

An Evaluation of Trace Metal Concentration in Terrestrial and Aquatic Environments near Artigas Antarctic Scientific Base (King George Island, Maritime Antarctica)

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Received: 19 July 2018 / Accepted: 20 November 2018 / Published online: 3 December 2018
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Abstract An evaluation of the concentration of metals in terrestrial and aquatic environments near Artigas Antarctic Scientific Base was assessed. Granulometric characteristics, total organic matter content, concentration of metals (Cd, Cr, Cu, Mn, Ni, Pb and Zn) and metalloid (As) in soil, marine and freshwater sediments were determined. The geoaccumulation index (Igeo) was used in order to analyse the contamination magnitude. Samples were collected in summer 2015–2016 covering 31 sampling stations; 15 terrestrial/soil stations (T0–T14) were placed considering the distribution of Artigas Base buildings and the septic tanks' location. Eleven freshwater stations were placed along the three meltwater streams near Artigas Base (S0–S10), and two in Uruguay Lake (L1 and L2). Finally, three marine

stations in Maxwell Bay were placed one near the Artigas Base (AB) and two far from it in North Cove (NC1, NC2). Some of the terrestrial stations (T2, T10, T11 and T13) presented the highest concentration of metals and Igeo values, which was associated to anthropic activities. Highest metal levels were related to fuel storage and handling, but also, with sewage release and the presence of old leaded paint residues. These polluted sites were limited to a restricted area of Artigas Base, not affecting surrounding environments. Concentrations of the analysed metals in unpolluted sites had the same order of magnitude recorded in other unpolluted areas of the Fildes Peninsula and other Antarctic regions.

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Keywords Human impact · Heavy metals · Sediment · Soil · Antarctica

1 Introduction

Antarctica is the remotest continent on the planet and a symbol of the last great wilderness, often described as the last pristine environment on Earth (Bargagli 2008; Cowan et al. 2011). Unfortunately, the 'pristine' concept is no longer accurate as impacts from human activities over the past few centuries have had cascading effects on the Antarctic ecosystem with important consequences on the environment, some of them irreversible (Tin et al. 2009, 2014). In particular, the increase of different human activities as exploitation of natural resources (e.g. fisheries), tourism and navigation, in

addition to the scientific stations established since the beginning of the twentieth century, have caused different impacts on the Antarctic environment. The introduction of non-indigenous species (Tin et al. 2009, 2014; Cowan et al. 2011; Braun et al. 2012, 2014), alterations in soil quality as consequences of waste and sewage management and construction activities can be mentioned among other impacts detected in the Antarctic environment (Tin et al. 2009, 2014; Ribeiro et al. 2011; Braun et al. 2014; Amaro et al. 2015; Tort et al. 2017).

In agreement with the Antarctic Treaty (SCAR 1959) that encourages the protection of the Antarctic environment, Uruguay as a signing nation is committed to design and implement environmental monitoring plans for Antarctic activities. To evaluate environmental alterations, the use of physical and chemical proxies, the consideration of standards and the determination of baseline concentrations has been suggested (Peter et al. 2008; Tin et al. 2009). In this sense, metals can be used as proxies of reference conditions and for inferring human-induced changes (Birch 2011; Du Du Laing 2011). These elements naturally occur in the earth crust. However, human activities have introduced high loads to the environment which can accumulate in sediments, and are potentially toxic to biota with direct consequences on biological processes (Luoma and Rainbow 2008; Wuana and Okieimen 2011).

The presence of heavy metals in the Antarctic continent is an emerging issue, considering both local and remote anthropogenic activities probably contributing to their presence in the area. However, high metal concentrations can also be attributed to the natural geological composition, i.e. as a result of the glacial erosion of volcanic rocks (Santos et al. 2005; Ribeiro et al. 2011; Trevizani et al. 2016; Romaniuk et al. 2018). There are several studies regarding metal contamination in the Antarctic environment, particularly in the South Shetlands Islands (Santos et al. 2005; Ribeiro et al. 2011; Amaro et al. 2015; Szopińska et al. 2016). These studies recorded high metal concentrations associated with anthropic activities, which in some occasions may have adverse effects on Antarctic fauna (Santos et al. 2005; Ribeiro et al. 2011; Lu et al. 2012; Alfonso et al. 2015).

King George Island is located 120 km away from the Antarctic continent. Its southern region, Fildes Peninsula, is the largest ice-free area of the island with six permanent scientific stations built between 1968 and 1994, which makes this area an important logistic centre. Artigas Antarctic Scientific Base (from now on

Artigas Base) is the Uruguayan permanent scientific station located in Fildes Peninsula. Environmental impacts such as enteric viruses and faecal sterols associated to wastewater and domestic sewage inputs have been recently reported in Artigas Base (Tort et al. 2017). Also, hydrocarbon pollution linked to diesel fuel and organic residue combustion, fuel storage and boat traffic has been reported near the service area and the boat storeroom (Rodríguez et al. 2018). However, none comprehensive studies about the potential sources of metals in terrestrial and aquatic environments near Artigas Base have been previously performed. The aim of this study was to evaluate the concentration of metals in surficial soil, marine and freshwater sediments near Artigas Base. Additionally, we aimed to link their distribution to natural and/or anthropogenic inputs and to physico-chemical characteristics (e.g. grain size and organic matter content) of soil and sediments. Furthermore, if anthropic impact is detected, quantify the magnitude of the impact with the geoaccumulation index.

