CONTAMINANT ASSESSMENT OF SURFACE SEDIMENTS FROM TANAPAG LAGOON, SAIPAN

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WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
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The true heroes of this study, from left to right: Carlos Ketebengang (diver), Jessica Tomokane (diver), and Clarence Igisiar (master boatman)

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

ABSTRACT

In June 1999, a pilot study was undertaken to determine levels of heavy metals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) in surface sediment cores (5 x 15 cm) from the southern end of Tanapag Lagoon off the western shore of central Saipan. Samples were collected from 32 nearshore sites (<500 m offshore) and nine outer lagoonal sites (>500 m offshore) between Flores Point to the north and Muchot Point to the south. Sets of three sediment cores were collected within an approximate 3m-diameter circle at each site. Each core was homogenized and analyzed separately, following petrographic and organic carbon determinations. Site mean values for each contaminant were subsequently derived from each core set. All data presented here are expressed on a dry weight basis.

The range of mean heavy metal concentrations (µg/g) for all nearshore sites were as follows: silver (Ag): <0.1-0.28; arsenic (As): 1.33-10.0; cadmium (Cd): <0.1-0.58; chromium (Cr): 1.40-9.67; copper (Cu): 0.22-27.8; mercury (Hg): 0.012-0.347; nickel (Ni): <0.2-5.06; lead (Pb): <0.4-40.6; tin (Sn): 0.08-36.1, and zinc (Zn): 1.63-127. Levels determined in the offshore sites were generally lower with maximum mean values of <0.1, 1.87, <0.1, 2.43, <0.1, 0.016, <0.2, 1.2, 0.24 and 2.09, determined for Ag, As, Cd, Cr, Cu, Hg, Ni, Pb, Sn and Zn, respectively. Highest overall values for all metals, except Ag and Sn, were found at site 14, in intertidal sediments at the southernmost end of Puerto Rico Dump.

Total PCB levels (Σ_{20} congeners) were generally low throughout the study area and ranged from a mean of <1 ng/g at all outer lagoonal sites to 16.6 ng/g near the dump (site 14). A relatively high mean level of 11.1 ng/g was also found in sediments near Saipan Harbor (site 9). PCB profiles in sediments from this site closely resembled Aroclor 1260, whereas those from site 14 appeared more like a combination of Aroclor 1260 and one of the lower chlorinated commercial mixtures, possibly Aroclor 1254. Almost all samples with detectable quantities of PCB were dominated by Cl_5-Cl_7 homologues. The most frequently encountered congeners were PCBs 101 and 153, detected in 57% and 59% of all sediment cores, respectively. The highly toxic planer/near planer congeners (PCBs 77, 105 and 126) were not detected in any sample analyzed.

PAHs were only detected in 33% of all offshore sediment cores compared with 81% from nearshore sites. Detectable PAH levels in sediments from the outer lagoonal sites were barely measurable in the majority of cases. Closer to shore, levels were often appreciably higher with mean values (Σ_{16} congeners) rising to 1.18 µg/g off the west edge of the dump (site 30), 1.22 µg/g in Outer Cove Marina (site 4) and 1.39 µg/g by the new docks (site 7). PAH profiles were highly variable throughout the study area and were dominated by the higher molecular weight compounds. The most frequently encountered and most abundant PAHs were the 4-ringed members, chrysene, benzo(*a*)anthracene, and pyrene. These congeners were detected in 71%, 61% and 60% of all sediment cores respectively. The high prevalence of pyrene indicated that combustion sources were a significant source of PAHs in the area. Sedimentary fluoranthene/pyrene and pyrene/benzo(*a*)pyrene ratios also suggested that hydrocarbon fuel spills contributed to the PAH contamination of nearshore waters.

The data for all three chemical groups are measured against previously proposed numerical guidelines for Guam sediments in order to determine degrees of relative abundance. They are also discussed in relation to possible sources of localized input, and are compared and contrasted with levels reported by other researchers elsewhere in the world. Discrepancies are addressed between our data and the earlier DEQ findings for sediments taken near the dump. Baseline contaminant levels for clean, nearshore and offshore tropical reef sediments are proposed. These are intended to assist environmental managers in preserving the integrity of pristine sites, identifying impacted and potentially impacted sites, and prioritizing management decisions regarding sediment disposal and remediation strategies where necessary. Finally, the data are compared with numerical sediment quality guidelines developed from an extensive biological effects database by NOAA scientists. Future directions for continued research are recommended in the closing comments.

INTRODUCTION

Tanapag Lagoon is a typical high-island barrier reef lagoon bordering the western shore of central Saipan (Fig 1). It is approximately 9 km long, 3 km at its widest point, and covers an area of around 13 km^2. Large expanses of patch reef, interspersed with sand and rubble, provide for a diversity of shallow water habitats and harbor rich assemblages of flora and fauna (Doty and Marsh 1977, Amesbury *et al.* 1979). In addition to its ecological significance, the lagoon supports a variety of recreational activities, and local people traditionally harvest many of its fisheries resources for food.

Over the last quarter century, the southern, nearshore section of Tanapag Lagoon has become heavily impacted by the activities of man. Primary sources of anthropogenic disturbances between Muchot Point and Flores Point, a distance of approximately 3-km, include a commercial port (Saipan Harbor) and bulk fuel facility, a sewer outfall, a municipal dump, and two small-boat marinas. The area is also heavily inundated by stormwater runoff during prolonged periods of wet weather.

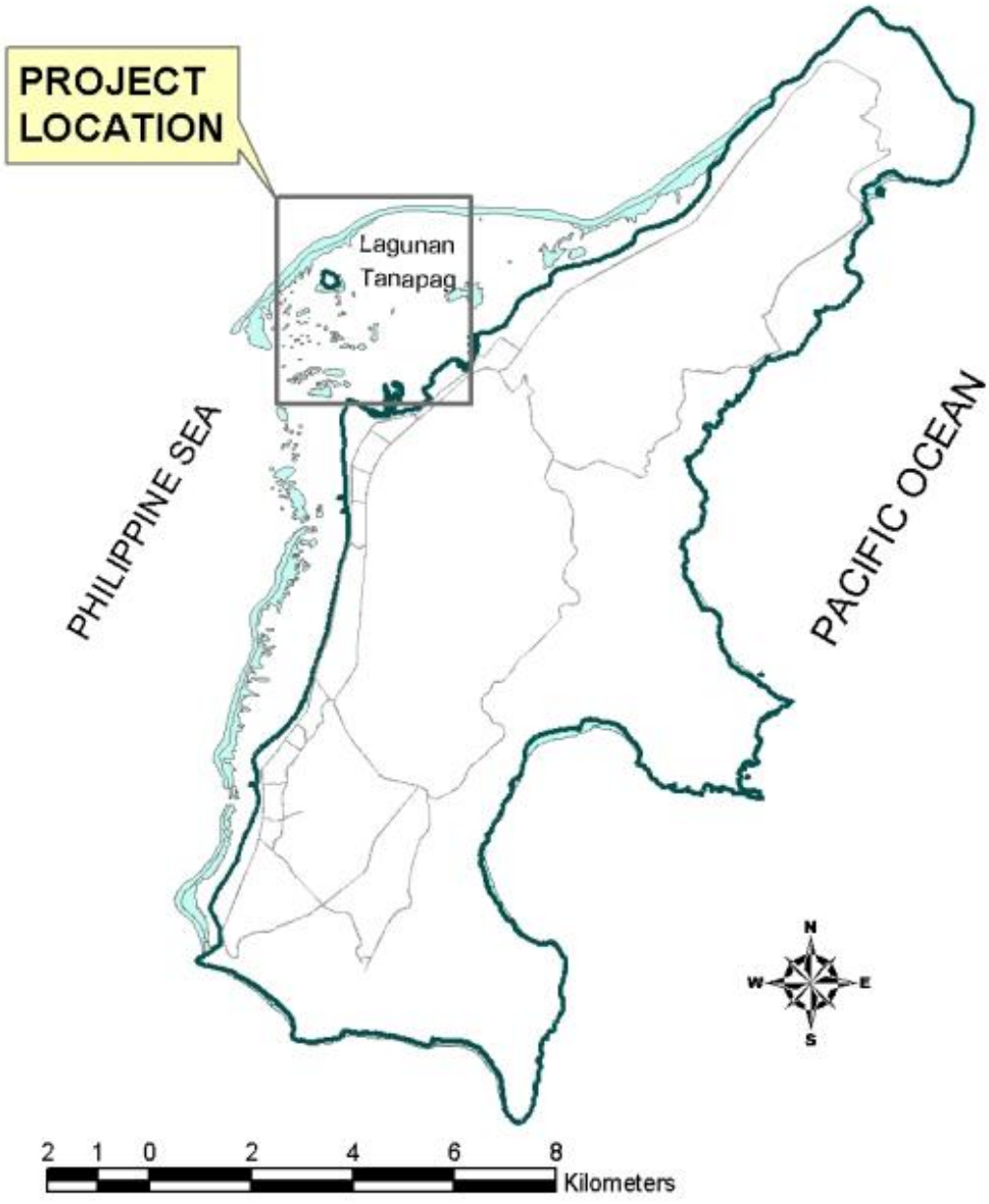
The municipal dump is of particular concern to the local community, and is perhaps the greatest environmental problem facing Saipan today. It is located at the edge of Saipan Harbor, within the district of Puerto Rico, and has served as the island's primary solid waste disposal site for over 40 years. It covers an area of around 20 acres and towers some 15-m above sea level at its highest point. Over the years, the Puerto Rico dump has spread beyond the initial confines of its natural shoreline boundaries, into the lagoon itself.

Records indicate that the dump was first initiated by the military shortly after World War II for the disposal of heavy scrap metal (e.g., junk tanks and vehicles) and unexploded ordnance devices (Ogden 1994). Since then, it has been a repository for every type of waste generated on island and is rumored to contain a plethora of toxic chemicals of both military and civilian origin (Ogden 1994). As the Puerto Rico dump was never designed for the safe disposal of hazardous wastes, local concerns over the mobilization of such chemicals into the abutting waters are understandable.

The effects of the Puerto Rico dump and other environmental perturbations noted above on the indigenous biota within the lagoon are largely unknown. Likewise, fundamental data describing the abundance and distribution of persistent and potentially toxic pollutants within the system is also lacking. Mindful of these shortcomings, a preliminary contaminant assessment of surface sediments within the lagoon was undertaken and is reported herein. The study is seen as an important first step towards achieving sustainable development of the resources within this environmentally sensitive area.

Sediments were the focus of this investigation because they act as major sinks for many of the more persistent and potentially toxic organic and inorganic chemicals introduced into the aquatic environment (Ingersoll 1995). Common examples of these include the heavy metals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs). The partitioning behavior of these contaminants is such that they tend to accumulate in sediments to

Figure 1: Map of Saipan



levels that are several orders of magnitude higher than in the surrounding water. Moreover, their deposition rates are generally related to their rates of input into the immediate area (Förstner 1990). The chemical analysis of sediments can, therefore, provide the investigator with a useful and convenient measure of environmental quality and is frequently incorporated into pollution monitoring surveys.

In the following study, we examined surficial sediments from 41 sites within Tanapag Lagoon. Chemical analysis was carried out to determine levels of the above three groups of pollutants. Some brief notes on the sources and significance of these contaminant groups are given below. More detailed comments on specific elements and compounds within each group are included in the discussion of results.

1. HEAVY METALS

Heavy metals are natural components of the lithosphere and are released into the environment via volcanism, weathering of rocks, and the activities of man. A comparison between natural and anthropogenic rates of metal mobilization from the earth's crust indicates the latter exceeds the former, by an order of magnitude or more, for several elements of environmental importance (e.g., Ag, Cd, Cr, Cu, Hg, Ni, Pb, Sn, Zn) (Bryan 1976, Baudo and Muntau 1990).

Primary industrial processes that release a variety of metals into waterways include mining, smelting and refining (Bryan 1976). In fact, almost all industrial processes that produce wastewater discharges are potential sources of heavy metals to the aquatic environment (Klein *et al.* 1974, Barnhart 1978). Domestic wastewater, sewage sludge, and urban runoff are also major heavy metal sources to rivers, estuaries and coastal waters (Connell and Miller 1984). Likewise, the burning of fossil fuels release considerable quantities of heavy metals that frequently account for a significant fraction of anthropogenically derived metal in nearshore sediments near urban and industrial growth centers (Bruland *et al*. 1974, Topping 1974). Ports, harbors, marinas and mooring sites, are also subjected to heavy metal inputs associated with recreational, commercial, and occasionally, military boating and shipping activities.

While a number of heavy metals are either essential for life (e.g. Cu, Zn) or highly desirable for optimum health (e.g. As, Cr, Ni, Sn) , there are those with no known biological function (e.g. Ag, Cd, Hg, Pb). However, irrespective of whether they are essential or not, all heavy metals form an important group of enzyme inhibitors when natural concentrations are exceeded (Bryan 1976). Thus, organisms living in or adjacent to sediments contaminated by heavy metals may suffer toxic effects that manifest themselves in the form of mass kills in grossly polluted situations (Carpenter 1924) to more subtle abnormal metabolic adjustments at the sub-lethal level (Tent 1987). In addition, bioaccumulation processes may be sufficient to diminish or destroy important food resources by making them unacceptable for human consumption.

In the following study we focused on the 10 heavy metals mentioned above. It can be seen from Table 1, that all of them have a diversity of uses in industry. As a consequence, they rank among the most common offenders from an environmental contamination standpoint. They also include several of the most toxic elements known to man.

Table 1

Past and Present Industrial Uses of the Heavy Metals Examined[a]

Metal	Uses of Metals and Compounds[b]
Arsenic	Component of pesticides; wood preservative; alloys; semi-conductors; medicines; glass and enamels.
Cadmium	Electroplating (anticorrosion coatings); thermoplastic stabilizers, e.g. in PVC; Ni-Cd batteries; alloys; solders; catalysts; engraving; semi-
conductors; biocides	TV tube phosphors; pigments in paints and plastics; glass ceramics;
Chromium	Metallurgy—ferrochromium alloys; refractory bricks; electroplating; industrial dyes; ink; tanning; paint; wood preservative; glass making;
cement	production.
Copper	Electrical industry; alloys; e.g. brass; chemical catalyst; anti-fouling paint; algaecide; wood preservative.
Lead	Storage batteries; leaded gasoline; pigments; red lead paint; ammunition; solder; cable covering; anti-fouling paint; glazing; PVC stabilizers.
Mercury	Chlorine production; electrical apparatus; anti-mildew paint; instruments; catalyst e.g. for PVC and acetaldehyde production; pesticides;
preservatives;	pharmaceuticals; dentistry; anti-fouling paint.
Nickel	Metallurgy—steel and other alloys; electroplating; catalyst; rechargeable Ni-Cd batteries.
Silver	Photography; electric conductors; sterling ware; solders; coinage; electroplating; catalyst; batteries; food and beverage processing.
Tin	Tinplate; solder; bronze; white metal; chemical reducing agent;
fungicide—	triphenyl tin acetate; anti-fouling paint—tributyl tin.
Zinc	Zinc based alloys; brass and bronze; galvanizing; rolled zinc; paints; batteries; rubber; sacrificial anodes on marine water craft.

[a] from Bryan (1976), Förstner and Wittmann (1981), Moore (1991), Bryan and Langston (1992)
[b] importance generally decreasing from left to right.

2. POLYCHLORINATED BIPHENYLS (PCBS)

Polychlorinated biphenyls (PCBs) are man-made chemicals that were first described in the literature over a century ago (Schmidt and Shultz 1881). They have the empirical formula $C_{12}H_{10-n}Cl_n$ (n = 1-10) of which there are 209 possible combinations (congeners) divided into nine isomeric groups or homologues (Cl_1-Cl_9) and decachlorobiphenyl (Cl_{10}) (see Fig. 2).

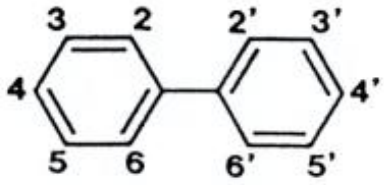
PCBs were first produced on a commercial level in 1929 (Hubbard 1964) and were used extensively in industry until the late 1970's when production ceased in many parts of the world following their discovery as global pollutants. Until that time however, they were widely used for a variety of industrial purposes including heat transfer fluids, hydraulic fluids, cutting oils, lubricants for use at high temperature and pressure, flame retardants, plasticizers, adhesives, inks, and dielectric fluids for use in capacitors and transformers.

The unusual industrial versatility of PCBs was related to their physical and chemical properties, namely their high electrical resistance, low vapor pressure and water solubility, compatibility with organic materials, and their thermal and chemical stability (Hutzinger *et al.* 1974). Unfortunately these very same properties, coupled with their widespread use and improper disposal, have resulted in the contamination by PCBs of every component of the global ecosystem (Mullin *et al.* 1984, Atlas *et al.* 1986, Tanabe and Tatsukawa 1986).

Routes of entry of PCBs into the aquatic environment are many and varied. The weathering and incineration of consumer goods containing PCBs, releases these compounds into the atmosphere where they may be dispersed far and wide, either as aerosols or associated with airborne particulates (Atlas *et al.* 1986). Leakages of contaminated lubricants, hydraulic fluids, heat transfer fluids, and dielectric fluids may be carried into nearshore waters in rivers and streams (Bopp *et al.* 1981), in urban runoff (Murphy and Carleo 1978) and in domestic and industrial wastewater discharges (Connell and Miller 1984). Other direct sources include dumped sewage sludge (West and Hatcher 1980) and anti-fouling paints containing PCB (Jensen *et al.* 1972). Once in the aquatic environment, PCBs, by virtue of their low water solubility, quickly become associated with particulate material and ultimately end up in the bottom sediments.

In the U.S., PCBs were produced exclusively by Monsanto under the trade name 'Aroclor'. Commercial Aroclor mixtures contain between 21% and 68 % chlorine by weight depending upon the duration of the chlorination process. The last two digits of the numerical descriptor of each Aroclor indicate the chlorine content of that particular mixture. Thus, Aroclor 1242, Aroclor 1254, and Aroclor 1262, three of the most commonly produced technical mixtures, contain 42%, 54% and 62% chlorine by weight, respectively. The only exception to this rule is Aroclor 1016, a special formulation containing 42% chlorine by weight, but without the higher chlorinated components of Aroclor 1242 itself (Stout 1986).

Figure 2. Structure of PCB Showing Numbering in the Biphenyl Ring System and the Number of PCB Congeners Possible



Chlorine Substitution	Number of Possible Congeners
Mono-	3
Di-	12
Tri-	24
Tetra-	42
Penta-	46
Hexa-	42
Hepta-	24
Octa-	12
Nona-	3
Deca-	1
Total:	209

Although 209 different PCB congeners are theoretically possible, the reaction conditions of the commercial process favored specific substitution patterns. For example, 2,4,6-substitution of one or both phenyl rings was very rare whereas 2,4,5-substitution was common. Likewise, the ionic chlorination mechanism produced very little 3- and 3,5-substitution, and 3+0, 4+1, 5+1 and 5+2 substituted congeners (Ballschmiter *et al.* 1987).

At least 20 congeners have never been found in any technical PCB mixture (De Voogt *et al.* 1990) and only about 100 account for all the environmental contamination attributable to PCBs. Still fewer congeners are both prevalent and demonstrably toxic. In fact, if potential toxicity, persistence and relative abundance in the environment are used as criteria, the number of environmentally threatening PCB congeners reduces to about 36 (McFarland and Clarke 1989).

Early work with PCBs demonstrated that these hydrophobic compounds were readily accumulated in the fatty tissues of living organism, often reaching alarmingly high levels in predatory species at the head of food chains (Wasserman *et al.* 1979). Their immunosuppressive effect and ability to induce hepatic microsomal enzyme systems in fish, birds and mammals was also realized fairly early on (WHO 1976). Recent toxicological studies have shown that a few PCB congeners are sterically similar to 2,3,7,8-tetrachlorobenzo-*p*-dioxin (TCDD) and have the ability to induce aryl hydrocarbon metabolizing mixed function oxidases (MFOs). A consequence of this is that relatively nontoxic foreign compounds, e.g., certain PAHs, may be bioactivated within living cells to cytotoxic or genotoxic metabolites (McFarland and Clark 1989, De Voogt *et al.* 1990).

In the following study, congener-specific analysis was undertaken using high-resolution techniques. Emphasis was placed on 20 chlorobiphenyls of greatest environmental importance and included representatives from nine of the 10 different isomeric groups (i.e., Cl_2-Cl_{10}).

3. POLYCYCLIC AROMATIC HYDROCARBONS (PAHS)

Polycyclic aromatic hydrocarbons (PAH), or polynuclear aromatic hydrocarbons as they are sometimes called, are a group of hydrocarbons composed of two or more fused benzene rings. They are ubiquitous environmental contaminants derived mainly from anthropogenic inputs with minor contributions from natural sources (Law *et al.* 1997). True PAHs are those compounds containing only hydrogen and carbon atoms and are differentiated here from polycyclic aromatic compounds that contain other atoms such as nitrogen, oxygen and sulfur (McElroy *et al.* 1989).

While PAHs are synthesized by some bacteria, plants and fungi, and are released into the environment by natural processes such as forest and grass fires, and marine oil seeps, anthropogenic activity accounts for most of the PAH released into the environment and is largely associated with the transportation, utilization and incomplete combustion of fossil fuels (McElroy *et al.* 1989). As a consequence, most PAHs enter the marine environment in urban runoff, municipal and industrial waste discharges, in bilge and fuel oil leaks associated with day-to-day shipping operations, in oil spills from maritime accidents and collisions (petrogenic PAHs), and via atmospheric deposition of particulate bound PAH from the

burning of coal, oil, petroleum, wood and other organic materials (pyrogenic PAHs). Because of their hydrophobic nature, PAHs are rapidly scavenged out of the water column by suspended particulate material and deposited in the bottom sediments. The importance of sediments as reservoirs of PAH is well known (McElroy *et al.* 1989).

The fused polyaromatic ring system of PAHs renders them relatively resistant to biodegradation, although a wide variety of bacteria, fungi and algae residing in aquatic sediments are able to metabolize a number of them. Apparently, degradation occurs most rapidly at the sediment-water interface and proceeds very slowly under anaerobic conditions (Meador *et al.* 1995). As a general rule, the rapidity with which PAHs are degraded is inversely related to molecular weight (Readman *et al.* 1982). Thus, naphthalene, a relatively non-toxic, two-ringed PAH, is readily degraded in natural sediments whereas benzo(*a*)pyrene, a potent five-ringed member, is not (Cerniglia and Heitkamp 1989).

In recent years, concern over the presence of PAHs in the environment has increased because certain members of this important class of chemicals have proved to be carcinogenic to experimental animals and are considered a potential health risk to man (Cerniglia and Heitkamp 1989). In the aquatic environment, some of the higher molecular weight PAHs have been linked with liver neoplasms in bottom dwelling fish (Malins *et al.* 1988).

In the following study, we considered 16 common PAH compounds ranging in size from two to six fused aromatic rings. They included a number of compounds known to be carcinogenic and/or genotoxic.

MATERIALS & METHODS

1. SEDIMENT COLLECTION AND PREPARATION

Sediment samples were collected from 32 nearshore stations, along transect lines running approximately parallel to the coast, between Flores Point and Muchot Point (Fig. 3). Sites were ~300-m to ~500-m apart, reducing to ~100-m, or less, in the vicinity of known or suspected point sources of contamination. Sediments from nine outer lagoonal sites were collected along three equally spaced transect lines (~1400-m apart) running seaward toward the barrier reef, between the same geographical boundaries (Fig. 4). These sites were located approximately 500-m, 1250-m and 2250-m from the shore, or closest nearshore station, along each transect line. All sites were located using digital-orthophoto-imagery maps with reference to prominent landmarks, compass bearings on fixed points of reference, and GPS.

All sediment samples were taken to a depth of 15 cm using hand-held aluminum corers (5 x 30 cm). Three such sediment cores were collected for separate analysis from within a 3-m diameter circle at each station. The charged corers were sealed with Teflon lined, plastic end-caps, wrapped in aluminum foil, labeled, and stored on ice prior to being deep frozen for air transportation back to Guam.

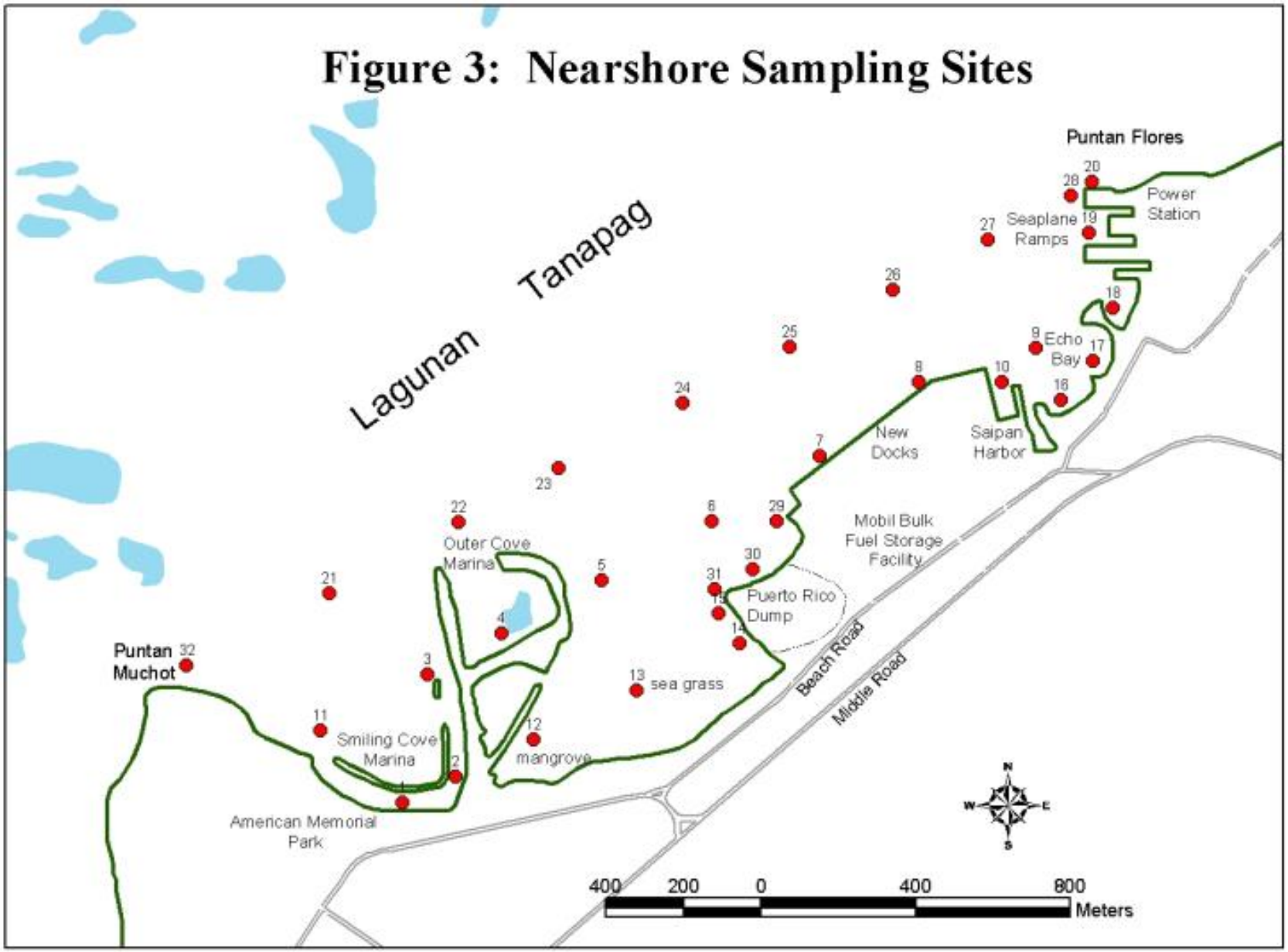
In the laboratory, the entire contents of each liner was dislodged into a glass bowl and thoroughly mixed with a polyethylene spatula following the removal of large rocks, shells and other such bulky materials. Samples for petrographic and particle size analysis were immediately set aside to dry at room temperature. Samples for total organic carbon (TOC) and heavy metal analysis were placed in acid cleaned, polyethylene vials and dried to constant weight at 60^{o}C while those for PCB and PAH analysis were air dried in the dark in shallow aluminum pans. Residual amounts of sediment samples were stored in pre-cleaned glass jars at -20^{o}C for further analysis if necessary.

Upon drying, sediments were disaggregated in non-contaminating containers with a heavy Teflon rod. Those samples for metal analysis were sieved through a 1 mm nylon sieve and stored in polyethylene vials at room temperature until required for analysis. Those for PCB and PAH analysis were sieved through a 1 mm stainless steel screen into clean glass vials for storage at -20^{o}C. Appropriate analytical methods for the above contaminants were adapted from the current SW-846 protocols developed by USEPA (1995) for the physical and chemical evaluation of solid waste, in addition to those recommended by the NOAA National Status and Trends Program for Marine Environmental Quality (NOAA 1993a-d). Appropriate quality control and quality assurance procedures including full procedural blanks, matrix spikes, and certified reference materials were built into the analytical protocols.

2. PETROGRAPHIC AND PARTICLE SIZE ANALYSIS

A general petrographic assessment of the collected sedimentary material was performed on air-dried samples and included Munsell Color, sorting and description of the dominant constituents. Visual observation, characterizations and measurements were made using a 10x Hastings Triplet monocular hand lens and a 5x-20x Bausch and Lomb binocular microscope. Grain size was estimated visually and later by a sieving program, the latter performed as

Figure 3: Nearshore Sampling Sites



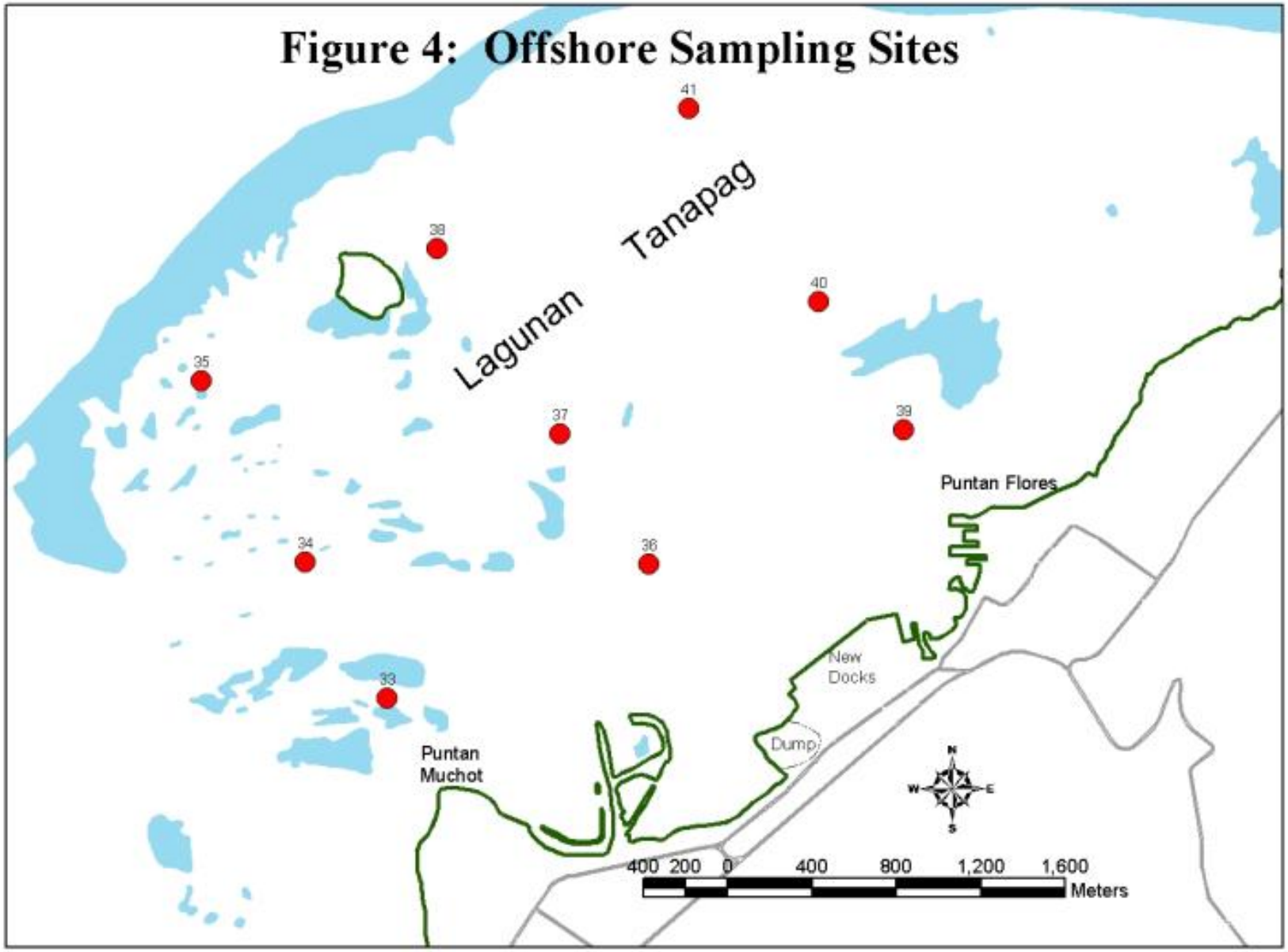


Figure 4: Offshore Sampling Sites
41
39
Tanapag
Lagunan
40
35
37
39
Puntan Flores
34
36
New
Docks
33
Dump
Puntan
Muchot
N
W
E
S
400 200 0 400 800 1,200 1,600
Meters

follows: Approximately 100 grams of air-dried sediment was gently crushed to break up desiccated clumps. The sample was then sieved for fifteen minutes through a sieve shaker column containing 10-, 18-, 35-, 60-, 120- and 230-mesh, 8-inch stainless-steel screens (U.S. Standard Series). This column produced the following seven size fractions:

- >2 mm (gravel)
- 1 mm to 2 mm (very coarse sand)
- 0.5 mm to 1 mm (coarse to very coarse sand)
- 0.25 mm to 0. 5 mm (medium to coarse sand)
- 0.125 mm to 0.25 mm (fine to medium sand)
- 63 μm to 0.125 mm (very fine to fine sand)
- <63 μm (silt and clay or "mud")

Color was estimated from comparisons with the standard Munsell soil color chart (Munsell, 1975). Munsell color notation is based on three parameters: hue, value and chroma. The symbol for hue is the letter abbreviation of a spectral color, e.g. Y for yellow, R for red, YR for yellow-red, etc., preceded by a number 1 to 10. Within each color, the hue becomes more yellow and less red as those numbers increase. Value numbers (darkness index) are designated as 5/, 6/ etc., and range for 0 for absolute black to 10 for absolute white. The notation for chroma (saturation index) consists of numbers ranging from 0 for neutral gray to 20 for most vivid colors.

The TOC content of each sediment sample was estimated following dichromate oxidation as described by Nelson and Sommers (1975).

3. HEAVY METAL ANALYSIS

The digestion of sediments for heavy metal analysis was accomplished by wet oxidation in concentrated hydrochloric and/or nitric acids. The extraction procedures were essentially similar to EPA method 3050A, designed specifically to release weakly to strongly bound metals in the sample without completely destroying the non-carbonate, mineral matrix of the sample. This method is particularly useful for identifying metal enrichment as a result of anthropogenic activities.

All reagents used were analytical grade and all glassware was acid-washed and deionized water rinsed prior to use. Standard stock solutions were purchased from a commercial supplier. Final analysis was carried out by atomic absorption spectroscopy (AAS). All analyses were performed in duplicate and were accompanied by appropriate method blanks and matrix spikes. Heavy metal recoveries from a soil certified standard reference material were within acceptable limits for all elements examined (see Table 2).

Adopted digestion and analytical procedures varied between metals as dictated by the physico-chemical properties of the elements themselves. A brief description of the different digestion and analytical methods employed is given below.

Table 2

Analysis of Standard Reference Materials

Analyte	Certified Value		This Study		
	Mean	Range	Mean	Range	
Metals (***PriorityPollutnT™/CLP Inorganic Soils*** **[Catalog Nº PPS-46; Lot Nº 242])**					
	µg/g dry wt.		µg/g dry wt.		n
Arsenic	58.6	41.1 – 76.1	57.5	51.3 – 63.8	5
Cadmium	185	143 – 228	195	183 – 208	5
Chromium	50.7	35.7 – 65.7	41.3	38.1 – 44.6	5
Copper	63.6	52.1 – 75.1	61.9	55.9 – 67.9	5
Lead	56.6	43.1 – 70.1	53.2	46.4 – 60.0	5
Mercury	1.29	0.83 – 1.74	1.19	0.96 – 1.42	5
Nickel	75.4	59.0 – 91.7	72.9	62.7 – 83.2	5
Silver	149	110 – 188	155	145 – 165	5
Tin	73.1	52.7 – 93.4	76.5	64.3 – 88.6	5
Zinc	69.6	51.1 – 88.1	64.8	58.2 – 71.4	5
PCBs (***RTC PCB in Soil*** **[Catalog Nº CRM911-050; Lot Nº J911])**					
	µg/g dry wt.		µg/g dry wt.		n
Aroclor 1254	1.34	0.61 - 2.07*	1.13	0.57 – 1.69	15
PAHs (***RTC PAH Contaminated Soil/Sediment*** **[Catalog Nº CRM104-100; Lot Nº CR12])**					
	µg/g dry wt.		µg/g dry wt.		n
Naphthalene	0.77	0.0 - 1.57*	nc	0.0 – 0.48	10
Acenaphthylene	1.21	0.0 - 2.98	0.05	0.0 – 0.13	10
Acenaphthene	0.77	0.27 - 1.28	0.38	0.0 – 1.48	10
Fluorene	0.65	0.25 - 1.05	1.37	0.0 – 4.07	10
Phenanthrene	5.79	2.11 -9.48	3.90	1.74 – 6.05	10
Anthracene	1.44	0.08 - 2.80	2.26	0.33 – 4.18	10
Fluoranthene	24.6	4.53 - 44.6	16.3	10.7 – 21.8	10
Pyrene	15.0	0.0 - 30.7	9.32	2.50 – 16.2	10
Benzo(*a*)anthracene	7.98	2.09 - 13.9	3.48	2.31 – 4.64	10
Chrysene	8.60	3.39 - 13.8	6.59	0.64 – 12.5	10
Benzo(b)fluoranthene	(9.69)	none given	4.87	3.52 – 6.23	10
Benzo(k)fluoranthene	(5.10)	none given	2.62	1.90 – 3.35	10
Benzo(a)pyrene	5.09	1.56 - 8.63	3.42	1.13 – 5.71	10
Benzo(ghi)perylene	3.58	0.0 - 8.08	3.89	2.10 – 5.68	10
Indeno(1,2,3,-cd)pyrene	4.46	0.0 - 9.09	2.00	1.24 – 2.77	10
Dibenzo(a,h)anthracene	(1.55)	none given	5.77	3.42 – 8.12	10

* Certificate of analysis for PCB and PAH standard reference materials gives only the 95% prediction interval about the certified mean.
PAH values listed in parentheses are not certified and are listed for information only.

3.1 Mercury:

Approximately 2 g of dried sediment was accurately weighed into a 125-ml glass Erlenmeyer flask followed by the slow addition of 15 ml of concentrated nitric acid. After all effervescence had subsided, the flask was capped with a Teflon stopper and heated in a boiling water bath for 3 h. After cooling, the contents of each flask was diluted to 75 ml with deionized water, thoroughly mixed and set aside to allow residual particulates to settle out. The solutions were then decanted into clean glass vials and stored at $4^{o}C$ until required for analysis.

