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ES&T RESEARCH

Sediment Contaminants in Casco Bay, Maine: Inventories, Sources, and Potential for Biological Impact

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An inventory-based approach to environmental assessment that determines concentrations of sedimentary contaminants, defines their origins, and assesses the potential for biological impact is illustrated in Casco Bay, ME. The most widespread contaminants in Casco Bay are petroleum and petroleum byproducts. The highest concentrations of contaminants are associated with population centers, effluent outfalls, and spills. The majority of PAH in sediments are the product of high-temperature combustion processes. PAH concentrations at sites in close proximity to Portland exceed values believed to produce toxic responses in marine benthic organisms. In contrast, PCB, DDTs, and chlordane concentrations in the sediments are below concentrations thought to produce toxic effects in marine organisms. Metal concentrations in sediments are also below those that elicit biological responses. The geographic distribution of contaminants is initially controlled by the proximity to sources, and the regional differences in concentrations are the result of sediment accumulation patterns. Detrital (terrestrial), autochthonous marine, pyrogenic, and petroleum sources for PAH, alkanes, and trace metals are defined.

Introduction

The systematic inventory of contaminants within coastal environments is often a first step in developing a logical and effective approach to preserving, protecting, and/or reclaiming resources impacted by human activities. While bulk inventories of chemicals alone cannot predict biological impacts or "ecosystem health", this first-order evaluation of the presence and magnitude of contamination can indicate which processes are most influential in controlling ecosystem exposure. Cause and effect must be linked by careful consideration of contaminant input, transport, ultimate fate, and biological impact. High-quality analyses, intensive sampling, and an evaluation of a broad spectrum of contaminants can contribute to defining those processes or activities most closely linked to detrimental or unwanted impacts. Innate in this type of approach is the generation of large, complex multicomponent data sets that must be fully integrated and rigorously evaluated. An approach utilizing comprehensive chemical inventories and a detailed statistical analysis of the data is reported for a study of Casco Bay, ME, sediments. Surficial sediments were evaluated as a long-term accumulator of contaminants, which are probably the main avenue of chronic exposure of the associated ecosystem.

Site Description

Casco Bay is situated along the Atlantic Coast of Maine and is bounded by Cape Small to the northeast and Cape Elizabeth to the southwest (Figure 1). The bay has a wealth of natural resources and marine habitats that support a rich and diverse ecosystem. The bay proper is a 400-km^2 embayment of the Gulf of Maine which includes Portland Harbor, a major docking facility and the principal fishing port of Maine. More than 300 mi of coastline and nearly 400 islands are encompassed by the bay (*1*).

Methods

Sediment samples were analyzed for trace metals, aliphatic and polycyclic aromatic hydrocarbons, pesticides and PCBs (Table 1). Matrix spikes, laboratory sample duplicates, and laboratory blanks were processed with each batch of samples (10–20 samples/batch). Duplicates were produced by subsampling in the laboratory. Standard reference materials (National Institute of Standards and Technology) were analyzed to audit the performance of the analytical methods. The quality assurance standards are those of the NOAA's National Status and Trend Program, of the EPA's Environmental Monitoring and Assessment Program-Near Coastal (EMAP-NC) and of the U.S. Fish and Wildlife Service (FWS) for trace contaminant analyses (*2*). These methods have undergone extensive intercalibration with EPA, NOAA, NIST and FWS. Detailed methods are provided elsewhere (*3*).

Sample Collection. Sediment samples were collected in August 1991 (Figure 1). Station locations were chosen to provide good areal coverage, sediments of different ages (including erosional features), and representative coverage of benthic communities. Bathymetry and sediment texture also guided site selection. The sampling sites are designated as CS, EB, IB, OB, SW, and WB (i.e., Cape Small, East Bay, Inner Bay, Outer Bay, Shallow Water, and West Bay, respectively). A number identifies the location within the bay. Samples were taken with either a Smith–McIntyre grab sampler, a ponar grab sampler, or by hand. All samples were carefully inspected to ensure that undisturbed sediments were collected.

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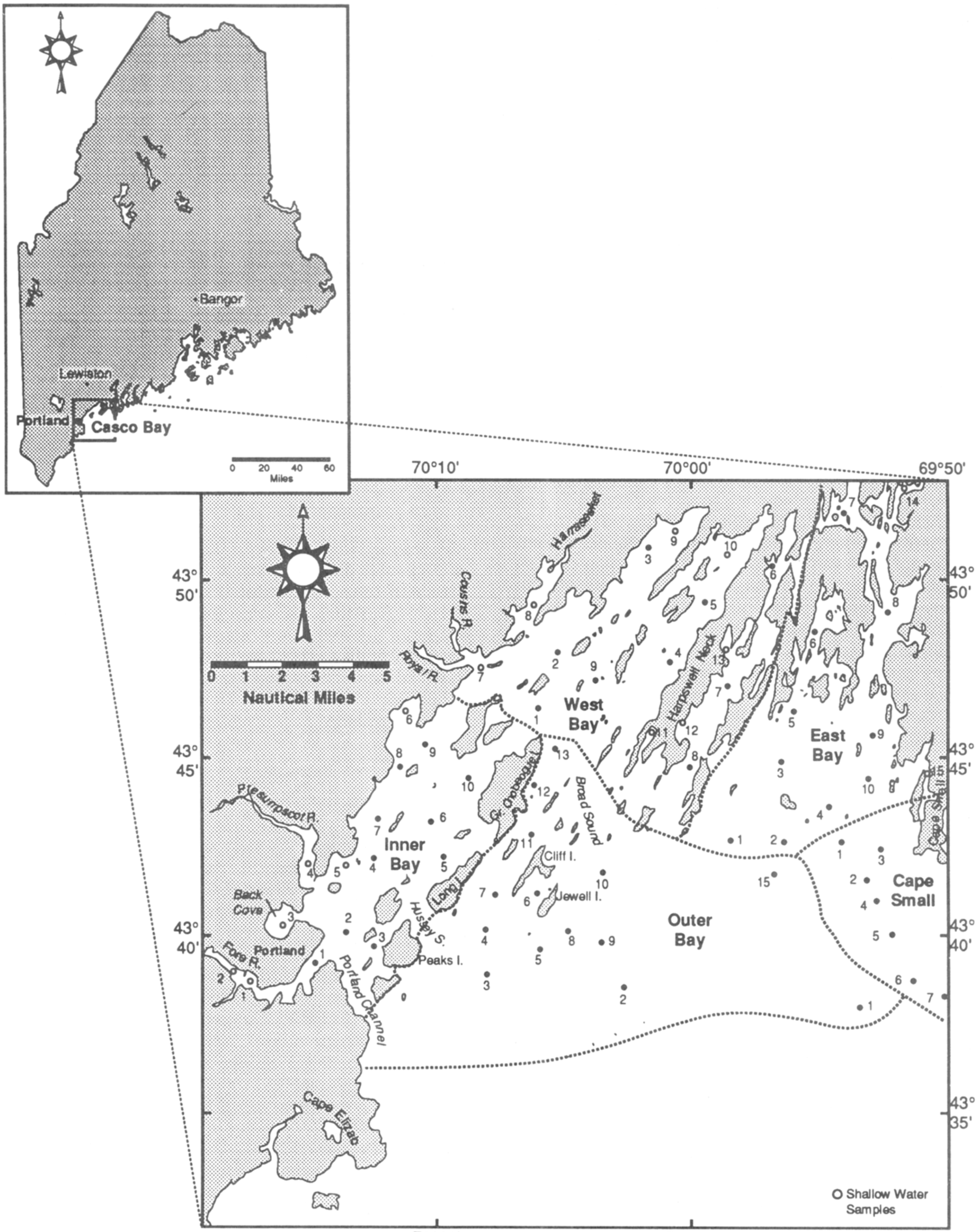

Figure 1. Location map for the Casco Bay study.

Hydrocarbons, Pesticides, and PCBs. The extraction method is that of Wade *et al.* (2). A total of 10 g of freeze-dried sediment was Soxhlet-extracted with methylene chloride and concentrated in Kuderna-Danish tubes. The extracts were fractionated by alumina:silica gel (80–100 mesh) chromatography. The extracts were sequentially eluted from the column with 50 mL of pentane (aliphatic fraction) and 200 mL of 1:1 pentane–dichloromethane (aromatic/PCB/pesticide fraction) and concentrated for instrumental analysis.

Table 1. Analytes Measured in Casco Bay Estuary Program[a]

Total Metals

cadmium
copper
lead
nickel
chromium
silver
zinc
iron
mercury
arsenic
selenium

Hydrocarbons

naphthalene
2-methylnaphthalene
1-methylnaphthalene
biphenyl
2,6-dimethylnaphthalene
acenaphthylene
acenaphthene
fluorene
phenanthrene
anthracene
2-methylphenanthrene
fluoranthene
pyrene
benz[*a*]anthracene
chrysene
benzo[*b*]fluoranthene
benzo[*k*]fluoranthene
benzo[*a*]pyrene
benzo[*e*]pyrene
perylene
indeno[1,2,3-*cd*]pyrene
dibenz[*a*,*h*]anthracene
benzo[*g*,*h*,*i*]perylene

In Addition

extended PAHs (alkylated homologues useful in differentiating oil from combustion sources)
aliphatic fraction quantitation including C_{12}–C_{34} *n*-alkanes, pristane, phytane, and the unresolved complex mixture

PCBs

congener-specific analysis of 20 individual PCBs including quantitative estimates of the amount of arochlor mixtures

Pesticides

aldrin
α-BHC
β-BHC
δ-BHC
γ-BHC
α-chlordane
γ-chlordane
dieldrin
endosulfan I
endosulfan II
endosulfan sulfate
endrin
endrin aldehyde
heptachlor
heptachlor epoxide
toxaphene
hexachlorobenzene
2,4′-DDE
2,4′-DDD
2,4′-DDT
4′,4-DDD
4′,4-DDE
4′,4-DDT

Ancillary Parameters

(1) TOC was determined by combustion in a Leco carbon analyzer to CO_2 and subsequent quantitation by IR
(2) grain size (sand, silt, and clay) was determined by the Folk settling method
(3) organic nitrogen was determined by a Kjeldahl digestion
(4) % solids (dry weight) are determined and reported for all samples

[a] Note: Organic analyte concentrations are reported on the basis of dry weight of sediment and are corrected for surrogate recoveries.