2 Material and Methods

2.1 Study Area

Artigas Base is located in Fildes Peninsula of King George Island, the biggest island of the South Shetland Archipelago (62° 11' 4" S; 58° 51' 7" W). This island has a relatively mild climate with a strong marine influence. As a consequence of the retraction of Collins Glacier towards the north, proglacial and paraglacial forms predominate in the north of Fildes Peninsula, where proglacial forms are still controlled directly by the action of the glacier (Vieira et al. 2015). Artigas Base is the scientific station nearest Collins Glacier, and is placed on Holocene raised beaches (Michel et al. 2014) with coarse sediments to rounded pebble-sized stones (López-Martínez et al. 2016) (Fig. 1). Artigas Base has 11 buildings, and a maximum capacity of 65 people, which is reached in summer. Its main constructions/buildings are the AINA building with dorms (II), the dining building (VIII) and the service area (X) where generators and fuel tanks are located (Fig. 1). For the storage of wastewater and domestic effluents, there are eight septic tanks and a grease tank, all located in areas close to the buildings. There is also a fuel storage area with recent modifications (where old iron fuel tanks were replaced by new stainless steel ones with

adaptations to avoid fuel spills). In the surrounding areas, there are several aquatic systems as lakes (proglacial and mixed), meltwater streams and the coastal zone of Maxwell Bay. Three meltwater streams from a proglacial lake run across Artigas Base area, which in this study were named AINA stream, Kitchen stream and Tanks stream (Fig. 1). Uruguay Lake is Artigas Base's freshwater source, which is a mixed lake of 69,781 m² located 624 m away from Collins Glacier (Alfonso et al. 2015) (Fig. 1). Maxwell Bay is used as a navigation route, with an increasing maritime traffic (Peter et al. 2008).

2.2 Sample Collection

Surficial sediment and soil samples were collected in summer 2015–2016 covering 31 sampling stations; 15 terrestrial/soil stations (T0–T14) were placed considering the distribution of Artigas Base buildings and the septic tanks' location; 11 stations were placed along the three meltwater streams (S0–S10) and 2 in Uruguay Lake (L1 and L2). Finally, three marine stations were placed in Maxwell Bay, one in front of Artigas Base (AB) and two in North Cove (NC1, NC2) (Fig. 1). Soil samples were collected near the septic tanks (T1, T2, T3, T5, T6, T7, T9, T10) and downhill (T4, T8, T14). Additionally, 3 sites were located near the fuel tanks (T11, T12, T13) (Fig. 1). For terrestrial stations, a control site without anthropic impact was identified as T0, located 200 m away from the last building. Along the 3

meltwater streams, 7 sites were located downhill the septic tanks (S1, S2, S3, S5–9, S6, S7, S10), and downstream (S4, S8, S11) (Fig. 1). For these sites, the control station (S0) was located upstream of AINA meltwater stream. In Uruguay Lake, 2 sediment samples were collected, 1 next to the water pump (L1) and the other one 20 m away (L2) (Fig. 1). Marine sediments were collected at 28 m depth, in front of the AINA meltwater stream mouth (AB), the only meltwater stream that reaches Maxwell Bay (Fig. 1). The other 2 marine sites were located in North Cove (where there is no human influence or meltwater stream), between 20 and 30 m depth (NC1, NC2) (Fig. 1). Surface soil samples were taken with a plastic spatula, while lake and marine surface sediments were collected with care from the centre of a van Veen grab (0.05 m²). All samples were stored in plastic bags at –20 °C until analysis.

2.3 Laboratory Analyses

Granulometric fractions were determined by the standard sieve method described in Suguio (1973) and then classified by the Wentworth scale (Wentworth 1922). Total organic matter (TOM) was determined by the loss on ignition method as described in Byers et al. (1978). The concentration of As, Cd, Cr, Cu, Mn, Ni, Pb and Zn was determined following the partial digestion method USEPA 3050B (USEPA 1996). This method consists of a strong acid digestion with HNO₃ and the addition of H₂O₂ to eliminate organic matter. The solution was then