Analysis was performed by flameless (cold vapor) AAS and involved the generation of metallic mercury vapor (Hg^{o}) following reduction with 2% stannous chloride (Hatch and Ott 1968). The process was facilitated using the syringe technique described by Stainton (1971). Calibration standards (5-20 ng/l) were made up in 20% nitric acid containing 0.05% potassium dichromate as a preservative (Feldman 1974).

3.2 Arsenic:

The digestion procedure was identical to that described above for mercury. However, analysis utilized the hydride generation technique whereby inorganic arsenic is converted to arsine gas (AsH_3) by reduction with 3% sodium borohydride in 1% sodium hydroxide. All calibration standards (1-10 μg/l) and sample dilutions were made up in 10% nitric acid.

3.3 Tin:

The hydride generation technique was also used for tin analysis. However, special precautions were necessary to minimize the problems known to be associated with this element, e.g. pH dependency, poor reproducibility and severe metal interferences (Beach 1992). To this end, sediment samples (~2 g) were initially digested with concentrated hydrochloric acid (~8 ml) to decompose the carbonates present. Following overnight evaporation to dryness on a hot-plate at $100^{o}C$, the samples were further digested in 10 ml of aqua regia (3:1 HCl and HNO_3) at $100^{o}C$ for 3 h. Upon cooling, sample volumes were adjusted to 100 ml with deionized water.

The generation of gaseous stannane (SnH_3) was achieved with 3% sodium borohydride in 0.5% sodium hydroxide solution. Matrix interferences were minimized by analyzing small sample volumes (1 ml) in 5 ml of saturated boric acid (~55 g/l) together with 0.5 ml of 10% nitric acid. For smaller sample volumes, additional amounts of dilute acid were added as necessary to minimize relative changes in pH. Calibration standards (5-20 μg/l) were made up in saturated boric acid solution on a daily basis.

3.4 All Other Metals:

Approximately 2 g of the dried sediment samples were weighed into 125 ml Erlenmeyer glass flasks, loosely capped with a Teflon stopper and digested with approximately 15 ml of concentrated nitric acid at $110\text{-}135^{o}C$ for 2 days. The digests were then evaporated to dryness and redissolved in 20 ml of 10% nitric acid with gentle warming. The contents of each flask was thoroughly mixed and allowed to stand for several minutes prior to analysis to permit settlement of residual particulates.

Analysis was performed by flame AAS, the contents of each flask being aspirated directly into the instrument. Corrections for non-atomic absorption were made simultaneously by the instrument using a deuterium continuum lamp. All calibration standards (0.2-10 mg/l) were made up in 10% nitric acid from a commercial mixed stock solution (100 mg/l of each metal).

4. POLYCHLORINATED BIPHENYL ANALYSIS:

Approximately 1 g of air-dried sediment was accurately weighed into a 10 ml Teflon centrifuge tube along with 0.25 g of activated copper to remove elemental sulfur (EPA method 3665A). The samples were extracted with 3 ml of n-hexane in a commercial microwave oven (700 watt-high energy setting) for sequential periods of 60, 30 and 15 seconds (see Ganzler *et al*. 1986). A rotating turntable insured homogeneous distribution of microwave radiation within the unit. Each tube was touched against a Vortex Genie for 5 seconds between heating cycles to ensure the extract was thoroughly mixed. After standing overnight the samples were vortexed again before centrifuging at 2500 rpm for 5 minutes.

The clear extracts were decanted into 3 ml graduated glass centrifuge tubes, placed in a warm water bath (45^{o}C) and reduced in volume (~0.25 ml) under a gentle stream of nitrogen. Cleanup was accomplished with 60-100 mesh Florisil, activated and stored at 110^{o}C. The Florisil columns (~0.25 g) were made up in disposable glass Pasteur pipettes (see EPA method 3620B) and rinsed with 2 x 1 ml volumes of hexane prior to use. Approximately 0.25 ml of hexane was used to complete the transfer process. Each column was then eluted with hexane under gentle pressure. The PCB fraction was recovered in the first 1.5 ml of hexane through the column. The cleaned up extract was reduced in volume to 0.1 ml and transferred to a clean, glass auto-sampler vial fitted with a small-volume (250 µl) insert.

Analysis was carried out using a Varian 3400CX Gas Chromatograph (GC) equipped with an electron capture detector and a 60 m x 0.25 mm i.d. fused silica MDN-5S, polymethyl-5% phenyl-siloxane (0.25µm film thickness) capillary column (Supelco). Gas flows (nitrogen) through the column and detector were 1 ml/min and 30 ml/min respectively. The initial column temperature was maintained at 50^{o}C for the first minute of each run. It was then ramped to 150^{o}C at 30^{o}C/min, then to 280^{o}C at 25^{o}C/min, where it was held for 20 min to give a total run time of 76 min. Both the injector and detector temperatures were held constant at 280^{o}C and 310^{o}C respectively.

PCB quantification was accomplished using a 20-congener calibration standard representing PCB homologues Cl_2 to Cl_{10} (NOAA 1993a). The congeners, listed in Table 3, were selected on the basis of their potential toxicity, bioaccumulation and/or frequency of occurrence in environmental samples. Complete chromatographic separation of all congeners was achieved, although several of them are known to co-elute with other PCB congeners present in commercial PCB mixtures (Table 3).

All calculations were based on peak area comparisons of components sharing identical retention times in both sample and standard. The surrogate, PCB 103 (100 pg/µl), and internal standard, pentachloronitrobenzene (250 pg/µl), were respectively added to the samples before (50 µl) and after (10 µl) extraction and cleanup to account for variations in method recoveries and automated GC injection efficiencies.

Table 3

PCB Congeners in Calibration Standard used to Quantify PCB Homologues in Surface Sediment Samples from Tanapag Lagoon, Saipan

PCB Congeners in Calibration Standard			Co-eluting PCB Congeners		
IUPAC[1] Number	Chlorine Atoms/mol.	Structural Arrangement	IUPAC Number	Chlorine Atoms/mol.	Structural Arrangement
8[a] (A1221/1242)	2	2,4’	5[a]	2	2,3
18[b] (A1016/1242)	3	2,2’,5	15[a] (A1221/1242)	2	4,4’
28[b] (A1016/1242)	3	2,4,4’	31[a] (A1242)	3	2,4’,5
44[b] (A1242/1254)	4	2,2’,3,5’	none		
52[b] (A1242/1254)	4	2,2’,5,5’	43[a]	4	2,2’,3,5
66[b] (A1254)	4	2,3’,4,4’	80[a] 95	4 5	3,3’,5,5’ 2,2’,3,5’,6
77[a c]	4	3,3’,4,4’	154[a]	6	2,2’,4,4’5,6
101[b] (A1254/1260)	5	2,2’,4,5,5’	79[a]	4	3,3’,4,5’
105[b]	5	2,3,3’,4,4’	none		
118[b] (A1254/1260)	5	2,3’,4,4’,5	106[a]	5	2, 3,3’,4,5
126[a c]	5	3,3’,4,4’,5	129	6	2,2’,3,3’,4,5’
128[b]	6	2,2’,3,3’,4,4’	none		
138[b] (A1254/1260)	6	2,2’,3,4,4’,5’	158[a]	6	2,3,3’,4,4’,6
153[b] (A1254/1260)	6	2,2’,4,4’,5,5’	none		
170[b] (A1260)	7	2,2’,3,3’,4,4’,5	none		
180[b] (A1260)	7	2,2’,3,4,4’,5,5’	none		
187[b]	7	2,2’,3,4’,5,5’,6	159[a] 182[a]	6 7	2,3,3’,4,5,5’ 2,2’,3,4,4’,5,6’
195[a]	8	2,2’,3,3’,4,4’,5,6	none		
206[a]	9	2,2’,3,3’,4,4’,5,5’,6	none		
209[a]	10	2,2’,3,3’,4,4’,5,5’,6,6’	none		

[a] not common (<10% occurrence) in environmental samples (from McFarland and Clarke 1989).
[b] major component of environmental mixtures (from NOAA 1993a); [c] highly toxic planar PCB. [1] International Union of Pure & Applied Chemistry.
Labels in parentheses indicate dominant components (≥ 2% by wt.) of the commercial PCB mixtures: Aroclors 1016, 1221, 1242, 1254 & 1260 (from De Voogt *et al.* 1990)
Compilation of chromatographic data from Ballschmiter and Zell (1980); Holden (1986); Ballschmiter *et al.* (1987); De Voogt *et al.* (1990); Rebbert *et al.* (1992); Wise *et al.* (1993); Schantz *et al.* (1993); Bright *et al.* (1995), using 60 m DB-5 (or equivalent) high resolution GC columns.

Full procedural blanks were periodically carried out in accordance with standard QA/QC protocols.

PCB homologue concentrations were estimated from the data by summing values obtained for congeners of similar chlorine content. The "total" PCB content of the sample ($\sum_{20}$PCB) was calculated from the sum of the individual congener data. Undetectable congeners were set to zero for this process. PCB recoveries (as Aroclor 1254) from the standard reference material employed were within acceptable limits of the certified mean (Table 2). Method detection limits for individual chlorobiphenyls in the standard mix ranged from 0.03-0.49 ng/g.

5. POLYCYCLIC AROMATIC HYDROCARBON ANALYSIS:

Sediment samples (1-1.5 g) were subjected to microwave extraction in the same way as described above for PCB, except that methylene chloride (3 ml) was used as the extracting solvent instead of hexane, and 50 µl of deuterated acenaphthene and benzo[a]pyrene (20 ng/µl) were used as the surrogate standards. Also, the heating cycles were of shorter duration (30, 15 and 15 seconds) owing to the lower boiling point of methylene chloride. Following centrifugation, the samples were decanted into 10 ml graduated glass centrifuge tubes, placed in a warm water bath (~45^{o}C) and reduced in volume (~0.75 ml). Solvent exchange into hexane (~1.25 ml) and further reduction in volume (~0.5 ml) was necessary prior to cleanup on silica gel (EPA method 3630C). The silica gel (230-400 mesh) was activated at 700^{o}C and stored at 110^{o}C prior to use.

A slurry of silica gel in methylene chloride was loaded into a series of disposable glass Pasteur pipettes. Gentle tapping facilitated settling and even packing of the columns which, on completion, were 4 cm in length and contained ~0.5 g of adsorbent. The columns were pre-eluted with 2 x 1-ml volumes of hexane to remove the methylene chloride and kept under hexane until required. Laboratory temperatures were maintained at or below 27^{o}C to prevent methylene chloride vapor pockets from forming in the columns during the preparation process.

The sample extracts (~0.5 ml) were transferred to the columns using clean glass pipettes and allowed to drain into the adsorbent. Approximately 0.25 ml of hexane was used to rinse each centrifuge tube and complete the transfer process. The columns were eluted with 1 ml of hexane to remove PCBs, sulfur, and aliphatic hydrocarbons, followed by 2 ml of methylene chloride/pentane (2:3, v/v) to recover the PAHs.

After cleanup, the eluates were reduced in volume (~0.5 ml) prior to solvent exchange with acetonitrile (1.0 ml). Further reduction in volume (0.1 ml) preceded transfer to clean, glass auto-sampler vials with small volume (250 µl) inserts. Finally, 10 µl of the internal standard, decafluorobiphenyl (500 ng/µl), was added to each vial before chromatographic analysis. Full procedural blanks were periodically carried out in accordance with standard QA/QC protocols.

Analysis was carried out by high performance liquid chromatography (HPLC) using a fluorescence/UV (diode array) detector system and a 10 cm x 4.6 mm i.d., stainless steel, LC-PAH column (Supelco) containing a porous silica stationary phase (3 µm particle size).

Following sample injection, isocratic elution with acetonitrile/water (4:6, v/v) occurred for the first three seconds followed by a linear gradient to 100% acetonitrile over the next 10 minutes. Elution with 100% acetonitrile continued for a further 5 min before the run was terminated. The solvent flow rate through the column was held constant at 1.8 ml/min.

Quantification with the more sensitive fluorescence detector was achieved with excitation at 280 nm and emission at 380 nm. The diode array provided a synchronous absorption scan from 190-357 nm, with a wavelength difference of 4 nm, and was used primarily for confirmatory analysis at the higher levels of detection.

The calibration standards were made up containing the 16 PAHs recommended by U.S. EPA (see EPA method 8310). These are listed in Table 4 together with their molecular weights and structural identities. Method detection limits with the fluorescence detector were as follows: naphthalene (20 ng/g), acenaphthene (6 ng/g), fluorene (14 ng/g), phenanthrene (12 ng/g), anthracene (6 ng/g), fluoranthene (8 ng/g), pyrene (3 ng/g), benzo(*a*)anthracene (1 ng/g), chrysene (4 ng/g), benzo(*b*)fluoranthene (8 ng/g), benzo(*k*)fluoranthene (8 ng/g), benzo(*a*)pyrene (11 ng/g), dibenzo(*a,h*)anthracene (14 ng/g), and benzo(*g,h,i*)perylene (30 ng/g). Detection limits for the non-fluorescing PAHs, acenaphthylene and indenol(*1,2,3-cd*)pyrene, were 5 ng/g and 11 ng/g respectively, using the UV diode array detector.

All calculations were based on peak area comparisons of components sharing identical retention times in both sample and standard. From these data, the "total" PAH content of the sample ($\sum_{16}$PAH) was calculated. Undetectable congeners were set to zero for this process. PAH recoveries from the standard reference material employed were within acceptable limits of the certified means (Table 2).

6. PRESENTATION OF DATA

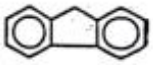
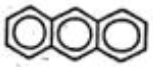
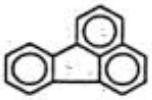
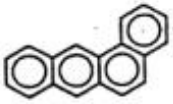
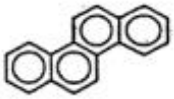
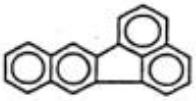
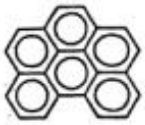
All the chemical data accumulated hitherto has been tabulated separately for each category of contaminant. This is intended to facilitate quick reference to the concentration and distribution of contaminant levels within and between sites monitored within Tanapag Lagoon. All mean values refer to arithmetic means unless stated otherwise.

The tabulated data are preceded by notes on contaminant occurrence in the sediments examined and to possible contributing sources. Comparisons are also made with levels reported in the literature for marine and estuarine sediments from elsewhere. Much of this published data has been tabulated for easy reference and appears in Tables 5-7 at the end of the current section. From such comparisons a preliminary appraisal of the current situation within the lagoon has been made.

Frequency distribution histograms of sediment particle size ranges are presented in Appendix A. Isoconcentration contour maps for TOC and each of the contaminants examined are included in Appendices B-E. These were generated with ArcView 8.1 GIS and Spatial Analyst extension using 'Spline' as the interpolation tool. The maps provide an immediate visual assessment of contaminant distribution and abundance within the study area including the identification and delineation of 'hot spots' and concentration gradients.

Table 4

Unsubstituted PAHs in Calibration Standard used to Quantify PAH Levels in Surface Sediments from Tanapag Lagoon, Saipan

IUPAC[1] Nomenclature	Molecular Wt.	Structural Identity
Naphthalene	128.19	
Acenaphthylene	152.21	
Acenaphthene	154.21	
Fluorene	166.23	
Phenanthrene	178.24	
Anthracene	178.24	
Fluoranthene	202.26	
Pyrene*	202.26	
Benzo(a)anthracene*	228.30	
Chrysene*	228.30	
Benzo(b)fluoranthene*	252.32	
Benzo(k)fluoranthene*	252.32	
Benzo(a)pyrene*	252.32	
Benzo(ghi)perylene	276.34	
Indeno(1,2,3-cd)pyrene*	276.34	
Dibenzo(a,h)anthracene*	278.36	

[1] International Union of Pure and Applied Chemistry; * = known carcinogen

It is perhaps pertinent to note here that previous contaminant data for Saipan sediments is limited to one unpublished study undertaken in 1987 by the Division of Environmental Quality (DEQ) in cooperation with the US EPA (Region IX). On this particular occasion, sediments were collected from six sites around the municipal dump and analyzed for various contaminants including heavy metals and PCBs. This study, identified hereafter as 'DEQ (1987),' is referred to extensively in the ensuing discussions.

Table 5

Heavy Metal Concentrations (µg/g dry wt.) in Marine and Estuarine Sediments from Other Areas of the World

Location	Site	Depth (cm)	Fraction	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Sn	Zn	Reference
Saipan	Puerto Rico Dump (foreshore)	surface	bulk sediment	ND-2.3	2.4-8.6	ND-2.7	6.3-39.3	4.8-68.8	0.125-0.181	ND-16.1	5.8-201	-	15.8-324	DEQ (1987)
Saipan	Baker Bay Area, Tanapag Lagoon	subsurface	bulk sediment	ND	ND	ND	6	ND	ND	ND	ND-35	ND	20-29	Unitek (1993)
Saipan	Tanapag Lagoon (nearshore)	0-15	<1 mm	<0.1-0.28	1.33-10.4	<0.1-0.58	1.4-9.67	0.22-27.8	0.012-0.101	<0.2-5.06	<0.4-40.6	0.08-36.1	1.63-127	This Study
Saipan	Tanapag Lagoon (>500 m offshore)	0-15	<1 mm	all <0.1	0.69-1.57	all <0.1	1.06-2.43	<0.1-2.43	0.003-0.016	<0.2-0.36	<0.4-1.2	<0.02-0.24	<0.02-2.09	This Study
Guam	Agana Boat Basin	0-30	<1 mm	all <0.2	1.00-6.00	all <0.2	3.61-28.8	0.56-74.7	0.005-0.107	1.01-19.9	1.99-70.7	<0.1-6.61	3.44-104	Denton *et al.* 1997
Guam	Outer Apra Harbor	0-30	<1 mm	all <0.2	1.16-10.7	0.27-2.18	3.59-17.1	1.00-142	0.011-0.403	<0.2-14.0	<1.00-96.3	<0.1-7.37	2.3-461	Denton *et al.* 1997
Guam	Outer Apra Harbor (Echo Wharf)	surface	bulk sediment	<0.23	<0.99	<0.17	16-18	--	--	--	17	<0.66	--	US Navy (PWC) 1997, unpublished
Guam	Outer Apra Harbor (SRF Industrial)	surface	>65µm	--	--	2.0-4.3	--	30-123	ND-0.43	9.3-21.5	53-129	ND-33	82-3548	Belt Collins Hawaii 1994
Guam	Outer Apra Harbor (SRF Industrial)	surface	<65µm	--	--	3.5-6.0	--	320-1435	0.08-4.6	22.6-51.2	142-395	31-143	234-856	Belt Collins Hawaii 1994
Guam	Outer Apra Harbor	0-10	bulk sediment	--	--	1.88-3.12	62.0-113	30.1-211	ND-0.99	10.3-21.4	50.5-132	200-535	34.1-223	Belt Collins Hawaii 1993
Guam	Outer Apra Harbor	70-80	bulk sediment	--	--	2.02-2.88	59.8-126	21.6-238	ND-1.74	8.8-190	45.9-138	184-522	16.2-236	Belt Collins Hawaii 1993
Guam	Inner Apra Harbor	0-10	bulk sediment	--	--	1.93-3.44	64.0-129	41.0-255	0.14-1.7	7.6-36.9	42.8-139	148-1055	51.9-279	Belt Collins Hawaii 1993
Guam	Inner Apra Harbor	70-80	bulk sediment	--	--	2.59-3.76	99.4-112	32.2-176	0.79-2.4	24.1-40.6	54.3-123	726-967	29.5-208	Belt Collins Hawaii 1993
Guam	Inner Apra Harbor (USS Proteus Site)	surface	bulk sediment	--	6.0*	--	34.0*	26.0*	0.36*	7.35*	132*	--	72.2*	Ogden 1996
Guam	Agate Marina	0-30	<1 mm	all <0.2	5.31-9.78	all <0.2	9.85-30.7	2.63-10.3	0.004-0.006	12.3-30.2	all <0.6	all <0.1	4.42-11.2	Denton *et al.* 1997
Guam	Merizo Pier	0-30	<1 mm	all<0.2	2.87-5.19	all <0.2	13.5-39.5	4.34-123	0.008-0.032	14.0-71.0	<1.00-27.1	<0.1-7.06	9.58-130	Denton *et al.* 1997
Philippines	Honda Bay, Palawan	surface	bulk sediment	--	--	--	--	--	0.031-570	--	--	--	--	Benoit *et al.* 1994
Hong Kong	Pearl River Estuary, Macao	surface	bulk sediment	--	12.6-34.6	0.36-8.29	4.0-38.6	--	--	--	14.5-66.7	--	--	Ferreira *et al.* 1996
Malaysia	Bintulu	surface	<500 µm	--	--	2.1-4.8	--	8.5-12.0	--	--	10.3-35.6	--	40-90	Ismail 1993
Taiwan	Kaohsiung Harbor	surface	<63 µm	--	--	0.1-4.64	--	37.9-505	--	--	34.3-138	--	--	Chen & Wu 1995
Australia-PNG	Torres Strait	surface	bulk sediment	--	--	0.05-0.09	--	--	--	--	--	--	--	Gladstone & Dight 1994
Australia-PNG	Torres Strait	surface	<100 µm	--	--	--	--	2-17	--	--	--	--	40-53	Brady *et al.* 1994

* only maximum concentration reported; ND = not detectable; dashes indicate no data

Table 5 (cont.)

Heavy Metal Concentrations (µg/g dry wt.) in Marine and Estuarine Sediments from Other Areas of the World

Location	Site	Depth (cm)	Fraction	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Sn	Zn	Reference
Australia	Halifax Bay, N. Queensland	surface	bulk sediment	--	--	--	--	--	0.004-0.016	--	--	--	--	Knauer 1976
Australia	Halifax Bay, N. Queensland	surface	bulk sediment	--	--	--	--	6-9.4	--	8.8-14	14-22	--	29-44	Knauer 1977
Australia	Sydney Coast	50-80	bulk sediment	--	9-14	0.1	6-14	5-25	0.05-0.45	3-9	10-90	--	30-90	Schneider & Davey 1995
Australia	Ninety Mile Beach, VIC	0-5	<63 µm	--	--	0.07-1.54	14.6-75.6	1.1-35.0	<0.05-1.20	5.4-20.5	0.1-44.3	--	--	Haynes *et al.* 1995
Fiji	Great Astrolabe Lagoon	surface	<100 µm	--	0.27-12.4	1.2-3.3	17-36	22-88	0.02-90.2	4-25	3-17	--	10-164	Morrison *et al.* 1997
Fiji	Suva Harbor (near dumpsite)	surface	<63 µm	--	0.7-45	0.74-3.04	16-106	59-306	0.2-1.34	17-38	19.3-272	--	88-670	Naidu & Morrison 1994
Fiji	Suva Harbor (near battery factory)	surface	<63 µm	--	--	0.8-198	11-80	64-1151	--	--	0.21-26.6 (%)	--	250-1063	Naidu & Morrison 1994
Antarctic	8 island sites	surface	<500 µm	--	--	4.0-22	2.4-66	3.9-106	--	5.5-92.2	22.5-128	--	28.6-271	Alam & Sadiq 1993
Arctic	Beaufort Sea	surface	bulk sediment	--	--	--	--	16-22	--	--	--	--	--	Sweeney & Naidu 1989
UK	Cardiff, Bristol Channel	surface	bulk sediment	--	--	--	--	40-160	--	--	160-300	--	350-1000	French 1993
UK	19 estuaries	surface	<100 µm	0.13-4.13	4.8-1740	0.13-2.17	24-207	7-2398	0.03-3.01	14-58	20-2753	0.4-161	46-2821	Bryan & Langston 1992
UK	Thames Estuary	surface	<63 µm	2.2-22	14-45	0.7-9.8	36-240	24-348	0.2-5.7	21-157	63-1634	13-69	115-1050	Attrill & Thomes 1995
England & Wales	Various coastal sites	surface	<2 mm	--	--	--	<5-100	--	--	--	3.1-110	--	3-153	Rowlatt & Lovell 1994
S.W. England	Various estuaries	surface	<100 µm	--	11-3732	--	--	--	--	--	--	--	--	Langston 1984
Irish Sea	39 stations in NW	surface	<63 µm	--	--	--	19.4-74.9	8.2-26.9	0.048-0.126	11.3-48.4	17.6-62.3	--	73.2-210	Service *et al.* 1996
N. Ireland	Strangford Lough	surface	<63 µm	--	--	--	67-199	--	0.07-0.29	30.8-62	30.2-65.8	--	82.6-141.6	Service 1993
S. Ireland	Cork Harbor	surface	<2 mm	<0.05	--	<0.05	3.4-17.2	9.7-18.8	0.053-0.24	11.5-15.8	17.9-44.2	--	65-1961	Berrow 1991
Denmark	Nissum Broad, Jutland	0-5	bulk sediment	--	--	--	--	--	0.58->2.27	--	--	--	--	Andersen 1992
Denmark	Nissum Broad, Jutland	5-15	bulk sediment	--	--	--	--	--	0.119->5.49	--	--	--	--	Andersen 1992
Denmark	Krikvig, Jutland	0-15	bulk sediment	--	--	--	--	--	0.005-0.016	--	--	--	--	Andersen 1992
Sweden	Baltic Sea	surface	bulk sediment	--	--	--	--	23-61	--	--	21-69	--	--	Blomqvist *et al.* 1992
Poland	Puck Bay, Baltic Sea	surface	<2 mm	11-27	--	0.7-5.7	120-235	49-122	--	--	53-330	--	195-960	Szefer *et al.* 1995

dashes indicate no data

Table 5 (cont.)

Heavy Metal Concentrations (µg/g dry wt.) in Marine and Estuarine Sediments from Other Areas of the World

Location	Site	Depth (cm)	Fraction	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Sn	Zn	Reference
Italy	N. Tyrrhenian Sea NW	surface	bulk sediment	--	--	1.45-5.04	--	17.1-39.7	--	--	24.2-44.1	--	39.5-63.3	Fabiano *et al.* 1994
Italy	Bay of Naples	0-3	bulk sediment	--	--	--	--	--	0.09-17.5	--	--	--	--	Baldi *et al.* 1983
Italy	Various coastal sites	surface	<63 µm	--	--	0.05-0.58	--	--	0.04-2.03	--	9-172	--	--	Giordano *et al.* 1992
Italy	Olbia Bay	surface	<2 mm-65 µm	--	--	0.2-10.5	3-27	2-38	--	--	0.5-56	--	14-153	Schintu *et al.* 1991
Italy	Venice Lagoon	surface	<5 mm	--	--	0.23-1.92	41-106	7.8-32	--	14-20	17-40	--	77-306	Sfriso *et al.* 1995
N. Spain	Bidasoa Estuary	surface	<100 µm	0.7-2.4	--	0.4-1.5	32-79	36-221	--	22-44	70-298	--	219-736	Saiz-Salinas *et al.* 1996
Spain	Pasajes Harbour	3-5	bulk sediment	--	--	1.1-14.9	61-299	156-2140	--	34-162	124-854	--	420-5620	Legorburu & Canton 1991
Spain	Pasajes Harbour	3-5	<63 µm	--	--	1.2-16	25-290	25-539	--	17-214	45-703	--	232-995	Legorburu & Canton 1991
Spain	Guipúzcoa	surface	<63 µm	--	--	0.37-1.18	45-262	30-101	--	23-284	18-102	--	57-487	Legorburu & Canton 1992
Greece	Rhodes Harbour	surface	<63 µm	--	--	0.006-0.17	3.7-118	9.1-101	--	--	19-230	--	12-242	Angelidis & Aloupi 1995
Turkey	Izmir Bay	surface	bulk sediment	--	--	--	27-345	11-94	0.06-0.55	--	49-116	--	--	Balci & Turkoglu 1993
Israel	E. Mediterranean coastline	surface	<250 µm	--	--	0.04-1.68	--	0.84-52.3	0.004-0.462	--	3.19-48.3	--	2.40-162	Herut *et al.* 1993
India	Bay of Bengal	surface	bulk sediment	--	--	0.46-6.05	11-394	2-105	0.058-0.56	--	5-130	--	13-144	Subramanian & Mohanachandran 1990
S. Pakistan	Arabian Sea	surface	<0.2 µm	0.27-0.73		0.1-0.83	24.3-39.1	20.3-38.4	0.51-2.40	57.2-102	2.4-15.7	--	24.5-146	Tariq *et al.* 1993
Jordan	Gulf of Aqaba	0-20	bulk sediment	--	--	2-6.2	--	6.8-9.7	--	19-90	83-140	--	32.61	Abu-Hilal & Badran 1990
Kuwaite	Qaruh Island	surface	bulk sediment	0.04	32.6	0.77	2.85	1.2	--	15.0	1.03	--	1.28	Fowler *et al.* 1993
Kuwait & Saudi Arabia	W. Persian Gulf	surface	bulk sediment	--	--	--	4-174	3-41	--	6-198	--	--	13-119	Basaham & Al-Lihaibi 1993
Saudi Arabia	Abu Ali	surface	bulk sediment	--	--	1.8-6.4	4.8-25	2.6-8.0	--	3.2-39.1	8.4-35.8	--	2.4-20.2	Al-Arfaj & Alam 1993
Saudi Arabia	various sites	surface	bulk sediment	0.12-0.2	4.61-22.7	0.10-0.25	24.6-99.2	3.14-5.53	--	7.86-27.8	1.70-4.44	--	3.41-10.2	Fowler *et al.* 1993
Bahrain	various sites	surface	bulk sediment	0.04-0.04	29.2-35.2	0.01-0.75	3.84-11.9	1.16-17.6	--	9.4-19.6	0.64-24.0	--	2.34-3.79	Fowler *et al.* 1993
UEA	various sites	surface	bulk sediment	0.10-0.13	20.6-22.5	0.02-1.91	71.9-81.8	1.34-7.76	--	9.40-25.0	0.54-3.6	--	1.56-3.40	Fowler *et al.* 1993
Oman	various sites	surface	bulk sediment	0.15-0.73	24.7-32.0	0.07-0.93	66.0-357	1.60-13.9	--	9.9-439	0.07-25.9	--	7.70-26.3	Fowler *et al.* 1993

dashes indicate no data

Table 5 (cont.)

Heavy Metal Concentrations (µg/g dry wt.) in Marine and Estuarine Sediments from Other Areas of the World

Location	Site	Depth (cm)	Fraction	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Sn	Zn	Reference
Africa	Kenyan Coast	surface	bulk sediment	--	--	0.01-0.34	--	3-42	--	--	0.5-15.8	--	2-117	Everaarts & Nieuwenhuize 1995
Canada	Saguenay fjord	surface	bulk sediment	--	--	--	40.4-56.4	20.6-28.2	<0.05-3.63	25.1-32.8	--	--	88-133	Gagnon *et al.* 1993
USA	Indian River Lagoon, Florida	surface	bulk sediment	--	0.6-15	<0.01-0.04	5.1-104	1.0-206	0.006-0.61	0.6-23	0.9-42	--	2.6-277	Trocine & Trefry 1996
USA	Gulf of Maine	0-5	bulk sediment	--	--	0.23-2.6	33.7-97.0	15.1-216	--	19.7-71.4	10.4-210	17.9-56.8	61.6-287	Larsen & Gaudette 1995
USA	Jamaica Bay, NY	surface	bulk sediment	--	--	<0.05-5.2	--	1.4-450	--	--	<0.7-500	--	--	Seidemann 1991
Cuba	Havana City	surface	<150-65 µm	--	--	--	22-225	24-567	0.48-32	3.5-94	50-967	--	68-3218	Gonzalez & Torres 1990
Cuba	Havana City	surface	<63 µm	--	--	--	22-339	18-716	0.64-76	11-112	44-903	--	72-3736	Gonzalez & Torres 1990
West Indies	Coast of Tobago	surface	<180 µm	--	--	0.04-2.12	--	0.06-16	--	--	0.3-20.9	--	0.1-39.3	Rajkumar & Persad 1994
S. America	Coquimbo Coast, Chile	surface	bulk sediment	--	--	5-20	50-210	--	--	--	--	--	--	Trucco *et al.* 1990
S. America	Montevideo coast	surface	<250 µm	--	--	0.05-0.231	0.48-57	nd-109	0.011-0.254	--	0.7-141	--	2.4-105	Moyano *et al.*. 1993
S. America	Guarapina Lagoon, Rio de Janeiro	surface	<63 µm	--	--	--	30-65	18-62	--	2-45	2-88	--	62-122	Knoppers *et al.* 1990

dashes indicate no data

Table 6

PCB Concentrations in Marine and Estuarine Sediments from Other Regions of the World

Location	Site	Depth (cm)	Fraction	Total PCB (ng/g)	Reference
Saipan	Puerto Rico Dump (foreshore)	surface	bulk sediment	ND-1,528	DEQ 1987
Saipan	Baker Bay area, Tanapag Lagoon	subsurface	bulk sediment	14-24	Unitek 1993
Saipan	Tanapag Lagoon (nearshore)	0-15	<1 mm	ND-16.6	This Study
Saipan	Tanapag Lagoon (>500 m offshore)	0-15	<1 mm	all ND	This Study
Guam	Agana Boat Basin	0-30	<1 mm	0.73-11.23	Denton *et al.* 1997
Guam	Apra Harbor	0-30	<1 mm	0.21-341	Denton *et al.* 1997
Guam	Agat Marina	0-30	<1 mm	<0.04-0.81	Denton *et al.* 1997
Guam	Merizo Pier	0-30	<1 mm	0.39-5.12	Denton *et al.* 1997
Japan	Osaka Bay	0-5	bulk sediment	2.5-240	Tanabe *et al.* 1991
Japan	Osaka Bay	0-5	bulk sediment	63-240	Iwata *et al.* 1994
India	Mandovi Estuary, Goa	0-5	bulk sediment	170	Iwata *et al.* 1994
Thailand	Chao Phraya Estuary, Bangkok	0-5	bulk sediment	11	Iwata *et al.* 1994
Vietnam	Ho Chi Minh	0-5	bulk sediment	2.3-8.9	Iwata *et al.* 1994
Papua New Guinea	Port Moresby	0-5	bulk sediment	3.3-24	Iwata *et al.* 1994
Vanuatu	Efate Island	0-5	bulk sediment	<0.07-0.20	Harrison *et al.* 1996
Tonga	Tongatapu Island	0-5	bulk sediment	<0.13-12.1	Harrison *et al.* 1996

ND = not detectable

Table 6 (cont.)

PCB Concentrations in Marine and Estuarine Sediments from Other Regions of the World

Location	Site	Depth (cm)	Fraction	Total PCB (ng/g)	Reference
Australia	Brisbane River Estuary	surface	bulk sediment	ND-58	Shaw & Connell 1980
Australia	Parramata Estuary, NSW	0-5	bulk sediment	160	Iwata *et al.* 1994
Australia	Harvey Estuary, WA	0-5	bulk sediment	0.69	Iwata *et al.* 1994
USA	Elkhorn Slough, CA	5-7.5	bulk sediment	25-147	Rice *et al.* 1993
USA	Moss Landing Harbor	5-7.5	bulk sediment	158-1782	Rice *et al.* 1993
USA	Monterey Bay	5-7.5	bulk sediment	2-23	Rice *et al.* 1993
USA	Chesapeake Bay	surface	bulk sediment	4-400	Sayler *et al.* 1978
USA	New York Bight	0-40	bulk sediment	0.5-2200	West & Hatcher 1980
USA	New Bedford Harbor, MS	0-41	bulk sediment	1.27-28.8	Brownawell & Farrington 1986
Mexico	San Quintin Bay	surface	bulk sediments	all <10	Gutierrez Galindo *et al.* 1996
Canadian Arctic	Queen Maud Gulf, NWT	surface	bulk sediment	0.052-0.44	Bright *et al.* 1995
Canadian Arctic	Cambridge Bay, NWT	surface	bulk sediment	0.14-0.45	Bright *et al.* 1995
UK	Humber Estuary	surface	<1 mm	ND-72	Tyler & Milward 1996
UK	Humber Estuary	0-10	<63 μm	2.9-19.7	Klamer & Fomsgaard 1993

ND = not detectable

Table 6 (cont.)

PCB Concentrations in Marine and Estuarine Sediments from Other Regions of the World

Location	Site	Depth (cm)	Fraction	Total PCB (ng/g)	Reference
UK	Irish Sea Basin	0-10	<63-3500 μm	0.2-42	Thompson *et al.* 1996
Sweden	Gulf of Bothnia	surface	bulk sediments	2-14	Van Bavel *et al.* 1996
Holland	Rhine-Meuse Estuary	surface	bulk sediment	50-1000	Duinker & Hillebrand 1979
E. Spain	Alicante coast	2-3	bulk sediments	0.27-9.69	Prats *et al.* 1992
Monaco	NW Mediterranean	0-21	bulk sediment	10.5-61.1	Burns & Villeneuve 1983
Italy	Bay of Naples, Tyrrhenian Sea	0-3	bulk sediment	6-3200	Baldi *et al.* 1983
Italy	Naples Offshore	0-3	bulk sediment	9-170	Baldi *et al.* 1983
Italy	North Adriatic Sea	0-35	bulk sediment	3-80	Caricchia *et al.* 1993
Italy	Tiber Estuary	surface	bulk sediment	28-770	Puccetti & Leoni 1980
E. Sicily	Ionian Sea	0-5	bulk sediment	0.8-49	Amico *et al*. 1982
E. Sicily	Augusta Harbor	0-5	bulk sediment	130-457	Amico *et al*. 1982
S. Greece	Aegean Sea	surface	bulk sediment	1.3-775	Dexter & Pavlou 1973
Turkey	E. Mediterranean coast	surface	bulk sediment	2-4	Bastürk *et al.* 1980

Table 7

PAH Concentrations in Marine and Estuarine Sediments from Other Regions of the World

Location	Site	Depth (cm)	Fraction	Total PAH (ng/g)	n[1]	Reference
Saipan	Baker Bay area, Tanapag Lagoon	subsurface	bulk sediment	ND	16	Unitek 1993
Saipan	Tanapag Lagoon (nearshore)	0-15	<1 mm	ND-1390	16	This Study
Saipan	Tanapag Lagoon (>500 m offshore)	0-15	<1 mm	ND-50	16	This Study
Guam	Agana Boat Basin	0-30	<1 mm	20-1900	16	Denton *et al.* 1997
Guam	Apra Harbor	0-30	<1 mm	20-8140	16	Denton *et al.* 1997
Guam	Agat Marina	0-30	<1 mm	ND-10	16	Denton *et al.* 1997
Guam	Merizo Pier	0-30	<1 mm	40-520	16	Denton *et al.* 1997
USA	Sarasota Bay, Florida	surface	bulk sediment	16-26771	11	Sherblom *et al.* 1995
USA	Elkhorn Slough, CA	5-7.5	bulk sediment	157-375	13	Rice *et al.* 1993
USA	Moss Landing, CA	5-7.5	bulk sediment	1470-3080	13	Rice *et al.* 1993
USA	Monterey Bay, CA	5-7.5	bulk sediment	24-114	13	Rice *et al.* 1993
USA	San Diego, CA	1-5	bulk sediment	7.1-983	26	Zeng *et al.* 1997
Caribbean	Guadeloupe Isl. laggons.	3-5	<200 μm	103-1657	9	Bernard *et al.* 1996
Mexico	San Quintin Bay, Baja, CA	surface	bulk sediment	all <50	?	Gutierrez Galindo *et al.* 1996
South America	Montevideo Coast	surface	<250 μm	100-940	18	Moyano *et al.* 1993
Antarctic Peninsula	Arthur Harbor	surface	bulk sediment	ND-14491	14	Kennicutt *et al.* 1992

[1] n = number of individual PAH's analyzed; ND = not detected

Table 7 (cont.)

