

# Trace metals in sediments of four harbours in Guam

G.R.W. Denton <sup>a,\*</sup>, Lucrina P. Concepcion <sup>a</sup>, H.R. Wood <sup>a</sup>, R.J. Morrison <sup>b</sup>

<sup>a</sup> *Water and Environmental Research Institute of the Western Pacific, University of Guam, Mangilao 96913, Guam*

<sup>b</sup> *School of Earth and Environmental Sciences, University of Wollongong, NSW2522, Australia*

Harbours, because of the associated shipping activities, are often sites of serious marine pollution. As a result of the work of international (e.g., the International Maritime Organization and the United Nations Environment Program) and national agencies, there have been significant improvements recently in the operations and environments of many harbours, but historical activities have often left a pollution impact in the sediments. Guam (13°28'N, 144°45'E) has been the major shipping centre in Micronesia for about 400 years, but there have been few studies of the impacts on the coastal environment of such activities. This paper reports the first major study of trace metals in sediments of four harbours in Guam.

Users of Guam's harbours have included the military (since World War II), commercial shippers, commercial and recreational fishermen, tourist operators (dinner cruises, diving, jet-skiing, sailing, etc.), and the general public. All associated activities have the potential to impact on the local marine environment and only in the last 20–30 years have any controls on pollution been introduced. As a result, some contamination of sediments is to be expected, but the extent was unknown before this study. The four harbours (Fig. 1a) were selected on the following basis: Agana Boat Basin (major small boat harbour—5 sites); Outer Apra Harbour (heavily used commercial and military port—30 sites); Agat Marina (newly constructed small boat harbour—4 sites); and Merizo Pier (small boat harbour away from industrial activity—5 sites).

Sediment samples were collected by scuba divers between May 16 and June 12, 1997. Site selection (Fig. 1b–e) was based primarily on proximity to potential sources of contamination (e.g., storm water outlets, mooring sites, wharves, piers, fueling stations, electrical substations, etc.) along presumed concentration gradients. Site locations were pinpointed using digital orthophoto imagery maps with reference to prominent landmarks. Samples were collected at depths ranging from 0.5 to 17 m, using stainless steel core samplers (5 × 30 cm) fitted with pre-cleaned aluminium liners and Teflon lined plastic end-caps. A slide hammer was

used to push each corer 15–30 cm into the sediment depending on the nature of the underlying substrate. Three cores were sampled within a 3 m diameter circle at each site, and each core was analysed separately. Because of difficulties encountered in extracting the charged liners from the body of the corers, the collected sediments were expelled into clean aluminium liners by inversion, wrapped in aluminium foil and stored on ice.

In the laboratory, the entire contents of each liner were dislodged into a glass bowl and thoroughly mixed with a polyethylene spatula following the removal of large rocks, shells and other such bulky materials. Sub-samples for petrographic and particle size analysis were dried at room temperature, and sub-samples for metal analyses were placed in acid cleaned polyethylene vials and dried to constant weight at 60 °C. Residual sediment samples were stored in pre-cleaned glass jars at –20 °C for further analysis if necessary.

Petrographic assessment (colour, sorting, dominant constituent identification and particle size) was made on the dried sediments. Sieve shaker analysis produced data on 4 size fractions: >2 mm (gravel); 1–2 mm (very coarse sand); 1 mm–63 µm (coarse to very fine sand); <63 µm (silt + clay). The organic carbon content of each sample was estimated following dichromate oxidation as described by Nelson and Sommers (1975). Full method details and results of these parameters are available in Denton et al. (1997).

After drying and sieving through a 1 mm nylon screen, trace metal analysis of the sediments used wet oxidation in concentrated nitric and/or hydrochloric acids, following procedures essentially similar to USEPA method 3050A in SW-846 (USEPA, 1996), with final analysis using atomic absorption spectrophotometry (AAS). 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. All analyses were performed in duplicate and were accompanied by appropriate method blanks and matrix spikes. Metal recoveries from a certified soil standard reference material were within acceptable limits for all elements examined (see Table 1).

For most elements, dried sediments (approximately 2 g) were weighed into Erlenmeyer flasks (125 mL), loosely capped with a Teflon stopper and digested with

\* Corresponding author. Tel.: +1 671 735 2690; fax: +1 671 734 8890.

E-mail address: gdenton@uog9.uog.edu (G.R.W. Denton).