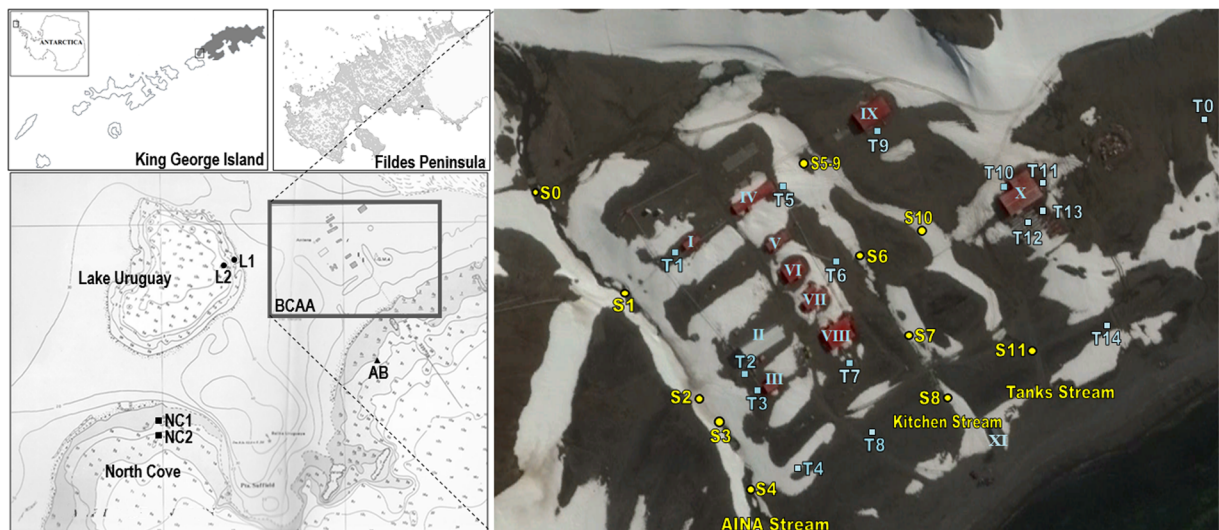


Fig. 1 Artigas Base location and sample stations. L (lake), S (meltwater streams), T (terrestrial) and marine (NC and AB). I–XI are the different buildings of the base.

filtered and diluted to be analysed with an inductively coupled plasma-optical emission spectroscopy (ICP-OES - Varian Vista 710ES). Accuracy of the procedure was determined by analysing the certificated reference material SS-2 EnviroMAT.

In order to evaluate if the analysed sediments were impacted, the geoaccumulation index (Igeo) (Müller 1986) was used, and calculated as follows:

$$I_{geo} = \log_2 \left[\frac{C_n}{B_n \times 1.5} \right]$$

where C_n is the metal concentration found for metal 'n'. B_n is the basal concentration for metal 'n' and 1.5 is used to minimise possible lithogenic effects.

In the present study, basal concentrations of the different metals were the average concentration found by Lu et al. (2012) and Abakumov et al. (2017), except for Cr. Both mentioned studies analysed trace metal concentration in pristine soils of Fildes Peninsula.

Due to the difference in the magnitude of Cr concentration found by Lu et al. (2012) and Abakumov et al. (2017), compared to the one found in the present study, just for this element basal concentration considered to calculate the index was the one found in T0.

In addition, to classify the sediment quality of the analysed sites, the seven contamination classes proposed by Müller (1986) were used according to the obtained Igeo value (Table 1).

2.4 Statistical Analyses

Metal concentrations in soils and sediments are largely controlled by particle size (Birch 2017). In order to avoid the effect of grain size variability on metal concentration, data was size-normalised (< 63 µm). Cluster

analysis helps to reveal different regions that may give a better understanding of the sources, possibly natural and/or anthropogenic (Alkarkhi et al. 2009; Birch 2017). In this sense, to identify groups with similar levels of metals, a cluster analysis was performed considering the grain size-normalised concentrations of As, Cr, Cu, Mn, Ni, Pb and Zn. Data was previously standardised, Euclidean distance was used and groups defined by Ward's Method. Additionally, to infer associations between organic matter and grain size, Spearman correlation coefficient was used. Statistical analyses were performed using the free software PAST 3.21.

3 Results

3.1 Grain Size and Total Organic Matter

Sediment varied greatly in size among the studied sites, where sands and gravels were the predominant granulometric fractions. Among terrestrial/soil stations, there was a dominance of coarse fractions. T0, T2, T3, T4, T7 and T8 presented a dominance of gravel that ranged between 51.10 and 94.10% (Fig. 2). In stations T5, T6, T10 and T13, proportion of gravel and coarse sand was similar, gravel ranging between 41.14 and 46.53% and coarse sand between 36.23 and 46.60%. Also, in stations T1, T9, and T11, coarse sand was the predominant grain size, varying from 44.81 to 75.99% (Fig. 2). T14 was the station with the highest mud content (17.70%) (Fig. 2). Meltwater stream sediments were also dominated by coarse fractions. In stations S0, S2, S3, S4, S7 and S8, gravel was the dominant grain size, representing between 45.10 and 73.29%, while in stations S5–9, S6, S10 and S11, coarse sand predominated with values ranging from 55.94 to 66.40% (Fig. 2). Station S1 showed similar percentages of gravel (34.80%) and mud (32.71%) (Fig. 2). AINA stream was the meltwater stream with the highest mud content, ranging between 12.76 and 32.71%, while in Kitchen and Tanks streams mud content ranged from 1.96 to 6.06%. Lake stations showed a predominance of mud and fine sand (21.54 and 42.90% for L1, and 43.92 and 37.48% for L2, of mud and fine sand, respectively) (Fig. 2). Additionally, in marine stations, there was a prevalence of sandy fractions (coarse and medium sands). In AB station, coarse sand predominated (47.92%) followed by gravel (24.33%). In contrast, North Cove stations showed a predominance of coarse