Aliphatic hydrocarbons (n-C_{13}–n-C_{34}), pristane, and phytane were analyzed by gas chromatography (HP-5980) in the splitless mode with flame ionization detection (FID). A 30 m × 0.32 mm i.d. fused-silica column with DB-5 bonded phase (J&W Scientific, Inc.) provided component separations. The FID was calibrated at five concentrations, and deuterated *n*-alkanes were used as surrogates and internal standards. Aromatic hydrocarbons were quantified by gas chromatography with mass spectrometric detection (HP-5890-GC and HP-5970-MSD). The samples were injected in the splitless mode onto a 30 m x 0.25 mm (0.32 μm film thickness) DB-5 fused silica capillary column (J&W Scientific Inc.) at an initial temperature of 60 °C and temperature programmed at 12 °C/min to 300 °C and held at the final temperature for 6 min. The mass spectral data were acquired, and the molecular ions for each of the PAH analytes were used for quantification. The GC/MS was calibrated by the injection of standards at five concentrations. Analyte identifications were based on the retention time of the quantitation ion for each analyte and a series of confirmation ions. Deurated aromatic compounds were used for surrogates and internal standards.

Pesticides and PCBs were separated by gas chromatography in the splitless mode using an electron capture detector (ECD). A 30 m × 0.32 mm i.d. fused-silica column with DB-5 bonded phase (J&W Scientific, Inc.) provided component separations. Four calibration solutions were used to generate a nonlinear calibration curve. A sample containing only PCBs was used to confirm the identification of each PCB congener. The surrogates DBOFB (dibromooctafluorobiphenyl), PCB-103 and PCB-198 for pesticide and PCB analysis were added during the extraction. The internal standard, TCMX (tetrachloro-*m*-xylene), was added prior to GC/ECD analysis. The chromatographic conditions for the pesticide–PCB analysis were 100 °C for 1 min, then 5 °C/min until 140 °C, hold for 1 min, then 1.5 °C/min to 250 °C, hold for 1 min, and then 10 °C/min to a final temperature of 300 °C, which was held for 5 min.

Trace Metals. The major analytical technique used for trace metal determination was atomic absorption spectrophotometry (AAS) in the flame mode for those elements in high enough concentration. Graphite furnace (GC/AAS) or cold vapor techniques were used when necessary. Samples were pressure-digested in 50-mL closed all-Teflon "bombs" (Savillex Co.; Brooks *et al.*, 1988). Sediment aliquots (ca. 200 mg) were digested at 130 °C in a mixture of nitric, perchloric, and hydrofluoric acids. A saturated boric acid solution was then added to complete the dissolution. Various dilutions were made on the clear digest solutions to bring them within the calibration of the AAS. Standard reference materials and blanks were digested and analyzed with every batch of samples.

Concentrations of Fe, Mn, and Zn were determined by flame AAS using a Perkin-Elmer Model 306 instrument, following the manufacturer's recommendations with only slight modifications. Calibration curves were constructed from commercial standards. Concentrations of Ag, As, Cd, Cr, Cu, Ni, Pb, and Se were determined with a Perkin-Elmer Zeeman 3030 instrument equipped with an HGA-600 furnace and AS-60 autosampler. Matrix modifiers and analytical conditions for the furnace and spectrophotometer were based on the manufacturer's recommendations, with modifications as appropriate to maximize sensitivity and minimize interferences. Mercury was determined by cold vapor AAS following a slightly modified EPA Method 245.5 aqua-regia/permanganate digestion. A headspace sampling procedure was used to remove Hg from the digest in contrast to the more common stripping procedure. A UV monitor (Laboratory Data Control Co.) with a 30-cm path length cell was used for Hg detection and quantification.

Organic Carbon and Grain Size. Organic carbon (OC) was determined by detection of CO_2 by an infrared spectrometer after combustion in an O_2 stream (LECO WR-12 total carbon system). Samples were acidified using dilute HCl in methanol and then dried. Method blanks and duplicate samples were analyzed every 20 samples. Data are reported as micrograms of carbon per gram of dry weight. All glassware and utensils are preheated prior to use.

Sediment grain size was determined by the procedure of Folk (*4*), utilizing sieving to separate gravel and sand fractions from the clay and silt fractions. The latter fractions were subsequently separated by the pipet (settling rate) method. Detailed descriptions of the methods utilized in measuring OC and grain size are reported in Brooks *et al.* (*5*).

Principal Components Analysis (PCA). The organic and inorganic data were analyzed using PCA (*6*). The results of PCA are highly dependent on the pretreatment or scaling of the data matrix. The data for this study consist of a wide variety of analytes that range several orders of magnitude in their absolute values. Because PCA is a least-squares method, variables with large variance will have large loadings. To avoid this bias, the entire data matrix was first scaled by dividing each variable by the standard deviation. This scaling assigns every variable a variance of 1.0 so that each variable has the same influence in the PCA model. The technique of cross-validation was used to establish the significance of each principal component (*7*). PCA was performed on a personal computer using the program SIRIUS (Pattern Recognition Systems A/S, Bergen, Norway).

Results

Hydrocarbons. Aliphatic hydrocarbons were detected at all stations sampled. The majority of resolved alkanes had odd-carbon chain lengths with 23–33 carbons indicative of plant biowaxes (Figure 2; refs 8–10). N-C_{15}, n-C_{17}, n-C_{19}, n-C_{21}, and pristane were often more abundant than the co-occurring even carbon-numbered normal alkanes and phytane, suggesting a phytoplankton input (*8-10*). Total alkanes and unresolved complex mixture (UCM) concentrations varied from 151 to 10 078 ppb dry wt and from 2 to 335 ppm dry wt, respectively. PAHs were also detected at all locations sampled. The predominant PAHs are highly condensed ring structures with few alkylations indicating a pyrogenic or combustion source (Figure 3; refs 11–14). Four-ring and larger PAHs account for more than 60% of sedimentary PAHs in Casco Bay. Total PAH concentrations varied from 16 to 20 798 ppb dry wt.

The western part of Casco Bay (Inner Bay) is most highly contaminated with PAH. Sediments from the Fore River area and locations close to Portland contain the highest concentrations of PAH. In general, contaminants decrease in concentration with distance from populated areas. However, regionally elevated PAH concentrations are also present at a few sites in East Bay and Cape Small. One station in the Cape Small (CS-4) region was unusual compared to other sites in the region. Most Cape Small stations contained <1.0% organic carbon and more than 65% sand, whereas sediment from station CS-4 contained 2.7% organic carbon and only 29.9% sand. Total alkanes, UCM, and total PAH concentrations were elevated at this location as well. Sediments at station EB-9 also had high concentrations of total PAH. An organic carbon content of 4.6% at EB-9 is the highest for all of the sediments sampled.

PCBs and Pesticides. Total PCB concentrations for the study area range from 0.4 to 485 ppb dry wt with a median concentration of 15 ppb. Total PCBs are highest in the Inner Bay in close proximity to Portland. Concentrations are lowest in Cape Small and West Bay with a few anomalous values in East Bay. The site from Cape Small with a total PCB concentration of 40 ppb dry wt has a higher TOC content (2.8%) than other samples from Cape Small.

Total DDT concentrations for the study area range from below the method detection limit (0.25 ppb) to 21 ppb dry weight. The DDTs were dominated by the *p,p'*-isomers. This is expected since technical-grade DDT is primarily the *p,p'*- isomer (75–85%). In the environment, DDT is metabolized to DDD and DDE. In some samples, DDD is the major metabolite while in other samples DDE predominates. Samples from the Inner Bay and associated shallow water sites exhibit DDD > DDE while at most other locations DDE > DDD. There is a relatively high percentage of undegraded DDT in Casco Bay sediments. The geographic distribution of total DDT concentrations is similar to that found for PCBs. The Inner Bay has the highest concentration in Casco Bay. East Bay and Outer Bay have intermediate concentrations, West Bay has lower concentrations, and the Cape Small region has the lowest concentrations.

The highest values of total chlordane are at Inner Bay sites. East Bay and Outer Bay sites are intermediate, while West Bay and Cape Small sites exhibit the lowest concentrations. Total chlordane concentrations range from below the method detection limit (0.25 ppb) to 4.9 ppb dry wt. Other organochlorine pesticides including aldrin, BHC, dieldrin, endosulfan (I, II, and sulfate), endrin, endrin aldehyde, heptachlor, heptachlor epoxide, toxaphene, and hexachlorobenzene were near or below the method detection limit (<0.25 ppb).