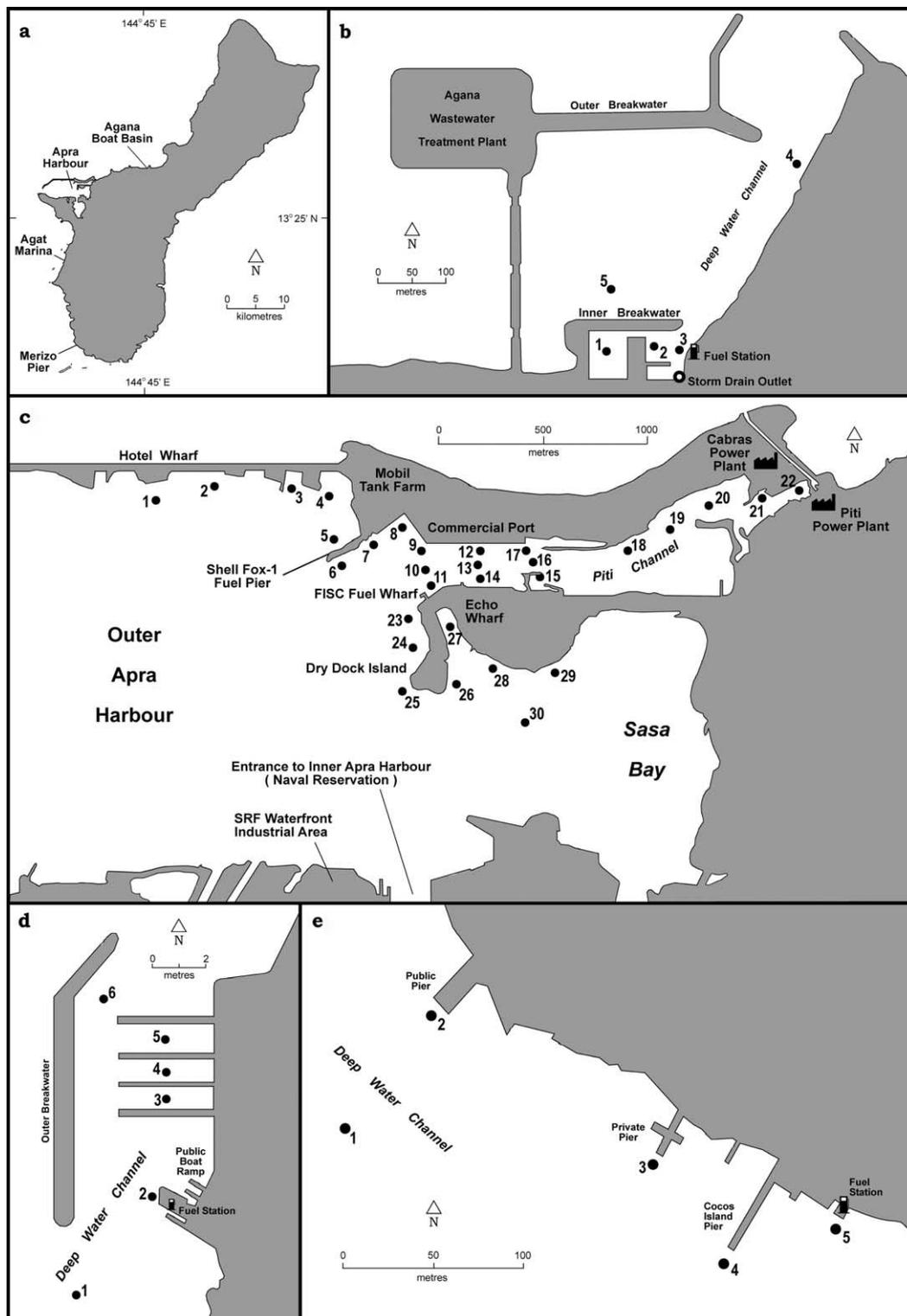


Fig. 1. (a) Locations of harbours studied on Guam and sediment sampling sites at: (b) Agana Boat Basin, (c) Outer Apra Harbour, (d) Agat Marina and (e) Merizo Pier.

concentrated nitric acid (15 mL) at 110–135 °C for 2 days. The digests were then evaporated to dryness and redissolved in 10% nitric acid (20 mL) with gentle warming. The contents of each flask were thoroughly mixed

and allowed to stand for several minutes prior to analysis to permit settlement of residual particulates. 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). Corrections for non-atomic absorption were made simultaneously by the AAS instrument with a deuterium continuum lamp.

For mercury and arsenic analyses, the sediments (2 g) were reacted with concentrated nitric acid (15 mL) by heating on a water bath for 3 h. After cooling, the contents of each flask were 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 °C until required for analysis. Mercury determinations were made by flameless (cold vapour) AAS (Hatch and Ott, 1968) 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). Arsenic analysis utilized the hydride generation technique following reduction of the sample 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.

The hydride generation technique was also used for tin, but 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). Sediment samples (~2 g) were initially digested with concentrated hydrochloric acid (~8 mL) to decompose the carbonates present. Following evaporation to dryness on a hot plate (100 °C), the samples were further digested in aqua regia (3:1 HCl and HNO<sub>3</sub>, 10 mL) at 100 °C for 3 h. Upon cooling, sample volumes were adjusted to 100 ml with deionized water. Stannane generation was achieved with 3% sodium borohydride in 0.5% sodium hydroxide. Matrix interferences were minimized by analysing small sample volumes (1 mL) in 5 mL of saturated boric acid (50 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 changes in pH. Calibration standards (5–20 µg/L) were made up in saturated boric acid solution on a daily basis.

Results of the metal analyses are summarised in Tables 2–5, and some literature data for other Pacific sites are summarised in Table 6. Despite attempts to effectively homogenize sediment samples prior to analysis, high within-site variability was occasionally observed. This was attributed to minute metallic or metal containing particles residing in the sediment. For

Table 1  
Analysis of standard reference material (PriorityPollutnT<sup>TM</sup>/CLP Inorganic Soils [Catalog No. PPS-46; Lot No. 233]) (all results in µg/g dry wt.)

Analyte	Certified value		This study		
	Mean	Range	Mean	Range	<i>n</i>
Arsenic	108	94.1–122	112	109–121	4
Cadmium	114	91.4–137	108	106–110	2
Chromium	42.2	37.3–47.1	43.1	42.4–43.7	2
Copper	68.9	62.9–74.9	66.4	64.5–68.3	2
Lead	44.3	39.6–49.0	47.9	45.4–50.4	2
Mercury	1.71	1.42–2.00	1.31	1.22–1.48	11
Nickel	71.8	63.8–79.8	71.9	71.0–72.8	2
Silver	59.7	45.1–74.3	53.2	50.4–56.1	2
Tin	79.0	70.3–87.7	79.4	71.9–88.0	8
Zinc	85.6	76.1–94.8	92.5	91.0–94.7	2

Table 2  
Trace metals in sediments from Agana Boat Basin (µg/g dry wt.)

