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Metals, Petroleum Hydrocarbons and Organochlorines in Inshore Sediments and Waters of Mombasa, Kenya

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A coastal zone pollution monitoring programme for developing countries, the Land–Ocean Contamination Study (LOCS), was initiated by the British Geological Survey (BGS) under funding from the United Kingdom Overseas Development Administration in 1995. The central objective of LOCS is the provision of contaminant monitoring, impact amelioration and integrated coastal zone management protocols to meet the specific social, technical and economic requirements of tropical developing regions.

A geochemical and oceanographic survey of the inshore waters and sediments of Mombasa, Kenya was undertaken by BGS in liaison with the Kenya Marine and Fisheries Research Institute as a component of the LOCS programme during the period September 1995–January 1996 (Williams *et al.*, 1996a). The administrative district of Mombasa occupies a 275-km^2 area on the Indian Ocean coast, centred on latitude 4.05°S and longitude 39.65°E (Fig. 1). The district comprises the island settlement of Mombasa (now connected to the mainland by the *ca* 1 km Makupa causeway) and a series of urban developments to the north-east, west and south-west, the combined population of which exceeds 500 000. Mombasa Island is bounded by the Port Kilindini and Port Reitz creek complexes to the south and west and by the Mombasa Harbour–Port Tudor complex to the east and north. Fluvial inputs to these systems are provided by the Shimba, Mwache, Komboni and Tsalu Rivers, each with annual discharges in the range $10–50 \times 10^6 m^3$. The open coastline to the north-east and south-west of Mombasa is fringed by a multiple reef (typically 1–1.5 km offshore) which extends virtually unbroken for a distance of 60 km between Mtwapa and Gazi.

The vulnerability of both the inshore and nearshore environments to contamination arising from the urban and industrial expansion of Mombasa (compounded by recent tourist development) has been widely documented (e.g. UNEP, 1982). An inventory of industrial activities in Mombasa Municipality (Munga *et al.*, 1994) indicates that suspended solid discharges may currently exceed 21 000 t yr^{-1}. The impact and fate of this contaminant flux within the coastal environment has not, however, previously been ascertained.

In the LOCS survey, samples of water, suspended particulate matter (SPM) and sediment were collected from 48 stations within Mombasa's estuarine creeks and along the reef front extending north-eastwards (in accordance with the prevailing current regime) some 13 km to Mtwapa (Fig. 1). All sites were positioned using a Silva™ non-differential global positioning system (GPS). Mid-column water samples were collected under both ebb and flood tide conditions during independent campaigns in September 1995 and January 1996. *In situ* measurements of water temperature, dissolved oxygen (DO), pH, Eh, turbidity, conductivity

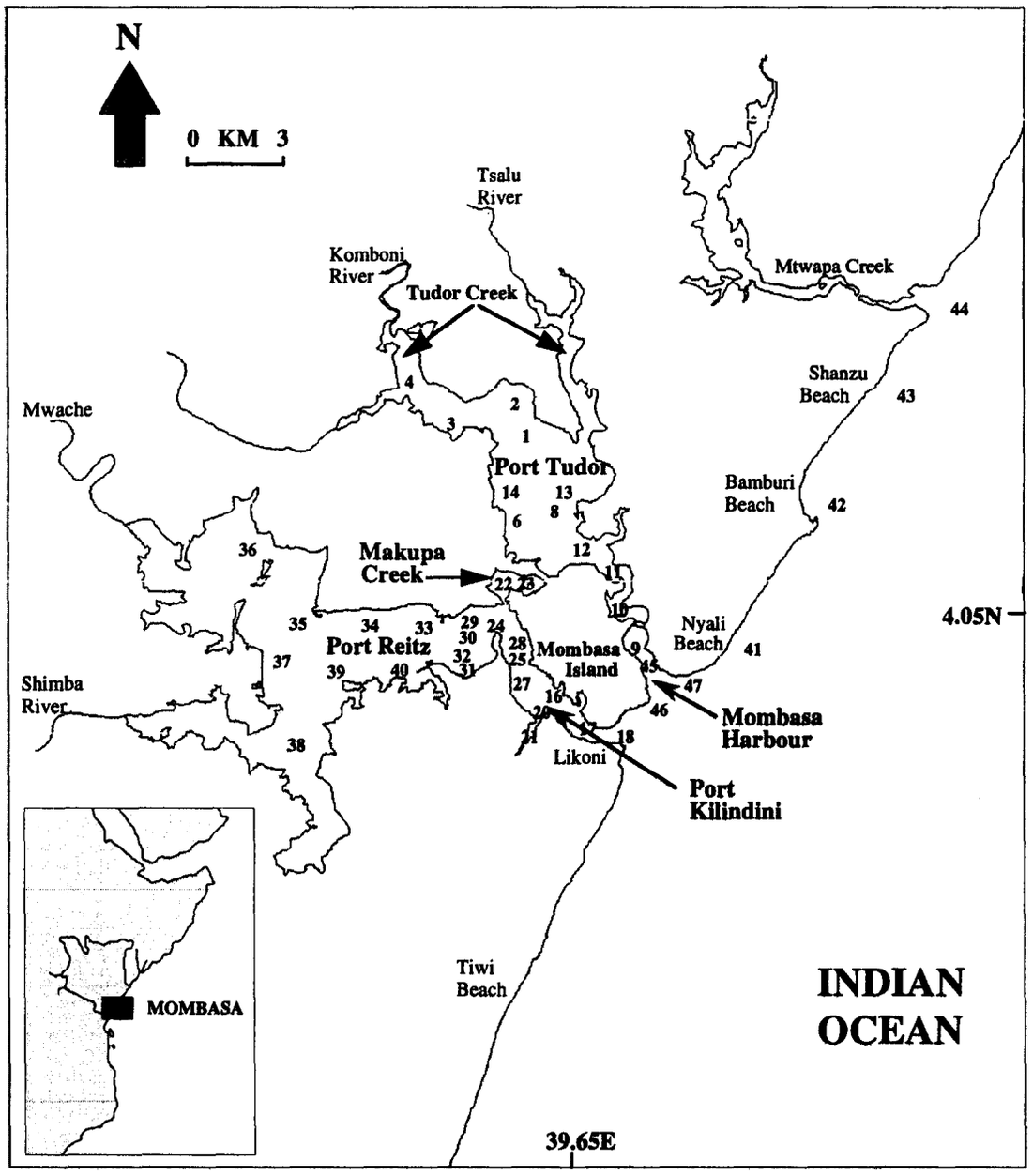

Fig. 1 Regional location and physiography of Mombasa, showing the position of LOCS sampling stations.

