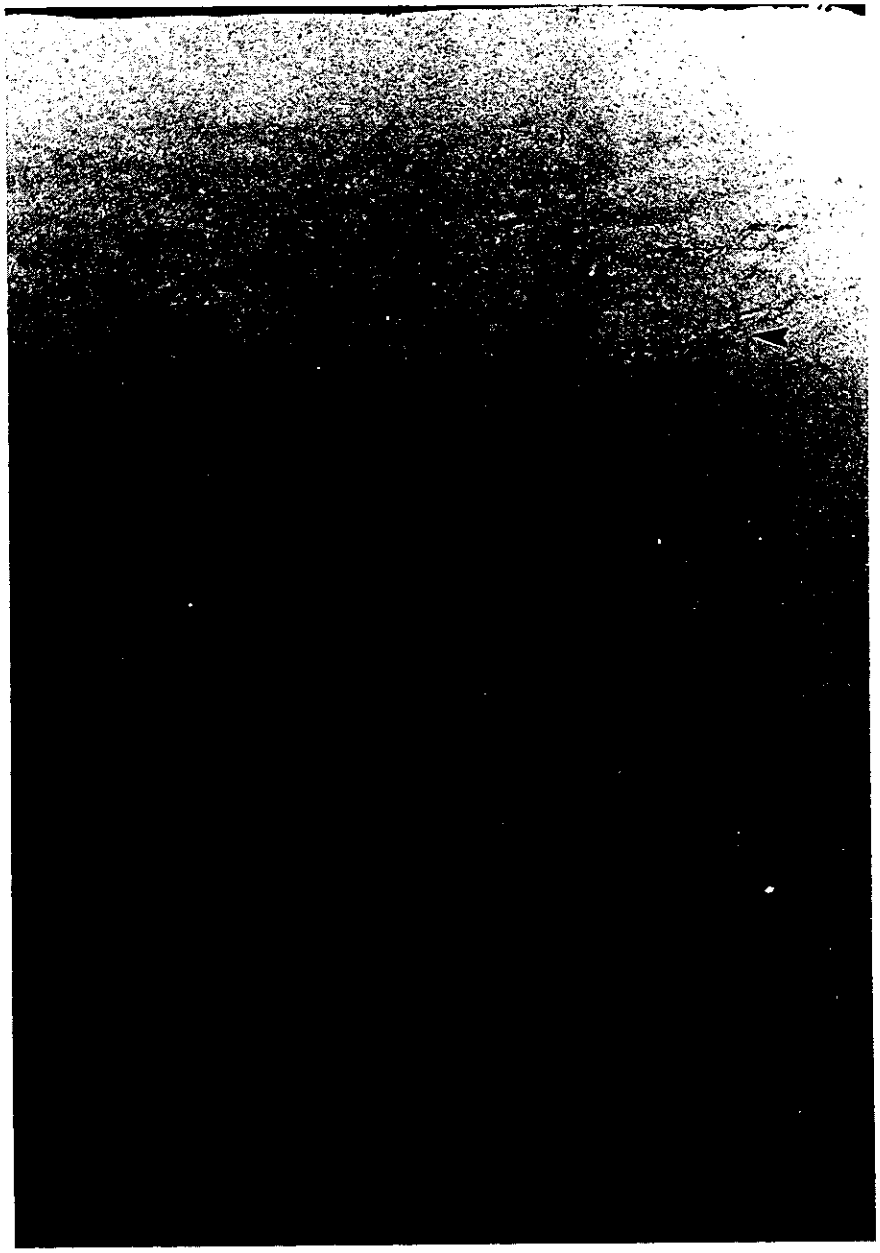


Figure 3-8. Station 69 shows evidence of at least two recently introduced sedimentary layers. The contacts are marked by arrows. The inference that these two layers have been recently introduce is based on the absence of biogenic mixing which would otherwise destroy such stratigraphy within a few days to weeks. Scale =1X.

SAIC

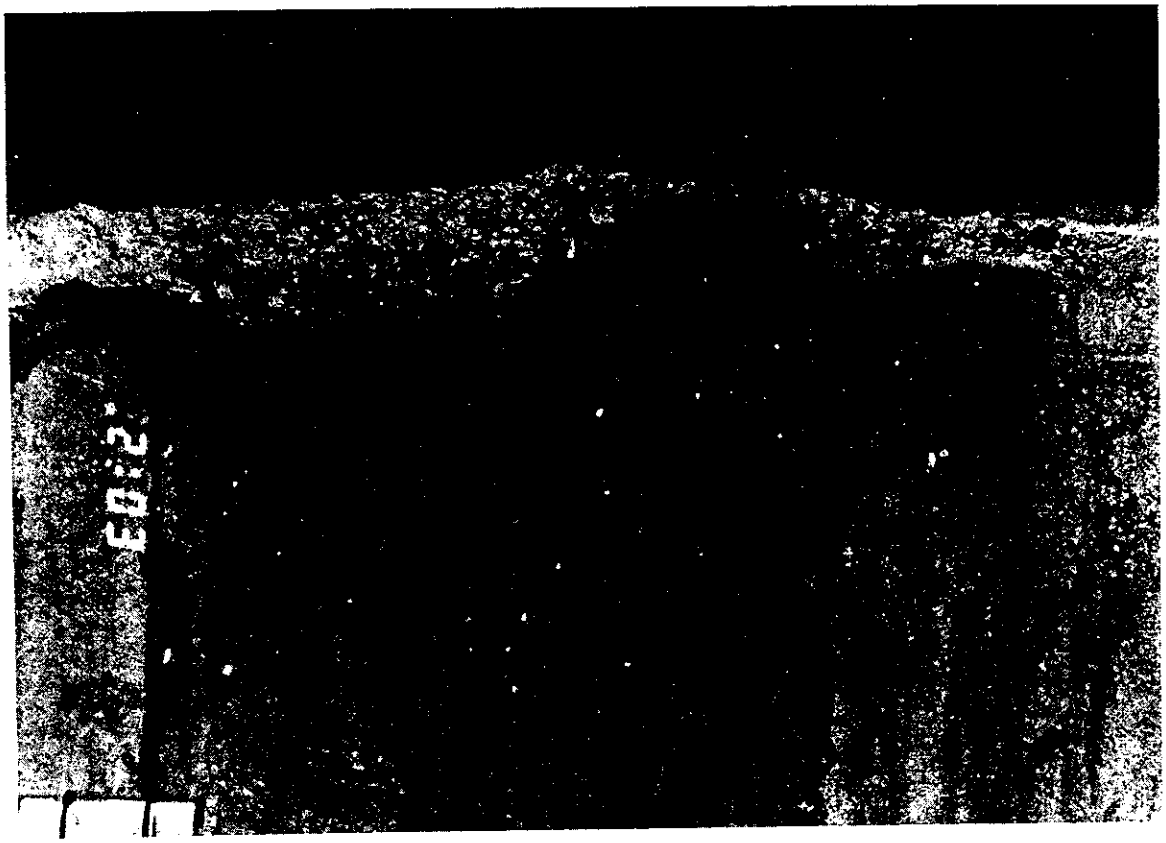
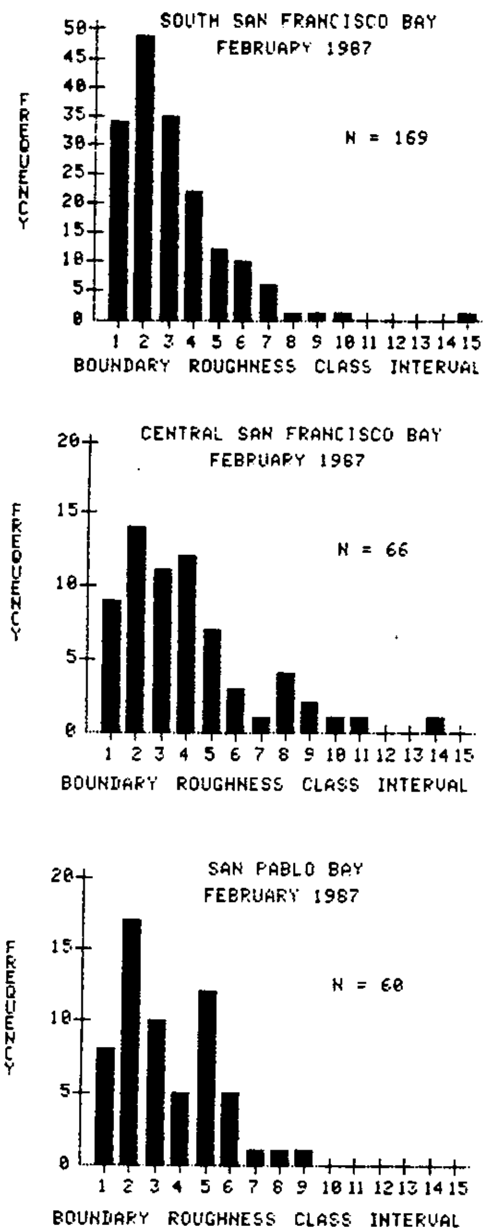


Figure 3-9. Station 45 shows the introduction of a low reflectance sedimentary layer overlying higher-reflectance sediment. Scale = 1X.



KEY

Class Interval	Range of Boundary Roughness (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

Figure 3-10. The frequency distributions of surface boundary roughness for each region of San Francisco Bay. Note different scales on the vertical axis.

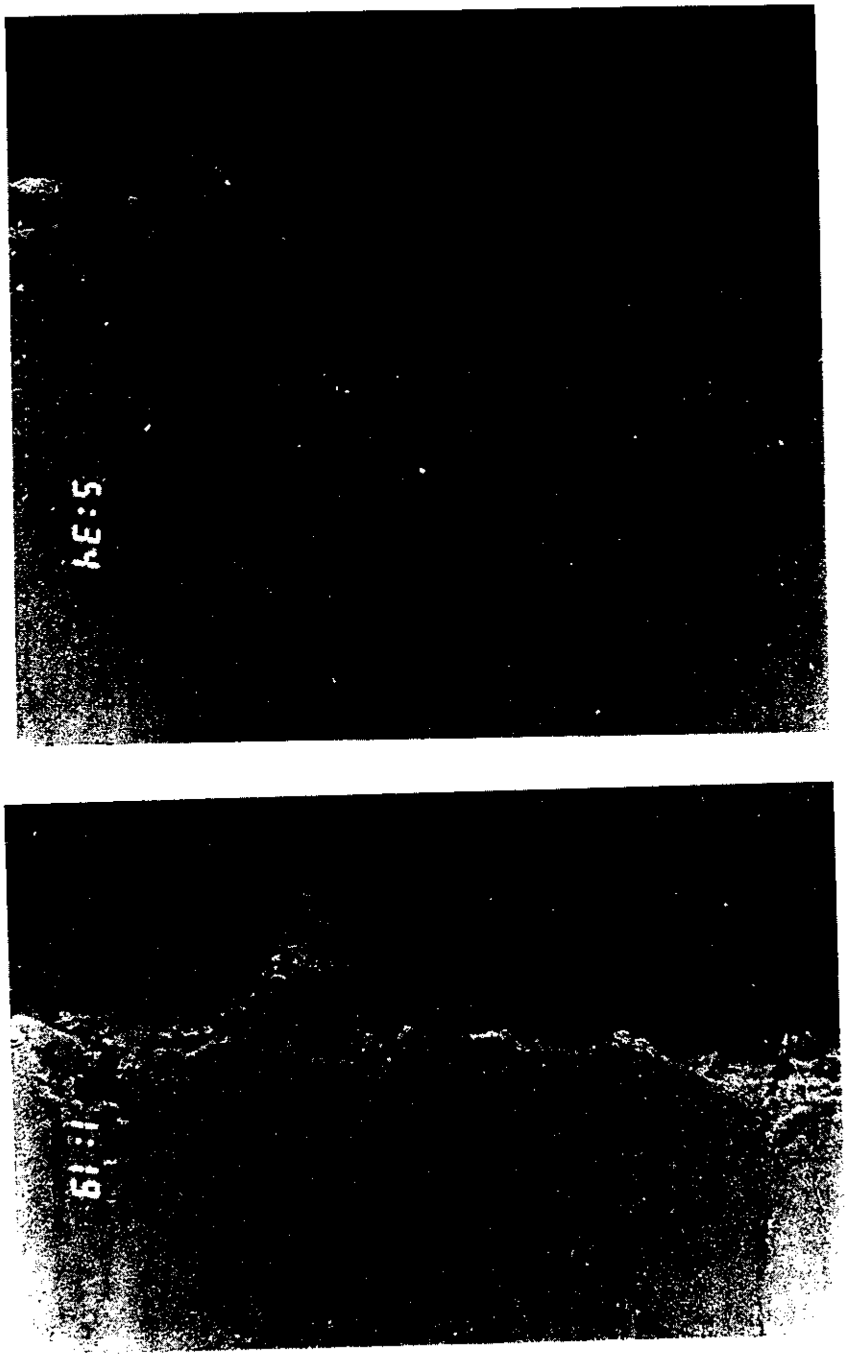


Figure 3-11. Emplacement of mud clasts onto an ampeliscid mat at Stations 52 (top) and 54 (bottom). These clasts may be the result of burrowing activity by macrofauna other than amphipods. Scale: actual width of images = 15.2 cm.

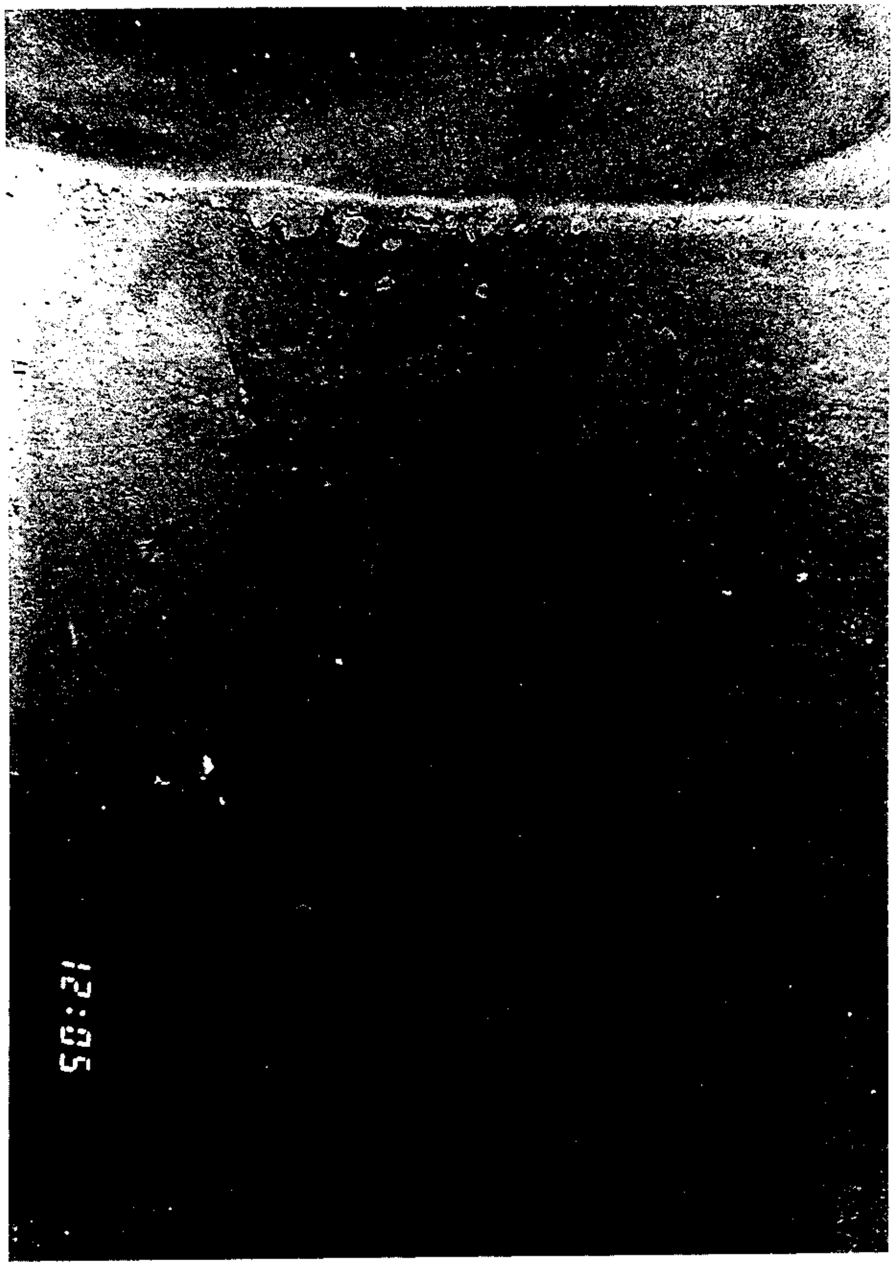


Figure 3-12. Low reflectance sediment at depth (between arrows) at Station 47 may reflect the past input of dredged material at this site. Width of image = 15 cm.

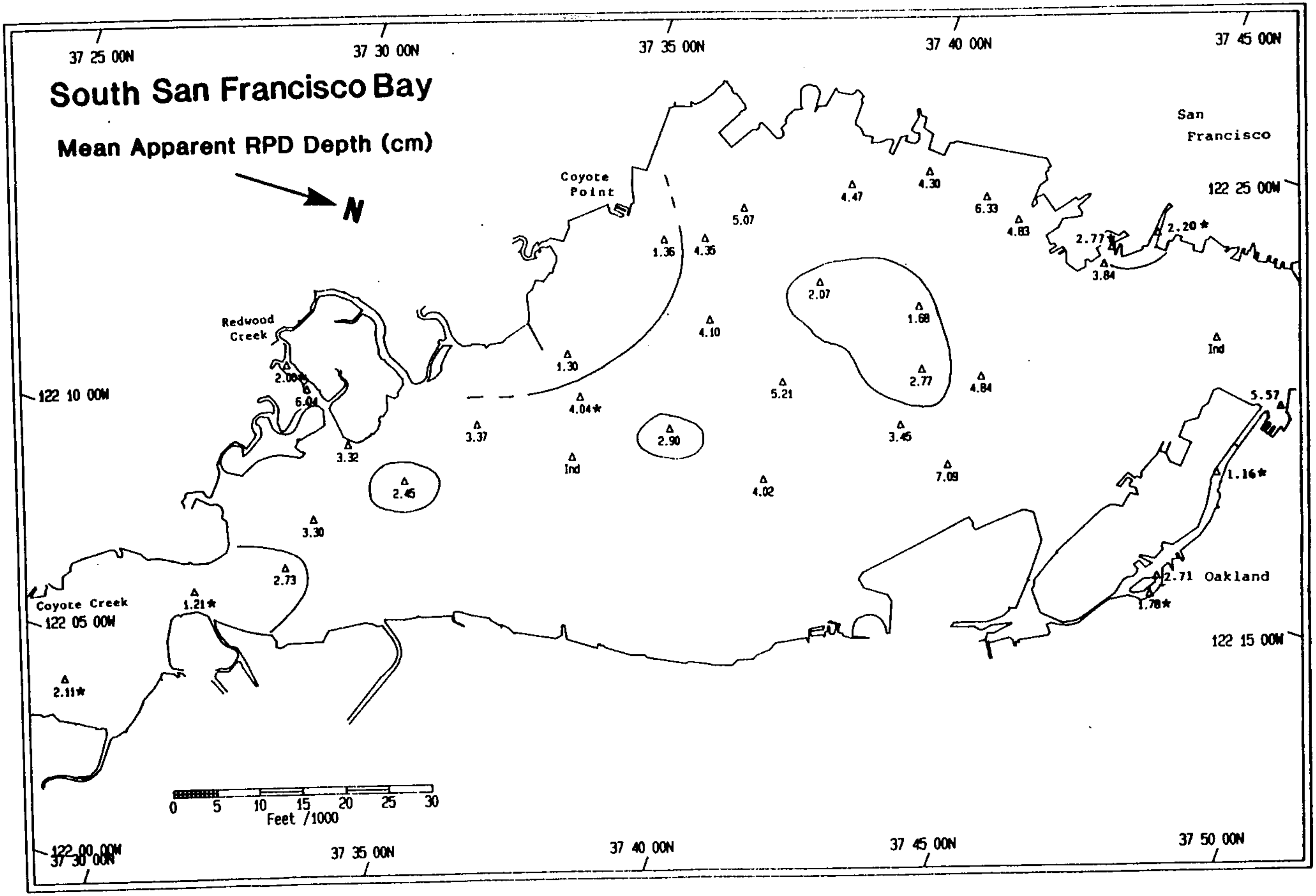


Figure 3-13a. The distribution of apparent RPD depths, averaged by station. The contours delimit regions exhibiting apparent RPD depths less than 3.0 cm. An '*' indicates the presence of apparent high sediment oxygen demand. An 'Ind' indicates that the RPD is indeterminate. Station designations are provided

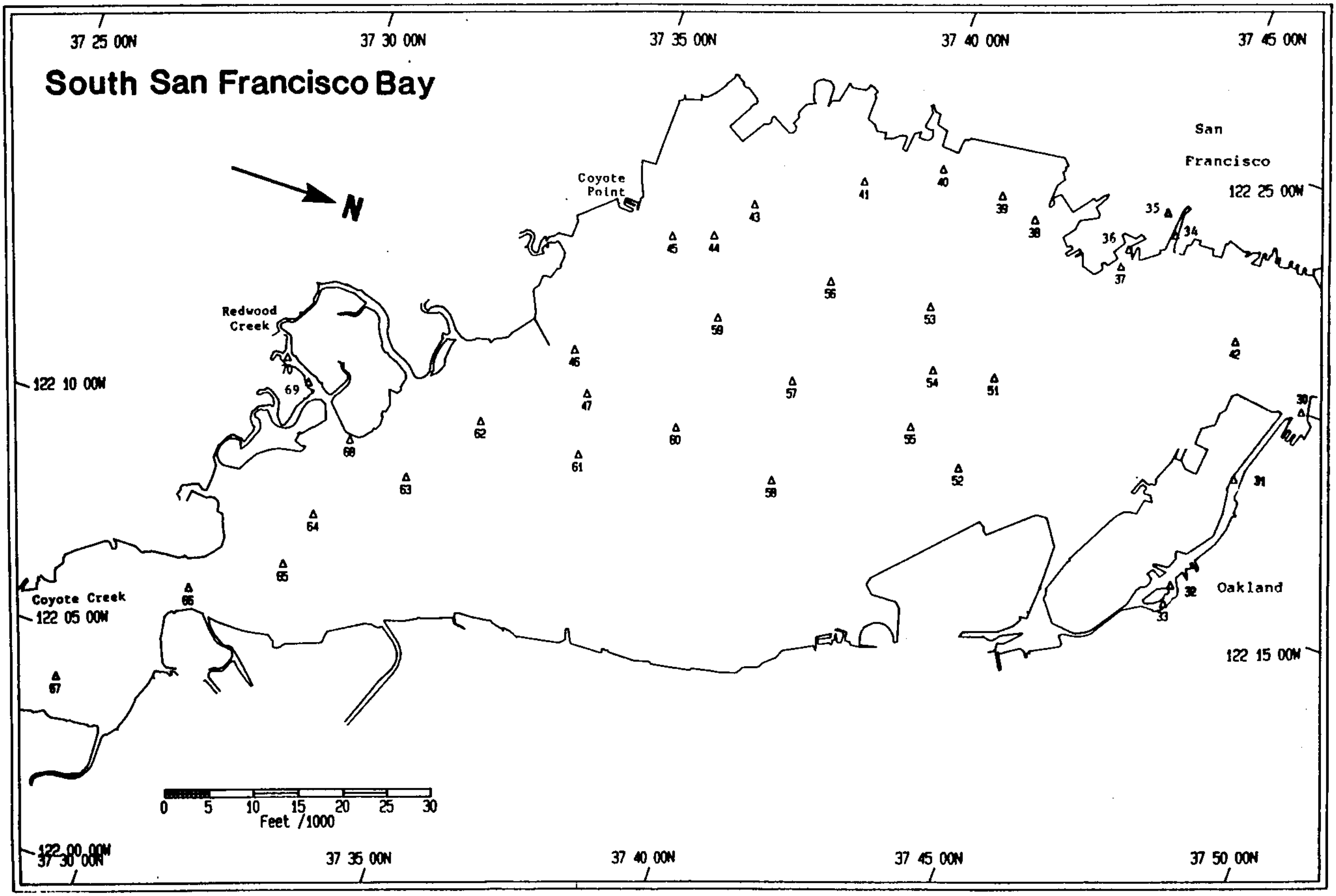


Figure 3-13b. Locations and designations of stations in South San Francisco Bay.

Figure 3-14. Station 66 consists of low reflectance sediment at the interface, indicating high sedment oxygen demand. The ampeliscid tubes at the surface appear to be in various stages of exhumation and decay. This may reflect a retrograde condition due to the high SOD. Scale = 1X.

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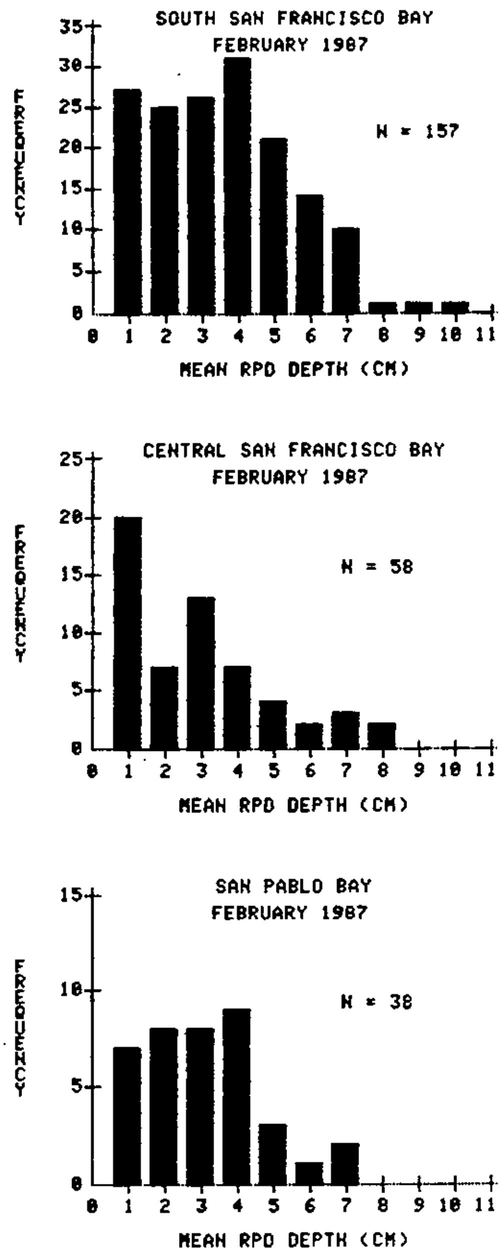

Figure 3-15. The frequency distributions of mean apparent RPD values for each region of San Francisco Bay. Note different scales on the vertical axis.