Site	Statistic	Ag	As	Cd	Cr	Cu	Hg <sup>a</sup>	Ni	Pb	Sn	Zn
1 (a–c)	Mean <sup>b</sup>	nc	3.31	nc	12.0	74.7	61.2	6.96	30.7	2.93	47.7
	Range	<0.21–<0.24	2.47–3.98	<0.07–<0.08	10.9–14.2	65.2–88.5	45.8–98.3	5.67–8.96	25.4–50.1	2.03–3.86	41.2–58.9
2 (a–c)	Mean	nc	6.00	nc	28.8	64.6	107	19.9	70.7	6.61	104
	Range	<0.18–<0.36	4.63–7.19	<0.13–<0.27	26.4–31.2	48.0–96.1	95.8–123	18.9–21.2	54.6–113	4.57–10.9	86.3–126
3 (a–c)	Mean	nc	1.35	nc	3.99	1.91	9.16	1.45	11.1	3.11	4.45
	Range	<0.18–<0.25	0.92–2.18	<0.14–<0.16	3.16–4.83	0.81–38.0	5.14–15.9	1.19–1.79	3.35–324	1.65–7.36	2.61–7.77
4 (a–c)	Mean	nc	1.03	nc	4.25	3.01	4.59	1.48	1.99	nc	4.57
	Range	<0.19–<0.24	0.92–1.23	<0.12–<0.17	3.65–5.05	0.78–15.1	4.01–5.85	0.56–2.47	1.02–3.08	<0.09–0.22	1.79–37.0
5 (a–c)	Mean	nc	1.00	nc	3.61	0.56	4.77	1.01	3.46	nc	3.44
	Range	<0.22–<0.24	0.81–1.30	<0.14–<0.14	3.18–4.08	0.49–1.01	3.10–6.46	0.56–1.67	2.72–4.35	<0.09–<0.10	3.05–4.12

nc = not calculable.

<sup>a</sup> Mercury data expressed as ng/g dry wt.

<sup>b</sup> Mean = geometric mean.

Table 3  
Trace metals in sediments from Apra Harbour ( $\mu\text{g/g}$  dry wt.)

Site	Statistic	Ag	As	Cd	Cr	Cu	Hg <sup>a</sup>	Ni	Pb	Sn	Zn
1 (a-c)	Mean <sup>b</sup>	nc	10.7	0.59	12.4	142	403	4.04	96.3	7.37	461
	Range	<0.16–<0.2	7.11–17.0	0.27–2.18	8.61–14.1	85.8–181	137–741	2.34–10.0	80.2–107	6.54–7.91	404–552
2 (a-c)	Mean	nc	2.01	nc	3.59	3.12	14.3	nc	4.81	1.00	8.35
	Range	<0.17–<0.22	1.77–2.32	<0.08–<0.10	3.09–4.20	1.60–12.6	10.69–18.6	<0.22–<0.28	3.47–9.61	0.20–4.93	6.39–11.7
3 (a-c)	Mean	nc	1.24	nc	3.74	2.79	20.2	nc	6.07	0.54	12.9
	Range	<0.18–<0.21	1.00–1.40	<0.08–<0.10	3.28–4.42	2.15–3.96	16.7–23.5	<0.28–1.05	4.76–8.33	0.19–2.52	9.38–17.7
4 (a-c)	Mean	nc	3.70	nc	9.58	8.35	127	3.10	7.68	0.76	20.9
	Range	<0.17–<0.22	3.29–4.01	<0.08–<0.10	8.55–10.6	7.74–9.15	83.5–174	2.61–3.78	6.25–9.04	0.60–0.95	19.9–22.8
5 (a-c)	Mean	nc	3.77	nc	7.46	8.70	68.3	2.74	15.7	1.05	23.5
	Range	<0.19–<0.21	3.43–4.43	<0.09–<0.10	7.11–7.78	8.15–10.0	56.7–74.7	2.36–3.38	14.4–18.5	0.91–1.23	22.4–24.6
6 (a-c)	Mean	nc	8.64	nc	13.7	29.0	219	6.83	36.5	2.73	88.3
	Range	<0.17–<0.22	8.07–9.75	<0.08–<0.10	12.2–16.6	27.9–30.3	202–256	6.42–7.06	32.8–41.9	1.98–3.50	78.6–104
7 (a-c)	Mean	nc	4.67	nc	13.5	91.6	144	5.28	63.9	2.29	159
	Range	<0.16–<0.19	3.88–5.19	<0.07–0.21	10.1–21.0	72.7–127	107–264	4.57–6.03	52.6–86.7	2.06–2.79	144–188
8 (a-c)	Mean	nc	3.73	nc	10.3	40.2	87.7	3.73	39.2	1.90	142
	Range	<0.16–<0.20	3.31–4.36	<0.07–0.36	8.28–13.4	33.7–57.1	67.9–107	3.36–4.18	30.1–53.3	1.70–2.26	112–227
9 (a-c)	Mean	nc	4.45	nc	9.02	21.8	41.9	4.21	31.3	0.91	109
	Range	<0.18–1.80	3.96–4.81	<0.07–0.31	7.68–13.5	14.2–47.2	35.9–48.4	3.88–4.61	23.2–48.2	0.84–1.02	75.7–182
10 (a-c)	Mean	nc	3.81	nc	7.09	3.43	31.2	3.85	4.46	0.25	9.45
	Range	<0.20–<0.22	3.44–4.23	<0.08–<0.09	5.33–8.46	1.57–4.81	18.0–47.3	3.13–4.59	3.00–5.77	0.15–0.39	4.62–14.4
11 (a-c)	Mean	nc	3.50	nc	7.77	7.32	68.5	4.73	7.49	0.71	22.3
	Range	<0.18–<0.22	3.17–4.00	<0.07–<0.09	6.72–9.48	5.26–10.2	39.1–473	4.13–5.49	6.62–8.38	0.47–1.25	14.9–27.7
12 (a-c)	Mean	nc	4.00	nc	7.36	9.43	25.4	4.54	9.42	0.64	36.4
	Range	<0.17–<0.22	3.46–4.73	<0.07–<0.17	6.53–8.29	7.94–11.8	23.8–27.2	3.08–11.0	6.97–19.9	0.35–1.92	24.3–109
13 (a-c)	Mean	nc	3.79	nc	8.41	8.27	38.1	4.27	5.82	0.38	21.6
	Range	<0.17–<0.22	3.02–4.54	<0.12–<0.16	7.86–9.48	7.49–9.24	32.1–45.5	3.57–4.93	5.07–6.74	0.33–0.43	19.9–23.1
14 (a-c)	Mean	nc	3.30	nc	9.27	10.8	41.9	5.58	7.19	0.54	24.7
	Range	<0.19–<0.20	2.61–3.88	<0.14–<0.16	8.46–10.7	9.99–11.9	38.7–45.5	5.24–5.96	5.80–8.07	0.47–0.67	23.4–26.8
15 (a-c)	Mean	nc	2.81	nc	6.04	3.65	14.0	3.87	2.72	nc	11.9
	Range	<0.19–<0.21	2.24–3.15	<0.15–<0.16	5.61–6.29	3.36–4.20	11.4–21.2	3.42–4.33	2.11–3.30	<0.08–<0.09	9.53–16.9
16 (a-c)	Mean	nc	3.81	nc	10.7	14.5	45.4	7.43	9.27	0.62	31.2
	Range	<0.18–<0.22	2.92–4.90	<0.14–<0.17	10.1–11.1	13.3–17.0	43.1–46.8	7.16–7.93	8.26–10.4	0.49–0.74	29.6–34.8
17 (a-c)	Mean	nc	5.12	nc	17.1	57.8	47.3	8.87	65.0	5.65	143
	Range	<0.17–<0.22	4.27–6.16	<0.13–0.37	13.6–20.1	46.6–73.6	44.9–52.4	7.83–11.0	41.0–123	2.18–35.7	115–179
18 (a-c)	Mean	nc	1.53	nc	4.95	1.00	6.18	2.39	nc	nc	2.30
	Range	<0.19–<0.22	1.30–1.81	<0.13–<0.17	4.66–5.29	0.81–1.26	4.82–7.23	2.19–2.55	<0.58–1.41	<0.07–<0.08	1.66–2.78
19 (a-c)	Mean	nc	2.38	nc	5.04	4.71	14.2	2.85	4.51	nc	6.74
	Range	<0.19–<0.21	2.20–2.63	<0.15–<0.17	4.16–5.52	3.73–5.98	11.9–18.1	1.81–3.83	3.33–6.91	<0.09–<0.10	4.77–8.46
20 (a-c)	Mean	nc	3.15	nc	6.13	6.34	21.1	7.33	4.38	nc	11.4
	Range	<0.19–<0.22	2.96–3.55	<0.14–<0.17	5.52–6.64	5.00–8.03	19.3–23.5	6.05–8.61	3.47–5.73	<0.10–0.32	10.3–13.3