and salinity were made using a pHOX™ 902 sonde and datalogger. Calibration of the component probes in the sonde was carried out daily using *1.* 2% Na_2SO_3 (zero DO), *2.* pH 4.0 and pH 10.0 buffer solutions, *3.* potassium ferro- and ferricyanide redox standards of 125 and 350 mV, *4.* KCl conductivity standards of 100, 1000 and 50 000 µS, and *5.* polymeric turbidity solutions of 1, 100 and 1000 FTU. Water samples for trace metal analysis were recovered in a 2.5 l acrylic Kemmerer sampler, activated by a messenger. A 0.5-l volume of sample was immediately vacuum-pumped through a 0.45-µm cellulose acetate membrane (Sartorius™) into a HNO_3-washed HDPE bottle (Nalgene™) and acidified with 1% v/v HNO_3 (ARISTAR). Analysis for a suite of 6 heavy metals (Cd, Cr, Cu, Ni, Pb, Zn) was carried out by anodic stripping voltammetry (ASV) at the UK Environment Agency laboratory, Llanelli, Wales, to operational detection limits of 0.042 µg l^{-1} Cd, 0.35 µg l^{-1} Cr, 0.005 µg l^{-1} Cu, 0.058 µg l^{-1} Ni, 0.024 µg l^{-1} Pb and 0.1 µg l^{-1} Zn.

Samples of SPM were obtained from a 1-l volume of mid-column water during the filtration of samples for dissolved metal analysis (1995 campaign only). Pre-weighed cellulose acetate membranes were utilized, thus allowing precise determination of the mass of SPM residues without removal from the filter. Digestion of both the residues and the retaining membranes was carried out at 105°C in sealed PTFE bombs containing 5 ml HNO_3 + 2 ml $HClO_4$ + 2 ml HF. All digests were analysed for 13 trace elements by

inductively coupled plasma mass spectrometry (ICP-MS). A suite of pristine filter membranes was prepared and analysed using identical reagents, and appropriate background corrections were applied to the SPM dataset.

Stations characterized by silt and mud sediment lithologies were sampled using a 1.1-m long, 50 mm internal diameter pneumatic piston corer, facilitating the recovery of stratified samples with negligible disturbance of the interfacial layer. Sites with sand or gravel dominated surface lithofacies (in the lower reaches of Mombasa Harbour, Port Kilindini and along the Nyali-Mtwapa reef front) were sampled with a stainless steel Van Veen grab sampler. All cores were retained upright during transportation and were sub-sampled at 2–5 cm resolution within 24 h of collection. Near-surface redox conditions were established during core extrusion with a Pt electrode and a Hanna Insts^{TM} mV meter. Sediment granulometry was established by wet sieving of core/grab sub-samples to 63 μm, with additional characterisation of the <63 μm fraction using Sedigraph.

The concentrations of major oxides and 13 trace elements in the <150 μm fraction of 252 sediment sub-samples (representing a maximum of 20 stratigraphic levels per coring station) were determined by X-ray fluorescence (XRF). The solid phase speciation of 11 metals (Fe, Mn, Al, Co, Cr, Cu, Pb, Zn, V, Ni, Cd) was established for selected sites using an extractive procedure based on that of Breward and Peachey (1983), entailing *1.* agitation of 1 g fresh sediment in 1N ammonium acetate solution to remove exchangeable metals, *2.* application of 1N ammonia solution to extract the organic fraction, with subsequent isolation of fulvic and humic components by HCl precipitation, *3.* partial digestion of the inorganic residue in 0.1N hydroxylamine hydrochloride in 25% v/v acetic acid to extract hydrous Fe and Mn oxides, and *4.* total digestion of the inorganic residue in concentrated nitric + perchloric + hydrofluoric acids to liberate metals held in detrital silicates and other residual minerals. All leachates were analysed by inductively coupled plasma emission spectrometry (ICP-ES). Reagent blanks were prepared and simultaneously analysed with each leachate. Surficial sediment from 6 stations, plus sub-surface samples from a Makupa Creek site (MB23) were analysed for *n*-alkanes, polycyclic aromatic hydrocarbons (PAHs) and organo-chlorines by a combination of high pressure liquid chromatography (HPLC), gas chromatography (GC) and GC mass-spectrometry (GCMS) following hexane solvent extraction.

Physicochemical data for the 1995 Mombasa sea-water suite are given in Table 1. The 1996 suite is not presented, as the temporal variance (based on ANOVA) was found to be $<10\%$. With the exception of Pb (for which relatively high values of up to 1.9 μg l^{-1} were recorded) the median concentrations of dissolved metals (Cd <0.042 μg l^{-1}, Cr <0.35 μg l^{-1}, Cu 2.63 μg l^{-1}, Ni 0.28 μg l^{-1} and Zn 8.1 μg l^{-1}) were found to lie within the global background range for marine waters (e.g. Fergusson, 1990). However, ANOVA studies of data for six discrete sectors of the study area (A, upper Tudor Creek; B, Port Tudor and Mombasa Harbour; C, Port Kilindini; D, Makupa Creek; E, Port Reitz; and F, the North Coast reef front) highlighted significant local variability. Elevated concentrations of Cu (to 20.5 μg l^{-1}) and Ni (to 0.65 μg l^{-1}) in the uppermost reaches of Tudor Creek reflected the natural hydro-chemical signature of terrestrial runoff, while a substantial anthropogenic Ni flux into Makupa Creek (probably derived from the adjacent Kibarani landfill site) was indicated by ambient concentrations of Ni up to 0.975 μg l^{-1} in a system characterized by a short (24 h) water residence time (Rees *et al.*, 1996). The reef front waters north of Mombasa (MB41-MB44) showed marked enrichment of Cd, Pb and Zn during both the 1995 and 1996 campaigns, although the derivation of a plausible metal source remains problematic. The recorded Zn concentration range of 24–69 μg l^{-1} in these waters exceeded the median for the total Mombasa suite by at least a factor of 3.