PAH Concentrations in Marine and Estuarine Sediments from Other Regions of the World

Location	Site	Depth (cm)	Fraction	Total PAH (ng/g)	n[1]	Reference
Antarctica	Signy Island	surface	fine silt	14-280	12	Cripps 1992
Australia	Rowley Shelf Isls., WA	surface	bulk sediment	<5	16	Pendoley 1992
Australia	Perth, WA	surface	bulk sediment	1-3200	11	Burt & Ebell 1995
UK	Humber Estuary	surface	<63 μm	700-2700	13	Klamer & Fomsgaard 1993
Baltic Sea	Various	surface	mud/sand	9.53-1871	15	Witt 1995
Rotterdam	Caland Canal	surface	bulk sediment	2100-3200	16	Van Den Hurk *et al.* 1997
France	Rhone Delta	surface	bulk sediment	1225-2427	16	Lipiatou & Saliot 1991
France	Gulf of Lions	surface	bulk sediment	182-763	16	Lipiatou & Saliot 1991
France	Lazaret Bay, Toulon	surface	2 μm->500 μm	1440-48090	14	Benlahcen *et al*. 1997
Monaco	Ligurian Sea	0-2	bulk sediment	599-847	12	Burns and Villeneuve 1983
Italy	N. Adriatic Sea	0-35	bulk sediment	18-577	12	Caricchia *et al.* 1993
Italy	Spotorno	surface	63-200 μm	1720	14	Benlahcen *et al*. 1997
Italy	Adriatic Coast	0-20	<63μm	27-527	10	Guzzella & De Paolis 1994
Corsica	Scandola	surface	>500 μm	119	14	Benlahcen *et al*. 1997
Persian Gulf	Mina Al Fahal, Gulf of Oman	surface	<63 μm	398-787	13	Badawy *et al.* 1993

[1] n = number of individual PAH's analyzed

RESULTS & DISCUSSION

A. PHYSICAL ANALYSIS

1. PETROGRAPHY AND PARTICLE SIZE ANALYSIS

A visual characterization of air-dried sediment samples is indicated in Table 8. The data are biased towards sediments larger than fine sand (>0.125 mm). More rigorous grain size analyses are summarized in Table 9 and presented as frequency distribution histograms in Appendix A. The compositional elements that were identifiable are listed in the right-hand column of Table 8 in their approximate order of relative abundance.

1.1 Composition:

The sediments in Tanapag Lagoon range in composition from medium to fine grained sand in some of the more sheltered areas (e.g. adjacent to the docks, harbor and small boat marinas) to progressively coarser material offshore. By and large they are poorly sorted and consist predominantly of biogenic calcium carbonate derived directly from the reef platform and margin (autochthonous) with small additions (<1%) originating from nearby terrigenous sources (allochthonous). Grain size frequency distributions often varied considerably between sediment cores taken from the same site (see Appendix A)

In addition to sand-sized particles that are generally resolvable as to composition, there are significant silt- and clay-sized fines (<0.0625mm) in all but a few samples that cannot be resolved with ordinary binocular microscopes. Based on earlier reef sediment studies on Guam (Emery 1963, Denton *et al*. 1997), Saipan (Cloud 1959), and the northern islands of the CNMI (Siegrist *et al*. 1991), this fraction could include whole or fragments of microorganisms (e.g. otoliths, diatoms etc); carbonate muds resulting from bio-erosion and physical abrasion of reef carbonates; chemically precipitated cement crystals (micrite) mechanically stirred up and re-deposited in storms; and/or terrigenous clay minerals and oxides derived from storm-water runoff and wind transport off the surrounding hillsides.

The most significant departure from all earlier reef-sediment studies in the Mariana Islands is the small but persistent presence of anthropogenic grains (e.g. plastic, fiberglass, etc.) within many inshore samples of Tanapag Lagoon.

1.2 Color:

Bulk sediment color is caused by the color of the dominant minerals. Unweathered volcanic minerals tend to be dark green and olive, or black; weathered volcanic minerals tend to be tan, yellows, reds, purples, and pinks. The former colors are those associated with ferrous iron minerals; the latter with mixtures of ferric iron phases and clay minerals.

Color of reef carbonate sediment reflects the very light colors of pure calcium carbonate minerals, calcite and aragonite, that comprise the shells and tests of the dominant organisms, modified by small percentages (<1%) of microscopically fine yellow oxide pigments washed or blown off the land. This results in colors throughout the sampling sites of 5Y and 10YR hues.

Table 8

Petrographic Description of Tanapag Lagoon Sediments (5-20 X magnification)

#	~Depth (m)	Munsell Color	Texture	Visual Composition
1A		5Y7/2	p-sort, silty fine sand	mol, foram, mol, cal
1B	3	5Y7/2	p-sort, silty fine sand	mol, foram, mol, cal
1C		5Y7/3	m-sort, silty, med-fine sand	mol, foram, mol, cal, plastic
2A		2.5Y7.5/2	m-sort, sandy silt	mol, corals, wd
2B	3	2.5Y7/2	m-sort silty, medium-fine sand	mol, wt, corals, wd
2C		5Y7/2	m-sort, silty, medium-fine sand	mol, corals, wt, foram, wd
3A		2.5Y7/2	p-sort silty medium-fine sand	Ha, foram, mol, wd
3B	5	2.5Y7/2	p-sort silty medium-fine sand	Ha, foram, crx, mol, glass, wd
3C		2.5Y7/2	p-sort silty medium-fine sand	Ha, foram, crx, coral, mol, glass,
4A		2.5Y7/2	m-sort, medium-coarse sand	mol, foram, coral, cal, crx, rusty metal, wd
4B	5	2.5Y7/2	p-sort coarse sand	mol, foram, coral, cal, crx, rusty metal, wd
4C		2.5Y7/2	p-sort medium-fine sand	mol, foram, coral, cal, rusty metal, wd
5A		2.5Y7/3	m-sort coarse-medium sand	crx, mol, Ha, coral, cal, tar balls
5B	5	2.5Y7/2	m-sort coarse-medium sand	crx, mol, Ha, coral, cal, foram
5C		2.5Y7/2	m-sort coarse-medium sand	crx, mol, Ha, coral, cal, wt, bry
6A		5Y6/3	p-sort coarse-medium sand	crx, mol, corals, wt, echn, foram
6B	15	5Y6/3	p-sort coarse-medium sand	crx, mol, corals, wt, echn, foram
6C		5Y7/2	p-sort coarse-medium sand	crx, mol, corals, wt, rhodo, foram
7A		5Y8/3	m-sort medium-fine silty sand	Ha, mol, xls, echn, coral, wd
7B	15	5Y8/2	p-sort coarse-medium sand	Ha, crx, mol, echn, coral, wt, wd
7C		5Y8/3	p-sort coarse-medium sand	Ha, crx, mol, coral, tg, wd
8A		5Y7/2	m-sort silty fine sand	foram, crx, mol, wt, ss,
8B	15	5Y7/2	m-sort silty fine sand	foram, mol, crx, coral, wt, ss,
8C		5Y7/2	m-sort silty fine sand	foram, mol, crx, wt
9A		10YR7/2	m-sort fine sandy silt	foram, mol, coral, cal, ss
9B	15	10YR7/2	m-sort fine sandy silt	foram, mol, coral, crx, wt,
9C		5YR7/2	m-sort fine silty sand	foram, mol, wt, coral, crx
10A		2.5Y7/2	m-sort fine sandy silt	mol, echn, coral, crx, wd
10B	15	2.5Y7/2	m-sort fine sandy silt	mol, echn, coral, cal, crx, wd
10C		2.5Y7/2	m-sort medium-fine sandy silt	mol, echn, coral, wood, crx, foram, plastic
11A		10YR7/2	p-sort gravelly coarse sand	Ha, wt, foram, plastic
11B	0.5	10YR7/2	p-sort gravelly coarse sand	Ha, wt, foram, plastic
11C		10YR7/2	p-sort gravelly coarse sand	Ha, wt, coral, foram
12A		2.5Y6/2	p-sort gravelly coarse sand	mol, crx, cal, arth, Ha, wood
12B	0.5	2.5Y6/2	p-sort gravelly coarse sand	mol, crx, wood, wt, coral, ba
12C		2.5Y6/2	p-sort gravelly coarse sand	mol, crx, plastic, wt
13A		5Y6/2	p-sort gravelly coarse sand	mol, crx, arth, plastic
13B	0.3	5Y6/2	p-sort gravelly coarse sand	mol, crx, Ha, wood, plastic
13C		5Y6/2	p-sort gravelly coarse sand	mol, wt, crx, coral, arth, glass, ba, wd
14A		2.5Y6/2	p-sort coarse sand	mol, crx, wt, arth, glass, coral, wd
14B	0.3	2.5Y5/2	p-sort coarse sand	mol, crx, cal, rhodo, wd
14C		2.5Y6/2	p-sort coarse sand	mol, crx, cal, wt, coral, wd
15A		5Y5/3	p-sort coarse sand	crx mol, wt, coral, foram, wd
15B	1.0	5Y5/3	p-sort coarse sand	mol, wt, crx, coral, foram, coral, cal
15C		5Y6/3	p-sort coarse sand	crx, mol, wt, coral, cal, bry, wd, foram
16A	1.3	5Y6/3	m-sort medium-coarse sand	foram, mol, crx, coral, cal, wt, wd
16B		5Y6/3	m-sort medium-coarse sand	foram, mol, coral, cal, wt, wd. ss
16C		5Y6/3	m-sort medium-coarse sand	foram, mol, coral, cal, wt, ss

Table 8 (cont.)

Petrographic Description of Tanapag Lagoon Sediments (5-20 X magnification)

#	~Depth (m)	Munsell Color	Texture	Visual Composition
17A		5Y7/3	p-sort medium-coarse sand	mol, coral, crx, echn, wood, glass
17B	1.3	5Y7/3	p-sort medium-coarse sand	mol, coral, crx, cal, wood, glass
17C		5Y7/3	p-sort medium-coarse sand	mol, coral, crx, cal, wood, glass
18A		5Y7/3	p-sort gravelly coarse sand	coral, crx, mol, foram
18B	0.7	5Y7/3	p-sort gravelly coarse sand	coral, abraded crx, mol, foram
18C		5Y7/3	p-sort gravelly coarse sand	coral, abraded crx, mol, foram
19A		5Y5/3	p-sort very coarse sand	Ha, wt, crx, mol, coral, bry, xls
19B	0.7	5Y5/3	p-sort very coarse sand	Ha, crx, forams, wt, mol, coral, glass
19C		5Y5/3	p-sort very coarse sand	foram, crx, coral, Ha, wt, mol, fbrs
20A		2.5Y7/4	vp-sort coarse sand	mol, crx, coral, cal, rhodo, foram, wt, bry
20B	1	2.5Y6/2	vp-sort coarse sand	crx, mol, coral, cal, Ha, rhodo, foram, wt, bry
20C		2.5Y7/2	vp-sort coarse sand	crx, mol, coral, cal, rhodo, foram, bry
21A		5Y7/3	m-sort coarse sand	cal, crx, mol, coral, foram, echn, bry, ss
21B	3	5Y7/2	m-sort coarse sand	coral, crx, mol, foram, Ha, echn, bry
21C		5Y7.5/2	m-sort coarse sand	cal, crx, mol, coral, foram, Ha, echn, bry
22A		5Y8/2	m-sort, coarse sand	Ha, coral, cal, foram, crx, wt, bry
22B	8	5Y8/2	m-sort, coarse sand	Ha, coral, cal, foram, crx, bry
22C		5Y8/2	m-sort, coarse sand	Ha, coral, cal, foram, crx, bry
23A		5Y7/2	m-sort medium-coarse sand	cal, coral, crx, mol, foram, rhodo, ss
23B	15	5Y7/2	m-sort medium-coarse sand	coral, crx, cal, mol, foram, rhodo, ss
23C		5Y7/2	m-sort medium-coarse sand	cal, mol, coral, crx, foram, bry, rhodo, ss
24A		5Y7/2	vp-sort medium-coarse sand	foram, mol, coral, crx, cal, wt, ss
24B	9	5Y7/2	vp-sort medium-coarse sand	mol, foram, coral, crx, cal, bry, wd
24C		5Y7/3	vp-sort medium-coarse sand	foram, mol, coral, crx, cal, wt
25A		5Y7.5/2	p-sort fine sand	mol, cal, foram, coral, crx, echn
25B	16	5Y7.5/2	p-sort fine sand	mol, coral, abraded cal, foram, crx
25C		5Y7.5/2	p-sort fine sand	mol, cal, coral, foram, crx, echn, bry
26A		5Y7/2-8/1	m-sort fine sandy silt	mol, Ha, crx, foram, echn
26B	14	5Y7/2-8/1	m-sort fine sandy silt	mol, Ha, crx, foram
26C		5Y7/2	m-sort fine sandy silt	mol, crx, Ha, cal, coral, echn
27A		2.5Y7/2	m-sort fine sandy silt	coral, foram, cal, mol, crx
27B	12	2.5Y7/2	m-sort fine sandy silt	coral, foram, cal, mol, crx, bry
27C		2.5Y7/2	m-sort fine sandy silt	coral, mol, foram, cal, wd
28A		5Y6/3	p-sort coarse sand	Ha, coral, cal, crx, mol, foram, plastic, wd
28B	0.7	5Y6/3	p-sort coarse sand	Ha, coral, mol, cal, crx, foram wd
28C		5Y6/3	p-sort coarse sand	Ha, cal, crx, coral, mol, foram, wd
29A		5Y7.5/2	p-sort fine silty sand	Ha, foram, coral, crx, xls, wd, rubber
29B	8	5Y7/2	vp-sort medium-fine sand	foram, Ha mol, wt, wd, plastic
29C		5Y6/2	vp-sort, gravelly coarse sand	coral, xls, crx, mol
30A		5Y7/2	vp-sort medium-coarse sand	Ha, mol, cal, coral, wd, plastic
30B	9	5Y7/3	vp-sort medium-coarse sand	mol, crx, cal, Ha, wd, plastic, fbr
30C		5Y6/3	vp-sort medium-coarse sand	Ha, mol, cal, coral, crx, arth, wd, plastic, ba
31A		5Y7/2.5	m-sort coarse sand	coral, cal, mol, crx, bry, foram, ss
31B	?	5Y6/2	p-sort coarse gravelly sand	cal coral, crx, mol, echn, foram, wt, coral, cal
31C		5Y7/2.5	p-sort medium-coarse sand	mol, coral, crx, bry, foram, ss
32A		5Y7/3	vp-sort gravelly sand	crx, coral, whole & frags mol, cal, foram, echn, Ha,
32B	0.7	5Y7/3	vp-sort gravelly sand	crx, coral, whole & frags mol, cal, foram, Ha, echn
32C		5Y7/3	vp-sort gravelly sand	coral, crx, whole & frags mol, cal, foram, Ha, bry

Table 8 (cont.)

Petrographic Description of Tanapag Lagoon Sediments (5-20 X magnification)

#	~Depth (m)	Munsell Color	Texture	Visual Composition
33A		2.5YR8/2	m-well sort med sand	Ha, coral, mol, crx, arth, foram, echn, wt
33B	3	2.5YR8/2	m-well sort med sand	Ha, coral, mol, crx, arth, foram, echn, bry, wt
33C		2.5YR7.5/2	m-well sort med sand	coral, Ha, mol, crx, arth, foram, echn
34A		5Y8/2	m-sort very coarse sand	cal, mol, coral, crx, echn, foram, bry
34B	11	5Y8/2	m-sort very coarse sand	cal, mol, coral, crx, echn, foram, bry cal
34C		5Y8/2	m-sort very coarse sand	mol, coral, crx, echn, foram, bry
35A		5Y8/2	p-sort gravelly coarse sand	cal, mol, coral, crx, echn, cal, foram, bry
35B	6	5Y8/2	p-sort gravelly coarse sand	mol, coral, crx, echn, foram, cal, bry
35C		5Y8/2	p-sort gravelly coarse sand	coral, crx, mol, echn, cal, foram, bry
36A		5Y8/3	p-sort silty sand	foram, cal, crx, coral, mol, ss, wt, echn
36B	15	5Y8/3	p-sort silty sand	foram, cal, crx, mol, coral, ss, wt, echn
36C		5Y8/3	p-sort silty sand	foram, crx, cal, mol, coral, echn
37A		5Y7.5/2	p-sort medium-coarse sand	mol, coral, Ha, cal. crx, foram, rhodo, echn, wt, bry
37B	9	5Y7.5/2	p-sort medium-coarse sand	mol, coral, Ha, cal. crx, rhodo, echn, wt, bry
37C		5Y8/2	p-sort medium-coarse sand	mol, coral, cal, Ha, foram, crx, echn, wt, bry
38A		5Y7/3	vp-sort coarse sand	coral, mol, foram cal. crx, echn, wt, bry
38B	2	5Y7/2	vp-sort coarse sand	mol, cal, coral, crx, wt, bry
38C		5Y7/2	vp-sort coarse sand	mol, coral, foram, cal. crx, rhodo, echn, wt, bry
39A		5Y7/2	m-sort coarse-medium sand	mol, coral, foram, Ha, cal. crx, rhodo, echn, bry
39B	2	5Y7/2	m-sort coarse-medium sand	mol, coral, cal, crx, foram, rhodo, echn, bry
39C		5Y7/3	m-sort coarse-medium sand	mol, cal, coral, Ha, crx, rhodo, echn, wt, bry
40A		5Y8/2.5	mw-sort coarse sand	mol, coral, foram, cal. crx, echn, wt, bry
40B	2.5	5Y8/2.5	mw-sort coarse sand	coral, mol, cal. crx, rhodo, echn, wt, bry
40C		5Y8/2.5	mw-sort coarse sand	mol, coral, cal. foram, crx, echn, wt, bry
41A		5Y8/2	m-sort coarse sand	coral, crx, rhodo, cal, foram, echn, wt, bry
41B	1.3	5Y7.5/2.5	m-sort coarse sand	coral, cal. crx, rhodo, echn, wt, bry
41C		5Y8/2	m-sort coarse sand	cal, coral, crx, Ha, echn, wt, bry

The following is a listing of the compositional classes observed with the abbreviations used in the above table indicated in parenthesis.

Autochthonous Sediment (derived from the reef itself):

Corals: Abraded and pristine grains of scleractinian corals and Milliporina, spicules from Alyconaria corals
Algae: Whole and fragments of calcareous green alga **(Ha)** and coralline red alga **(cal).**
Coralgal Aggregate: **(crx)** Abraded grains of platform pavement, an aggregate predominantly of coralline red algae, scleractinian coral, encrusting Foraminifera and vermetid algae.
Molluscs: **(mol)** Both whole and fragmented shells of pelecypoda and gastropods, often smoothed along edges by abrasion.
Benthic Foraminifera: **(foram)** Whole and fragments of Amphistegina, Baculogypsina, Gypsina, Heterostegina, and Marginopora
Echinoid: **(echn)** Spines and plates
Annelida: **(wt)** Worm tubes
Coated grains: **(rhodo)** Fragments of concretionary structures all called rhodoliths
Sponge: Spicules **(ss)**
Bryozoan: Fragments **(bry)**
Arthropod: Carapace fragments **(arth)**

Allochthonous Sediment (derived from outside the reef, particularly from surface water runoff):

Crystalline Limestone **(xls)**
Terrestrial Plants: **(wd)**
Anthropogenic: Plastic, glass, fibers **(fbr)**, bituminous asphalt **(ba)**, rubber, tar balls

Uniformity of Grain Size (standard deviation of the sample grain size expressed in phi units):

Very well-sorted	**(vw-sort)**	Φ Limits = 0.35
Well sorted	**(w-sort)**	Φ Limits = 0.35-0.50
Moderately well sorted	**(mw-sort)**	Φ Limits = 0.50-0.71
Moderately sorted	**(m-sort)**	Φ Limits = 0.71-1.0
Poorly sorted	**(p-sort)**	Φ Limits = 1.0-2.0
Very poorly sorted	**(vp-sort)**	Φ Limits = 2.0-4.0

Table 9

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-1A	1.46	1.76	11.4	16.8	16.0	20.1	32.6	1.86
S-1B	1.24	6.31	15.9	18.1	14.4	16.5	27.5	1.55
S-1C	2.42	4.66	21.6	17.9	17.5	13.6	22.3	1.19
S-2A	1.16	5.78	10.8	11.2	12.0	21.5	37.5	1.02
S-2B	1.25	4.62	7.93	20.2	20.8	22.3	22.9	0.84
S-2C	7.31	8.17	9.47	12.4	16.1	19.5	27.1	0.97
S-3A	23.3	12.9	10.6	9.18	10.7	15.4	17.9	1.14
S-3B	18.6	13.2	10.8	10.4	15.0	19.1	13.0	0.71
S-3C	6.30	13.1	13.2	9.53	19.4	20.0	18.4	0.99
S-4A	3.48	22.3	16.7	14.6	11.9	9.71	21.4	1.25
S-4B	16.1	23.4	13.2	11.1	10.6	10.9	14.8	1.14
S-4C	0.40	1.47	4.19	8.39	22.6	27.4	35.5	0.97
S-5A	11.0	18.8	23.6	23.8	14.3	5.47	2.89	0.36
S-5B	7.00	11.5	24.4	30.2	18.4	5.12	3.47	0.38
S-5C	1.85	7.87	30.3	34.8	20.7	3.79	0.76	0.31

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-6A	2.22	2.53	3.12	5.66	7.89	18.6	60.0	0.83
S-6B	0.91	2.13	2.49	3.86	8.25	16.4	66.0	0.70
S-6C	13.4	3.82	4.34	7.86	9.73	14.9	45.9	0.80
S-7A	3.02	1.62	5.56	14.1	24.5	23.0	28.2	0.69
S-7B	6.90	4.58	7.81	15.2	25.7	21.7	18.2	0.47
S-7C	6.44	5.60	8.24	16.6	24.2	19.2	19.7	0.48
S-8A	1.18	2.63	6.00	6.48	11.5	18.0	54.2	0.77
S-8B	3.04	6.72	10.0	13.0	11.6	13.6	42.0	0.86
S-8C	4.87	6.10	7.81	11.3	11.9	14.2	43.8	0.87
S-9A	0.24	0.75	1.96	3.13	5.86	27.0	61.1	0.68
S-9B	0.61	1.15	0.99	1.93	5.45	27.1	62.7	0.79
S-9C	0.78	1.27	3.92	7.61	16.4	29.1	40.9	0.67
S-10A	0.00	0.04	1.22	6.36	9.86	19.8	62.7	1.07
S-10B	0.29	4.66	7.19	6.72	8.17	15.7	57.2	1.08
S-10C	0.00	0.89	7.84	10.4	15.1	16.0	49.8	1.14

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-11A	11.5	16.6	22.5	24.1	16.8	5.29	3.24	0.59
S-11B	11.4	17.7	22.4	22.9	16.0	6.17	3.36	0.86
S-11C	10.8	20.3	24.7	23.6	14.1	4.31	2.12	0.81
S-12A	19.3	18.8	22.6	17.8	11.5	4.91	5.10	2.18
S-12B	23.4	19.1	21.6	16.9	11.3	4.34	3.47	2.02
S-12C	18.0	23.3	27.7	17.4	8.61	2.70	2.20	2.19
S-13A	6.54	13.5	30.1	29.9	14.7	3.67	1.62	0.74
S-13B	12.0	21.4	25.9	22.8	12.3	3.79	1.81	0.97
S-13C	10.4	20.8	25.2	23.7	13.1	4.14	2.57	1.01
S-14A	11.2	16.8	19.8	19.7	8.71	15.8	8.13	2.81
S-14B	26.8	18.8	15.2	13.0	11.1	7.32	7.68	3.62
S-14C	13.0	19.7	19.5	16.9	13.6	8.18	9.09	3.03
S-15A	14.2	21.6	22.3	21.8	13.0	3.77	3.35	0.98
S-15B	12.1	23.0	24.8	23.4	12.8	2.47	1.40	0.88
S-15C	11.7	18.2	20.8	24.0	16.6	4.89	3.81	1.25

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-16A	3.29	14.4	32.2	31.3	16.3	1.59	0.97	0.30
S-16B	3.06	8.07	24.8	35.5	21.4	3.36	3.82	0.37
S-16C	3.74	7.41	23.9	36.3	21.0	3.94	3.73	0.41
S-17A	10.7	11.8	24.9	25.3	18.1	3.21	6.00	0.37
S-17B	3.79	8.90	29.2	33.6	18.2	2.45	3.84	0.38
S-17C	3.91	11.6	29.3	29.6	18.6	2.43	4.52	0.36
S-18A	19.4	16.4	19.4	25.5	16.6	2.13	0.50	0.41
S-18B	13.0	16.6	22.5	27.8	16.3	2.21	1.51	0.43
S-18C	15.0	16.6	23.9	29.5	14.2	0.75	0.08	0.42
S-19A	19.3	17.2	25.2	23.7	11.4	2.05	1.14	0.53
S-19B	7.25	16.5	26.3	33.0	15.7	0.95	0.30	0.53
S-19C	5.63	10.3	26.5	39.4	15.3	2.68	0.16	0.63
S-20A	18.5	15.2	22.4	26.6	13.1	2.94	1.28	0.82
S-20B	14.9	13.1	25.3	27.0	14.9	3.81	1.03	1.20
S-20C	16.7	11.2	18.1	28.7	20.4	4.00	0.90	0.63

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-21A	21.4	27.8	22.3	15.3	10.0	2.65	0.55	0.47
S-21B	23.1	29.0	21.4	13.5	7.91	3.00	2.11	0.32
S-21C	7.77	16.5	22.5	21.0	19.2	8.96	3.98	0.39
S-22A	8.28	18.0	28.0	21.8	14.3	6.14	3.56	0.28
S-22B	8.31	14.2	24.2	22.4	17.4	9.14	4.37	0.35
S-22C	9.48	15.8	23.5	21.8	16.5	8.67	4.12	0.43
S-23A	0.39	6.43	25.5	24.6	21.2	15.4	6.55	0.33
S-23B	0.04	6.40	24.8	23.3	21.7	16.9	6.89	0.35
S-23C	0.06	6.86	26.7	27.9	28.3	8.06	2.14	0.35
S-24A	3.37	4.78	12.9	17.1	17.4	19.2	25.3	0.67
S-24B	4.58	3.53	10.9	11.3	15.0	21.5	33.1	0.88
S-24C	4.94	7.22	15.1	15.0	15.5	17.5	24.8	0.66
S-25A	0.67	2.17	1.76	3.61	6.92	20.0	64.8	0.90
S-25B	0.19	1.35	1.49	3.20	8.11	18.8	66.9	0.96
S-25C	0.19	0.29	2.15	1.67	7.91	19.9	67.9	0.95

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-26A	0.15	0.61	2.64	3.50	8.76	28.4	56.0	1.20
S-26B	0.60	1.71	2.66	4.90	12.4	25.3	52.4	0.88
S-26C	2.55	3.18	3.30	5.01	11.5	22.0	52.4	0.90
S-27A	0.48	1.77	4.62	8.16	10.6	19.2	55.2	1.24
S-27B	0.25	2.11	1.92	2.11	5.71	23.2	64.7	1.20
S-27C	0.64	2.80	2.95	2.99	9.12	22.6	58.9	1.17
S-28A	0.47	1.90	10.1	42.8	37.0	4.93	2.82	0.46
S-28B	0.35	1.40	9.25	49.9	33.2	3.58	2.30	0.48
S-28C	0.69	2.73	11.21	46.0	34.2	3.11	2.01	0.44
S-29A	0.40	2.21	9.31	14.9	15.0	22.3	35.9	0.64
S-29B	1.45	2.66	7.19	16.1	24.8	23.0	24.9	0.66
S-29C	11.7	5.84	10.2	15.3	19.5	17.2	20.4	0.62
S-30A	3.21	5.27	11.7	16.9	25.3	19.0	18.5	0.56
S-30B	3.16	4.71	13.0	16.6	27.9	21.7	13.0	0.73
S-30C	2.51	6.09	17.3	23.3	28.6	13.4	8.82	0.63

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-31A	11.7	20.5	24.5	23.9	14.1	3.46	1.86	0.38
S-31B	11.0	20.9	27.1	23.6	13.0	3.28	1.08	0.37
S-31C	23.1	22.5	22.9	17.6	10.0	2.83	0.97	0.43
S-32A	23.3	17.5	15.9	18.9	21.3	2.16	0.92	0.52
S-32B	17.0	21.1	20.9	19.8	19.8	1.28	0.13	0.48
S-32C	17.7	16.1	15.4	17.7	28.0	3.66	1.44	0.41
S-33A	0.24	1.28	9.84	50.9	36.2	1.09	0.43	0.26
S-33B	0.47	1.61	13.5	52.4	30.8	0.86	0.35	0.27
S-33C	0.75	1.70	10.7	54.2	31.2	0.92	0.52	0.22
S-34A	19.4	21.4	38.2	19.3	1.53	0.07	0.04	0.28
S-34B	27.8	13.7	31.2	24.3	2.27	0.37	0.39	0.31
S-34C	26.4	22.5	34.4	14.5	1.56	0.29	0.24	0.30
S-35A	17.5	24.6	27.1	22.3	6.83	1.37	0.31	0.30
S-35B	29.8	21.7	22.7	18.3	5.82	1.27	0.47	0.27
S-35C	22.7	20.6	25.1	24.7	6.39	0.33	0.16	0.28

Table 9 (cont.)

Particle Size Distribution Analysis and Organic Carbon in Sediments from Tanapag Lagoon, Saipan

Site # and Core Identity	Sieved Fractions (%)							Total Organic Carbon (%)
	>2.0 mm	<2.0 mm - >1.0 mm	<1.0 mm - >0.5mm	<0.5mm - >0.25mm	<0.25mm - >0.125mm	<0.125mm - >0.063mm	<0.063mm	
S-36A	9.18	3.76	7.41	9.84	16.5	28.3	25.1	0.63
S-36B	12.0	5.54	7.56	10.0	15.9	26.3	22.6	0.62
S-36C	3.46	2.83	6.53	12.2	21.3	32.2	21.5	0.47
S-37A	2.57	3.83	10.2	17.7	54.3	10.6	0.76	0.33
S-37B	1.52	2.70	8.99	18.6	60.9	7.00	0.31	0.33
S-37C	2.01	2.18	6.62	15.7	61.4	11.4	0.62	0.35
S-38A	5.05	13.0	34.2	38.3	8.30	0.86	0.35	0.34
S-38B	5.76	14.4	33.9	35.7	8.65	1.18	0.45	0.37
S-38C	5.95	12.9	33.5	37.7	9.13	0.80	0.08	0.35
S-39A	4.20	5.56	18.4	46.6	24.1	0.94	0.24	0.42
S-39B	0.38	5.61	17.2	40.5	30.8	4.23	1.29	0.38
S-39C	2.10	3.79	14.5	46.2	29.6	3.32	0.43	0.32
S-40A	4.27	12.5	48.3	29.6	4.65	0.31	0.41	0.25
S-40B	0.83	5.33	41.8	44.3	7.41	0.18	0.12	0.31
S-40C	2.07	9.52	43.31	38.3	6.28	0.30	0.21	0.27
S-41A	17.8	21.1	29.5	23.6	6.08	1.04	0.91	0.32
S-41B	24.3	18.4	25.1	23.5	6.70	1.03	1.02	0.39
S-41C	12.5	12.3	29.9	33.0	9.20	1.66	1.30	0.43

Some variation also arises between sieve fractions within a given sample. This is caused by the fact that shells of the dominant organisms on the reef break down mechanically into certain sieve sizes, and thus control the color of that size fraction. Thus segments of the green alga *Halimeda* (dead white) dominated the color of the >2 mm fraction, while tests of the benthic foram *Baculogypsina* determined the 10YR7/3 color of the 0.5-1.00 mm fraction of many samples.

1.3. Total Organic Carbon (TOC):

The TOC content of individual sediment cores is presented in Table 9 and showed little within-site variability. In contrast, between-site differences were often considerable. This was especially true of nearshore sites where levels ranged from 0.28-3.62% with an overall mean of 0.84%. TOC values for the outer lagoonal sites ranged from 0.25–0.63% with an overall mean of 0.38%. The highest TOC levels were found at sites 14 (2.81-3.62%) and 12 (2.02-2.19%). While both these sites are down current of the Puerto Rico dump, they are also in an area of extensive natural sea-grass beds and fringing mangroves, two major contributors of organic carbon to the nearshore environment. The distribution of TOC in surface sediments throughout the study area is summarized as an isoconcentration contour map in Appendix B.

Both grain size distribution and organic matter content play a major role in determining the affinity of aquatic sediments for heavy metals and organic compounds like PCBs and PAHs. Small sediment grains generally have higher sorptive surface areas than larger grained materials and are replete with cation exchange sites at the silt and clay level. Consequently, they serve as major repositories for heavy metals compared with coarser grained sample fractions. Organic matter also has a net abundance of negatively charged sites that readily attract and bond with heavy metals and other polyvalent cations. Thus, sediments rich in organic carbon tend to capture and retain significantly higher concentrations of trace elements compared to those that are organic matter depleted. Likewise, lipophilic organics have a much higher affinity for organic matter than they do for most mineral surfaces. While the sorptive processes are different here than they are for metals, the net result is the same. Hence, clean sands do not accumulate lipophilic compounds as readily or as effectively as organic rich, bottom deposits of similar grain size.

While grain size distributions and organic carbon content are reported here for all sediments analyzed, their interactive effects on resident contaminant loadings were outside the scope of this investigation and remain to be determined.

B. CHEMICAL ANALYSIS

Guidelines for classifying coralline sediments from Guam according to their heavy metal, PCB and PAH content have been proposed by Denton *et al.* (1997) and are presented in Table 10. The five categories of contaminant abundance and their corresponding concentration ranges were adopted after extensive field observations and review of the available literature. They take into account the toxicity, pollution potential, and natural/normal abundance of each contaminant listed. The contaminant ranges listed in the 'clean' and 'lightly contaminated' categories are considered unlikely to cause any adverse biological effects based on comparisons with toxicity databases published elsewhere (Long 1992, Long *et al.* 1995, 1998, MacDonald *et al*. 1996). The classification scheme permits the investigator to make a rapid, first-order assessment of pollution levels in reef sediments and is used for such purposes during the following discussions.

1. HEAVY METALS IN TANAPAG LAGOON SEDIMENTS

The heavy metal data obtained during the present study are summarized in Table 11 and presented as isoconcentration contour maps in Appendix C. Despite attempts to effectively homogenize sediment samples prior to analysis, high within-subsite variability was occasionally observed[1]. This was attributed to minute metallic or metal containing particles residing in the sediment. For this reason, the geometric mean was used to determine average metal concentrations at each site in order to minimize the influence of such outliers on the true mean. The following discussions are organized on a metal-by-metal basis and all referenced data are expressed on a dry weight basis unless stated otherwise.

1.1 Silver (Ag):

Silver ranks among the most toxic of heavy metals to aquatic organisms (Moore 1991). In uncontaminated sediments, levels are in the order of 0.1 μg/g (Bryan and Langston 1992). Enrichment is usually associated with inputs from mining wastes or sewage (Thornton *et al.* 1975, Halcrow *et al.* 1973). Contributions from the latter source have placed silver among the heavy metals of greatest concern in the San Francisco Bay Area, where levels in excess of 10 μg/g have been reported (Louma and Phillips 1988). The highest levels reported in the literature, are 40 μg/g for Acushnet estuary, New Bedford Harbor, Massachusetts (Summerheyes *et al.* 1977), and 190 μg/g in grossly polluted sediments from Sorfjord, Norway (Skei *et al.* 1976).

