Trace metals in Fanga'uta Lagoon, Kingdom of Tonga

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Fanga'uta Lagoon is the most important water body on Tongatapu, the main island of the Tonga group. The Lagoon occupies a central position on Tongatapu (Fig. 1), and has played a major part in the life of the surrounding communities, with about 30,000 people residing within its catchment. The Lagoon is a food source for both fin (mainly mullet) and shellfish, and is widely used for recreation. Previous studies have investigated the ecology of the Lagoon (Zann et al., 1984), water quality (Naidu et al., 1991; Aalbersberg et al., 1992) and contamination by organochlorine compounds (Harrison et al., 1996).

The island of Tongatapu is a raised coral platform that has been extensively covered with andesite volcanic ash from two major events, dated at approximately 20,000 and 5000 y.b.p. (Cowie et al., 1991), giving relatively young and halloysite-dominated soils. The sediments in Fanga'uta Lagoon are, therefore, a mixture of reef carbonate materials and eroded halloysitic soil derived from terrestrial run-off.

In recent years, considerable community concern has been expressed about possible metal contamination of the lagoon by dumping (of batteries, car parts, metal containers, etc.), groundwater inflow from terrestrial sites of contamination (dumps, etc.), or discharge from industries surrounding the lagoon established during the 1990s. The only data available on metals is limited to metals in shellfish reported in Naidu et al. (1991), based on sampling in 1988. As part of a baseline study for the development of a management plan for the lagoon, biological, chemical and physical studies were undertaken in the lagoon in 1999. These studies showed that the lagoon was highly eutrophic (Morrison, 1999), and sediments contained pesticide residues (Chen et al., 1999). This paper summarises the findings of a study of sediments and shellfish in the lagoon for contamination by metals.

Eight sediment sampling sites within Fanga'uta Lagoon were selected (from the 30 sites being used in a wider lagoon study) on the basis of possible contamination from urban activities (sites 5, 7, 8, 11), agricultural runoff (1, 4, 30) and a relatively clean area (13) (Fig. 1). Sediment was also collected from Sopu, a coastal fringing reef site away from the lagoon where shellfish were available for collection. Sediment samples were collected at each site by hand in acid-washed plastic bags. At each site, 5–6 scoops of surface (0–10 cm) material were collected, mixed in a plastic bag and a composite sub-sample of about 1 kg (wet weight) retained. The samples were subsampled using coning and quartering and the subsamples air-dried, with any large (>20 mm largest diameter) stones or shell fragments removed. The dried material was then ground to pass through a 250 μm sieve and stored in plastic bottles. All sampling, drying, grinding and sieving was completed using non-metallic equipment.

Soil samples were collected at three sites from which sediment run-off into the lagoon occurs (TON 1, 2, 3, Fig. 1). At each site composite samples were collected (0–10 cm) using a W-transect, with at least 12 subsamples being composited. After thorough mixing, each composite was subsampled to give a sample of about 1 kg. In the laboratory, the samples were treated in the same way as the sediments.

Shellfish samples were collected samples from three locations (between sites 3 and 6—Fanga'uta; site 16—Fanga Kakau; between sites 26–28—Vaini, Fig. 1) within the lagoon (i.e., sampling was undertaken in each of the main sectors of the lagoon), and from Sopu as a relatively unpolluted area where the same shellfish species were known to occur. Samples of *Gafarium tumidum* (Roeding) and *G. pectinatum* (L.) (most samples analysed were of the latter species) were collected in August, 1999. Following collection the samples were depurated in clean seawater for 24 h. Following depuration the samples were visually sized and then measured (length and breadth) with vernier calipers. The precision of the measurement was ±0.05 mm. The samples were then frozen and transported to the laboratory.

All analyses were carried out at the laboratories of the Australian Nuclear Science and Technology Organisation (ANSTO). Sediment samples, together with a certified reference material (NRCC Marine Sediment Reference Material No. PASC-1), were digested using a mixture of hydrofluoric, perchloric, hydrochloric and nitric acids, followed by analysis by inductively coupled plasma—optical emission spectrometry (ICP-OES—Ca, Mg, Fe, Al, K, Na, Sr, P) or inductively coupled plasma—mass spectrometry (ICP-MS—Cu, Pb, Zn, Ni,