Metal concentration data for the Mombasa SPM suite are given in Table 2. Median abundances were found to decline in the order Mn > Zn > Cu > Ni > V > Pb > Cr > As > Co > Th > Mo > U > Cd. First-row transition elements (e.g. Mn, V, Cr, Co, Ni), As and Mo showed systematic enrichment in the upper sector of Tudor Creek, relative to all other inshore waters. Zn, although enriched in Tudor Creek, displayed highest concentrations (>6000 mg kg^{-1} dry weight, with coincident Pb enrichment to 210 mg kg^{-1}) along the North Coast reef front. The lowest concentrations of As, Cd, Cu, Mo, Ni, Pb and Zn were recorded in SPM from Port Reitz. The prevalence of As, Co, Cu, Cr, Ni and V in Port Kilindini and Port Reitz (which host all major shipping, petrochemicals and sewage installations) at concentrations up to an order of magnitude lower than in the largely unin-dustrialized Tudor Creek catchment suggests that the anthropogenic influence on SPM chemistry is negligible. A more critical control appears to be the contribution of mangrove-derived clastic detritus to the total SPM assemblage. Williams *et al.* (1996a) have shown this material to accumulate a range of trace cations (both in the mangrove environment and following outwash into the water column) through surface adsorption to virtually ubiquitous Fe/Mn oxide coatings.

Major oxide and trace element data for surficial sediments (the 0–2 cm horizons of piston cores, plus all grab samples) are given in Table 3. The spatial distributions of all major oxides and several minor/trace transition metals (including Co, Cr, Ni and V) were found to closely reflect sediment provenance and lithology, with no clear anthropogenic overprint. Considerable independence from any lithological con-

TABLE 1

Physicochemical data for Mombasa seawater samples. Absent data fields indicate that parameters were not determined. All trace metal data are expressed in ($\mu g\ l^{-1}$).

Reference	Sample	Long (°)	Lat(°)	pH	Eh(mV)	DO ($mg\ l^{-1}$)	DO (% sat)	Temp (°C)	Cond (μS)	Salinity (%)	Turb (FTU)	Pb	Cd	Cu	Zn	Cr	Ni
E386793	MB1	39.653	−4.002	7.70		3.4	63.0	27.4	51200	33.6	30	0.571	<0.042	20.500	8.120	<0.350	0.179
E386794	MB2	39.644	−3.988	7.60		3.3	63.0	27.4	51000	33.4	44	0.472	<0.042	6.210	12.600	<0.350	0.595
E386795	MB3	39.626	−3.989	7.50		3.4	54.0	27.6	50700	33.2	49	0.460	<0.042	5.850	9.570	<0.380	0.610
E386796	MB4	39.612	−3.981	7.50		3.7	70.0	27.9	50500	33.1	60	0.460	<0.042	2.640	7.800	<0.350	0.565
E366797	MB5	39.651	−4.028	8.00	190	4.2	80.0	27.5	52400	34.4	39	0.658	<0.042	2.380	10.000	<0.350	0.512
E386798	MB6	39.644	−4.017	7.80	196	3.8	74.0	27.6	52200	34.3	50	0.409	<0.042	3.040	12.600	<0.350	0.653
E386799	MB7	39.649	−4.025	7.90	190	4.0	78.0	27.4	52200	34.4	48	0.536	<0.042	2.760	7.740	<0.350	0.409
E386600	MB8	39.652	−4.016	7.90	173	4.1	79.0	27.0	52000	34.6	52	1.090	<0.042	2.810	8.120	<0.350	0.327
E386801	MB9	39.678	−4.044	8.00		3.9	76.0	26.5	52900	34.8	92	1.880	<0.042	3.880	18.000	0.680	0.169
E366802	MB10	39.671	−4.038	8.00		4.1	78.0	26.8	53000	34.8	71	0.923	>0.042	3.170	6.780	0.350	0.426
E386803	MB11	39.673	−4.029	7.90		3.9	75.0	26.9	52900	34.7	67	0.599	<0.042	2.860	18.900	0.470	0.414
E386604	MB12	39.664	−4.023	7.80		3.6	68.0	27.0	52400	34.5	72	0.534	<0.042	3.110	8.620	<0.350	0.292
	MB13	39.657	−4.006	7.60		3.9	75.0	27.8	51900	34.1	96						
	MB14	39.646	−4.007	7.70		3.6	71.0	27.6	52100	34.2	89						
E386805	MB15											0.024	<0.042	0.051	2.000	<0.350	0.058
E386806	MB16	39.656	−4.065	8.20	126	4.5	86.0	26.4	53400	35.2	41	0.888	<0.042	3.170	9.900	<0.350	0.280
E386807	MB17	39.662	−4.070	8.20	85	4.5	85.0	26.2	53500	35.3	41	0.830	<0.042	4.270	15.600	<0.350	0.207
E386808	MB18	39.664	−4.075	8.20	90	4.6	90.0	26.7	53500	35.3	44	0.444	<0.042	1.840	10.700	0.450	0.275
E386609	MB19			8.20	86	4.9	92.0	26.5	53500	354	44	0.463	<0.042	1.670	9.930	<0.350	0.325
E386810	MB21	39.648	−4.076	8.20		4.7	92.0	26.9	53500	352	45	0.950	<0.042	1.990	6.780	<0.350	0.252
E366811	MB22	39.642	−4.035	8.00	120	3.3	65.0	27.5	53000	350	54	0.806	<0.042	2.740	10.200	<0.350	0.975
E386812	MB23	39.639	−4.035	8.10	67	4.1	80.0	28.1	53400	352	74	0.698	<0.042	2.200	7.600	<0.350	0.858
E386813	MB24	39.639	−4.040	8.10	93	4.1	80.0	27.1	56600	354	60	1.970	<0.042	1.940	5.220	<0.350	0.156
E386814	MB25	39.640	−4.053	8.10		4.6	88.0	26.8	53600	353	74	0.677	<0.042	2.020	4.100	<0.350	0.190
E386815	MB26											0.127	<0.042	0.051	2.000	<0.350	0.058
E386616	MB27	39.643	−4.062	8.10	90	4.4	85.0	26.6	53500	354	69	1.290	0.049	1.910	9.120	<0.350	0.395
E386817	MB28	39.645	−4.048	8.10	68	4.4	86.0	26.9	53500	353	71	0.594	<0.042	2.190	5.110	<0.350	0.286
E386818	MB29	39.630	−4.041	8.00	67	4.4	85.0	27.4	53400	352	84	1.120	<0.042	1.640	6.050	0.410	0.277
	MB30	39.630	−4.049	8.10		4.4	85.0	26.9	53500	353	76						
E366819	MB33	39.624	−4.044	8.10	90	4.2	82.0	26.8	53500	353	73	0.794	<0.042	2.620	5.580	0.390	0.237
E366820	MB34	39.608	−4.046	8.00	90	4.4	86.0	27.4	53400	352	73	0.623	<0.042	3.250	13.200	<0.350	0.362
E386821	MB35	39.585	−4.048	7.90		4.4	85.0	27.4	53400	35.2	75	0.494	<0.042	2.890	4.920	<0.350	0.241
E356822	MB36	39.582	−4.033	7.80		4.0	79.0	27.6	53200	350	82	1.410	<0.042	3.950	5.720	<0.350	0.282
E366823	MB38	39.581	−4.075	7.70		3.4	69.0	27.5	53000	350	79	0.648	<0.042	4.480	3.100	<0.350	0.419
E386824	MB39	39.590	−4.059	7.96		4.1	81.0	27.5	53500	353	78	0.517	<0.042	2.210	9.520	<0.350	0.228
E386825	MB41	39.712	−4.058	8.30		6.1	116.0	26.4	53700	354	51	1.340	0.576	1.680	67.100	<0.350	0.326
E386826	MB42	39.741	−4.004	8.20		5.0	98.0	25.7	53500	355	53	1.080	0.676	3.680	69.600	0.420	0.124
E386827	MB43	39.750	−3.989	8.30		5.6	105.0	25.9	53800	355	50	1.290	0.173	2.880	24.000	<0.350	0.214
E386828	MB44	39.765	−3.961	8.20		5.1	96.0	25.7	53900	355	51	1.420	0.540	2.640	49.900	0.350	0.149
E386829	MB45	39.677	−4.053	8.10		5.2	102.0	28.4	53300	351	56	1.400	<0.042	1.760	7.800	<0.350	0.260
E386830	MB46	39.682	−4.064	8.20		5.4	105.0	26.9	53500	354	51	1.230	<0.042	1.260	5.030	<0.350	0.441
E386831	MB47	39.681	−4.053	8.20		4.8	92.0	26.4	53500	354	49	0.728	<0.042	1.470	11.400	<0.350	0.464
E386832	MB48											0.181	<0.042	0.051	2.000	<0.350	0.058
MEDIAN												0.677	22.640		8.370		0.282