Table 1 Classification levels for the Geoaccumulation Index values Müller (1986)

Igeo value	Class	Sediment quality
< 0	0	Unpolluted
0–1	1	Unpolluted to moderately polluted
1–2	2	Moderately polluted
2–3	3	Moderately to highly polluted
3–4	4	Highly polluted
4–5	5	Highly polluted to severely polluted
> 5	6	Severely polluted

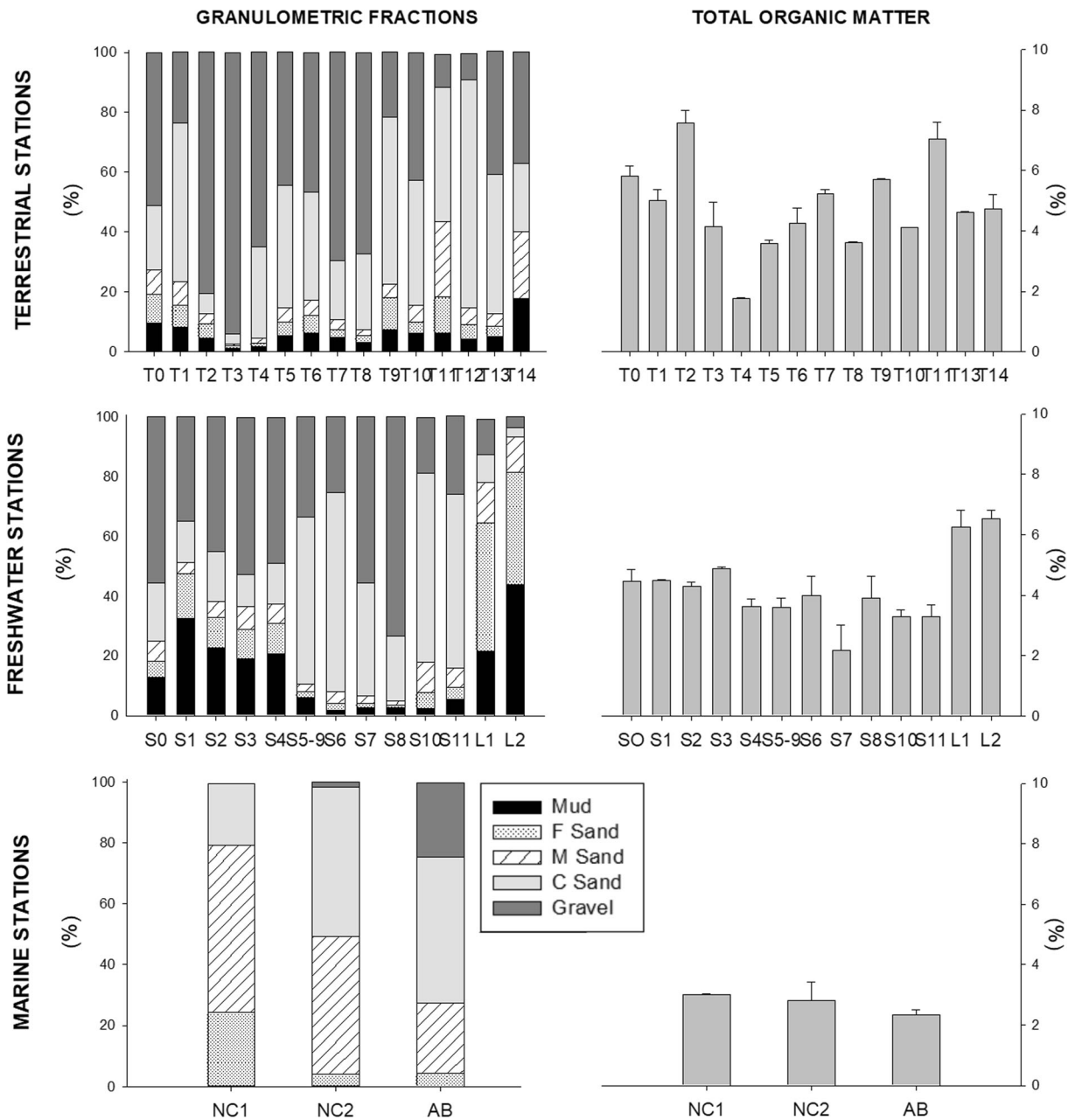


Fig. 2 Grain size and total organic matter content (%) for terrestrial, freshwater and marine stations

and medium sand with values from 20.34 to 49.12% and from 45.30 to 49.12%, for NC1 and NC2, respectively (Fig. 2).

