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Influence of glacial runoff on baseline metal accumulation in the Antarctic limpet *Nacella concinna* from King George Island

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The nearshore environment of King George Island, where eight countries have been operating year-round stations, has been exposed to pollutant input arising from station operations, such as fossil fuel burning, waste disposal, and oil spills. Signs of metal pollution have been reported in soils, lichens and seawater near the station (Lee et al., 1990; KORDI, 1998; Hong et al., 1999).

The patellid limpet *Nacella concinna* (Strebler, 1908) is the most conspicuous and usually the only large invertebrate species found in the intertidal zone of Antarctic waters. *N. concinna* occurs in dense patches in intertidal and shallow subtidal zones around the Antarctic Peninsula and the adjacent islands (Walker, 1972; Picken, 1980) where station densities are higher than anywhere else in Antarctica. The ecology and physiology of *N. concinna* are relatively well known, which is expected to facilitate the potential use of this species as a biomonitor (Pickens, 1980; Davenport, 1988; Clarke, 1989, 1990; Nolan, 1991; Beaumont and Wei, 1991; Brêthes et al., 1994; Peck et al., 1996). A previous study showed that *N. concinna* accumulated most metals to a considerable degree and thus suggested its potential as a biomonitor of metal pollution in the Antarctic intertidal areas where stations are located (Ahn et al., 1999). A recent study

further elucidated the baseline accumulation pattern with respect to sex and tissue type (Ahn et al., 2002).

The previous studies have noted that baseline concentrations of some metals, in particular Cu, Mn and Fe were highly elevated in the tissue of *N. concinna* from King George Island as compared to the populations from other Antarctic regions. The elevation of these metals has been ascribed to inflow of glacier-melt water laden with Cu and other metals derived from lithogenic sources via weathering processes during austral summer (Ahn et al., 1999, 2002). Cu, Mn and Fe levels were also much higher in the marine sediment of King George Island (49–88 µg Cu g⁻¹ dry matter, >500 µg Mn g⁻¹, >24,000 µg Fe g⁻¹) than in the Peninsula regions (<15.3 µg Cu g⁻¹, <259 µg Mn g⁻¹, <22,700 µg Fe g⁻¹) (Alam and Sadiq, 1993; Ahn et al., 1996). In fact, these elements are enriched in the terrestrial volcanic rocks near the study area (Jwa and Lee, 1992; Lee et al., 1996), and turbid melt-water streams from terrigenous icefields and submerged glaciers have been observed during austral summer; this indicates that substantial amounts of lithogenic particles containing these elements have been introduced into the bay associated with the land runoff (Chang et al., 1990; Ahn, 1994; Yoo et al., 1999). In Admiralty Bay, which is adjacent to the Marian Cove, annual inflow (occurring mainly during austral summer) of terrigenous suspended particles brought about by melt-water streams was estimated at as much as 200,000–240,000 t (2000 tons per day) (Pecherzewski, 1980).

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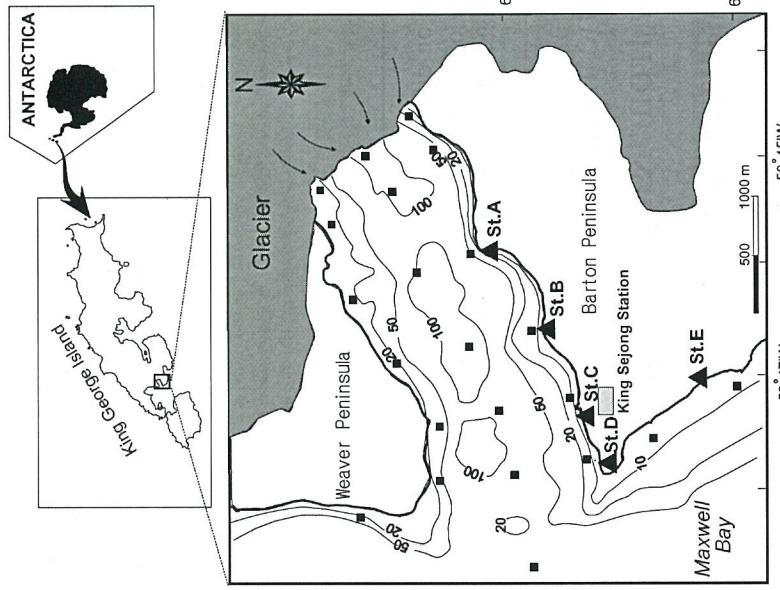