TABLE 2

Concentrations of selected trace elements (mg kg^{-1} dry weight) in suspended particulate matter (SPM) from the inshore waters of Mombasa.

Sample	As	Cd	Cr	Co	Cu	Pb	Mn	Mo	Ni	Th	U	V	Zn
MB1	11.5	0.50	78.3	14.1	221.1	48.0	516.1	3.40	135.0	9.1	2.6	123.0	303.0
MB2	12.2	0.40	105.0	18.4	189.5	53.0	690.0	6.00	160.2	10.9	3.0	163.6	359.0
MB3	10.4	0.67	105.3	19.6	93.6	44.0	745.7	3.80	215.5	10.4	3.0	160.4	412.0
MB4	16.3	2.20	146.0	27.0	141.5	55.0	113.0	4.20	78.0	14.5	3.8	227.0	442.0
MB5	7.2	7.90	45.3	8.5	96.1	52.0	423.0	2.40	50.0	4.6	1.5	65.3	412.0
MB6	14.8	0.42	86.0	11.4	75.0	39.0	528.0	3.30	75.0	7.8	2.5	114.0	238.0
MB7	15.1	1.10	82.5	14.4	143.1	62.0	628.1	4.00	62.5	9.3	2.8	131.8	435.0
MB8	16.7	1.70	78.0	13.8	84.2	38.0	560.7	3.90	102.1	8.1	2.6	118.2	467.0
MB9	5.4	0.35	22.8	4.6	55.7	23.0	229.2	1.50	50.2	3.5	1.1	36.8	272.0
MB10	6.8	0.16	60.0	7.6	96.3	27.0	349.0	3.00	67.1	5.1	1.7	63.3	264.0
MB11	11.4	0.40	64.0	11.2	137.9	41.0	531.0	3.10	49.2	7.1	2.3	91.3	378.0
MB12	8.8	1.04	49.1	8.8	104.5	37.0	394.1	2.90	205.0	5.0	1.7	75.4	284.0
MB16	8.6	0.58	35.1	6.6	95.8	41.0	403.1	3.10	74.6	5.1	2.1	55.6	430.0
MB17	4.3	0.58	26.3	5.1	60.0	46.0	330.7	2.30	37.3	4.3	1.4	35.8	273.0
MB18	6.8	0.47	57.2	6.1	113.1	32.0	399.5	2.40	55.2	7.5	1.8	59.3	577.0
MB19	3.1	0.40	30.0	4.1	60.0	17.0	293.8	2.70	58.6	4.1	1.5	43.6	307.0
MB21	5.8	0.33	26.0	4.7	48.0	32.0	278.0	1.50	22.0	4.0	1.1	35.3	181.0
MB22	6.8	0.33	25.0	2.8	124.4	41.0	276.6	3.00	516.1	2.2	1.1	32.7	300.0
MB23	8.9	0.64	16.6	2.8	20.6	23.0	231.0	2.50	17.4	7.7	1.2	25.9	276.0
MB24	2.4	0.01	23.0	4.5	20.0	12.0	270.0	0.50	17.5	3.0	0.7	32.5	110.0
MB25	1.7	0.04	6.4	1.6	6.0	3.0	88.7	0.16	4.8	1.2	0.3	10.1	46.0
MB27	3.8	0.01	22.1	3.9	60.0	13.0	225.6	0.73	19.5	3.0	0.6	25.6	162.0
MB28	7.1	0.01	20.2	4.2	13.0	10.0	227.3	0.33	11.8	2.9	0.6	18.5	151.0
MB29	3.1	0.07	50.7	3.9	20.0	11.0	238.9	0.53	69.6	2.8	0.7	29.2	158.0
MB30	2.0	0.01	3.9	0.8	24.0	5.0	80.9	0.15	1.9	0.4	0.2	8.2	49.0
MB33	0.0	0.01	13.5	2.9	6.5	30.0	177.1	0.32	3.1	55.4	6.7	20.5	80.0
MB34	3.6	0.01	27.5	5.8	16.0	11.0	386.3	0.49	9.0	5.3	1.1	43.5	87.0
MB35	3.6	0.01	22.0	4.4	10.4	9.0	259.6	0.72	13.6	3.6	0.7	29.6	74.0
MB36	1.0	0.01	17.9	4.0	10.6	7.0	292.6	0.43	8.0	3.6	0.8	30.7	75.0
MB38	2.8	0.01	32.2	6.1	26.2	11.0	272.2	0.83	14.0	4.1	1.1	51.2	100.0
MB41	4.0	1.20	15.2	2.4	100.0	77.0	105.2	0.76	10.0	0.6	0.5	10.0	3,013.0
MB42	23.8	3.40	97.3	8.5	78.1	210.0	858.1	1.40	36.2	5.6	1.3	63.9	6,425.0
MB43	3.1	0.84	3.6	0.6	14.4	38.0	37.2	1.10	0.6	0.6	0.2	4.8	959.0
MB44	11.0	2.70	38.2	4.1	558	112.0	346.4	1.10	12.9	27.6	1.0	24.1	4,089.0
MB45	6.1	1.40	16.0	2.1	594	52.0	83.5	1.10	9.1	2.1	0.8	20.3	367.0
MB48	1.4	0.76	8.2	0.6	211	10.0	35.2	0.17	1.1	0.6	0.1	7.6	345.0
MB47	2.0	0.12	4.2	0.6	39.1	6.0	43.4	0.36	0.6	0.6	0.2	7.3	67.0