Trace Metals. Sediment trace metal data show considerable geographic variation with generally higher values

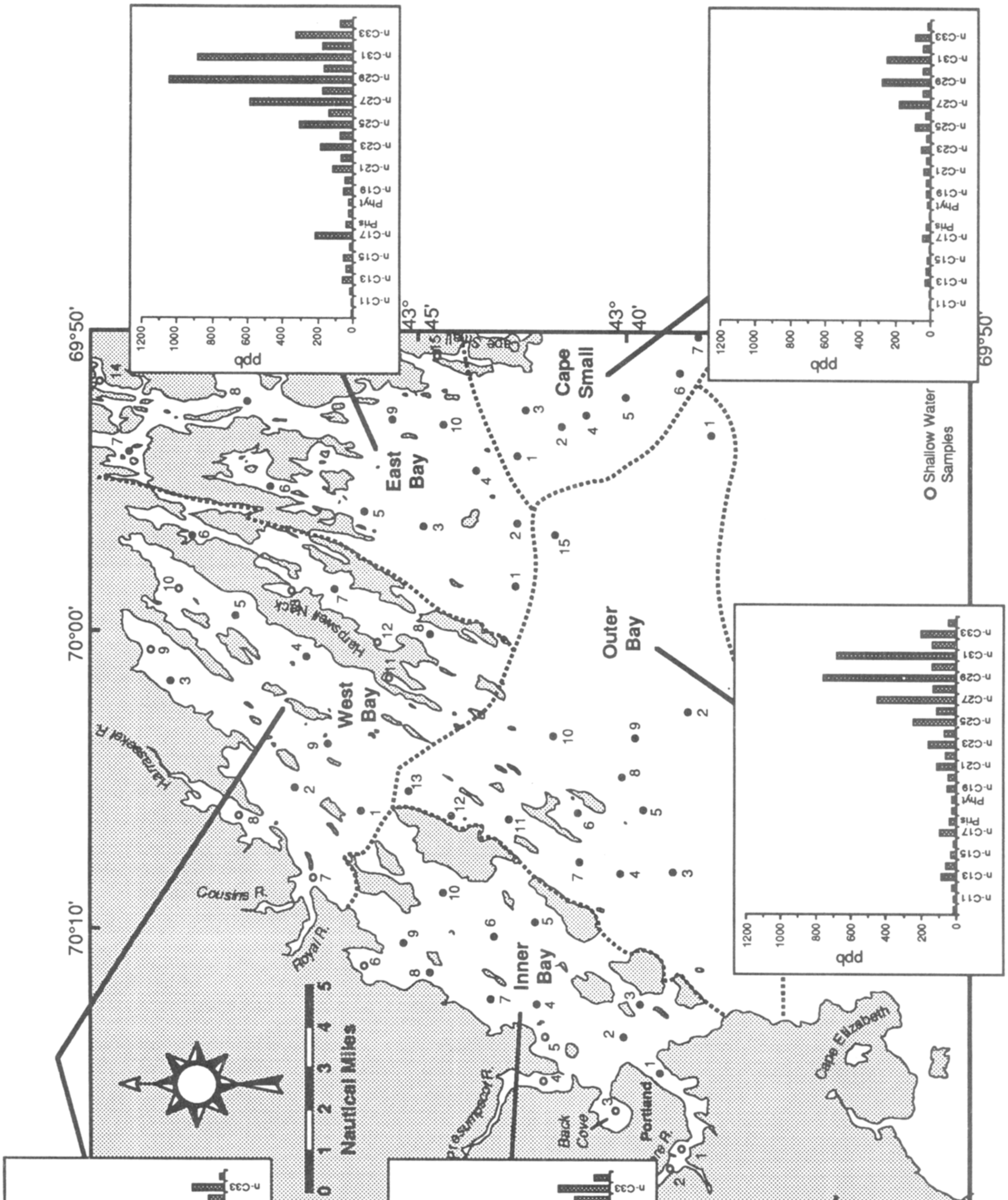

Figure 2. Average normal alkane and isoprenoid concentrations (ppb dry weight, surrogate corrected) and distributions in sediments from Casco Bay.

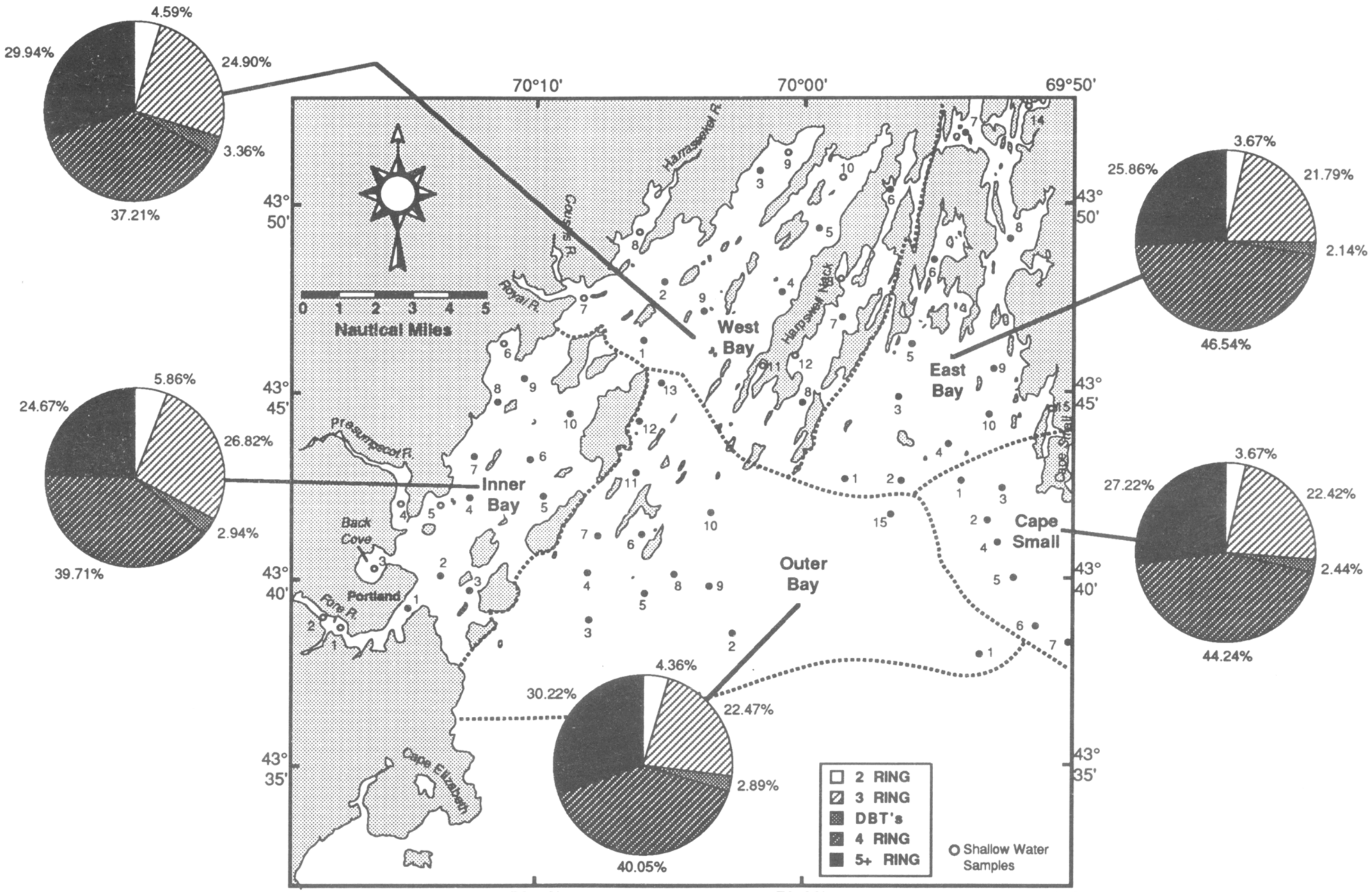

Figure 3. Average PAH compositions in sediments by region within Casco Bay.

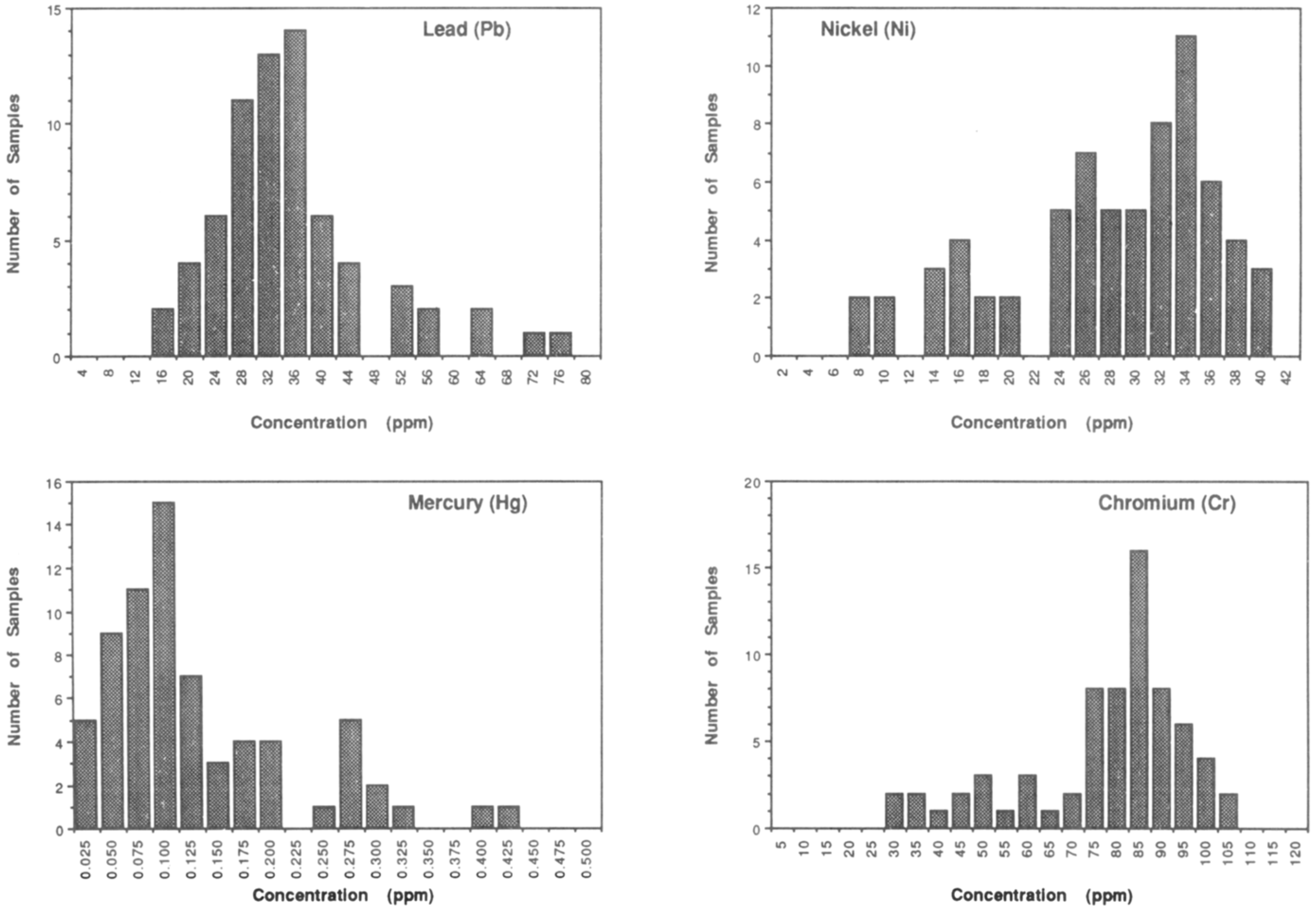

Figure 4. Frequency plots of lead, nickel, mercury and chromium concentrations (ppm dry weight) in sediments from Casco Bay.

in the Inner Bay. Sediment variability in trace metal content is largely due to variations in mineralogy and grain size. The data for Ag, Cd, Pb, and Hg show positive skewness on frequency plots (Figure 4), whereas the other metals are more normally distributed or, as in the case of Cr and Ni, exhibit negative skewness. Positive skewness suggests additions of metals by human activities to a normally distributed background. Negative skewness is most likely caused by the uneven geographic distribution of quartz or other low-metal minerals.