Previous data for silver in Saipan sediments are confined to samples taken from six sites around the seaward perimeter of the Puerto Rico dump in the late 80's (DEQ 1987). Levels were undetectable at all sites except for one in the vicinity of site 14 (Fig. 3) where a value of 2.3 μg/g was recorded. We failed to substantiate this during the current study. In fact, levels found were consistently low with levels rarely exceeding the limits of analytical detection (~0.2 μg/g) at all sites visited. It is noteworthy that the recent analysis of sediments from four harbors on Guam also failed to find detectable levels of this metal (Denton *et al.* 1997). It

[1] As a general rule, sample analysis was repeated if the variation between replicates was greater than 50%

Table 10

Suggested Numerical Guidelines for Classifying Contaminant Levels in Calcareous Reef Sediments of Biogenic Origin[a]

Metal	Degree of Contamination				
	Clean	Light	Moderate	Heavy	Gross
HEAVY METALS (µg/g dry wt.)					
Arsenic	1-3	6-10	>10-25	>25-50	>50
Cadmium	<0.1	0.1-0.5	>0.5-1	>1-10	>10
Chromium	3-5	10-25	>25-50	>50-100	>100
Copper	1-3	6-20	>20-50	>50-100	>100
Lead	<1	1-10	>10-50	>50-100	>100
Mercury[b]	0.005-0.01	0.02-0.1	>0.1-0.3	>0.3-1	>1
Nickel	1-3	6-20	>20-50	>50-100	>100
Silver	<0.1	0.1-0.5	>0.5-1	>1-10	>10
Tin[b]	<0.1	0.1-5	>5-25	>25-50	>50
Zinc	3-5	10-50	>50-100	>100-300	>300
ΣPCBS (ng/g dry wt.)					
	<1	1-10	>10-100	>100-1000	>1000
ΣPAHS (µg/g dry wt.)					
	<0.050	0.05-0.5	>0.5-5	>5.0-50	>50

[a] after Denton *et al.* 1997; [b] as total metal

Table 11

Heavy Metals in Sediments from Tanapag Lagoon, Saipan

Site	Statistic	Heavy Metals (μg/g dry wt.)									
		Ag	As	Cd	Cr	Cu	Hg*	Ni	Pb	Sn	Zn
1 (a-c)	mean**	nc	6.71	nc	6.55	16.7	47.4	1.38	7.50	1.51	25.7
	range	<0.11 - <0.12	6.08 - 7.50	<0.04 - 0.06	5.30 - 8.01	13.6 - 19.6	40.5 - 53.1	1.13 - 1.58	5.77 - 8.99	1.27 - 1.69	22.0 - 29.6
2 (a-c)	mean	nc	6.20	nc	5.65	9.44	33.0	0.85	4.79	1.15	16.4
	range	<0.10 - <0.12	5.53 - 6.67	<0.03 - 0.11	5.25 - 6.08	8.18 - 10.8	30.4 - 36.5	0.67 - 1.16	4.08 - 5.43	0.89 - 1.64	15.0 - 17.2
3 (a-c)	mean	nc	2.49	nc	3.58	4.13	25.4	nc	2.08	0.76	8.93
	range	<0.11 - <0.12	2.10 - 3.29	<0.04 - <0.04	2.82 - 4.31	2.72 - 6.46	23.6 - 28.8	<0.20 - 0.62	1.09 - 3.15	0.59 - 0.98	5.89 - 11.0
4 (a-c)	mean	nc	5.79	nc	6.71	12.2	85.2	1.60	13.6	3.45	34.6
	range	<0.09 - <0.11	4.64 - 6.94	<0.03 - 0.15	5.70 - 8.27	8.73 - 14.5	82.1 - 87.4	1.15 - 2.03	8.73 - 18.0	2.68 - 4.40	25.6 - 42.3
5 (a-c)	mean	nc	3.95	nc	1.66	0.75	35.6	nc	1.09	0.35	5.37
	range	<0.08 - <0.12	3.40 - 4.61	<0.03 - <0.04	1.00 - 5.47	0.40 - 1.25	29.3 - 40.3	<0.15 - <0.21	0.34 - 2.40	0.31 - 0.40	3.68 - 12.0
6 (a-c)	mean	nc	6.81	nc	5.94	6.09	100	1.64	26.2	36.10	40.5
	range	<0.10 - <0.23	3.95 - 9.78	<0.03 - 0.30	3.65 - 9.93	4.18 - 10.1	86.0 - 127	0.61 - 4.89	6.61 - 121	1.53 - 209	19.7 - 186
7 (a-c)	mean	nc	4.11	0.08	3.25	7.87	347	1.58	6.49	1.27	19.8
	range	<0.10 - <0.12	3.65 - 4.82	0.04 - 0.13	2.86 - 3.81	5.97 - 11.5	113 - 862	1.24 - 2.05	4.97 - 8.49	1.22 - 1.31	15.3 - 41.6
8 (a-c)	mean	nc	3.28	0.12	4.61	7.44	85.3	2.06	7.53	3.88	21.5
	range	<0.10 - <0.12	2.67 - 3.83	0.07 - 0.28	4.19 - 5.46	6.25 - 9.46	73.9 - 111	1.97 - 2.16	5.67 - 11.4	3.34 - 4.68	17.4 - 26.9
9 (a-c)	mean	nc	3.76	0.08	3.53	5.40	83.8	1.27	4.14	1.22	15.4
	range	<0.10 - <0.11	3.25 - 4.37	0.07 - 0.11	3.19 - 3.68	4.39 - 6.38	78.7 - 87.0	1.07 - 1.48	3.93 - 4.60	1.11 - 1.37	14.3 - 15.9
10 (a-c)	mean	nc	3.65	0.10	5.90	12.8	109	2.07	9.47	2.95	26.2
	range	<0.09 - <0.12	3.50 - 3.86	0.08 - 0.11	5.56 - 6.33	11.8 - 13.8	98.8 - 119	1.91 - 2.20	8.72 - 10.5	2.44 - 3.30	23.9 - 29.4

* mercury data expressed as ng/g dry wt.; ** mean = geometric mean; nc = not calculable

Table 11 (continued)

Heavy Metals in Sediments from Tanapag Lagoon, Saipan

Site	Statistic	Heavy Metals (μg/g dry wt.)									
		Ag	As	Cd	Cr	Cu	Hg*	Ni	Pb	Sn	Zn
11 (a-c)	mean**	nc	1.59	0.06	3.35	2.27	21.3	0.88	0.86	0.55	5.28
	range	<0.09 - <0.12	1.34 - 2.17	0.03 - 0.09	2.95 - 3.60	1.70 - 3.09	17.1 - 25.5	0.77 - 1.07	0.45 - 1.34	0.47 - 0.65	3.46 - 6.99
12 (a-c)	mean	nc	2.46	0.21	9.01	8.94	67.7	2.13	7.36	1.90	22.7
	range	<0.10 - <0.12	2.07 - 2.81	0.19 - 0.26	7.42 - 10.2	6.76 - 11.4	55.5 - 83.3	1.74 - 2.83	6.13 - 8.28	1.45 - 2.29	17.9 - 25.8
13 (a-c)	mean	nc	4.37	0.13	4.02	2.43	33.8	0.85	3.85	0.90	13.8
	range	<0.10 - <0.12	4.28 - 4.51	0.08 - 0.20	3.54 - 4.71	1.97 - 3.31	29.7 - 39.8	0.72 - 0.96	2.89 - 5.04	0.80 - 1.07	11.6 - 16.0
14 (a-c)	mean	nc	10.04	0.58	9.67	27.8	101	5.06	40.6	3.54	127
	range	<0.10 - <0.11	9.56 - 10.8	0.54 - 0.61	8.84 - 11.0	25.6 - 32.5	97.7 - 106	4.74 - 5.23	36.1 - 43.4	3.34 - 3.94	119 - 134
15 (a-c)	mean	nc	5.73	0.24	5.03	8.87	52.7	1.52	12.04	2.15	38.6
	range	<0.09 - <0.12	3.98 - 7.49	0.21 - 0.31	3.67 - 9.44	6.77 - 11.9	41.8 - 60.4	1.11 - 1.80	9.47 - 15.1	1.98 - 2.47	31.0 - 46.5
16 (a-c)	mean	nc	1.46	0.10	1.40	1.42	21.0	0.33	1.29	0.62	3.24
	range	<0.09 - <0.12	1.05 - 2.11	0.09 - 0.12	0.91 - 1.71	0.74 - 1.99	14.7 - 27.7	0.22 - 0.49	0.70 - 1.79	0.58 - 0.68	1.84 - 4.51
17 (a-c)	mean	nc	1.78	0.14	1.48	1.19	21.8	nc	1.94	0.63	5.01
	range	<0.09 - <0.12	1.72 - 1.85	0.11 - 0.18	1.18 - 1.91	0.98 - 1.54	17.6 - 25.6	<0.16 - 0.37	1.53 - 2.27	0.59 - 0.71	4.38 - 6.38
18 (a-c)	mean	nc	1.91	0.12	1.54	0.92	18.4	nc	0.90	0.69	5.27
	range	<0.10 - <0.12	1.63 - 2.20	0.09 - 0.14	1.30 - 1.68	0.70 - 1.01	13.4 - 25.4	<0.17 - 0.25	0.64 - 1.52	0.63 - 0.72	3.76 - 9.20
19 (a-c)	mean	nc	2.81	nc	2.24	6.95	22.6	nc	2.92	1.00	11.3
	range	<0.10 - <0.11	2.25 - 3.30	<0.03 - <0.04	1.86 - 2.47	5.03 - 14.4	18.0 - 25.3	<0.21 - 0.41	2.49 - 3.42	0.91 - 1.07	10.2 - 12.9
20 (a-c)	mean	nc	3.36	nc	3.05	4.67	23.7	0.65	7.84	1.35	17.7
	range	<0.10 - <0.12	2.87 - 4.25	<0.03 - 0.11	2.73 - 3.63	2.82 - 7.60	16.8 - 31.6	0.46 - 1.02	5.32 - 12.9	1.11 - 1.52	12.2 - 25.6

* mercury data expressed as ng/g dry wt.; ** mean = geometric mean; nc = not calculable

Table 11 (continued)

Heavy Metals in Sediments from Tanapag Lagoon, Saipan

Site	Statistic	Heavy Metals (μg/g dry wt.)									
		Ag	As	Cd	Cr	Cu	Hg*	Ni	Pb	Sn	Zn
21 (a-c)	mean**	nc	1.33	nc	2.85	0.22	10.9	0.28	nc	0.30	1.63
	range	<0.09 - <0.12	1.12 - 1.85	<0.03 - <0.04	2.37 - 3.74	0.14 - 0.27	9.46 - 12.2	0.16 - 0.40	<0.32 - <0.42	0.23 - 0.48	1.20 - 2.72
22 (a-c)	mean	nc	1.66	nc	2.12	0.30	9.73	0.31	nc	0.32	2.84
	range	<0.10 - <0.12	1.45 - 1.86	<0.03 - 0.08	1.82 - 2.36	0.13 - 0.52	6.34 - 13.1	<0.20 - 0.53	<0.36 - 1.95	0.22 - 0.47	1.60 - 21.0
23 (a-c)	mean	nc	1.76	nc	2.13	0.35	18.1	0.29	nc	0.36	2.63
	range	<0.09 - <0.11	1.71 - 1.86	<0.03 - <0.04	2.02 - 2.35	0.29 - 0.45	17.0 - 19.7	0.20 - 0.46	<0.32 - <0.40	0.29 - 0.41	2.21 - 3.13
24 (a-c)	mean	nc	2.56	nc	2.67	1.90	39.5	0.57	1.33	0.85	6.53
	range	<0.10 - 0.33	2.32 - 2.70	<0.03 - <0.04	2.36 - 2.89	1.46 - 2.22	37.0 - 45.1	0.39 - 0.76	0.94 - 1.67	0.76 - 1.00	5.39 - 7.17
25 (a-c)	mean	0.28	2.86	0.06	3.18	3.61	52.7	0.88	1.29	0.72	8.99
	range	0.23 - 0.32	2.32 - 3.20	0.05 - 0.07	2.94 - 3.53	3.29 - 3.91	47.7 - 56.5	0.67 - 1.06	0.93 - 1.65	0.50 - 1.19	8.12 - 9.94
26 (a-c)	mean	0.17	3.95	nc	3.18	3.46	60.3	1.35	2.06	0.67	8.86
	range	0.07 - 0.31	3.25 - 4.63	<0.03 - 0.08	3.04 - 3.36	2.88 - 4.06	43.5 - 86.3	1.13 - 1.70	1.82 - 2.28	0.49 - 0.81	7.98 - 10.3
27 (a-c)	mean	0.27	3.88	nc	3.73	4.69	44.4	1.42	2.12	0.78	11.6
	range	0.22 - 0.30	3.38 - 4.36	<0.04 - 0.12	3.42 - 4.11	4.03 - 5.19	40.3 - 47.6	1.12 - 1.84	1.56 - 2.52	0.55 - 0.98	10.1 - 13.6
28 (a-c)	mean	nc	1.99	nc	2.27	1.02	12.1	0.35	nc	0.18	2.42
	range	<0.08 - <0.10	1.87 - 2.09	<0.03 - <0.04	2.14 - 2.52	0.85 - 1.20	11.6 - 12.4	0.23 - 0.47	<0.28 - <0.35	0.15 - 0.22	2.18 - 2.75
29 (a-c)	mean	0.16	3.14	nc	2.71	5.13	55.0	0.78	3.55	1.22	15.2
	range	0.10 - 0.24	2.41 - 2.59	<0.03 - <0.04	2.38 - 2.91	3.94 - 6.94	41.4 - 85.2	0.72 - 0.86	2.44 - 5.20	0.86 - 1.78	12.3 - 21.9
30 (a-c)	mean	0.17	4.52	0.06	3.12	8.31	64.6	1.16	6.90	1.93	25.8
	range	0.12 - 0.26	4.05 - 5.60	0.05 - 0.10	2.64 - 3.72	5.97 - 12.6	55.1 - 82.3	0.84 - 1.80	4.36 - 9.48	1.45 - 2.30	20.8 - 31.4

* mercury data expressed as ng/g dry wt.; ** mean = geometric mean; nc = not calculable

Table 11 (continued)

Heavy Metals in Sediments from Tanapag Lagoon, Saipan

Site	Statistic	Heavy Metals (μg/g dry wt.)									
		Ag	As	Cd	Cr	Cu	Hg*	Ni	Pb	Sn	Zn
31 (a-c)	mean**	nc	2.91	nc	2.74	2.02	30.7	nc	6.68	7.05	13.4
	range	<0.08 - <0.12	2.64 - 3.29	<0.03 - 0.08	2.13 - 3.38	1.36 - 2.49	22.9 - 41.7	<0.16 - 0.31	3.56 - 23.7	1.45 - 68.1	7.90 - 31.9
32 (a-c)	mean	nc	1.38	nc	2.65	0.62	12.1	nc	nc	0.08	1.76
	range	<0.08 - <0.11	1.14 - 1.58	<0.03 - <0.04	2.29 - 2.98	0.48 - 0.75	9.28 - 14.0	<0.13 - <0.17	<0.04 - 0.88	0.03 - 0.29	1.55 - 2.06
33 (a-c)	mean	nc	0.82	nc	2.43	nc	5.37	nc	nc	nc	0.53
	range	<0.07 - <0.11	0.73 - 0.89	<0.03 - <0.04	2.11 - 3.44	<0.07 - 0.11	3.46 - 7.01	<0.12 - <0.18	<0.26 - <0.37	<0.02 - 0.08	0.41 - 0.58
34 (a-c)	mean	nc	0.69	nc	1.51	nc	3.95	nc	nc	0.10	0.15
	range	<0.09 - <0.11	0.62 - 0.74	<0.03 - <0.04	1.40 - 1.64	<0.08 - <0.11	2.78 - 5.21	<0.14 - <0.17	<0.29 - <0.37	0.07 - 0.14	0.09 - 0.45
35 (a-c)	mean	nc	0.90	nc	1.11	nc	3.57	nc	nc	0.08	0.10
	range	<0.08 - <0.11	0.62 - 1.09	< 0.03 - <0.04	0.96 - 1.17	<0.08 - <0.11	3.21- 4.25	<0.13 - <0.17	<0.27 - <0.37	0.04 - 0.14	0.05 - 0.27
36 (a-c)	mean	nc	1.53	nc	2.20	0.78	16.2	0.36	nc	0.24	2.09
	range	<0.08 - <0.10	1.44 - 1.59	< 0.03 - <0.04	2.03 - 2.44	0.68 - 0.86	13.4 - 20.9	0.26 - 0.61	<0.28 - <0.35	0.15 - 0.34	1.68 - 2.96
37 (a-c)	mean	nc	1.87	nc	1.43	nc	5.89	nc	1.20	nc	0.78
	range	<0.08 - <0.11	1.72 - 2.04	<0.06 - 0.13	1.30 - 2.25	<0.08 - 0.28	5.25 - 6.98	<0.14 - <0.18	1.03 - 1.35	<0.02 - 0.22	0.39 - 3.74
38 (a-c)	mean	nc	0.99	nc	2.07	nc	3.54	nc	nc	nc	nc
	range	<0.08 - <0.10	0.89 - 1.13	<0.05 - <0.06	1.83 - 2.32	<0.07 - <0.10	2.84 - 4.08	<0.13 - <0.17	<0.55 - 0.75	<0.02 - 0.03	<0.03 - <0.04
39 (a-c)	mean	nc	1.57	nc	2.38	nc	4.54	nc	nc	0.05	nc
	range	<0.08 - <0.10	1.53 - 1.63	<0.05 - <0.06	2.26 - 2.60	<0.08 - <0.10	4.02 - 5.16	<0.14 - <0.16	<0.45 - 0.88	0.04 - 0.06	<0.03 - 0.10
40 (a-c)	mean	nc	1.15	nc	1.62	nc	2.88	nc	nc	nc	nc
	range	<0.06 - <0.09	0.97 - 1.35	<0.04 - <0.06	1.45 - 1.76	<0.06 - <0.09	2.14 - 4.46	<0.11 - <0.16	<0.36 - <0.53	<0.02 - 0.08	<0.02 - <0.03
41 (a-c)	mean	nc	0.76	nc	1.06	nc	5.16	nc	nc	nc	nc
	range	<0.07 - <0.11	0.56 - 1.05	<0.05 - <0.07	0.96 - 1.17	<0.07 - <0.11	4.76 - 5.39	<0.13 - <0.19	<0.42 - <0.62	<0.02 - 0.15	<0.03 - <0.04

* mercury data expressed as ng/g dry wt.; ** mean = geometric mean; nc = not calculable

therefore seems reasonably safe to assume that silver is not an element of major environmental concern in this part of the world.

1.2 Arsenic (As):

Arsenic, in the form normally encountered in the environment, does not appear to be particularly toxic to aquatic organisms (Moore 1991). The most important source of this element to the aquatic environment is domestic wastewater, reflecting the use of arsenic in household preparations and in small industries that discharge effluents to municipal waste systems. Other major sources include sewage sludge, manufacturing process, smelting and refining (Moore 1991).

Arsenic levels determined in UK estuaries ranged from 5 μg/g in uncontaminated sediments from the Axe Estuary to 3732 μg/g in polluted sediments from Restronguet Creek, Cornwall, which receives drainage from metal mining areas (Langston, 1984, 1985). Levels previously reported for Guam harbor sediments ranged from <1.0-17.0 μg/g (Denton *et al.* 1997).

In the present study, mean sedimentary arsenic levels ranged from a low of 0.69 μg/g at site 41, in the outer lagoon, to a high of 10.0 μg/g at site 14, off the southern face of the dump. Arsenic levels determined earlier by DEQ (1987) in sediments from around the dump ranged from 2.4-8.6 μg/g with an overall geometric mean of 3.93 μg/g. Pooling all data from our study for sites located close to the dump (sites 14, 15, 29, 30 and 31) gives a similar geometric mean value of 4.46 μg/g.

Denton *et al.* (1997) advocate that sedimentary arsenic levels of 1-3 μg/g in this part of the world are reflective of clean environments while 6-10 μg/g are indicative of lightly polluted situations (Table 10). Based on their criteria, therefore, all nine outer sites and a little under half the nearshore sites in Tanapag Lagoon may be classified as clean while the remainder are only lightly contaminated with arsenic.

1.3 Cadmium (Cd):

Cadmium, particularly as the free cadmium ion, is highly toxic to most plant and animal species (Moore 1991). The main anthropogenic sources of cadmium relate to metallurgical industries, municipal effluents, sewage sludge and mine wastes. Other sources are fossil fuels and some phosphorus containing fertilizers (UNEP 1985).

Recent literature values for this element in coastal sediments range from <0.01-33 μg/g (see Table 5). Apparently, concentrations in relatively pristine areas are around 0.2 μg/g or less with levels exceeding 100 μg/g at grossly contaminated sites (Naidu and Morrison 1994).

Reviewing the data obtained during the present study, it is clear, then, that cadmium is currently not a problem metal at any of the sites examined although some mild enrichment was evident at site 14 close to Puerto Rico dump. Here, levels encountered in the three cores ranged from 0.54-0.61 μg/g with a mean of 0.58 μg/g. These values are somewhat lower than the range of 1.0-2.7 μg/g found earlier by DEQ (1987) in sediments off the western edge of the dump (Table 5).

1.4 Chromium (Cr):

Chromium is only moderately toxic to aquatic organisms (Moore 1991). Coastal marine sources of this element are dominated by input from rivers, urban runoff, domestic and industrial wastewaters and sewage sludge (Moore 1991). In harbor locations, additional contributions from the metallic components of watercraft, anti-fouling paints, and wood preservatives can also be expected.

Chromium levels in uncontaminated sediments vary according to their mineralogical characteristics and range between 10-100 µg/g (Turekian and Wedepole 1961). Calcareous sediments of biogenic origin like those found in coral reef environments are typically lower and normally contain 3-5 µg/g (Denton *et al.* 1997). In severely contaminated areas, sedimentary chromium concentrations have been known to exceed 2000 µg/g (Young and Means 1987).

Chromium levels previously determined for Guam harbor sediments ranged from 3.09-52.7 µg/g and were indicative of fairly clean conditions overall, with light to moderate enrichment in places (Denton *et al.* 1997). The same may be said for the earlier DEQ (1987) data for Saipan sediments in the vicinity of Puerto Rico dump (Table 5).

Mean levels of sedimentary chromium found during the present investigation ranged from 1.06-9.67 µg/g. The highest values occurred in samples from around the dump (sites 14 and 15), the port (site 10), and the small-boat marinas (sites 1, 2, 4 and 12). However, all fall into the non-polluted category according to the classification scheme presented in Table 10.

1.5 Copper (Cu):

Copper is highly toxic to most aquatic plants and invertebrates (Brown and Ahsanulla 1971, Denton and Burdon-Jones 1982) and is one of the most toxic heavy metals to fish (Denton and Burdon-Jones 1986, Moore 1991). Inputs of this element into natural waters are derived from numerous sources including mining, smelting, domestic and industrial wastewaters, steam electrical production, incinerator emissions, and the dumping of sewage sludge (Moore 1991). While coastal waters are generally dominated by inputs from rivers and atmospheric sources (Nriagu 1989), algaecides and anti-fouling paints remain a primary source of copper to harbor areas.

Copper has a high affinity for clays, iron and manganese oxides, and carbonate materials (Moore 1991). As a consequence residues are often elevated in sediments near localized sources of input. In reviewing the literature, it is apparent that copper levels in clean, non-geochemically enriched sediments are in the order of 10 µg/g or less (see Table 5). In contrast, levels in excess of 2000 µg/g have been reported for copper polluted sediments (Legoburu and Canton 1991, Bryan and Langston 1992). Previous studies on Guam revealed copper levels of less than 1 µg/g in clean coastal sediments rising to a high of 181 µg/g in the relatively copper enriched waters of Apra Harbor (Denton *et al.* 1997).

In the current study, copper concentrations were <1 µg/g in sediments from all nine outer lagoonal site. Greater enrichment was apparent in several of the nearshore sites particularly in areas subjected to a high incidence of boating and shipping activities. The highest mean

copper level recorded was 27.8 μg/g in the sub-tidal sediments of site 14, at the southernmost edge of Puerto Rico dump. This was the only site where the degree of copper enrichment fell into the moderately polluted category (Table 10). Data from this site also falls within the range previously found by DEQ (1987) in sediments from this general area (see Table 5).

A point worth mentioning here is that anthropogenic copper is predominantly associated with the clay and silt fraction of calcareous sediments (Belt Collins Hawaii, 1994). Thus, variations in the particle size distribution between samples may well account for some of the inter-station copper variability observed during the present work.

1.6 Mercury (Hg):

Mercury is highly toxic to aquatic organisms, particularly in the organic form (Moore 1991). The number one anthropogenic source of mercury to the environment is discharge from coal-burning power plants followed by atmospheric fallout from other sources (e.g. incineration of municipal refuse), chemical manufacturing processes, and the discharge of domestic wastes (Moore 1991). Mercury levels in urban runoff are generally very low (Marsalek and Schroeter 1988) although relatively high concentrations have been found in oil and other petroleum products (Patterson *et al.* 1987). Thus, some enrichment can be expected in harbor areas. It is also pertinent to note here that mercury was once extensively used in anti-fouling paints to prevent the growth of marine organisms on ship hulls. In 1969, for example, 12% of the mercury used in the U.S. went into such paints (Gerlach 1981).

Baseline levels of total mercury in uncontaminated sediments are reportedly in the order of 30 ng/g (Bryan and Langston 1992, Benoit *et al.* 1994). However, values published for pristine sediments from the tropical north Queensland coast of Australia were somewhat lower than this and ranged from 4-16 ng/g (Knauer 1976). Following an extensive survey of sediments on Guam, Denton *et al.* (1997) concluded that mercury concentrations of 5-10 ng/g were typical of biogenic carbonates in uncontaminated environments. They further classified sediments with mercury levels of 20-100 ng/g as lightly enriched whereas those with values of up to 300 ng/g were ranked as moderately contaminated. Mercury concentrations between 300-1000 ng/g were indicative of heavily contaminated sediments (Table 10).

In light of the above, it is clear that sediments in the offshore region of Tanapag Lagoon are comparatively free of mercury contamination. The slightly elevated mercury levels determined in sediments from site 36 likely reflect the relatively close proximity of this particular station to the sewer outfall. Closer to shore, some mercury enrichment was noted and presumably mirrors the greater incidence of boat and shipping activities together with runoff from the land. In most cases, however, the degree of contamination was relatively modest and fell within the lightly contaminated category noted above. Moderate mercury contamination was evident in sediments from site 10, at the entrance of Saipan Harbor (mean: 109 ng/g), and from site 14 (mean: 101 ng/g) on the leeward side of the dump.

Pervious DEQ data for mercury in sediments from around the Puerto Rico dump are included in Table 5. Detectable levels were recorded in sediments from four of six sites and ranged from 125-181 ng/g with a geometric mean of 151 ng/g. Mercury levels detected at comparable sites during the present study, i.e. sites 14, 15, 29, 30 and 31 (see Fig. 3), were

appreciably lower than the earlier DEQ data and ranged from 23-106 ng/g with an overall mean of 52 ng/g.

The only heavily contaminated sediment identified during the present study was found alongside the new docks, at site 7. Here, levels ranged from 113-862 ng/g and were comparable with the highest mercury concentrations found in Apra Harbor sediments on Guam (Denton *et al.* 1997).

Although sedimentary mercury concentrations at certain sites were relatively high by local standards, they pale in comparison to levels encountered in severely polluted waters from other parts of the world. For example, up to 6 µg/g mercury was recorded by Langston (1986) for sediments taken from the Mersey Estuary in the UK, while Benoit *et al.* (1994), reported a maximum mercury concentration of 570 µg/g in sediments from Honda Bay in the Philippines. Perhaps the all-time highest values reported for mercury in marine sediments (in excess of 2000 µg/g) are from samples collected from the grossly contaminated Minimata Bay area in Japan (Tokuomi 1969).

It is noteworthy that mercury, like copper, is also primarily associated with the silt and clay fraction of biogenic carbonates (Belt Collins Hawaii 1994). Thus, the generally higher mercury levels found at the nearshore sites may be, at least in part, a reflection of the finer textured sediments found there (see Table 9).

1.7 Nickel (Ni):

Nickel is only moderately toxic to most species of aquatic plants and is one of the least toxic inorganic agents to invertebrates and fish (Denton and Burdon-Jones, 1986, Moore 1991). The major source of discharge to natural waters is municipal wastewater (Sung *et al.* 1986) followed by smelting and the refining of nonferrous metals. Total nickel residues in clean coastal sediments typically range between 10 and 20 µg/g (Bryan and Langston 1992), but may fall below 1 µg/g in unpolluted coastal regions, away from nickel bearing geological formations (Moore 1991). In contaminated regions, concentrations may exceed 200 µg/g (Fowler 1993). Sedimentary nickel levels recently determined in Guam harbors ranged from <0.2-71.0 µg/g (Denton *et al.* 1997). Baseline levels throughout the area were estimated at 1-3 µg/g.

Nickel concentrations determined in sediments during the present investigation ranged from less than 1 µg/g at all offshore sites to 5.06 µg/g at site 14, near the dump. There was evidence of light enrichment in many of the other nearshore sites although nowhere did levels exceed 3 µg/g. In fact, all sites except 8, 10 and 12 yielded sedimentary nickel levels of less than 2 µg/g. Clearly, nickel is not a problem metal in Tanapag Lagoon. This conclusion is supported by the earlier DEQ (1987) investigation that showed undetectable quantities of nickel in five out of six sediment samples from around Puerto Rico dump (Table 5).

1.8 Lead (Pb):

Inorganic lead is moderately toxic to aquatic plants and ranks behind mercury, cadmium, copper and zinc in order of toxicity to invertebrates and fish (Denton and Burdon-Jones

1986). In contrast, organolead compounds, particularly the alkyl-lead compounds used as antiknock agents in gasoline, are highly toxic to all forms of life (Moore 1991).

Primary sources of lead into natural waters include manufacturing processes (particularly metals), atmospheric deposition (e.g. from pyrometallurgical nonferrous metal production, the combustion of leaded fuels, the burning of wood and coal, and the incineration of municipal refuse), domestic wastewaters, sewage and sewage sludges (Nriagu and Pacyna 1988).

Lead is barely soluble in seawater and is readily adsorbed by hydrous metal oxides, clay minerals and organic materials. Consequently, it is not highly mobile in the aquatic environment, and tends to accumulate in sediments close to its point of entry into the hydrosphere. Harbor sediments are typically enriched (Table 5) owing to the long-term use of alkyl-lead compounds in boat fuels, the use of anti-corrosion lead-based paints, lead containing biocides (used as lead "boosters" in copper-based paints), and lead pipe, sheet and fittings used in water craft construction (UNEP 1985).

Residues in the 15-50 μg/g range are frequently reported for coastal and estuarine sediments worldwide (Moore 1991). However, levels may be 1-2 orders of magnitude higher, or more, in polluted sediments near wastewater outfalls (Louma and Phillips 1988) or lead mining operations (Bryan and Langston 1992). The highest level reported to date is 266 mg/g in sediments adjacent to a battery factory in Suva Harbor, Fiji (Naidu and Morrison 1994). Lead levels in clean coastal environments are reported to be around 25 μg/g or less (Schafer and Bascom 1976, UNEP 1985, Bryan and Langston, 1992). Recent studies conducted on Guam suggest that baseline levels for lead in uncontaminated carbonate sediments are <1 μg/g (Denton *et al.* 1997).

In the present work, all offshore sediments were classified as clean with the exception site 36, near the sewer outfall, where light enrichment was apparent (Table 11). Closer to shore, sedimentary lead concentrations were generally higher, no doubt a reflection of the relatively high intensity of harbor and boating activities in the area. However the degree of contamination was fairly modest compared with harbors from other parts of the world (Table 5). In fact, only sites 6 and 14, were classified as moderately contaminated (Table 10) with mean sedimentary lead levels of 26.2 μg/g and 40.6 μg/g, respectively. The close proximity of both sites to the dump is noteworthy and suggests that the latter may well be a primary point source of this element to marine sediments in the immediate vicinity. The fact that DEQ (1987) found lead levels of 100-200 μg/g in sediments from the same general area in the late 80's lends credence to this hypothesis (Table 5).

1.9 Tin (Sn):

Naturally occurring inorganic tin is relatively harmless to aquatic organisms in direct contrast to anthropogenic organotin compounds which are highly toxic. (UNEP 1985, Bryan and Langston 1992). The primary sources of inorganic tin to surface waters are base metal mining and smelting operations; municipal wastewater and sewage sludge; combustion of fossil fuels, particularly oil and, to a lesser extent, coal; steel and tinplate manufacture; tanning; and atmospheric deposition, particularly near municipal incinerators (Moore 1991, Bryan and Langston 1992).

The number one source of organotins is the dissolution of tributyltin (TBT) and related compounds used in anti-fouling paints (Moore 1991). Apart from being highly toxic, TBT is very persistent with an estimated half-life of about 2 years (de Mora *et al.* 1989). As a consequence, levels of this compound are frequently elevated in the sediments and water of harbors, ports and marinas.

Tributyltin compounds consist of a tin (Sn) atom covalently bonded to three butyl (C_3H_9-) moieties and an associated anion (X). A number of organotin compounds have been used as ingredients in paints, pesticides and preservatives, including trialkyltins (e.g., bis(tributyltin) oxide (TBTO), bis(tributyltin) sulfide, tributyltin acetate, tributyltin fluoride, tributyltin naphthenate, and tributyltin resinate), triaryltins (e.g., triphenyltin hydroxide), dialkyltins (e.g., (TBTFl) dibutyltin dilaurte, dibutyltin isooctylmercaptonacetate, and dibutyltin maleate), and monooctyltins (e.g., monooctyltin tris isooctyl mercaptoacetate). In aquatic systems, the distribution of TBT species is dependent on pH and salinity. In seawater, the hydrated TBT cation, tributyltin chloride (TBTCl), bis(tributyltin carbonate), and tributyltin hydroxide are in equilibrium (USEPA 2000).

All forms of tin are relatively insoluble and hence are readily sorbed by suspended solids upon entry into the hydrosphere. As a consequence they are quickly transported to bottom sediments. Natural tin concentrations in uncontaminated, non-mineralized marine sediments usually lie between 0.1-1.0 μg/g but in geologically enriched areas may exceed 1000 μg/g (Bryan *et al.* 1985, Bryan and Langston 1992). Typical surface sediment values for TBT reportedly range from 0.005-0.5 μg/g (as Sn) depending on the proximity to areas of high boating/shipping activity, and usually accounts for less than 5% of the total tin present (Bryan and Langston 1992). However, Maguire (1987) found an extremely high TBT-Sn level of 10.3 μg/g in the sediments of Vancouver Harbor, Canada, while Stewart and de Mora (1992) determined an all time high of 38 μg/g in Suva Harbor, Fiji.

Baseline levels of tin in uncontaminated calcareous sediments are lower than 0.1 μg/g, while concentrations between 0.1-5.0 μg/g are indicative of light anthropogenic enrichment (see Table 10). In the present study, the great majority of sites fell into the latter category with concentrations generally decreasing in a seaward direction away from the coast. Moderate tin enrichment was identified in one of the three sediment cores from site 31 with replicate analyses yielding values of 3.5-68.1 μg/g with an overall mean of 15.49 μg/g. The highest level encountered during the study was found in one of the cores removed from site 6. In this particular instance, replicate analyses yielded values ranging from 122-209 μg/g (mean of 172 μg/g). However, analysis of the remaining two cores from this site produced levels of 1.44 to 1.48 μg/g indicating that the tin contamination was highly localized possibly emanating from dislodged flakes of antifouling paint or specks of solder associated with maritime construction/repair activities.

What proportion of the additional tin loading in Tanapag Lagoon sediments represents TBT, and other organotin compounds, is currently unknown. Ballpark estimates are in the order of 10-100 ng/g assuming TBT accounts for 1% of the total tin present. The impact of TBT at this level on local sediment dwelling organisms also remains to be determined, and ultimately

depends on the partitioning behavior of TBT into sediment pore waters. If a conservative sediment-to-water ratio of $1x10^5$-to-1 (see Cleary and Stebbing 1987) is applied to the sediment TBT estimates given above, pore water concentrations of 0.1-1.0 ng/l are obtained. This range lies dangerously close to TBT toxic thresholds reported for a number of marine organisms. For example, laboratory experiments have shown that levels as low as 1 ng/l can induce deleterious, sub-lethal effects in sensitive invertebrate species (Bryan *et al.* 1989, Chagot *et al.* 1990, Gibbs *et al.* 1991). Likewise, 10-100 ng/l is sufficient to kill certain embryonic and larval organism and juvenile fish (Ward *et al.* 1981, Bryan and Gibbs 1991).

The biological availability of sediment-bound TBT is controlled by a wide range of parameters including pH, salinity and organic carbon content (USEPA 2000). Langston and Burt (1991) found that the deposit feeding bivalve, *Scrobicularia plana,* responded primarily to particulate associated TBT rather than amounts in solution in pore waters. Apparently, this species has virtually disappeared from areas of SW England where sediment-bound TBT concentrations exceed 800 ng/g (dry weight). Other studies have shown that mollusks are adversely effected by sediment concentrations of TBT as low as 10 ng/g, while some copepod crustaceans, echinoderms, polychaetes, tunicates, phytoplankton, and fish respond to sediment TBT concentrations between 10 and 100 ng/g (Bryan and Gibbs 1991). The toxicity of TBT to tropical marine organisms and its potential impact on coral reef communities has received scant attention to date.

TBT has been described as the most toxic substance ever deliberately introduced into the aquatic environment (Goldberg 1986). Its dramatic effect on the growth and reproductive success of several invertebrate species, particularly mollusks, is now well documented. In fact, the once flourishing oyster fisheries along the coasts of eastern England and western France were decimated as a result of unrestricted use of TBT-based anti-fouling paints from early 1970's until the mid 1980's (Alzieu *et al.* 1986, Alzieu 1991, Dowson *et al.* 1993).

Small boats and pleasure craft are believed to be the primary source of TBT contamination to the aquatic environment. For this reason, legislation banning the use of TBT-based biocides on boats of less than 25 m in length was introduced in several countries, including the U.S.A., between 1986 and 1989 (Evans *et al.* 1995). There are, as yet, no restrictions prohibiting the use of this biocide on larger vessels. Thus, sedimentary TBT levels can be expected to increase in the vicinity of ports, harbors, navigational channels, and deep-water anchorage sites used by commercial shipping traffic.

1.10 Zinc (Zn):

Zinc is a very common environmental contaminant and usually outranks all other metals considered here in terms of abundance. It is not particularly toxic, which is fortunate, because it is sometimes released into the sea in substantial quantities (Bryan and Langston 1992). Major sources of this element to the aquatic environment include the discharge of domestic wastewaters; coal-burning power plants; manufacturing processes involving metals; and atmospheric fallout (Moore 1991). Approximately one third of all atmospheric zinc emissions are from natural sources, the rest emanating from metal production (smelting and refining); the burning of coal and oil; and from fertilizer and cement production (Nriagu 1989, Nriagu and Pacyna 1988).

Sediments are a primary repositories for zinc in the aquatic environment, and residues in excess of 3000 μg/g have been found in the vicinity of mines and smelters (Poulton 1987, Bryan *et al.* 1985). Enclosed harbors, with restricted water circulation, are particularly prone to zinc contamination from a variety of localized sources including brass and galvanized fittings on boats, wharves and piers; zinc-based anti-corrosion and anti-fouling paints; zinc sacrificial anodes; and numerous metallic structures. Other important sources in these areas are contaminated windblown dust and surface runoff from a multitude of contributing harbor activities. Not surprisingly, then, some of the highest sedimentary zinc levels ever reported come from harbor areas. For example, Legorburu and Canton (1991) found a maximum of 5620 μg/g in sediments from Pasajes Harbour in Spain, while Poulton (1987) recorded a high of 5700 μg/g for Hamilton Harbour in Canada.

Sediments from uncontaminated waters typically contain zinc concentrations in the order of 5-50 μg/g depending upon local geology (Moore 1991). Levels normally encountered in carbonate sediments from pristine reef waters, away from coastal influences, are normally less than 1 μg/g (Burdon-Jones and Denton 1984). Closer to shore, they are usually higher and may be appreciably so, near urban and commercial growth centers. Coastal sediments on Guam, for instance, contained zinc levels that ranged from baseline values of 2-3 μg/g, in relatively clean areas, to well over 100 μg/g in areas impacted by boating and shipping activities, and discharges from storm drains and sewer outfalls (Denton *et al.* 1997). Likewise, previous data for Saipan identified a similarly broad range of 15.8-324 μg/g in sediments receiving zinc contaminated water, dust, and debris from the Puerto Rico dump (DEQ 1987).

In the present study, mean sedimentary zinc concentrations in the offshore portion of Tanapag Lagoon were 0.1 μg/g, or lower, at outer barrier sites 35, 38 and 41, rising to 2.09 μg/g at site 36 near the sewer outfall. Significantly higher concentrations were present in sediments from almost all of the nearshore sites with levels peaking at 127 μg/g at site 14, at the southernmost edge of the dump. This was the only heavily contaminated site according to the classification scheme shown in Table 10. Sedimentary zinc levels at all other sites fell into the clean or lightly contaminated category.

2. POLYCHLORINATED BIPHENYLS IN TANAPAG LAGOON SEDIMENTS

The PCB data obtained during the present study are summarized in Table 12. The data are presented as the total PCB concentrations (sum of the detectable congeners from the standard mix) and rank order of abundance of PCB homologues in sediment samples from each site. The following discussions deal with each of these components separately. The identification of dominant PCB congeners in contaminated samples is also considered. All referenced data are expressed on a dry weight basis unless stated otherwise.

Table 12

PCBs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{20} PCB Concentration (ng/g dry wt.)			Overall Order of Abundance of Detectable PCB Homologues (Cl_2B to $Cl_{10}B$)
	Mean	Median	Range	
1 (a-c)	4.09	3.11	3.09 – 6.07	$Cl_7B > Cl_{10}B > Cl_6B > Cl_2B > Cl_9B > Cl_5B > Cl_8B$
2 (a-c)	2.35	1.83	1.78 – 3.45	$Cl_6B > Cl_7B > Cl_2B > Cl_5B$
3 (a-c)	NC	0.25	BDL – 0.29	Cl_6B
4 (a-c)	4.87	4.93	3.55 – 6.12	$Cl_{10}B > Cl_7B > Cl_6B > Cl_9B > Cl_5B$
5 (a-c)	NC	BDL	BDL	
6 (a-c)	5.44	3.91	3.98 – 8.62	$Cl_7B > Cl_6B > Cl_5B > Cl_{10}B > Cl_2B > Cl_9B$
7 (a-c)	4.64	4.68	4.47 – 4.77	$Cl_5B > Cl_6B > Cl_7B > Cl_3B > Cl_{10}B > Cl_2B > Cl_9B$
8 (a-c)	4.86	3.92	3.52 – 7.13	$Cl_7B > Cl_6B > Cl_5B > Cl_{10}B > Cl_9B$
9 (a-c)	11.1	2.83	2.64 – 27.7	$Cl_7B > Cl_6B > Cl_5B > Cl_8B > Cl_9B > Cl_{10}B$
10 (a-c)	8.53	9.48	6.22 – 9.89	$Cl_7B > Cl_6B > Cl_{10}B > Cl_5B > Cl_9B > Cl_8B$

NC = not calculable
BDL = below detection limits

Table 12 (cont.)