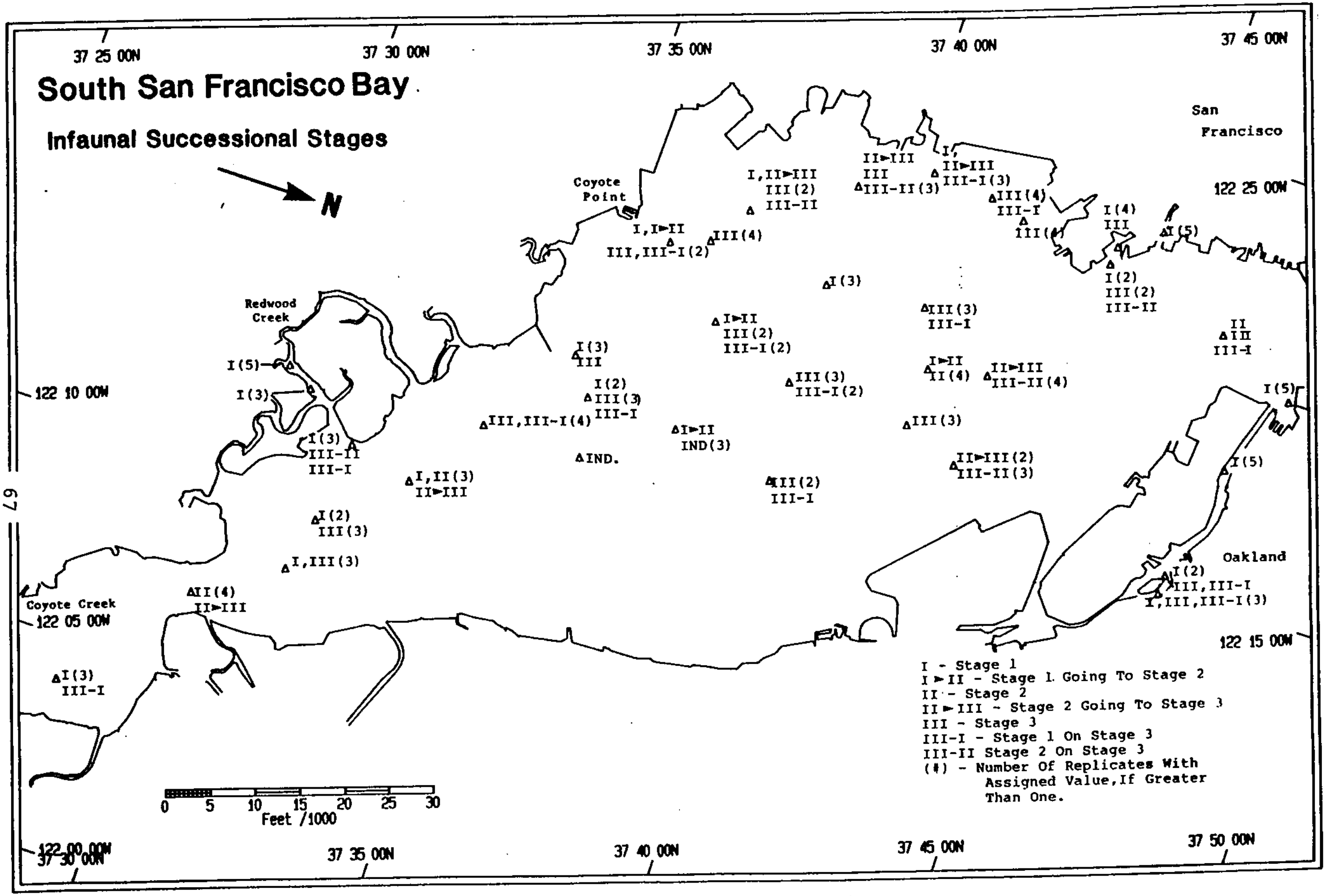

Figure 3-16a. The mapped distribution of successional stages in the South Bay. For a detailed explanation of the meaning of the various successional stages, refer to Section 2.2.1 in the text. Station designations are provided in

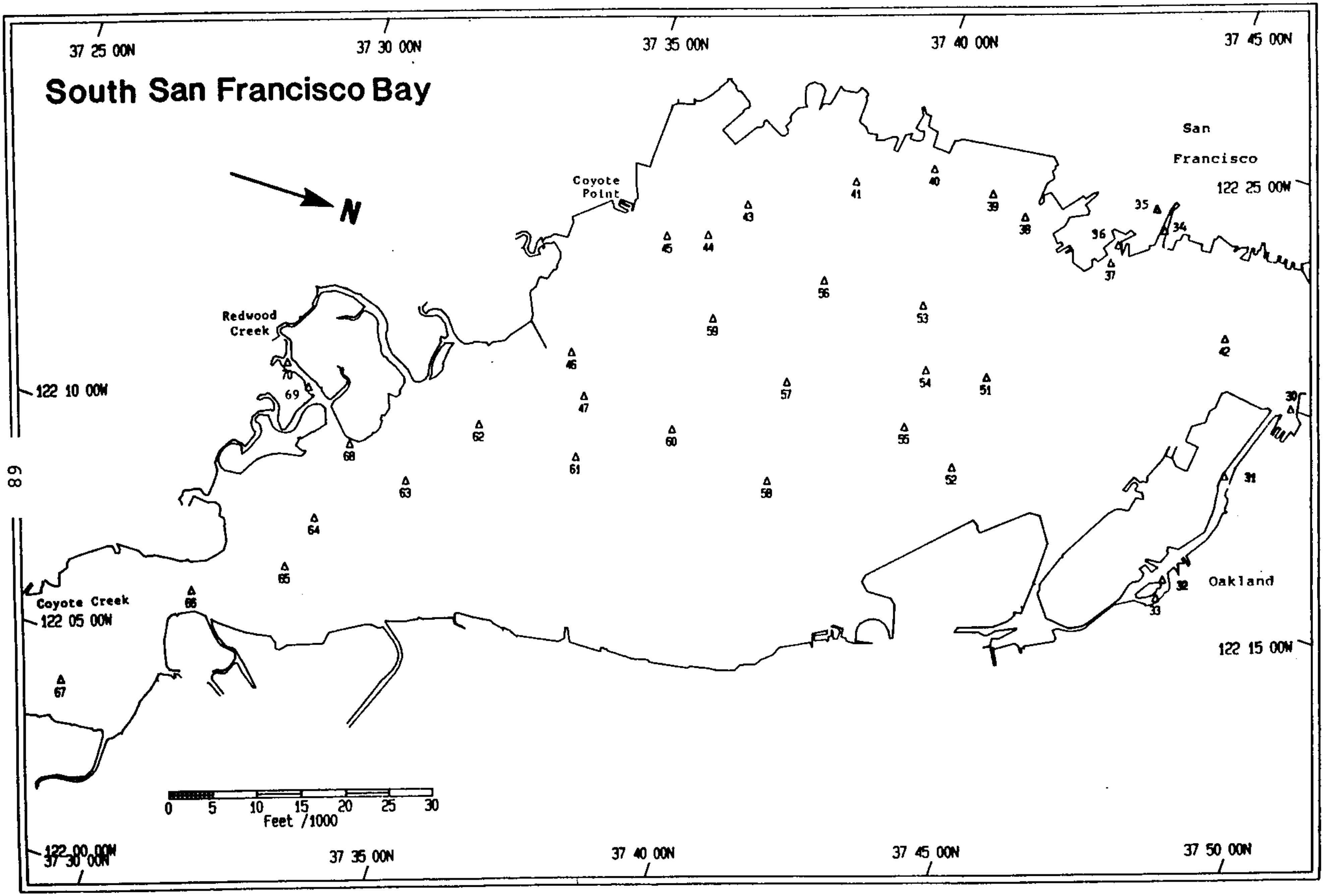

Figure 3-16b. Locations and designations of stations in South San Francisco Bay.

Figure 3-17. Stage III infauna are recognized by the presence of feeding voids which form around the head-ends of these deposit feeders (arrows). Station 37. Also, note the contrast in sediment reflectance between this image from station 37 and station 66 (Figure 3-25). Scale = 1X.

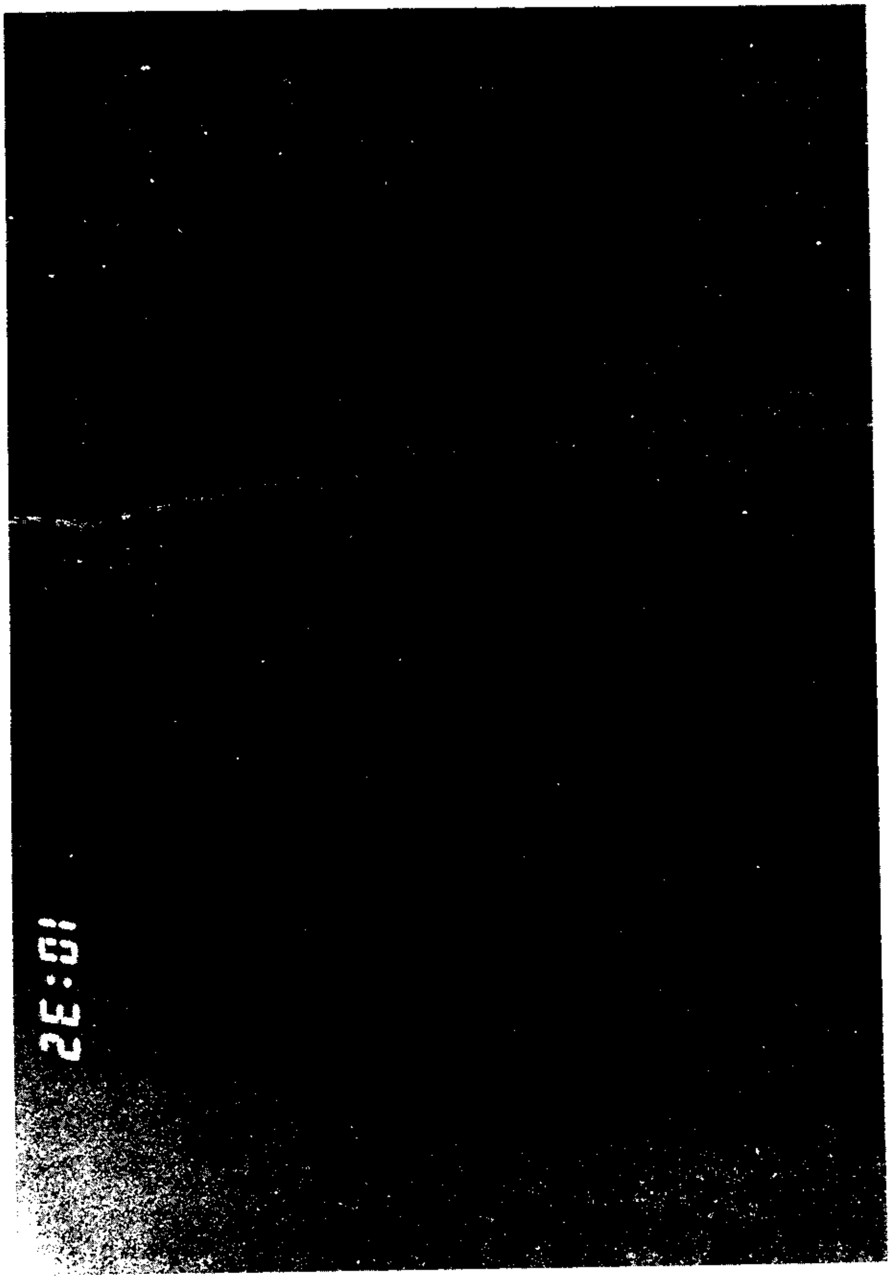

Figure 3-18. Many of the Stage III feeding voids observed in this survey are relatively small in size (arrows); this suggests that these infauna are themselves small (Station 39). Scale =1X.

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Figure 3-19. A REMOTS image from station 41 showing the caudal end of a large polychaete tube (arrow), which may be the maldanid Asychis elongata. A ripped-up ampeliscid tube mat is also evident. Scale = 1X.

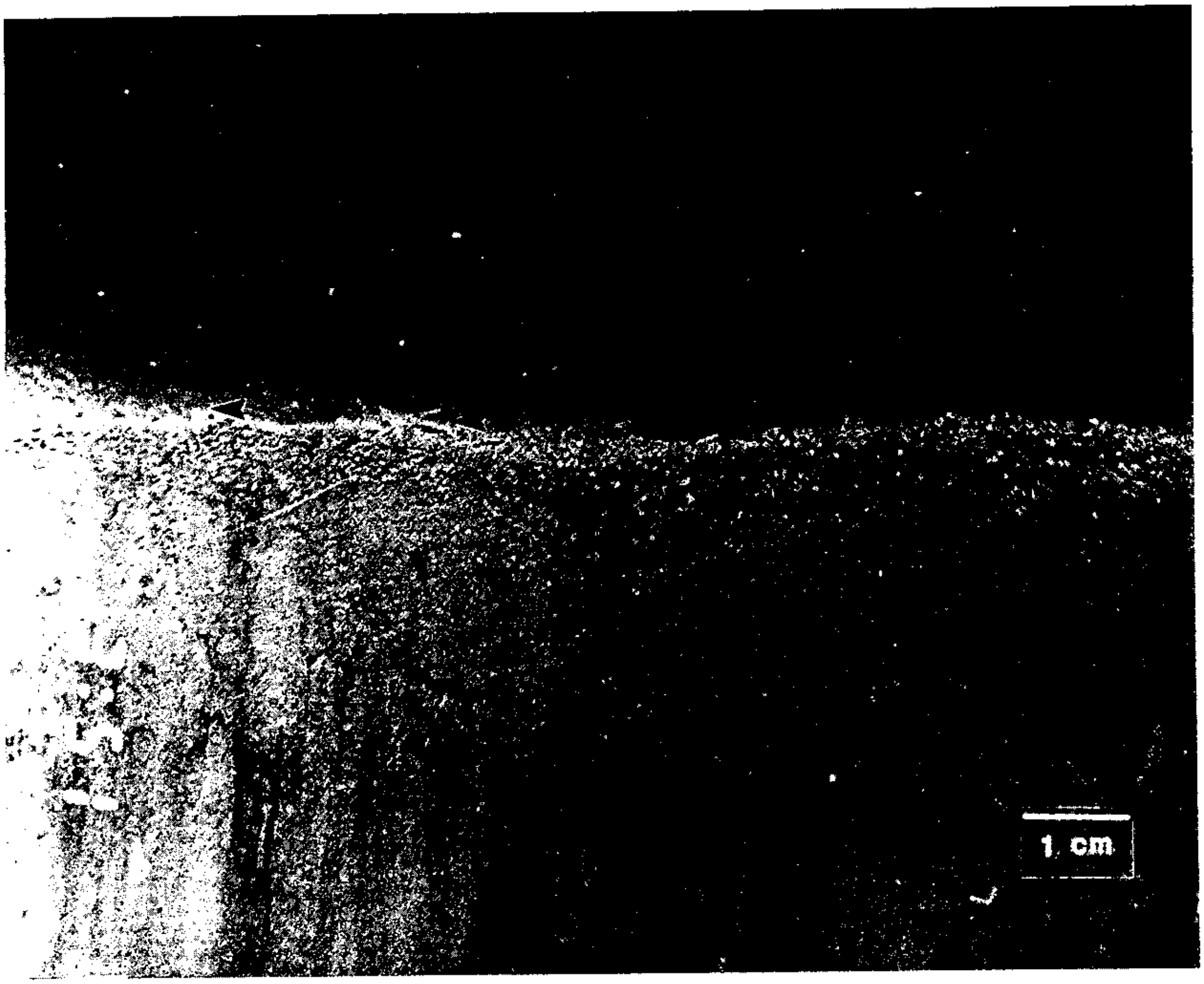

Figure 3-20. A dense Stage I aggregation of surface-dwelling, small polychaetes or oligochaetes at station 34 (arrows). These dense aggregations are commonly missed if sieve sizes are larger than 300 micrometer. Scale = 1X.

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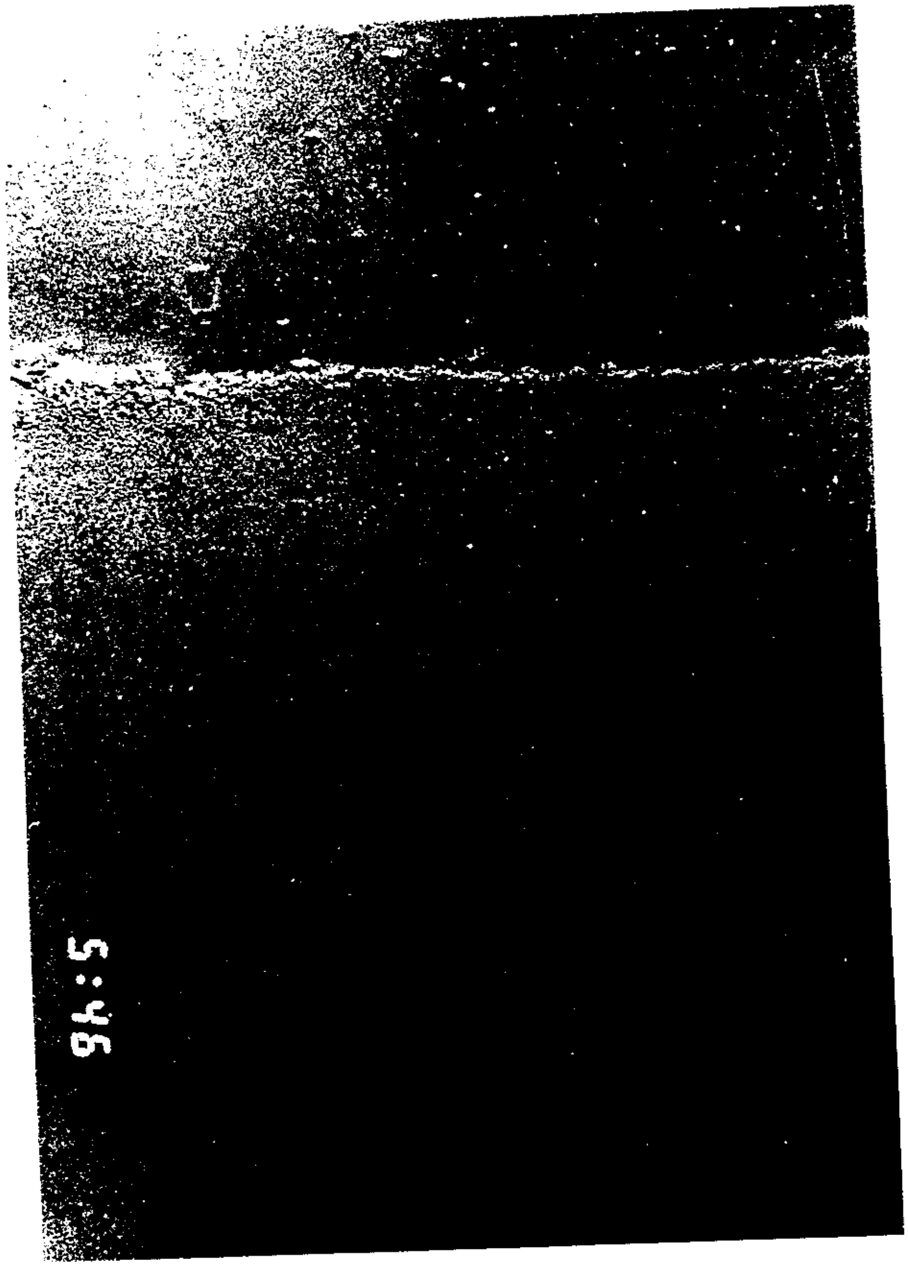

Figure 3-21. Station 31, located in Oakland inner harbor, lacks evidence of Stage III infauna (no head-down feeding voids). Scale = 1X.

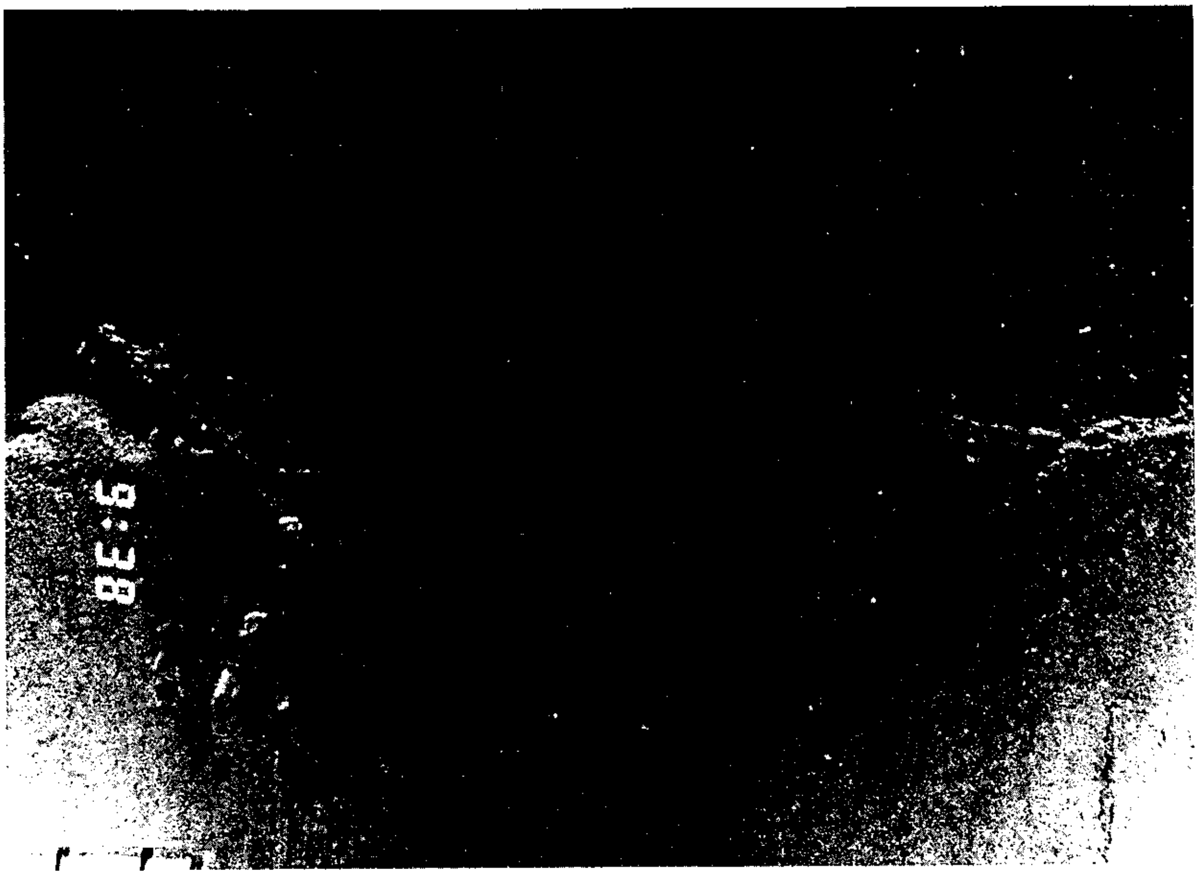

Figure 3-22. Aggregations of tubicolous amphipods at Station 41. Note high reflectance of the sediment which suggests that pore water sulphides are low (inventory of labile organic matter is low). Scale = 1X.

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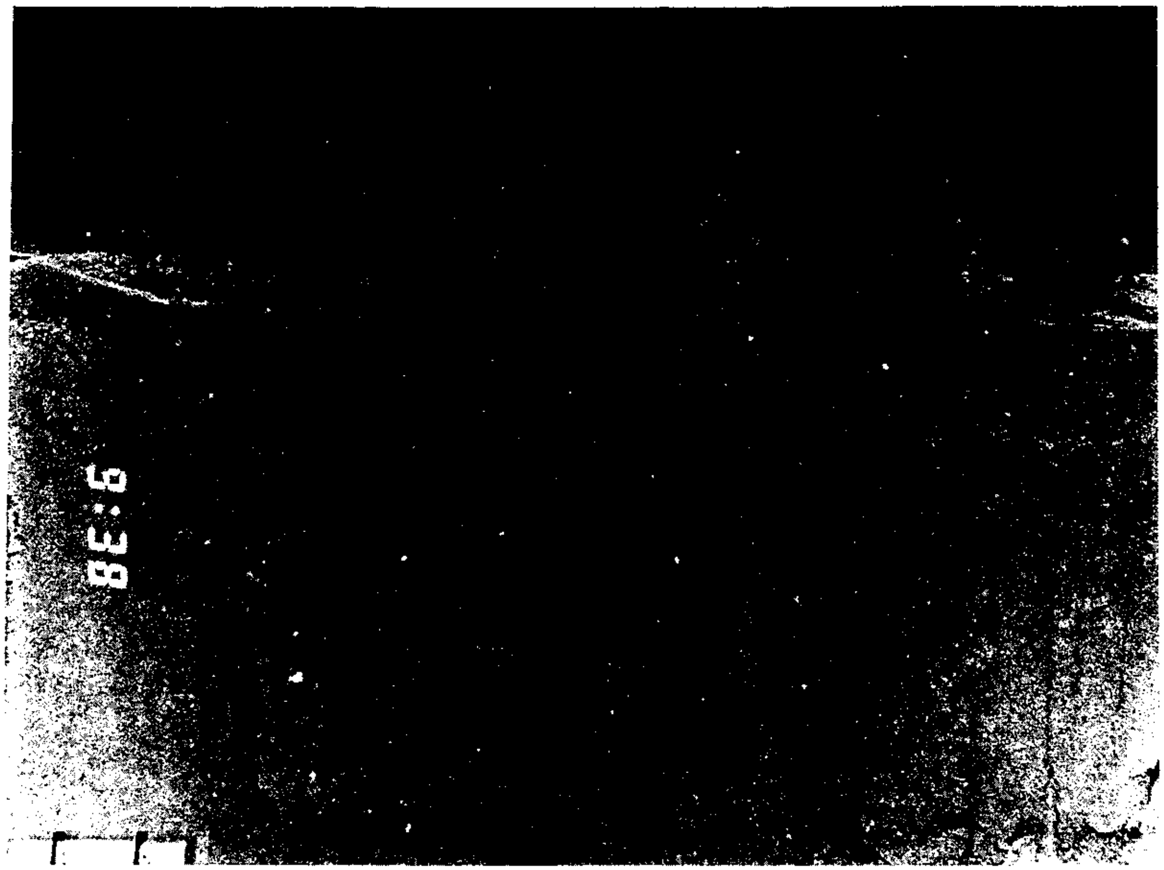

Figure 3-23. A ripped-up ampeliscid tube mat at Station 41. Such erosional events can be expected to result in changes in community or size-class structure. Scale = 1X.

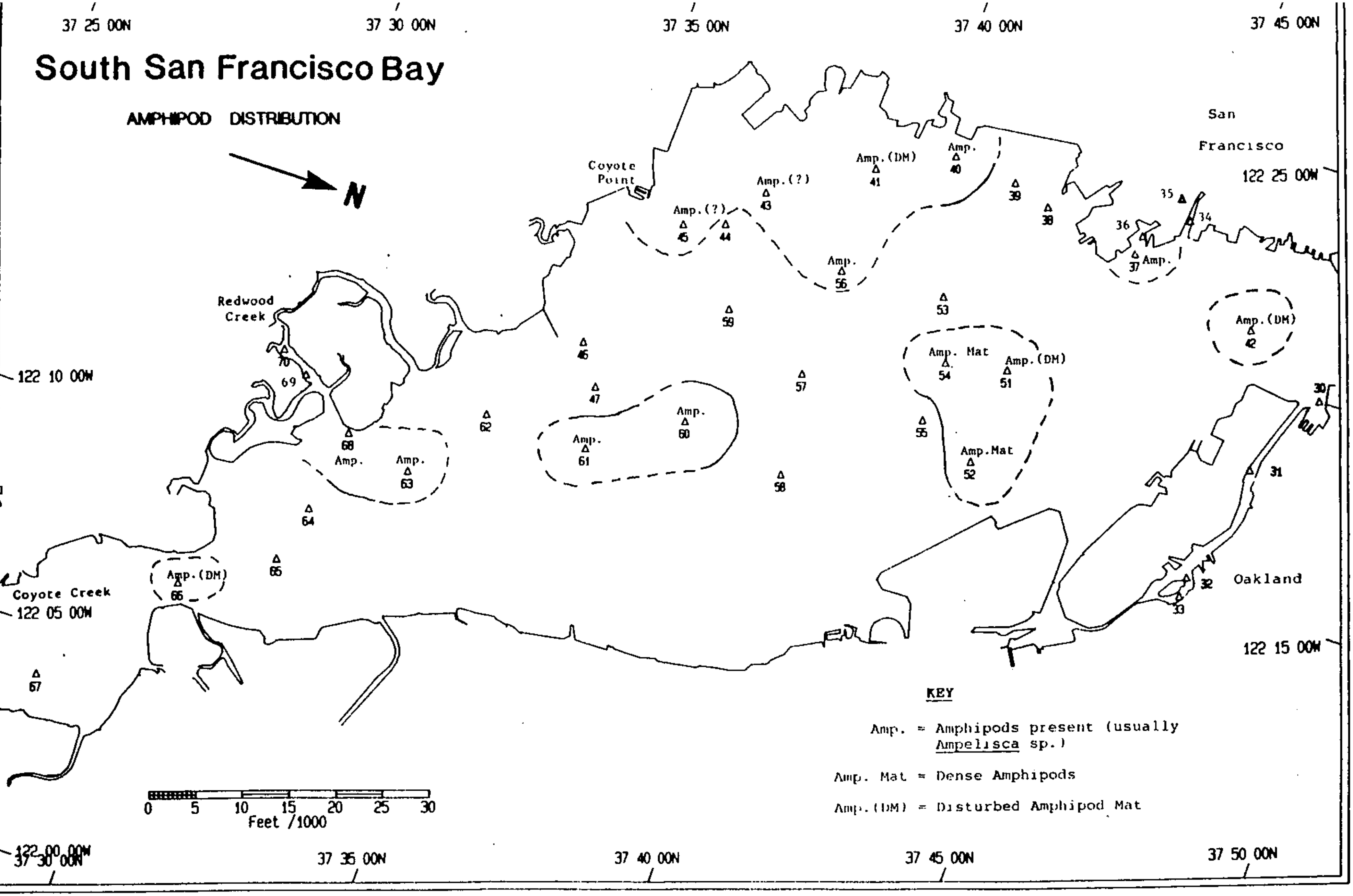

Figure 3-24. The mapped distribution of tubicolous amphipods (contours) in south San Francisco Bay.

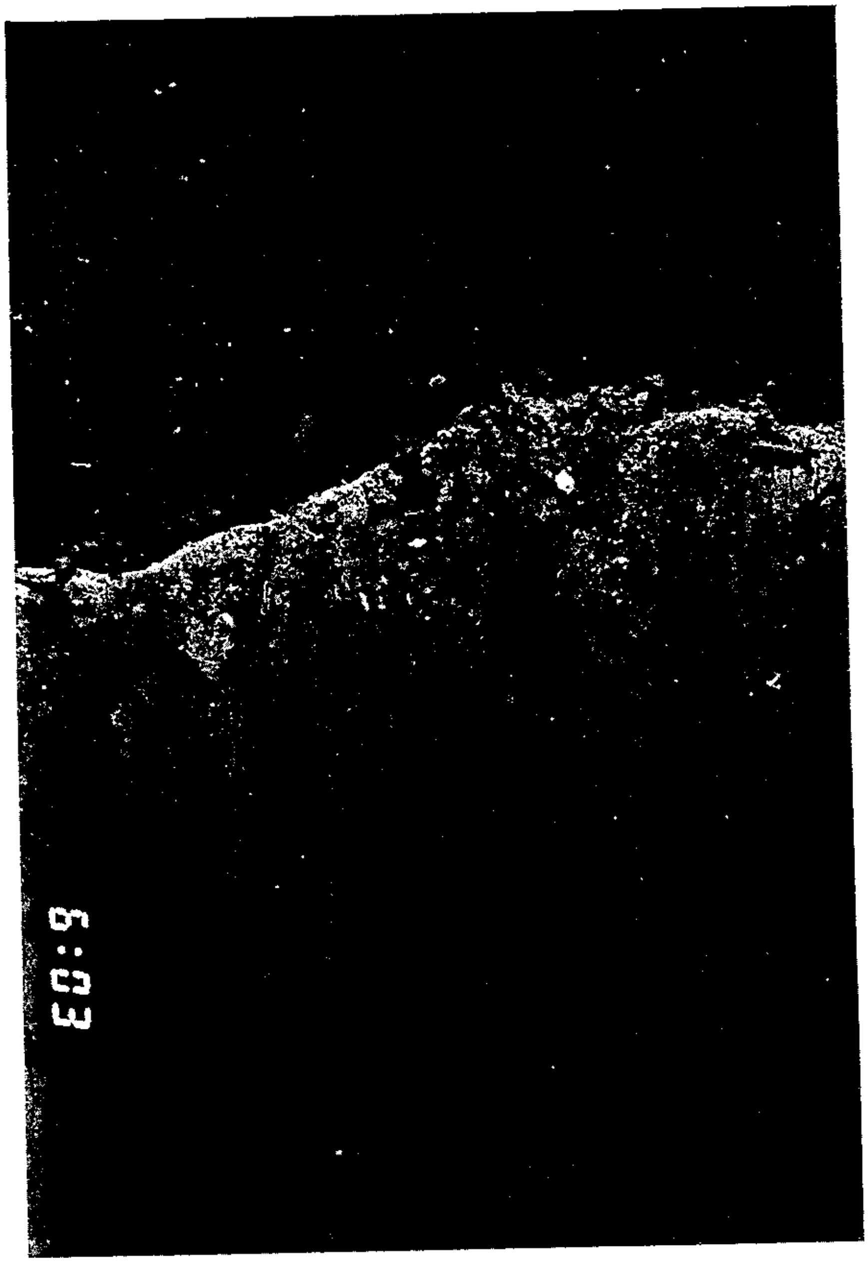

Figure 3-25. An amphipod mat at Station 66 associated with apparently high sediment oxygen demand (note low reflectance sulphidic sediment near the interface). Scale = 1X.