Fig. 1. Geographic location of King George Island and the sampling sites in Marian Cove. Several stations have been operated for years on King George Island. Limpets, *N. concinna*, were collected from the intertidal zones near the King Sejong Station in early January of 2001. Rectangles represent the sites for seawater sampling, and triangles for limpet sampling. Arrows indicate the input of glacial runoff. Bathymetric contours (in meters) were provided by Korea Ocean Research & Development Institute (1994).

The aim of this study was to elucidate the influence of glacial runoff during austral summer on baseline metal accumulation in the limpet *N. concinna*. We collected limpets from several sites receiving varying degrees of melt-water runoff and investigated spatial variation of metal concentrations in the limpet tissue with reference to metal concentrations in the ambient seawater. Natural elevation of some metals associated with the process of glacial-melt water runoff is discussed.

The Marian Cove, where King Sejong Station is located, is one of the fjords within Maxwell Bay on King George Island, and it receives a substantial amount of glacier-melt water during austral summer (Fig. 1). *N. concinna* were collected in early January 2001 from four stations along the shoreline of the cove (Sts. A, B, C and D) and also, as a reference site, from a remote site outside of the cove (St. E); St. A was closest to the sources of melt-water runoff and submerged glaciers and St. E was near the inlet of Maxwell Bay, and likely least influenced by the melt-water input. Collected limpets were depurated in filtered and aerated seawater for 2 days at 1 °C, and then the feces produced was collected

by decanting the supernatant water. After being depurated, the limpets were frozen for ease of dissection, and the shell was removed from each half-frozen limpet. Shell dimensions were determined to the nearest 0.01 mm with vernier calipers. Whole flesh and feces were freeze-dried for about 48 hours at the station and then transported to the lab in Korea.

We also collected some macroalgae in the intertidal areas at two extreme sites: St. A (the nearest to the glacial input), and St. E (the farthest from the glacial input). Seaweed fronds free from visible epiphytes, particulates and animals were cut into plastic bags and the fronds were washed 1–2 times with 0.2-µm filtered seawater to remove any remaining visible particulates. Seaweed samples were then rinsed with deionized water to remove salt, and freeze-dried at the station before being transported to Korea. Freeze-dried limpet tissue and seaweed samples were ground and homogenized, and then digested with concentrated nitric acid (Suprapur®, Merck) following the procedures described by Ahn et al. (2002). Metal concentrations were determined by inductively coupled plasma (ICP)/AES (JOBIN YVON, JY 38 Ultraice) for Cu, Mn, Fe and Zn, and ICP/MS (VG Elemental, PQ II Plus) for Cd and Pb. The accuracy of the analytical method used for the limpet tissue was tested using standard reference materials (SRMs) for oyster (SRM 1566a, NIST, USA) and mussel (CRM 278, IRMM, Belgium). Recovery rates of the oyster and mussel tissues were 90–110%.

During the investigation, seawater was also sampled. Seawater was sampled from a total of 22 stations on a same date. At each station, 1-l water sample was taken from a rubber boat. Water sample was obtained from 20-cm depth below the sea surface and at least 2-m away in horizontal distance from the boat using a plastic bottle-holding rod to prevent contamination. Each bottle was then sealed with an acid-rinsed plastic bag and taken to the lab at the station for separating into dissolved and particulate fractions. All the sampling bottles and device were acid-cleaned prior to use.