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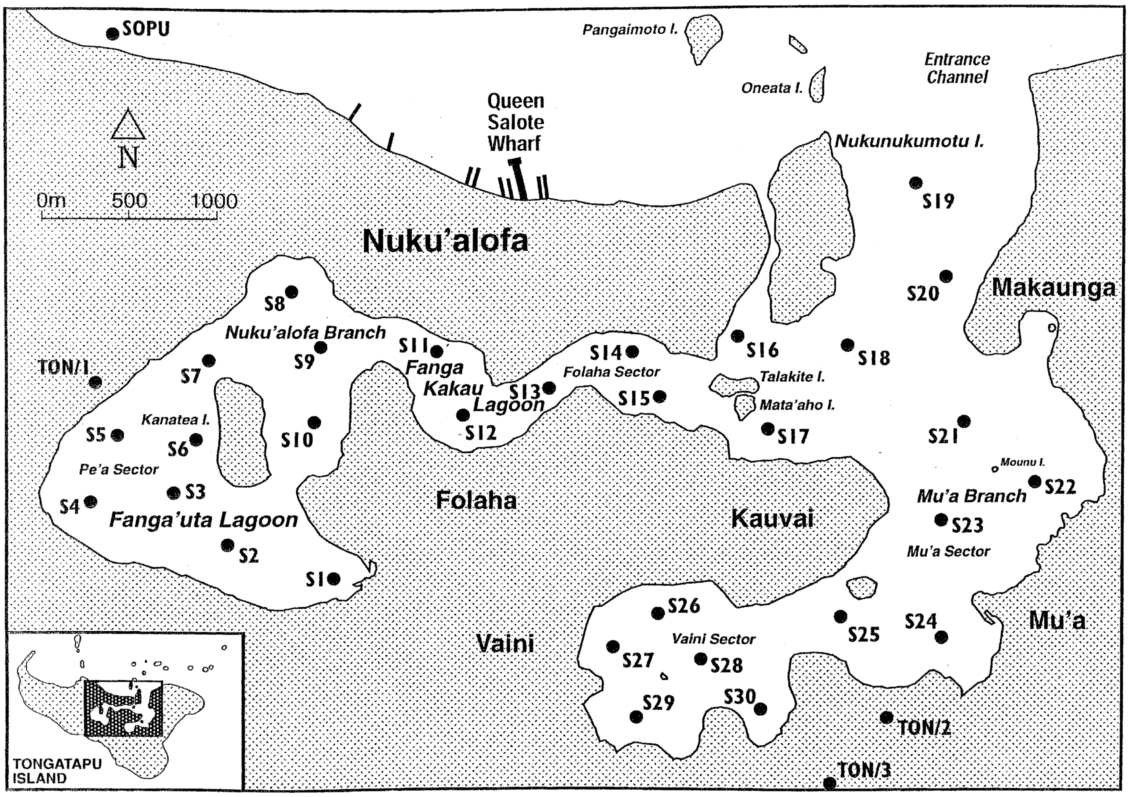

Fig. 1. Location of sampling sites around Fanga'uta Lagoon.

Cd, Mn, Sn As) or cold vapour—atomic absorption spectrophotometry (CV-AAS—Hg).

For shellfish, the soft tissue of each sample was separated from the shell and the samples oven-dried at <40 °C. Both the dry and wet weights of each sample were recorded. Each sample was then microwave digested using hydrogen peroxide/nitric acid/hydrofluoric acid (ANSTO method VEC-I-9-01-018) and analysed using either ICP-MS (for Cu, Ni, Zn, As, Mn, Sr, Cr, Se, Be, Ti, V, Co, Zr, Mo, Ag, Cd, Sn, Sb, Te, Cs, Ba, W, Hg, Tl, Pb, Th and U, ANSTO method VEC-I-9-03-007) or ICP AES (for Al, Bi, Ca, Cr, Fe, In, K, Li, Lu, Mg, Na, P, S, Sc and Y, ANSTO method VEC-I-9-03-002). The methods used were modifications of those contained in USEPA SW-846 (USEPA, 1998; methods 3051, 6020 and 6010A respectively). The modifications included minor variations in the proportions of sample/digestor or the internal standard used in the methods. A standard reference material (SRM-2976 from the National Institute of Standards and Technology) was also analysed (Table 3).

The results given in the tables include only those elements where the majority of samples were above the detection limits. In all other cases, the samples had concentrations below the instrumental detection limit. A statistical analysis of the data was completed using the Statistica package.