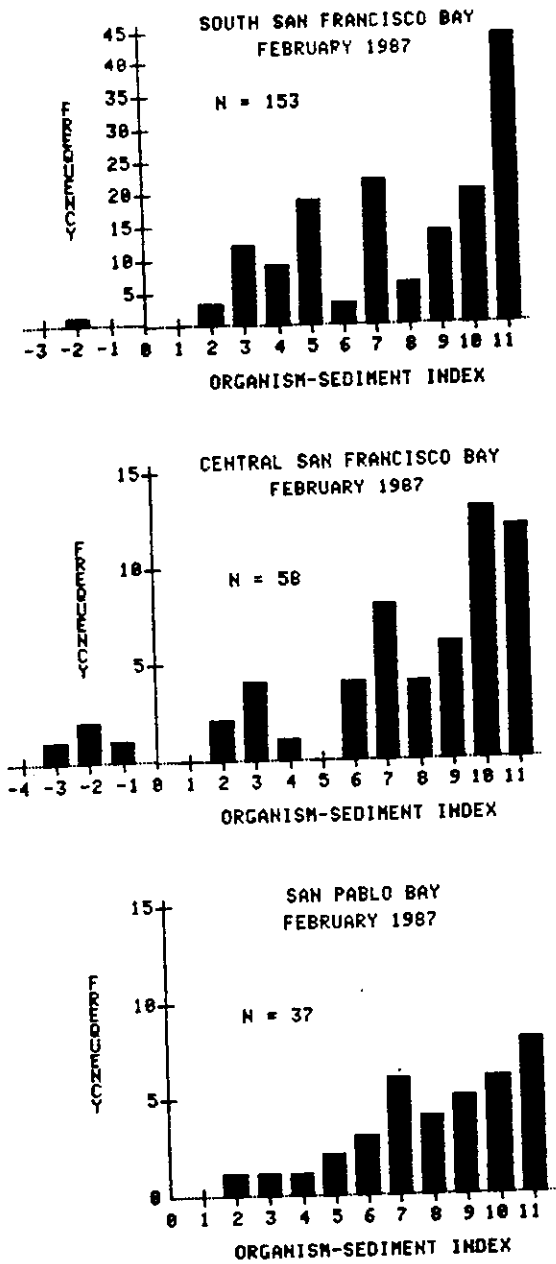

Figure 3-26. The frequency distributions of Organism-Sediment Index values for each region of San Francisco Bay. Note different scales on the vertical axis.

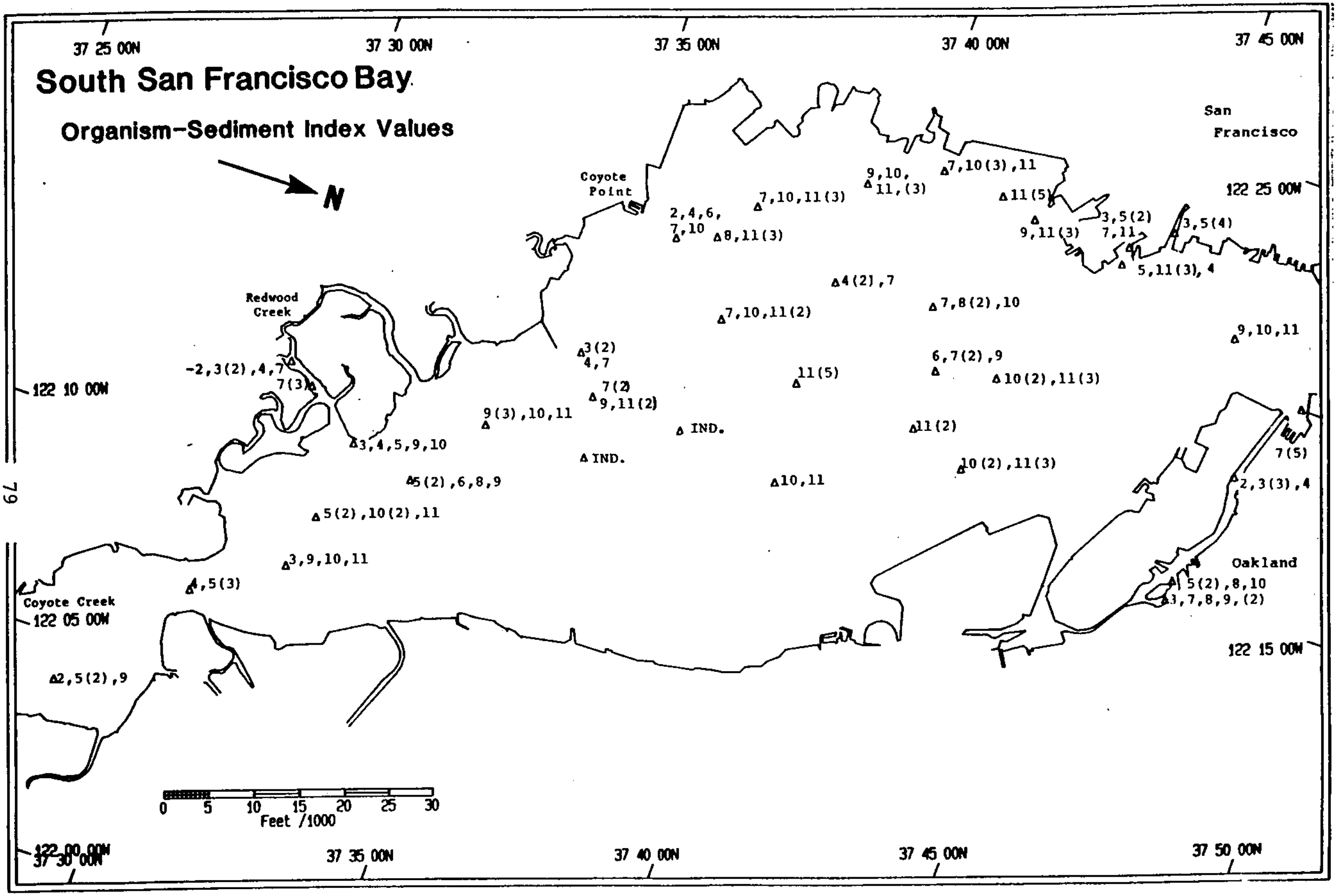

Figure 3-27a. Organism-Sediment Index values in the South Bay. The number in ( ) indicates the number of replicates with that value, if greater than 1. An 'Ind' indicates an indeterminate OSI. Station designations are provided in Figure

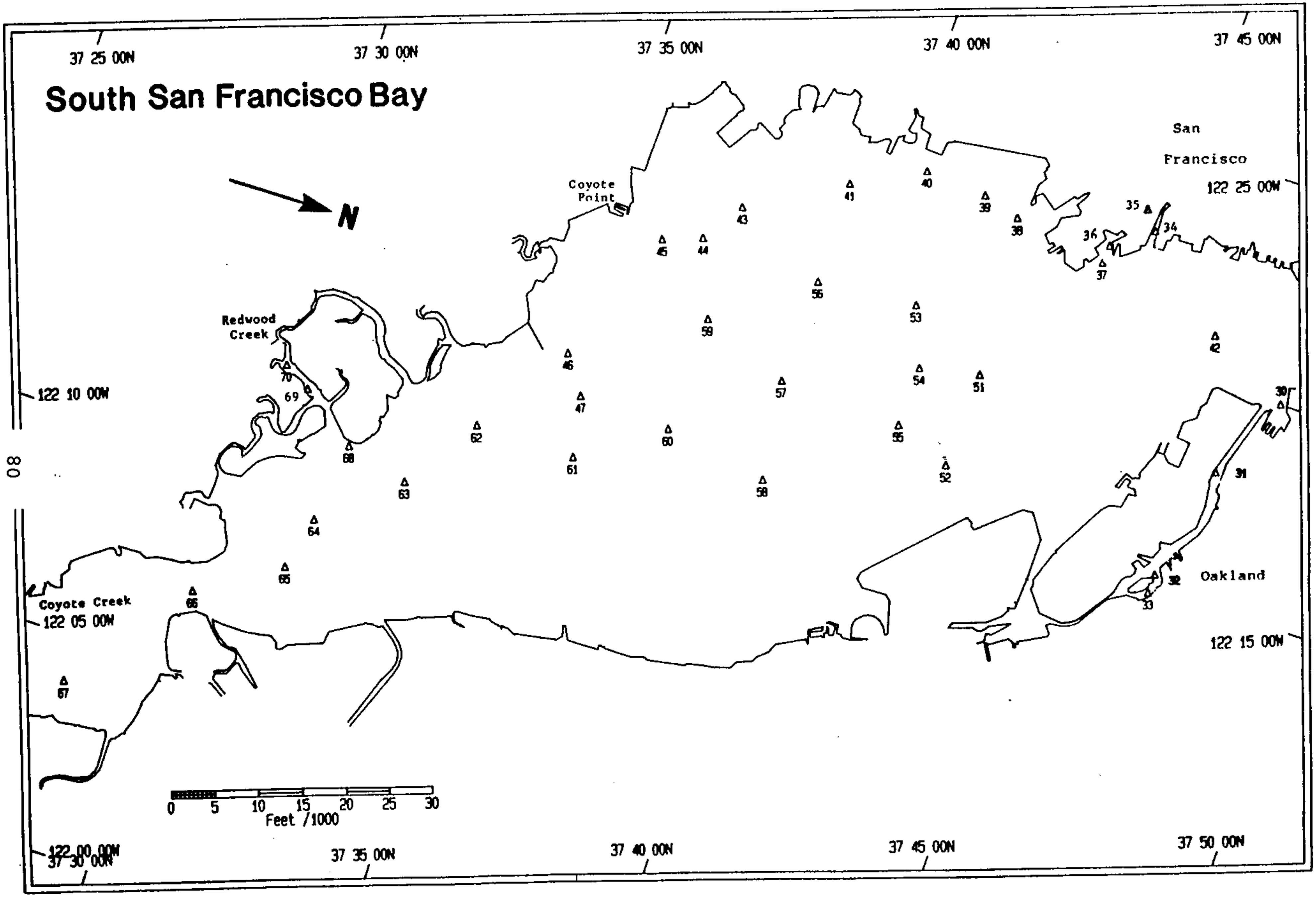

Figure 3-27b. Locations and designations of stations in South San Francisco Bay.

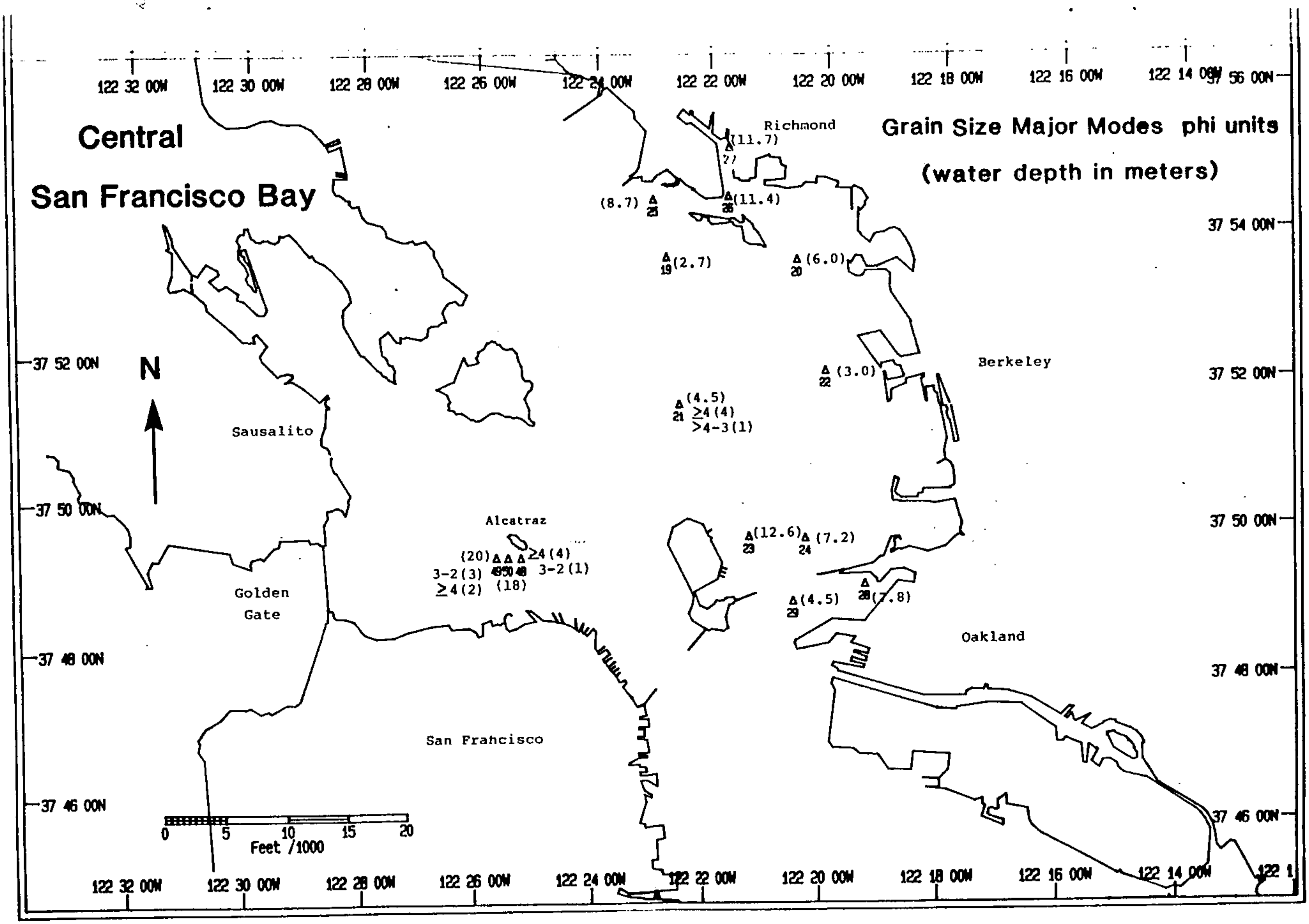

Figure 3-28. Central Bay station names, water depth in meters (# in parentheses), and grain-size major mode in phi units, e.g. >4-3 Parenthetical number following phi range indicates the number of replicate images with that value. All stations without assigned grain-size values exhibited only >4 phi major modes.

Figure 3-29. Station 49 consists of a rippled bottom. These unusual ripples consist of silt-clay intercalated with sand. This station is located near a sand-silt-clay facies boundary, associated with the edge of the Alcatraz Disposal site. Scale =1X.

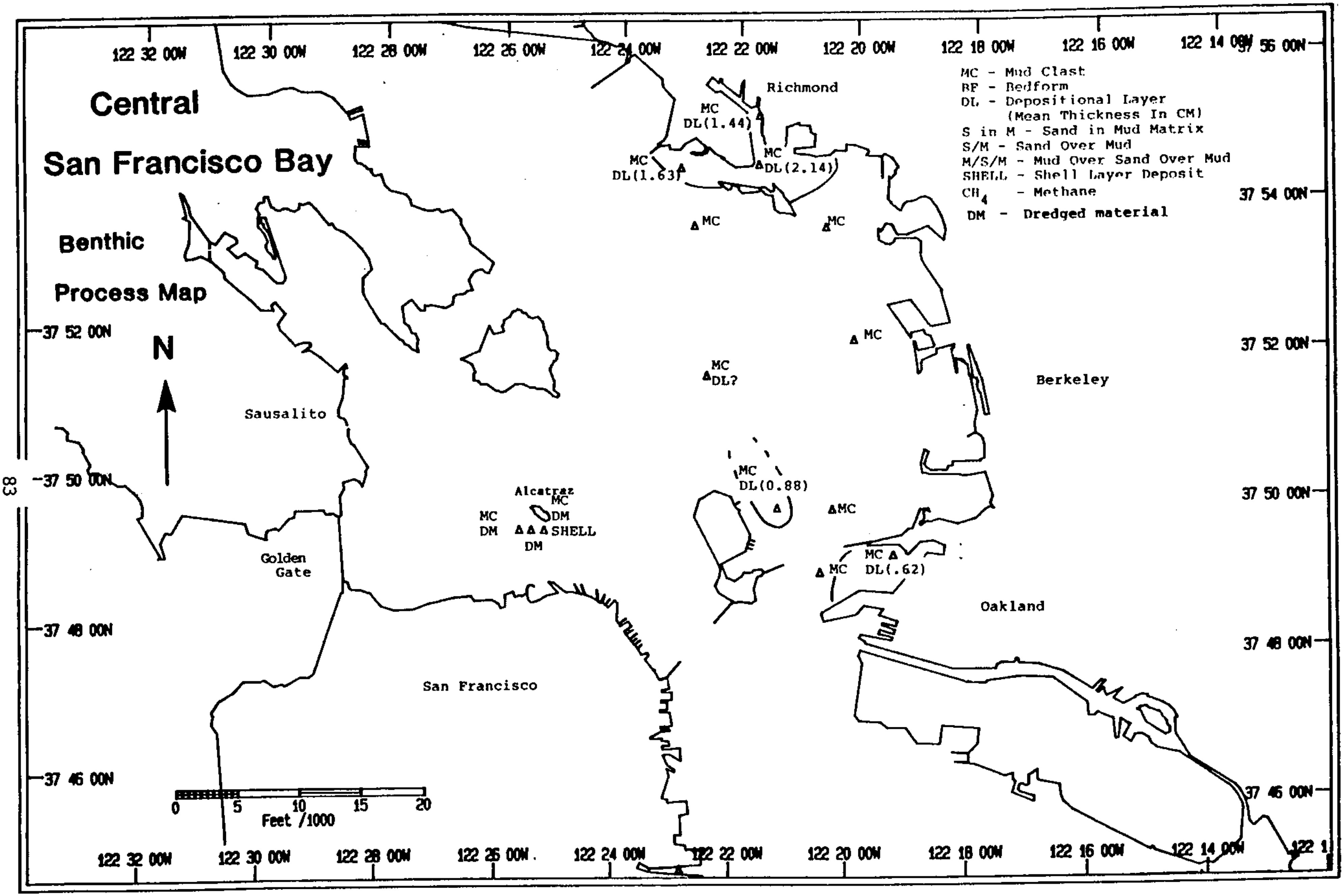

Figure 3-30a. A benthic process map for the Central Bay. The contours delimit relatively low kinetic regions. Station designations are provided in Figure 3-30b (following page).

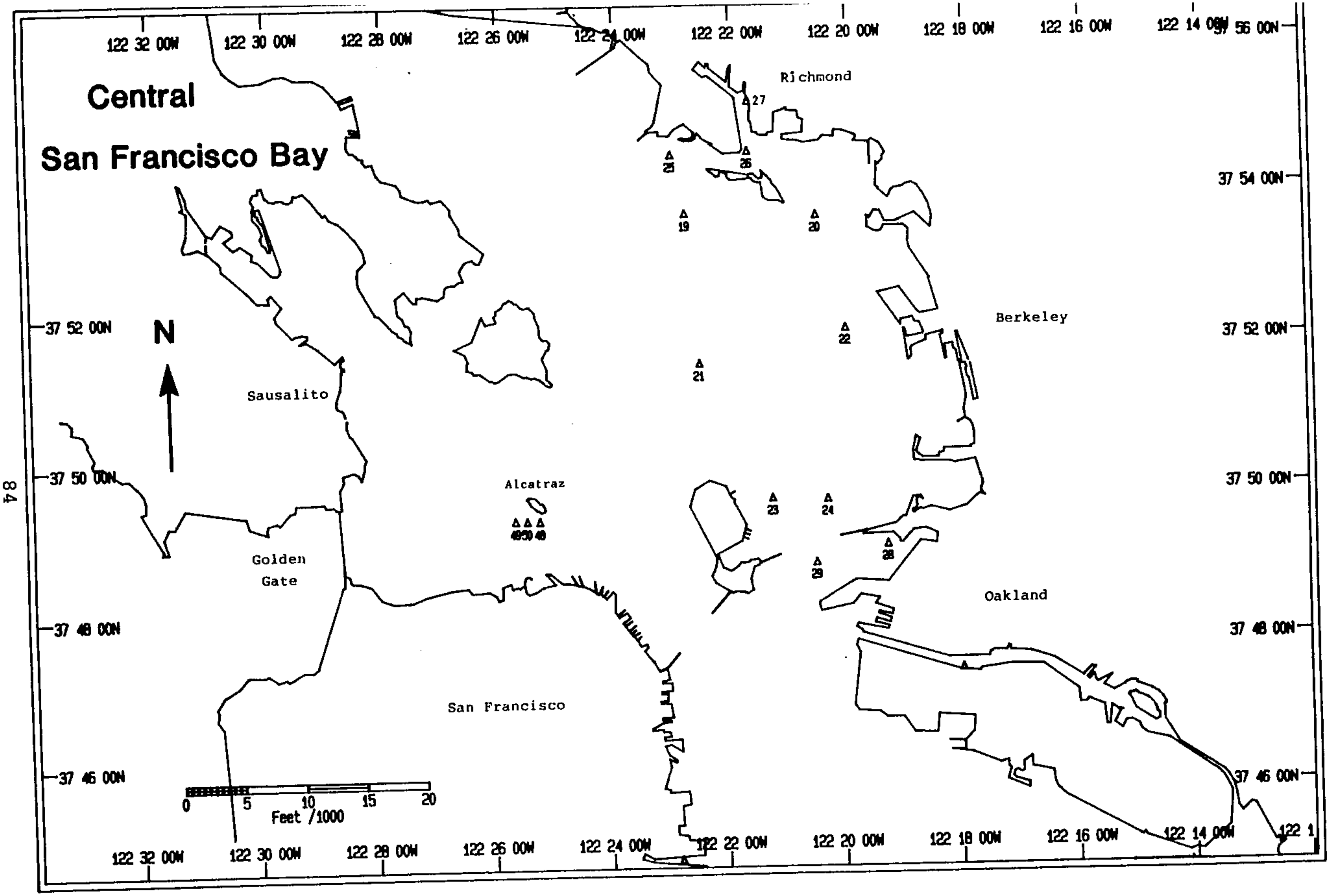

Figure 3-30b. Locations and designations of stations in Central San Francisco Bay.

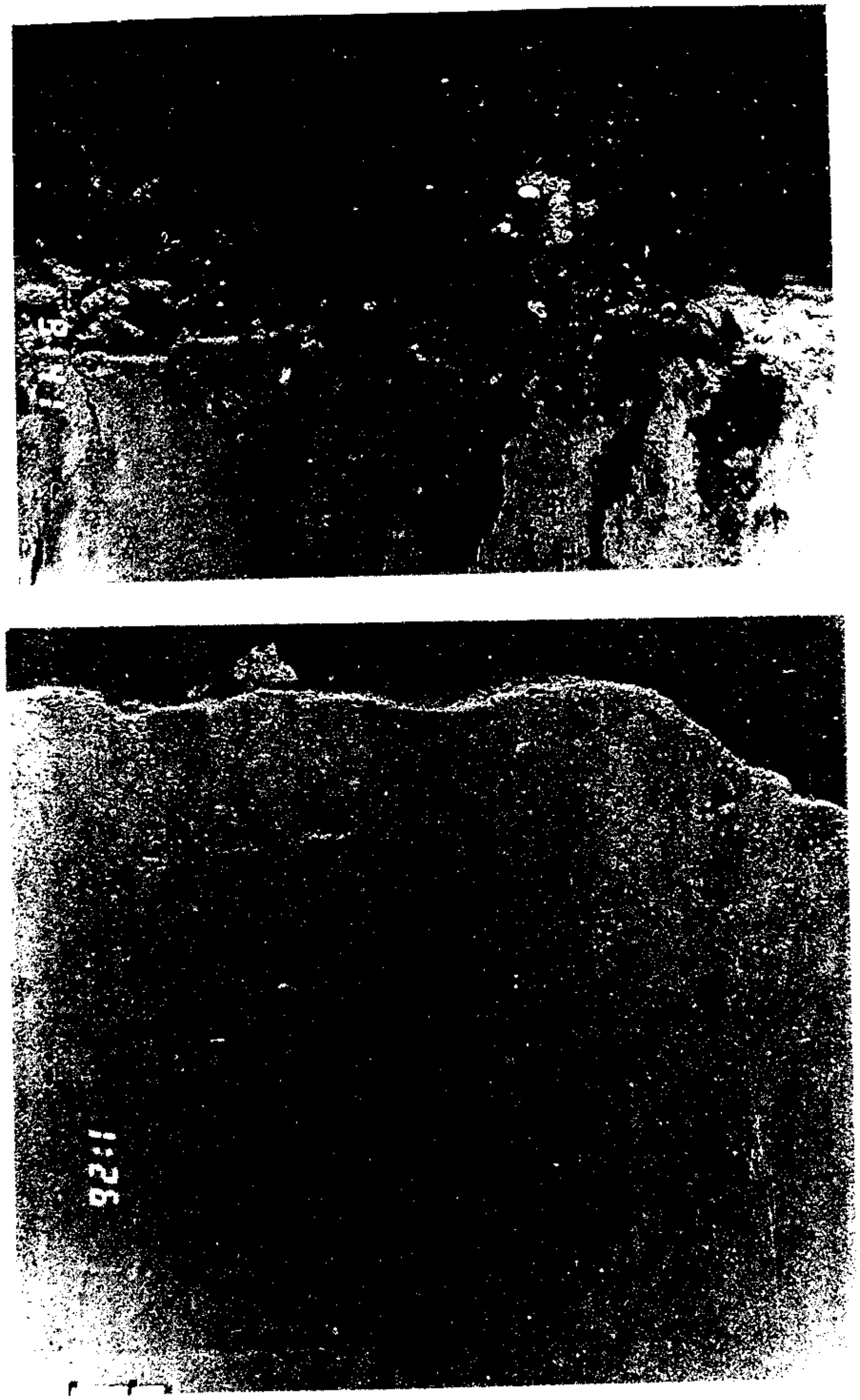

Figure 3-31. Station 20 (top) and 21 (bottom) showing mud clasts at the surface. These appear to be locally derived because of their angularity. Mud clasts which have been transported some distance are usually rounded. Scale =1X.

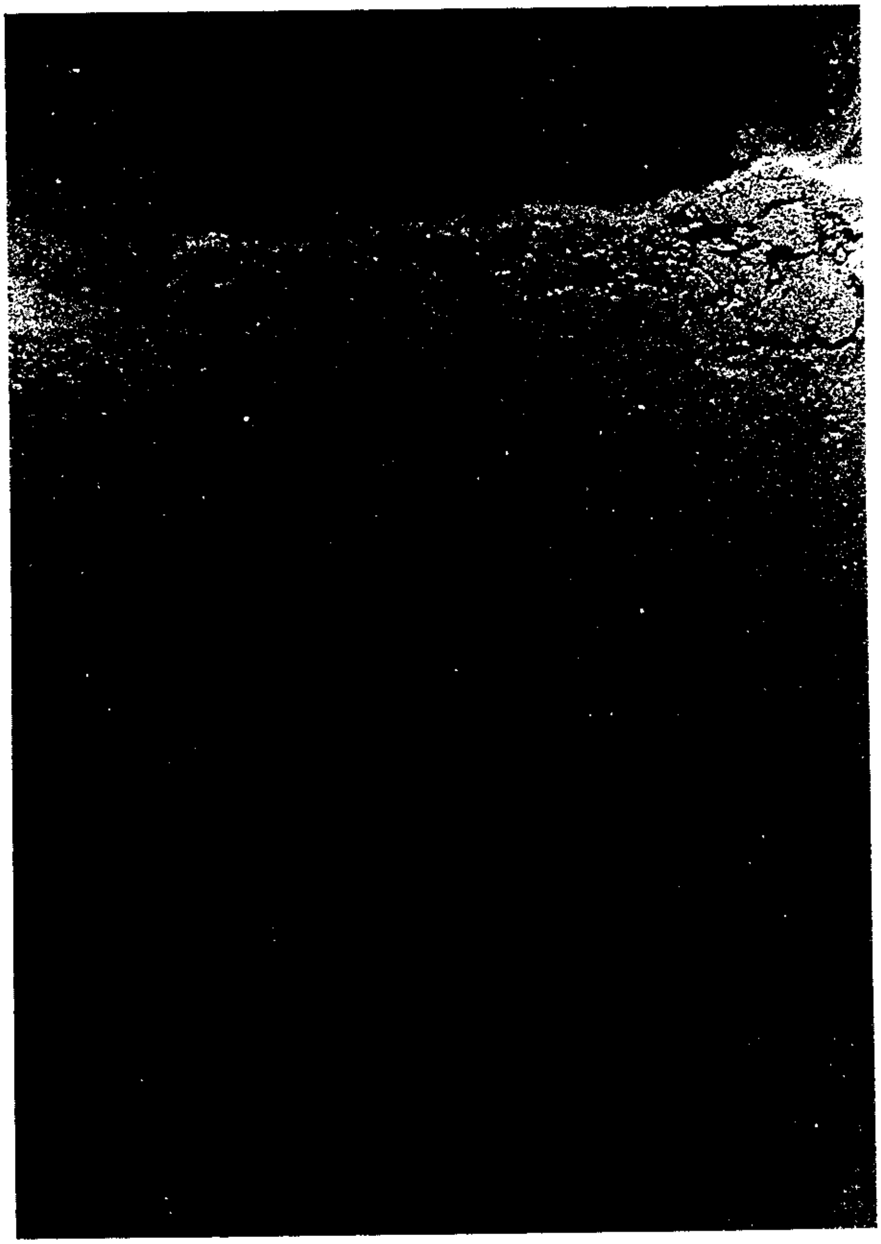

Figure 3-32. An REMOTS image from station 25 showing an apparently recently introduced sedimentary layer consisting largely of small subrounded mud clasts. Scale = 1X.