21 (a-c)	Mean	nc	3.26	nc	9.50	18.0	13.7	14.0	6.63	0.24	34.3
	Range	<0.17–<0.20	2.91–3.75	<0.13–<0.16	7.98–10.8	14.3–22.0	9.23–17.0	11.4–19.6	5.55–7.41	0.17–0.44	28.4–43.8
22 (a-c)	Mean	nc	2.96	nc	7.38	5.28	23.1	5.48	12.8	3.06	23.9
	Range	<0.18–<0.22	2.59–3.51	<0.14–<0.17	5.12–9.61	3.61–9.33	19.8–26.7	3.41–8.75	3.54–53.9	0.38–44.0	12.7–47.3
23 (a-c)	Mean	nc	1.16	nc	3.91	2.23	15.7	1.66	2.18	nc	5.67
	Range	<0.17–<0.22	0.98–1.73	<0.13–<0.17	3.49–4.54	1.89–3.17	11.9–50.7	1.45–1.98	1.50–2.85	<0.10–<0.10	4.86–7.74
24 (a-c)	Mean <sup>b</sup>	nc	4.60	nc	9.62	15.8	88.1	2.56	22.0	1.02	43.0
	Range	<0.19–<0.22	4.25–4.88	<0.15–<0.17	7.81–14.3	10.5–34.3	70.9–111	1.98–4.76	15.0–34.9	0.90–1.24	31.6–53.4
25 (a-c)	Mean	nc	9.05	nc	10.2	48.7	263	8.12	48.9	2.09	117
	Range	<0.19–<0.24	6.91–12.5	<0.11–<0.14	8.68–13.2	35.7–75.4	160–428	5.70–17.4	33.6–85.5	2.08–2.10	85.1–163
26 (a-c)	Mean	nc	5.73	nc	7.71	13.8	16.9	4.04	17.4	0.33	35.6
	Range	<0.19–<0.23	4.35–10.2	<0.11–0.19	6.87–8.87	10.2–20.1	14.6–20.3	3.34–5.30	10.4–22.8	0.18–0.50	29.0–45.2
27 (a-c)	Mean	nc	7.36	nc	14.4	52.0	110	7.14	48.6	1.89	148
	Range	<0.19–<0.24	4.93–9.69	<0.14–0.60	11.1–21.9	21.5–153	64.3–167	6.28–8.29	17.9–194	0.56–4.21	45.7–451
28 (a-c)	Mean	nc	3.67	nc	7.27	4.83	22.0	4.17	2.28	nc	8.64
	Range	<0.21–<0.22	3.46–3.91	<0.13–<0.13	6.71–7.84	4.41–5.26	18.9–26.0	3.65–4.48	1.73–2.98	<0.09–<0.10	7.70–9.88
29 (a-c)	Mean	nc	2.27	nc	5.07	2.22	10.5	2.54	1.63	nc	3.22
	Range	<0.20–<0.24	2.08–2.47	<0.12–0.20	4.25–5.94	1.66–2.78	8.27–14.5	1.95–2.90	1.09–2.22	<0.10–2.28	2.40–3.83
30 (a-c)	Mean	nc	4.07	nc	10.9	10.9	43.6	8.90	6.26	0.29	27.2
	Range	<0.20–<0.24	3.84–4.68	<0.12–<0.15	9.89–12.7	9.24–13.8	32.5–55.5	8.01–10.9	4.88–8.79	0.17–0.46	23.1–35.5

nc = not calculable.