TOM in terrestrial stations ranged between $1.8 \pm 0.1\%$ and $7.6 \pm 0.4\%$ (Fig. 2). The highest TOM content was recorded in stations T2 and T11 (7.6 and 7.0, respectively), whereas the lowest content corresponds to station T4 (1.76%) (Fig. 2). Also, TOM showed little

variation within the different aquatic systems. In this sense, in meltwater streams, TOM values presented an average of $3.8 \pm 0.7\%$ (Fig. 2). Lake sediments showed an average TOM of $6.4 \pm 0.2\%$ while marine sediments presented the lowest values ($2.7 \pm 0.3\%$) (Fig. 2).

Spearman correlation coefficient between mud percentage and total organic matter was 0.62 ($n = 30$, $p < 0.01$).

3.2 Metal Concentrations

Average values obtained for the reference material lied within the range recommended by USEPA (1996) (Table 2). The exception was Cd which concentration was below the limit of detection of the method (0.683 mg/kg) for all samples.

Considering total concentrations in marine and freshwater sediments, all analysed metals presented values in the same order of magnitude (Table 3). However, terrestrial stations' metal values were more variable. Considering this, highest concentrations of Cr, Pb and Zn were found in stations T2, T10, T11 and T13 (Table 3).

Based on the dendrogram resulting from the cluster analysis (Fig. 3), two main clusters were identified, differentiating marine stations (NC1, NC2 and AB) from the others. Additionally, in the branch with the terrestrial and freshwater stations, two sub-branches were observed, one grouping terrestrial stations T2, T10, T11 and T13 (which presented the highest concentrations of Cr, Pb and Zn), and the other sub-branch with the rest of the terrestrial and freshwater stations (Fig. 3).

3.3 Geoaccumulation Index (Igeo)

Igeo results are presented in Table 4. In all analysed stations, Cu, Mn, and Ni Igeo values were 0. However, Igeo values calculated for As, Zn, Cr and Pb were more variable in the different matrices. In this sense, in terrestrial stations, Igeo presented similar trends than the metal concentration, with the highest values for stations T2, T10, T11 and T13 with values that ranged between moderately to highly polluted (1–3). In addition, As values were also higher than 0 in AINA stream sediments and all marine stations (Table 4).

4 Discussion

The predominance of coarse fractions (gravel and coarse sand) found in the present study is in agreement with the soil characteristics already determined in previous studies along Fildes Peninsula (Michel et al. 2014; López-Martínez et al. 2016). The highest total organic matter (TOM) content was observed in T2, which is located near a septic tank. This can be associated to the release of domestic effluents, considering the fact that overflowing was observed in that station. In the rest of the stations, TOM content is similar to values reported in other areas of the South Shetland Islands (e.g. Cury et al. 2014). Lake sediments presented higher TOM content than the meltwater streams; this could be a consequence of a well-developed microbial mat observed on the lake's surficial sediments.

As expected, a positive correlation was observed between TOM and fine-grained sediments. However, as metal concentrations usually increases as grain size decreases (Horowitz 1985), unexpected low correlations between fine-grained sediment and metal concentration were observed. This was also observed by Santos et al. (2005) near Ferraz Station, also located in King George Island, suggesting that high metal concentrations may be related to the proximity of the sources but not connected with soil/sediment fine grain size deposition. The same pattern was reported on hydrocarbon distribution in soil and meltwater stream sediments near Artigas Base (Rodríguez et al. 2018).

Total concentrations of Cu, Cr, Mn, Ni, Pb and Zn recorded in the present study for the different analysed matrices (soil, marine and freshwater sediments) were contrasted with concentrations reported in the literature for other Antarctic regions (Table 5). Comparative

Table 2 Assigned and obtained mean values for the certified reference material SS-2 EnviroMAT ($n = 4$)

	Reference (mg/kg)	Confidence (mg/kg)		Tolerance (mg/kg)		Obtained (mg/kg)
As	75	65	85	25	125	90 ± 12
Cd	2					2 ± 0
Cr	34	30	38	14	54	32 ± 2
Cu	191	182	200	139	243	170 ± 18
Mn	457	433	481	324	590	466 ± 85
Ni	54	50	58	33	75	48 ± 7
Pb	126	116	136	68	184	109 ± 15
Zn	467	444	490	337	597	462 ± 41

N/A not available

Table 3 Metalloid and heavy metals (As, Zn, Cu, Mn, Ni, Cr and Pb) concentrations ($\text{mg}\cdot\text{kg}^{-1}$) in soil, freshwater and marine stations near Artigas Base