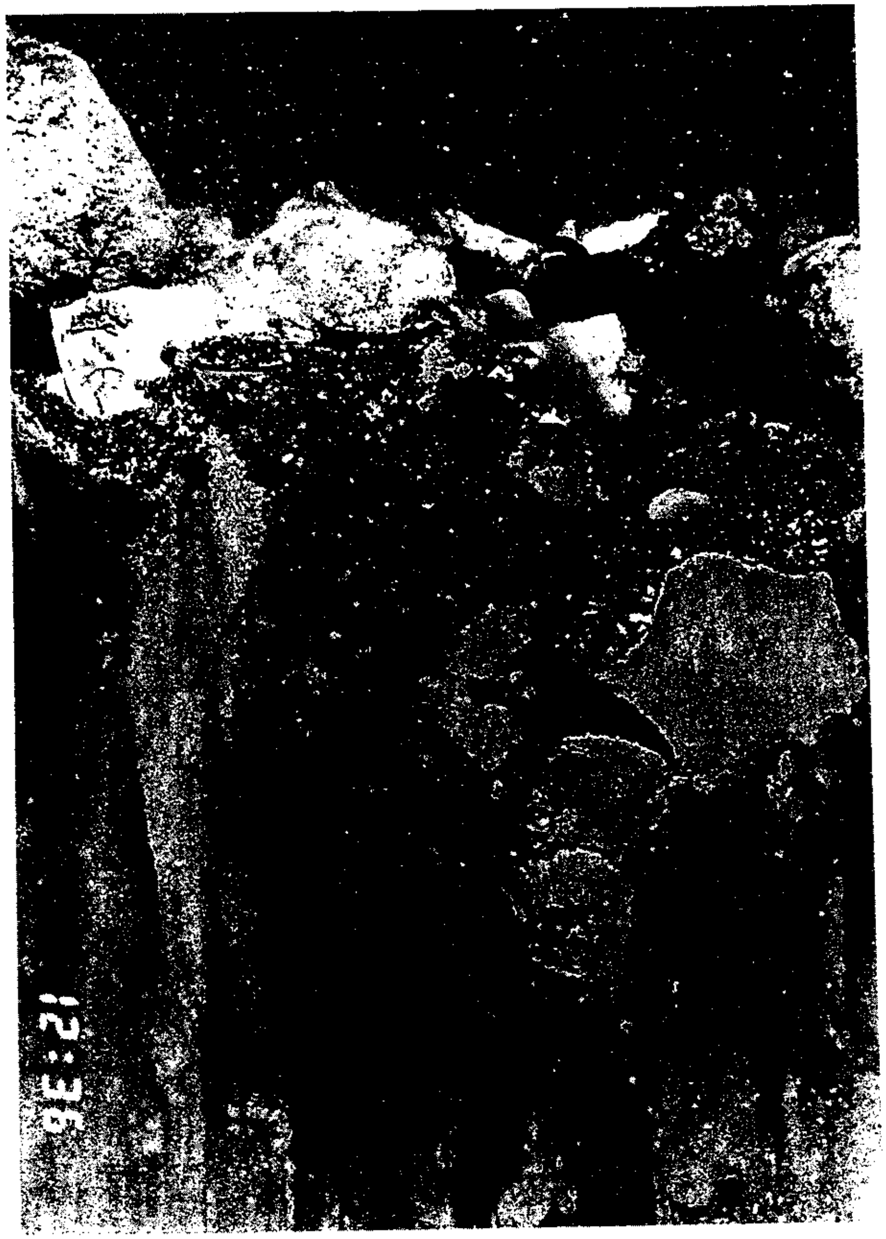

Figure 3-33. A REMOTS image from station 48 showing a surface shell lag layer and a chaotic sedimentary fabric. This is characteristic of sediments disposed at the Alcatraz Disposal Site. Scale = 1X.

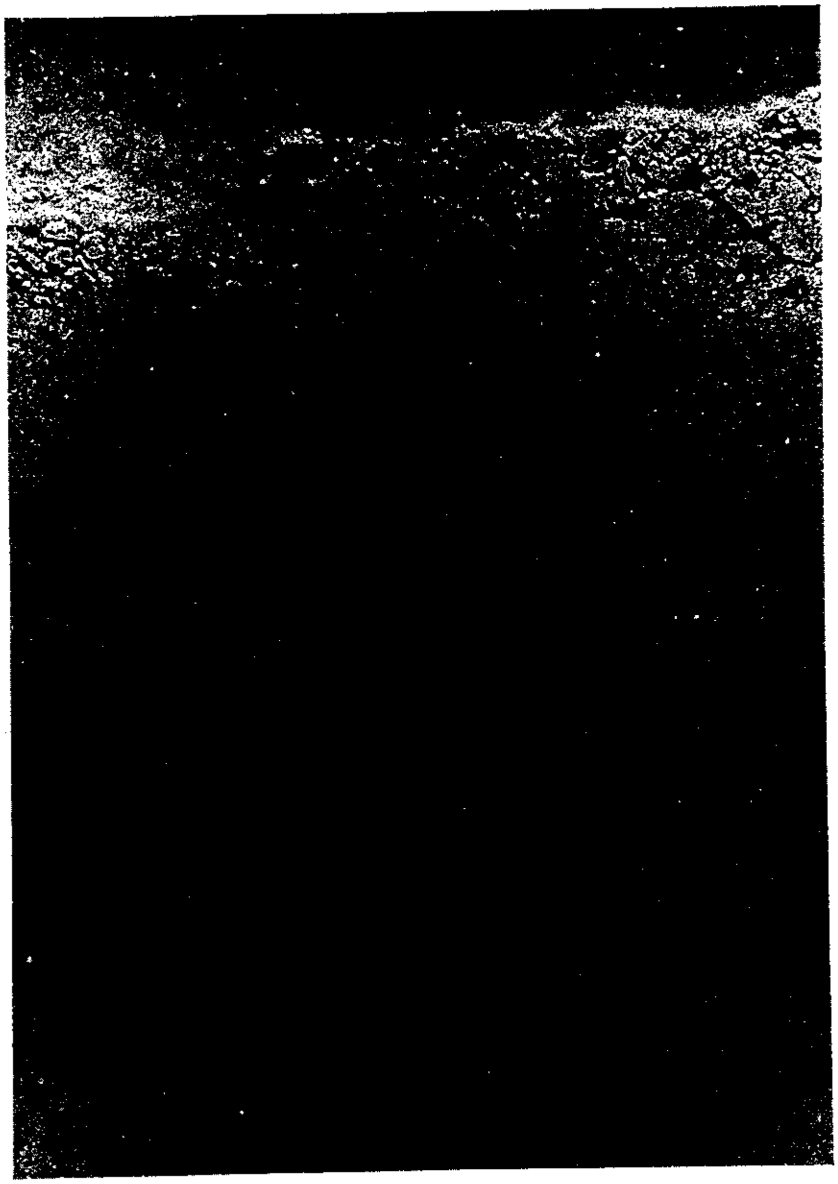

Figure 3-34. Station 25 shows evidence of having received at least two major inputs of sediment in the recent past. Arrows mark the bottom horizons of these two layers. Scale= 1X.

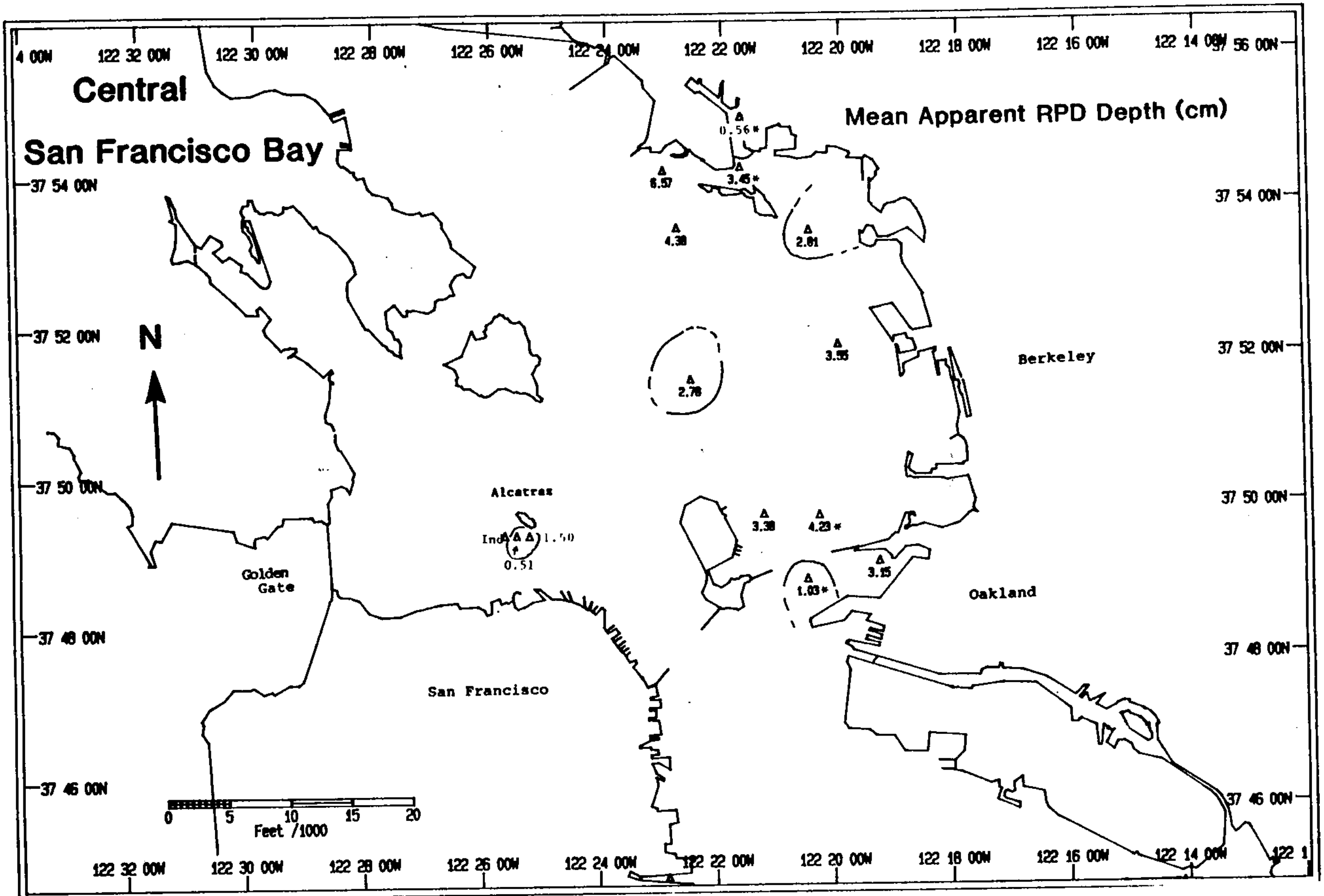

Figure 3-35a. The distribution of apparent RPD depths, averaged by station. The contours delimit regions exhibiting apparent RPD depths less than 3.0 cm. An '*' indicates the presence of apparent high sediment oxygen demand. An 'Ind' indicates the RPD is indeterminate. Station designations are provided in Figure 3-35b (following page).

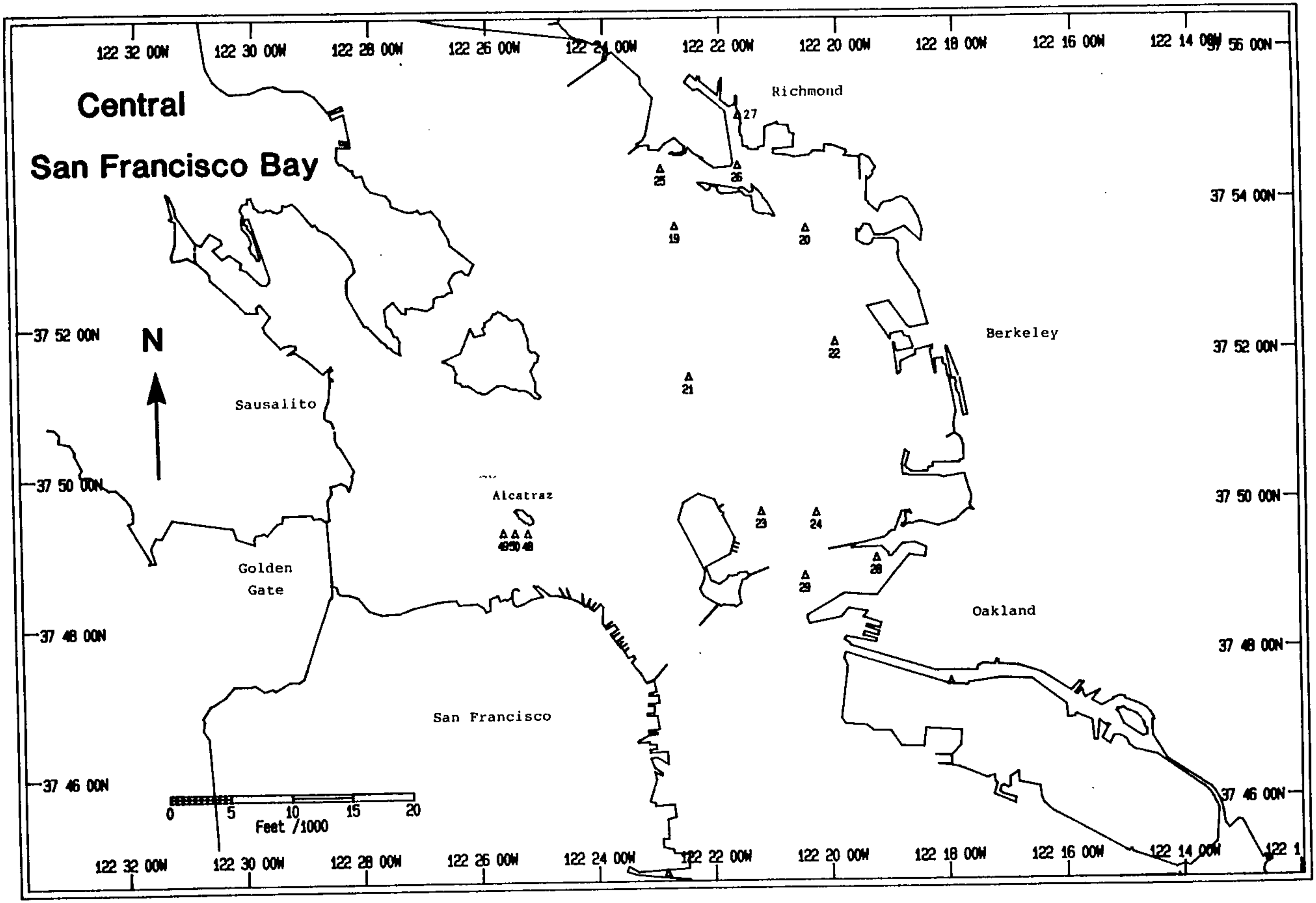

Figure 3-35b. Locations and designations of stations in Central San Francisco Bay.

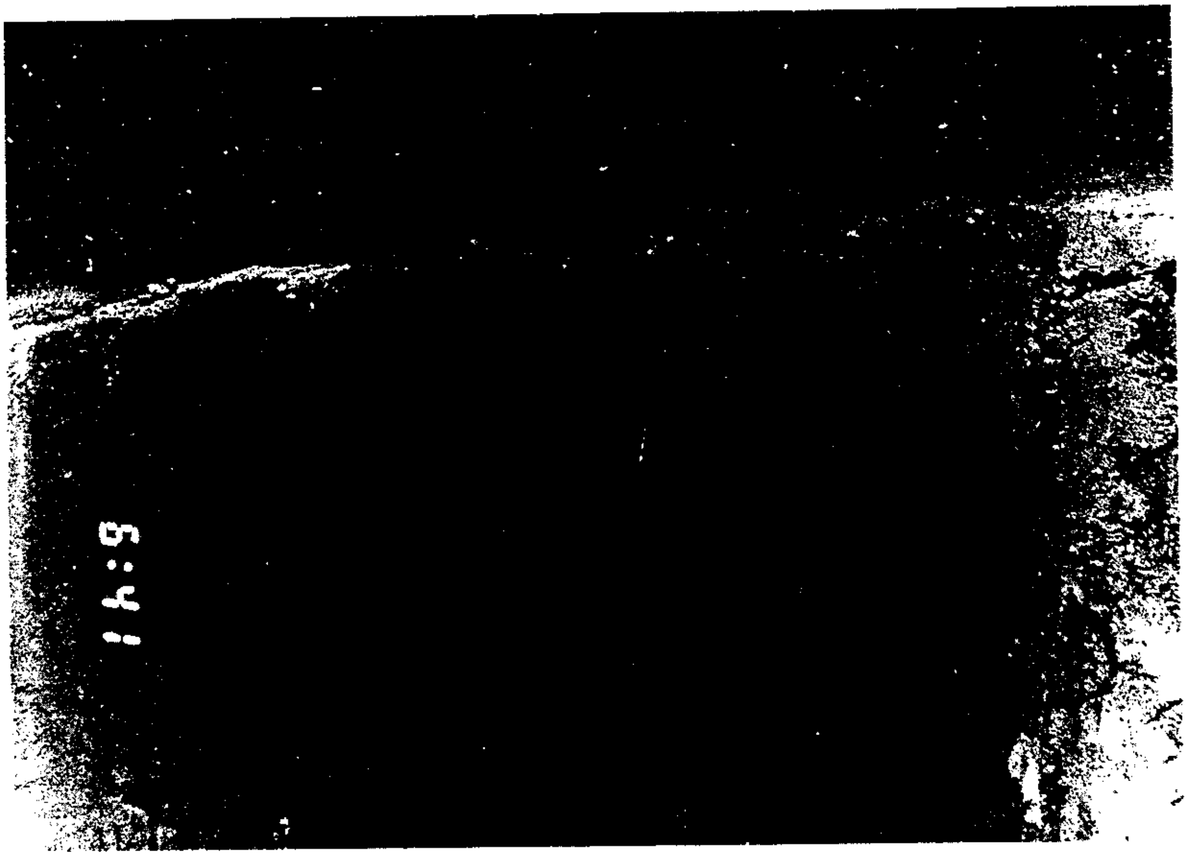

Figure 3-36. Station 29, located just outside of outer Oakland Harbor, shows evidence of high organic loading (low reflectance sediment all the way up to the sediment-water interface). This station is a candidate for high SOD. This also may reflect the recent erosion of oxidized surface sediments. Scale = 1X.

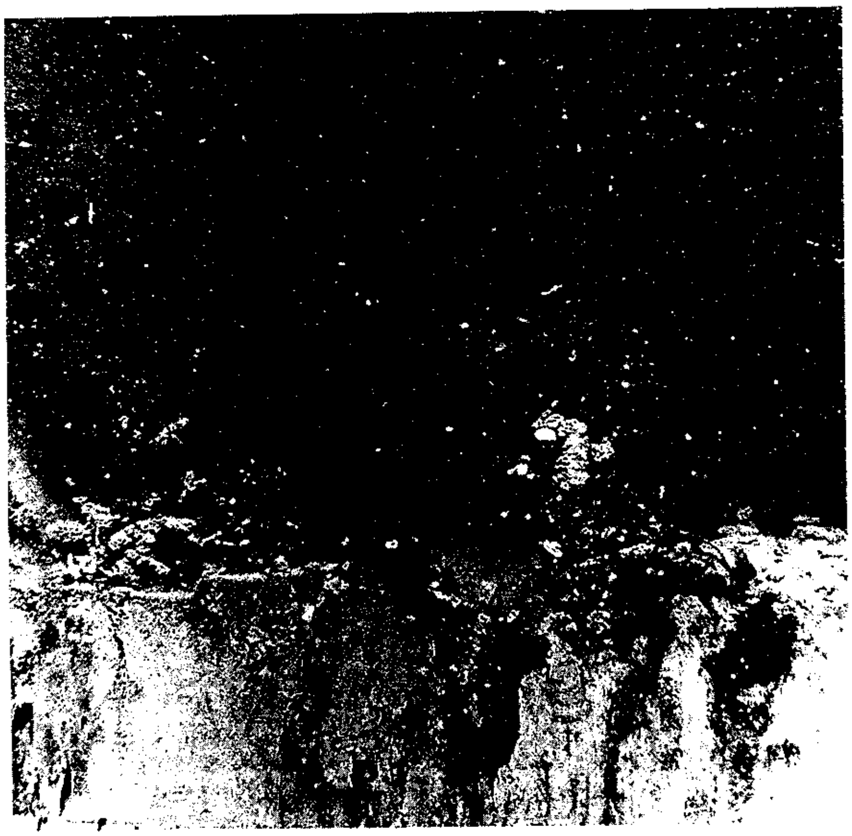

Figure 3-37. The dark filamentous material at the surface of Station 20 is interpreted to be algal in origin. The decay of this plant material may result in high SOD at this station. Scale: actual width of images = 15.2 cm.

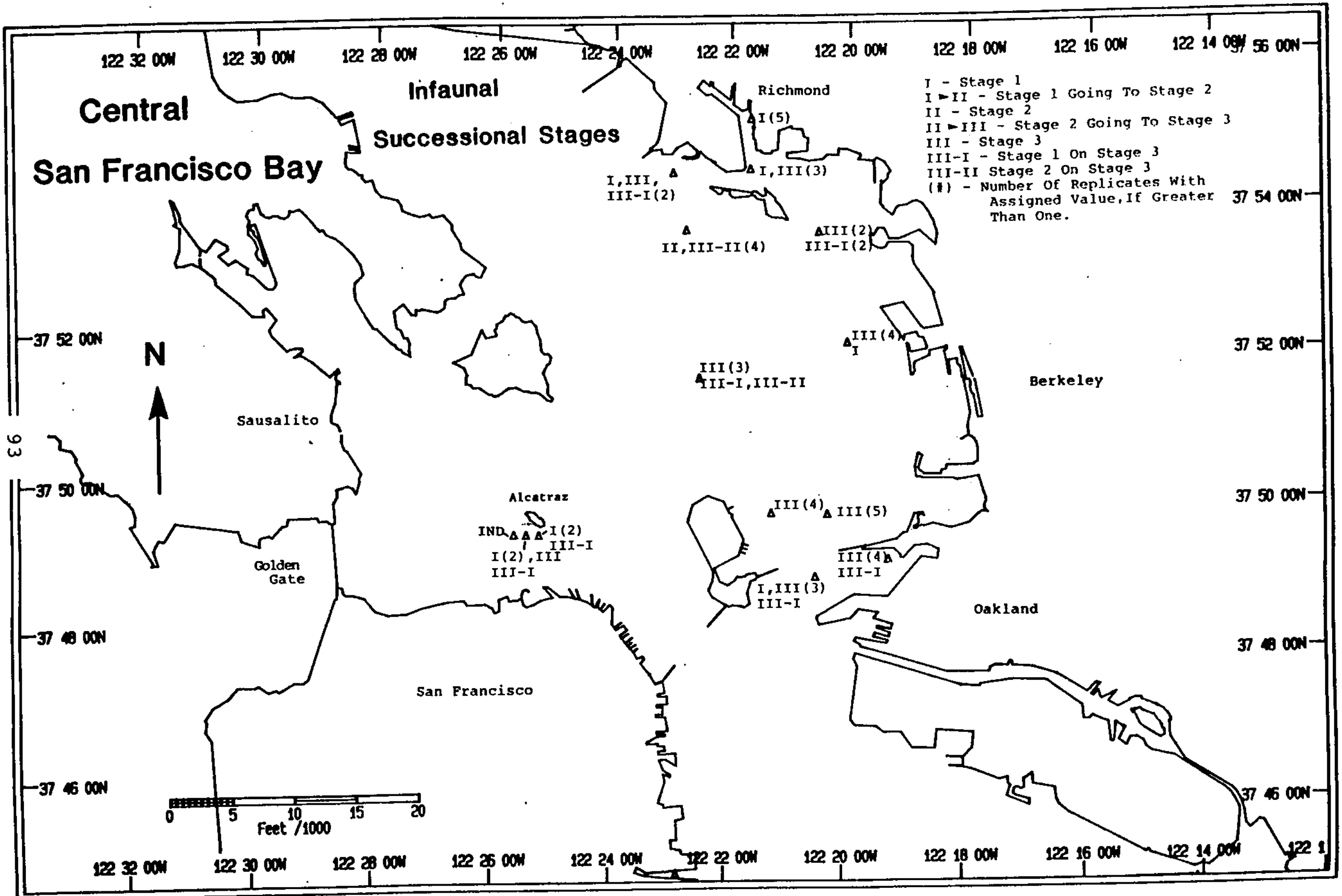

Figure 3-38a. The mapped distribution of successional stages in the Central Bay. Station designations are provided in Figure 3-38b (following page).

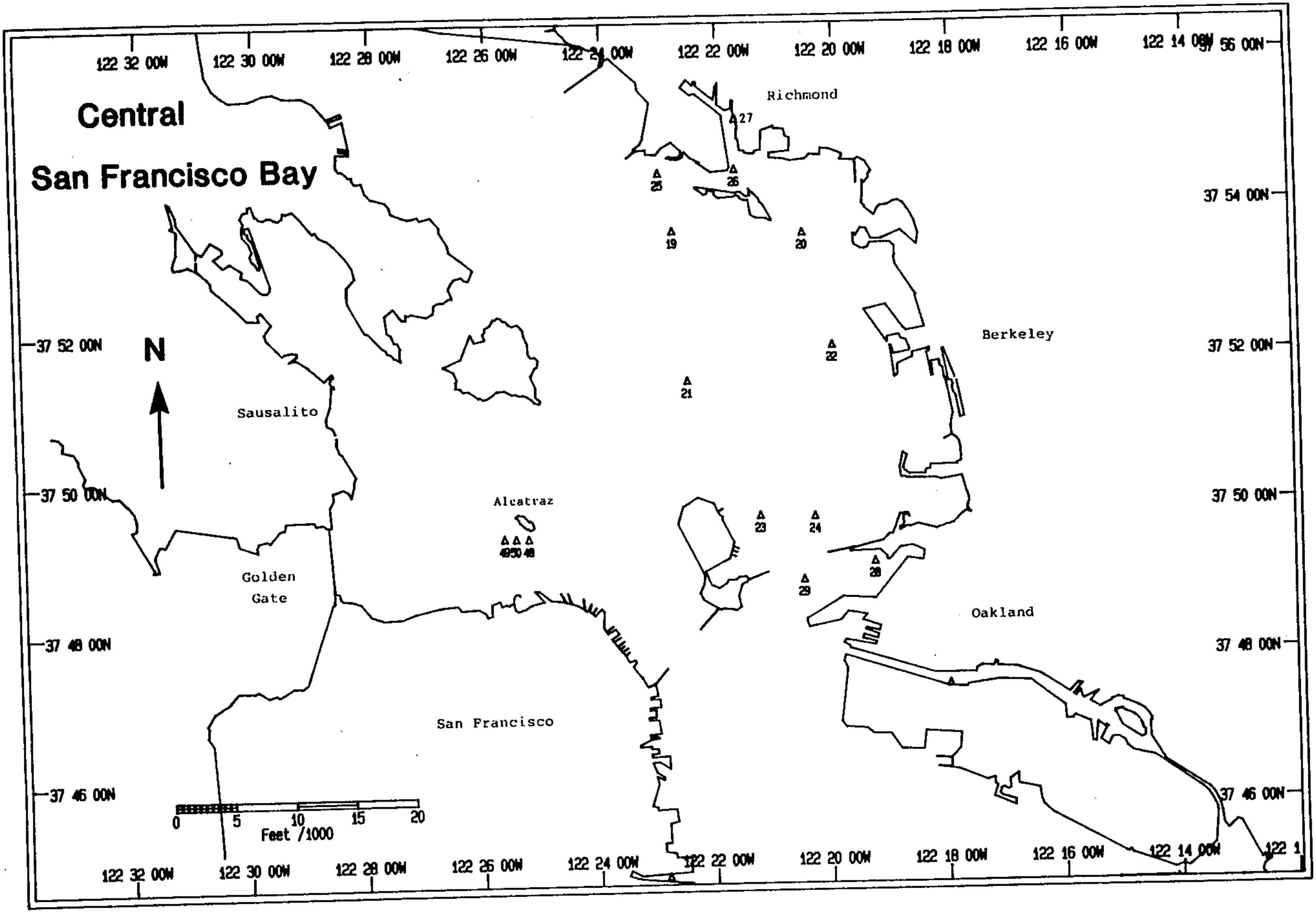

Figure 3-38b. Locations and designations of stations in Central San Francisco Bay.

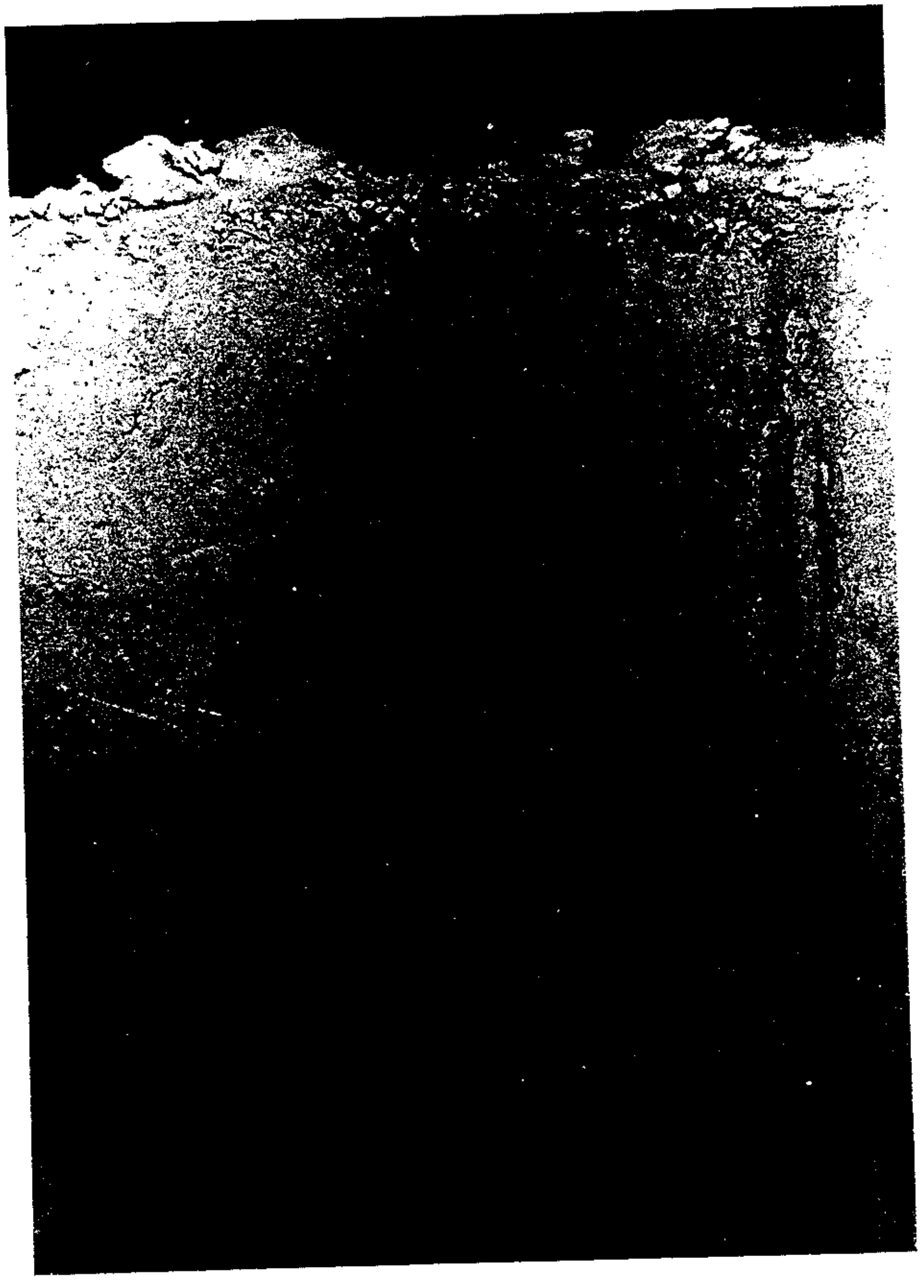

Figure 3-39. Small and poorly developed Stage III feeding voids at Station 28. Scale = 1X.