PCBs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{20} PCB Concentration (ng/g dry wt.)			Overall Order of Abundance of Detectable PCB Homologues (Cl_2B to $Cl_{10}B$)
	Mean	Median	Range	
11 (a-c)	NC	BDL	BDL	
12 (a-c)	0.51	0.48	0.25 – 0.81	$Cl_6B > Cl_5B > Cl_7B$
13 (a-c)	0.59	0.40	0.38 – 1.00	$Cl_5B > Cl_7B > Cl_{10}B > Cl_6B$
14 (a-c)	16.6	15.9	14.9 – 18.8	$Cl_7B > Cl_6B > Cl_{10}B > Cl_5B > Cl_2B > Cl_9B > Cl_8B$
15 (a-c)	4.26	3.57	3.42 – 5.80	$Cl_7B > Cl_6B > Cl_{10}B > Cl_5B > Cl_8B$
16 (a-c)	NC	BDL	BDL – 0.39	Cl_5B
17 (a-c)	1.58	1.32	1.08 – 2.34	$Cl_7B > Cl_6B > Cl_5B > Cl_{10}B$
18 (a-c)	NC	0.31	BDL – 0.37	Cl_5B
19 (a-c)	NC	BDL	BDL – 0.38	Cl_5B
20 (a-c)	2.80	2.61	0.83 – 4.97	$Cl_6B > Cl_7B > Cl_5B$

NC = not calculable
BDL = below detection limits

Table 12 (cont.)

PCBs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{20} PCB Concentration (ng/g dry wt.)			Overall Order of Abundance of Detectable PCB Homologues (Cl_2B to $Cl_{10}B$)
	Mean	Median	Range	
21 (a-c)	NC	BDL	BDL – 0.45	Cl_5B
22 (a-c)	NC	BDL	BDL – 0.34	Cl_5B
23 (a-c)	NC	BDL	BDL – 0.37	Cl_5B
24 (a-c)	0.53	0.46	0.33 – 0.79	$Cl_5B > Cl_6B$
25 (a-c)	3.78	1.04	0.41 – 9.89	$Cl_{10}B > Cl_9B > Cl_5B > Cl_6B > Cl_7B$
26 (a-c)	2.00	1.91	1.52 – 1.91	$Cl_{10}B > Cl_9B > Cl_6B > Cl_7B > Cl_5B$
27 (a-c)	0.70	0.75	0.30 – 1.06	$Cl_6B > Cl_7B > Cl_5B > Cl_{10}B$
28 (a-c)	NC	BDL	BDL	
29 (a-c)	3.52	3.91	2.50 – 4.14	$Cl_7B > Cl_6B > Cl_{10}B > Cl_9B > Cl_5B > Cl_8B$
30 (a-c)	2.60	2.33	1.96 – 3.50	$Cl_7B > Cl_6B > Cl_5B > Cl_{10}B$

NC = not calculable
BDL = below detection limits

Table 12 (cont.)

PCBs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{20} PCB Concentration (ng/g dry wt.)			Overall Order of Abundance of Detectable PCB Homologues (Cl_2B to $Cl_{10}B$)
	Mean	Median	Range	
31 (a-c)	NC	0.19	BDL - 0.34	Cl_6B
32 (a-c)	NC	BDL	BDL	
33 (a-c)	NC	BDL	BDL	
34 (a-c)	NC	BDL	BDL	
35 (a-c)	NC	BDL	BDL	
36 (a-c)	NC	BDL	BDL	
37 (a-c)	NC	BDL	BDL	
38 (a-c)	NC	BDL	BDL	
39 (a-c)	NC	BDL	BDL	
40 (a-c)	NC	BDL	BDL	
41 (a-c)	NC	BDL	BDL	

NC = not calculable
BDL = below detection limits

A visual representation of PCB distribution and abundance throughout the study area is depicted by an isoconcentration contour map in Appendix D.

2.1 Total PCB Concentrations (ΣPCB):

By the time leading manufacturers of PCB had ceased production of these compounds in the late 1970's, the cumulative world production had reached a staggering 1.2 million tons (Bletchley 1984). Of this, approximately 65% can still be accounted for in amounts held in storage, contained in landfills, and currently in use in older electrical equipment (e.g., large capacitors and transformers, small capacitors used for fluorescent lights, small electric motors, and compressors used in refrigerators and air conditioners). Almost all of the remainder, some 370 x 10^3 t, is bound up in coastal sediments and dissolved in open ocean water (Tanabe 1988). PCBs, by virtue of their recalcitrant nature, are, therefore, likely to be with us for a long time to come. In point of fact, less than 5% of PCB produced worldwide has been destroyed to date.

The ubiquity of PCBs in the environment is a function of their resilience to chemical attack, and their small but nonetheless significant vapor pressure. Once airborne, they can, therefore, be transported thousands of miles from their original source to remote corners of the planet (Atlas *et al.* 1986, Iwata *et al.* 1993, Tanabe *et al.* 1994). In fact, aerial transport is considered to be the major route of PCBs to the open ocean (Tanabe and Tatsukawa 1986). In contrast, domestic and industrial wastes are the primary sources of PCB to coastal waters adjacent to urban growth centers (Iwata *et al.*1994).

World baseline levels for total PCBs in clean coastal sediments are less than 1 ng/g and largely reflect atmospheric transport processes (Fowler 1986, Phillips 1986). In grossly polluted situations receiving inputs from localized point sources, levels as high as 61 µg/g have been reported (Nisbet 1976). Typical PCB concentrations found in marine and estuarine sediments from around the world are presented in Table 6. The values are representative of sediments from relatively uncontaminated through to grossly polluted areas.

In the current study, all offshore sites in Tanapag Lagoon were relatively free of PCB contamination with total levels (Σ_{20}PCB) consistently below 1 ng/g (Table 12). Somewhat higher levels were generally observed closer to shore with a maximum mean value of 16.6 ng/g recorded at site 14, adjacent to Puerto Rico dump. Relatively high mean levels were also encountered at site 9 (11.1 ng/g) and 10 (8.53 ng/g). Only sediments from sites 9 and 14 were classified as moderately polluted with PCBs, according to the guidelines presented in Table 10. Elsewhere in the study area, they were ranked as either clean or lightly contaminated.

Examples of the PCB profiles in sediments from sites 9 and 14 are shown in Figs. 5 and 6, respectively[2]. Interestingly, the profile from site 9 closely resembles the technical PCB mixture, Aroclor 1260, whereas that obtained from site 14 is more like a combination of Aroclor 1260 and one or more of the lower chlorinated commercial mixtures, possibly Aroclor.

[2] The dominant peaks eluting between the internal standard, pentachloronitrobenzene, and the surrogate, PCB 103, were determined to be methodological contaminants.

Figure 5: Polychlorinated Biphenyls (PCBs) in Sediments from Tanapag Lagoon, Saipan

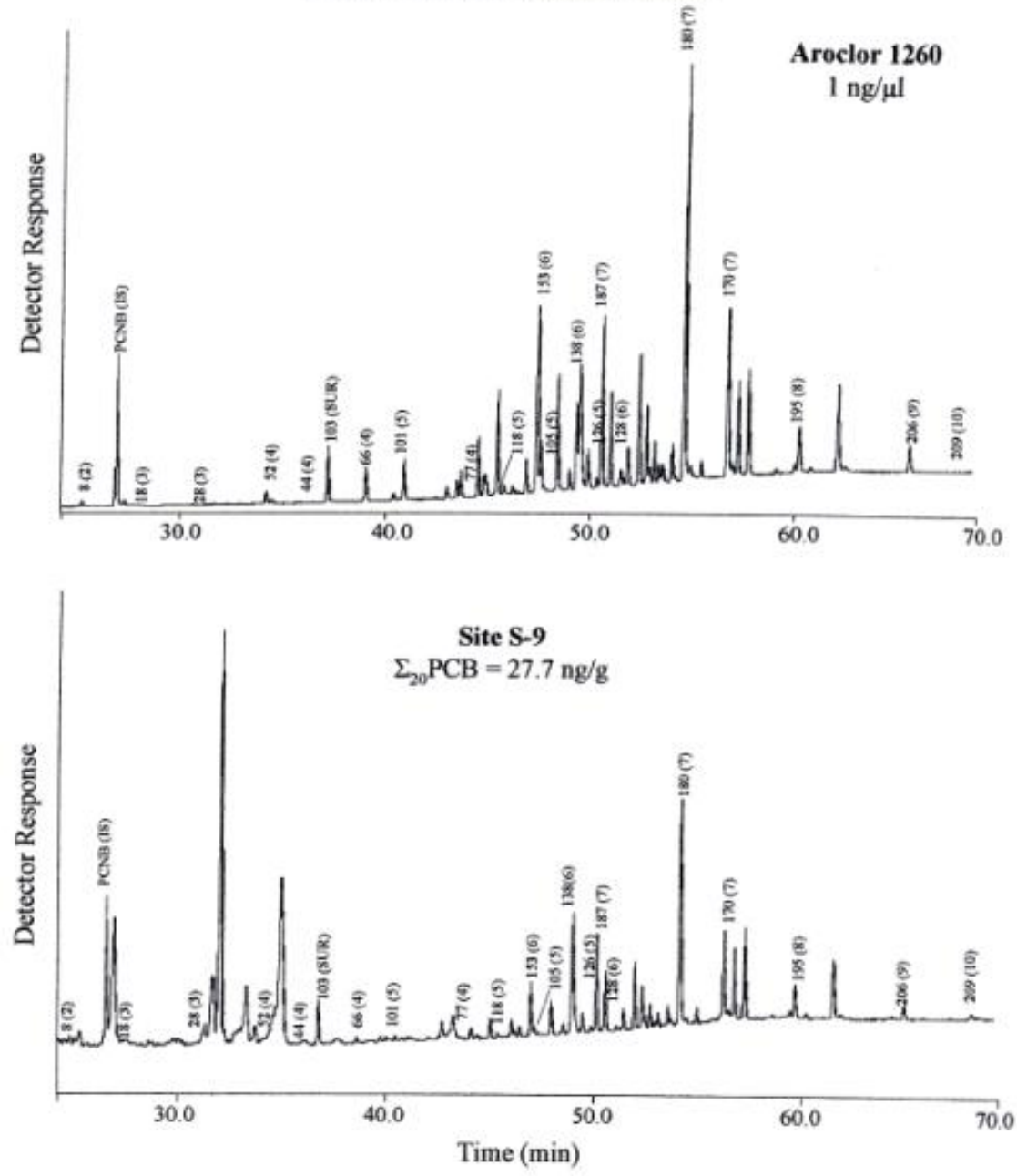
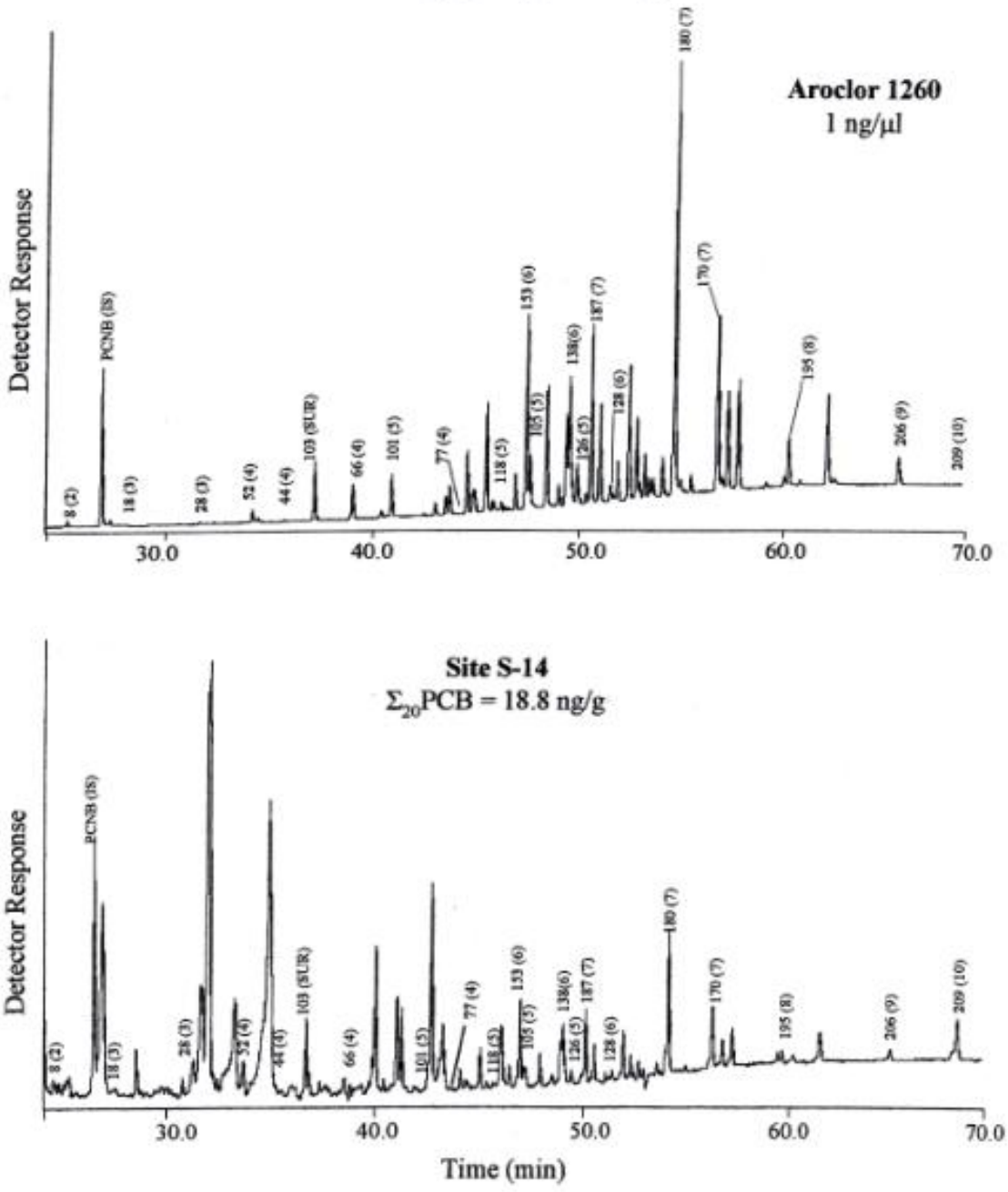


Figure 6: Polychlorinated Biphenyls (PCBs) in Sediments from Tanapag Lagoon, Saipan



1254. Both commercial preparations were commonly used as dielectric fluids in electrical transformers up until the late 1970's. Whether any of these transformers remain in service in Saipan today is unknown.

The Puerto Rico dump is rumored to have been a past dumping ground for electrical transformers containing PCBs (Ogden 1994). Indirect evidence supporting this claim emerged during the late 1980's when a very high total PCB concentration of 1528 ng/g (as Aroclor 1260) was found in sediments from one of six sites bordering the dump (DEQ 1987). The site in question was located in shallow waters off the southwest point of the dump, a position that closely coincides with our site 31. However, we were unable to substantiate the presence of gross PCB contamination in this area. On the contrary, levels encountered in all three sediment cores from site 31 were less than 1 ng/g. Quite possibly, the original area of contamination was very small and passed over during the current study. A highly localized source would certainly explain why DEQ failed to detect PCBs at any of their other sites around the dump. Alternatively, it may have been buried under new sedimentary deposits that have accumulated in the area over the last decade or so. In any event, there does not appear to be a major PCB threat to benthic communities in this area at the present time.

The only other study of PCBs in Tanapag Lagoon sediments was undertaken in 1993 as part of a harbor-dredging project (Unitek 1993). On this occasion, two sub-surface sediment samples were collected from the Baker Bay area, approximately one hundred meters north of Puerto Rico dump. Baker Bay has since been filled in and is part of a new dock structure. The sediments were from the bottom of a 1.2-m hole that had been excavated by divers using a water jet. Total PCBs ranged from 14-24 ng/g which is very close to the highest values reported for individual sediment cores during the current work (i.e., 18.8 ng/g and 27.7 ng/g at sites 14 and 9, respectively).

2.2 Dominant PCB Homologues:

PCB profiles in environmental samples are frequently very different from those encountered in technical mixtures (Courtney and Denton 1976, Stalling *et al.* 1987). This largely reflects dissimilarities between individual chlorobiphenyls regarding their water solubility, vapor pressure and resistance to chemical and biological attack. As a general rule, water solubility, vapor pressure, and resistance to photochemical breakdown decrease with increased chlorination, whereas the reverse is often the case with respect to biodegradation (Sawhney 1986). Thus, the lower chlorinated chlorobiphenyls tend to be more mobile in the environment than their higher chlorinated counterparts and are frequently found in relatively high proportions in remote oceanic areas and coastal regions distanced from specific point sources (Atlas and Giam 1981, Boon *et al.* 1985, Tanabe and Tatsukawa 1986, Iwata *et al.* 1993, Klamer and Fomsgaard 1993, Bright *et al.* 1995, Denton *et al.* 1997). In contrast, the higher chlorinated biphenyls tend to predominate in sediments near sources of high contamination, particularly in aged samples (Stout, 1986, De Voogt 1990, Caricchia *et al.* 1993, Thompson *et al*. 1996).

In the current work, almost all of the samples with detectable quantities of PCB were dominated by Cl_5-Cl_7 homologues. This isomeric group contains 112 of the 209 possible PCB

configurations (see Fig. 1) and is found in high proportions in several Aroclor formulations (Hutzinger *et al.* 1974, Brownawell and Farrington 1986, Ballschmiter *et al.* 1989, McFarland and Clarke 1989). It follows then, that Cl_5-Cl_7 homologues will be prevalent in environmental samples taken near localized point sources of such commercial PCB mixtures.

The general absence of the lower chlorinated homologues in the great majority of samples may reflect natural aging processes at work. If such is the case, then the implication is that no new PCB inputs of significant proportion have occurred in the area in recent times. Alternatively most of the PCB contamination in Tanapag Lagoon may be associated with Aroclor 1260. This particular mixture contains virtually no PCBs with less than four chlorine atoms per molecule. The relatively high abundance of the Cl_8-Cl_{10} homologues in a number of samples analyzed certainly adds weight to this hypothesis. These higher chlorinated PCBs are not found in Aroclor 1254 or commercial mixtures of lower chlorine content (Ballschmiter *et al.* 1989, De Voogt *et al.* 1990).

2.3 Dominant PCB Congeners:

Overall, 182 different chlorobiphenyls have been identified in technical PCB mixtures although individual mixtures probably contain less than half this number (Ballschmiter and Zell 1980, Holden 1986, De Voogt *et al.* 1990). Moreover, each mixture usually contains no more than 15 or so dominant congeners (>2% by weight) with several others present only in trace amounts (De Voogt *et al.* 1990).

As noted above, not all congeners present in technical mixtures are persistent. In fact, many are rapidly degraded by microorganisms in soil and sediments, and hence disappear within a comparatively short time of entering the environment. This is especially true for lower chlorinated members with unsubstituted *meta* and *para* carbons on one or both biphenyl rings (Bright 1995). On the other hand, many of the higher chlorinated components that are relatively abundant in technical PCB mixtures are almost always found as major constituents of the total PCB content in abiotic samples (De Voogt 1990). This is particularly so for congeners with no unsubstituted *meta* and *para* carbons on one or both biphenyl rings, e.g., PCBs 28, 110, 118, 138, 153, and 180.

In the present study, several of the congeners used in the calibration standard are major components of various Aroclor preparations and their retention times matched primary peaks on many of the sample chromatograms. While several of them are known to share similar retention times to other chlorobiphenyls, under the chromatographic conditions employed here, all co-eluting congeners are relatively uncommon in environmental samples (McFarland and Clarke 1989). Thus, possible interference from these compounds during the quantification process was considered to be minimal.

PCB profiles in sediments collected from Tanapag Lagoon varied considerably between stations. However, certain trends were apparent. For example, seven of the 20 congeners in the calibration standard were not detected in any sample analyzed. These included: PCB 28 (a trichlorobiphenyl), PCBs 44, 52, 66 and 77 (tetrachlorobiphenyls), and PCBs 105 and 126

(petachlorobiphenyls). It is noteworthy that the non-*ortho* substituted PCBs 77 and 126[3], and the mono-*ortho* substituted PCB 105, behave similarly to 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) from a toxicological standpoint and are highly potent (De Voogt *et al.* 1990). Their ability to adopt a planar (PCB 77 and 126) or near planar (PCB 105) configuration, similar to that of TCDD, is of central importance here. Fortunately, all three congeners only occur in trace amounts (parts per million) in technical PCB mixtures, and are normally found in relatively low concentrations (parts per trillion) in environmental samples (Jones 1988, McFarland and Clarke 1989, NOAA 1993a).

The remaining 13 congeners analyzed were ranked according to the number of times they were detected in all 96 nearshore sediment cores. The two most frequently encountered congeners were PCBs 101 and 153. These are major components of technical PCB formulations and were found in 57% and 59% of the sediment cores respectively. They were followed in decreasing order by PCB 180 (53%) > PCB 187 (49%) > PCB 209 (40%) > PCB 170 (37%) > PCB 206 (31%) > PCB 138 (21%) > PCB 8 (13%) > PCB 195 (10%) > PCB 128 (9%) > PCB 118 (6%) > PCB 18 (2%). A similar ranking emerged, when these congeners were placed in order of overall relative abundance, for those sites yielding quantifiable levels of PCB. The only difference was that PCB 138 usually preceded PCB 206 in order of abundance.

All 13 congeners, except PCBs 8, 18 and 187, are known or suspected inducers of microsomal mixed function oxidase (MFO) enzyme systems in living organisms. However, only the near planar PCBs 118, 128, 138 and 170 induce the production of microsomal aryl hydrocarbon hydroxylase (AHH), an enzyme that typifies TCDD-like toxicity. This particular MFO bioactivates relatively innocuous PAH compounds into highly toxic metabolites. PCB 118 is the most biochemically active, as well as the most toxic, of the four near planar congeners mentioned above. According to De Voogt *et al.* (1990), this congener is the most widely measured PCB that can adopt an almost planar structure, and is relatively abundant in most environmental compartments. In the present study, however, its frequency of occurrence and relative abundance was rather low.

All of the PCB congeners referred to above have been found in the environment by other workers, as noted by McFarland and Clarke (1989). These authors examined 59 published accounts of congener-specific analysis in various biotic samples. Like us, they also found that PCBs 101 and 153 were the most frequently encountered congeners, appearing in 36% and 37% of the literature respectively. Of the remaining congeners referred to above, PCBs 18, 118, 128, 138, 170, 180 and 187 were reported in more than 20% of the papers considered, while PCBs 195 and 206 were identified 10% and 15% of the time, respectively. PCBs 8 and 209, on the other hand, were reported comparatively infrequently and only appeared in 7% and 8% of the publications examined. Their study also showed a strong positive relationship between the frequency of environmental occurrence and the relative abundance of the above congeners.

[3] PCB 126 is more toxic than any other PCB, and while it is 50 times less toxic than TCDD, relative concentrations in the environment frequently yield TCDD equivalent concentrations greater than that of TCDD by itself.

McFarland and Clarke's findings compare reasonably well with the PCB rankings noted above for sediments from Tanapag Lagoon, with two notable exceptions. First, PCBs 18 and 118 were commonly encountered in their study but not in ours. Second, they came across relatively few accounts of PCB 209 in biota, whereas we found this congener in 40% of all our nearshore sediment samples. These discrepancies lend support to our suspicion that Aroclor 1260 is currently the dominant commercial PCB mixture contaminating sediments in Tanapag Lagoon. This, of course, contrasts sharply to many other areas of the world where Aroclor 1254 is the more common contaminant - often in combination with Aroclor 1242. However, the fact that PCB 209 is found only in Aroclor 1260, while PCB 18 never is, gives some credence to the idea. Additionally, PCB 118, while present in both Aroclors 1254 and 1260, is around four times less concentrated in the latter formulation (De Voogt *et al.* 1990).

3. POLYCYCLIC AROMATIC HYDROCARBONS IN HARBOR SEDIMENTS

The PAH data obtained during the present study are numerically summarized in Table 13. The table presents the total PAH (Σ_{16}PAH) concentrations determined at each site in addition to the rank order of abundance of the individual PAH compounds detected. The findings are pictorially summarized in the form of an isoconcentration contour map in Appendix E. The significance of the findings is discussed in relation to published data from other parts of the world. All referenced data are expressed on a dry weight basis unless stated otherwise.

3.1 Total PAH Concentrations (ΣPAH):

Although many PAHs arise from natural sources (volcanoes, forest fires, oil seeps, diagenesis, and biosynthesis), anthropogenic sources of PAHs are far more important with some 230,000 t entering the marine environment every year (Law 1986). The incomplete combustion of fossil fuels and other organic materials is generally considered to be the primary source of anthropogenic PAHs (Hites *et al.* 1980a, Gschwend and Hites 1981). However, in some areas, notably ports and harbors, pyrolytic PAHs are augmented by petroluem-derived PAHs from fuel spills and oil discharges associated with shipping activity (Johnson *et al.* 1985). Industrial and domestic wastewaters, including raw sewage and storm sewer runoff, may also deliver significant quantities of PAHs to the marine environment (Neff 1979).

Total PAH levels (ΣPAH) in uncontaminated sediments are generally less than 5 ng/g (Pierce *et al.* 1986, Van Fleet *et al.* 1986) although background levels of 10-15 ng/g have been reported for some unimpacted, deep-sea sediments (Hites *et al.* 1980b). A selection of data for ΣPAH concentrations in marine and estuarine sediments from various parts of the world are presented in Table 7. It can be seen that levels generally range from less than 5 ng/g in clean sediments, to around 50 μg/g in sediments from heavily contaminated areas. However, in highly contaminated waters, notably estuaries, ports and harbors, sedimentary ΣPAH concentrations may exceed 1000 μg/g. Sediments collected near a coking facility in Nova Scotia in 1980, for example, contained ΣPAH levels of up to 2,830 μg/g (Eisler 1987). An all time high of 6000 μg/g was reported for sediments from the creosote-contaminated waters of Eagle Harbor in Puget Sound (Swartz *et al.* 1989).

Data for ΣPAHs in tropical sediments are relatively limited. Levels reported for sediments from the Australian Great Barrier Reef ranged from <0.8 ng/g in uncontaminated regions to a

Table 13

PAHs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{16}PAH Concentration (µg/g dry wt.)			Overall Order of Abundance of Detectable PAH Congeners
	Mean	Median	Range	
1 (a-c)	0.50	0.41	0.38 – 0.71	BPE>INP>BBF>BKF>BAP>CHR>PYR>BAA>ACE
2 (a-c)	0.42	0.29	0.25 – 0.71	BPE>DBA>BBF>BKF>INP>BAP>CHR>PYR>BAA>FLU>ACE
3 (a-c)	0.09	0.09	0.02 – 0.16	BAP>PYR>CHR>BBF>FLU>INP>BAA
4 (a-c)	1.22	1.31	0.94 – 1.42	BPE>BAP>BBF>INP>CHR>BKF>PYR>FLU>BAA>DBA>ANT
5 (a-c)	NC	BDL	BDL	
6 (a-c)	NC	0.13	BDL – 1.23	BPE>BAP>PYR>BBF>INP>FLU>CHR>BKF>BAA>ANT
7 (a-c)	1.39	1.48	0.24 – 2.44	PYR>DBA>BAP>CHR>BBF>FLU>BPE>INP>BAA>BKF>ANT
8 (a-c)	0.43	0.50	0.28 – 0.50	BBF>CHR>BAP>PYR>INP>BPE>BKF>BAA>DBA>FLU
9 (a-c)	0.29	0.29	0.02 – 0.56	BPE>BAP>CHR>INP>FLU>BAA>BBF>PYR>BKF

NC = not calculable; BDL = below detection limits
Key to PAH abbreviations used are included at the end of this Table

Table 13 (cont.)

PAHs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{16}PAH Concentration (µg/g dry wt.)			Overall Order of Abundance of Detectable PAH Congeners
	Mean	Median	Range	
10 (a-c)	0.97	1.03	0.85 – 1.04	BAP>PYR>CHR>BKF>BBF>FLU>INP>BAA>BPE>ANT
11 (a-c)	0.05	0.01	0.01 – 0.12	CHR>PYR
12 (a-c)	0.20	0.18	0.18 – 0.24	BKF>CHR>BBF>PYR>BAA
13 (a-c)	0.44	0.47	0.20 – 0.64	CHR>DBA>BBF>PYR
14 (a-c)	0.77	0.93	0.33 – 1.05	CHR>BAP>PYR>BKF>DBA>BBF>FLU>BAA>ANT
15 (a-c)	0.12	0.11	0.01 – 0.23	CHR>BAA>PYR
16 (a-c)	NC	BDL	BDL – 0.01	BAA
17 (a-c)	NC	0.01	BDL – 0.01	CHR>BAA
18 (a-c)	NC	BDL	BDL – 0.004	BAA

NC = not calculable; BDL = below detection limits
Key to PAH abbreviations used are included at the end of this Table

Table 13 (cont.)

PAHs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{16}PAH Concentration (µg/g dry wt.)			Overall Order of Abundance of Detectable PAH Congeners
	Mean	Median	Range	
19 (a-c)	NC	0.01	BDL – 1.36	BAP>INP>BKF>BAA
20 (a-c)	0.03	0.02	0.01 – 0.06	BPE>CHR>DBA>BAA>PYR
21 (a-c)	NC	BDL	BDL – 0.40	BPE
22 (a-c)	NC	BDL	BDL – 0.07	BAP
23 (a-c)	NC	0.15	BDL – 0.16	BPE>INP>BAA
24 (a-c)	0.03	0.01	0.01 – 0.08	INP>CHR>BAA>PYR
25 (a-c)	0.33	0.34	0.02 – 0.65	BPE>CHR>PYR>BAA
26 (a-c)	0.06	0.02	0.01 – 0.16	DBA>CHR>PYR>BAA
27 (a-c)	0.04	0.04	0.04 – 0.05	INP>CHR>BAA>PYR

NC = not calculable; BDL = below detection limits
Key to PAH abbreviations used are included at the end of this Table

Table 13 (cont.)

PAHs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{16}PAH Concentration (µg/g dry wt.)			Overall Order of Abundance of Detectable PAH Congeners
	Mean	Median	Range	
28 (a-c)	NC	BDL	BDL	
29 (a-c)	0.78	0.68	0.35 – 1.29	BAP>DBA>CHR>PYR>INP>BBF>FLU>BAA>BPE>BKF>ANT
30 (a-c)	1.18	0.20	0.10 – 3.23	CHR>PYR>FLU>BAP>BBF>BAA>DBA>BPE>BKF>ANT>PHE>INP
31 (a-c)	0.06	0.01	0.01 – 0.15	BPE>CHR
32 (a-c)	NC	BDL	BDL	
33 (a-c)	NC	0.02	BDL - 0.20	BPE>DBA>BAA
34 (a-c)	NC	BDL	BDL - 0.03	DBA
35 (a-c)	NC	BDL	BDL	
36 (a-c)	0.05	0.04	0.01 – 0.10	INP>DBA>BAA>CHR>PYR

NC = not calculable; BDL = below detection limits
Key to PAH abbreviations used are included at the end of this Table

Table 13 (cont.)

PAHs in Sediments from Tanapag Lagoon, Saipan

Site	Σ_{16}PAH Concentration (µg/g dry wt.)			Overall Order of Abundance of Detectable PAH Congeners
	Mean	Median	Range	
37 (a-c)	NC	BDL	BDL – 0.004	BAA
38 (a-c)	NC	0.15	BDL – 0.17	BPE
39 (a-c)	NC	BDL	BDL – 0.44	BPE
40 (a-c)	NC	BDL	BDL – 0.17	BPE
41 (a-c)	NC	BDL	BDL	

NC = not calculable; BDL = below detection limits

PAH Abbreviations (in order of molecular weight):

NAP	Naphthalene	BAA	Benzo(a)anthracene
ACY	Acenaphthylene	CHR	Chrysene
ACE	Acenaphthene	BBF	Benzo(b)fluoranthene
FLR	Fluorene	BKF	Benzo(k)fluoranthene
PHE	Phenanthrene	BAP	Benzo(a)pyrene
ANT	Anthracene	BPE	Benzo(ghi)perylene
FLU	Fluoranthene	INP	Indenol(1,2,3-cd)pyrene
PYR	Pyrene	DBA	Dibenzo(a,h)anthracene

high of 13.4 μg/g at sites regularly frequented by powerboats (Smith *et al.* 1985). A similar range, peaking at 10.7 μg/g, was encountered for Σ_{16}PAH in harbor sediments from Guam (Denton *et al.* 1997).

In the current study, PAHs were only detected in 33% of all offshore sediment cores compared with 81% from nearshore sites. Σ_{16}PAH concentrations ranged from non-detectable to barely measurable in the majority of offshore samples. Closer to shore, levels were often appreciably higher rising to 2.44 μg/g near the docks (site 7) and 3.23 μg/g near the dump (site 30). Typical PAH profiles (UV detection at 254 nm) in sediments from each location are shown in Figs. 7 and 8, respectively.

According to the United Nations Environment Program (UNEP 1994), ΣPAH levels of ~0.5 μg/g constitute a moderate degree of contamination whereas levels exceeding 10 μg/g are classified as highly contaminated. Denton *et al.* (1997) further refined this classification scheme by proposing that Σ_{16}PAH levels of 0.05-0.5 μg/g are indicative of light enrichment while concentrations between 0.5-5 μg/g represent a moderate degree of contamination. Sediment samples from the small-boat marinas (sites 1, 2 and 4), around the dump, (sites 13, 14, 29 and 30), the docks (sites 6, 7 and 8), the main harbor and immediately adjacent areas (sites 9 and 10), fell into the latter category. All other sites were classified as either lightly contaminated or clean.

3.2 PAH Assemblages:

It is well known that the composition of environmental PAH mixtures vary according to their source. For example, 2- and 3-ring PAHs are most likely related to petrogenic hydrocarbon spillages such as diesel and fuel oil, whilst 4- to 6-ring compounds are primarily produced as a result of fossil fuel combustion (Prahl and Carpenter 1984, Prahl *et al.* 1984). The notable exceptions to this general rule are for the 3-ringed compounds, anthracene and phenanthrene. The former is a product of combustion and is not present in petroleum (Hellou 1996) while the latter is common to both petroleum and combustion sources of PAH (Rice *et al.* 1993).

While it is theoretically possible to differentiate between petrogenic and pyrogenic sources of PAH in sediments, based on the molecular weights of the dominant parent constituents, losses of the lighter PAHs due to volatilization, dissolution and dispersion, as well as biodegradation often makes this task difficult, if not impossible. The crucial factor here of course is time. Fresh petroleum/oil spills leave a readily identifiable signature that becomes progressively more difficult to recognize in aged samples. In the latter instance, the low molecular weight PAHs generally tend to be more abundant in the water column whereas the underlying sediments usually show a predominance of the heavier compounds (Benlahcen *et al.* 1997).

The PAH profiles in sediments analyzed during the present study were dominated by the higher molecular weight compounds. Whether these are predominantly derived from combustion or reflect aged petrochemical spills is not clear. Given the nature and extent of the human activities in the area, it seems likely that both sources are important. It also follows that the relative importance of each source will vary both in space and time.