Station		As	Zn	Cu	Mn	Ni	Cr	Pb
Soil	T0	3.29	53.80	56.11	590.33	7.23	6.98	2.98
	T1	3.67	130.04	57.73	557.53	4.28	26.13	13.32
	T2	4.02	106.28	85.08	652.97	3.62	21.46	61.95
	T3	2.99	48.24	47.47	429.04	3.55	2.96	3.99
	T4	2.25	44.23	33.37	344.75	3.73	3.35	3.23
	T5	3.04	66.22	47.31	521.92	5.98	17.35	8.69
	T6	4.36	50.75	55.42	535.43	3.78	7.64	9.32
	T7	3.69	97.15	67.10	535.52	4.13	20.57	10.52
	T8	3.55	43.00	56.41	409.63	3.86	3.93	4.56
	T9	2.98	47.87	46.05	527.77	6.77	6.45	2.79
	T10	20.98	435.56	82.97	494.97	7.91	22.83	28.39
	T11	2.54	375.54	65.10	423.22	13.63	35.01	59.06
	T13	4.75	231.75	54.81	492.50	6.12	22.92	31.23
	T14	3.07	49.50	54.96	587.06	8.98	7.73	3.44
Freshwater sediments	S0	10.16	49.04	65.81	610.90	6.91	7.81	4.68
	S1	12.56	57.24	72.06	672.55	6.50	7.42	5.60
	S2	12.39	52.03	63.48	638.33	7.30	7.42	5.29
	S3	12.99	56.45	70.73	674.01	7.22	6.54	4.80
	S4	11.14	53.08	62.90	631.81	7.67	6.97	4.28
	S5–9	5.71	59.41	60.58	671.79	3.62	3.28	4.47
	S6	3.53	77.06	77.90	615.57	2.68	2.90	5.10
	S7	3.54	77.56	73.58	547.13	3.78	3.91	5.59
	S8	5.35	65.46	57.95	422.15	5.56	3.83	4.88
	S10	3.10	54.46	50.02	466.74	3.26	3.25	3.61
	S11	3.06	54.36	46.97	420.10	3.56	3.72	4.48
Marine sediments	L1	3.91	45.50	55.32	400.94	4.06	3.36	3.01
	L2	4.42	57.76	50.47	606.47	4.12	4.53	2.95
	NC1	5.44	35.92	41.00	631.44	2.49	2.63	1.96
	NC2	4.88	33.26	31.36	790.43	2.46	2.46	2.00
	AB	5.07	42.51	38.90	704.48	4.08	4.90	2.33

T terrestrial/soil stations; freshwater stations: *S* stream, *L* lake; marine stations: *AB* Artigas Base, *NC* North Cove

analyses revealed that metal concentrations found in sediments of the aquatic systems near Artigas Base (surficial marine and freshwater sediments) were similar to values reported in unpolluted areas along the Fildes Peninsula and other Antarctic regions (Vodopivec et al. 2001; Santos et al. 2005; Negri et al. 2006; Ianni et al. 2010). Additionally, Igeo values for the analysed marine sediments and meltwater streams' sediments (< 0 , or slightly higher than 0) suggest unpolluted conditions. Therefore, the analysed aquatic systems can be assumed as unpolluted. Probably, metal concentrations registered

originate from natural sources and the observed variation between freshwater and marine sediments was related to differences in the mineral composition of soil and rocks. In this sense, high Cu and Zn content was already reported by Ribeiro et al. (2011), Alfonso et al. (2015), Trevizani et al. (2016), and Romaniuk et al. (2018). In all the previously mentioned studies, high concentration of these elements was associated to a mineralogical origin where basalt-andesite rocks predominate (Vieira et al. 2015; Hernández et al. 2018). Specifically, on Uruguay Lake, the sediments consist of

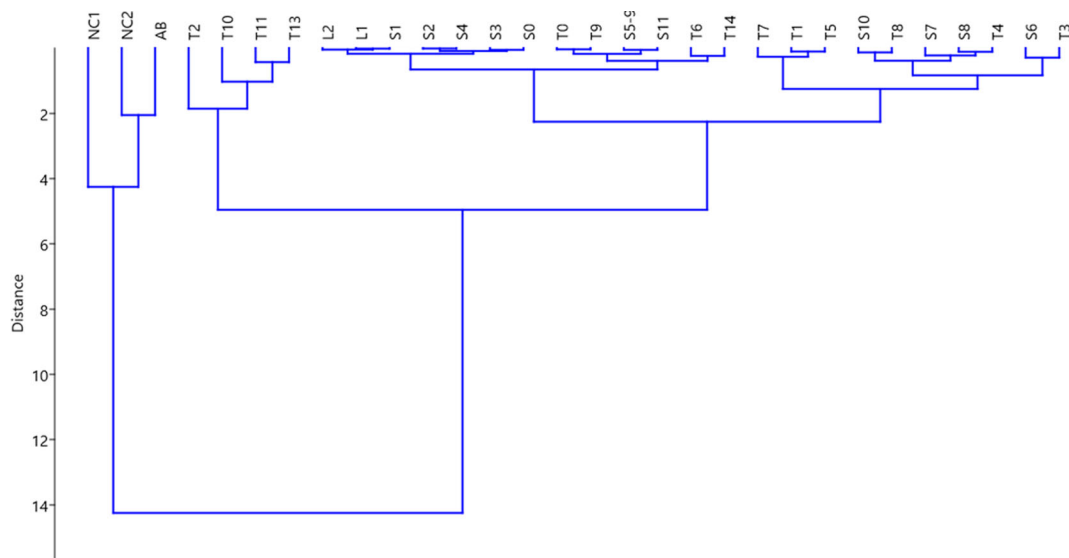


Fig. 3 Dendrogram based on all the analysed variables along the terrestrial, freshwater and marine environments near the BCAA

plagioclase (the most abundant phases), followed by zeolite, clinopyroxene, quartz, olivine, calcite and Fe-Ti oxides (magnetite, generally Ti-rich), with small amounts of clay and accessory minerals (Hernández et al. 2018).