The analytical data for the quality control samples are given in Table 1 (for sediments) and in Table 3 (for shellfish). The agreement between the measured and expected concentrations in the standard reference materials for the elements with certified values was excellent, although Cu in shellfish could be improved. For those elements with reference values, the agreement between the measured and expected concentrations was, in general, satisfactory to excellent. All of the concentrations measured in the Tonga samples were of a similar magnitude to those cited for the standard reference materials.

The metal concentrations in sediments are summarised in Table 1. Detection limits of the methods used are also provided in Table 1. A correlation matrix, obtained using the Statistica computing package is given in Table 2.

The results show that the samples are free from any significant contamination by the metals studied. The sediment samples were dominated by calcium as would be expected from materials generated in or close to a reef environment. The sediments also contained significant concentrations of magnesium and sodium, with iron, aluminium and strontium also being present in amounts approaching 10,000 mg/kg. Strontium values mirrored those of Ca as would be expected in unpolluted sites.

For the trace metals that are commonly found in contaminated sites, the concentrations were all low with

Table 1
Fanga'uta sediments metals data

Sample ID	Ca (mg/kg)	Mg (mg/kg)	Fe (mg/kg)	Al (mg/kg)	K (mg/kg)	Na (mg/kg)	Sr (mg/kg)	P (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Ni (mg/kg)	Cd (mg/kg)	Mn (mg/kg)	Sn (mg/kg)	As (mg/kg)	Hg (mg/kg)
FANGA'UTA 1	183,000	15,000	14,100	16,700	1000	15,400	3130	190	13	3	25	11	<0.1	298	<0.5	3	0.02
FANGA'UTA 4	232,000	11,300	9810	11,700	650	11,000	4110	130	10	7	25	12	0.1	274	<0.5	3	0.02
FANGA'UTA 5	209,000	12,400	9250	11,100	850	14,100	3960	165	8	6	27	11	<0.1	238	<0.5	4	<0.005
FANGA'UTA 7	234,000	9190	6920	7510	<500	8650	3020	160	7	8	25	13	<0.1	199	<0.5	2	0.04
FANGA'UTA 8	223,000	10,300	9950	10,900	700	11,500	3450	200	10	6	26	12	<0.1	208	<0.5	3	0.02
FANGA'UTA 11	161,000	15,500	15,800	19,400	1200	20,500	2960	380	15	4	38	12	<0.1	232	<0.5	8	0.02
FANGA'UTA 13	288,000	12,900	4680	5140	<500	7720	4760	225	9	3	13	12	<0.1	106	<0.5	4	0.02
FANGA'UTA 30	189,000	13,000	15,600	17,300	1050	15,900	2420	450	14	3	30	14	<0.1	458	<0.5	13	0.02
TON/1	10,300	4050	95,500	87,000	2700	1130	144	2030	164	9	187	24	0.7	3300	2	13	0.02
TON/2	14,400	3990	103,000	92,500	3650	1010	273	5310	163	31	208	25	0.9	3850	17.7	19	0.06
TON/3	7440	3590	114,000	97,000	2850	960	99	1470	180	6	187	24	0.9	4550	1.2	9	0.06
SOPU	351,500	19,150	1550	1355	244	6765	4535	272	2	<1	6	<2	0.1	27	0.6	8	0.10
PASC-1 reference material	20,500	14,000	42,000	56,000	12,000	31,500	283	935	360	385	805	39	2.4	354	32.2	177	4.2
Certified value	20,890	14,578	48,668	64,747	12,447	32,645	277 ±11	1109	452 ±16	404 ±20	824 ±22	44.1 ±2.0	2.38 ±0.2	470 ±12	41.1 ±3.1	211 ±11	4.57 ±0.16
Method	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-OES	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	CV-AAS
Detection limit	50	20	100	100	500	50	1	30	2	1	5	2	0.1	0.5	0.5	1	0.005