Figure 7: Polycyclic Aromatic Hydrocarbons (PAHs) in Sediments from Tanapag Lagoon, Saipan

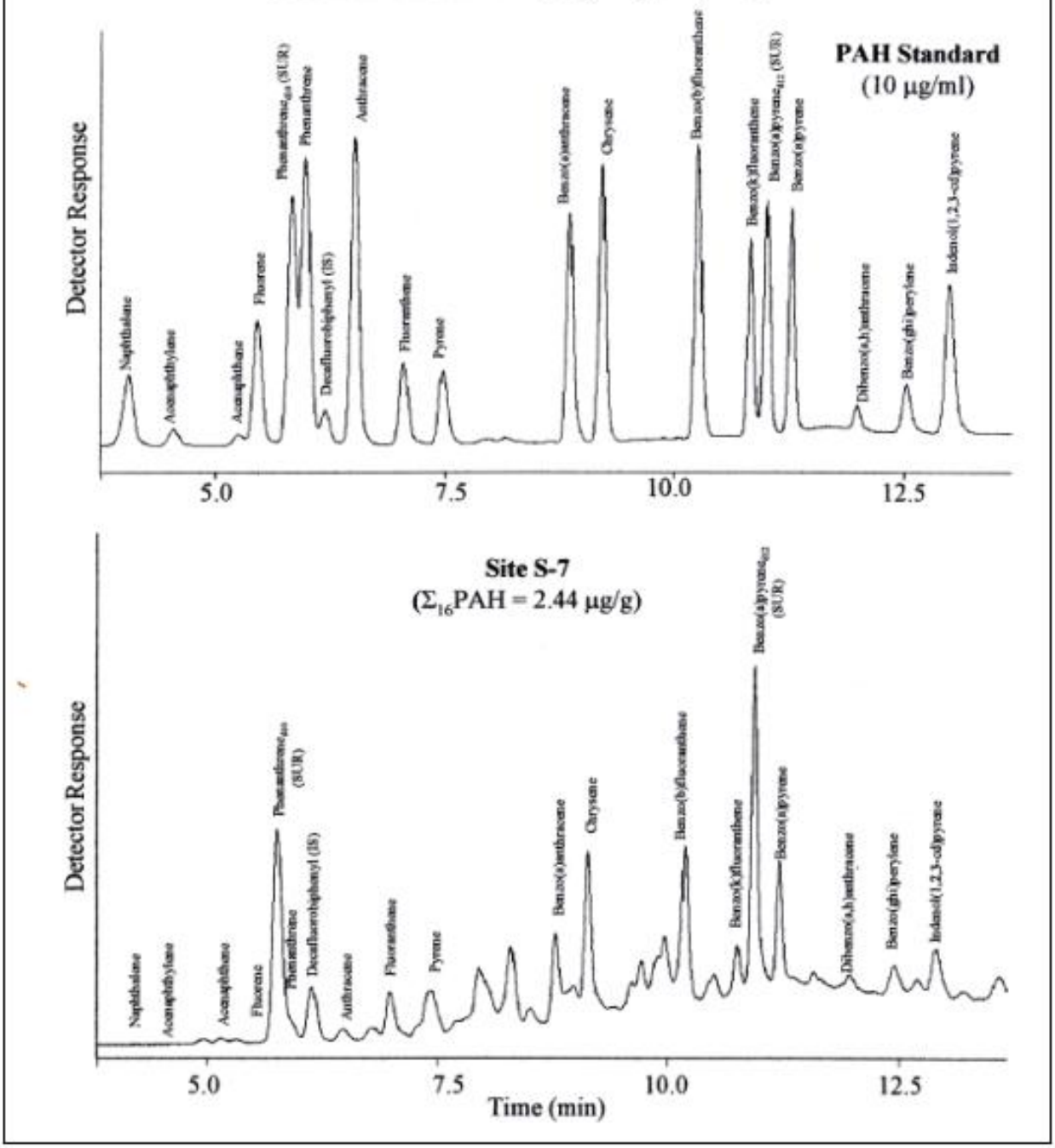
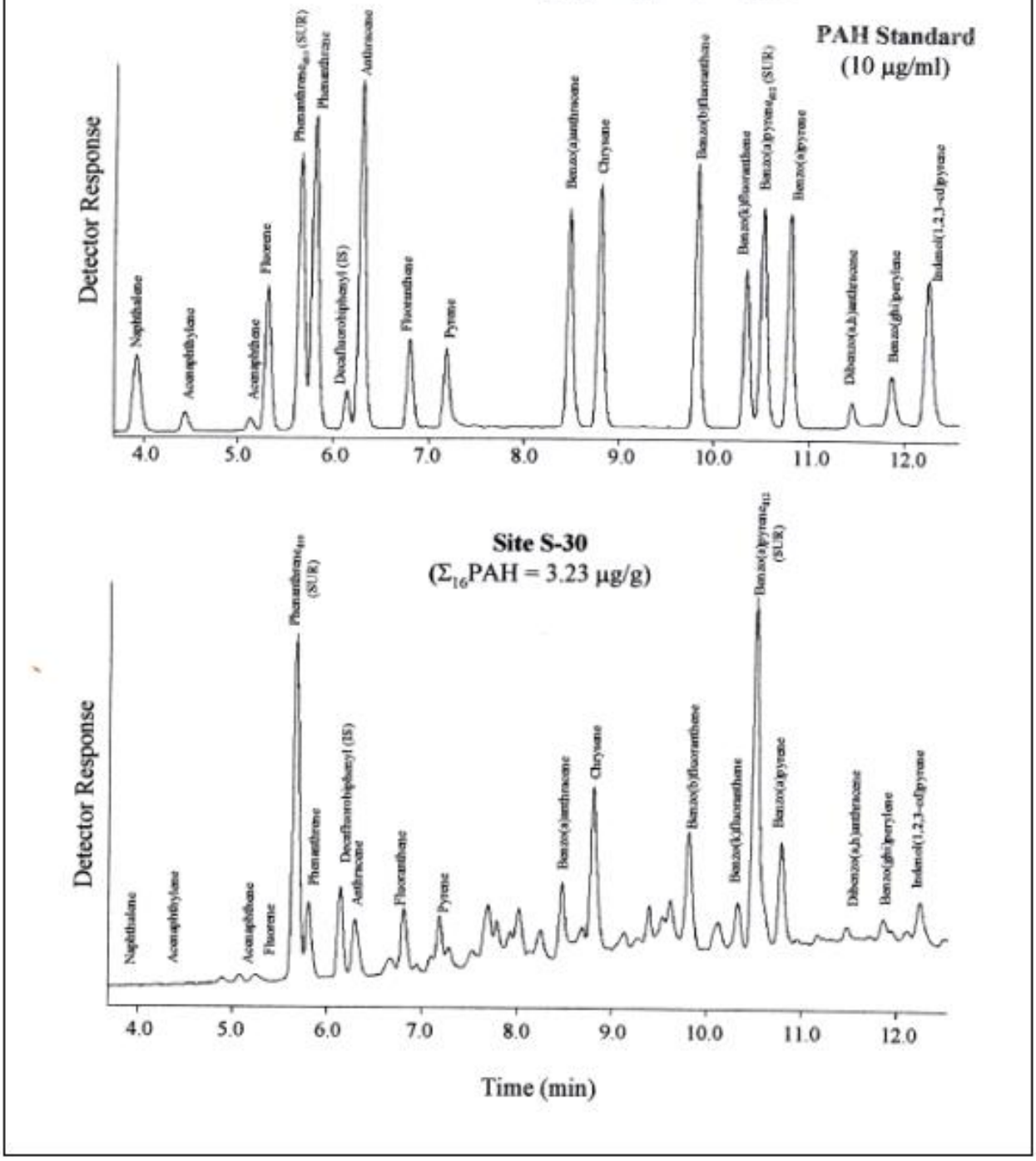


Figure 8: Polycyclic Aromatic Hydrocarbons (PAHs) in Sediments from Tanapag Lagoon, Saipan



This notwithstanding, pyrogenic PAHs derived from boat engine exhaust streams are likely to be distributed throughout the lagoon, whereas petrogenic PAHs associated with fuel spills are probably more prevalent in the marinas, along the docks, and in the main port. In the latter context, the notable absence of lighter PAH members, naphthalene, acenaphthylene and fluorene, suggests that no major fuel spills had occurred in Tanapag Lagoon in the recent past, prior to this study. These congeners have relatively low affinities for sedimentary materials (Neff 1979, Connell and Miller 1984) and are degraded fairly rapidly compared with their higher molecular weight counterparts (Cernglia and Heitkamp 1989). Consequently, they are relatively abundant only in sediments contaminated by fresh petroleum spills.

Some researchers have attempted to differentiate between petrogenic and pyrogenic sources of PAHs in sediments using ratios between certain individual components present in the extract. For example, Benlahcen *et al.* (1997) maintained that a fluoranthene/pyrene ratio of >1 is indicative of combustion sources, whereas Buttini (1992) claimed that a pyrene/benzo(*a*)pyrene ratio of <1 is the signature of unburned petroleum, compared with ratios of 2-12 and 50-100 for gasoline and diesel exhausts respectively. The rationale behind this diagnostic tool stems from the fact that PAH assemblages produced by pyrolysis are qualitatively very similar, irrespective of the fuel type and combustion conditions (Neff 1979). Likewise, the relative abundances of several unsubstituted PAHs in oils and petroleum distillates remain fairly constant despite major quantitative differences between the various petrochemical mixtures. We examined the above PAH ratios in nearshore sediment cores collected during the present work and found reasonable agreement between them. For example, petrogenic PAH contamination was indicated in 71% of the cores using the fluoranthene/pyrene ratio, and in 95% of the cores using the pyrene/benzo(*a*)pyrene ratio.

The utility of this method in identifying primary PAH sources is limited by differential degradation rates of the above PAH congeners in aquatic sediments. Further departures from source profiles also occur as a result of differential partitioning rates of individual congeners between sediment and water phases (Neff 1979). In the absence of continued inputs, such discrepancies are expected to increase over time. Thus, the more recent the petrochemical spill, the more reliable the information obtained from the congener ratio analysis described above.

An analysis of the frequency of occurrence and relative abundance of each PAH congener was performed on all quantifiable data sets obtained during the current work. The most frequently encountered PAHs were the 4-ringed members, chrysene, benzo(*a*)anthracene, and pyrene. These occurred in 71%, 61% and 60% of the sediment cores respectively. The frequency of occurrence of the remaining congeners were as follows: benzo(*b*)fluoranthene (40%) > benzo(*a*)pyrene (36%) > benzo(*k*)fluoranthene and benzo(*g,h,i*)pyrelene (33%) > indenol(*1,2,3-cd*)pyrene (30%) > fluoranthene and dibenz(*a,h*)anthracene (22%) > anthracene (11%) > acenaphthene (2%) > phenanthrene (1%). The 2- and 3- ringed members, naphthalene, acenaphthylene and fluorene were not detected in any of the sediment cores examined.

A similar pattern emerged when all detectable congeners were ranked in order abundance. In this particular instance, chrysene was the most abundant congener in the majority of samples,

followed in descending rank order of relative abundance by: pyrene > benzo(*a*)anthracene > benzo(*b*)fluoranthene > benzo(*a*)pyrene > benzo(*ghi*)pyrelene > benzo(*k*)fluoranthene > indenol(*1,2,3-cd*)pyrene > dibenz(*a,h*)anthracene > fluoranthene > anthracene > acenaphthene > phenanthrene.

According to Fowler *et al*. (1993), pyrene is normally produced through combustion processes and typically ranges between 0.010-1.500 µg/g in coastal sediments of the world. Pyrene levels encountered during the present study ranged from 0.003 µg/g, or less, in sediments from all outer lagoonal sites, up to 0.453 µg/g in one of the sediment cores from site 30, off the western edge of the dump. The common occurrence and high relative abundance of this particular congener throughout the area certainly supports the earlier suggestion that combustion processes are a significant source of PAHs to Tanapag Lagoon.

One of the most well studied PAH congeners is benzo(*a*)pyrene because of the genotoxic properties of some of its metabolites. This notable PAH is a product of combustion and a component of petroleum products. Concentrations reported in the literature for sediments throughout the world range from sub-parts per billion in remote areas, up to 15 µg/g in grossly polluted waters. Neff (1979) noted that highest benzo(*a*)pyrene levels always occurred adjacent to regions of high population or intense industrial activity. Concentrations found in individual sediment cores during the present study ranged from <0.011 µg/g at all offshore sites, to 1.019 µg/g at site 19 adjacent to the power station. Elsewhere in the study area, levels did not exceed 0.344 µg/g (site 6) and were mostly below 0.100 µg/g. These values compare reasonably well with those recently determined in sediments from the Mediterranean (Lipiatou and Saliot 1991) and are indicative of light to moderate benzo(*a*)pyrene contamination.

4. DATA SUMMARY

Table 14 attempts to summarize the findings of the current study by listing all sites where mean contaminant levels exceeded those classified as 'clean' in Table 10. A total of 174 exceedances were identified and frequently occurred for two or more contaminants in sediment from the same station. However, 90% of these fell within the 'lightly contaminated' category and, as such, were unremarkable. Less than 2% of the exceedances were characteristic of' heavy contamination' and there were no cases of 'gross contamination' for any of the contaminants examined.

In summarizing the main points, it can be seen that site 14, beside the dump, was moderately contaminated with cadmium, copper, lead and mercury, and heavily contaminated with zinc. This area was also moderately contaminated with PAHs (sites 14, 29 and 30). Likewise, total PAHs were moderately high at site 4, inside the small-boat marina. Lead was moderately enriched in sediments from this site also.

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Table 14

Summary of Contaminant Abundance[a] in Sediments from Tanapag Lagoon

Contaminant	Degree of Contamination			
	Light	Moderate	Heavy	Gross
	(sites)	(sites)	(sites)	(sites)
HEAVY METALS				
Arsenic	1,2,6,14,	none	none	none
Cadmium	8,12,13,15,17,18	14	none	none
Chromium	none	none	none	none
Copper	1,2,4,6-8,10,12,15,19,30	14	none	none
Lead	1-3,5,7-10,12,13,16,17,19,20,24-27,29-31,36	4,6,14,15	none	none
Mercury[a]	1-6,8,9,11-13,15-21,23-32,36	10,14	7	none
Nickel	none	none	none	none
Silver	25-27,29,30	none	none	none
Tin[a]	1-5,7-10,7-31,35,36	none	6	none
Zinc	1,2,4,6-10,12,13,15,19,20,27,29-31	none	14	none
$\sum_{20}$PCBs	1,2,4,6-8,10,15,17,20,25,26,29,30	9,14	none	none
$\sum_{16}$PAHs	1-3,8,9,11-13,15,25,26,31,36	4,7,10,14,29,30	none	none

[a]Classification scheme proposed by Denton *et al.* (1997). Sites not listed are classified as 'clean' for that contaminant; [a] as total metal

Site 6, located 50 m of the western edge of the dump, showed a moderate and heavy degree of enrichment for lead and tin, respectively. Sediments from the main port and immediately adjacent areas were moderately contaminated with mercury, PAHs (site 10) and PCBs (site 9 and 16). Finally, heavy mercury contamination and moderate amounts of PAH were identified in sediments from site 7, beside the new dock. In all, sediments from 10 nearshore sites revealed mean contaminant levels that were classified as either moderately or heavily polluted. No offshore site yielded data that fell within either of these two categories.

GENERAL CONCLUSIONS

This study was designed to identify the distribution and abundance of heavy metals, PCBs and PAHs in surface sediments from Tanapag Lagoon. It is the first comprehensive survey of its kind in the region, and should command the attention of local agencies and personnel involved in environmental protection and resource management. The survey has clearly identified zones of contaminant enrichment throughout the study area and provides a useful database with which future levels may be compared and evaluated. It has also facilitated a greater understanding of background levels expected in clean sediments from nearshore and offshore locations in a tropical marine environment. In this closing chapter, the ecological significance of the findings is briefly addressed. Some thought is also given to the impact of recent dock constructions and dredging activities on the contaminant levels encountered and the major discrepancies observed between some of the earlier DEQ (1987) data and that gathered here. Finally, we highlight areas where we feel further monitoring and pollution assessment would be justified.

1. Database Extension For Clean Reef Sediments

In a previous study, we established realistic concentration ranges for heavy metals, PCBs and PAHs in clean, coastal sediments from Guam (Denton *et al.* 1997). Such sediments are composed largely of degraded reef carbonates and are typical of tropical coral reef environments in this part of the world. They rarely contain PCB in excess of 1 ng/g and seldom contain PAHs of any significance. Also, the heavy metal content is typically low compared with sediments of mineral origin from other regions.

It was anticipated that clean reef sediments collected from further offshore, while unlikely to reflect major changes in PCB or PAH concentrations, would contain lower levels of heavy metals than their nearshore counterparts by virtue of the distance that separates them from natural contributions derived from land. Data from the present study tends to confirm this and allow for the expansion of the previous database to include offshore sediments as shown in Table 15. Upon review of this table it is evident that uncontaminated nearshore and offshore sediments are noticeably different for some of the more abundant crustal elements like copper, nickel and zinc. Baseline mercury levels in offshore sediments also seem to be marginally lower than the natural range previously estimated for clean, coastal sediments on Guam. While these baseline estimates are of immediate use to local environmental managers for monitoring purposes, further refinement is necessary to determine the variable effects of grain size distribution and organic carbon content on these predicted ranges.

2. Use of Numerical Sediment Quality Guidelines to Predict Biological Effects

The full impact of contaminated sediments on biotic communities cannot be determined from chemical analysis alone. Other interpretive tools are necessary to predict potential adverse biological effects. These include toxicity and bioaccumulation tests, equilibrium partitioning studies for organics, and acid volatile sulfide (ASV) determinations for metals. In addition, various numerical sediment quality guidelines (SQGs) are available to assist with the evaluation. These have been developed by various procedures and have approach specific advantages and limitations. While they cannot be expected to apply equally to all sediment

Table 15

Suggested Concentration Ranges for Heavy Metals, PCBs and PAHs in Clean Reef Sediments from Nearshore and Offshore Locations

Contaminant	Nearshore[a]	Offshore[b]
HEAVY METALS (µg/g dry wt.)		
Arsenic	1-3	0.5-2.0
Cadmium	<0.1	<0.1
Chromium	3-5	1-3
Copper	1-3	<0.1
Lead	<1	<1
Mercury[c]	0.005-0.01	0.002-0.005
Nickel	1-3	<0.2
Silver	<0.1	<0.1
Tin[c]	<0.1	<0.1
Zinc	3-5	<1
∑PCBs (ng/g dry wt.)	<1	<1
∑PAHs: (ng/g dry wt.)	<50	<50

[a] from Denton *et al.* 1997; [b] this study; [c] as total metal

types and sets of environmental conditions, they do provide a useful point of reference for the identification of contaminants and sites of potential concern, and are of value from the standpoint of prioritizing actions and management decisions.

The most widely accepted SQG are those developed by Long and colleagues (Long and Morgan 1990, Long 1992, Long and MacDonald 1992, Long *et al.* 1995) for the US National Oceanographic and Atmospheric Administration (NOAA), National Status and Trends (NS&T) Program. These guidelines were initially intended for informal use by NOAA scientists as a means of separating out potential problem areas from their vast database. They were empirically derived from the systematic analysis of numerous field, laboratory, and modeling studies that linked sediment contaminant data with biological effects information in the U.S. The statistical approach involved ranking the effects data in order of concentration for each contaminant considered and calculating the 10^{th} and 50^{th} percentile of concentrations associated with adverse biological effects. These percentiles were referred to as the *Effects Range Low* (ERL) and *Effects Range Median* (ERM), respectively. These well known benchmarks conveniently separate out three contaminant concentration categories, namely those that are 'rarely,' (≤ ERL), 'occasionally' (> ERL to < ERM), and 'frequently' (≥ ERM) associated with biological effects.

This so called 'weight of evidence approach' (WEA), originally designed for the northeastern and western areas of the U.S., was later expanded and refined by MacDonald and co-workers to accommodate Florida sediment monitoring sites in the southeastern part of the country (MacDonald *et al.* 1996). Besides the greatly expanded database, MacDonald's modified WEA utilized both 'effects' and 'no effects' data sets to derive a *Threshold Effects Level* (TEL) and the *Probable Effects Level* (PEL) for each contaminant considered. In this instance, the contaminant concentration categories separated out are referred to as the 'minimal effects range' (≤ TEL), the 'possible effects range' (> TEL to < PEL), and the 'probable effects range' (≥ PEL).

Both sets of SQG described above are listed in Table 16 for most of contaminants examined during the present study. It can be seen that those developed by MacDonald's group for the Florida Department of Environmental Protection (DEP) are generally more conservative than those formulated by Long and co-workers for the NS&T Program. Nevertheless, their use should be exercised with caution and common sense. Sediments frequently contain an array of toxic contaminants and the combined biological effects of these may not be adequately addressed by the use of SQG alone. Fewer than 40 SQG have so far been developed. Notable by their absence are SQGs for such high priority pollutants as TBT, individual PCB congeners and several common PAHs.

Such limitations notwithstanding, the data obtained during the current work were evaluated with reference to the TEL and PEL benchmarks listed in Table 16. In this instance, only the contaminant geometric means were used for such purposes. The results of the comparative analyses are summarized in Table 17. It is encouraging to note that were no PEL exceedances within the study area for any of the contaminants listed.

Table 16

Biological Effects-Based Sediment Quality Guidelines (SQGs) Commonly Used in the USA Today

Contaminant	NOAA National Status and Trends Program[a]		Florida Department of Environmental Protection[b]	
	Effects Range-Low (ERL)	Effects Range-Median (ERM)	Threshold Effects Level (TEL)	Probable Effects Level (PEL)
HEAVY METALS (µg/g dry wt.)				
Arsenic	8.2	70	7.24	41.6
Cadmium	1.2	9.6	0.68	4.21
Chromium	81	370	52.3	160
Copper	34	270	18.7	108
Lead	46.7	218	30.2	112
Mercury	0.15	0.71	0.13	0.7
Nickel	20.9	51.6	15.9	42.8
Silver	1.0	3.7	0.73	1.77
Zinc	150	410	124	271
PCBs (ng/g dry wt.)				
Total PCBs	22.7	180	21.6	189
PAHs (ng/g dry wt.)				
Acenaphthene	16	500	6.71	88.9
Acenaphthylene	44	640	5.87	128
Anthracene	85.3	1,100	46.9	245
Fluorene	19	540	21.2	144
Naphthalene	160	2,100	34.6	391
Phenanthrene	240	1,500	86.7	544
Benz(*a*)anthracene	261	1,600	74.8	693
Benzo(*a*)pyrene	430	1,600	88.8	763
Chrysene	384	2,800	108	846
Dibenz(*a,h*)anthracene	63.4	260	6.22[c]	135
Fluoranthene	600	5,100	113	1,494
Pyrene	665	2,600	153	1,398
Total PAHs	4,022	44,792	1,684	16,770

[a] Long and Morgan 1990; [b] MacDonald *et al.* (1996); [c] below analytical detection limits of instrument used during this study. Currently, no SQGs for tin (TBT), individual PCB congeners, or the PAH congeners: benzo(*b*)fluoranthene, benzo(*k*)fluoranthene, benzo(*ghi*) perylene and indenol(1,2,3-cd)pyrene.

Table 17

Tanapag Lagoon Sediment Sites Identified as Potentially Toxic to Resident Biota

Contaminant	Exceedances of Threshold Effects Level (TEL)	Exceedances of Probable Effects Level (PEL)
HEAVY METALS (µg/g dry wt.)	(TEL)	(PEL)
Arsenic	7.24: sites 14	41.6: none
Cadmium	0.68: none	4.21: none
Chromium	52.3: none	160: none
Copper	18.7: site 14	108: none
Lead	30.2: site 14	112: none
Mercury	0.13: site 7	0.7: none
Nickel	15.9: none	42.8: none
Silver	0.73: none	1.77: none
Zinc	124: site 14	271: none
PCBs (ng/g dry wt.)		
Total PCBs	21.6: none	189: none
PAHs (ng/g dry wt.)		
Acenaphthene	6.71: none	88.9: none
Acenaphthylene	5.87: none	128: none
Anthracene	46.9: none	245: none
Fluorene	21.2: none	144: none
Naphthalene	34.6: none	391: none
Phenanthrene	86.7: none	544: none
Benz(*a*)anthracene	74.8: site 7	693: none
Benzo(*a*)pyrene	88.8: sites 4, 7, 10, 29, & 30	763: none
Chrysene	108: sites 10, 13 &14	846: none
Dibenz(*a,h*)anthracene	6.22: sites 2, 7, 8, 13, 14, 29 & 33	135: none
Fluoranthene	113: none	1,494: none
Pyrene	153: none	1,398: none
Total PAHs	1,684: none	16,770: none

SQGs for TEL and PEL were taken from MacDonald *et al.* (1996). Currently, there are no reliable SQGs for tin (TBT), individual PCB congeners, or the PAH congeners benzo(*b*)fluoranthene, benzo(*k*)fluoranthene, benzo(*ghi*) perylene and indenol(1,2,3-cd)pyrene. All comparative evaluations based on geometric mean contaminant concentrations from three sediment cores per site

TEL exceedances, suggesting possible biological effects, were identified at site 14, near the dump, for arsenic, copper, lead, mercury and zinc. Sediments from site 7, adjacent to the new dock, also exceeded the TEL for mercury. The fact that mercury and lead are non essential, accumulative poisons warrants further investigation to determine whether either metal is being concentrated to unacceptable levels by edible marine resources frequenting these areas.

Several waterfront sites yielded TEL exceedances for one or more of three PAHs, benzo(*a*)pyrene (5 sites), chrysene (3 sites), and dibenz(*a,h*)anthracene (6 sites). This is significant because several PAHs including benzo(*a*)pyrene are known to be enzymatically transformed by mixed function oxidases (MFOs) into active metabolites that exert mutagenic, toxic and carcinogenic effects in mammals and fish (James 1989). In fact, there now exists a strong body of evidence linking sedimentary levels of PAHs to liver cancer and other chronic diseases in benthic fish from polluted areas in the U.S. (Baumann *et al.* 1982, Black 1983, Malins *et al.* 1984, Malins *et al.* 1988, Varanasi *et al.* 1989). Threshold concentrations for these maladies have yet to be accurately determined although it is known that ΣPAH levels as low as 1.0 μg/g are sufficient to induce significant MFO activity in fish (Payne *et al.* 1988). Noteworthy in this regard is the fact that mean Σ_{16}PAH levels encountered during the present study approached or exceeded 1.0 μg/g at sites 4, 7, 10, 14, 29 and 30.

There were no TEL exceedances for ΣPCB at any site. However, Σ_{20}PCBs encountered at site 14 (16.6 ng/g) were not too far removed from the TEL benchmark of 21.6 ng/g. More stringent threshold SQGs have been developed for PCBs in other countries. In Canada for example, the *Lowest Effect Level* (LEL) adopted by Ontario Ministry of Environment for Aroclor 1016 is 7 ng/g (Persaud *et al.* 1989). This is significantly lower than levels encountered in sediments from site 14. Sediments from around Saipan Harbor (sites 9 and 10) also contained Σ_{20}PCB concentrations slightly in excess of this particular benchmark.

3. SEDIMENT CHEMISTRY CLOSE TO PUERTO RICO DUMP: PAST VS. PRESENT FINDINGS

Perhaps the biggest surprise to emerge from the current work was the apparent improvement in sediment chemistry from around the Puerto Rico dump compared to findings of the DEQ study conducted a little over a decade earlier (DEQ 1987). Although their study was limited to just six grab samples, it clearly revealed significant heavy metal enrichment of bottom sediments in the vicinity of the dump. For example, their highest concentrations of cadmium, copper, chromium, lead, silver and zinc were 2.7, 68.8, 39.3, 201, 2.3 and 324 μg/g respectively. Our highest values from that area were 0.58, 27.8, 9.67, 40.6, <0.2 and 127 μg/g for each metal, respectively. Thus, levels differ between the two data sets by factors of ~2-10. The data set discrepancies for PCBs are even greater with DEQ recording an extremely high A1260 equivalent value of 1528 ng/g in a sample taken near the western edge of the dump. This is approximately two orders of magnitude higher than the Σ_{20}PCB maxima (16.6 ng/g) found in the same area during the present work.

Increased sediment rates associated with various activities carried out in the area during the 1990's seem the most plausible reason for the above noted discrepancies. Such activities generally evolved around the port expansion project and the temporary use of dredged sediments to cover trash at the Puerto Rico dump. Both events are briefly reviewed here.

The construction of the new docks commenced in 1993 under the *Saipan Harbor Improvement Project* and continued until 1997. During this process, Charlie Bay was back filled and placed under concrete as part of the port expansion plan. In so doing it provided a continuous link between Charlie Dock to the north and Baker Dock to the south, almost doubling the docking and berthing facilities in that immediate area.

The dock construction and accompanying dredging activities generated a significant, long-term increase in suspended sediment loads in the immediate vicinity. Drifting sediment plumes generally moved with the prevailing currents in a southwesterly direction from the construction site towards the dump (Bearden, personal observation). In all probability these silt plumes resulted in increased sedimentation rates all along this area.

Additional contributions to the suspended sediment load in this location came in early 1997, when the Saipan Department of Public Works started covering trash at the dump with sediments dredged from a deep water shipping lane located some distance offshore. Over 500,000 cubic yards of dredged material were placed on the dump, up until late 1998 when the practice ceased. Most of the material was placed on the northeast and southeast sides of the dump resulting in side slopes that were very steep (>1:1) and unstable. As a consequence, they were heavily eroded during the wet season. Landslides were also common and severe wave and storm damage was evident all along the seaward facing side of the dump after four typhoons passed the island in 1997 (Bearden, personal observation).

There is little doubt, then, that the seafloor immediately in front of the dump experienced heavy sedimentation rates over this time frame. It, therefore, seems reasonable to assume that the 6 inch cores analyzed during the present investigation probably contained significant quantities of relatively clean dredged material eroded from the face of the dump. Obviously deeper cores are necessary to support this hypothesis, but it does seem likely under the circumstance. If our assumption is correct, the highly contaminated sediments observed earlier by the DEQ (1987) have not improved at all; they've simply been covered up. However, whether they now exist below the bioturbation zone, such that their associated contaminants are largely unavailable to the biota, remains to be seen. Even if they are at present, it seems hardly likely that they will stay this way permanently given the instability of surface sediments in this part of the world during typhoon conditions.

4. FUTURE DIRECTIONS

On the basis of the work already completed, the following recommendations are made for future investigations in Saipan's coastal waters:

- Deeper cores are warranted in the vicinity of Saipan Harbor, the new docks, and the Puerto Rico dump to determine the true chemistry of underlying sediments and their potential for impacting the resident biota. Such cores should be of sufficient length to predate the harbor expansion and dredging activities noted above. They should also be sectioned prior to analysis to determine historic profiles for all contaminants of interest.

- A need exists for investigations of greater geographical coverage of the western seaboard, extending from San Roque in the north to San Antonio at the southern end of the island. Emphasis should be given to those areas impacted or potentially impacted by domestic and industrial discharges, including sewer outfalls and brines from desalination plants; cooling waters from power plants; stormwater and irrigation runoff; motor powered water-craft used for recreational and commercial purposes, as well as any additional small-boat harbors and/or marinas.

- Emphasis should be placed on expanding the chemical database to incorporate other organic compounds including TBT, dioxins, the persistent organochlorine pesticides, and the alkylated PAHs.

- Surveys should be undertaken to evaluate the bioaccumulation potential of persistent, potentially toxic contaminants in dominant components of the biota, within each identified area of enrichment. This will provide valuable data from both a public health and ecological viewpoint. In addition, promising bio-indicators for future monitoring work will be identified.

- There is also a need to establish baseline contaminant levels in sediments and biota for the cleaner relatively unimpacted stretches of coastline on the western side of the island. Without such vital information, the effects of future developments in the area will be difficult to assess.

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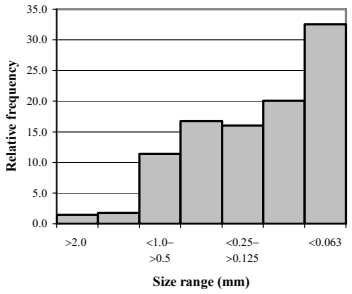
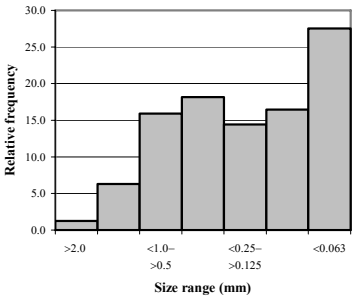
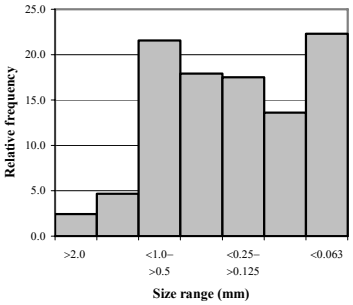
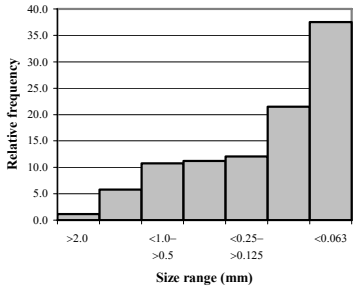
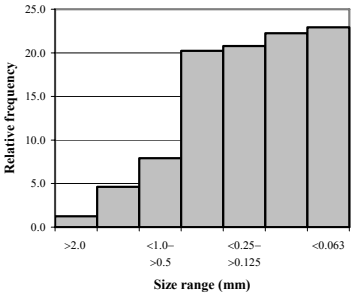
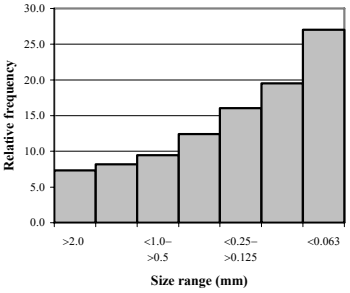
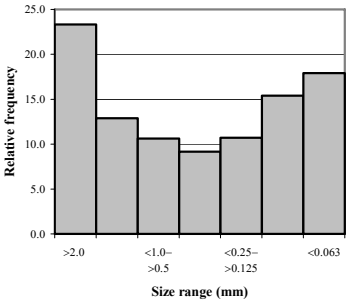
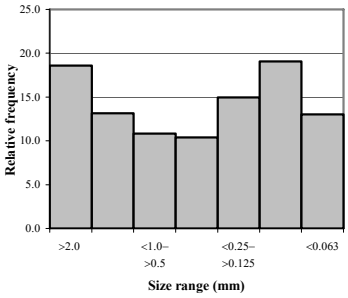
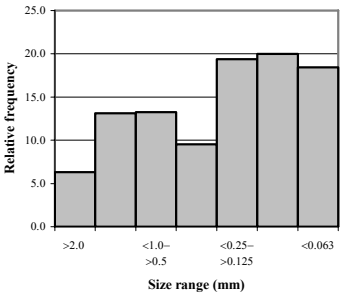
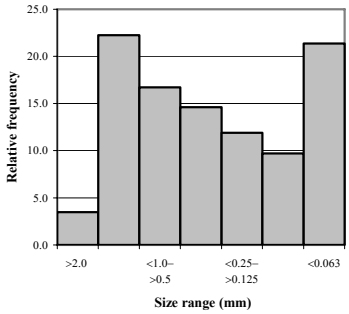
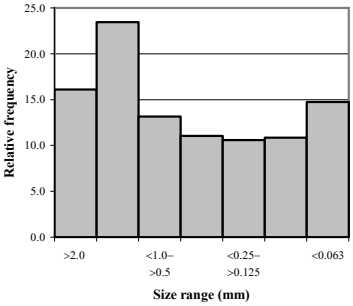
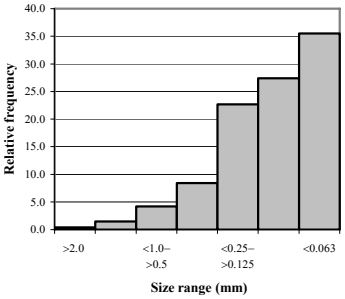
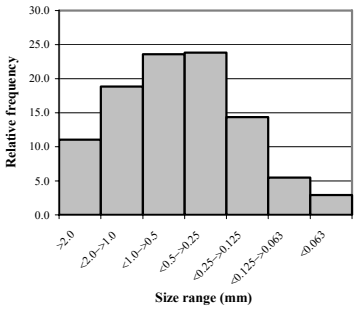
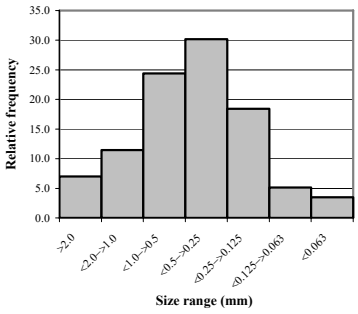
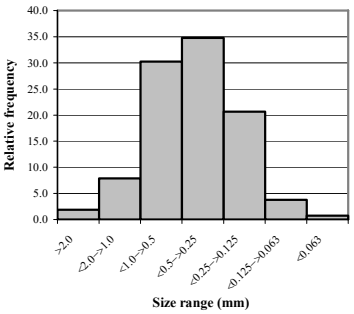
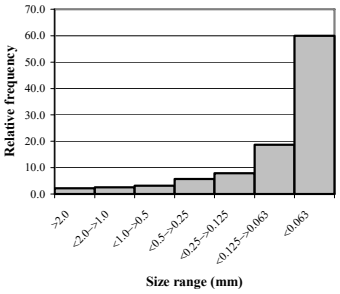
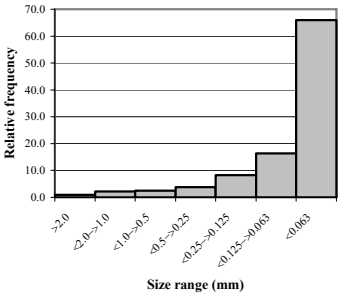
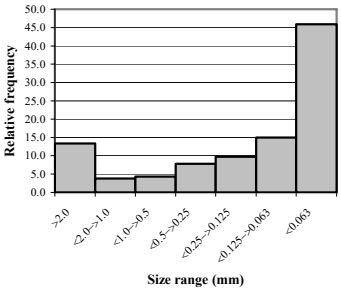
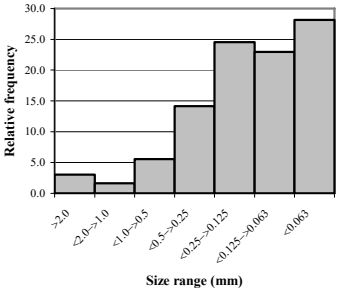
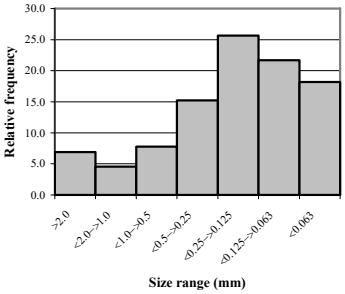
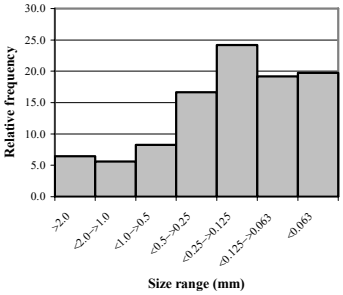
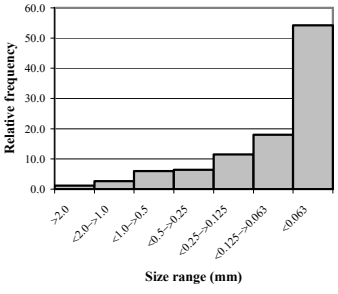
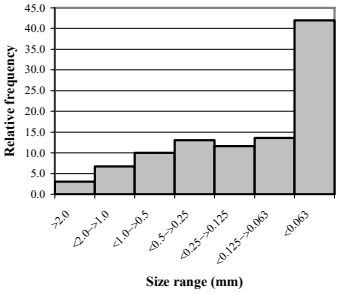
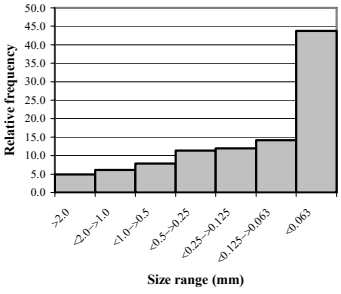
APPENDIX A

Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag lagoon, Saipan

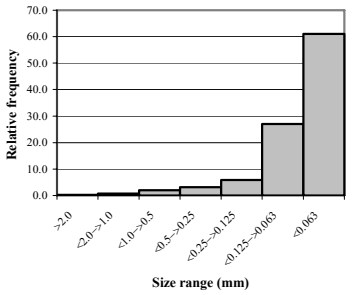
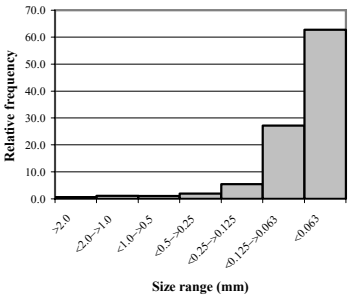
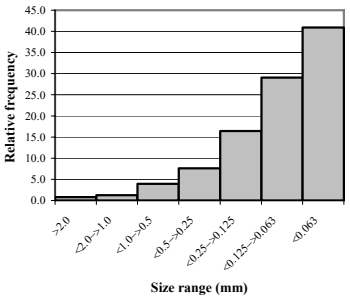
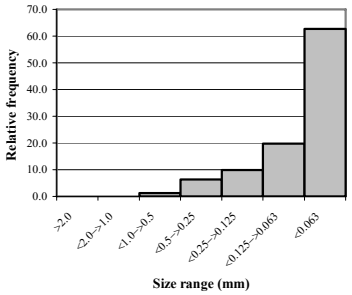
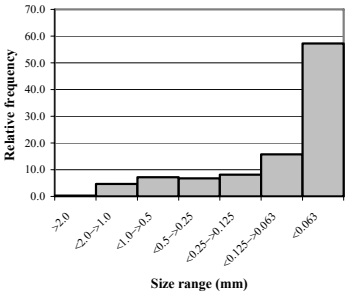
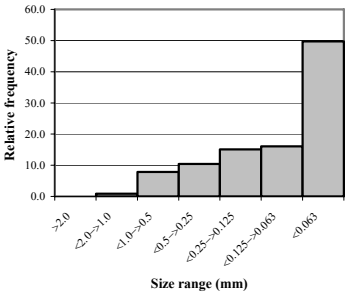
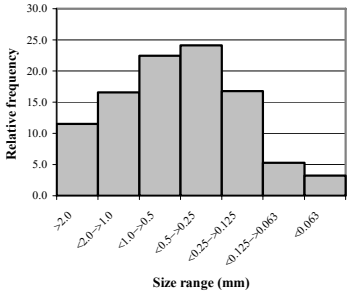
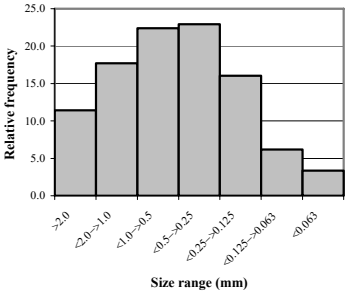
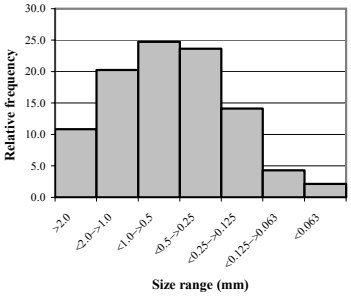
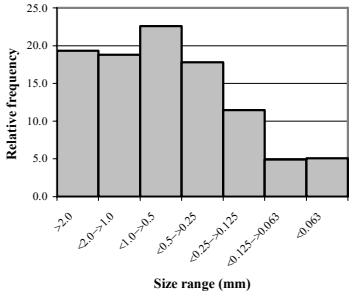
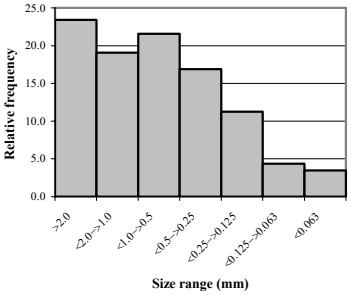
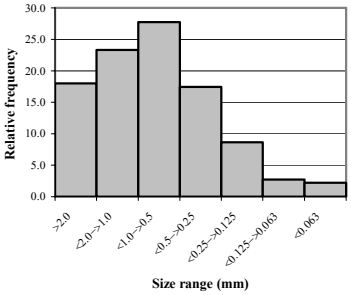
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
1			
2			
3			
4			