On the other hand, despite As values found in AINA stream and marine stations are higher than in terrestrial stations and the other freshwater sediments, those values are still within natural range (Ribeiro et al. 2011; Amaro et al. 2015; Romaniuk et al. 2018). Some authors associate higher As concentrations to penguin dropping (Xie and Sun 2008), which can explain higher but natural concentrations of this element near to aquatic systems. Despite, the aim of the present work was not to assess the association between trace elements and the mineralogy of soils, differences observed between sites considered as unpolluted might be associated to distinctive mineral composition of soil and rocks as these are the terrigenous sources to the adjacent marine and freshwater sediments (Santos et al. 2005).

Metals in most of the terrestrial stations presented values within the same order of magnitude reported in the literature to other unpolluted area of the Fildes Peninsula and other unpolluted Antarctic regions. The exception was Cr that showed lower values (Table 3). However, the highest concentrations of Cr, Pb and Zn recorded in the stations located next to the septic tanks (T2 and T10) and the fuel tanks (T11 and T13) can be assumed as polluted levels. In these stations, the sediment content of Cr was between two and three times

higher than the average concentration found in unpolluted sites. In addition, Pb content was between five and ten times higher, and Zn content between two and seven times higher than levels found in unpolluted sites. These results are in agreement with previous studies (Krzyszowska 1993; Santos et al. 2005; Padeiro et al. 2016; Abakumov et al. 2017 and Romaniuk et al. 2018), in which high metal concentrations in Antarctic soils were associated to anthropic impact such as sewage effluents, landfills, paint residues, fuel storage and areas contaminated with fuel spills. In this sense, these metals are associated to different anthropic sources (i.e. Cr: colourants, metal structures; Pb: batteries, gasoline additives, paint, inks and pigments and fuel tanks; Zn: stainless steel, galvanisation, oils and paints) (Wuana and Okieimen 2011; Padeiro et al. 2016; Romaniuk et al. 2018). Furthermore, Santos et al. (2005) as well as Negri et al. (2006) associated sewage outfalls to the highest concentration of Cu, Zn and Cd in Antarctic soils. Considering that stations T11 and T13 are located near the fuel tanks, high metal concentrations could be associated to fuel handling. In station T2 located near the AINA building and the septic tank, high concentrations of Pb and other metals might be associated to old leaded paint (old paint traces were observed during analyses) as well as sewage release. Also, in station T10, sewage seemed to be the main source of metals. To infer the magnitude of the impact in the mentioned stations, Igeo seemed to be a good indicator. In this sense, stations T2, T10, T11 and T13 were classified

Table 4 Geoaccumulation index (Igeo) values for the analysed elements in the different matrices

Station		As	Zn	Cu	Mn	Ni	Cr	Pb
Soil	T0	-0.32	-0.38	-1.05	-0.67	-1.16	-0.59	-1.52
	T1	-0.16	0.89	-1.00	-0.76	-1.92	1.32	0.64
	T2	-0.03	0.60	-0.45	-0.53	-2.16	1.03	2.86
	T3	-0.46	-0.54	-1.29	-1.13	-2.19	-1.83	-1.10
	T4	-0.87	-0.67	-1.80	-1.45	-2.12	-1.65	-1.40
	T5	-0.44	-0.08	-1.29	-0.85	-1.44	0.72	0.02
	T6	0.09	-0.47	-1.06	-0.82	-2.10	-0.46	0.12
	T7	-0.15	0.47	-0.79	-0.82	-1.97	0.97	0.30
	T8	-0.21	-0.71	-1.04	-1.20	-2.07	-1.42	-0.91
	T9	-0.46	-0.55	-1.33	-0.84	-1.26	-0.70	-1.61
	T10	<u>2.35</u>	<u>2.63</u>	-0.48	-0.93	-1.03	<u>1.12</u>	<u>1.73</u>
	T11	-0.70	<u>2.42</u>	-0.83	-1.15	-0.25	<u>1.74</u>	<u>2.79</u>
	T13	0.21	<u>1.72</u>	-1.08	-0.94	-1.40	<u>1.13</u>	<u>1.87</u>
	T14	-0.42	-0.50	-1.08	-0.68	-0.85	-0.44	-1.31
Freshwater sediments	S0	<u>1.31</u>	-0.52	-0.82	-0.63	-1.23	-0.43	-0.87
	S1	<u>1.61</u>	-0.29	-0.68	-0.49	-1.32	-0.50	-0.61
	S2	<u>1.59</u>	-0.43	-0.87	-0.56	-1.15	-0.50	-0.69
	S3	<u>1.66</u>	-0.31	-0.71	-0.48	-1.17	-0.68	-0.83
	S4	<u>1.44</u>	-0.40	-0.88	-0.58	-1.08	-0.59	-1.00
	S5-9	0.48	-0.24	-0.94	-0.49	-2.16	-1.68	-0.94
	S6	-0.22	0.14	-0.57	-0.61	-2.59	-1.86	-0.75
	S7	-0.21	0.15	-0.65	-0.78	-2.10	-1.43	-0.61
	S8	0.38	-0.10	-1.00	-1.16	-1.54	-1.46	-0.81
	S10	-0.41	-0.36	-1.21	-1.01	-2.31	-1.69	-1.24
	S11	-0.43	-0.37	-1.30	-1.17	-2.18	-1.50	-0.93
Marine sediments	L1	-0.07	-0.62	-1.07	-1.23	-1.99	-1.64	-1.51
	L2	0.11	-0.28	-1.20	-0.64	-1.98	-1.21	-1.54
	NC1	0.40	-0.97	-1.50	-0.58	-2.70	-2.00	-2.13
	NC2	0.25	-1.08	-1.88	-0.25	-2.72	-2.10	-2.10
	AB	0.31	-0.72	-1.57	-0.42	-1.99	-1.10	-1.87