Human activities also contribute trace metals to the environment. Cross-plots of Fe or Al versus trace metals often identify anomalous concentrations that lie off the best-fit line for background data (Figure 5). When Casco Bay Cr and Ni data are plotted vs Fe, the data fall along a best-fit line with an approximately 0 intercept, suggesting a natural distribution. On the other hand, cross-plots of Zn, Pb, and Fe indicate that some samples are enriched in metals (Figure 5). The enriched samples are from the Inner Bay near Portland.

Based on the definition of O'Connor (*15*) "high" values are as follows: Cd, 1.3 ppm; Cr, 230 ppm; Cu, 87 ppm; Pb, 87 ppm; Hg, 0.51 ppm; Ag, 1.2 ppm; and Zn, 280 ppm for sediments which are 100% silt and clay. For a sediment consisting partly of quartz sand, these values would be reduced proportionally (e.g., multiplied by 0.75 for a sediment with 25% sand). Few of the metal concentrations detected in Casco Bay would be classified as high on this basis. Whereas some of the Cd, Pb, Ag, Zn, and Hg values found in Casco Bay sediments suggest an influence from human activities, they are not high in comparison to samples collected away from obvious point sources of pollutant inputs (*15*).

Discussion

Regional Distribution. One or more anthropogenic contaminants (trace metals, PCBs, DDTs, chlordane, or PAH) were detected at all locations sampled in Casco Bay. The geographic distribution of contaminants is initially controlled by the regional occurence of sources. The most elevated contaminants are derived from the utilization of fossil fuels. The predominant sources of PAH are combustion processes associated with urbanized and industrialized locations. The Inner Bay region directly offshore of Portland contains the highest levels of trace metals, PCBs, DDTs, chlordanes, and hydrocarbons. In general, for contaminants other than PAH, the levels of contamination would not be considered high on a national basis (*15*). PAH concentrations are high in the Inner Bay and are comparable to other contaminated estuaries (*15, 16*).

To compare the distribution of all of the contaminants measured, each site was ranked from 1 to 65 based on the abundance of each suite of contaminants. If a contaminant was below the MDL, it was given a ranking of 1. If multiple stations had the same concentrations, they were given the same relative ranking. Organic and inorganic contaminants were assessed separately, the cumulative rankings for each site were summed, and the sites were sorted from low to high values (Tables 2 and 3). This approach provides an indication of where contaminants are geographically located. Based on these variations, the highest 25% of organic contaminants are located at 10 Inner Bay, two

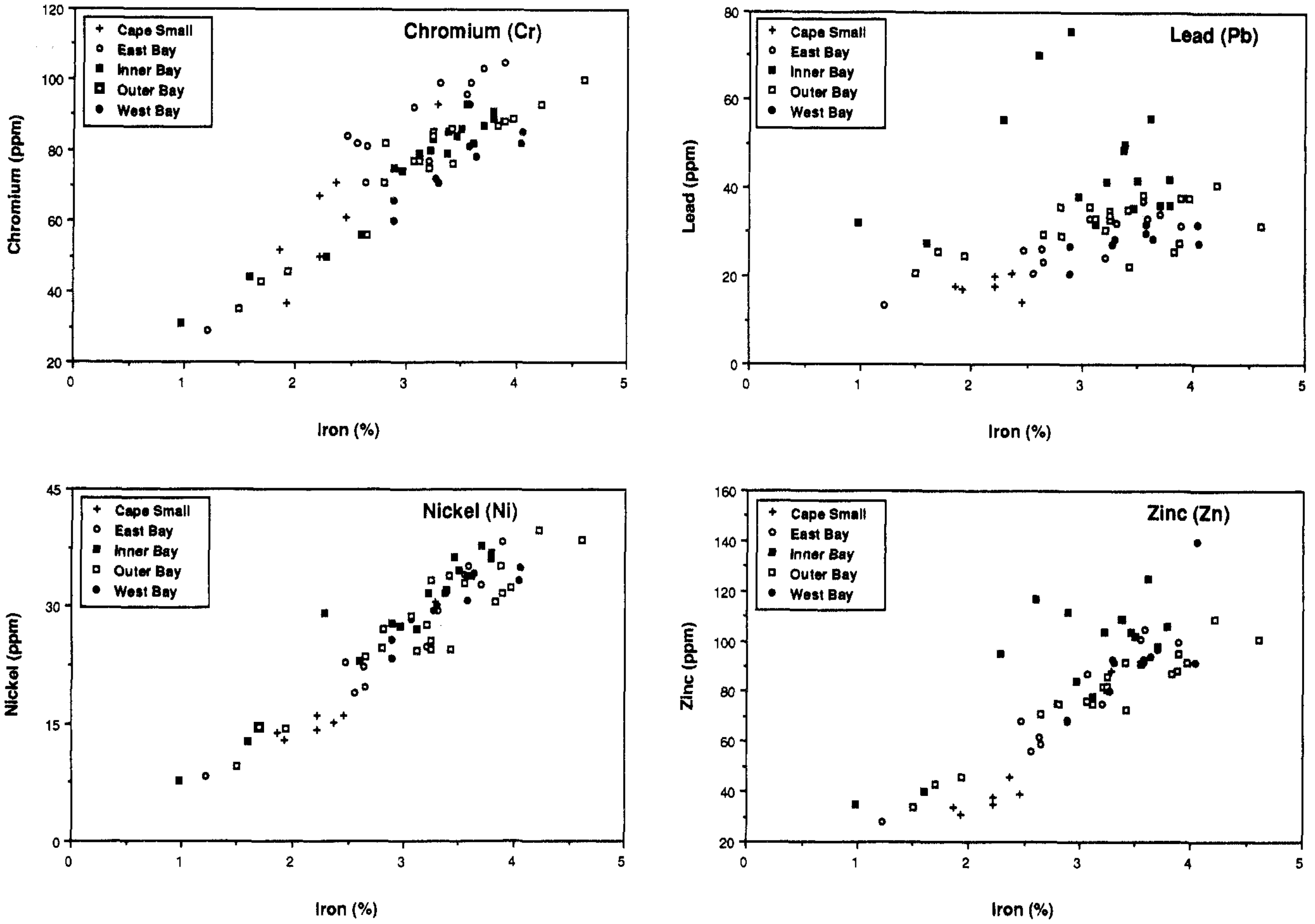

Figure 5. Relationship between chromium, lead, nickel, and zinc concentrations (ppm dry weight) and iron content (% dry weight) in sediments from Casco Bay.

Outer Bay, three East Bay, and one Cape Small sites. Eight of the 10 most highly contaminated stations are located in the Inner Bay region, including the six highest stations. The lowest levels of organic contaminants are in the Cape Small and West Bay regions. High levels of a variety of organic contaminants tend to occur at the same location.

For inorganic contamination, only those metals believed to be influenced by anthropogenic inputs were used to rank the sample locations, i.e., Ag, Cd, Pb, Zn, and Hg. Based on the summation of inorganic contaminant rankings, 25% of the locations with the highest levels were as follows: 12 Inner Bay, three East Bay, and one Outer Bay locations. Nine of the 10 highest locations are in the Inner Bay region, including the eight highest stations. Lowest metal concentrations occur in the Cape Small region. Eleven stations are ranked in the highest 25% on both the inorganic and organic contaminant rankings (Figure 6). They are almost exclusively Inner Bay locations, i.e., 9 of 11.

Principal Components Analysis. A total of four significant principal components (PC) were extracted from the Casco Bay data. PC 1 accounts for 48.9% of the total variance. The loadings for this PC show the sand content of the sediments inversely correlated with all other measured variables. PC 1 is inversely correlated with sand content and positively correlated with the TOC content of the sediments (Figure 7). This principal component reflects differences in the concentration of the targeted analytes due to variations in sediment texture. This finding is more significant than might appear at first consideration, as it implies that regional differences in concentrations result in part from sediment accumulation patterns. Thus, areas of fine-grained sediment accumulation such as the Inner Bay have high scores for PC 1 and exhibit high concentrations, while sediments in areas that are characterized by a dynamic physical environment and little sediment accumulation such as the Outer Bay have low scores for PC 1 and exhibit lower concentrations. It is also notable that both the organic and inorganic contaminants exhibit the same general trend. Shallow water samples SW-1 and SW-2 were identified as outliers because their compositions were anomalous relative to the other sediments (extreme enrichment in PAH and PCB, respectively). These samples were excluded from the PCA analysis.

PC 2 (12.3% of the total variance) and PC 3 (6.1% of the total variance) are related to the *composition* of organic and inorganic contaminants in the sediments. Since principal components are orthogonal, the processes governing PC 2 and PC 3 are independent of PC 1. Hence, the information contained in these principal components is more representative of contaminant sources in the sediments and is not related to absolute concentrations.