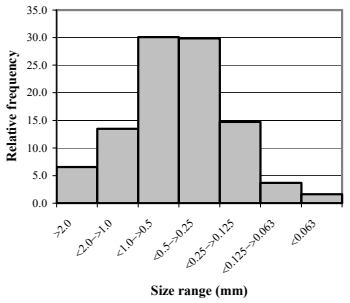
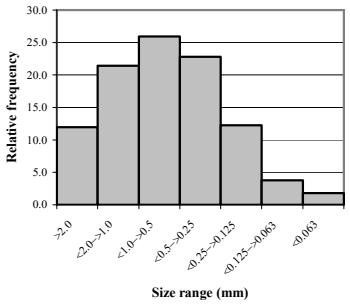
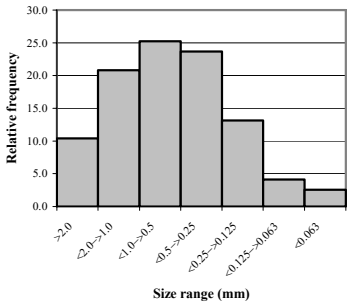
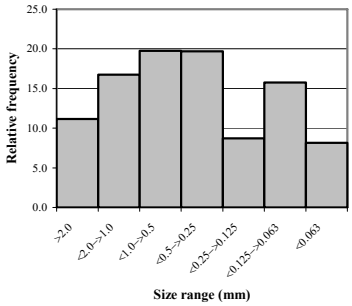
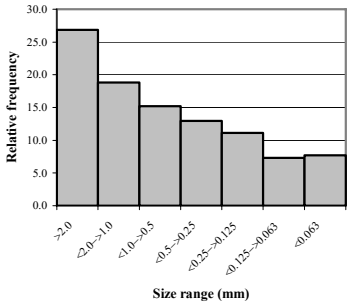
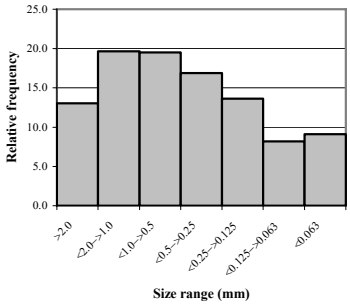
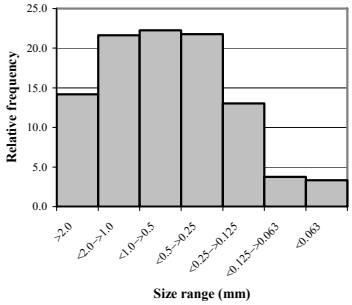
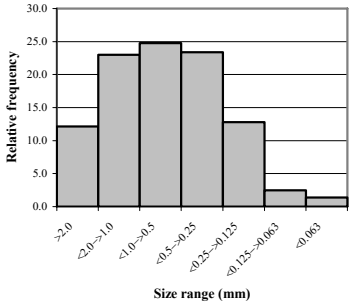
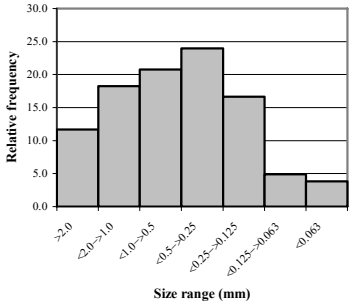
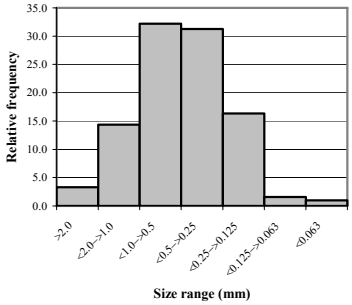
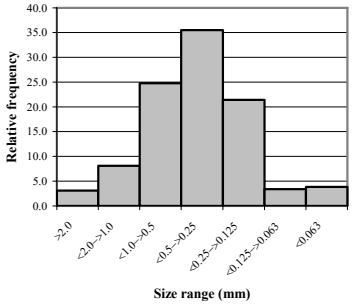
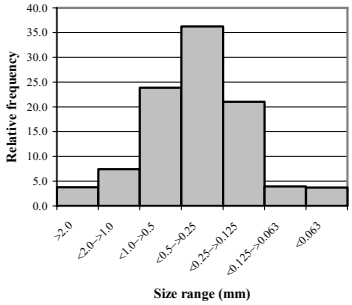
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
5			
6			
7			
8			

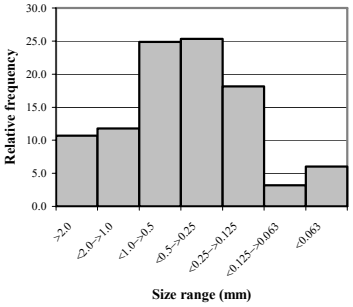
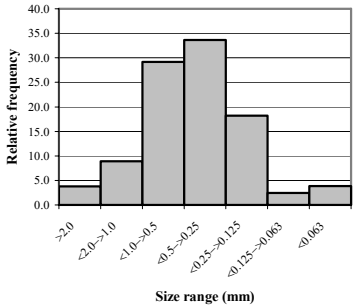
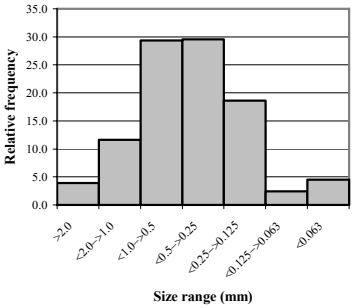
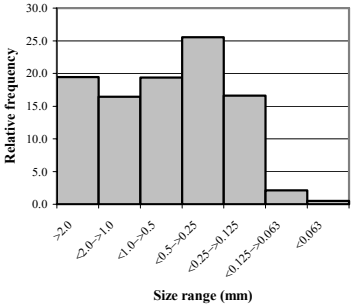
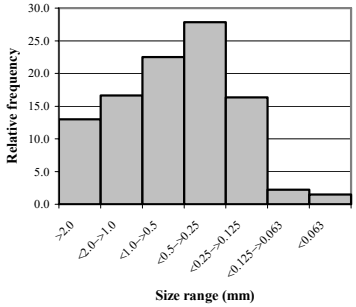
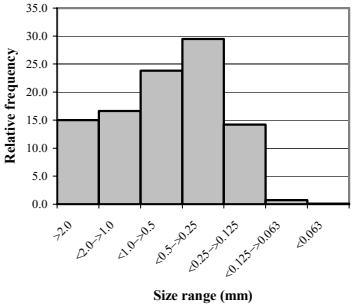
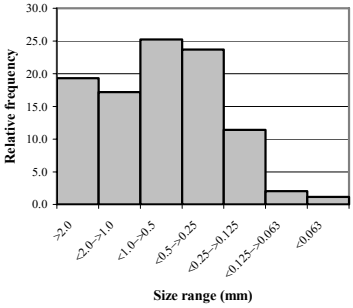
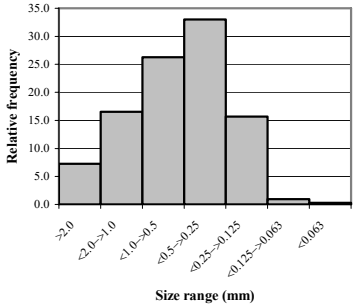
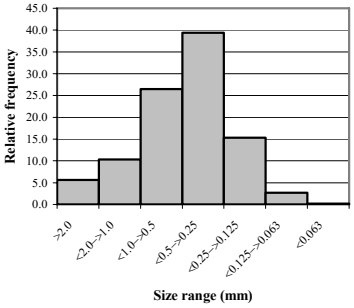
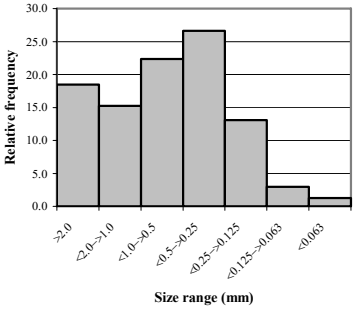
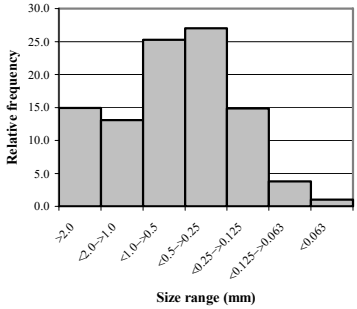
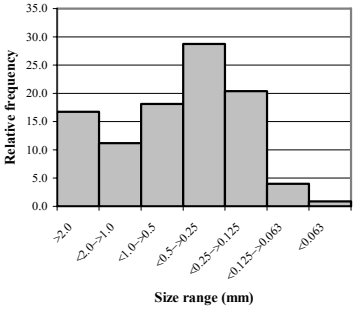
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
9			
10			
11			
12			

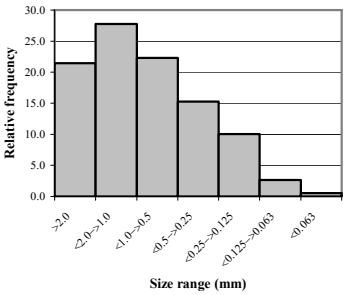
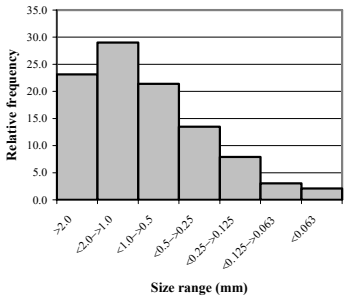
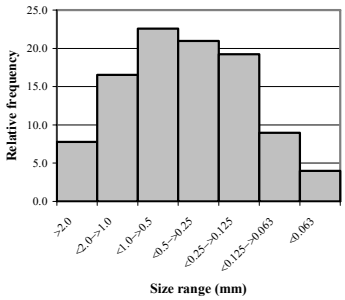
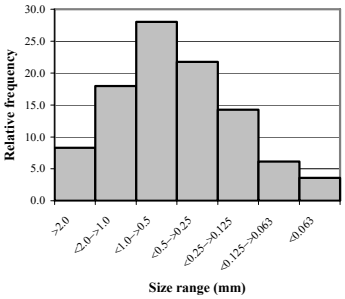
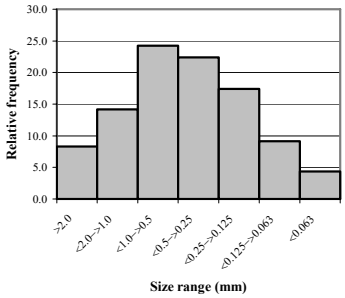
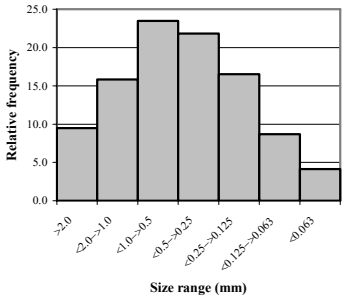
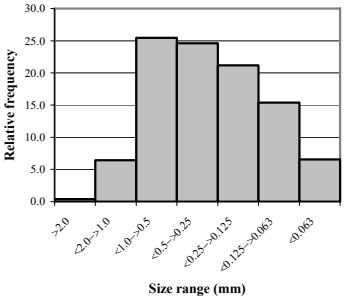
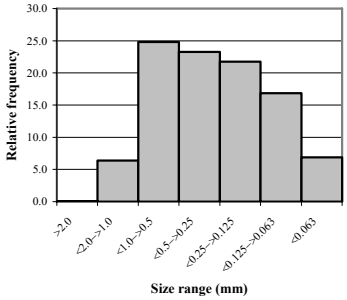
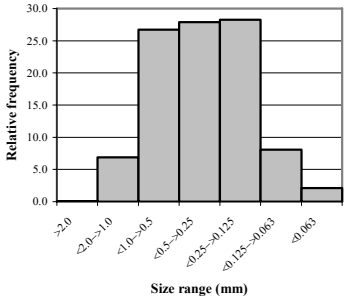
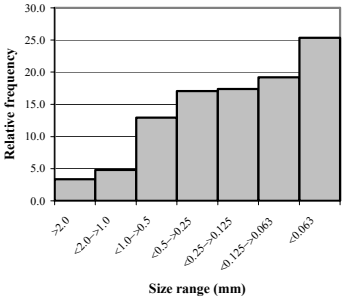
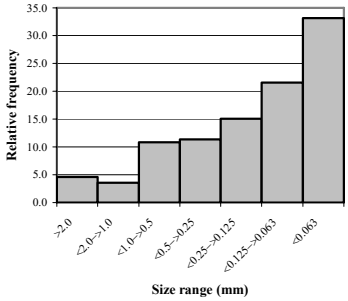
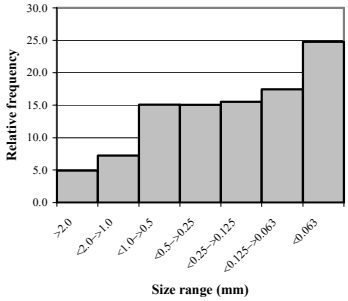
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
13			
14			
15			
16			

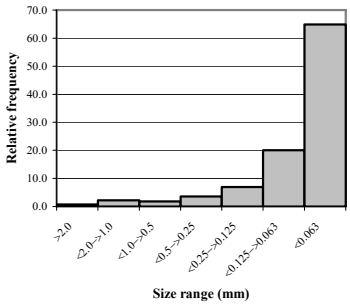
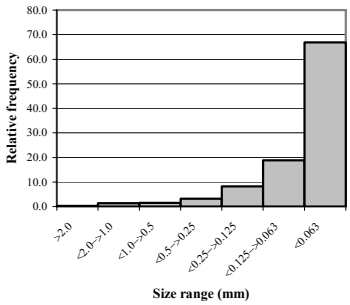
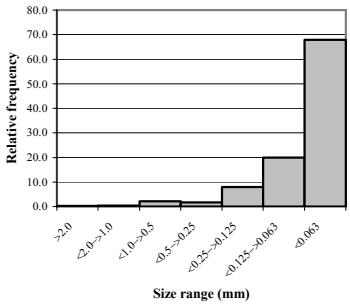
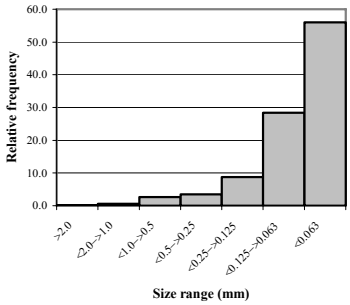
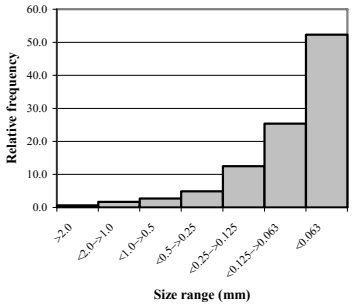
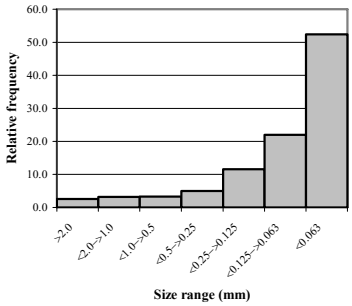
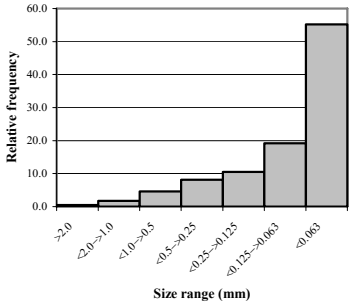
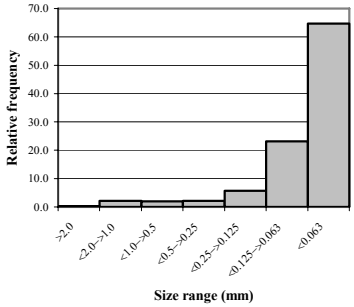
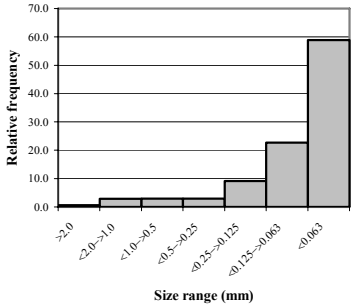
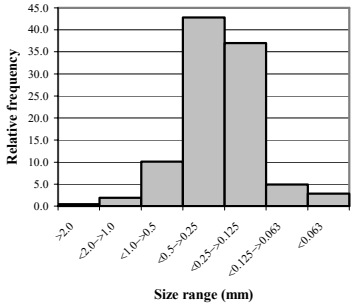
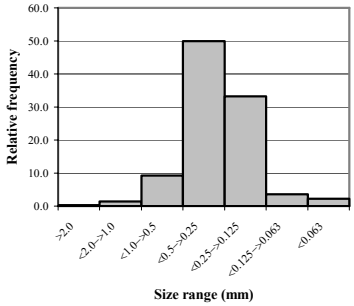
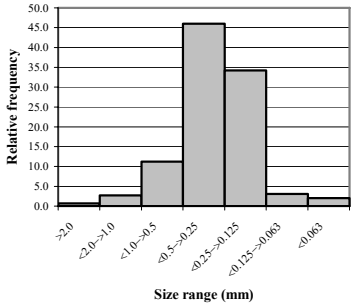
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
17			
18			
19			
20			

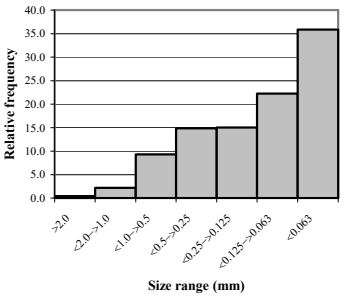
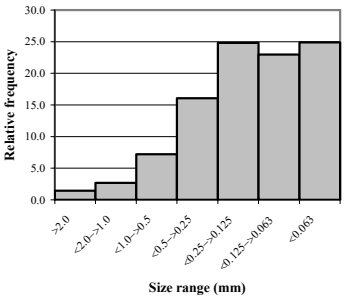
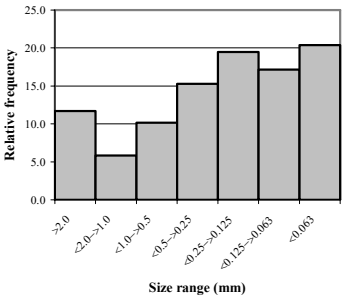
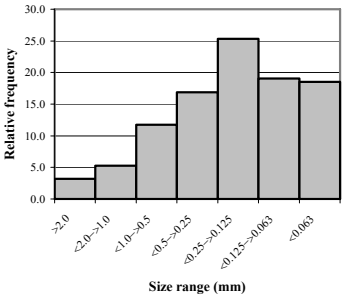
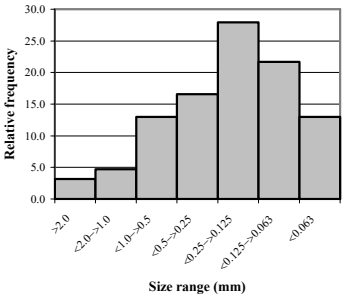
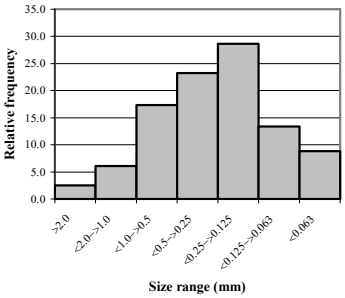
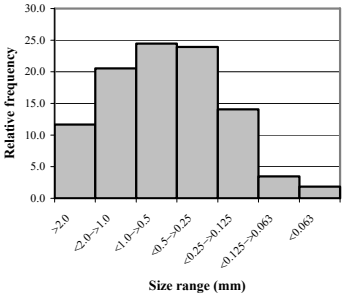
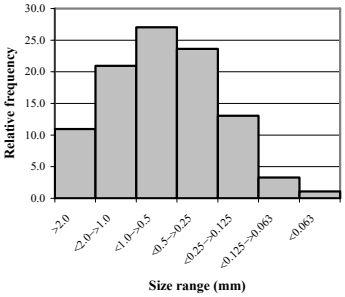
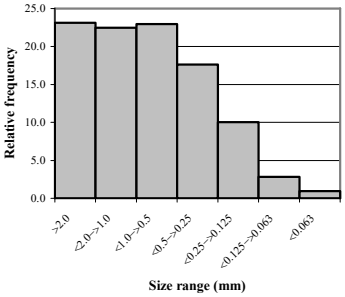
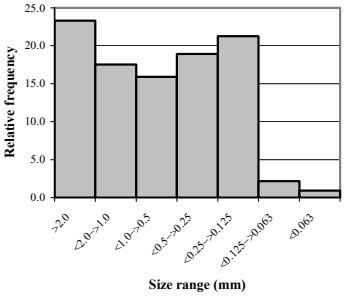
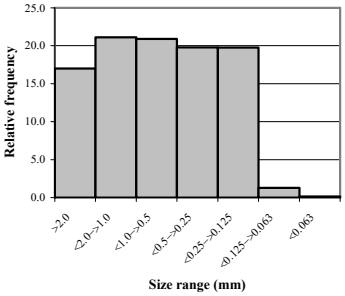
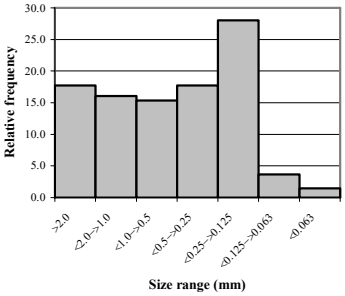
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
21			
22			
23			
24			

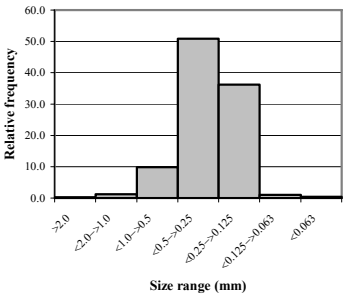
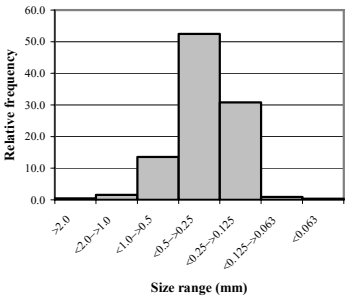
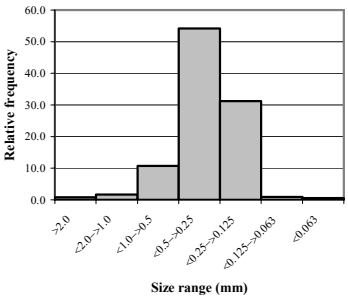
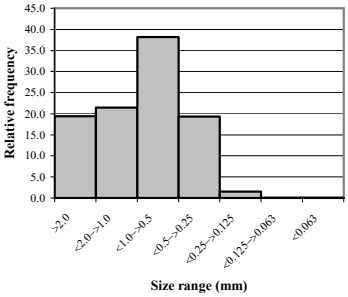
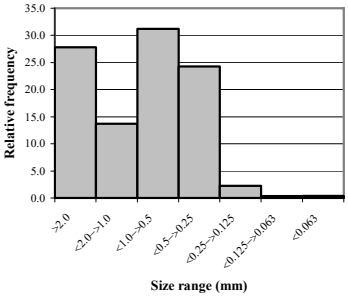
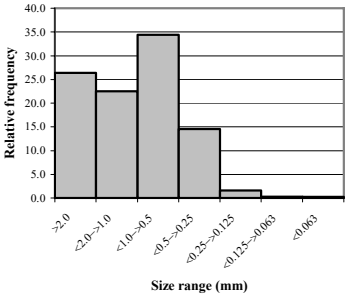
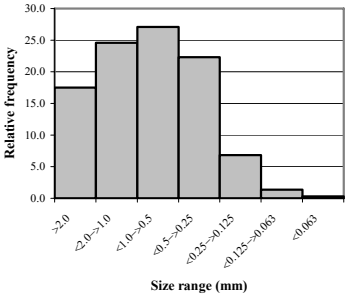
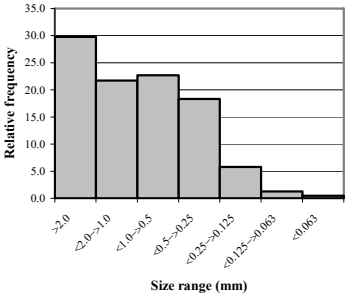
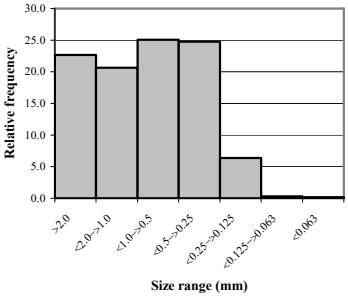
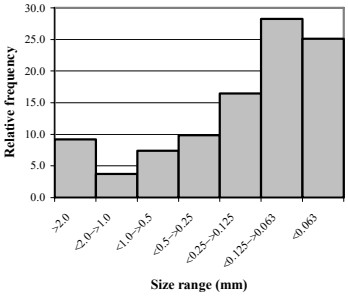
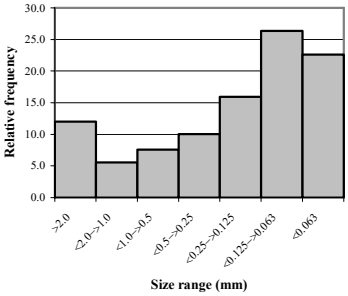
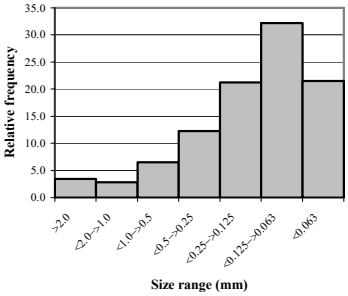
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
25			
26			
27			
28			

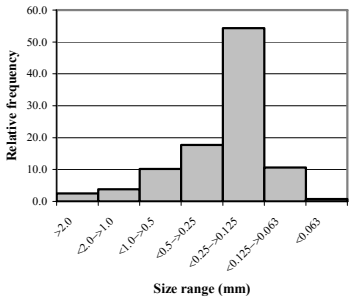
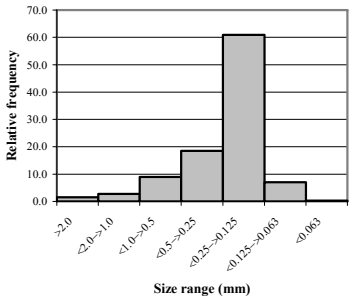
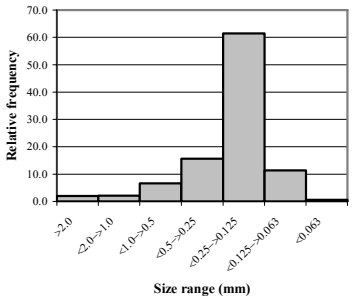
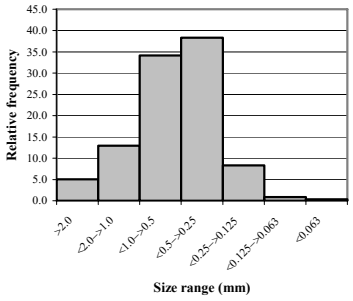
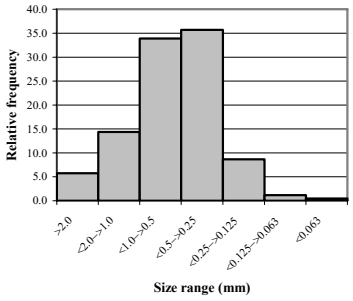
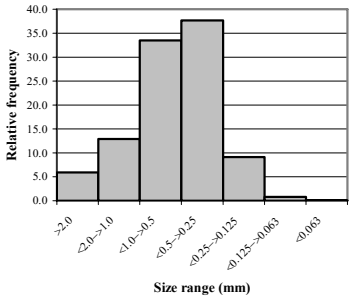
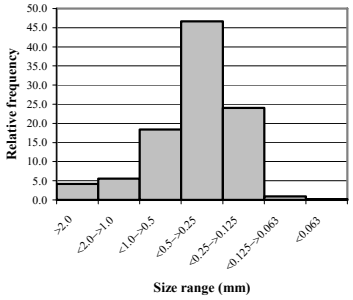
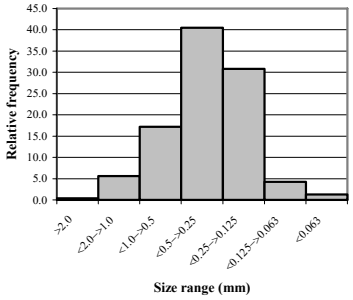
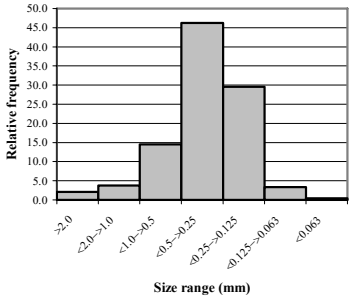
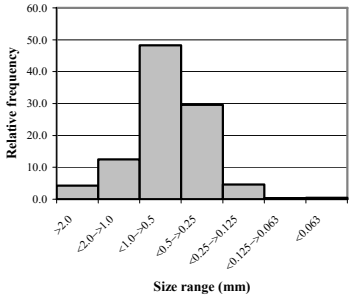
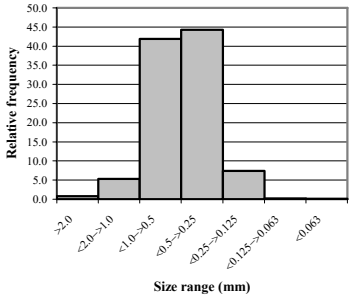
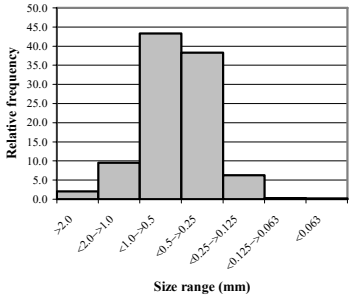
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
29			
30			
31			
32			

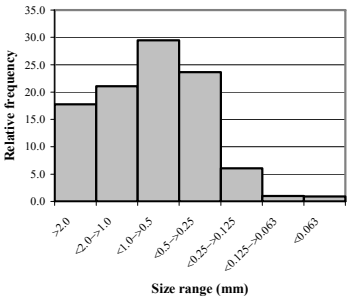
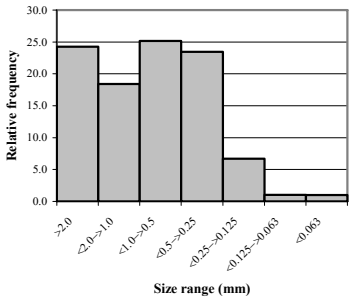
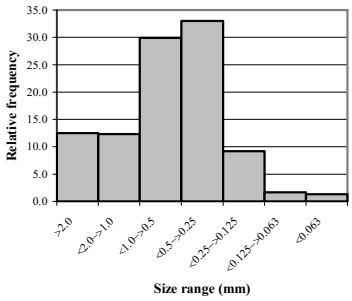
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	B	C
33			
34			
35			
36			

Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core A	Core B	Core C
37			
38			
39			
40			

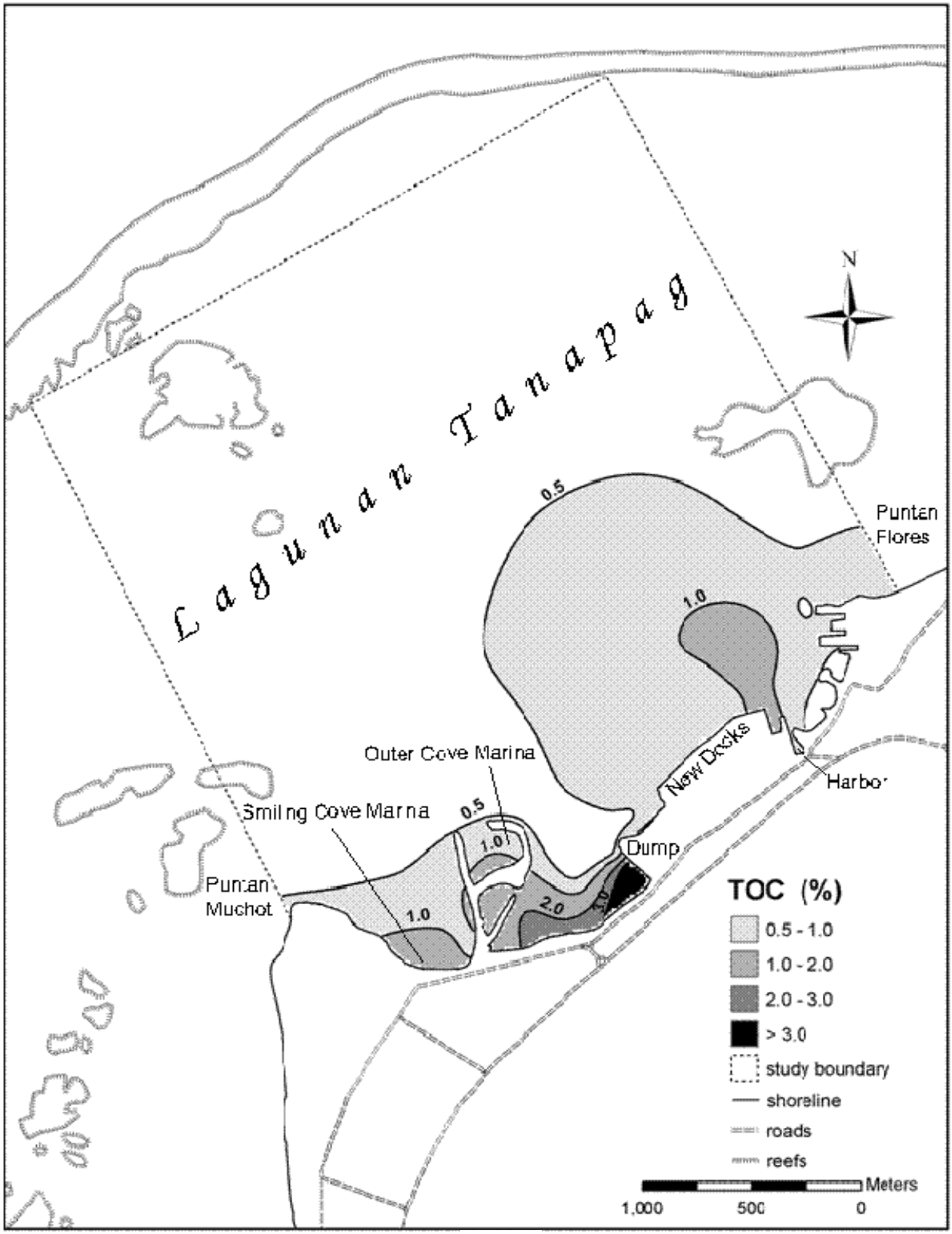
Frequency Distribution Histograms of Particle Size Ranges in Surface Sediments from Tanapag Lagoon, Saipan

Site	Core		
	A	**B**	**C**
41			

APPENDIX B

Isoconcentration Contour Map of Total Organic Carbon in Surface Sediments of Tanapag Lagoon, Saipan

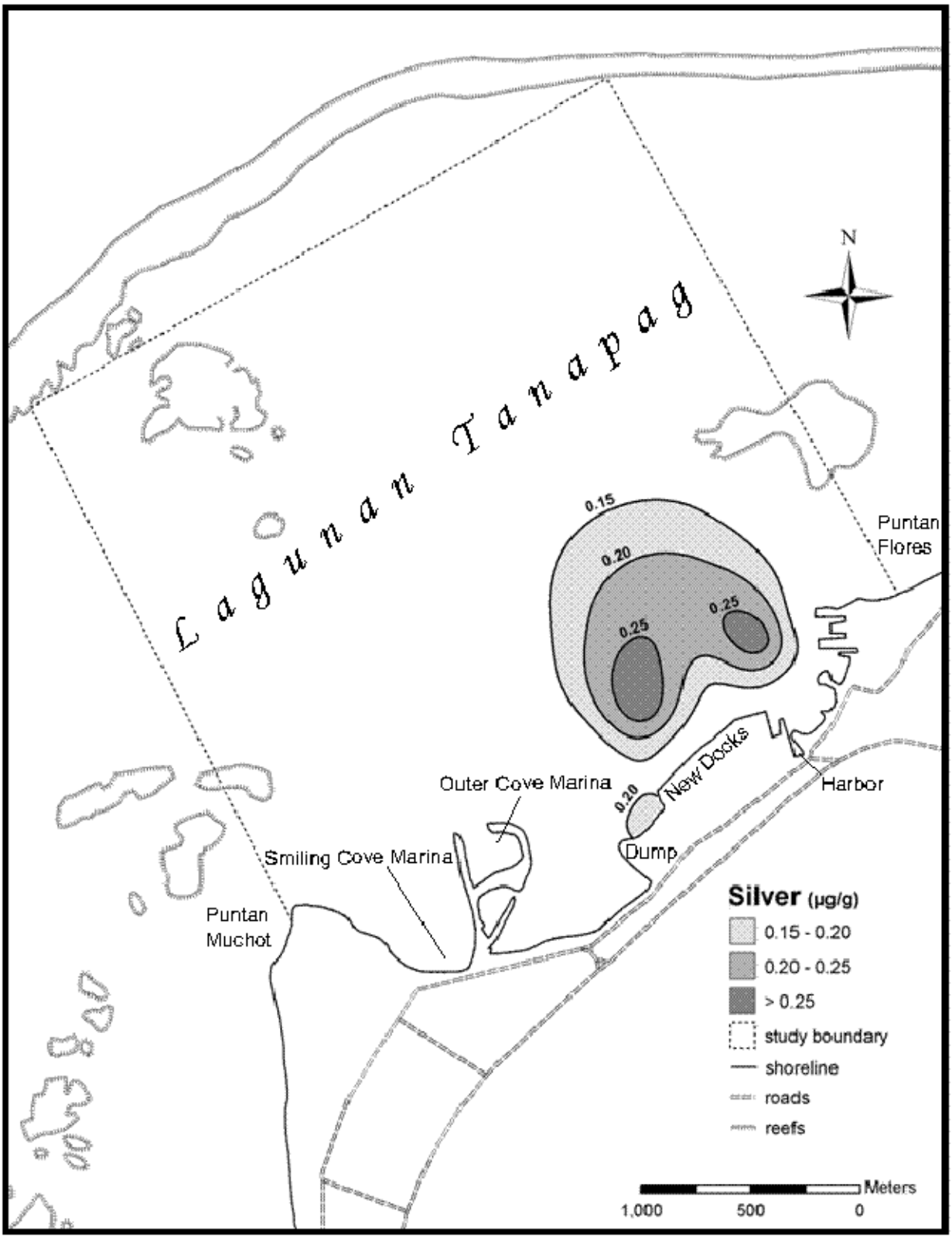
Distribution and Abundance of Total Organic Carbon (TOC) in Surface Sediments of Tanapag Lagoon, Saipan