In bold are the Igeo values higher than 0 and underlined values between 1 and 3

Table 5 Natural total concentration of heavy metals (mg/kg) in different Antarctic systems

	Reference	Location	Cu	Cr	Mn	Ni	Pb	Zn
Soil	This report	Artigas Base	52.2 ± 9.1	10.3 ± 8.1	503.9 ± 81.6	5.2 ± 1.9	6.3 ± 3.8	63.1 ± 28.5
	1	McMurdo Station	27–52	95–249		45–150	1.0–10.6	111–119
	2	Fildes Peninsula	89.5	22.6	640	10.4	5.4	51.4
Freshwater sediments	3	Fildes Peninsula	65.0 ± 13.0		616.3 ± 183.8	11.2 ± 3.9	6.0 ± 1.5	42.1 ± 8.1
	This report	AINA Stream	63.8 ± 9.7	5.2 ± 2.0	579.2 ± 99.3	5.3 ± 1.9	4.8 ± 0.6	59.7 ± 9.7
	4	Stream A	58.6 ± 4.9	3.6 ± 0.8	1292 ± 99		6.2 ± 0.5	78.8 ± 6.1
		Stream B	59.3 ± 3.3	5.0 ± 0.7	1308 ± 115		3.8 ± 0.4	67.9 ± 3.0
Marine sediments	This report	Uruguay Lake	52.9 ± 3.4	3.9 ± 0.8	503.7 ± 145.3	4.1 ± 0.04	3.0 ± 0.05	51.6 ± 8.7
	4	Lagoon near Potter Cove	82.7 ± 6.4	3.0 ± 0.8	1418 ± 77		5.8 ± 0.5	63.4 ± 6.3
	This report	North Cove	36.2 ± 6.8	2.5 ± 0.1	710.9 ± 112.4	2.5 ± 0.02	2.0 ± 0.03	34.6 ± 1.9
	4	Potter Cove (20 m depth)	156.3 ± 7.1	7.7 ± 0.6	1130 ± 60		5.5 ± 0.3	63.0 ± 2.9
	5	Admiralty Bay	67	35	527	7.9	5.5	52
	6	McMurdo Sound	57 ± 1				< 2 (-)	92 ± 3
	7	Ross Sea	23.5	65	1048	40.0	4.7	120

1 Crocket (1998), 2 Lu et al. (2012), 3 Abakumov et al. (2017), 4 Vodopivec et al. (2001), 5 Santos et al. (2005), 6 Negri et al. (2006), 7 Ianni et al. (2010)

from moderately to highly polluted and the remaining stations as unpolluted.

5 Conclusions

Some of the terrestrial stations (T2, T10, T11 and T13) presented the highest concentration of metals associated with anthropic activities. These polluted sites were limited to a restricted area of Artigas Base, not affecting surrounding environments. Highest metal concentrations corresponded to the service area where the generators and fuel tanks are located and to the AINA building. Highest metal levels were related to fuel storage and handling, but also, with sewage release and the presence of old leaded paint residues. Concentrations of the analysed metals in unpolluted sites had the same order of magnitude recorded in other unpolluted areas of the Fildes Peninsula and other Antarctic regions.

Acknowledgments The authors would like to thank CSIC (Comisión Sectorial de Investigación Científica, Universidad de la República) and the Uruguayan Antarctic Institute (IAU) for their support. SNI-ANII (Agencia Nacional de Investigación e Innovación) is acknowledged for its support to N Venturini. Special thanks to the crew 'Antarkos XXXI' of Artigas Antarctic Scientific Base for helping during sampling surveys. Also, the Department of Scientific Coordination of the IAU is very much acknowledged by the authors for supporting the development of this work. This work is part of the Project IAU-P-DCC-15.

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