PC 2 is correlated positively with the Fe and saturated hydrocarbon content of the sediments (Figure 8). This most likely reflects a detrital component enriched in plant wax *n*-alkanes and inorganic clastics derived from continental erosion (*8-10*). A loadings cross-plot for PC 2 versus PC 3 (Figure 9) shows that, although all *n*-alkanes are positively loaded in PC 2, C_{23}, C_{25}, C_{27} and C_{29} *n*-alkanes have the highest loadings, consistent with this interpretation. Figure 9 also shows that nearly all the aromatic

Table 2. Casco Bay Estuary Program Site Rankings Based on Organic Contaminant Data, 1991 (ppb dry wt surrogate corrected)

station no.	total PAHs (ppb)	total PAH ranking	total chlordane (ppb)	total chlordane ranking	total DDTs (ppb)	total DDT ranking	total PCBs (ppb)	total PCB ranking	total organic ranking
CS-1	93	2	0.01	1	0.01	1	0.6	2	6
CS-7	16	1	0.02	3	0.02	2	0.4	1	7
CS-3	515	6	0.02	2	0.10	4	2.0	5	17
WB-3	421	4	0.07	4	0.18	5	2.6	6	19
SW-8	445	5	0.16	12	0.47	8	1.6	3	28
SW-10	595	8	0.11	6	0.30	6	4.5	9	29
CS-2	362	3	0.24	19	0.04	3	1.7	4	29
CS-6	672	9	0.15	10	0.50	9	3.8	7	35
SW-12	1094	16	0.23	16	0.72	10	5.5	11	53
WB-6	774	11	0.23	15	0.94	14	6.0	13	53
SW-9	734	10	0.23	17	0.73	11	8.1	17	55
WB-2	146	22	0.16	11	1.01	15	7.2	14	62
SW-5	911	13	0.15	9	1.63	26	7.3	16	64
WB-8	1112	18	0.11	5	1.52	25	8.4	18	66
SW-7	807	12	0.25	20	1.70	29	5.2	10	71
SW-13	961	14	0.19	14	1.23	21	9.8	23	72
CS-5	546	7	1.32	53	0.33	7	3.9	8	75
WB-7	1329	20	0.12	7	1.36	23	10.2	25	75
OB-1	1433	21	0.41	27	1.09	18	7.2	15	81
OB-11	1312	19	0.24	18	1.11	19	11.6	28	84
OB-7	1650	30	0.45	30	1.03	16	5.5	12	88
SW-14	1059	15	0.25	21	1.94	34	9.1	21	91
EB-1	2230	37	0.60	35	0.86	13	9.0	20	105
EB-2	2875	45	0.57	33	0.82	12	8.9	19	109
WB-4	1495	24	0.56	31	1.83	31	11.5	27	113
SW-6	1526	26	0.30	23	2.29	41	10.0	24	114
WB-5	1102	17	0.57	32	1.91	33	14.1	34	116
EB-4	2791	44	0.16	13	1.37	24	14.3	35	116
OB-4	1964	36	0.64	37	1.26	22	9.6	22	117
OB-6	1631	28	0.13	8	2.33	43	18.8	42	121
OB-13	1568	29	0.85	42	1.69	28	11.5	26	125
OB-8	1865	33	0.39	25	1.72	30	17.4	39	127
EB-10	4545	55	0.43	28	1.12	20	13.5	31	134
WB-9	1901	34	0.33	24	2.28	40	16.3	38	136
WB-1	1490	23	0.91	43	2.42	45	11.8	29	140
OB-12	1696	31	0.74	39	2.00	35	14.4	36	141
SW-11	1501	25	0.98	46	3.10	49	13.9	32	152
OB-5	2964	48	0.60	34	1.65	27	18.9	43	152
IB-9	1945	35	0.78	41	3.56	50	13.4	30	156
EB-3	2939	46	1.06	47	2.26	39	14.0	33	165
IB-5	2545	40	0.96	45	2.40	44	15.8	37	166
OB-9	2706	41	0.77	40	2.08	36	22.2	49	166
EB-8	3459	52	0.26	22	2.81	48	19.6	46	168
EB-5	2944	47	0.40	26	2.55	47	23.7	50	170
SW-15	7180	59	1.60	55	1.07	17	17.9	40	171
SW-4	1530	27	1.12	48	3.93	54	19.1	44	173
OB-2	1817	32	1.89	59	2.31	42	18.1	41	174
OB-10	2269	39	1.25	51	2.09	37	20.0	48	175
IB-6	3068	49	0.62	36	2.53	46	27.9	53	184
OB-15	4004	54	1.13	49	2.17	38	19.4	45	186
IB-8	2723	42	0.93	44	4.44	57	19.9	47	190
CS-4	7454	61	0.71	38	1.89	32	40.0	59	190
OB-3	3727	53	0.43	29	4.12	55	30.7	54	191
IB-10	2737	43	1.13	50	3.69	51	27.9	52	196
EB-6	2233	38	1.72	57	3.86	52	35.7	57	204
EB-7	4872	56	1.30	52	3.86	53	23.9	51	212
IB-4	3273	51	1.39	54	7.63	59	31.8	55	219
IB-7	3109	50	1.84	58	4.70	58	33.7	56	222
EB-9	7340	60	1.91	60	4.16	56	37.3	58	234
IB-2	6392	58	1.63	56	9.91	61	47.6	61	236
IB-3	5059	57	2.49	61	9.02	60	42.2	60	238
SW-1	20748	65	3.47	63	10.10	62	72.3	62	252
IB-1	9174	63	2.89	62	14.50	63	79.2	64	252
SW-3	7517	62	4.91	65	20.42	65	77.1	63	255
SW-2	12588	64	3.98	64	16.81	64	485.0	65	257

hydrocarbons measured are loaded negatively in PC 2. One exception is the alkylated chrysenes, which show a slight positive loading in PC 2. Thus, PC 2 can also be regarded as a saturate/aromatic hydrocarbon ratio. These results indicate that saturated and aromatic hydrocarbons in Casco Bay have different origins, which is generally consistent with the known geochemistries of these classes of compounds.

PC 3 differentiates individual saturated and aromatic hydrocarbons based on molecular weight (Figure 9). Most

Table 3. Casco Bay Estuary Program Site Rankings Based on Selected Metal Data, 1991 (ppm dry wt)

station no.	Ag (μg/g)	Ag ranking	Cd (μg/g)	Cd ranking	Hg (μg/g)	Hg ranking	Pb (μg/g)	Pb ranking	Zn (μg/g)	Zn ranking	total ranking
CS-7	0.05	1	0.069	5	<0.006	1	17.1	3	31	2	12
CS-3	0.06	1	0.053	3	0.008	1	17.6	4	35	4	13
CS-2	0.07	1	0.060	4	0.019	2	17.8	5	34	3	15
CS-1	0.05	1	0.071	6	<0.006	1	14.1	2	39	6	16
CS-5	0.09	3	0.036	1	0.031	3	20.0	6	38	5	18
CS-6	0.07	1	0.051	2	0.046	6	20.8	9	46	9	27
SW-8	0.09	3	0.150	14	0.019	2	20.5	7	34	3	29
SW-15	0.08	2	0.192	21	0.048	7	13.6	1	28	1	32
SW-7	0.07	1	0.155	15	0.032	4	24.7	13	46	9	42
EB-4	0.10	4	0.076	7	0.058	10	23.3	11	59	11	43
EB-10	0.08	2	0.121	10	0.069	15	20.6	8	56	10	45
OB-11	0.10	4	0.168	17	0.049	8	25.5	14	43	8	51
EB-1	0.11	5	0.127	12	0.059	11	26.2	16	62	12	56
WB-3	0.11	5	0.258	28	0.031	3	20.5	7	69	14	57
EB-2	0.11	5	0.175	19	0.077	20	25.8	15	68	13	72
SW-5	0.12	6	0.245	27	0.062	13	27.5	20	40	7	73
OB-1	0.14	8	0.118	9	0.065	14	27.7	21	88	27	79
WB-6	0.11	5	0.088	8	0.057	9	31.7	30	92	29	81
WB-8	0.13	7	0.293	30	0.077	20	26.8	17	68	13	87
SW-10	0.16	10	0.486	48	0.037	5	22.2	10	73	16	89
WB-7	0.11	5	0.312	32	0.071	17	27.1	18	80	20	92
SW-9	0.17	11	0.400	38	0.037	5	25.5	14	87	25	93
OB-15	0.16	10	0.155	15	0.102	28	29.3	24	75	17	94
SW-12	0.25	16	0.355	35	0.048	7	29.4	25	71	15	98
SW-4	0.19	12	0.213	24	0.097	27	32.0	32	35	4	99
SW-14	0.16	10	0.414	40	0.082	22	24.3	12	75	17	101
SW-13	0.15	9	0.125	11	0.073	18	31.5	28	101	36	102
OB-10	0.14	8	0.156	16	0.081	21	33.8	38	82	22	105
OB-2	0.12	6	0.133	13	0.058	10	37.7	49	92	29	107
OB-13	0.15	9	0.268	29	0.082	22	30.6	27	82	22	109
OB-8	0.14	8	0.176	20	0.087	24	35.7	43	76	18	113
SW-6	0.13	7	0.435	45	0.061	12	31.7	30	78	19	113
OB-5	0.15	9	0.200	22	0.085	23	34.7	40	81	21	115
OB-4	0.17	11	0.226	25	0.104	29	33.1	36	75	17	118
WB-2	0.17	11	0.358	36	0.076	19	29.7	26	92	29	121
WB-1	0.15	9	0.430	42	0.087	24	28.4	22	93	30	127
OB-7	0.16	10	0.245	27	0.113	32	35.8	44	75	17	130
WB-4	0.17	11	0.444	46	0.082	22	28.6	23	94	31	133
WB-9	0.36	21	0.302	31	0.087	24	31.9	31	93	30	137
OB-9	0.17	11	0.174	18	0.113	32	38.3	51	91	28	140
CS-4	0.20	13	0.208	23	0.190	43	32.4	34	88	27	140
WB-5	0.15	9	0.529	52	0.069	16	27.4	19	140	45	141
SW-11	0.16	10	0.239	26	0.096	26	37.6	48	95	32	142
IB-5	0.20	13	0.325	33	0.094	25	38.1	50	84	23	144
EB-3	0.19	12	0.431	43	0.112	31	33.2	37	87	26	149
EB-9	0.19	12	0.401	39	0.148	36	32.1	33	92	29	149
OB-12	0.19	12	0.434	44	0.118	33	35.1	41	92	29	159
OB-6	0.26	17	0.592	58	0.106	30	32.8	35	86	24	164
EB-7	0.20	13	0.608	59	0.153	37	31.6	29	100	35	173
OB-3	0.20	13	0.327	34	0.141	35	40.7	52	109	41	175
IB-10	0.23	14	0.501	50	0.170	39	36.0	45	98	34	182
EB-8	0.23	14	0.720	60	0.181	42	34.1	39	97	33	188
IB-6	0.25	16	0.392	37	0.195	44	41.2	53	104	38	188
IB-8	0.24	15	0.573	56	0.168	38	35.3	42	104	38	189
EB-6	0.29	19	1.320	63	0.137	34	33.2	37	105	39	192
IB-9	0.23	14	0.557	53	0.173	40	36.2	46	106	40	193
EB-5	0.23	14	0.794	61	0.176	41	37.0	47	101	36	199
IB-7	0.32	20	0.424	41	0.234	45	42.1	55	106	40	201
SW-1	0.46	23	0.488	49	0.264	46	55.5	58	95	32	208
IB-4	0.27	18	0.571	55	0.274	49	41.5	54	102	37	213
IB-2	0.46	23	0.524	51	0.271	48	49.9	57	109	41	220
IB-3	0.39	22	0.574	57	0.264	46	48.5	56	109	41	222
SW-2	0.57	24	0.478	47	0.392	50	70.3	60	117	43	224
IB-1	0.57	24	0.564	54	0.269	47	55.6	59	125	44	228
SW-3	0.78	25	0.908	62	0.424	51	75.6	61	112	42	241