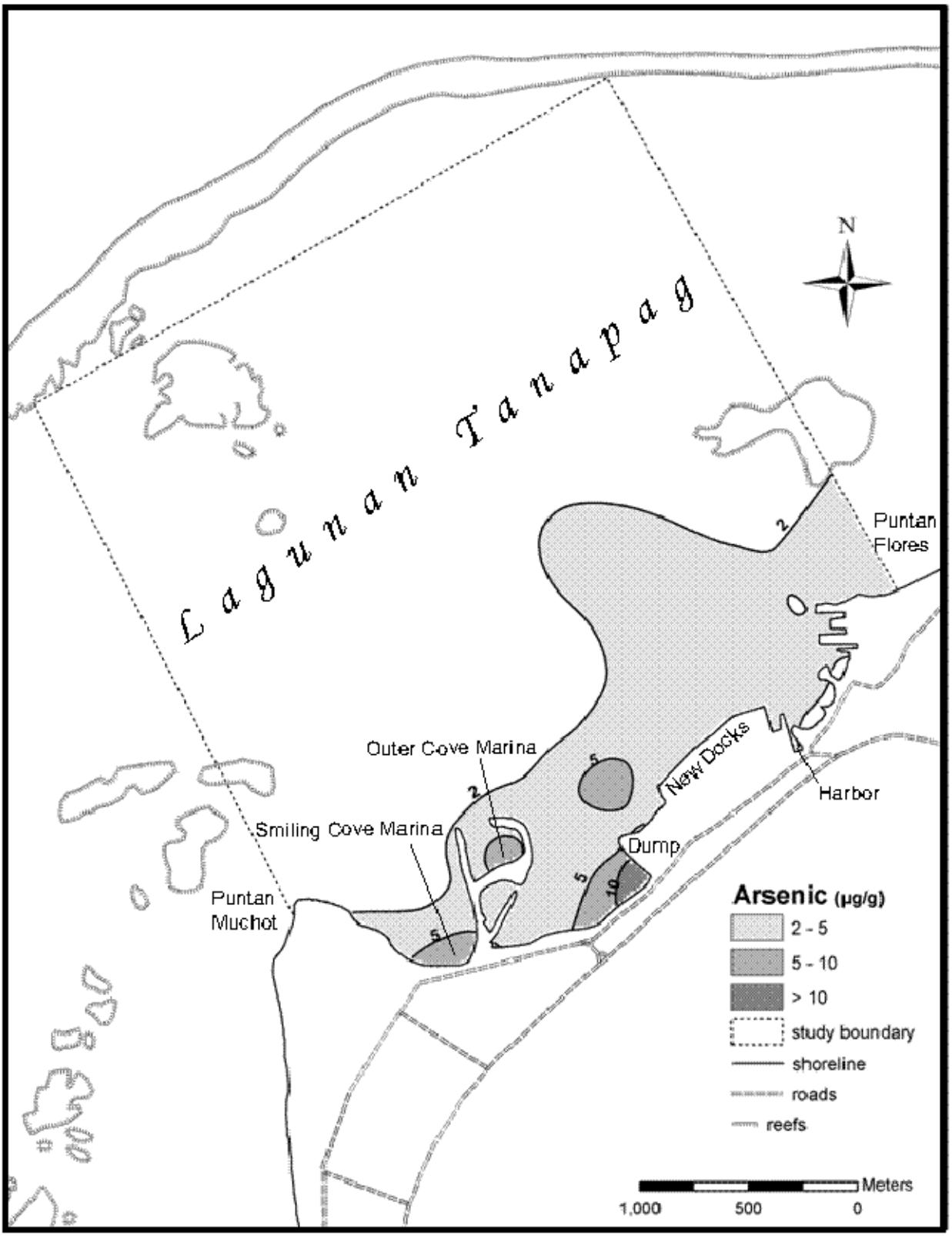
APPENDIX C

Isoconcentration Contour Maps of Heavy Metals in Surface Sediments of Tanapag Lagoon, Saipan

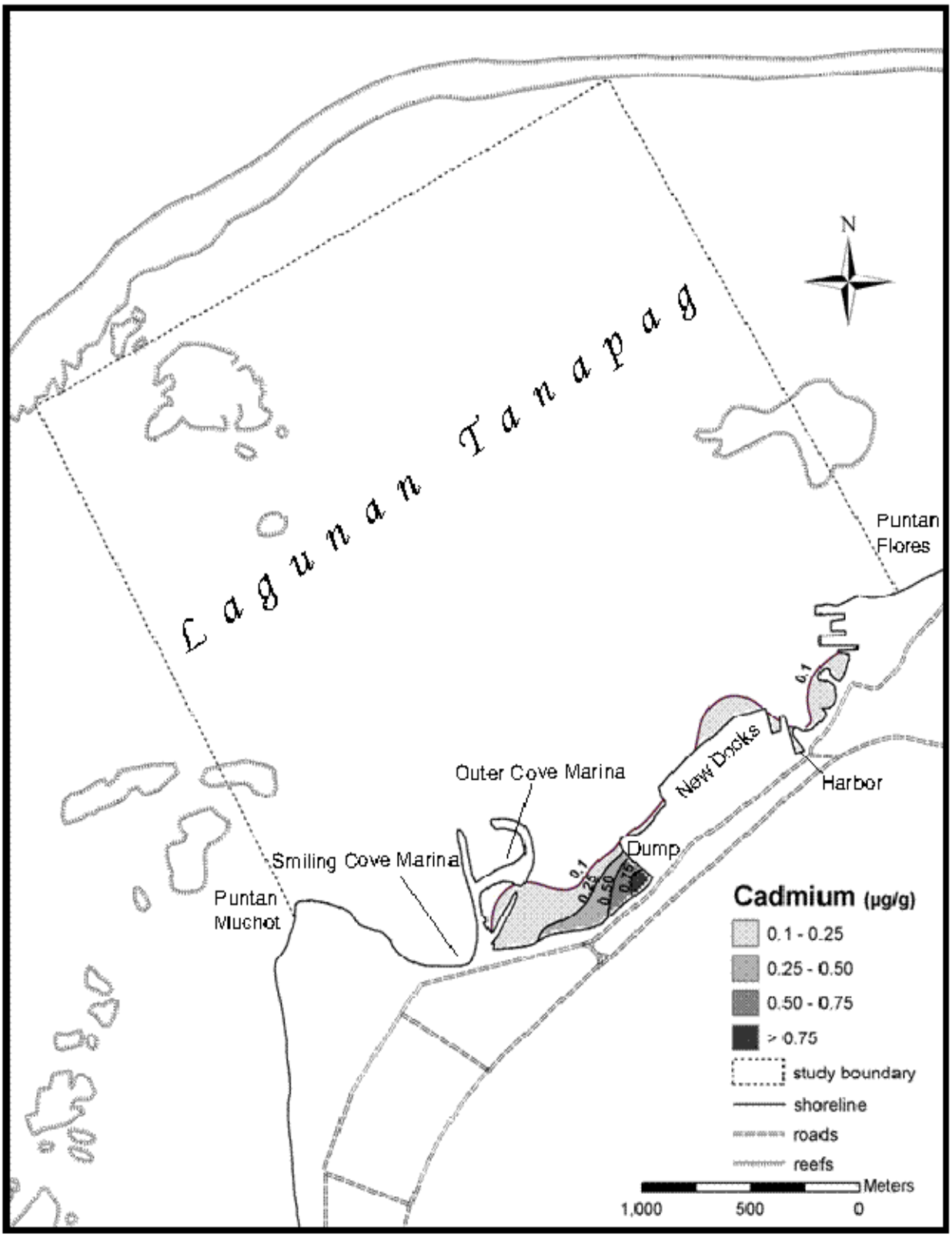
Distribution and Abundance of Silver (Ag) in Surface Sediments of Tanapag Lagoon, Saipan



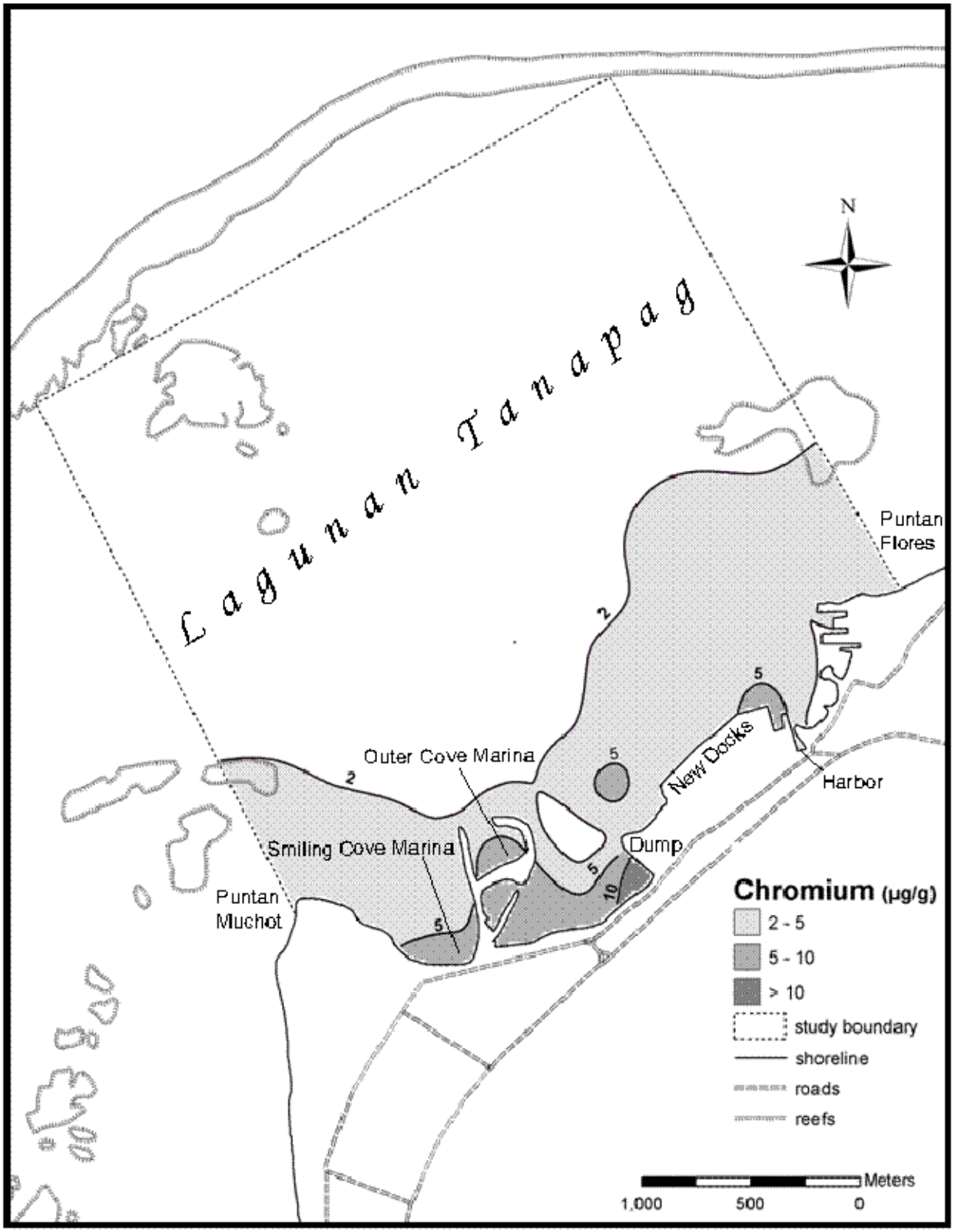
Distribution and Abundance of Arsenic (As) in Surface Sediments of Tanapag Lagoon, Saipan



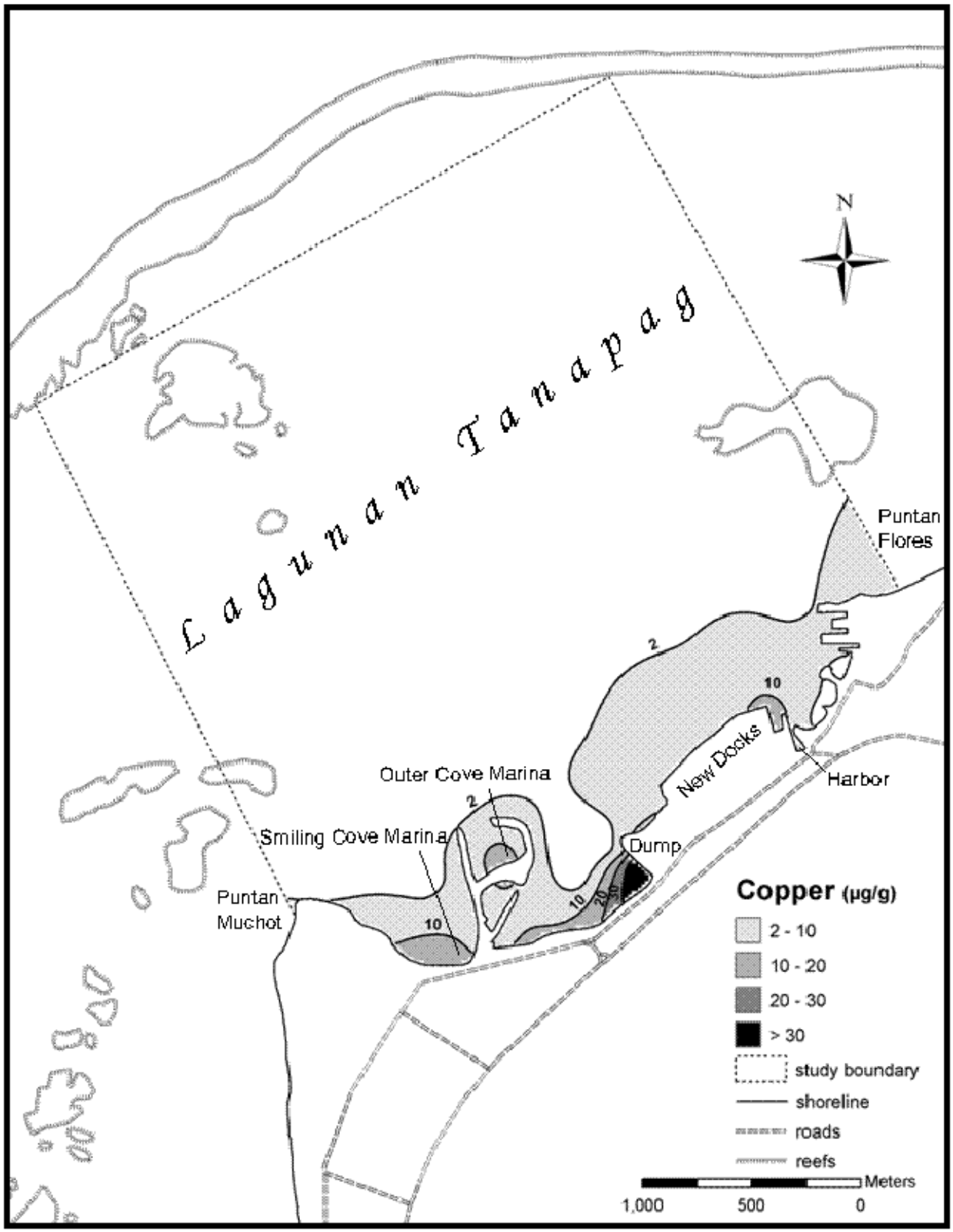
Distribution and Abundance of Cadmium (Cd) in Surface Sediments of Tanapag Lagoon, Saipan



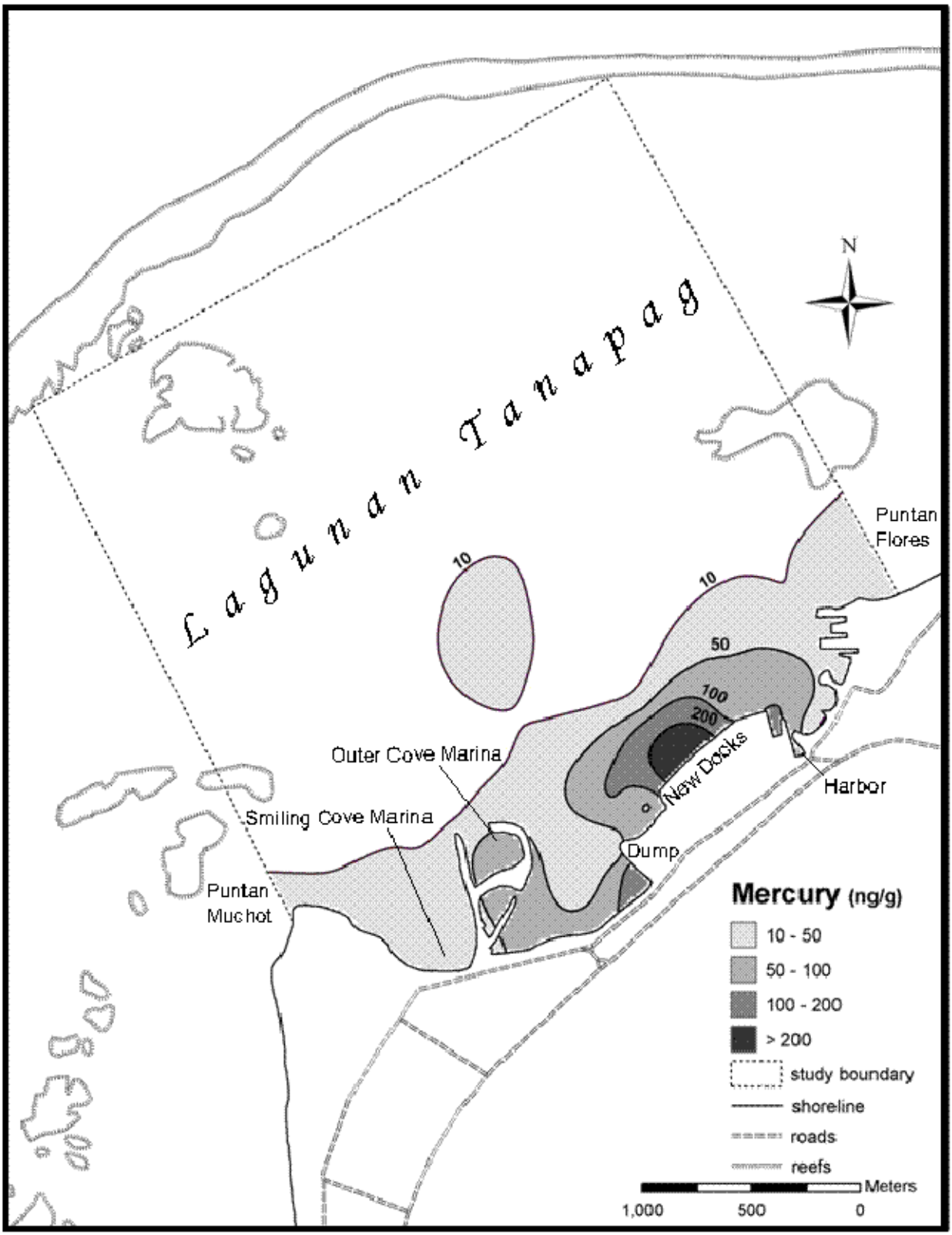
Distribution and Abundance of Chromium (Cr) in Surface Sediments of Tanapag Lagoon, Saipan



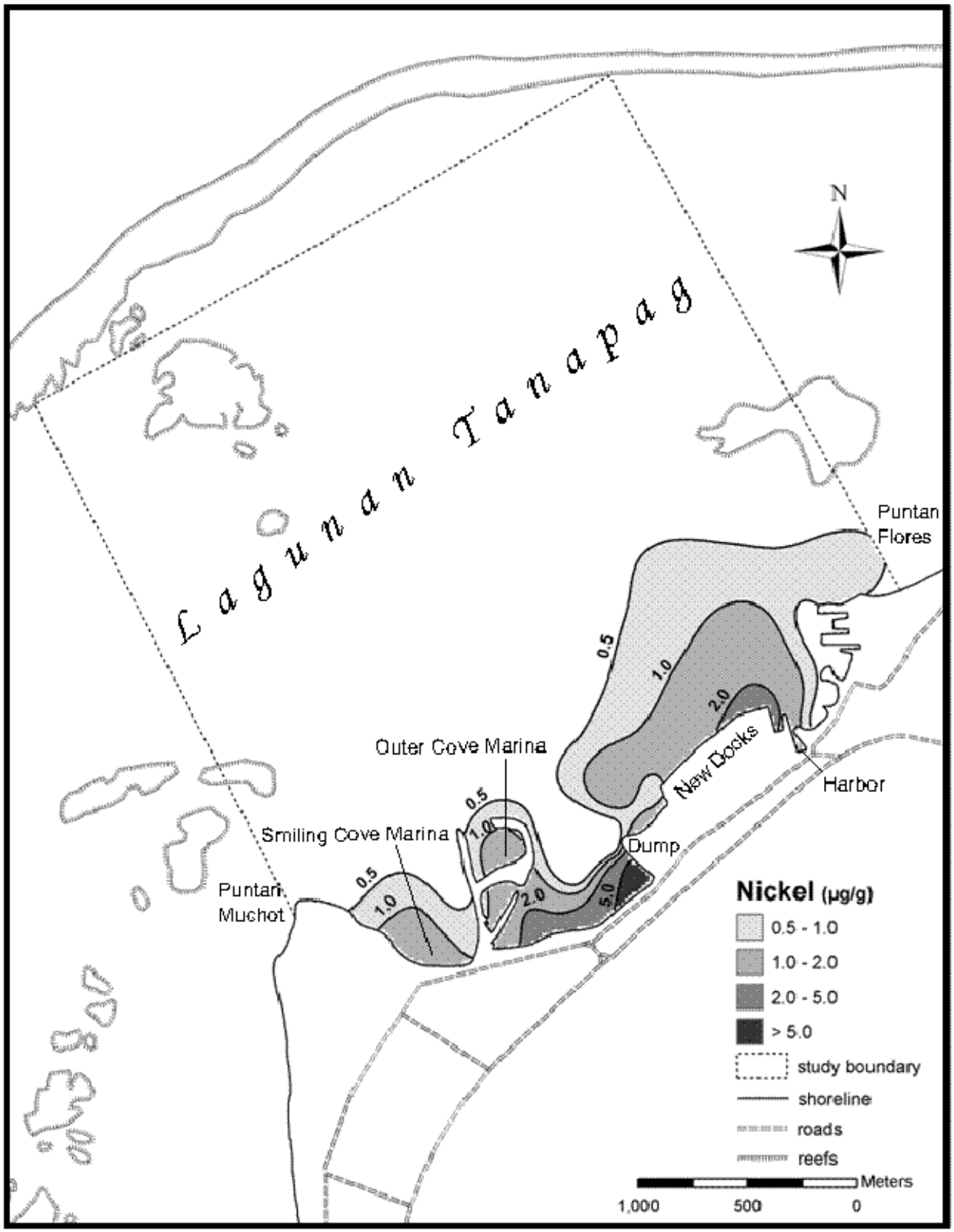
Distribution and Abundance of Copper (Cu) in Surface Sediments of Tanapag Lagoon, Saipan



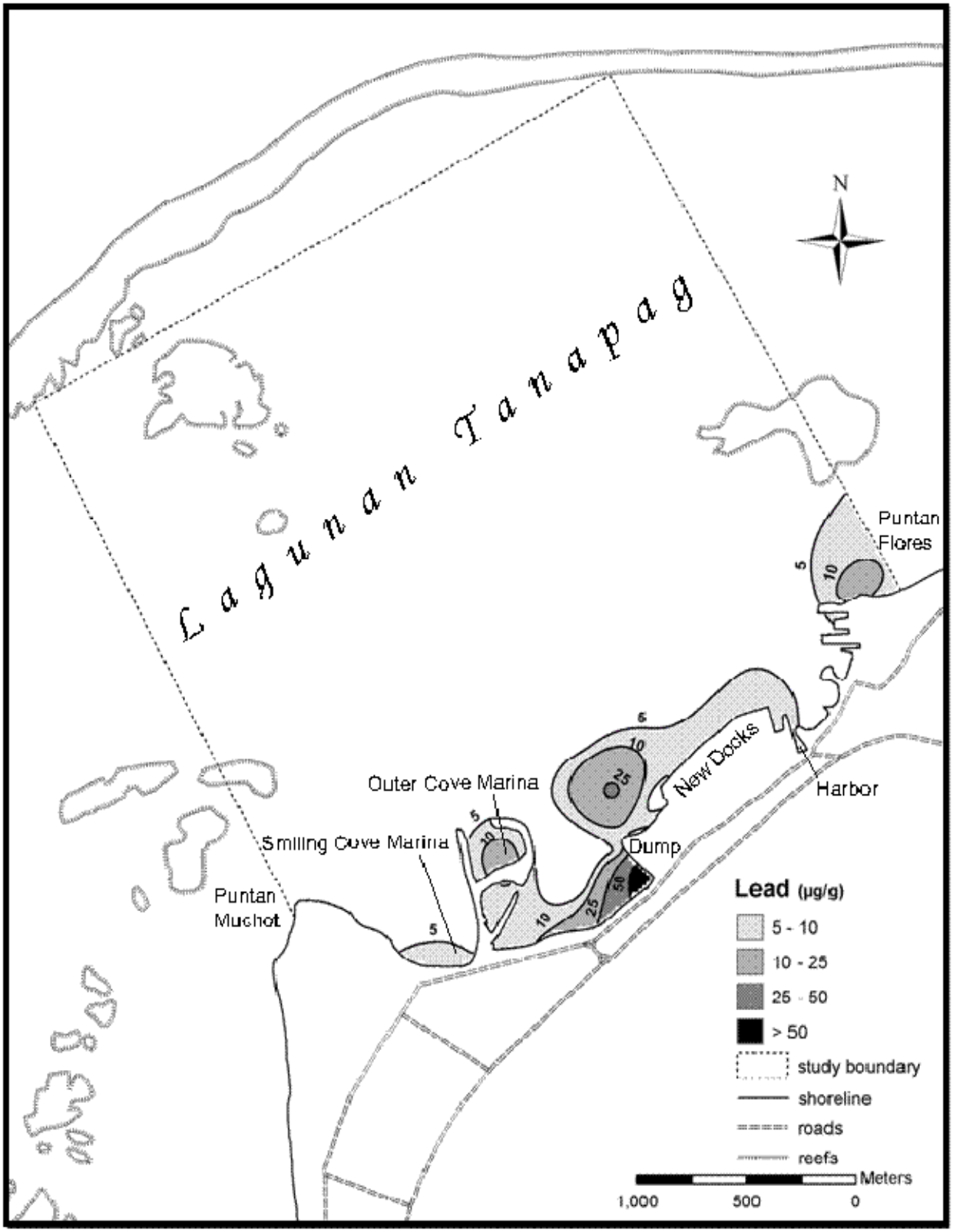
Distribution and Abundance of Mercury (Hg) in Surface Sediments of Tanapag Lagoon, Saipan



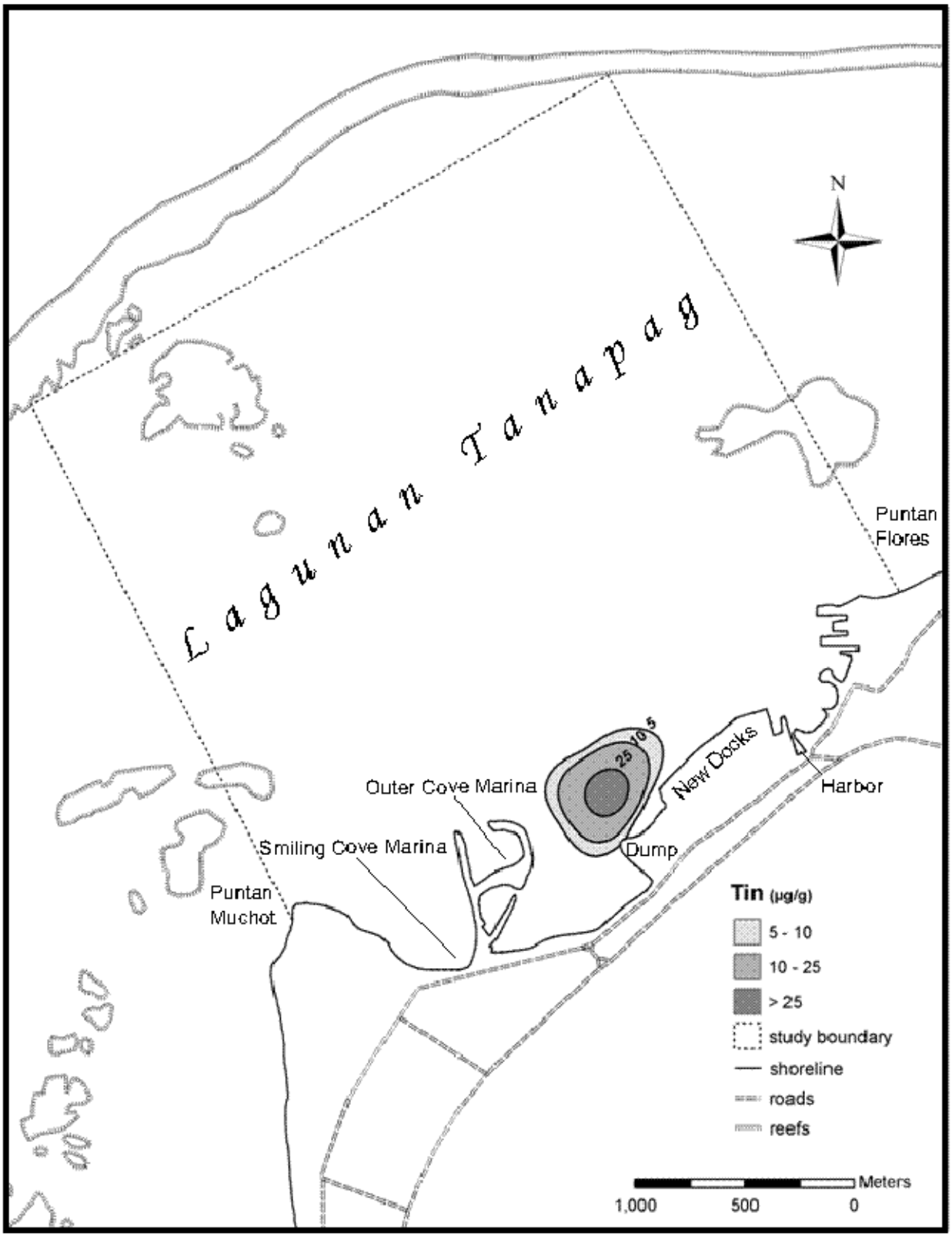
Distribution and Abundance of Nickel (Ni) in Surface Sediments of Tanapag Lagoon, Saipan



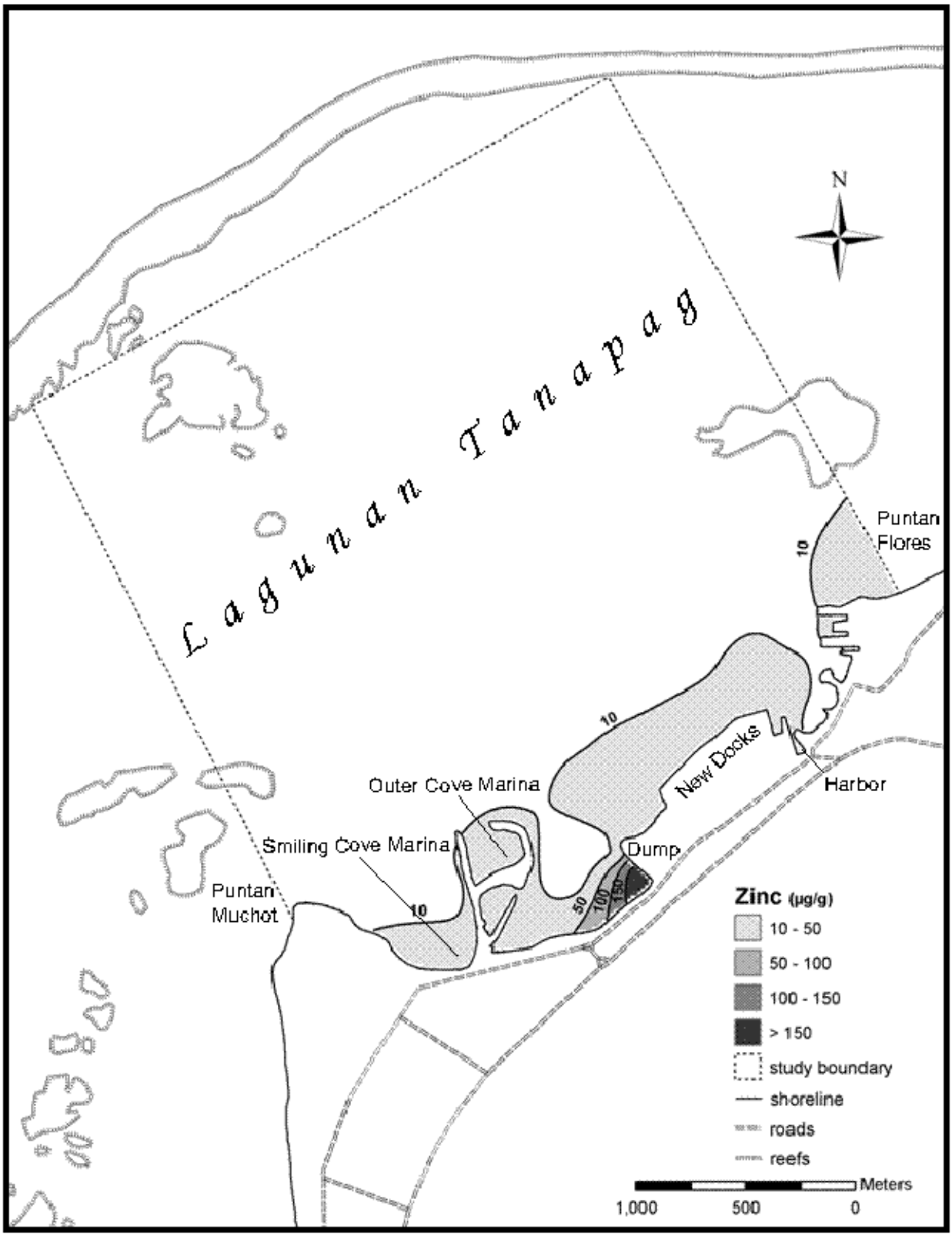
Distribution and Abundance of Lead (Pb) in Surface Sediments of Tanapag Lagoon, Saipan



Distribution and Abundance of Tin (Sn) in Surface Sediments of Tanapag Lagoon, Saipan



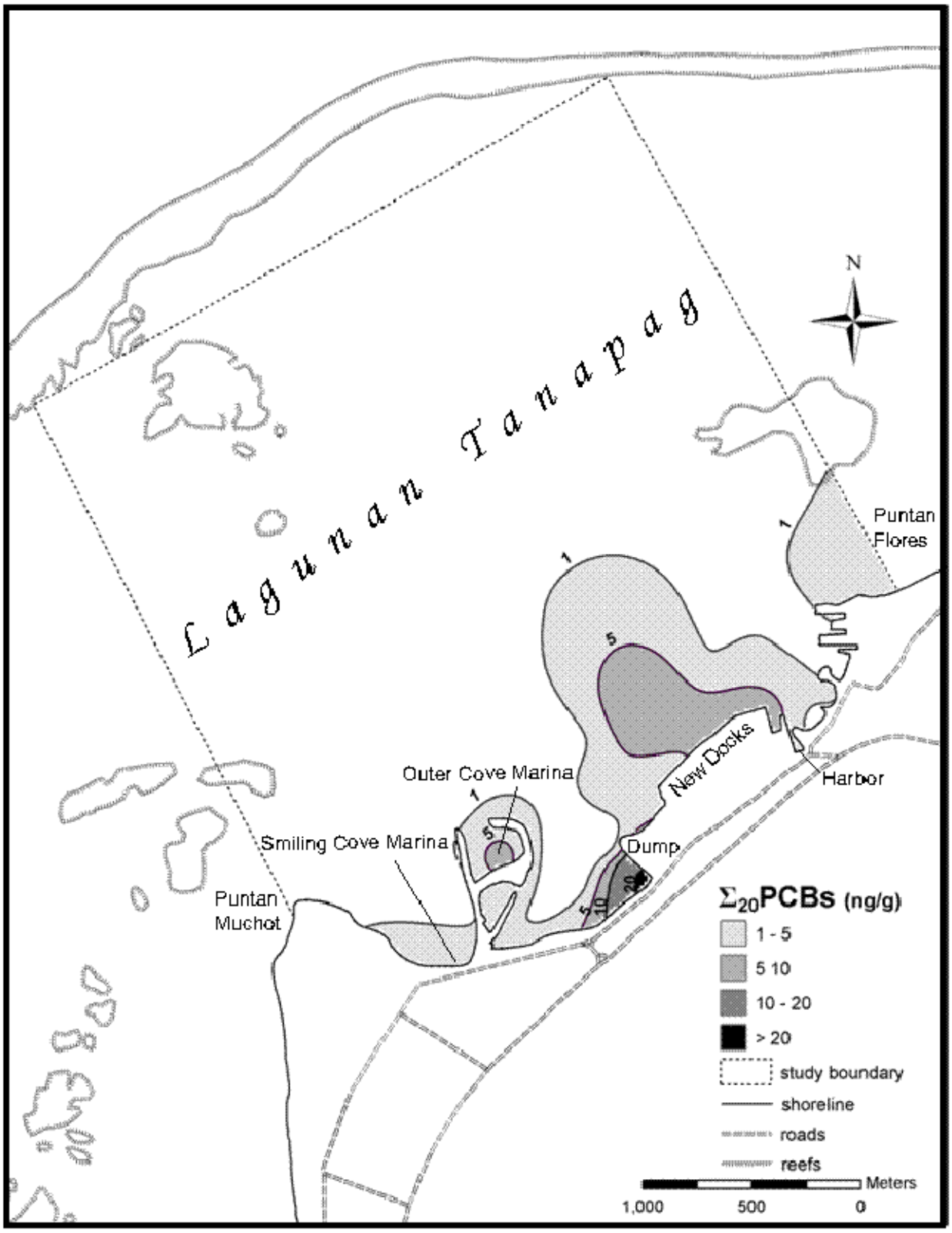
Distribution and Abundance of Zinc (Zn) in Surface Sediments of Tanapag Lagoon, Saipan



APPENDIX D

Isoconcentration Contour Map of PCBs in Surface Sediments of Tanapag Lagoon, Saipan

Distribution and Abundance of Polychlorinated Biphenyls (PCBs) in Surface Sediments in Tanapag Lagoon, Saipan



APPENDIX E

Isoconcentration Contour Map of PAHs in Surface Sediments of Tanapag Lagoon, Saipan

Distribution and Abundance of Polycylic Aromatic Hydrocarbons (PAHs) in Surface Sediments of Tanapag Lagoon, Saipan