trol was, however, observed for Cu, Pb and Zn which yielded weak (or negative) statistical correlations with Al_2O_3, SiO_2 and TiO_2 (Pearson $R<0.2$) and strong within-group covariability ($R=0.67$ to 0.97). Sporadic enrichment of these heavy metals (two standard deviations greater than the mean) was recorded in the lower reaches of Port Kilindini (maxima 1177 mg kg^{-1} Cu, 427 mg kg^{-1} Pb, 283 mg kg^{-1} Zn), Makupa Creek (maxima 43 mg kg^{-1} Cu, 44 mg kg^{-1} Pb, 225 mg kg^{-1} Zn), the north-eastern shore of Port Reitz (maxima 26 mg kg^{-1} Cu, 30 mg kg^{-1} Pb, 190 mg kg^{-1} Zn) and on the east of Mombasa Island. The anomalies can be tentatively ascribed to specific point sources including Kipevu oil terminal and the adjacent sewage outfall into Port Reitz; Kibarani landfill (Makupa Creek); and sewage outfalls from Mombasa Island into Port Kilindini and Mombasa Harbour.

Chemostratigraphic analyses of Mombasa cores highlighted enrichment (to two-fold greater than basal concentrations) of several heavy metals including Co, Cr, Cu, Ni, Pb, V and Zn in the uppermost 5–10 cm of sediment at most sites (Fig. 2). At Makupa Creek, a deeper though probably synchronous increase was observed at *ca* 20 cm depth, due to localized catchment disturbance (probably by landfill activities) and a resultant increase of sediment flux (Rees *et al.*, 1996). With an average present-day sedimentation rate of 1–2 mm yr^{-1} (Rees *et al.*, 1996), the accelerated sedimentary incorporation of potentially toxic metals may be broadly synchronous with urban development. There is, however, strong evidence that the profiles are controlled by a progressive transition from a quartzo-feldspathic silt/sand assemblage with marine-derived shelly fragments (downward of 20 cm) to fine clastic material containing *ca* 20% organic matter in the surficial sediment. At most stations, the downcore profiles of Co, Cr, Cu, Ni, Pb and Zn were closely covariant with Al_2O_3 and TiO_2 ($R>0.7$), and normalization against these major oxides effectively removed the concentration gradients portrayed in the bulk downcore plots.

Solid phase partitioning data for Makupa Creek (MB23) and Port Tudor (MB5) sediments confirmed that exchangeable (highly bioavailable) metals are of negligible significance to the total sediment load. Organo-metallic complexes form an important host

TABLE 3

Major oxide (%) and trace element (mg kg^{-1} dry weight) concentrations in interfacial sediments from Mombasa sampling stations.