<sup>a</sup> Mercury data expressed as ng/g dry wt.

<sup>b</sup> Mean = geometric mean.

Table 4  
Trace metals in sediments from Agat Marina ( $\mu\text{g/g}$  dry wt.)

Site	Statistic	Ag	As	Cd	Cr	Cu	Hg <sup>a</sup>	Ni	Pb	Sn	Zn
1 (a-c)	Mean <sup>b</sup>	nc	6.92	nc	20.7	7.68	4.96	23.4	nc	nc	7.54
	Range	<0.19–<0.23	5.74–9.44	<0.06–<0.08	17.7–28.5	6.1–10.6	4.17–6.42	19.2–32.2	<0.46–<0.56	<0.09–<0.10	6.36–10.2
2 (a-c)	Mean	nc	6.37	nc	12.5	5.13	3.83	16.4	nc	nc	7.64
	Range	<0.19–<0.24	5.84–7.12	<0.06–<0.08	10.9–16.4	4.37–6.45	2.75–6.47	14.4–21.0	<0.44–<0.57	<0.09–<0.10	6.57–9.94
3 (a-c)	Mean	nc	5.85	nc	12.2	2.63	3.93	10.8	nc	nc	4.80
	Range	<0.18–<0.23	5.57–6.21	<0.06–<0.08	9.13–14.6	2.19–3.16	2.72–6.16	9.70–11.7	<0.40–<0.49	<0.09–<0.10	4.14–6.47
4 (a-c)	Mean	nc	6.21	nc	10.3	3.20	4.18	12.4	nc	nc	4.94
	Range	<0.20–<0.22	5.74–6.65	<0.07–<0.07	8.17–11.9	2.77–3.79	3.15–7.30	11.4–13.5	<0.43–<0.48	<0.09–<0.10	4.24–5.74
5 (a-c)	Mean	nc	9.78	nc	30.7	10.3	5.62	30.2	nc	nc	11.2
	Range	<0.20–<0.25	8.58–11.1	<0.07–<0.08	27.5–33.2	9.37–11.0	4.22–7.05	26.8–32.8	<0.43–<0.54	<0.09–<0.01	10.7–11.9
6 (a-c)	Mean	nc	5.31	nc	9.85	3.14	4.19	12.3	nc	nc	4.42
	Range	<0.21–<0.24	4.57–6.49	<0.07–<0.08	7.98–11.2	2.51–3.45	3.17–5.64	9.72–13.8	<0.46–<0.53	<0.09–<0.09	3.29–5.07

nc = not calculable.

<sup>a</sup> Mercury data expressed as ng/g dry wt.

<sup>b</sup> Mean = geometric mean.

Table 5  
Trace metals in sediments from Merizo Pier ( $\mu\text{g/g}$  dry wt.)

Site	Statistic	Ag	As	Cd	Cr	Cu	Hg <sup>a</sup>	Ni	Pb	Sn	Zn
1 (a-c)	Mean <sup>b</sup>	nc	2.87	nc	13.5	4.34	8.02	14.0	nc	nc	9.58
	Range	<0.20–<0.25	2.43–3.11	<0.12–<0.16	12.2–15.2	3.55–5.21	7.53–8.32	12.4–15.5	<0.38–10.6	<0.08–0.13	7.17–13.7
2 (a-c)	Mean	nc	4.62	nc	28.3	33.2	16.1	59.4	43.2	7.06	57.8
	Range	<0.23–<0.25	3.27–6.23	<0.14–0.22	23.5–38.6	27.2–39.8	12.6–20.5	45.3–88.5	14.4–129	2.00–43.1	54.0–62.2
3 (a-c)	Mean	nc	4.82	nc	21.1	43.1	12.0	43.3	12.7	1.76	68.1
	Range	<0.17–<0.25	3.54–5.85	<0.12–0.24	17.1–26.2	30.8–123	9.96–13.7	36.8–46.9	8.92–40.1	1.32–3.11	49.7–92.9
4 (a-c)	Mean	nc	4.41	nc	20.4	25.8	12.9	35.5	8.40	0.86	44.7
	Range	<0.19–<0.25	3.55–5.58	<0.12–<0.15	14.4–32.2	12.0–45.0	11.1–15.2	23.7–57.8	5.36–11.9	0.80–0.91	26.8–65.6
5 (a-c)	Mean	nc	5.19	nc	39.5	123	32.0	71.0	27.1	1.74	130
	Range	<0.20–<0.25	4.70–5.68	<0.12–<0.15	33.0–52.7	83.1–168	20.4–73.3	58.1–102	16.3–58.8	1.54–1.93	93.8–167

nc = not calculable.

<sup>a</sup> Mercury data expressed as ng/g dry wt.

<sup>b</sup> Mean = geometric mean.

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 sediment mineralogy varied from almost 100% reef derived material to almost 100% weathered volcanics, depending on local factors such as the size and slope stability in the adjacent watershed, wave energy and bathymetry. No significant correlations were found between metal concentrations and particle size distribution or organic carbon contents.