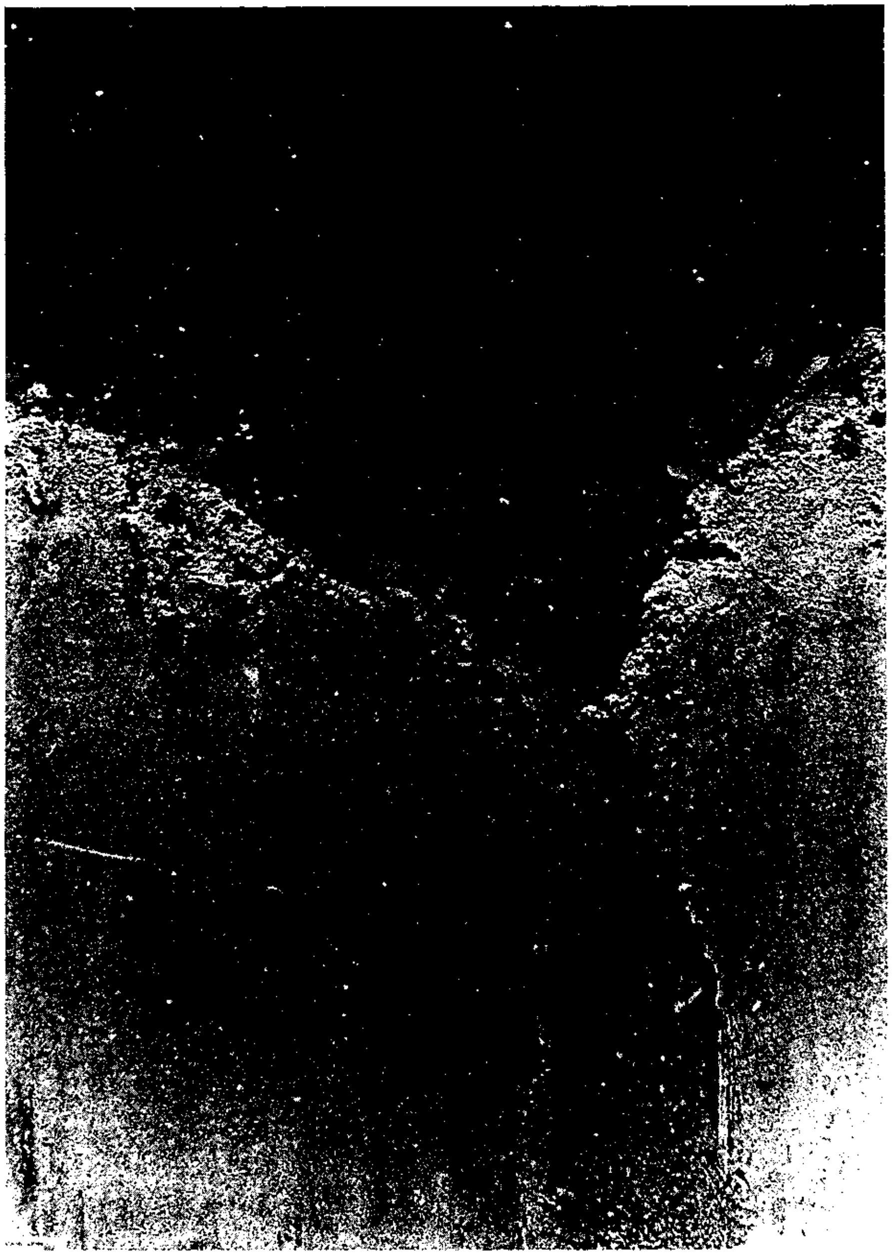

Figure 3-40. Spatial competition between a large burrowing organism and a surface mat of ampeliscid amphipods at Station 19. Scale = 1X.

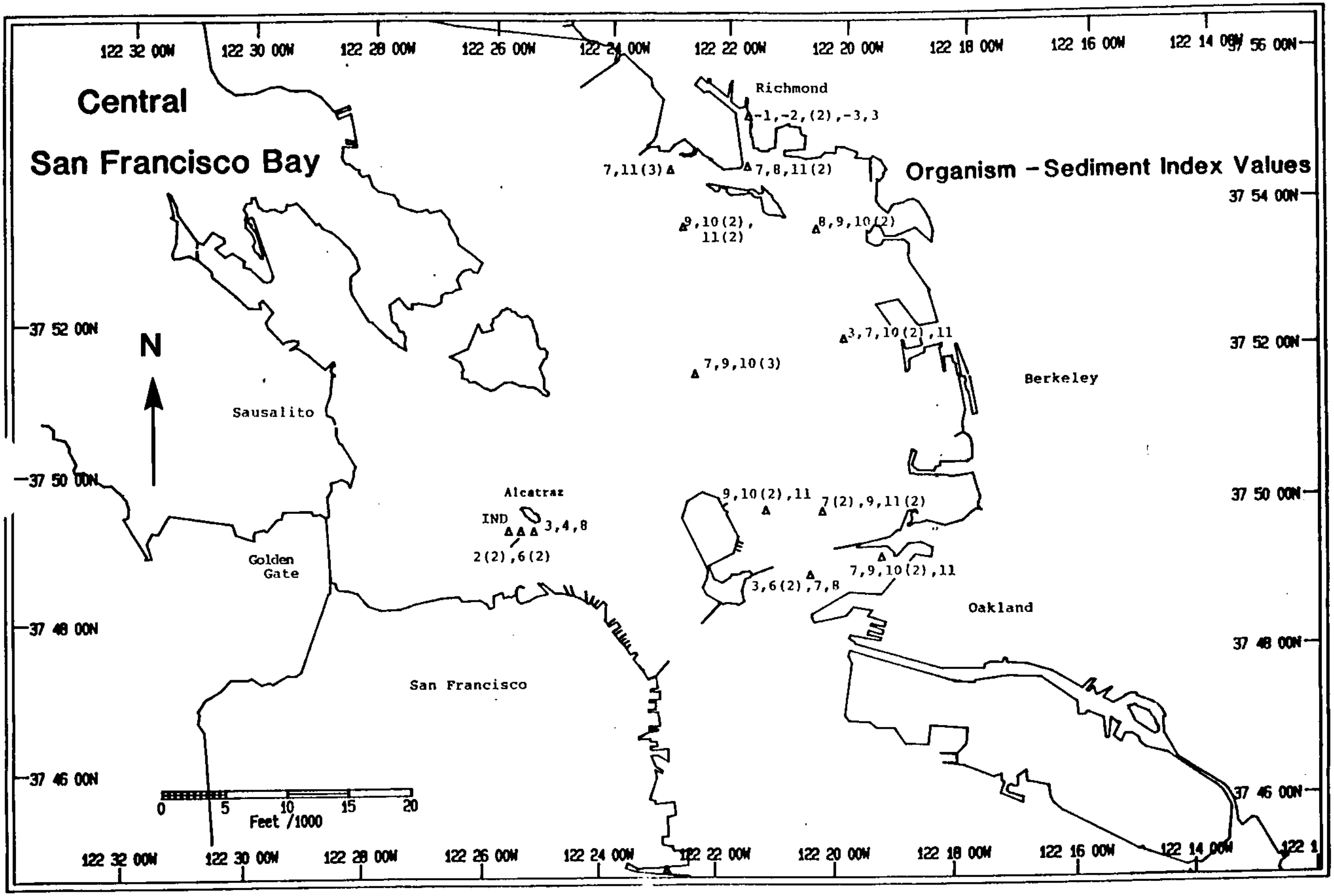

Figure 3-41a. Organism-Sediment Index values in the Central Bay. The number in ( ) indicates the number of replicates with that value, if greater than 1. An 'Ind' indicates an indeterminate OSI. Station designations are provided in Figure 3-41b (following page).

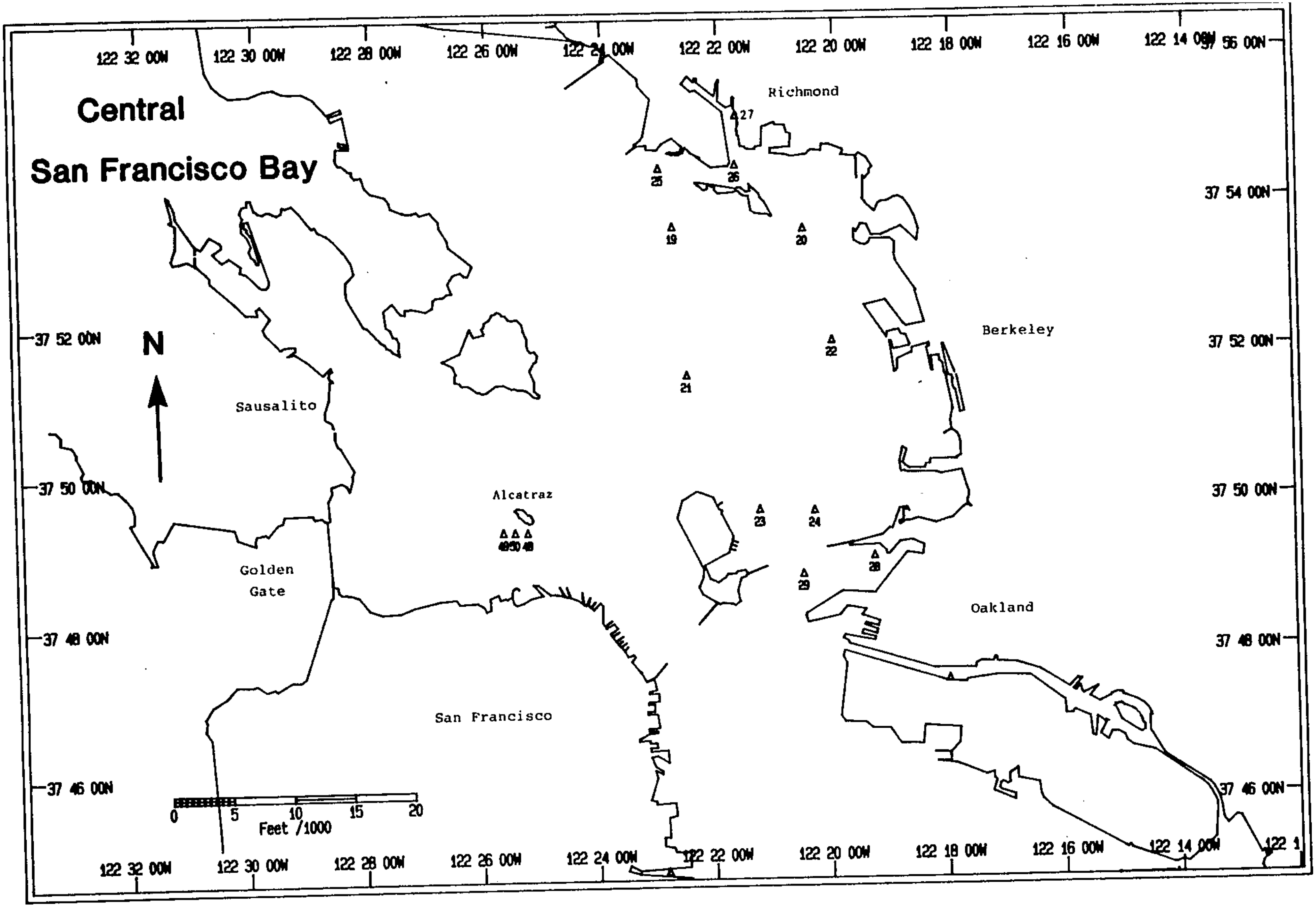

Figure 3-41b. Locations and designations of stations in Central San Francisco Bay.

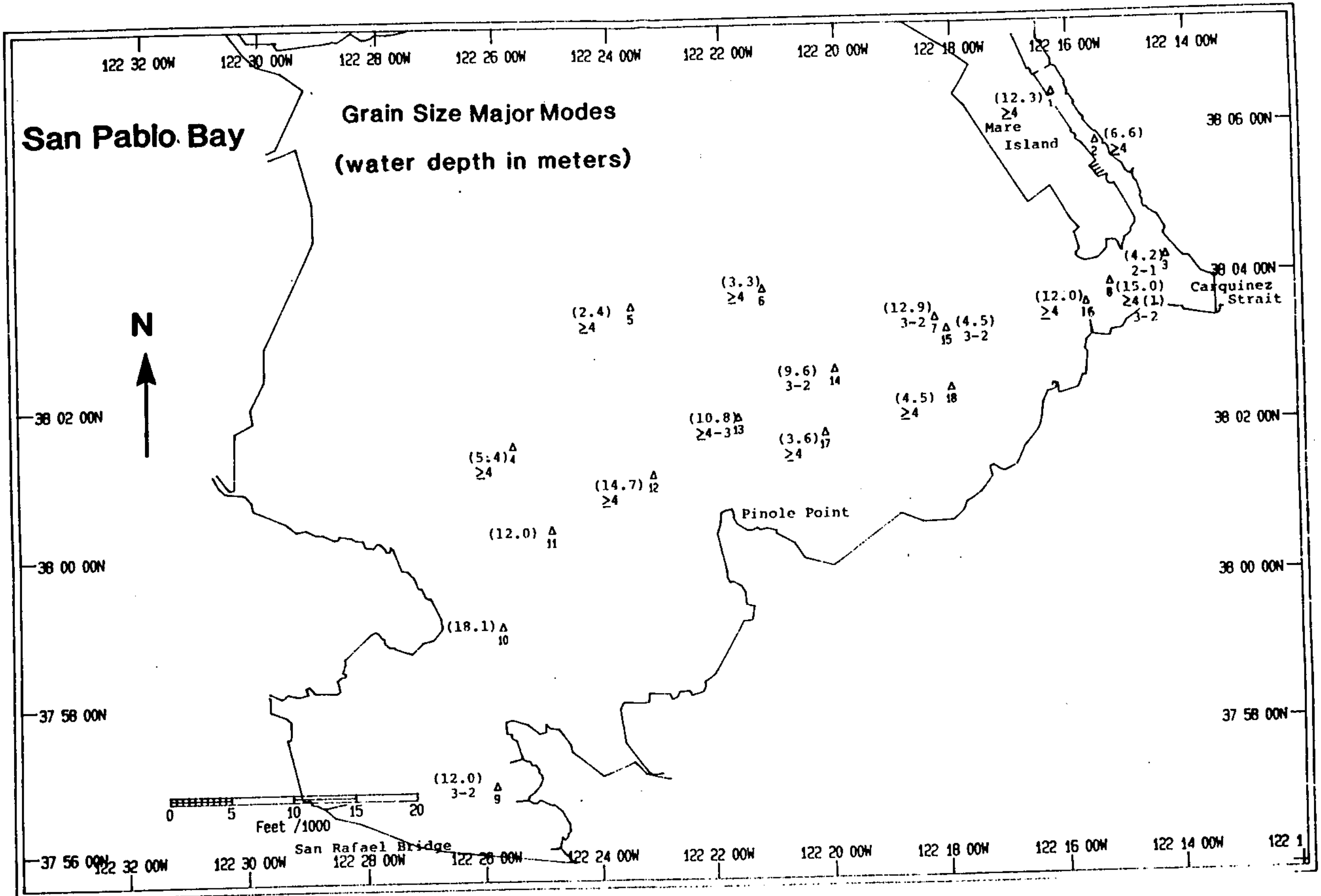

Figure 3-42. San Pablo Bay station names, water depth in meters (# in parentheses), and grain-size major mode in phi units, e.g. >4-3 Parenthetical number following phi range indicates the number of replicate images with that value. All stations without assigned grain-size values exhibited only >4 phi major modes. No REMOTS data was obtained at stations 10 and 11.

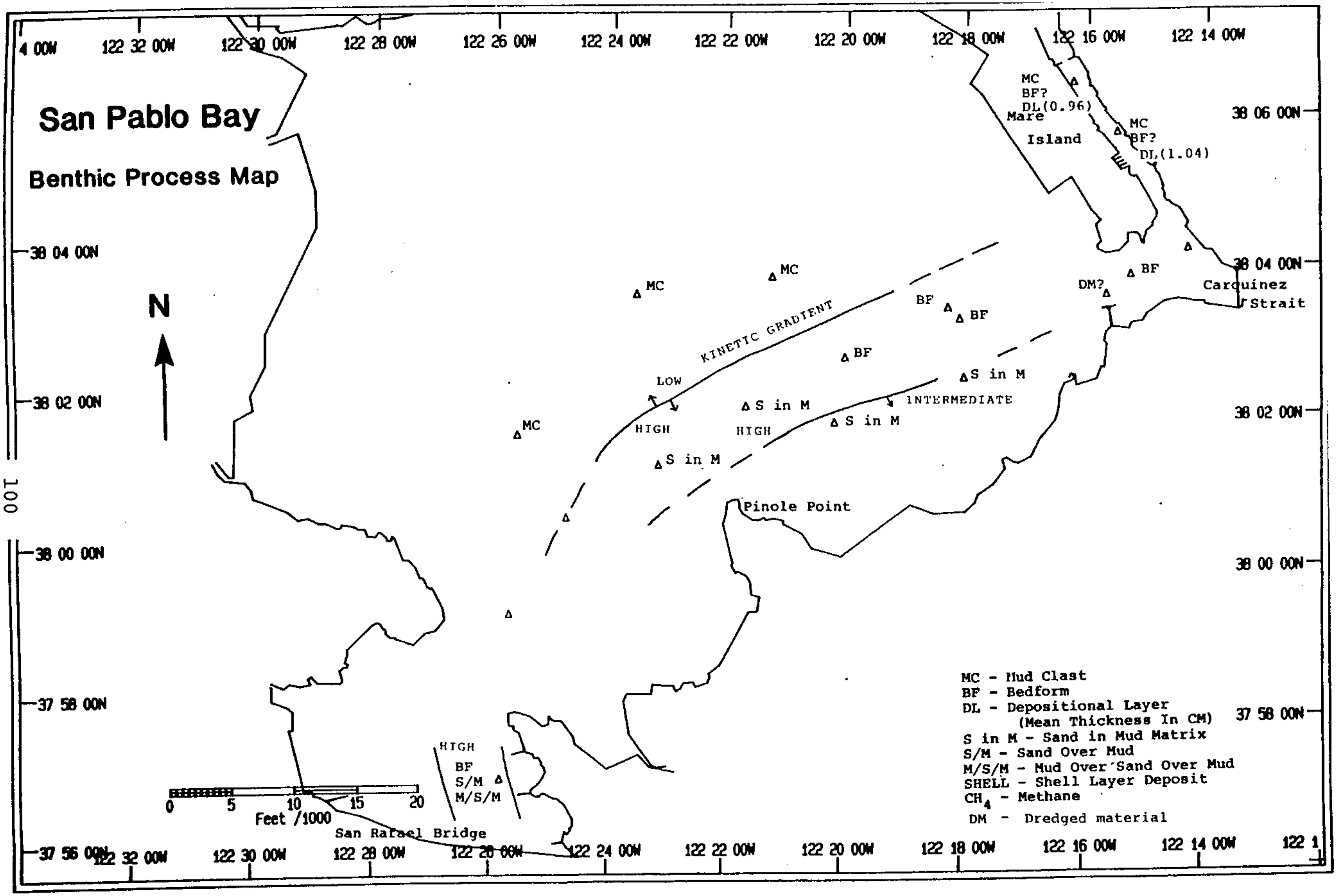

Figure 3-43a. A benthic process map of the San Pablo Bay. The contours separate low and high kinetic regions. Station designations are provided in Figure 3-43b (following page).

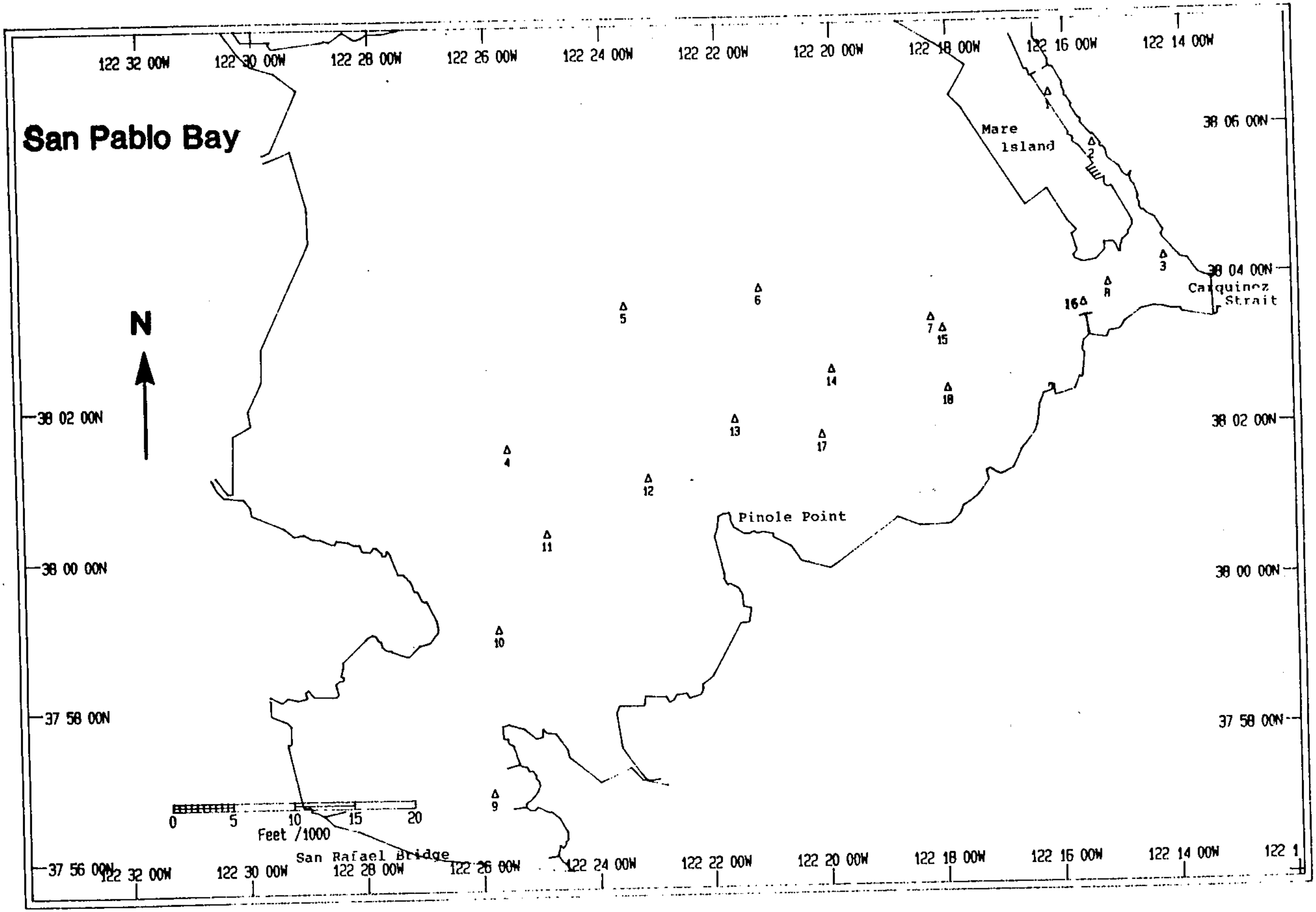

Figure 3-43b. Locations and designations of stations in San Pablo Bay.

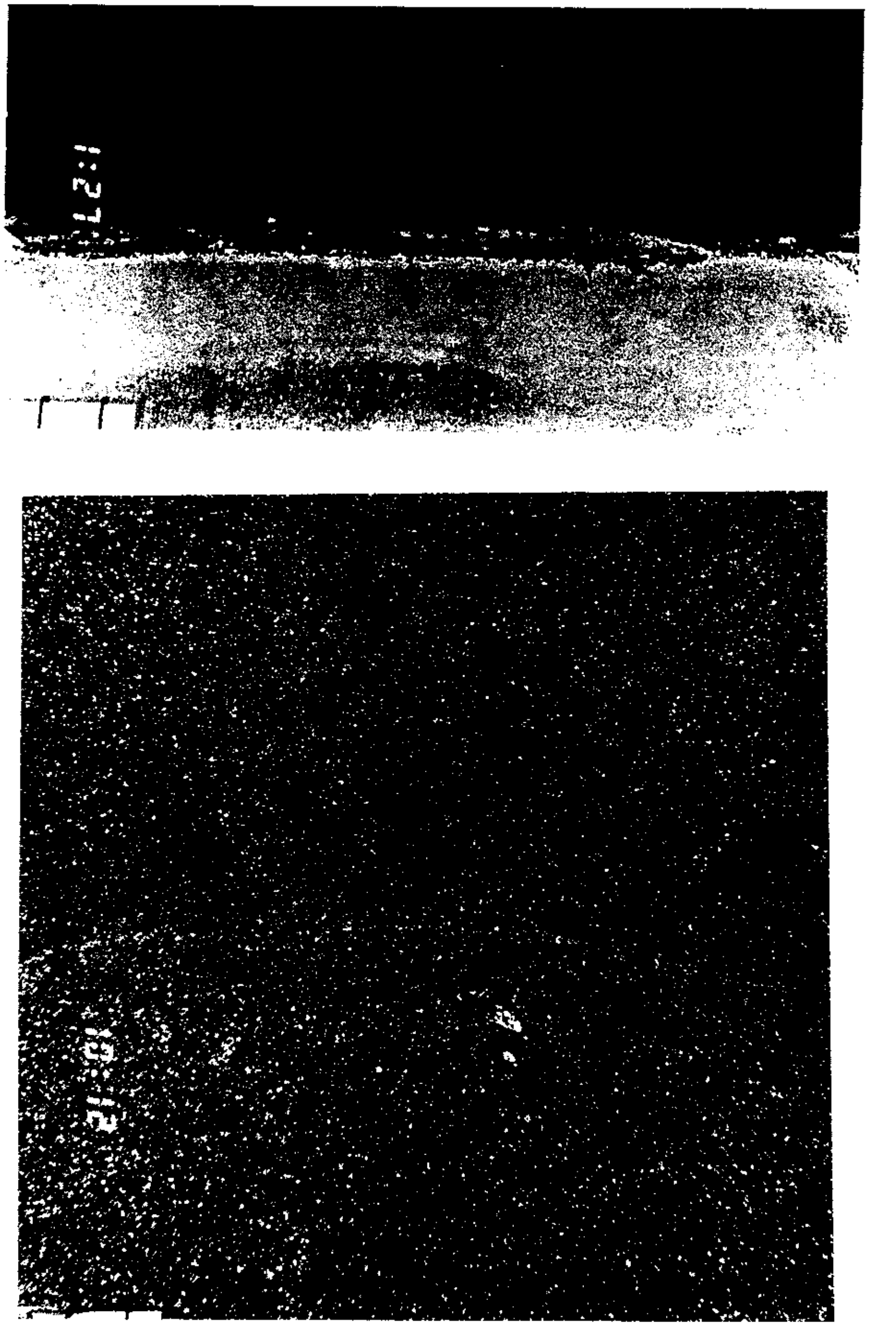

Figure 3-44. Station 8 (top) shows the presence of an overconsolidated mud covered with a thin layer of sand on the channel floor. Station 15 (bottom) consists of a rippled sand bottom on this channel bottom. Both of these stations apparently lack abundant macrofauna. Scale: actual width of images = 15.2 cm.