Table 2
Correlation matrix for Fanga'uta sediments data

	Ca	Mg	Fe	Al	K	Na	Sr	P	Cu	Pb	Zn	Ni	Cd	Mn	Sn	As	Hg
Ca	1																
	$p = –$																
Mg	0.788	1															
	$p = 0.004$	$p = –$															
Fe	−0.9628	−0.8858	1														
	$p = 0.000$	$p = 0.000$	$p = –$														
Al	−0.9725	−0.8734	0.9987	1													
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = –$													
K	−0.9553	−0.7051	0.9102	0.9245	1												
	$p = 0.000$	$p = 0.015$	$p = 0.000$	$p = 0.000$	$p = –$												
Na	0.6407	0.9355	−0.804	−0.7854	−0.554	1											
	$p = 0.034$	$p = 0.000$	$p = 0.003$	$p = 0.004$	$p = 0.077$	$p = –$											
Sr	0.9701	0.8201	−0.941	−0.9475	−0.893	0.6645	1										
	$p = 0.000$	$p = 0.002$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.026$	$p = –$										
P	−0.7616	−0.7115	0.7876	0.7991	0.8226	−0.6609	−0.7435	1									
	$p = 0.006$	$p = 0.014$	$p = 0.004$	$p = 0.003$	$p = 0.002$	$p = 0.027$	$p = 0.009$	$p = –$									
Cu	−0.9523	−0.8995	0.9975	0.9959	0.8914	−0.8312	−0.9312	0.7815	1								
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.002$	$p = 0.000$	$p = 0.005$	$p = –$								
Pb	−0.5476	−0.6124	0.5789	0.5892	0.638	−0.5616	−0.5342	0.9329	0.5723	1							
	$p = 0.081$	$p = 0.045$	$p = 0.062$	$p = 0.056$	$p = 0.035$	$p = 0.072$	$p = 0.090$	$p = 0.000$	$p = 0.066$	$p = –$							
Zn	−0.9616	−0.8953	0.9914	0.9941	0.9176	−0.8098	−0.939	0.8425	0.9921	0.6564	1						
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.003$	$p = 0.000$	$p = 0.001$	$p = 0.000$	$p = 0.028$	$p = –$						
Ni	−0.9335	−0.9182	0.9823	0.9818	0.874	−0.8434	−0.9417	0.8262	0.9858	0.6336	0.9882	1					
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.001$	$p = 0.000$	$p = 0.002$	$p = 0.000$	$p = 0.036$	$p = 0.000$	$p = –$					
Cd	−0.922	−0.9094	0.9841	0.9809	0.8884	−0.8486	−0.8913	0.8141	0.9838	0.6448	0.9818	0.9738	1				
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.001$	$p = 0.000$	$p = 0.002$	$p = 0.000$	$p = 0.032$	$p = 0.000$	$p = 0.000$	$p = –$				
Mn	−0.9433	−0.8968	0.9964	0.9911	0.8901	−0.8225	−0.9261	0.7745	0.9925	0.5728	0.9816	0.9771	0.9858	1			
	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = 0.002$	$p = 0.000$	$p = 0.005$	$p = 0.000$	$p = 0.066$	$p = 0.000$	$p = 0.000$	$p = 0.000$	$p = –$			
Sn	−0.5965	−0.5766	0.6266	0.638	0.6999	−0.5452	−0.5761	0.9679	0.6154	0.9759	0.6918	0.6693	0.6741	0.6192	1		
	$p = 0.053$	$p = 0.063$	$p = 0.039$	$p = 0.035$	$p = 0.017$	$p = 0.083$	$p = 0.064$	$p = 0.000$	$p = 0.044$	$p = 0.000$	$p = 0.018$	$p = 0.024$	$p = 0.023$	$p = 0.042$	$p = –$		
As	−0.7662	−0.5544	0.7306	0.7503	0.8184	−0.4394	−0.7799	0.8465	0.7183	0.6712	0.7681	0.7845	0.7032	0.7052	0.7558	1	
	$p = 0.006$	$p = 0.077$	$p = 0.011$	$p = 0.008$	$p = 0.002$	$p = 0.176$	$p = 0.005$	$p = 0.001$	$p = 0.013$	$p = 0.024$	$p = 0.006$	$p = 0.004$	$p = 0.016$	$p = 0.015$	$p = 0.007$	$p = –$	
Hg	−0.5976	−0.6861	0.6929	0.6759	0.5326	−0.6526	−0.6745	0.6527	0.6736	0.5891	0.6737	0.707	0.7161	0.7219	0.6148	0.4728	1
	$p = 0.052$	$p = 0.020$	$p = 0.018$	$p = 0.022$	$p = 0.092$	$p = 0.030$	$p = 0.023$	$p = 0.029$	$p = 0.023$	$p = 0.057$	$p = 0.023$	$p = 0.015$	$p = 0.013$	$p = 0.012$	$p = 0.044$	$p = 0.142$	$p = –$

Marked correlations are significant at $p < 0.05000$.