Sedimentary silver concentrations in Guam harbours were consistently below 0.2  $\mu\text{g/g}$  in line with levels normally encountered ( $\sim 0.1$   $\mu\text{g/g}$ ) in uncontaminated sediments (Bryan and Langston, 1992). Likewise, the great majority of arsenic, cadmium, chromium, and nickel determinations yielded values typical of relatively clean coastal environments. It is noteworthy that marked cadmium and chromium enrichment has previously been demonstrated in sediments from within Inner Apra Harbour, as well as from the immediately adjacent waters of Outer Apra Harbour in the vicinity of the Naval Ship Repair Facility (SRF) industrial area (Belt Collins Hawaii, 1993, 1994).

Copper concentrations in clean, non-geochemically enriched sediments are in the order of 10  $\mu\text{g/g}$  or less, while values in excess of 2000  $\mu\text{g/g}$  have been reported for copper polluted sediments (Legorburu and Canton, 1991; Bryan and Langston, 1992). In the current study, localized pockets of copper contamination were encountered at all locations except Agat Marina, where concentrations ranged from 2 to 10  $\mu\text{g/g}$ . At the Agana Boat Basin, Sites 1 and 2 were classified as “heavily polluted” according to USEPA criteria (Giesy and Hoke, 1990) as were Sites 1, 7, 17, 25 and 27 at Apra Harbor, and Site 5 at Merizo Pier. Site 6 at Apra Harbor and Sites 2–4 at Merizo Pier were “moderately polluted”. Maximum copper concentrations reported earlier for surface sediments taken from within Inner Apra Harbor and adjacent waters of the outer harbour area, are appreciably higher than those noted here (Belt Collins Hawaii, 1993). This may, to some extent, reflect grain size differences between the different samples.

Baseline levels of total mercury in uncontaminated sediments are in the order of 30 ng/g (Bryan and Langston, 1992; Benoit et al., 1994). Based on these data, concentrations found at Agat Marina, Merizo Pier (apart from Site 5 adjacent to a boat refuelling station) and in the outer harbour of Agana Boat Basin all fall into the “pristine” category. Some mercury enrichment was noted in the Agana Boat Basin inner harbour area (61.2–107 ng/g), presumably reflecting the greater number of permanent mooring sites coupled with restricted water movement in this area. The highest mercury concentrations were found at Apra Harbour, although, from the data, it is clear that contamination is not universally distributed; rather, it is restricted to localized

Table 6  
Trace metal concentrations ( $\mu\text{g/g}$  dry wt.) in marine and estuarine sediments from other Pacific coastal areas

Location	Site	Depth (cm)	Fraction	Ag	As	Cd	Cr	Cu	Hg	Ni	Pb	Sn	Zn	Reference
Guam	Outer Apra Harbour (Echo Wharf)	Surface	Bulk sediment	<0.23	<0.99	<0.17	16–18	–	–	–	17	<0.66	–	US Navy (PWC) 1997, unpublished
Guam	Outer Apra Harbour (SRF Industrial)	Surface	>65 $\mu\text{m}$	–	–	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 Harbour (SRF Industrial)	Surface	<65 $\mu\text{m}$	–	–	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 Harbour	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 Harbour	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 Harbour	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 Harbour	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 Harbour (USS Proteus Site)	Surface	Bulk sediment	–	6.0 <sup>a</sup>	–	34.0 <sup>a</sup>	26.0 <sup>a</sup>	0.36 <sup>a</sup>	7.35 <sup>a</sup>	132 <sup>a</sup>	–	72.2 <sup>a</sup>	Ogden (1996)
Fiji	Great Astrolabe Lagoon	Surface	Bulk sediment	–	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 Harbour (near dump)	Surface	Bulk sediment	–	0.7–45	0.74–3.04	16–106	59–306	0.2–1.34	17–38	19.3–272	–	88–670	Naidu and Morrison (1994)
Fiji	Laucala Bay	Surface	Bulk sediment	–	–	0.60–1.23	–	23.9–93.6	0.061–0.185	–	3.3–13.3	–	32–153	Morrison et al. (2001)
Tonga	Fanga'uta Lagoon	Surface	Bulk sediment	–	2–8	<0.1–0.1	–	7–15	<0.005–0.040	11–14	3–8	<0.05	13–38	Morrison and Brown (2003)
Tonga	Sopu	Surface	Bulk sediment	–	8	0.1	–	2	0.010	<2	<1	0.6	6	Morrison and Brown (2003)
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 $\mu\text{m}$	–	–	2.1–4.8	–	8.5–12.0	–	–	10.3–35.6	–	40–90	Ismail (1993)
Taiwan	Kaohsiung Harbour	Surface	<63 $\mu\text{m}$	–	–	0.1–4.64	–	37.9–505	–	–	34.3–138	–	–	Chen and Wu (1995)
Australia-PNG	Torres Strait	Surface	<100 $\mu\text{m}$	–	–	–	–	2–17	–	–	–	–	40–53	Brady et al. (1994)
Australia	Halifax Bay, N. Queensland	Surface	Bulk sediment	–	–	–	–	6–9.4	0.004–0.016	8.8–14	14–22	–	29–44	Knauer (1976, 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 and Davey (1995)
Australia	Ninety Mile Beach, VIC	0–5	<63 $\mu\text{m}$	–	–	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)

ND = not detectable; dashes indicate no data.

<sup>a</sup> Only maximum concentration reported.

areas. The highest values were found at Site 1 adjacent to the Hotel Wharf area (mean: 403 ng/g), Site 4 adjacent to the Mobil tank farm (mean: 127 ng/g), Sites 6 and 7 adjacent to the Shell Fox-1 fuel pier (mean: 219 ng/g and 144 ng/g respectively), and Sites 25 and 27 on Dry Dock Island (mean: 263 ng/g and 110 ng/g respectively). Mercury contents of sediments from all other Apra Harbor sites were <100 ng/g and, in several instances, were <30 ng/g. This is in marked contrast with mercury contents reported for unsorted Inner Apra Harbour sediments of up to 2.4 µg/g (Belt Collins Hawaii, 1993). These elevated values may be, at least in part, a reflection of the finer texture (10–40% silt + clay, Belt Collins Hawaii, 1994) in the inner harbour, compared with those sampled in the present study (1–21% silt + clay).