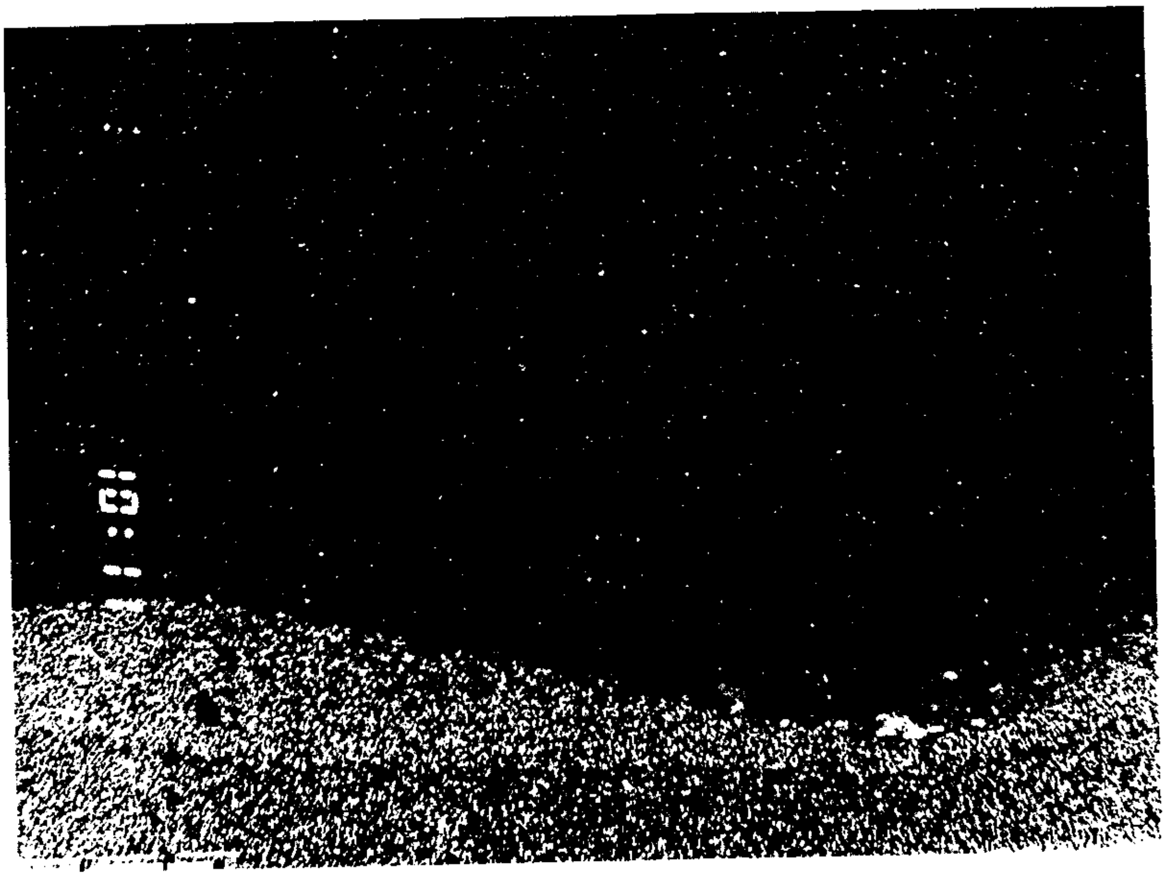

Figure 3-45. Channel sand ripples at Station 15 in San Pablo Bay. Bottom instability due to high current velocities may explain the apparent low biomass of infauna in the channels. Scale = 1X.

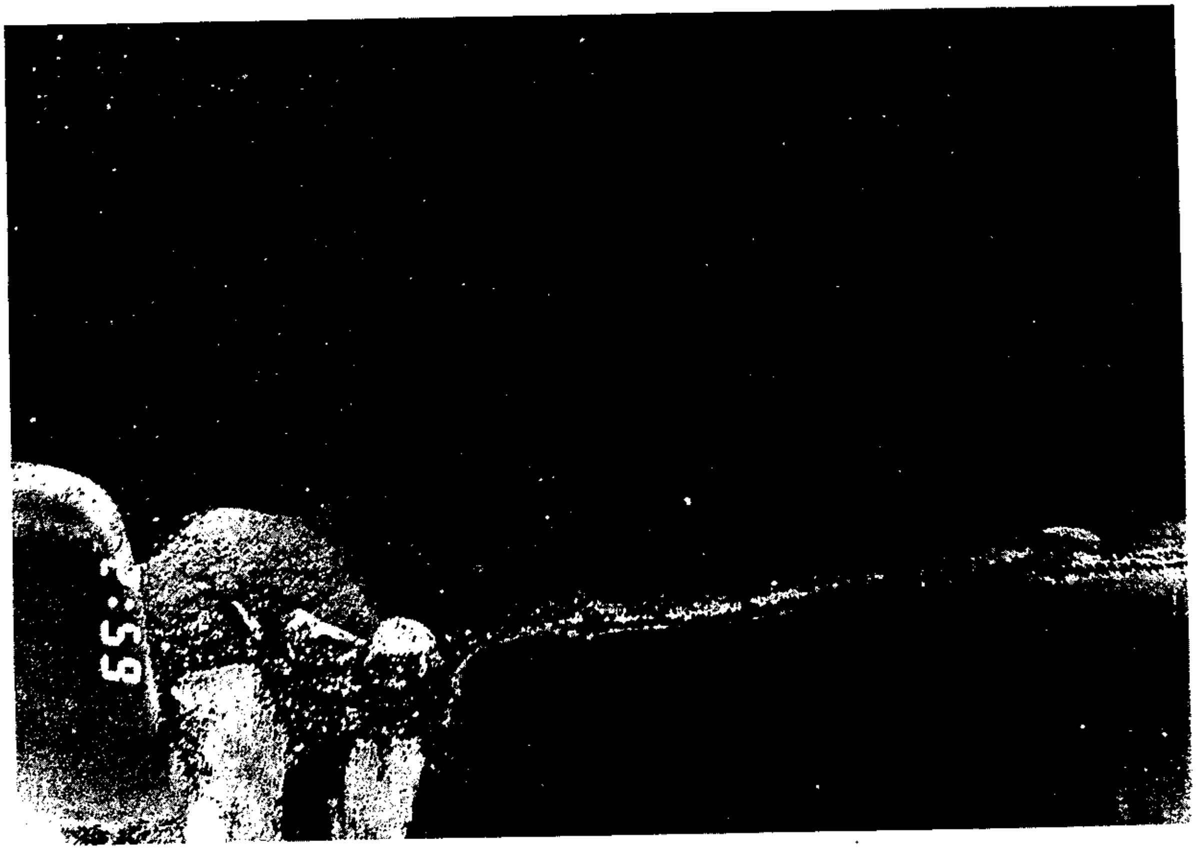

Figure 3-46. Overconsolidated sediment at Station 16; this may reflect the presence of disposed dredged material. Scale = 1X.

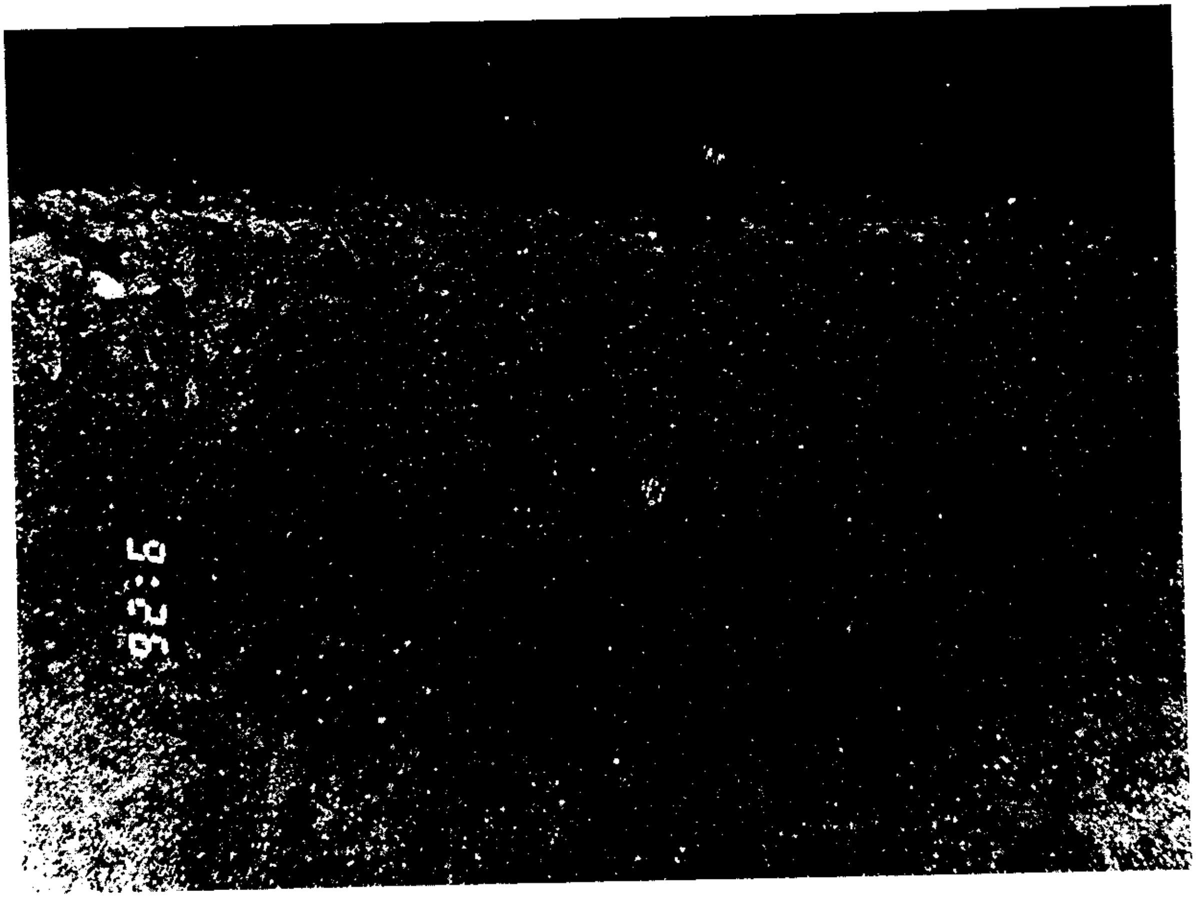

Figure 3-47. A burrow-mottled sand and silt-clay mixture at Station 13. This may result from changing kinetic regime with alternate inputs of sand and silt-clay. Subsequent (incomplete) biogenic mixing results in a mottled fabric. Also, note the amphipod tube mat at the interface. Scale = 1X.

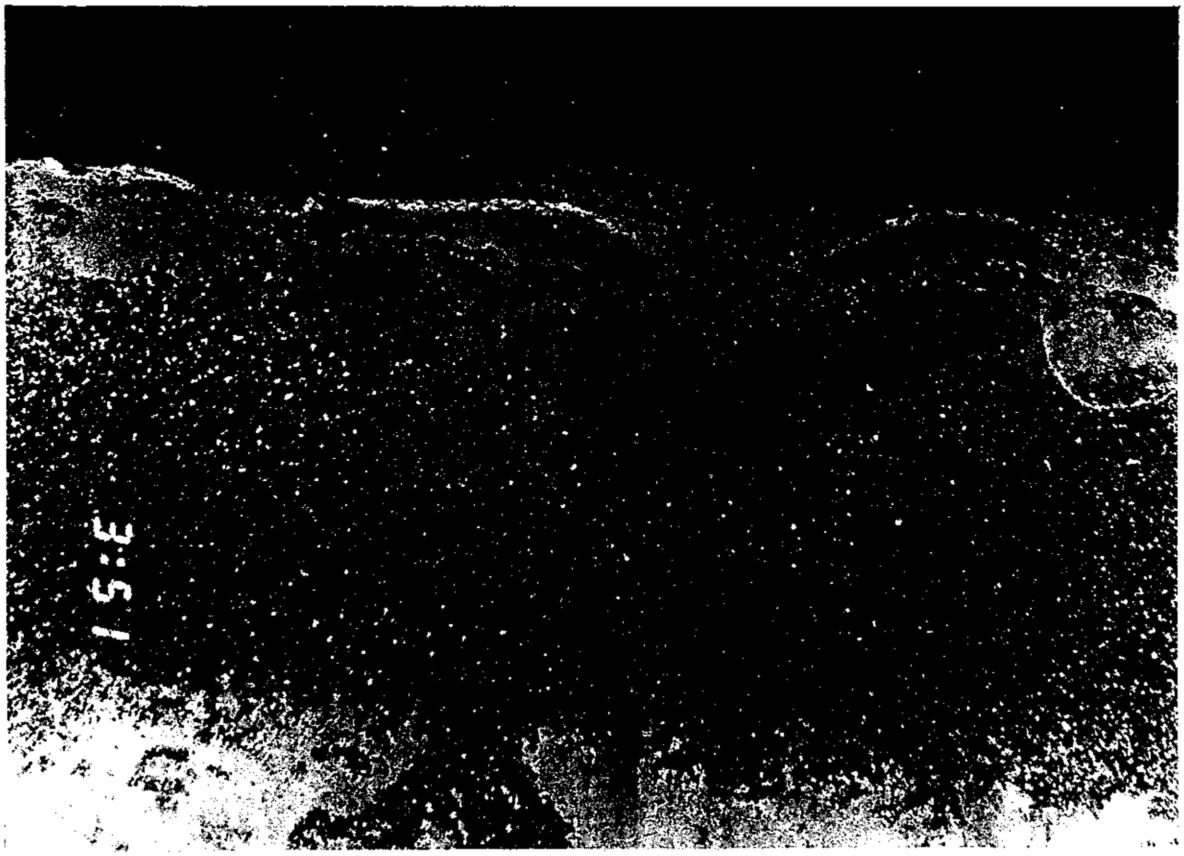

Figure 3-48. Intercalations of silt-clay and sand layers. This interstratification at Station 9 probably represents temporally changing kinetic conditions. Scale = 1X.

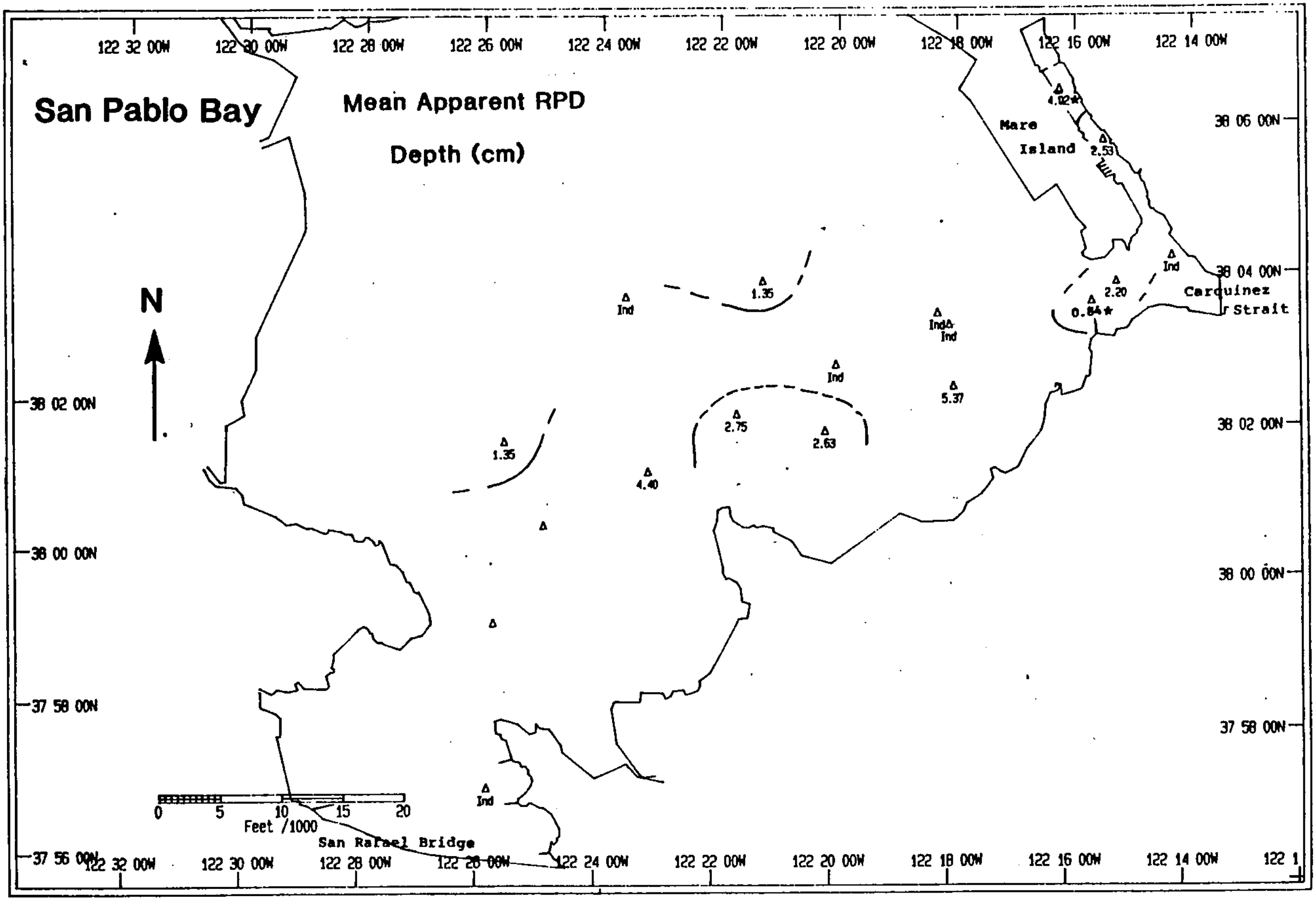

Figure 3-49a. The distribution of apparent RPD depths, averaged by station. The contours delimit regions exhibiting apparent RPD depths less than 3.0 cm. An '*' indicates the presence of apparent high sediment oxygen demand. An 'Ind' indicates the RPD is indeterminate. Station designations are provided in Figure 3-49b (following page).

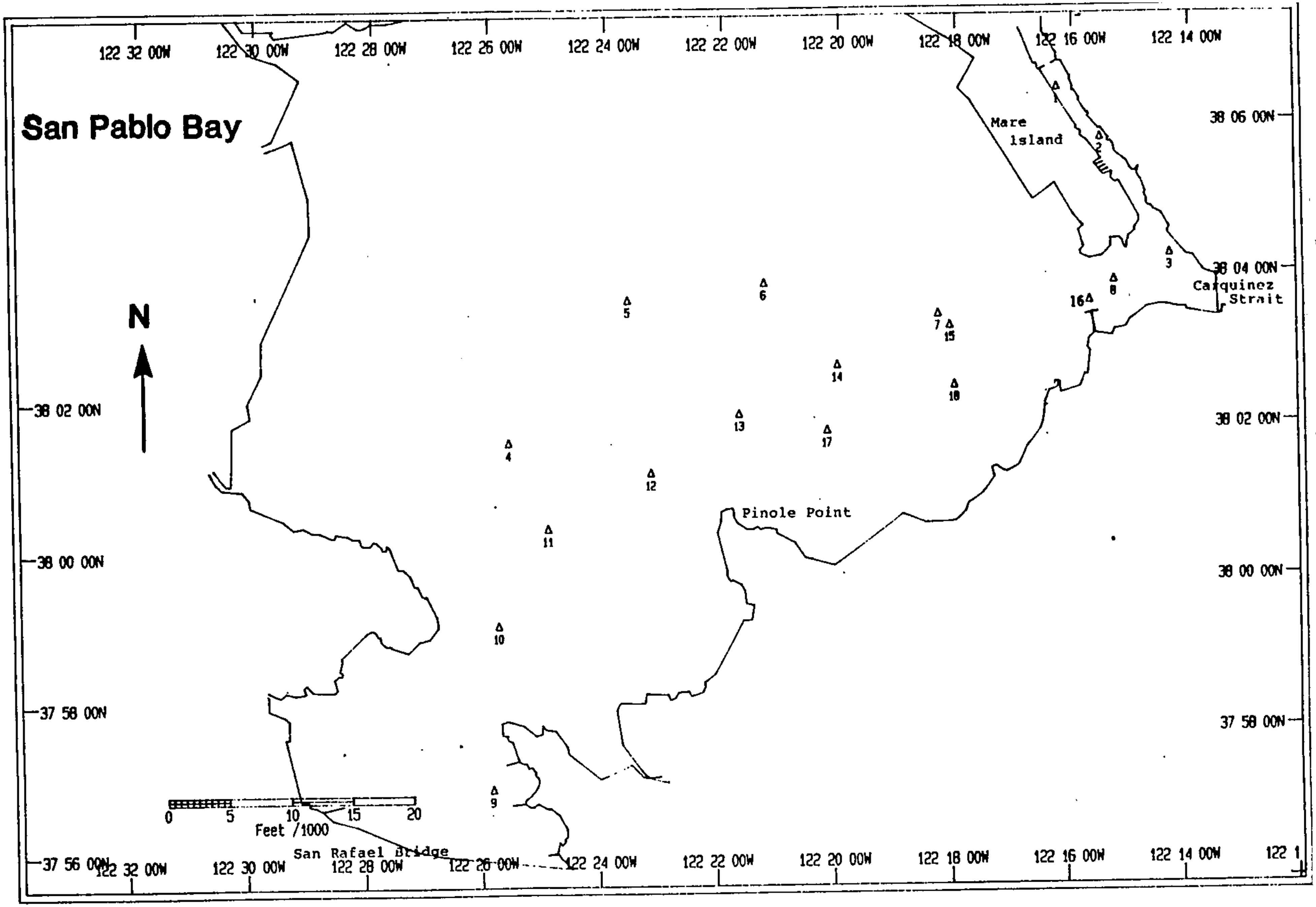

Figure 3-49b. Locations and designations of stations in San Pablo Bay.

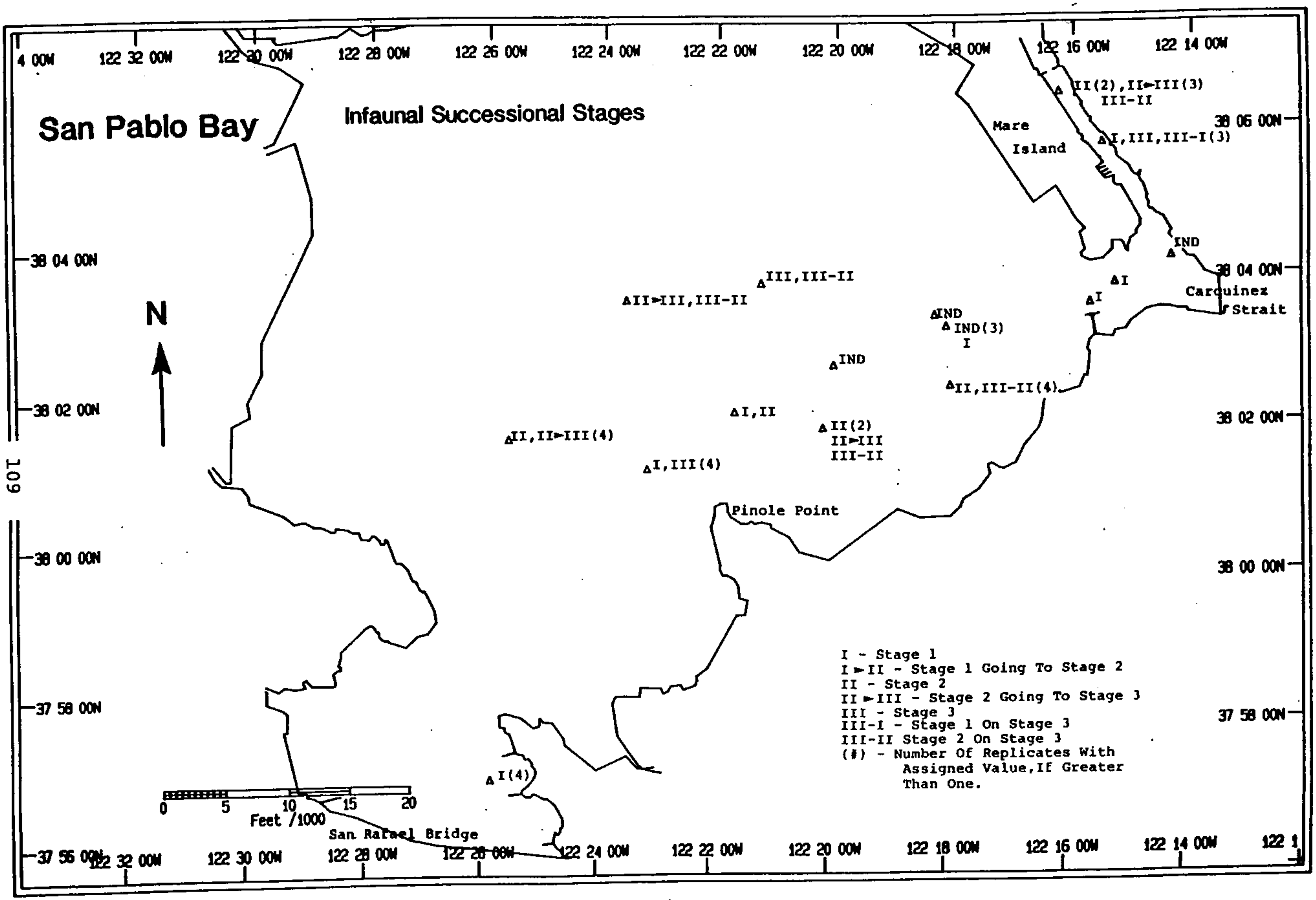

Figure 3-50a. The mapped distribution of successional stages in San Pablo Bay. Station designations are provided in Figure 3-50b (following page).

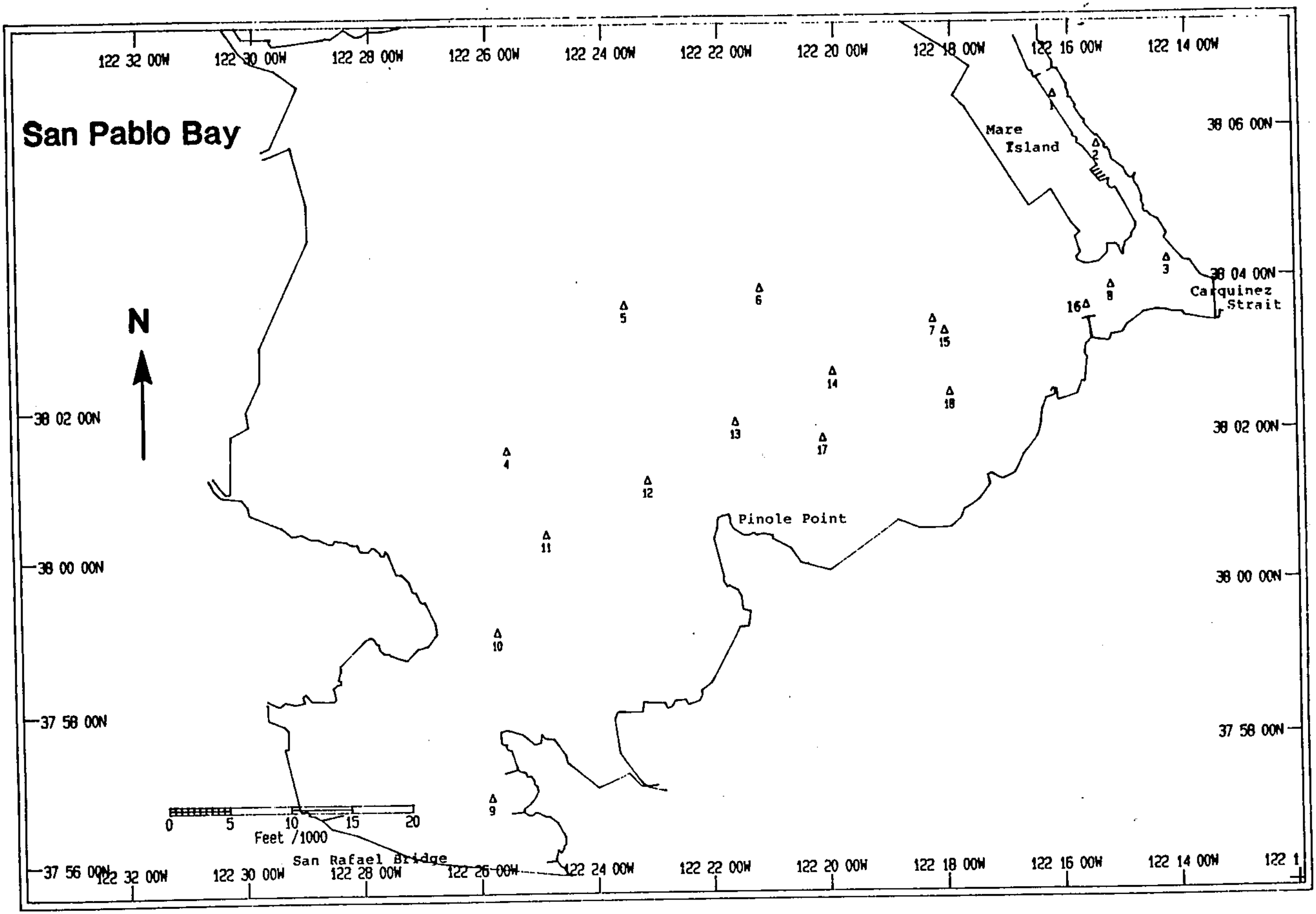

Figure 3-50b. Locations and designations of stations in San Pablo Bay.

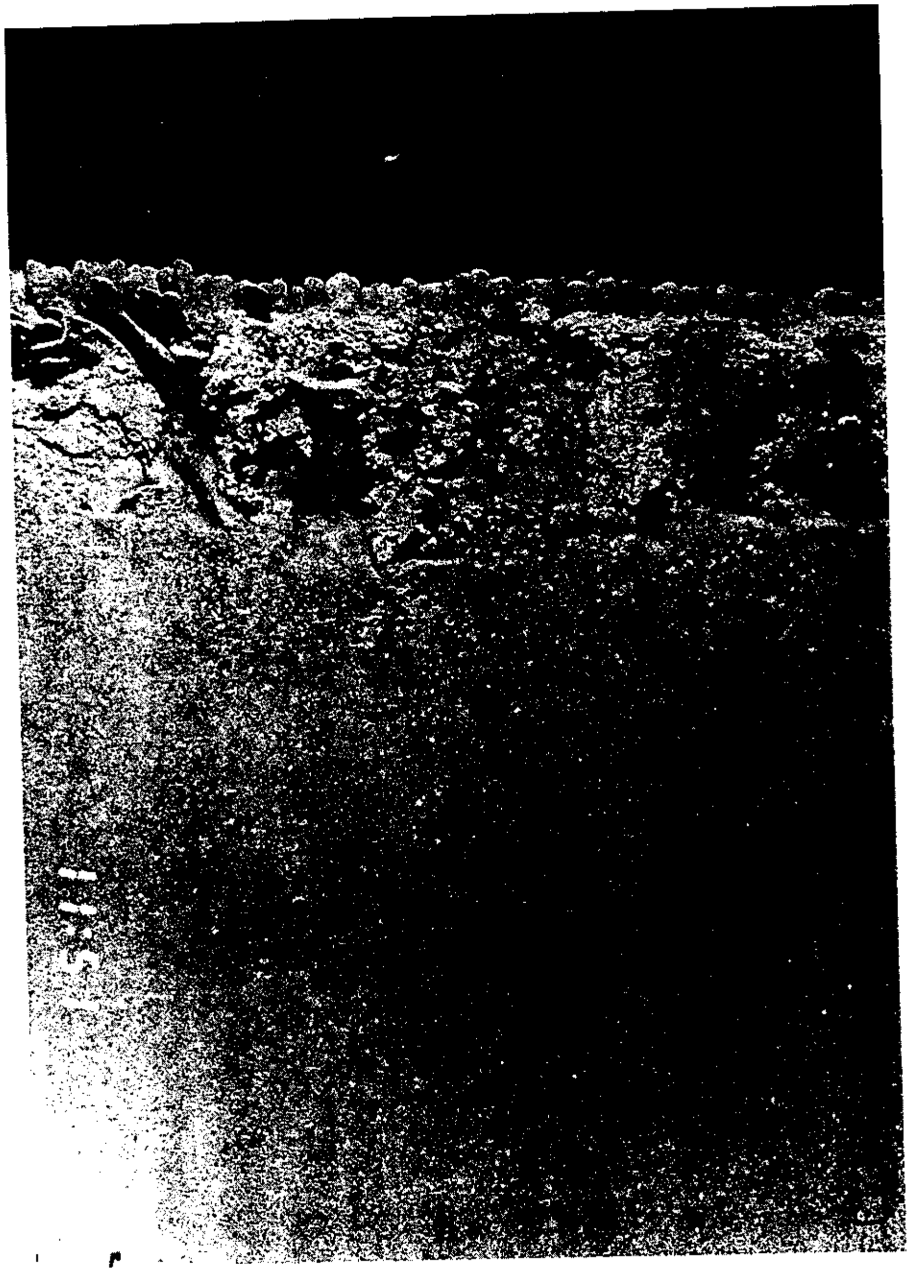

Figure 3-51. A well-developed ampeliscid mat at Station 1 in San Pablo Bay. See text for further discussion. Scale = 1X.