Sample	Al_2O_3	CaO	Fe_2O_3	MgO	MnO	K_2O	SiO_2	Na_2O	TiO_2	As	Ba	Cr	Co	Cu	Pb	Ni	Sr	Sn	V	Zn	Zr
MB1	10.94	0.59	3.88	1.3	0.031	2.46	64.46	2.5	0.585	10.0	540.0	45.0	11.0	15.0	19.0	16.0	107.0	1.5	69.0	47.0	585.0
MB2	12.38	0.30	4.10	1.5	0.020	2.86	62.12	2.8	0.654	9.0	549.0	54.0	14.0	16.0	21.0	20.0	103.0	1.5	88.0	51.0	482.0
MB3	16.44	0.44	7.31	2.0	0.030	2.59	51.81	2.6	1.077	7.0	333.0	91.0	20.0	31.0	25.0	34.0	75.0	1.5	143.0	99.0	285.0
MB4	16.44	0.36	8.34	2.1	0.074	2.56	49.77	3.3	1.223	6.0	349.0	105.0	26.0	41.0	24.0	38.0	80.0	1.5	163.0	96.0	185.0
MB5	15.43	0.94	7.37	2.3	0.061	2.48	46.48	4.8	1.039	18.0	268.0	94.0	20.0	26.0	25.0	32.0	105.0	3.0	139.0	85.0	163.0
MB6	13.72	4.41	5.92	2.1	0.032	2.37	47.92	3.5	0.819	18.0	287.0	71.0	17.0	24.0	21.0	28.0	358.0	1.5	108.0	81.0	259.0
MB7	6.87	16.25	3.14	1.2	0.023	1.52	45.68	2.0	0.370	16.0	268.0	26.0	10.0	12.0	14.0	12.0	1389.0	3.0	46.0	51.0	312.0
MB8	12.97	3.39	5.34	1.9	0.030	2.44	53.10	2.8	0.785	15.0	365.0	63.0	15.0	19.0	22.0	23.0	215.0	1.5	104.0	63.0	641.0
MB9	12.53	6.37	5.84	2.0	0.035	2.24	47.58	4.7	0.774	12.0	312.0	66.0	17.0	11.0	20.0	16.0	250.0	1.5	101.0	52.0	224.0
MB10	10.23	4.66	4.10	1.5	0.033	2.30	57.86	2.4	0.811	10.0	448.0	50.0	11.0	16.0	24.0	15.0	337.0	1.5	72.0	56.0	839.0
MB11	13.66	2.60	5.06	2.1	0.057	2.51	50.88	3.1	0.749	14.0	408.0	63.0	15.0	19.0	24.0	24.0	231.0	3.0	96.0	68.0	304.0
MB12	9.76	13.92	4.69	1.8	0.046	1.87	41.22	3.6	0.486	15.0	337.0	43.0	11.0	12.0	13.0	14.0	391.0	1.5	73.0	49.0	127.0
MB13	9.55	0.53	5.28	1.4	0.031	2.29	64.31	2.5	0.602	14.0	519.0	48.0	23.0	16.0	16.0	18.0	101.0	1.5	80.0	44.0	607.0
MB14	12.93	3.09	5.70	2.0	0.028	2.40	52.51	2.9	0.771	15.0	407.0	65.0	18.0	16.0	18.0	21.0	211.0	1.5	100.0	57.0	726.0
MB16	14.41	6.73	5.19	2.6	0.043	2.22	43.68	5.4	0.689	15.0	555.0	59.0	13.0	39.0	63.0	23.0	510.0	3.0	84.0	139.0	164.0
MB17	13.40	7.83	5.19	2.4	0.044	2.15	41.59	7.6	0.679	13.0	359.0	61.0	13.0	70.0	102.0	26.0	562.0	8.0	77.0	239.0	162.0
MB18	9.79	14.61	4.49	2.4	0.042	1.80	37.86	2.9	0.527	13.0	457.0	64.0	13.0	1177.0	427.0	17.0	816.0	6.0	58.0	283.0	233.0
MB20	12.43	9.15	4.34	2.3	0.055	2.14	46.48	2.6	0.600	14.0	299.0	50.0	13.0	24.0	28.0	21.0	690.0	1.5	70.0	86.0	208.0
MB21	12.88	8.20	4.59	2.5	0.040	2.12	42.05	3.2	0.627	12.0	304.0	57.0	11.0	30.0	51.0	22.0	639.0	5.0	73.0	118.0	188.0
MB22	15.18	2.14	6.35	2.5	0.031	2.44	47.90	4.1	0.837	11.0	322.0	81.0	17.0	43.0	44.0	30.0	170.0	5.0	110.0	225.0	163.0
MB23	12.58	1.67	5.81	2.2	0.036	3.33	38.32	10.0	0.736	13.0	251.0	70.0	17.0	33.0	35.0	30.0	151.0	1.5	106.0	156.0	119.0
MB24	12.20	1.67	5.80	1.7	0.043	2.06	37.96	10.0	0.784	12.0	309.0	66.0	18.0	26.0	30.0	27.0	168.0	4.0	92.0	100.0	159.0
MB25	14.80	3.34	5.07	2.3	0.042	2.37	48.57	3.7	0.730	11.0	369.0	57.0	14.0	21.0	24.0	23.0	290.0	4.0	85.0	78.0	234.0
MB27	14.90	5.52	5.02	2.6	0.052	2.29	45.74	4.6	0.716	11.0	317.0	57.0	15.0	23.0	23.0	24.0	461.0	3.0	85.0	83.0	189.0
MB28	14.59	3.24	5.70	2.3	0.046	2.26	42.92	6.4	0.802	10.0	326.0	63.0	16.0	30.0	41.0	28.0	276.0	4.0	93.0	115.0	178.0
MB29	11.51	5.71	3.26	1.5	0.029	1.98	54.12	1.7	0.559	5.0	373.0	52.0	12.0	16.0	28.0	17.0	151.0	1.5	58.0	190.0	498.0
MB30	13.26	2.85	4.57	2.1	0.037	2.12	49.66	7.1	0.653	8.0	357.0	51.0	16.0	17.0	20.0	21.0	236.0	1.5	77.0	69.0	401.0
MB31	14.66	1.63	5.83	2.4	0.047	2.29	46.39	7.5	0.810	13.0	324.0	65.0	17.0	23.0	22.0	26.0	160.0	3.0	98.0	82.0	222.0
MB32	16.91	1.49	6.15	2.6	0.046	2.48	48.84	6.0	0.876	11.0	336.0	72.0	18.0	24.0	25.0	29.0	149.0	3.0	103.0	88.0	200.0
MB33	15.07	3.73	5.16	2.3	0.039	2.34	49.48	3.0	0.737	10.0	379.0	63.0	15.0	27.0	29.0	24.0	217.0	3.0	89.0	123.0	253.0
MB34	15.02	1.01	5.00	2.0	0.031	2.41	53.79	3.3	0.752	8.0	449.0	57.0	15.0	16.0	21.0	21.0	122.0	3.0	84.0	70.0	269.0
MB35	13.58	1.42	4.19	1.6	0.051	2.31	57.07	2.6	0.634	5.0	626.0	51.0	13.0	13.0	16.0	17.0	137.0	1.5	74.0	44.0	503.0
MB36	11.49	0.34	2.33	1.0	0.017	2.26	63.30	2.8	0.424	2.0	660.0	25.0	8.0	7.0	15.0	10.0	138.0	1.5	42.0	25.0	460.0
MB37	15.85	0.97	4.90	2.1	0.034	2.40	52.47	2.9	0.761	7.0	412.0	60.0	16.0	17.0	18.0	21.0	117.0	1.5	84.0	61.0	272.0
MB38	15.83	0.85	6.40	2.4	0.029	2.56	50.55	4.1	0.931	8.0	334.0	82.0	20.0	26.0	17.0	29.0	93.0	1.5	115.0	72.0	383.0
MB39	13.37	0.66	3.64	1.5	0.035	2.28	58.19	2.5	0.569	4.0	524.0	47.0	12.0	12.0	17.0	14.0	122.0	1.5	66.0	42.0	383.0
MB40	10.89	4.19	3.96	1.9	0.030	2.06	55.90	1.9	0.556	10.0	374.0	46.0	13.0	13.0	15.0	15.0	293.0	1.5	56.0	44.0	535.0
MB41	1.22	32.79	0.17	2.2	0.006	0.83	28.36	1.9	0.039	1.0	139.0	4.0	0.5	3.0	4.0	3.0	2710.0	1.5	7.0	6.0	120.0
MB42	0.32	44.34	0.07	2.1	0.005	0.23	5.91	1.9	0.026	1.0	44.0	0.5	1.0	4.0	1.0	1.0	4118.0	1.5	3.0	5.0	90.0
MB43	0.23	44.84	0.06	3.0	0.005	0.19	2.93	2.2	0.008	1.0	34.0	0.5	0.5	1.0	1.0	1.0	2384.0	1.5	3.0	3.0	1.0
MB44	1.06	38.58	0.28	2.0	0.006	0.55	16.76	2.2	0.094	2.0	71.0	4.0	2.0	5.0	2.0	2.0	3802.0	1.5	10.0	9.0	173.0
MB45	7.80	7.27	2.04	1.2	0.017	2.21	54.58	1.7	0.600	6.0	641.0	40.0	4.0	45.0	71.0	10.0	371.0	19.0	390	221.0	1502.0
MB46	1.81	31.97	0.80	2.4	0.032	0.74	21.15	4.0	0.213	9.0	113.0	9.0	3.0	2.0	13.0	3.0	1730.0	4.0	10.0	17.0	321.0
MB47	7.22	8.90	1.59	1.4	0.014	2.15	55.09	2.1	0.362	4.0	459.0	19.0	5.0	8.0	19.0	8.0	685.0	1.5	33.0	28.0	518.0