n-alkanes in the range C_{10}–C_{22} are positively loaded in PC 3, as are the more highly alkylated (C_2 and higher) two- and three-ring aromatics: naphthalenes, fluorenes, phenanthrenes, and dibenzothiophenes. Pristane, phytane, and UCM hydrocarbons are also loaded positively in PC 3. In contrast, *n*-alkanes in the range C_{23}–C_{34} along with C_{15} and C_{17} are loaded negatively in PC 3. Aromatic hydrocarbons loaded negatively in PC 3 include most parent two- and three-ring compounds, their methyl-substituted homologs, and most four- and five-ring aromatic compounds.

Together, the loadings for PC 2 and PC 3 discriminate sources of organic and inorganic materials in the Casco Bay sediments. Hydrocarbons loaded positively in PC 2

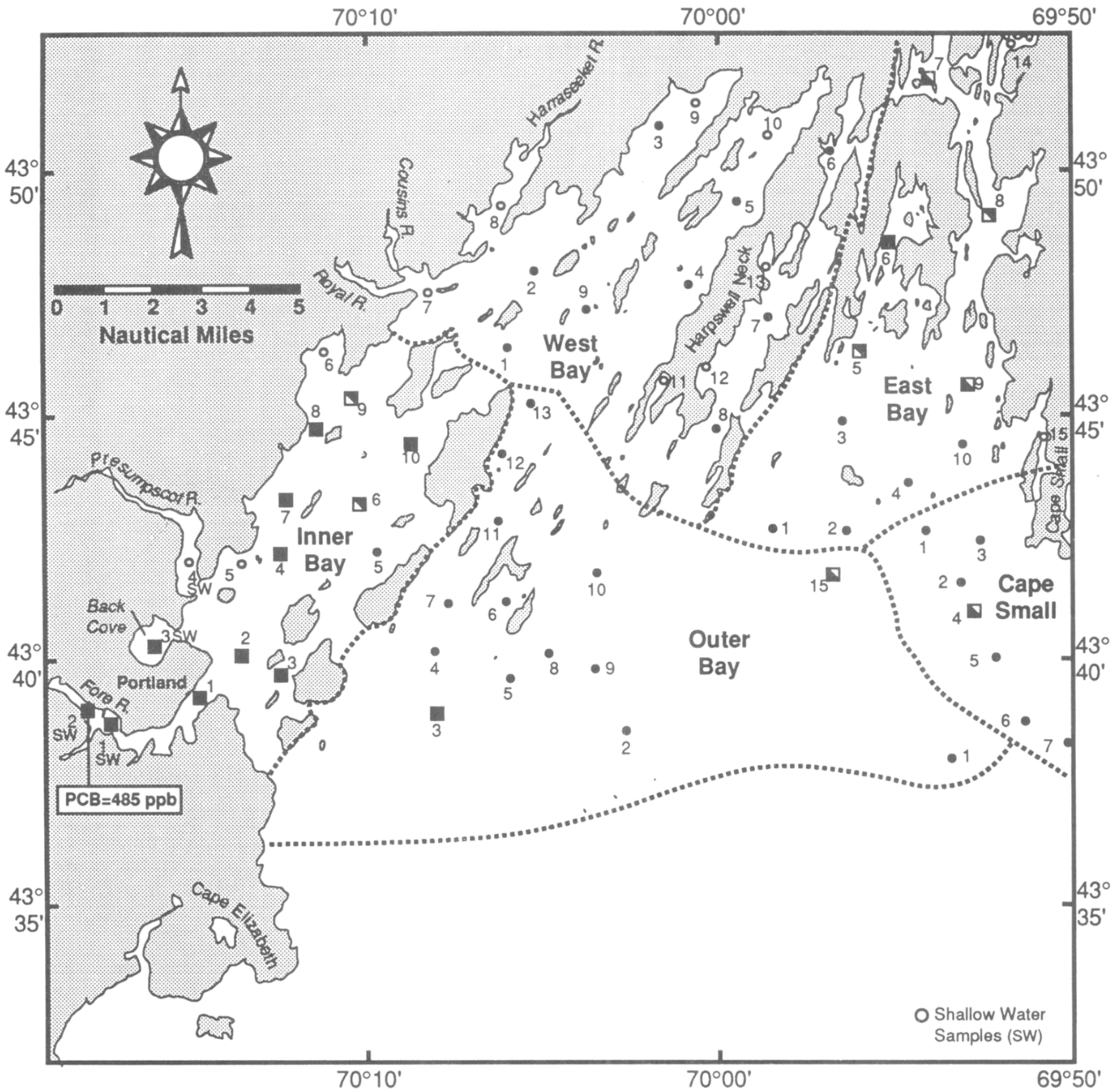

Figure 6. Location of the 25% high organic (◩) and inorganic (■) concentrations in sediments from Casco Bay.

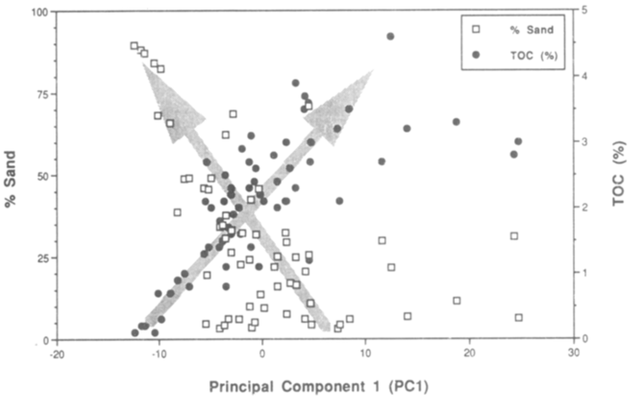

Figure 7. Relationship between PC 1, TOC (%), and sand content (%) for Casco Bay sediments.

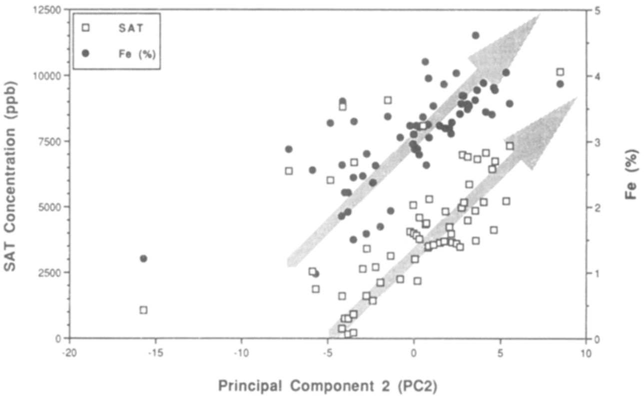

Figure 8. Relationship between PC 2, Fe content (%), and saturated aliphatic hydrocarbons (ppb) for Casco Bay sediments.

and negatively in PC 3 (lower right quadrant, Figure 9) include compounds of algal (C_{15} and C_{17}) and higher plant (C_{23}–C_{31}) origin (*8–10*). Other similarly loaded variables include Fe, Ni, Se, As, Cr, and percentage silt and clay (Figure 9). These distributions represent terrigenous detrital and autochthonous marine inputs. TOC is sim-

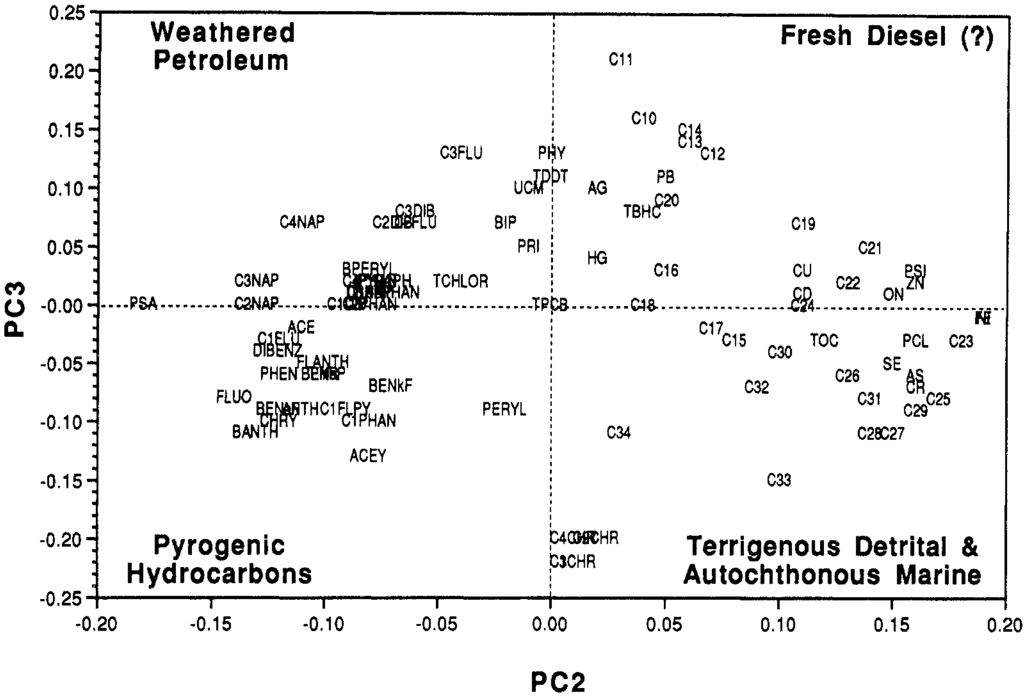

Figure 9. Relationship between PC2 and PC3 for PCA of Casco Bay contaminant data.