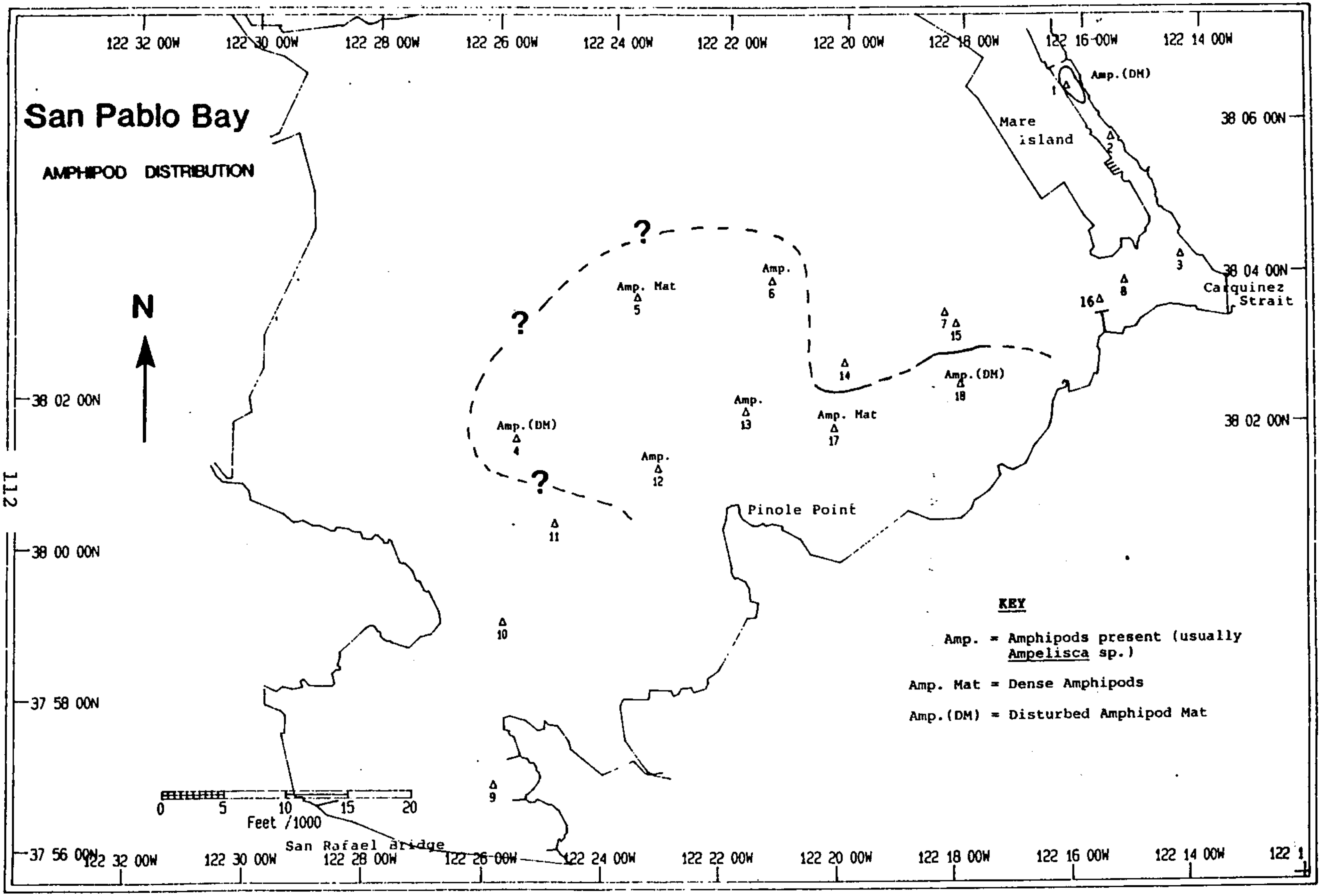

Figure 3-52. The mapped distribution of tubicolous amphipods (contours) in San Pablo Bay.

Figure 3-53. A REMOTS image from station 51 showing a physically disturbed Amphipod tube mat. Many areas occupied by ampeliscids are apparently disturbed. This can be related to bottom scour or biogenic excavation (i.e. predation). Scale = 1X.

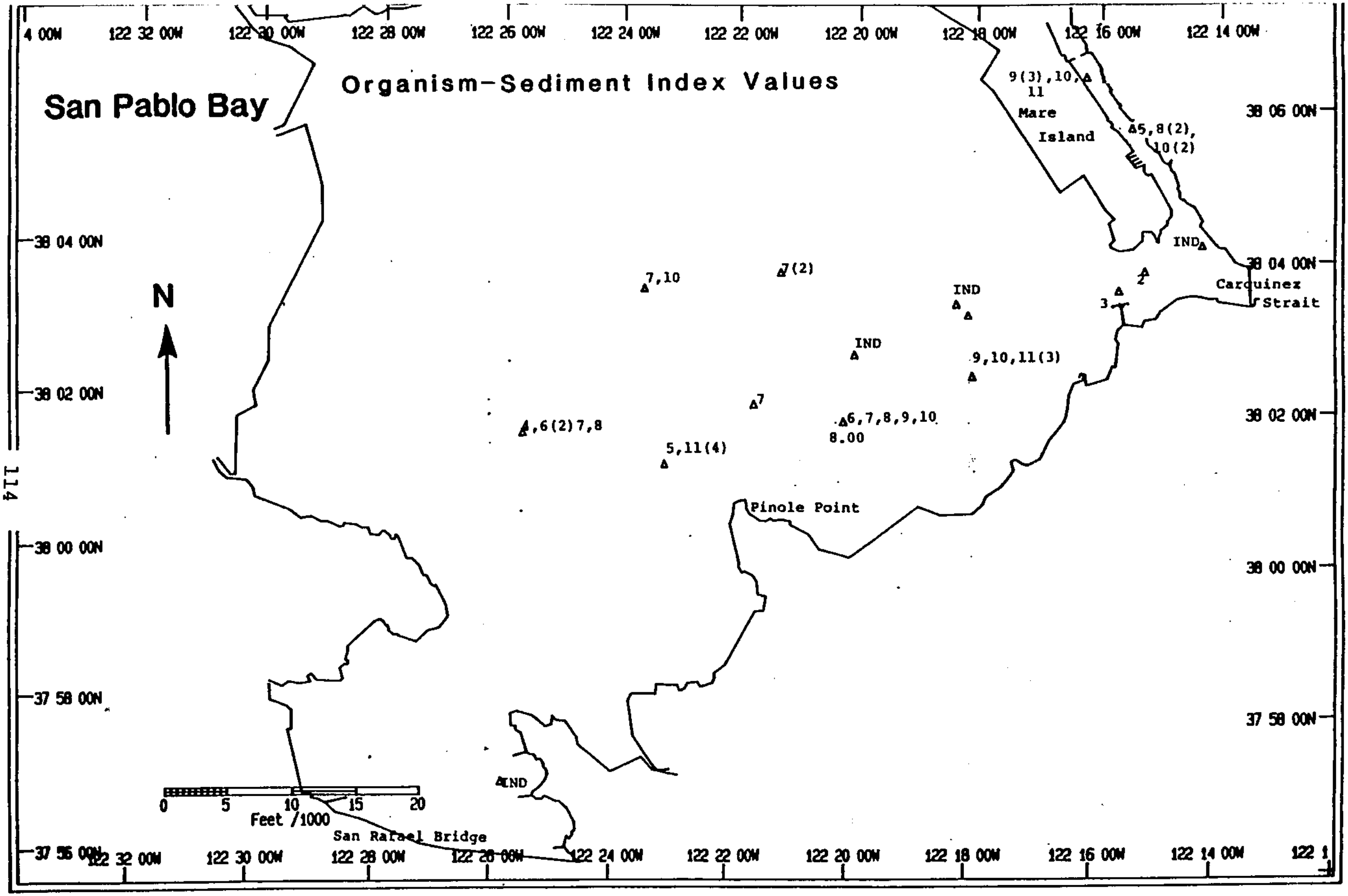

Figure 3-54a. Organism-Sediment Index values in San Pablo Bay. The number in ( ) indicates the number of replicates with that value, if greater than 1. An 'Ind' indicates an interdeterminate OSI. Station designations are provided in Figure 3-54b (following page).

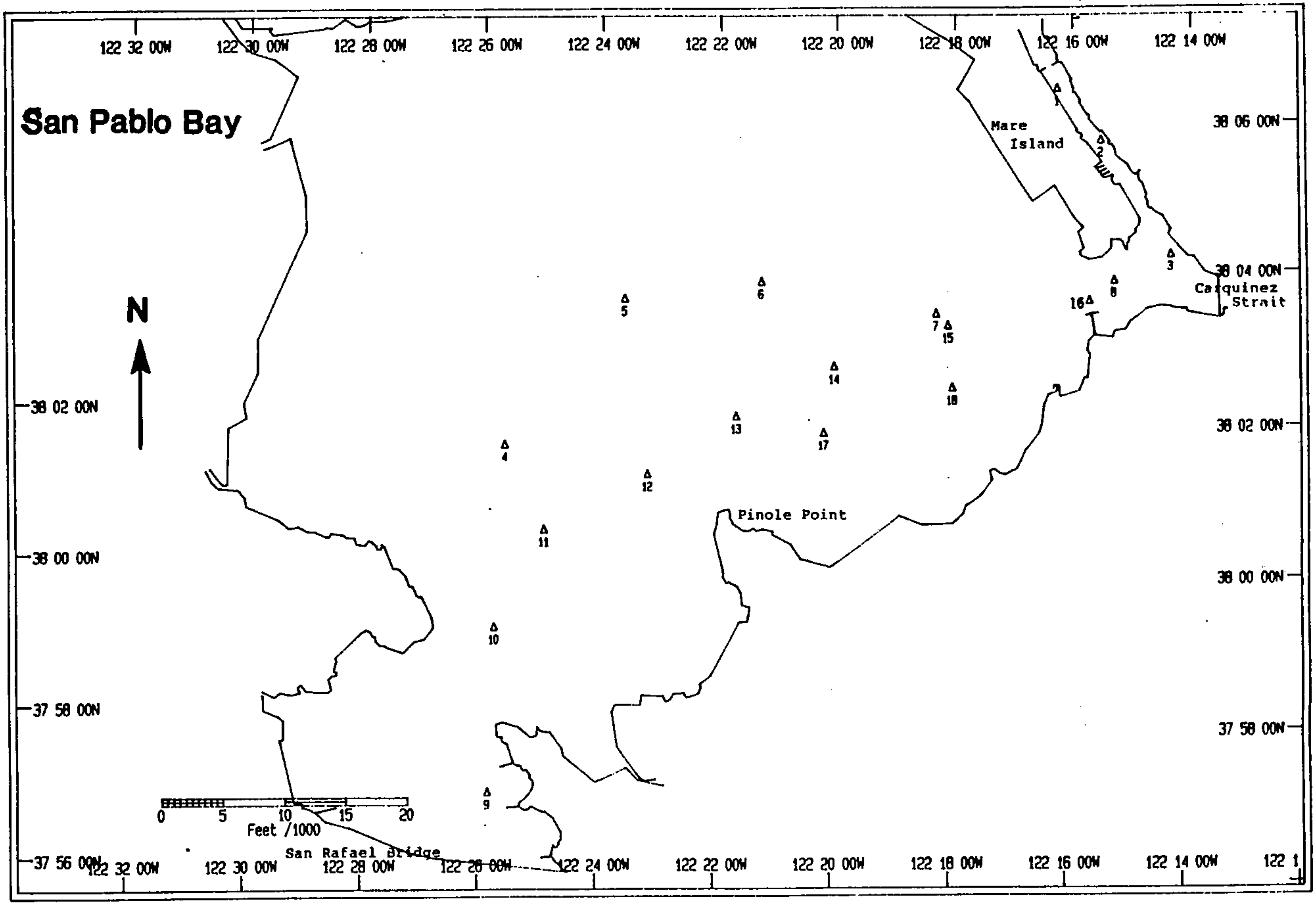

Figure 3-54b. Locations and designations of stations in San Pablo Bay.

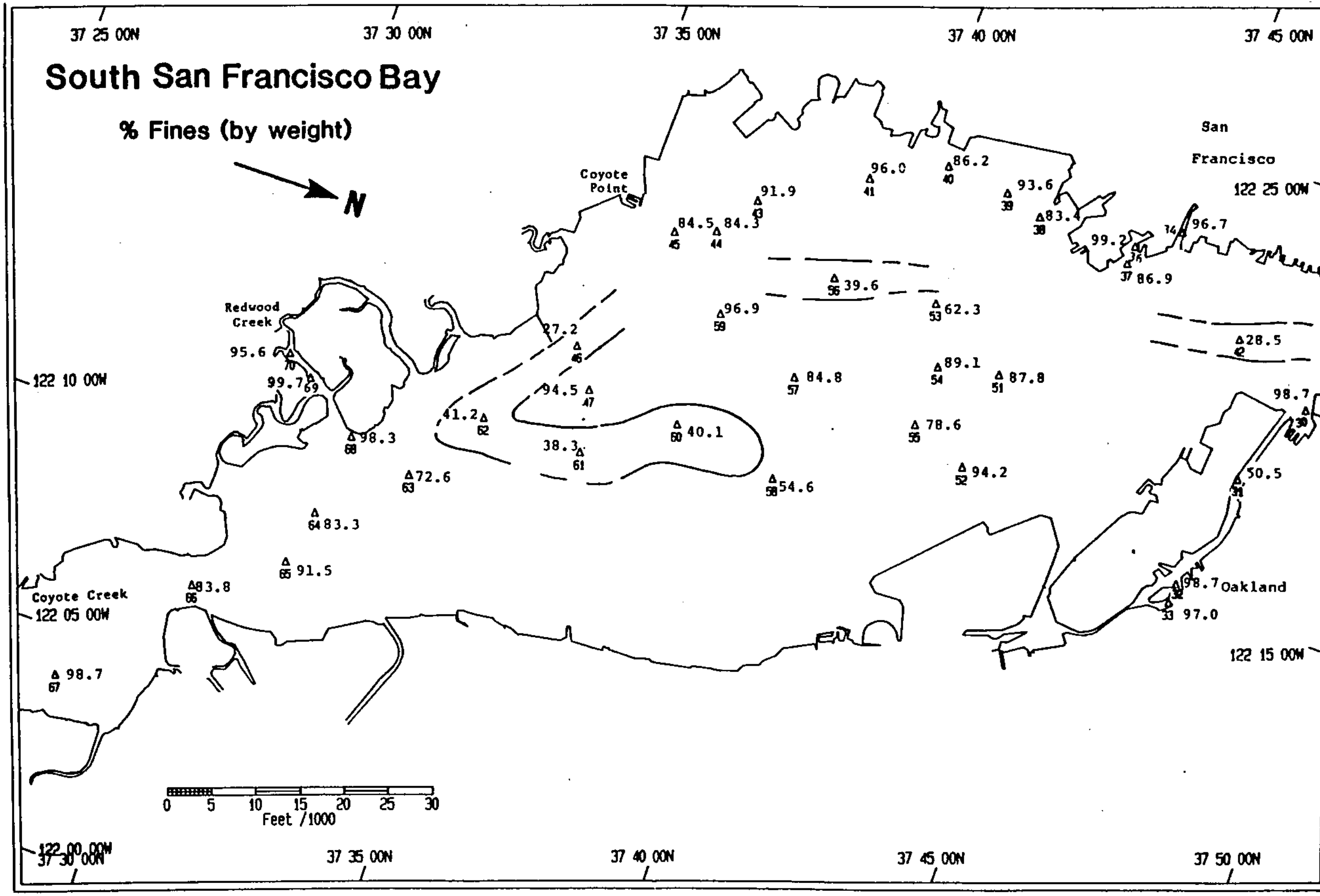

Figure 3-55. The distribution of fine-grained sediments (sieved samples) in the South Bay. Fine-grained sediments (.i.e, "FINES") are those having a grain size of ≥4 phi. The contour delimits areas comprised of less than 50% fine-grained material.

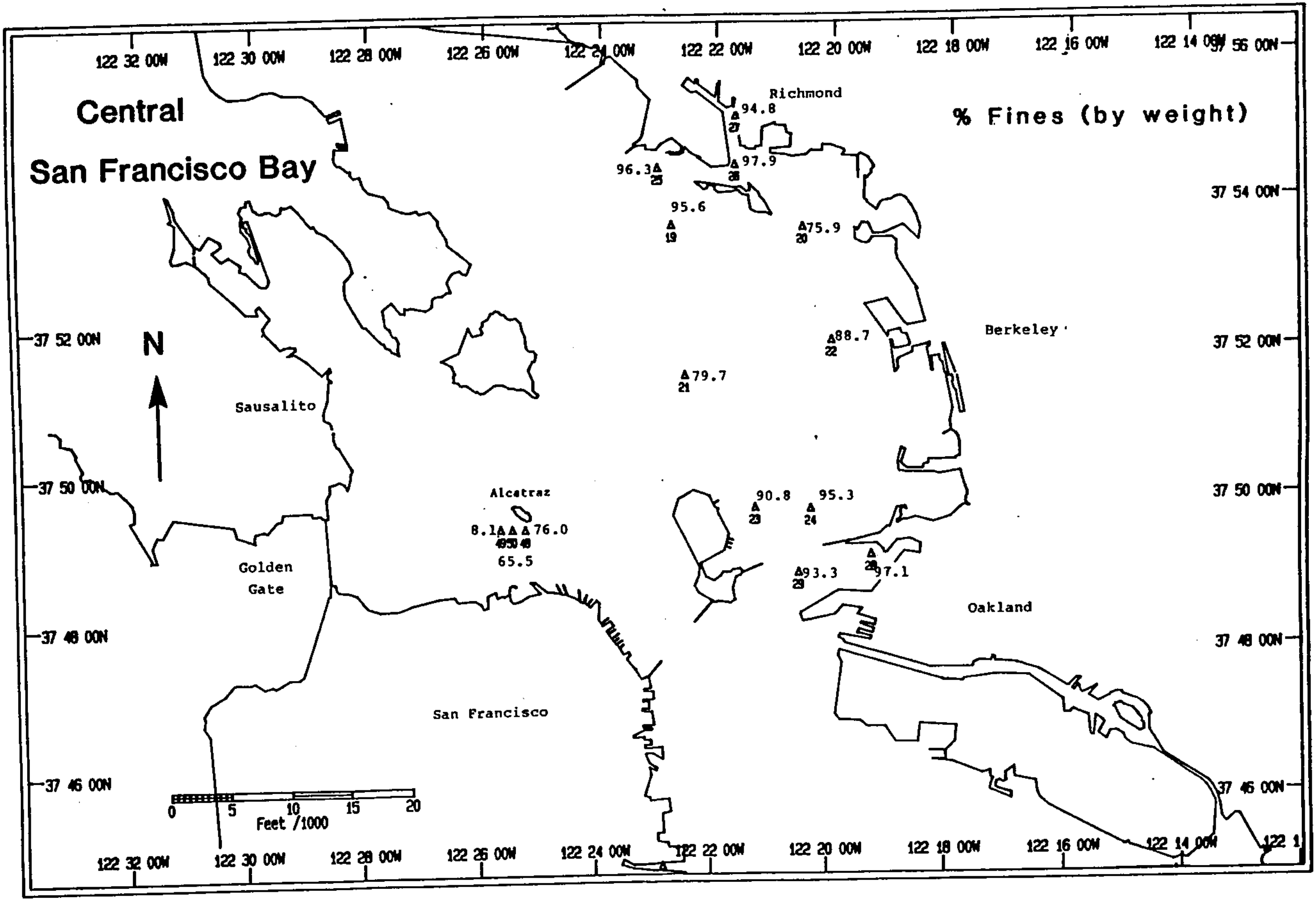

Figure 3-56. The distribution of fine-grained sediments (sieved samples) in Central Bay. Fine-grained sediments (i.e., "FINES") are those having a grain size of ≥4 phi.

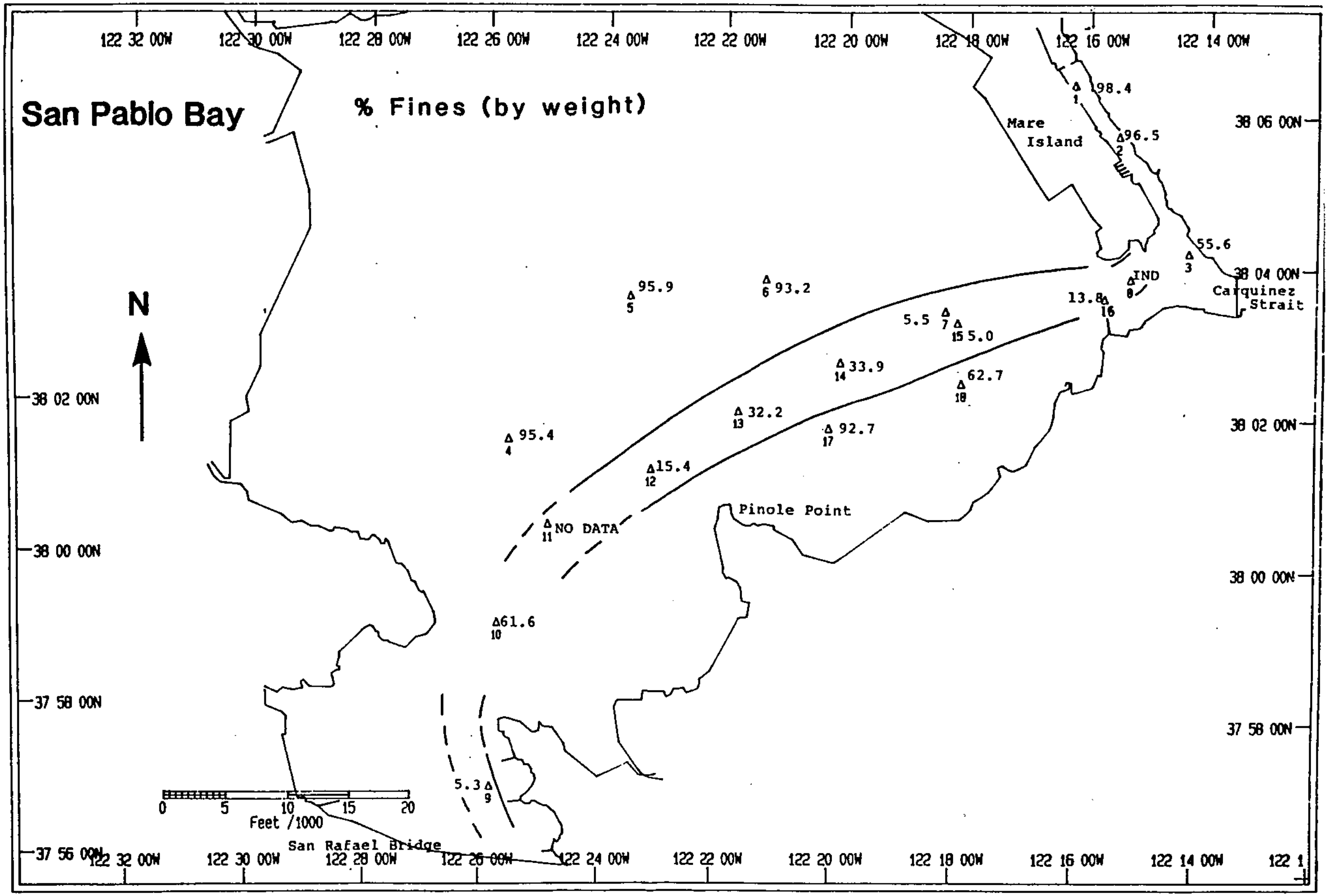

Figure 3-57. The distribution of fine-grained sediments (sieved samples) in San Pablo Bay. Fine-grained sediments (i.e., "FINES") are those having a grain size of $\geq$4 phi. The contour delimits areas comprised of less than 50% fine-grained material.

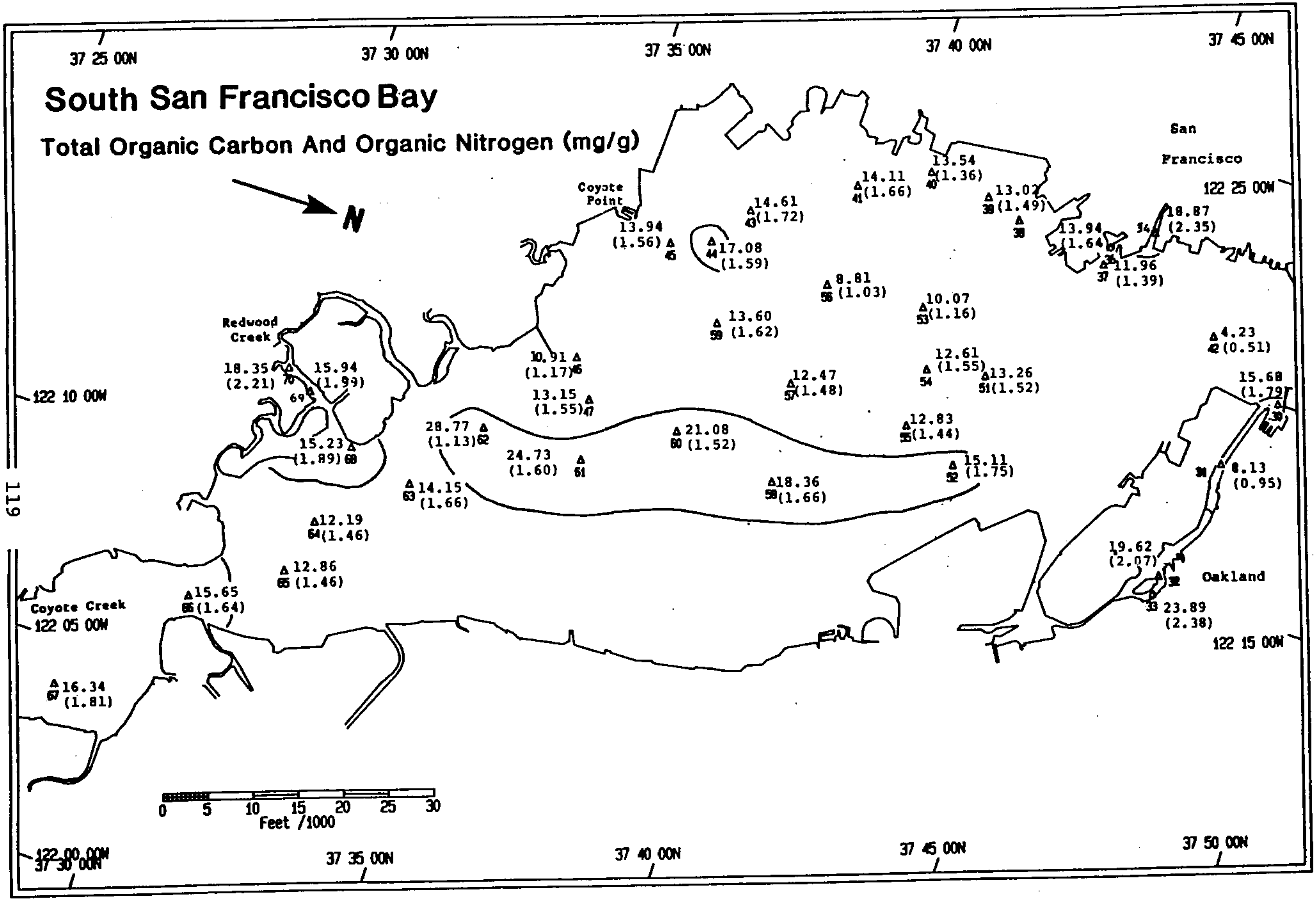

Figure 3-58. The distribution of total organic carbon in mg C/g and total organic nitrogen (the value in parentheses) in mg N/g in South Bay sediments. Areas

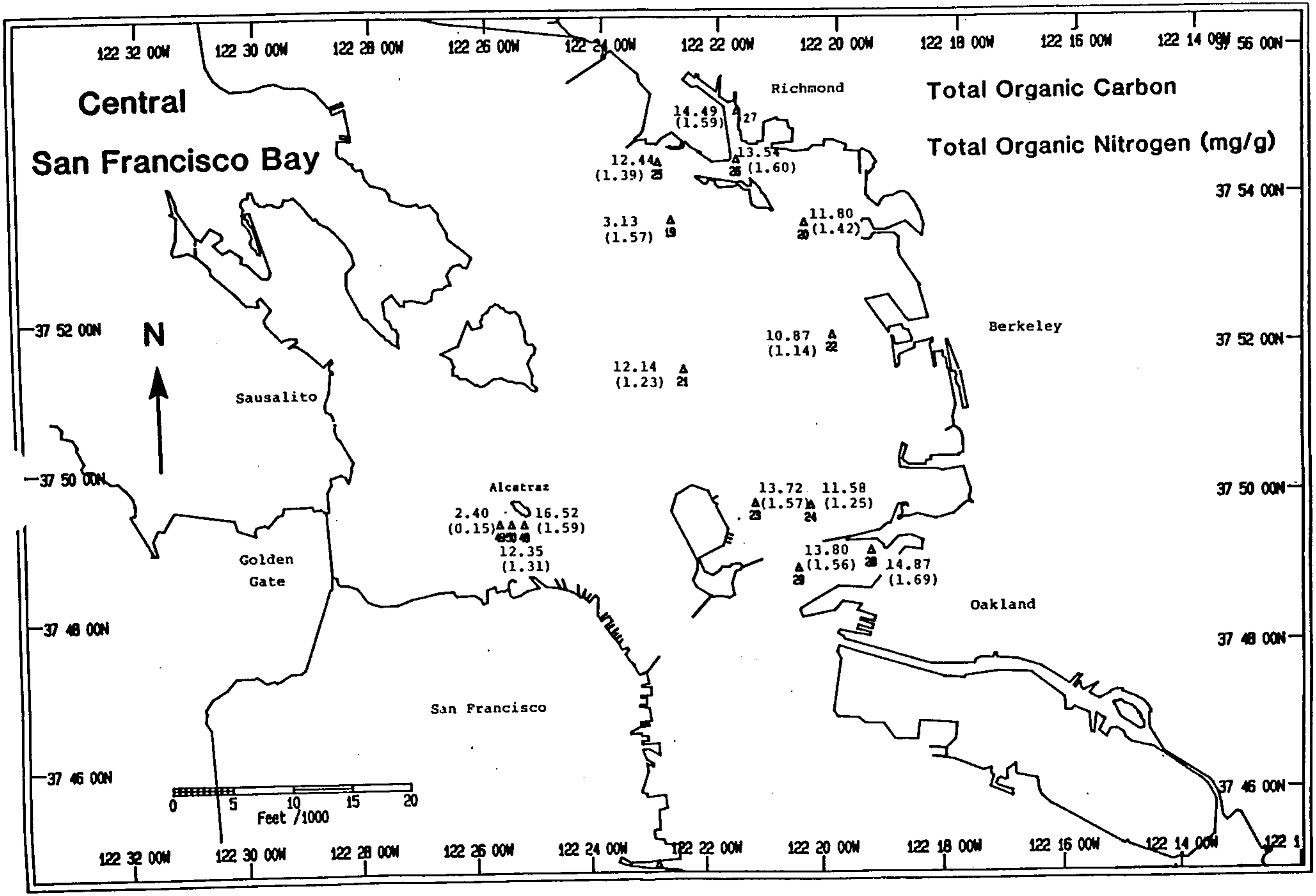

Figure 3-59. The distribution of total organic carbon in mg C/g and total organic nitrogen (the value in parentheses) in mg N/g in the Central Bay.