Metal concentrations in the collected seawater were determined in the dissolved and particulate fractions, separately. Dissolved fractions were concentrated by APCD/DDTC Freon extraction in a clean-air laboratory. Each concentrated sample was digested by adding quartz-distilled concentrated nitric acid, and then evaporated to dryness. The residue was then dissolved in diluted 0.01% nitric acid, and the metal concentrations finally determined by ICP/MS (Perkin-Elmer Elan 6100) and atomic absorption spectrometry (1100B with HGA700 & ASD70) following the procedures described by Danielsson et al. (1978). Particulate fractions were determined using the same instruments after total acid digestion according to Windom et al. (1991). Blanks and SRMs (CASS-3, MESS-2) for quality assurance testing were processed in the same way. Recovery rates of the SRMs

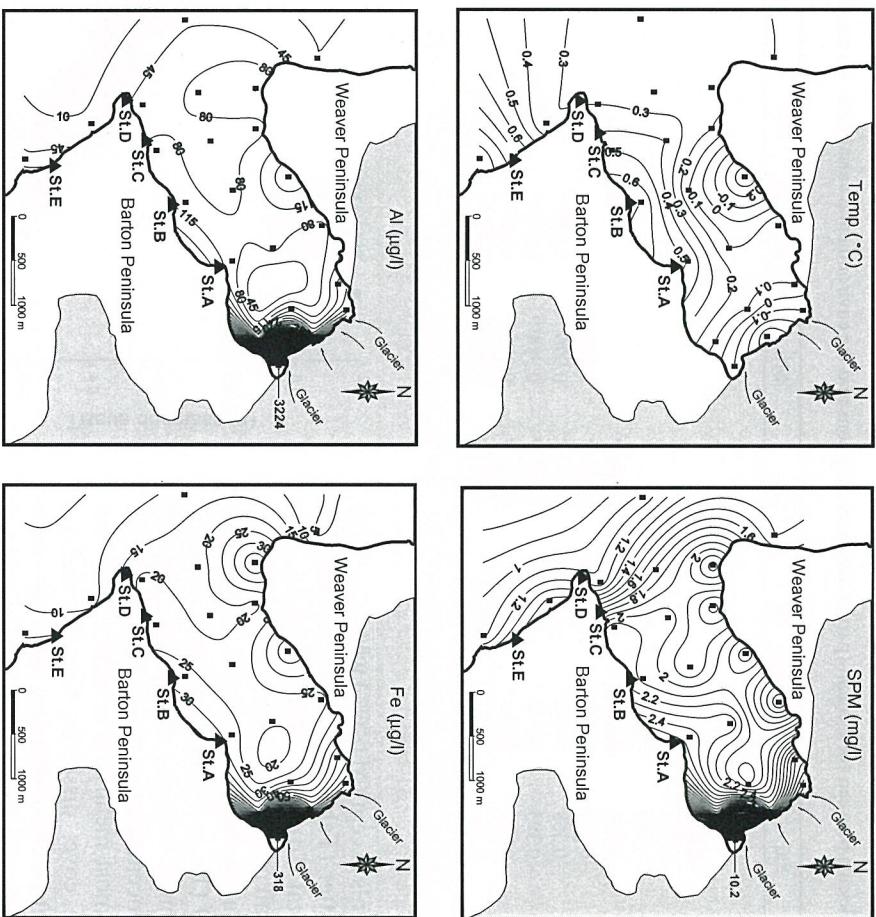


Fig. 2. Spatial variations of temperature (Temp), suspended particulate matter (SPM) and particulate Al and Fe concentrations in the surface seawater of Marian Cove.

ranged between 94–117% and 97–116%, respectively. Water temperature and salinity data were obtained from a long-term monitoring program conducted at the station (KORDI, 2001). Water temperature and salinity were measured using a conductivity meter (YSI 610-D).

A previous study on metal concentrations in *N. conchima* reported that some metals were significantly higher in females than in males (Ahn et al., 2002), but the concentration differences due to sex were not large and thought to be minimized by a random collection procedure if the male: female ratio within the sampled population was constant (Latouche and Mix, 1982). In this study, therefore, the male to female ratio was kept constant (1:2) among the different sampling sites to eliminate the sex effect. Due to large body size variation among the limpet samples from the different sites, differences in metal concentration between the sites were tested using analysis of covariance (ANCOVA). All the data were analyzed using a statistical program MINITAB 13 (MINITAB Inc.).