Sn not being detected in any sediment, Cd in only one sample (at a value just above the detection limit), and Hg being detected at very low concentrations. Copper was found at values above 10 mg/kg at only three sites (1, 11 and 30) where higher levels of Fe and Al were identified indicating that the Cu is probably associated with soil erosion (see comments on soils below). Lead concentrations were low in all sediments. Zinc, Ni and As concentrations were in the range normally found for natural (unpolluted) sediments (Chester, 1990).

The soil samples, as expected, show a different pattern of element distribution with Fe and Al being dominant and Ca being present in lower concentrations (Table 1). Since these materials were derived from andesitic ash, the trace metal concentrations were generally higher than in the sediments.

The patterns of sediment elemental composition are clearly shown in Table 2. Strong positive correlations were found for Ca/Sr; Fe with Al, Cu, Zn, Ni, Cd, Mn; Al with Cu, Zn, Ni, Cd, Mn; Cu with Zn, Ni, Cd, Mn; Zn with Ni, Cd, Mn; Ni with Cd and Mn, and Cd with Mn. Strong negative correlations were noted between Ca and Al, Fe, K, Cu and Zn. There are one or two interesting additional points to note in the data. There was a strong positive correlation between Sn with P and Pb. The association of Sn and Pb is commonly found, and there is often a strong correlation between Pb and P in volcanic soils in Pacific Island soils (Norrish and Rosser, 1983) due to formation of plumbogummite minerals. The second point is that relatively high concentrations of Pb and Sn were found for the soil sample TON/2. One possible explanation for the Pb could be the proximity to the main road, but one would expect a similar situation at TON/1. TON/2 also had a much higher P concentration than any other sample, and the inter-relationship P/Pb/Sn noted above shows a consistent pattern; the relatively high Pb and Sn concentrations may be a consequence of different composition of the andesitic parent material at this site.

Over 80 individual shellfish were analysed. The results of the laboratory analyses (as concentrations per unit dry weight) are summarised in Tables 3 and 4. Overall, the trace metal concentrations were relatively low and indicated no specific health risks. For all the Tonga samples, the concentrations of Pb, Sn, Hg and Cd were found to be below the detection limits—these vary slightly due to the different weights of individual specimens, but are generally <2 mg/kg dry weight. These values indicated no contamination of shellfish by these elements. The values for As ranged from 4–80 mg/kg dry weight, with very few values >50 mg/kg. These values were in a similar range to those found for As in *Anadara* sp. in Fiji's Great Astrolabe lagoon, a pristine marine area (Morrison et al., 1997).

A study of trace metals in shellfish in Fanga'uta Lagoon was carried out in 1988 (Naidu et al., 1991). While no detailed comparison can be made with the results of that study as the data were reported in terms of wet weights, the data appear to be similar. Assuming a wet:dry weight ratio of 10:1, the 1988 data convert to average values of Pb < 5 mg/kg, Cd < 1 mg/kg, Hg < 1 mg/kg, Cu 55 mg/kg, very similar to the results of the present study.

A summary of the main features of the results of the present study and some trends can be seen in Table 3 (median concentrations) and Table 4 (some trends) respectively. In general, the Fanga'uta samples had the highest levels of trace elements (Cu, Ni, As, Sr, Li, Al and Fe) as well as some major elements (Ca, Mg and Na). In particular, Cu, Sr, Li, Al, Ca, Mg and Na were relatively high in these samples. Of the trace metals usually considered a potential problem, the highest values obtained (Cu at 100–120 mg/kg), however, were not high enough to indicate any significant health problem (NSW Health, 2001). In contrast, the Mn concentrations were relatively low in the Fanga'uta samples. Further, the concentrations of Zn found in all lagoon samples were similar. Additionally, the concentrations of K, P and S samples were similar in all samples.

In general, the concentrations of Zn found in the samples from Sopu were higher than those found in samples from the lagoon. The concentration of As in these samples is also relatively high. Correlations between elements in shellfish were examined to assess if variations were of natural or anthropogenic origin. The concentrations of Mn and P, Sr and Al, Sr and Ca, Sr and Mg, K and S as well as Mg and Na were correlated at each sampling site. Of these correlations, Sr and Ca/Mg and Na were always highly positively correlated. Strontium and Ca are chemically similar and Mg and Na are the two main cationic constituents of sea water. All of the significant correlations found in this study appear to be natural in origin, no evidence of anthropogenic sources of metals was found.

The results of this investigation showed that there were no significant metal contamination problems in the Fanga'uta Lagoon. Concentrations of metals in sediments were in the range normally found for unpolluted sites. In addition, inter-element correlations indicated that the variations in concentrations could usually be explained by influx of terrestrial materials derived from surrounding soils.