Lead concentrations in clean coastal sediments are around 25 µg/g or less (Schafer and Bascom, 1976; UNEP, 1985; Bryan and Langston, 1992). Based on the data gathered during the present study for Agat Marina, it would appear that baseline levels for lead in uncontaminated carbonate sediments are <1 µg/g, although values of 3–5 µg/g were recorded for clean carbonate sediments at the Great Astrolabe Lagoon in Fiji (Morrison et al., 1997). The highest mean lead concentration recorded during the current work was 96.3 µg/g at Site 1 in Apra Harbour. Values >30 µg/g were detected at Apra Harbour Sites 6–9, 17, 25 and 27, although none exceeded the USEPA established maximum of 90 µg/g for non-polluted sediments (Giesy and Hoke, 1990). Lead concentrations of 43–139 µg/g have been reported for sediments from within Inner Apra Harbour (Belt Collins Hawaii, 1993), suggesting more widespread enrichment of lead in this area.

The impact of TBT and related compounds in the Pacific Islands marine environment is of concern following studies in Fiji where very high concentrations were found in sediments and imposex was noted in molluscs (Stewart and de Mora, 1992; Maata and Koshy, 2001). Tin was not detected in sediments from the recently constructed Agat Marina area. It would appear, then, that baseline concentrations of naturally occurring, inorganic tin in the calcareous sediments around Guam are below 0.1 µg/g. Concentrations significantly above this are thought to represent contributions from anthropogenic sources. Thus, enrichment factors of between 10 and 100 are apparent for several sites within each of the other three harbour locations studied. However, what proportion of this additional loading represents TBT and other organotin compounds is currently unknown. Particularly high total tin concentrations have been reported for sediments from Inner Apra Harbour, and the adjoining waters of the outer harbour area (Belt Collins Hawaii, 1993), ranking among the highest ever recorded. Paint chips associated with the cleaning and maintenance of naval ships, including hull sand-blasting

activities, are likely to be the principal source of this element. Thus, TBT and other organotin compounds are probably in high concentrations in sediments here. Clearly, further investigations are warranted to substantiate this and determine possible adverse ecological effects.

Uncontaminated sediments typically contain zinc concentrations of 5–50 µg/g depending upon local geology (Moore, 1991). Zinc concentrations found during the present study spanned two orders of magnitude ranging from baseline levels of 3–5 µg/g at uncontaminated sites to a maximum of 461 µg/g off Hotel Wharf (Site 1) in Apra Harbour. Based on the USEPA's criteria (Giesy and Hoke, 1990) for zinc-contaminated sediments, this was the only site classified as "heavily polluted". Sites 7–9, 17, 25 and 27 in Apra Harbour; Site 2 in Agana Boat Basin, and Site 5 at Merizo Pier were classified as "moderately polluted" while the remainder fell into the "non-polluted" category. Zinc values determined during the present investigation were reasonably comparable with those reported earlier for sediments from Inner Apra Harbour and adjacent waters (Belt Collins Hawaii, 1993), in sharp contrast to the other metals common to both studies.

Overall, the trace metal data show enrichment at some sites in the Agana Boat Basin and Merizo Pier, but the majority of sites within each of these locations are relatively clean. Agat Marina, a recently constructed small boat harbour showed the lowest contaminant concentrations. The highest metal concentrations were found at Apra Harbour, the oldest and largest harbour in Guam, with significant enrichment of several metals in the vicinity of Hotel Wharf, Commercial Port and Dry Dock Island. The concentrations measured in this study were generally well below those reported earlier for the Inner Apra Harbour (Belt Collins Hawaii, 1993), in particular the values for tin (up to 1055 µg/g) and mercury (up to 2.4 µg/g). The environmental consequences of these high metal concentrations are currently unknown and are under investigation.

### Acknowledgements

Our thanks to Vance Eflin, Danzel Narcis and Greg Pangelinan (Guam Environmental Protection Agency) for assistance with the sample collection, and to John Jocson (WERI) and Richard Miller (School of Earth and Environmental Sciences, University of Wollongong) for preparing the site maps. This work was funded, in part, by the National Oceanographic and Atmospheric Administration, Office of Ocean and Coastal Resource Management, and the Guam Coastal Management Program, Bureau of Planning, Government of Guam, through NOAA Grant Award #NA67OZ0365.