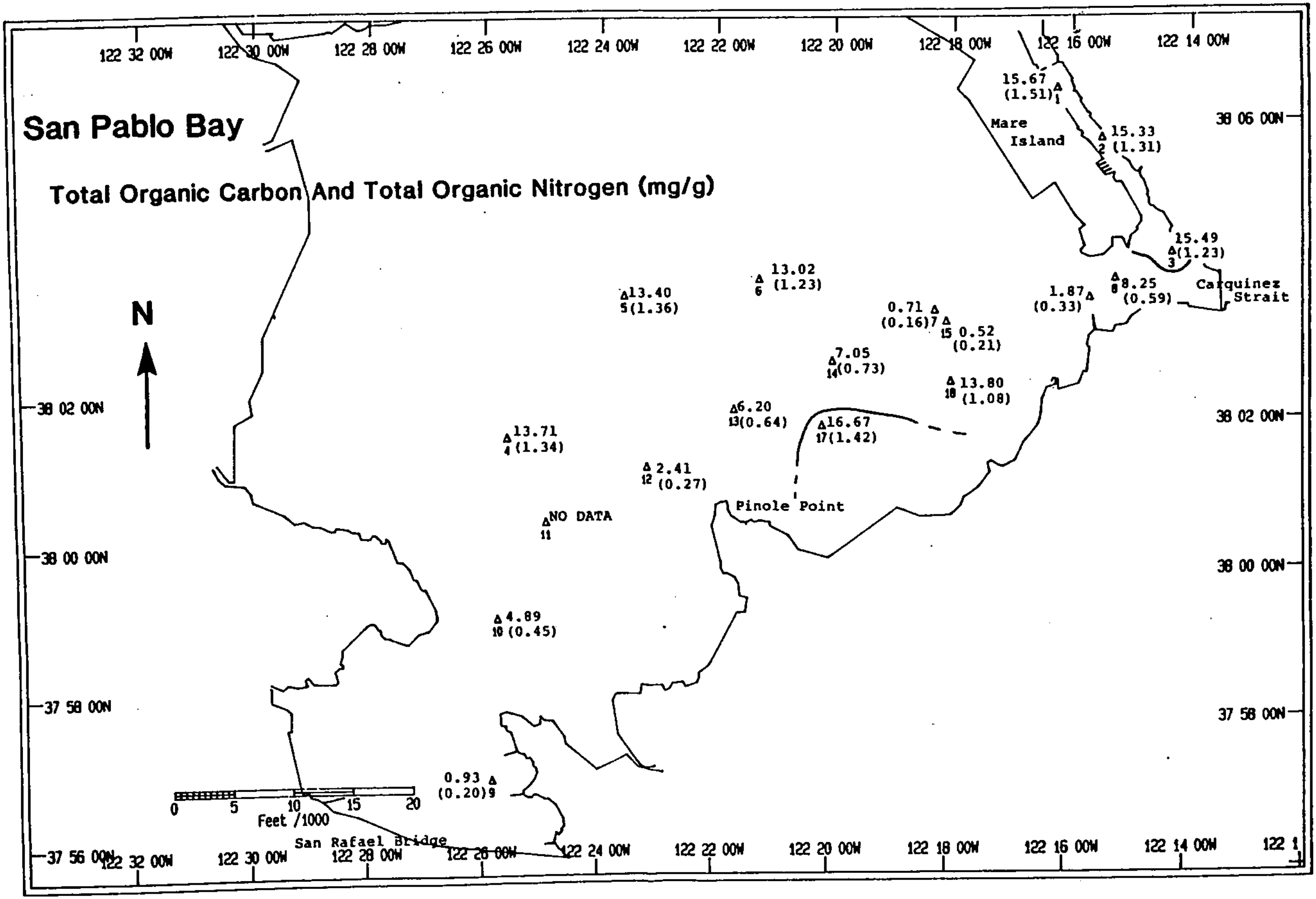

Figure 3-60. The distribution of total organic carbon in mg C/g and total organic nitrogen (the value in parentheses) in mg N/g in San Pablo Bay sediments. Areas with TOC valos greater than 15 mg C/g are delimited.

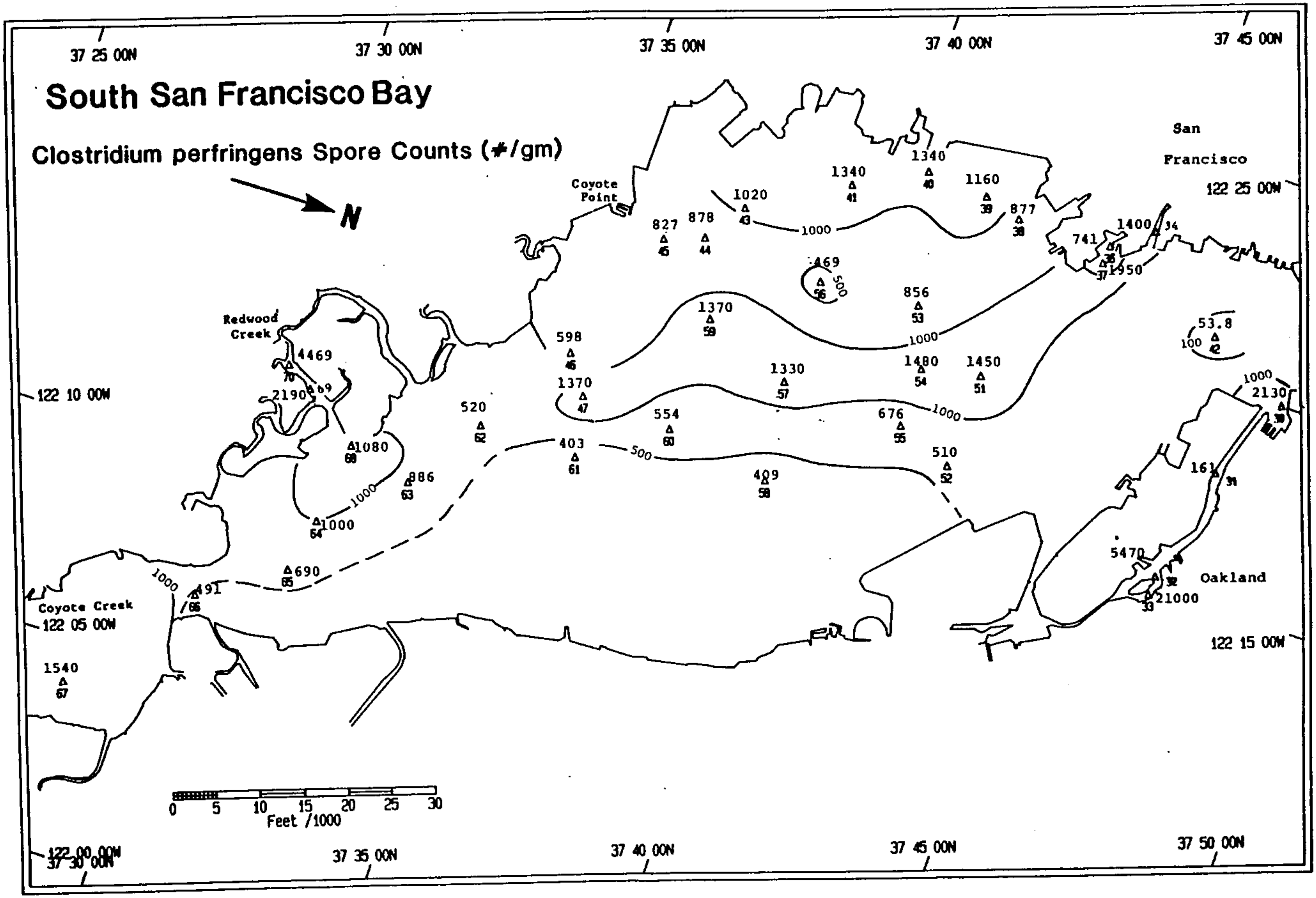

Figure 3-61. The contoured distribution of C. perfringens spores in the South Bay. Contour intervals are indicated.

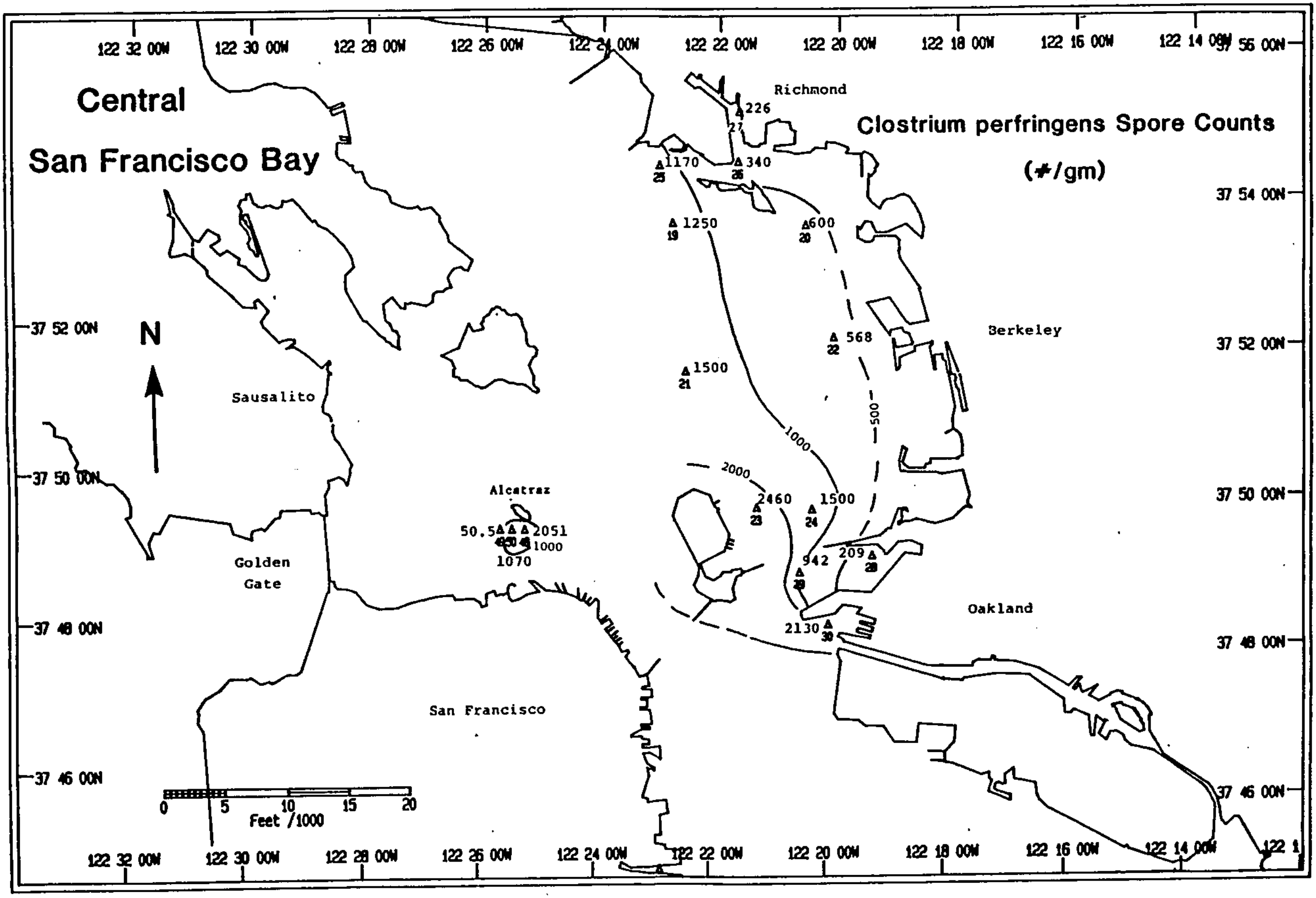

Figure 3-62. The contoured distribution of C. perfringens spores in the Central Bay. Contour intervals are indicated.

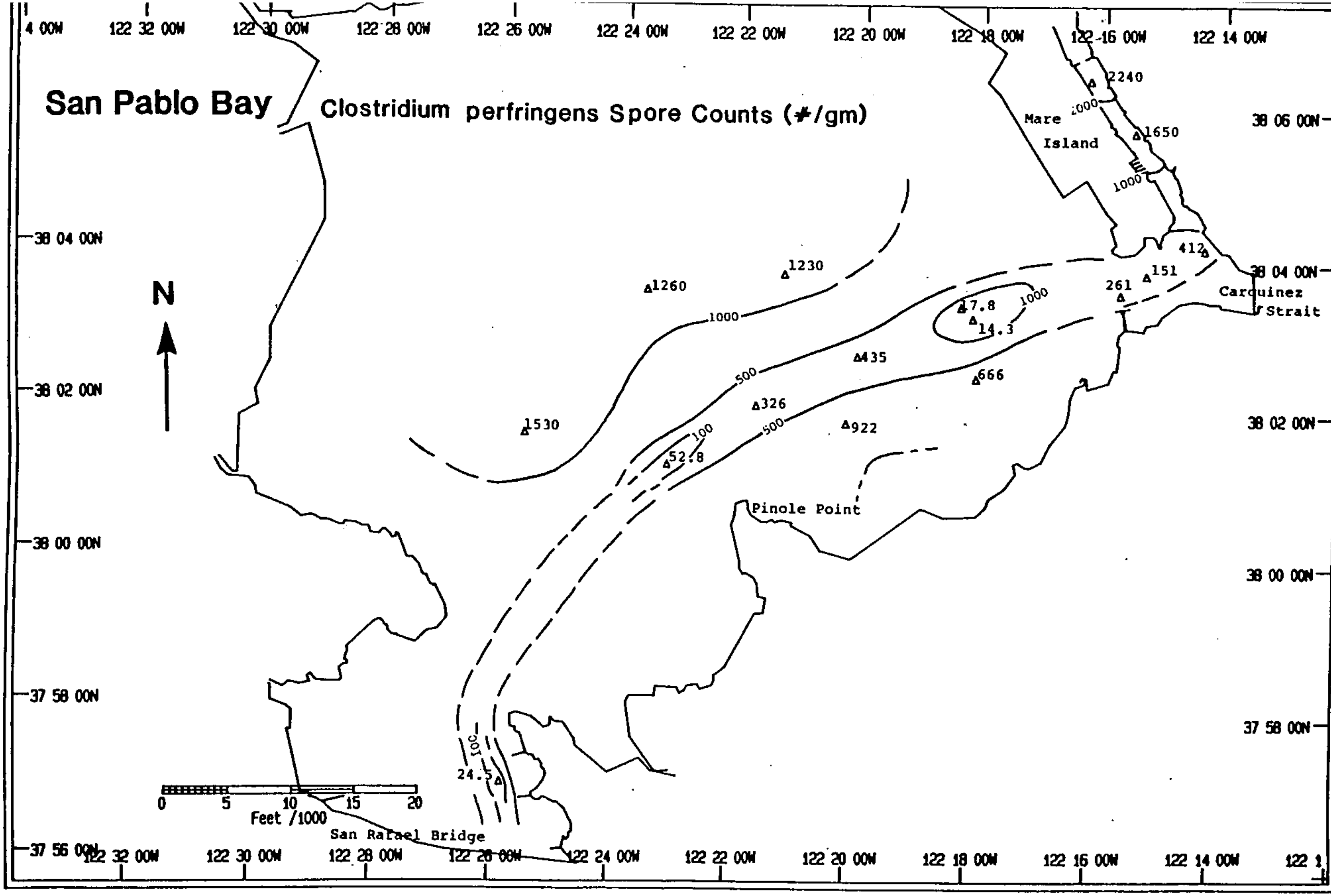

Figure 3-63a. The contoured distribution of C. perfringens spores in the San Pablo Bay. Contour intervals are indicated. Station designations are provided in Figure 3-63b (following page).

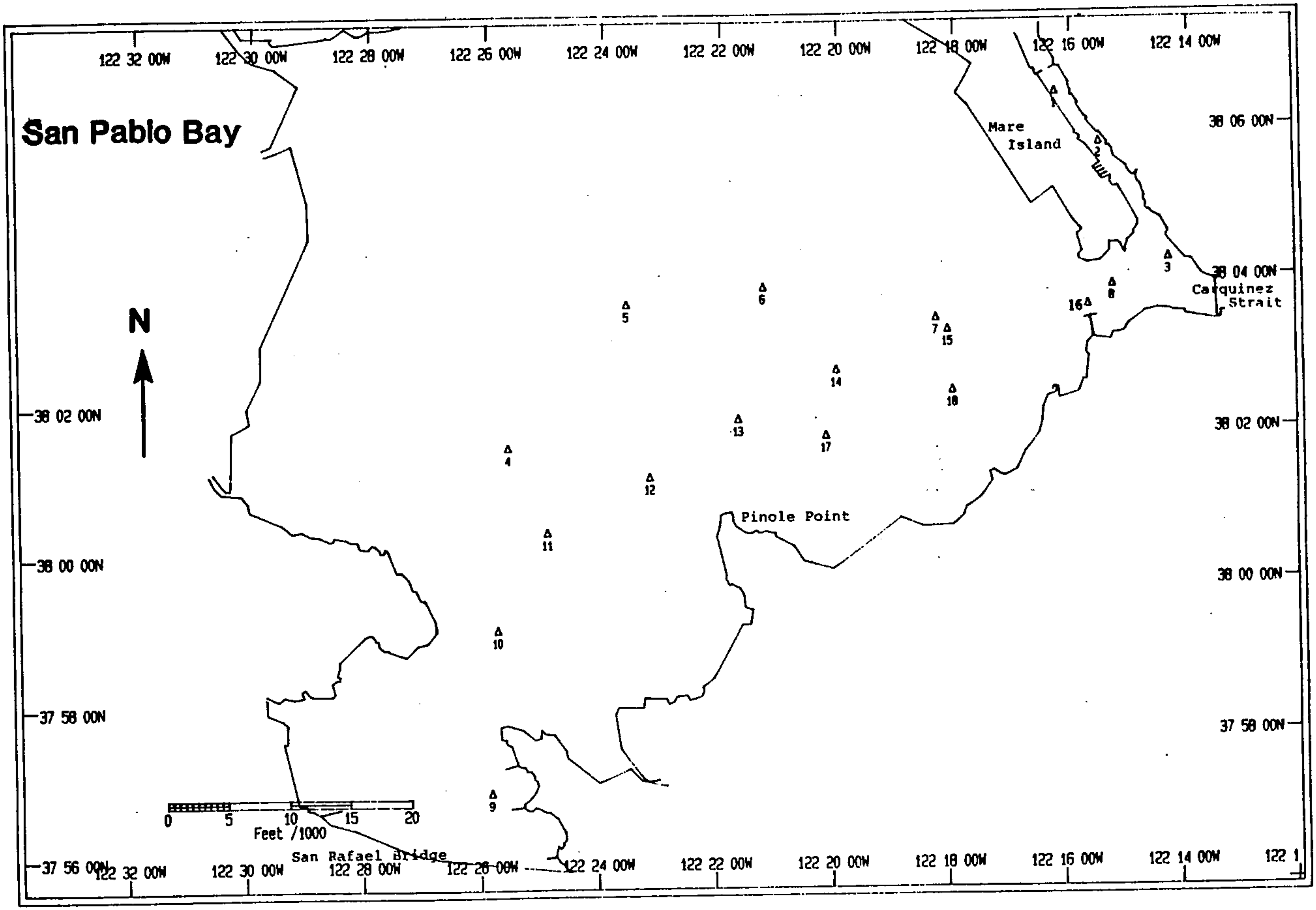

Figure 3-63b. Locations and designations of stations in San Pablo Bay.

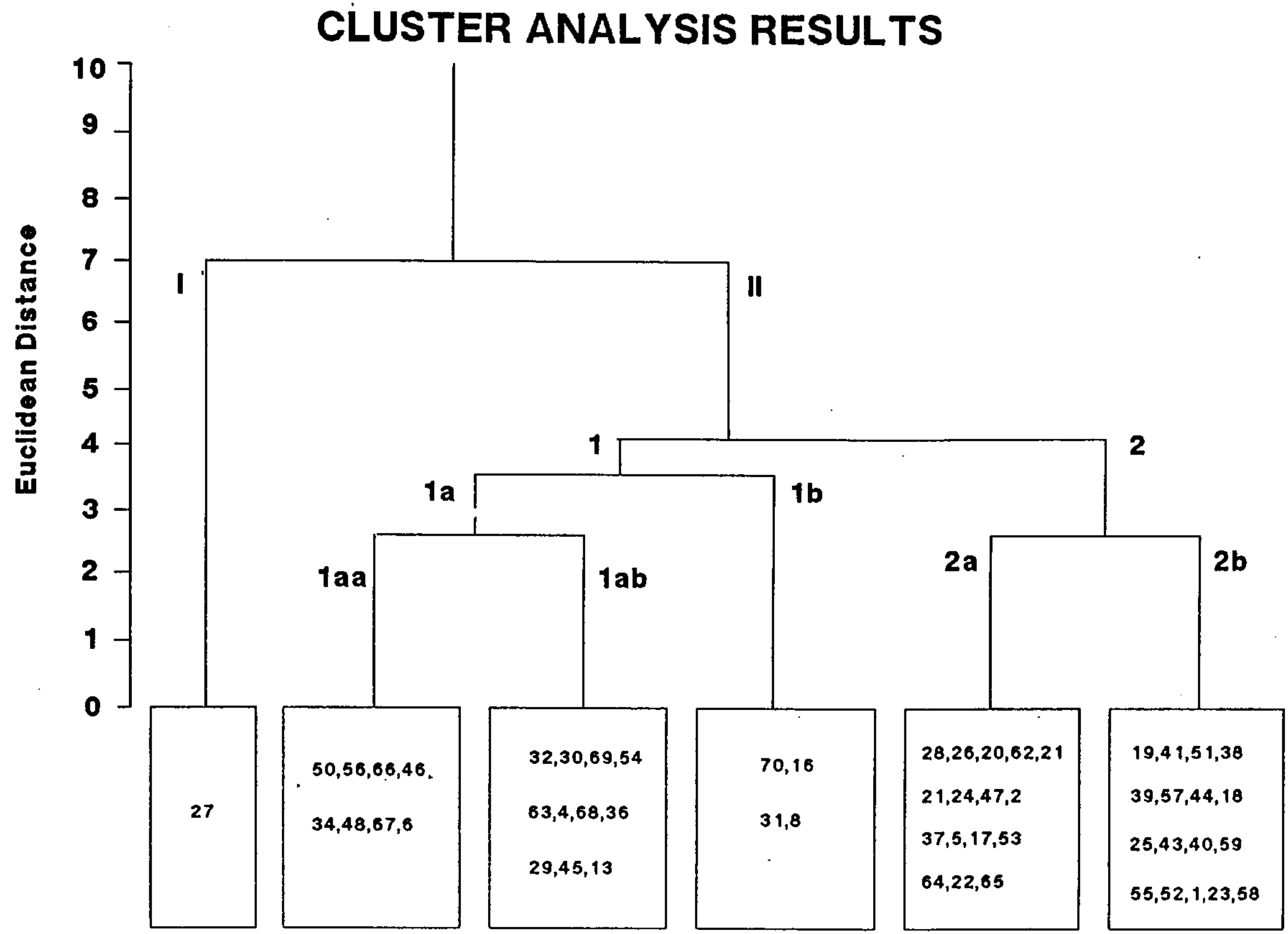

Figure 4-1. Results of the unweighted group average clustering of mean OSI values and C. perfringens counts. The numbers in the boxes represent stations sampled.

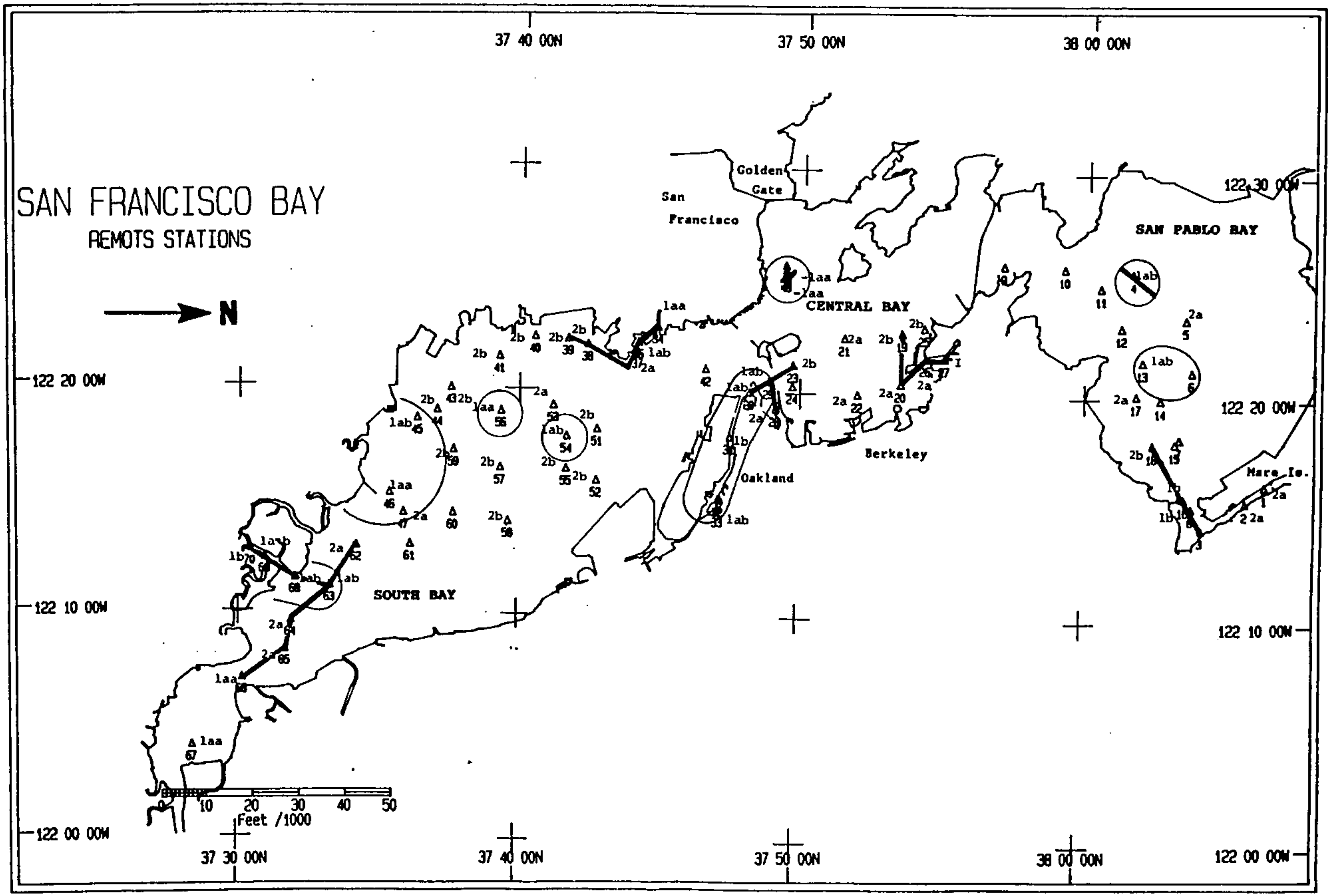

Figure 4-2. Spatial distribution of clustering results. The number/letter designation indicates the cluster level shown in Figure 4-1. All stations falling within the #1 cluster group are enclosed in the thin black lines. The thick black transects show suggested sampling areas for long-term monitoring.