ilarly loaded, suggesting that biogenic materials are an important contributor to the organic richness of the sediments (*17*). Hydrocarbons loaded negatively in both PC 2 and PC 3 (lower left quadrant, Figure 9) consist primarily of four- and five-ring aromatics that are generated from both natural and anthropogenic combustion processes. A combustion origin for these hydrocarbons is also supported by the covariance of the parent two- and three-ring aromatics which are structurally stable at high temperatures (*11–14*). The departure of the alkylated chrysenes from this trend suggests either a biogenic source for these compounds or possibly some interference in their analysis from biogenic material. Hydrocarbons loaded negatively in PC 2 and positively in PC 3 (upper left quadrant, Figure 9) include two- and three-ring aromatics containing a C_2 or greater alkylation. These compounds are the most abundant aromatic hydrocarbons in petroleum and petroleum byproducts. Pristane and UCM are similarly loaded, suggesting a weathered petroleum origin (*18, 19*). The source represented by the hydrocarbons that are loaded positively in both PC 2 and PC 3 (upper right quadrant, Figure 9) is equivocal. These consist primarily of n-alkanes in the range C_{10}–C_{22}, which might represent a relatively unweathered petroleum product, i.e., diesel fuel. Alternatively, the covariance of these hydrocarbons with the metals Pb, Ag, and Hg and total DDTs and BHC concentrations (Figure 9) suggest possible inputs from runoff associated with either agricultural or industrial activities. Principal component 4 (5.4% of the total variance) is characterized by high positive loadings for most of the chlorinated hydrocarbons analyzed and is less straightforward to interpret. It should be noted that the organochlorine compounds are generally low and near the method detection limit, thus indicating a relatively "noisy" data set.

Based on these interpretations, the distribution of samples in a scores cross-plot of PC 2 versus PC 3 (Figure 10) can be used to assess the regional influence of a variety of sources. Sediments exhibiting a predominantly biogenic influence from detrital and autochthonous sources (positive scores for PC 2, negative scores for PC 3) are found in the upper East Bay (EB-3, -5, -6, -7, and -8), and also at Outer Bay sites OB-1 and OB-12 and Inner Bay site IB-9. In contrast, the lower East Bay (EB-1, -2, -4, -9, and -10), as well as Outer Bay site OB-15 and shallow water site SW-15, contains a greater component originating from pyrogenic sources (negative scores for PC 2 and PC 3). Site CS-4 in Cape Small exhibits a composition similar to the lower East Bay sites. These distributions are significant in that the sites that are similar in composition are geographically clustered. This suggests subtle differences in the principal sources of hydrocarbons in the upper and lower East Bay.

Sites characterized by inputs of weathered petroleum (negative scores for PC 2, positive scores for PC 3) include the Inner Bay and shallow water sites nearest the city of Portland (IB-1 and -2 and SW-3, -4, and -5). This is probably the result of chronic inputs from runoff and point sources associated with urban activities. Surprisingly, however, the sandy sediments from Cape Small (CS-1, -2, -3, -5, -7, and, to a lesser extent CS-6) have contaminant compositions that are nearly identical to site IB-1. This is illustrated in the scores cross-plot in Figure 10, where the majority of Cape Small sites plot intermediate between the lower East Bay and shallow water sites SW-3 and SW-4 from the Inner Bay. This likely reflects aromatic hydrocarbon inputs from both pyrogenic and petroleum sources at these locations and suggests that, despite significantly lower concentrations, the assemblage of contaminants in Cape Small sediments is similar to those at some contaminated Inner Bay sites. Sites showing a relative enrichment in C_{10}–C_{22} n-alkanes (positive scores for PC 2 and PC 3) include nearly all the West Bay sites and shallow water sites SW-9, -10, -11, and -13 within the West Bay. Several nearby sites also exhibit a similar composition. These include Outer Bay site OB-13 and Inner Bay sites IB-6 and IB-10. Thus, although the origin of this compositional feature is uncertain, it appears to manifest itself over a limited portion of Casco Bay, suggesting a localized source. Several Outer Bay sites (OB-

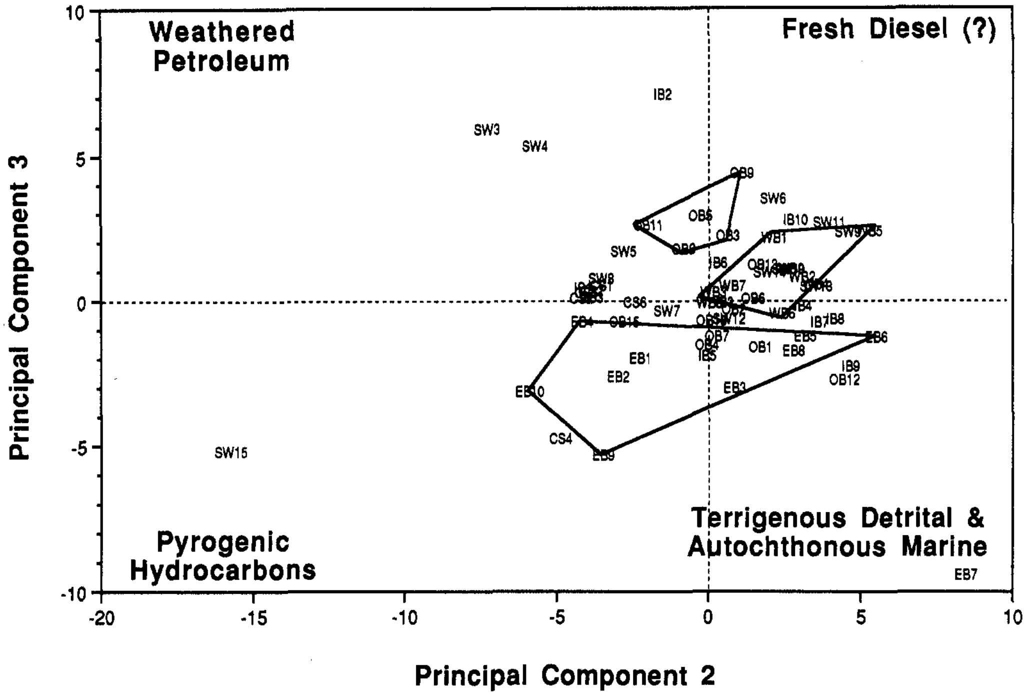

Figure 10. Suggested model for determining the source of hydrocarbons and trace metals in Casco Bay sediments.

Table 4. Comparison of ER-L, ER-M, Apparent Effects Thresholds, and Washington State Sediment Quality Criteria Concentrations for Selected Chemicals in Sediments and Values Measured in Casco Bay (after Long and Morgan, 1990; Washington State Dept. of Ecology Sediment Management Standards, Chapter 173–204 WAC)

						Casco Bay regions[f]									
						Inner Bay		West Bay		East Bay		Cape Small		Outer Bay	
chemical analyte	ER-L[a]	ER-M[b]	AET[c]	deg of confidence[d]	WSSQC[e]	min	max	min	max	min	max	min	max	min	max
						Trace Elements (ppm dry wt)									
arsenic	33	85	50	L/M	5.7	1.62	16.00	4.76	19.60	3.20	19.60	5.03	13.70	5.03	20.50
cadmium	5	9	5	H/H	5.1	0.213	0.908	0.088	0.529	0.076	1.320	0.036	0.208	0.036	0.592
chromium	80	145	NA[h]	M/M	26.0	31.00	91.00	35.00	100.00	29.00	105.00	37.00	93.00	43.00	93.00
copper	70	390	300	H/H	390	7.92	48.40	6.98	26.20	5.59	27.90	2.52	21.60	6.94	26.20
lead	35	110	300	M/H	450	27.50	75.60	20.50	37.60	13.60	37.00	14.10	32.40	25.50	40.70
mercury	0.15	1.3	1	M/H	0.41	0.061	0.424	0.019	0.096	0.048	0.181	<0.010	0.190	0.049	0.141
nickel	30	50	NSD[g]	M/M	NA	7.81	37.80	9.67	38.60	8.36	38.40	12.90	30.60	14.50	39.80
silver	1	2.2	1.7	M/M	6.1	0.12	0.78	0.07	0.36	0.08	0.29	<0.07	0.20	0.10	0.26
zinc	120	270	160	H/H	410	35.00	125.00	34.00	140.00	28.00	105.00	31.00	88.00	43.00	109.00

[a] ER-L, effects range-low. [b] ER-M, effects range-median. [c] AET, apparent effects threshold. [d] L, low; M, medium; H, high. [e] WSSQC, Washington State Sediment Quality Criteria, calculated ppb dry wt based on 2% TOC. [f] ppm dry weight. [g] NSD, not sufficient data. [h] NA, not available.

3, -5, -8, -9, and -11) exhibit a composition intermediate between the Inner Bay sites characterized by weathered petroleum and the West Bay sites enriched in lower molecular weight *n*-alkanes.

Potential for Biological Effects. Biological effects or sediment quality were not directly measured in this study. However, the concentrations of most organic contaminants detected are below the concentration levels that are believed to evoke toxic responses in marine benthic organisms (Tables 4–6). Long and Morgan (*9*) conducted an extensive review of articles that provide both concentrations of contaminants in sediments and observed biological effects. Six different approaches used in these studies were briefly described and reviewed. It was concluded that each approach had strengths and weaknesses, i.e., there is no perfect method for determining specific threshold concentrations for contaminants in sediment. They therefore derive consensus values by considering data from all of the studies reviewed. Sediment concentrations shown by the studies to cause biological effects, and judged to be valid, were ranked from low to high. A 10th and 50th percentile were then determined. Those were designated "effects range low" and "effects range median" (ER-L and ER-M). The Washington State Sediment Quality Criteria, the summary of data from Long and Morgan (*16*), and the Casco Bay results are compared in Tables 4–6.