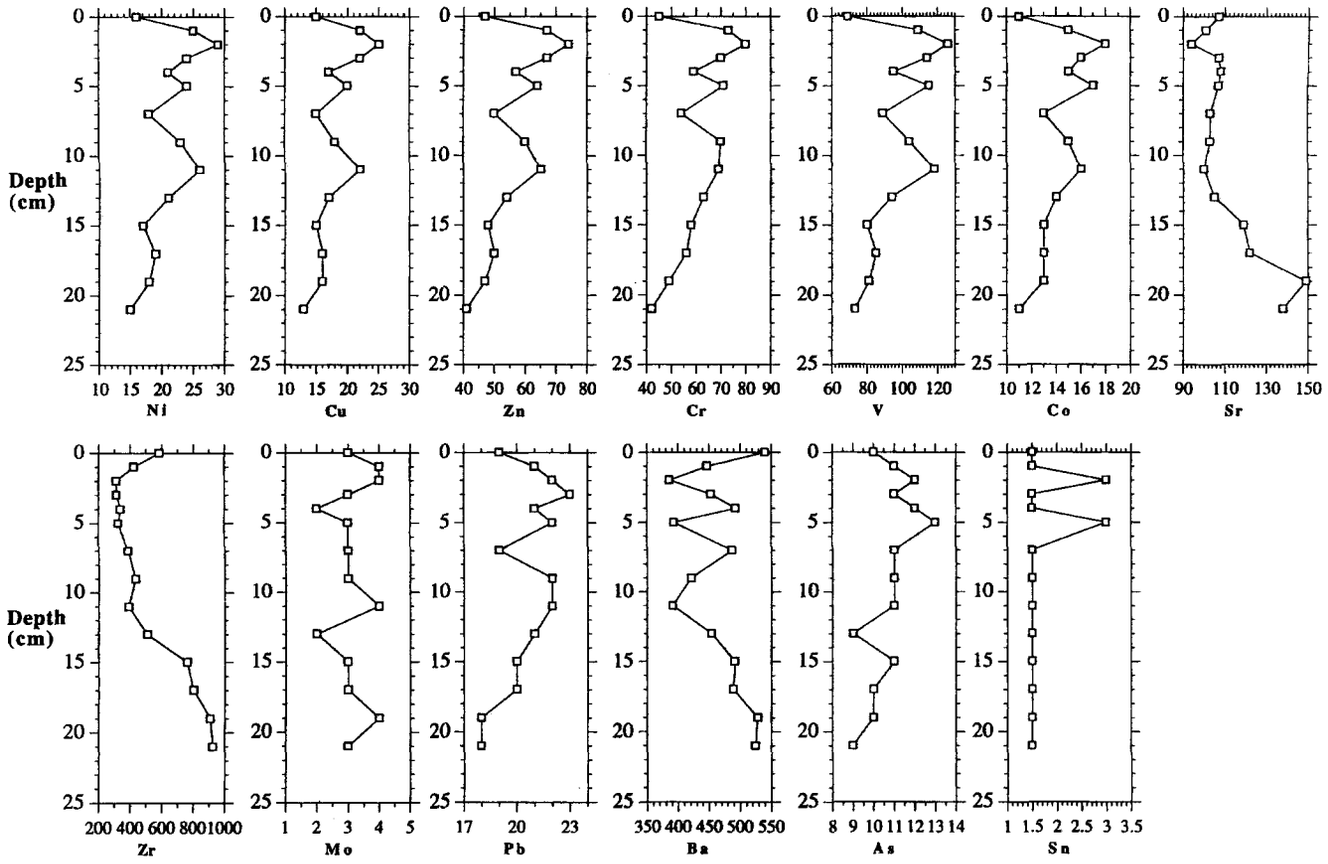

Fig. 2 Typical downcore trace metal profiles (mg kg^{-1} dry weight) in inshore sediments around Mombasa, exemplified by data from Tudor Creek site MB1.