## References

- Beach, L.M., 1992. Determination of tin by hydride generation. Varian AA-at-Work, No 107, 4p.
- Belt Collins Hawaii, 1993. Final Environmental Impact Statement for Proposed Facilities Development and Relocation of Navy Activities to the Territory of Guam from the Republic of the Philippines. U.S. Navy Pacific Division Naval Facilities Engineering Command. Prepared by the U.S. Navy in cooperation with the U.S. Air Force and the U.S. Army Corps of Engineers, July 1993.
- Belt Collins Hawaii, 1994. Environmental Assessment for Causeway to Drydock AFDM-8, Ship Repair Facility, Apra Harbor, Guam (Review Copy). Prepared for Pacific Division, Naval Facilities Engineering Command Pearl Harbor, Hawaii, June 1994.
- Benoit, G., Schwantes, J.M., Jacinto, G.S., Goud-Collins, M.R., 1994. Preliminary study of the redistribution and transformation of HgS from cinnabar mine tailings deposited in Honda Bay, Palawan, Philippines. *Marine Pollution Bulletin* 28, 754–759.
- Brady, B.A., Basil Johns, R., Smith, J.D., 1994. Trace metal geochemical association in sediments from the Cairns region of the Great Barrier Reef, Australia. *Marine Pollution Bulletin* 28, 230–234.
- Bryan, G.W., Langston, W.J., 1992. Bioavailability, accumulation and effects of heavy metals in sediments with special reference to United Kingdom estuaries: A review. *Environmental Pollution* 76, 89–131.
- Chen, M., Wu, H., 1995. Copper, cadmium and lead in sediments from the Kaohsiung River and its harbour area, Taiwan. *Marine Pollution Bulletin* 30, 879–884.
- Denton, G.R.W., Wood, H.R., Concepcion, L.P., Siegrist, H.G., Eflin, V.S., Narcis, D.K., Pangelinan, G.T., 1997. Analysis of In-place Contaminants in Marine sediments from Four Harbor Locations on Guam: A Pilot Study. Technical Report No. 81, Water and Environmental Research Institute of the Western Pacific, University of Guam, Mangilao, 122p.
- Feldman, C., 1974. Preservation of dilute mercury solutions. *Analytical Chemistry* 46, 99–102.
- Ferreira, M.F., Chiu, W.S., Cheok, H.K., Cheang, F., Sun, W., 1996. Accumulation of nutrients and heavy metals in surface sediments near Macao. *Marine Pollution Bulletin* 32, 420–425.
- Giesy, J.P., Hoke, R., 1990. Freshwater sediment quality criteria: Toxicity bioassessment. In: Baudo, R., Giesy, J., Muntau, H. (Eds.), *Sediments: Chemistry and Toxicity of In-Place Pollutants*. Lewis Publishers, Inc., pp. 265–348.
- Hatch, W.R., Ott, W.L., 1968. Determination of sub-microgram quantities of mercury by atomic absorption spectroscopy. *Analytical Chemistry* 40, 1085–1087.
- Haynes, D.D., Toohey, D., Clarke, D., Marney, D., 1995. Temporal and spatial variation in concentrations of trace metals in coastal sediments from the Ninety Mile Beach, Victoria, Australia. *Marine Pollution Bulletin* 30, 414–418.
- Ismail, A., 1993. Heavy metal concentrations in sediments off Bintulu, Malaysia. *Marine Pollution Bulletin* 26, 706–707.
- Knauer, G.A., 1976. Immediate industrial effects on sediment mercury concentrations in a clean coastal environment. *Marine Pollution Bulletin* 7, 112–115.
- Knauer, G.A., 1977. Immediate industrial effects on sediment metals in a clean coastal environment. *Marine Pollution Bulletin* 8, 249–254.
- Legorburu, I., Canton, L., 1991. Heavy metal concentrations in littoral sediments from Pasajes harbour, Spain. *Marine Pollution Bulletin* 24, 462–464.
- Maata, M., Koshy, K., 2001. A study on tributyltin contamination of marine sediments in the major ports of Fiji. *South Pacific Journal of Natural Science* 19, 1–4.
- Moore, J.W., 1991. *Inorganic Contaminants of Surface Waters, Research and Monitoring Priorities*. Springer-Verlag, New York, 334p.
- Morrison, R.J., Gangaiya, P., Naqasima, M.R., Naidu, R., 1997. Trace metal studies in the Great Astrolabe Lagoon, Fiji, a pristine marine environment. *Marine Pollution Bulletin* 34, 353–356.
- Morrison, R.J., Narayan, S.P., Gangaiya, P., 2001. Trace metal studies in Laucala Bay, Suva, Fiji. *Marine Pollution Bulletin* 42, 397–404.
- Morrison, R.J., Brown, P.L., 2003. Trace metals in Fanga'uta Lagoon, Kingdom of Tonga. *Marine Pollution Bulletin* 46, 146–152.
- Naidu, S., Morrison, R.J., 1994. Contamination of Suva Harbour, Fiji. *Marine Pollution Bulletin* 29, 126–130.
- Nelson, D.W., Sommers, L.E., 1975. A rapid and accurate procedure for the estimation of organic carbon in soil. *Proceedings of the Indiana Academy of Sciences* 84, 456–462.
- Ogden Environmental and Energy Services Co., Inc. (Ogden), 1996. Remedial Investigation Report for Dry Cleaning Shop Site, USS Proteus Fire Fighting Training Area Site, and Orote landfill Site, NAVACTS Guam. Volume I (Part 1 of 2). CTO 0047 Comprehensive Long-Term Environmental Action Navy (CLEAN) for Pacific Division, Naval Facilities Engineering Command Pearl Harbor, Hawaii, February 1996.
- Schneider, P.M., Davey, S.B., 1995. Sediment contaminants off the coast of Sydney, Australia: A model for their distribution. *Marine Pollution Bulletin* 31, 262–272.
- Schafer, H.A., Bascom, W., 1976. Sludge in Santa Monica Bay. South California Coastal Water Research Project, Annual Report, El Segundo, pp. 77–82.
- Stainton, M.P., 1971. Syringe procedure for the transfer of nanogram quantities of mercury vapor for flameless atomic absorption spectrophotometry. *Analytical Chemistry* 43, 625–627.
- Stewart, C., de Mora, S.J., 1992. Elevated tri(*n*-butyl)tin concentrations in shellfish and sediments from Suva Harbour, Fiji. *Applied Organometallic Chemistry* 6, 507–512.
- UNEP (United Nations Environment Program), 1985. *GESAMP: Cadmium, Lead and Tin in the Marine Environment*. United Nations Environment Program: Regional Seas Reports and Studies No. 56, 90pp.
- USEPA (US Environmental Protection Agency), 1996. *SW-846 Test Methods for Evaluating Solid Waste Physical/Chemical Methods*. US Environmental Protection Agency, Office of Solid Waste and the National Technical Information Service, Springfield, Virginia, CD-ROM.