The total PAH concentrations present in Inner Bay sediments are above the PAH concentrations thought to produce toxic responses in marine benthic organisms, i.e., total PAH ≥35 000 ppb (Table 4). Bioavailability and not necessarily absolute concentration are compared and also a factor in determining whether a contaminant evokes a biological response. For example, the mode of occurrence of PAH has been shown to vary widely depending on the original source (*19*). Coal or soot-associated combustion-derived PAHs are often tightly bound or occur in the interiors of particles. This mode of occurrence renders these PAHs largely inert as far as biological effects. In contrast, liquid hydrocarbons such as oil or creosote contain PAHs that are readily available to organisms and would be expected to induce toxicological effects. A majority of

Table 5. Comparison of ER-L, ER-M, Apparent Effects Thresholds, and Washington State Sediment Quality Criteria Concentrations for Selected Chemicals in Sediments and Values Measured in Casco Bay (after Long and Morgan, 1990; Washington State Dept. of Ecology Sediment Management Standards, Chapter 173–204 WAC)

						Casco Bay Regions^f									
						Inner Bay		West Bay		East Bay		Cape Small		Outer Bay	
chemical analyte	ER-L^a	ER-M^b	AET^c	deg of confidence^d	WSSQC^e	min	max	min	max	min	max	min	max	min	max
Polychlorinated Biphenyls (ppb)															
total PCBs	50	400	370	M/M	240	7.31	484.97	1.58	16.32	8.89	37.30	0.44	40.02	5.50	30.67
DDT and Metabolites (ppb)															
DDT	1	7	6	L/L		0.49	4.28	<0.20	0.96	0.40	2.01	<0.20	0.86	0.47	1.52
DDD	2	20	NSD^g	M/L		0.67	15.09	0.08	1.49	0.31	1.98	<0.07	0.62	0.34	2.04
DDE	2	15	NSD	L/L		0.18	3.84	<0.06	1.14	0.07	0.48	<0.06	0.40	0.06	0.63
total DDT	3	350	NA^h	M/M		1.63	20.42	<0.20	3.10	0.82	4.16	<0.20	1.89	1.03	4.12
Other Pesticides (ppb)															
lindane	NA	NA	NSD	NA		<0.07	0.48	<0.07	0.22	<0.07	0.35	<0.07	0.11	<0.07	0.34
chlordane	0.5	6	2	L/L		0.15	4.91	0.07	0.98	0.16	1.91	<0.07	1.32	0.13	1.89
heptachlor	NA	NA	NSD	NA		0.08	0.13	<0.04	0.05	<0.04	0.13	<0.04	<0.04	<0.04	0.04
dieldrin	0.02	8	NA	L/L		<0.16	0.94	<0.16	<0.16	<0.16	0.43	<0.16	2.46	<0.16	1.40
aldrin	NA	NA	NSD	NA		<0.28	<0.28	<0.28	<0.28	<0.28	<0.28	<0.28	<0.28	<0.28	<0.28
endrin	0.02	45	NSD	L/L		<0.06	0.84	<0.06	0.21	<0.06	0.17	<0.06	<0.06	<0.06	0.55
mirex	NA	NA	NSD	NA		<0.04	0.29	<0.04	0.08	<0.04	0.49	<0.04	0.66	<0.04	0.16

[a] *ER-L, effects range-low.* [b] ER-M, effects range-median. [c] AET, apparent effects threshold. [d] L, low; M, medium; H, high. [e] WSSQC, Washington State Sediment Quality Criteria, calculated ppb dry wt based on 2% TOC. [f] ppm dry weight. [g] NSD, not sufficient data. [h] NA, not available.

Table 6. Comparison of ER-L, ER-M, Apparent Effects Thresholds, and Washington State Sediment Quality Criteria Concentrations for Selected Chemicals in Sediments and Values Measured in Casco Bay (after Long and Morgan, 1990; Washington State Dept. of Ecology Sediment Management Standards, Chapter 173–204 WAC)

						Casco Bay regions^f									
						Inner Bay		West Bay		East Bay		Cape Small		Outer Bay	
chemical analyte	ER-L^a	ER-M^b	AET^c	deg of confidence^d	WSSQC^e	min	max	min	max	min	max	min	max	min	max
Polynuclear Aromatic Hydrocarbons (ppb dry wt surrogated corrected)															
acenaphthene	150	650	150	L/L	320	2	81	<1	3	2	19	<1	13	2	6
anthracene	85	960	300	L/M	4 400	6	255	3	15	8	107	<1	99	14	50
benz[*a*]anthracene	230	1600	550	L/M	2 200	30	655	12	56	34	481	1	360	48	173
benzo[*a*]pyrene	400	2500	700	M/M	1 980	43	741	17	100	50	498	1	433	62	209
benzo[*e*]pyrene	NA^h	NA	NSD^g	NA		37	514	14	74	37	276	1	271	48	140
biphenyl	NA	NA	NSD	NA		3	29	<2	7	4	12	<2	10	4	12
chrysene	400	2800	900	M/M	2 200	44	766	19	74	47	530	1	398	53	192
dibenz[*a*,*h*]anthracene	60	260	100	M/M	240	3	105	3	41	7	58	<0	64	11	73
2,6-dimethylnaphthylene	NA	NA	NSD	NA		4	130	1	9	3	28	<1	17	5	14
fluoranthene	600	3600	1000	H/H	3 200	90	1444	34	144	82	639	2	522	118	304
fluorene	35	640	350	L/L	460	4	201	1	7	4	96	<1	27	6	15
1-methylnaphthalene	NA	NA	NSD	NA		3	81	1	7	3	31	<1	20	5	11
2-methylnaphthalene	65	670	300	L/M	760	5	95	2	11	5	37	<1	34	8	17
1-methylphenanthrene	NA	NA	NSD	NA		10	311	5	14	0	68	<1	49	8	33
naphthalene	340	2100	500	M/H	7 400	8	135	2	14	7	46	<2	41	12	26
perylene	NA	NA	NSD	NA		17	216	9	56	31	110	<4	94	21	77
phenanthrene	225	1380	260	M/M	2 000	42	1036	17	71	41	550	1	269	57	160
pyrene	350	2200	1000	M/M	20 000	82	1552	31	137	78	560	2	562	1127	302
2,3,5-trimethylnaphthalene	NA	NA	NSD	NA		3	187	1	4	2	34	<1	9	3	6
total PAH	4000	35 000	22 000	L/L		911	20 748	421	1901	1059	7340	16	7454	1312	4004

[a] ER-L, effects range-low. [b] ER-M, effects range-median. [c] AET, apparent effects threshold. [d] L, low; M, medium; H, high. [e] WSSQC, Washington State Sediment Quality Criteria, calculated ppb dry wt based on 2% TOC. [f] ppm dry weight. [g] NSD, not sufficient data. [h] NA, not available.

the PAHs in this study are combustion related and thus may be in a sequestered form that significantly reduces their toxicity.

Long and Morgan (*16*) estimated that median concentrations of total PCB above 400 ppb dry wt elicits a toxic response in most benthic organisms. For this study, only one site (SW-2) is above this threshold. The DDT concentrations are low compared to concentrations known to cause a toxic response in most benthic organisms (*16*). Chlordane concentrations are "low" based on the definition of O'Connor (*15*) and should pose little or no threat of toxic biological effects (*16*).

A number of different approaches to determining the trace metal concentrations in sediments which lead to a biological response have been used, resulting in a large and confusing literature. Thomas (*20*) briefly describes eight different approaches to setting toxicity criteria for sediments, but no actual data are presented. Pavlov (*21*) compared results from one of these approaches, the equilibrium partitioning approach, to results from other commonly used methods. He shows that the concentration of a given metal needed to elicit a biological response, as determined by equilibrium partitioning and other methods, does not vary widely (except for Hg). The threshold concentrations for toxicity are much higher than those found in Casco Bay sediment.

None of the metal concentrations in the Casco Bay sediments are as high as Long and Morgan's (*16*) ER-M, and only a few are as high as the ER-Ls. For example, Casco Bay chromium concentrations are as high as 105 ppm, whereas the ER-L is 80 ppm. Many uncontaminated sediments from other parts of the world, however, contain chromium concentrations higher than 105 ppm, and it is unlikely that chromium in Casco Bay sediment would cause a biological effect. The same can be said for nickel and zinc, where Casco Bay concentrations are as high as 40 and 140 ppm compared to ER-Ls of 30 and 120 ppm, respectively. A few mercury concentrations in Casco Bay are also higher than the ER-L but are much lower than those of highly contaminated sediments from Hudson-Raritan, Long Island Sound, Boston Harbor and elsewhere (*15*). It is unlikely that mercury in Casco Bay sediment is causing an effect on marine organisms. As with PAH, bioavailability is an issue in determining trace metal toxicity.

Conclusions

Detailed, high-quality assured analysis of a broad spectrum of contaminants can be utilized to understand the dynamics of pollutants in coastal environments. The potential processes implicated in releasing these contaminants to the marine environment can be identified and their relative importance can be estimated. Statistical analysis of contaminant concentrations can be used to identify geographically consistent contaminant profiles and suggest the source of these pollutants. This approach was applied to Casco Bay, ME.

Anthropogenic contaminants are widespread throughout Casco Bay, but in most cases occur at exceedingly low concentrations. The focus of contamination is in the Inner Bay region directly associated with the densest population centers and industrialization. Multiple processes add contaminants to Casco Bay, and these chemicals have accumulated in bay sediments. Localized accumulations of various chemicals do occur, but even these areas are mostly below levels suspected of evoking toxic biological responses. In order to more specifically assign the sources of the observed contaminants, intense localized sampling and analysis of effluents and runoff patterns would be needed. To determine sediment quality, bioassays of sediments at suspect sites should be conducted to directly assess the potential for biological impacts.

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