for Cu (up to 50% of the total), V (up to 25%) and Zn (up to 10%), with fulvic fractions systematically dominant (*ca* 80% of the total organic loading). Hydroxylamine hydrochloride-extractable phases (mainly hydrous Mn oxides) constitute the major carrier of Mn (> 50% of the total), Co (50% total), Cu (30% total), Pb (100% total) and Zn (*ca* 60% total) in the uppermost 60 cm of sediment. These oxides were probably precipitated under aerobic conditions at the sediment–water interface, and are subject to progressive (kinetically constrained) dissolution during burial. Data acquired from the aqua-regia stage of the leaching sequence indicated that aluminosilicates, detrital sulphides and other resistate minerals dominated with respect to the total budgets of Al (> 85%), Cr (> 85%), Fe (> 60%), Ni (> 70%) and V (> 50%) at all stratigraphic levels.

GCMS analyses of surficial sediments from Makupa Creek (MB23), Port Reitz (MB27) and Port Tudor (MB1) yielded significant anomalies at the former site for toluene (12 mg kg^{-1} dry weight), hexanone (21 mg kg^{-1}), *n*-alkanes (24 mg kg^{-1}) and a complex suite of heavy hydrocarbons (3600 mg kg^{-1}). The concentrations of 16 PAH compounds in sediments from these localities were universally low (< 1 mg kg^{-1}). With the exception of a single anomaly for DDT (0.46 mg kg^{-1}) at a Tudor Creek site (MB5), all surficial sediments yielded values of < 0.1 mg kg^{-1} dry weight for major organochlorine groups including DDE, DDT, dieldrin, α-endosulphan, β-endosulphan, endrin, α-HCH, β-HCH hexachlorobenzene and trifluralin.

In view of the magnitude of annual industrial and domestic discharges currently known to prevail in the region the strictly limited evidence of degeneration of inshore/nearshore sediment and water quality attributable to Mombasa's recent urban expansion is striking. In addition to the suspended solid influxes derived from sewage (> 3500 t yr^{-1}), stormwater runoff (> 9000 t yr^{-1}) and routine industrial activities (> 20 000 t yr^{-1}; Munga *et al.*, 1994), the Mombasa creeks have been subject to at least two significant oil-spills in the past decade, the geochemical effects of which are now difficult to detect. This can be ascribed to specific physical, hydrodynamic and biogeochemical attributes which promote effective contaminant dispersal and/or degradation, as detailed by Williams *et al.* (1996a).

The LOCS Mombasa survey has provided a comprehensive baseline against which the effects of future urban and industrial expansion can be evaluated. The establishment of an appropriate system for

integrating the LOCS datasets with a wider range of environmental and socio-economic information is, however, vital to maximize their practical utility in coastal zone management (CZM). To this end, the LOCS database has been downloaded to a pre-existing thematic GIS for the Kenya coast, developed by UNEP OCA/PAC under a sub-project (EAF/6) of the Action Plan for the Protection, Management and Development of the Marine and Coastal Environment of the East African Region (Williams *et al.*, 1996b). It is anticipated that this integrated system will ultimately serve as a model for adoption throughout the East African region.

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Imposex in Three Species of *Thais* from Singapore, with Additional Observations on *T. clavigera* (Küster) from Japan

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Observations on imposex are provided for *Thais bitubercularis*, *T. clavigera* and *T. jubilaea* (Mollusca: Neogastropoda: Muricidae) from Singapore. The results suggest that the three species are affected by tributyltin. *Thais bitubercularis* appear to be least affected, while *T. jubilaea* was the most affected, in terms of the size of the pseudopenis. The sex ratios in most cases were in favour of the males, suggesting a higher mortality amongst females. Relative penial size (RPS) values were less than 25% but aborted capsules were present in the lumen of the capsule glands of females examined. In contrast, additional observations of *T. clavigera* from Japan had RPS values up to 88%. These differences probably reflect seasonal variation in male penial size, but the possibility that females respond to high concentrations of TBT by growing a larger pseudopenis despite blockage of the oviduct, should not be discounted. © 1997 Elsevier Science Ltd

It has previously been established that tributyltin (TBT) causes the imposition of male sex characters in females of neogastropods, and this is particularly well-reported in gastropods belonging to the family Muricidae (Mollusca: Prosobranchia; see Gibbs and Bryan, 1986; Bryan *et al.*, 1988; Fioroni *et al.*, 1992). The morphological characteristics induced in females exposed to TBT have been used to plot a dose–response relationship for some temperate species of the genera *Nucella* and *Ocenebra* (Gibbs *et al.*, 1987, 1990). At low concentrations (0.5–1 ng TBT l^{-1}) the females grow a small non-functional penis, and an incomplete vas deferens. At high TBT concentrations (typically above 5 ng TBT l^{-1}) the females have a fully grown penis and vas deferens comparable in size with those of mature males (Gibbs and Bryan, 1986). In some species, the vas deferens obstructs the vulva, causing a blockage of the oviduct (e.g. Gibbs *et al.*, 1987; Oehlmann *et al.*, 1991). This prevents the females from laying eggs, often resulting in the accumulation of eggs in the oviduct, and the eventual rupture of the capsule gland (Gibbs and Bryan, 1986; Gibbs *et al.*, 1987). The presence of other male sex organs, such as the prostate, seminal vesicles and testes, has been found in some females affected by high TBT concentrations (Gibbs *et al.*, 1988) although in a few populations affected by TBT, aphally has been reported in some individuals (Gibbs, 1993; Huet *et al.*, 1996). Effects are also felt at the population level. Because the young of *Nucella lapillus* undergo direct development (i.e. the eggs develop into miniature adults without passing through a planktonic stage) and have limited dispersal capabilities, populations rendered sterile by TBT become extinct, since there is little or no immigration (Bryan *et al.*, 1986).

Studies on species of Muricidae in the Malayan region are hampered by taxonomic confusion, particu-