Over 80 shellfish samples from the Fanga'uta Lagoon and nearby waters were analysed for trace metals. No major pollution or contamination problems have been identified from the results. For the trace metals expected to cause the major health problems, concentrations were either below the detection limits (generally <2 mg/kg dry weight) or were similar to values for shellfish in uncontaminated areas elsewhere. The results of this study are generally comparable with those of a previous study in 1988 (Naidu et al., 1991). Given the rapidly

Table 3
Summary table for Tongatapu shellfish metal concentrations (median concentrations and range ($n = 20$ for each location) (mg/kg, dry weight))

Location	Cu	Ni	Zn	As	Mn	Sr	Li	Se	Al	Ca	Fe	K	Mg	Na	P	S
Fanga Kakau	15 (12–53)	6.9 (<3–13)	43 (21–91)	24 (16–62)	79 (2.9–350)	52 (38–110)	0.9 (0.5–1.6)	3 (<1–9)	29.3 (12–70)	3470 (2680–9350)	411 (210–820)	9690 (7980–26,300)	7560 (5330–15,800)	54,400 (3970–117,000)	6350 (4830–20,400)	19,500 (17,800–22,500)
Fanga'uta	65 (27–120)	9.9 (<7–20)	41 (18–140)	38 (25–80)	4.0 (2.3–17)	93 (73–170)	1.7 (1.0–9.0)	3 (<2–40)	58.4 (32–350)	6280 (5100–15800)	769 (400–3300)	10,700 (8260–13,500)	11,600 (9580–16,600)	89,300 (70,900–128,000)	5570 (4000–6980)	21,700 (18,800–23,700)
Vaini	11 (2.0–14)	8.4 (0.9–14)	40 (8.7–340)	17 (3.4–60)	39 (5.5–690)	64 (11–110)	1.1 (0.8–4.3)	3 (1.4–5)	43.1 (20–110)	4450 (2910–8500)	716 (400–2500)	10,850 (9019–13,900)	8445 (7260–14,300)	60,250 (48,400–109,000)	6320 (5310–8800)	19,950 (18,100–25,400)
Sopu	9.0 (5.6–12)	7.4 (3.6–11)	58 (24–110)	42 (20–68)	4.5 (2.4–15)	61 (35–190)	0.6 (0.4–12)	4 (2–20)	54.6 (10–150)	4415 (2800–15,800)	398 (99–780)	8935 (7130–12,400)	5390 (4580–8710)	34,900 (23,000–58,000)	7440 (5970–15,600)	20,600 (14,200–23,800)
Reference material NIST SRM2976																
Measured value	6.7 ±0.6	<1	137±15	13±1	35±3	62±6	1.8 ±1.6	<2	125±3	6470 ±40	170±7	9700 ±140	4530 ±70	32,300 ±600	7190 ±40	14,700 ±200
Certified value	4.02 ±0.33	0.93 ±0.12	137±13	13.3 ±1.8	33±2*	93±2*	No data	1.87 ±0.15	134±34	7600 ±300*	171.0 ±4.9	9700 ±500*	5300 ±500*	35,000 ±1000*	8300*	19,000*

*Value not certified.

Table 4
Correlation table for Fanga'uta shellfish metals data

Element 1	Element 2	Sopu	Fanga Kakau	Fanga'uta	Vaini
Mn	P	−0.476	0.573	0.617	−0.479
Sr	Al	0.597	0.593	0.692	0.508
Sr	Ca	0.927	0.852	0.851	0.831
Sr	Mg	0.856	0.908	0.518	0.831
K	S	0.610	0.986	0.780	0.723
Na	Mg	0.901	0.995	0.936	0.981

Correlation table: only the correlations which are significant for all four sites are included.

changing environment around the Fanga'uta Lagoon due to increasing urbanisation and industrialisation, such studies should be carried out on a regular basis (every two years) to ensure that any changes are recognised quickly and appropriate action is taken to address any problems. While this study has determined that no major health problems arise from metals in shellfish consumed by the local community, other health problems such as microbiological contamination should be investigated as soon as possible and on a regular basis.

The management plan developed for Fanga'uta Lagoon must ensure that metal contamination of the lagoon is prevented so that the good sediment quality can be maintained to avoid any possible transfer of contaminants to shellfish or other marine resources that are likely to be consumed by the local population.

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