Fig. 2 shows that a distinct temperature gradient developed in the bay with the lowest temperature values near the sources of glacial runoff. Concentrations of suspended particulate matter (SPM), Al and Fe were

Table 1
Concentration ranges of suspended particulate matter (SPM, in mg l^{-1}) and of various metals (particulate and dissolved fractions, $\mu\text{g l}^{-1}$) in the surface seawater of Marian Cove during the 2000/2001 season

	Particulate		Dissolved	
	max	min	max	min
SPM	10.2	1.029		
Al	3224	ND		
Fe	318.0	4.029	ND	
Mn	23.41	0.195	ND	
Cu	2.438	0.026	0.393	0.140
Pb	0.580	0.025	0.052	0.006
Zn	3.034	0.147	0.598	0.240
Cd	0.004	0.0004	0.075	0.052
Co	0.456	0.003	0.029	0.002

Seawater samples were collected on the same date, December 8th, 2000. ND: not determined.

notably elevated at the sites near the melt-water sources (10.2 , 3.2 mg l^{-1} and $318 \mu\text{g l}^{-1}$, respectively), and sharply decreased with increasing distance from the melt-water sources. Cu, Mn, Pb and Zn also showed distributional patterns very similar to those of SPM, Al and Fe. Analysis showed that substantial portions (40% to

Table 2
Pearson correlation coefficients between the element (particulate) concentrations and the environmental variables in the seawater of Marian Cove in early January of 2001

	Temp	Sal	SPM	Al	Cu	Mn	Fe	Pb	Zn	Cd
Temp	0.298									
Sal	-0.304	-0.353								
SPM	-0.274	-0.353	0.973***							
Al	-0.334	-0.330	0.971***	0.994***						
Cu	-0.294	-0.356	0.977***	1.000***	0.996***					
Mn	-0.327	-0.372	0.984***	0.993***	0.992***	0.995***				
Fe	-0.289	-0.368	0.966***	0.996***	0.990***	0.996***	0.986***			
Pb	-0.291	-0.395	0.954***	0.987***	0.981***	0.988***	0.976***	0.991***		
Zn	-0.495*	-0.401	0.874***	0.895***	0.907***	0.901***	0.893***	0.906***	0.935***	
Cd	-0.303	-0.371	0.976***	0.999***	0.995***	1.000***	0.996***	0.996***	0.988***	0.904***
Co										

Temp: temperature; Sal: salinity; SPM: suspended particulate matter. Significance: *0.01 < p < 0.05; **0.001 < p < 0.001; *** p < 0.001, $n = 22$.

>90%) of all the metals except Cd (<6%) were associated with particulate matter (Table 1); Cd existed predominantly (>94% of total Cd) as the dissolved form. Particulate fractions of all metals analyzed covaried strongly with Al with correlation coefficient values ranging between 0.89 and 0.99 (Table 2); although particulate Cd constituted a very small fraction, its concentration also covaried with Al concentration. On the other hand, the dissolved forms of most metals were rather evenly distributed within the cove; dissolved Cu, Pb and Co showed some elevated concentrations near the meltwater input source, but the spatial patterns were not as distinct as those of their particulate forms. Thus the results of the present study show that the observed spatial variations of most metals were attributable to the concentration difference of their particulate forms.

The positive correlations between the concentrations of the particulate metals and Al demonstrate that the spatial variation of these elements in the seawater was not due to contamination, but due to natural process (Din, 1992). Al and all other particulate metal concentrations were also related to the concentration of SPM (Table 2); this implicated that these metals were introduced into the cove in association with lithogenic particles in the melt-water runoff. Although particulate Cd concentrations were very low, they were also related to Al and SPM. Relation with seawater temperature, on the other hand, was significant only for Cd; this is likely because the concentration differences of SPM and the other elements were much greater than the seawater temperature variation, while that of Cd was comparable to the water temperature variation.

Thirty one to 39 limpets were analyzed at each site. The limpets ranged from 17.2 to 36.7 mm shell length (SL), and the mean varied from 26.0 to 28.6 mm SL; the overall mean was 28 mm SL. We observed a positive correlation between SL and tissue dry mass (TDM) (Fig. 3), with TDM increasing as a power function of SL, at all sites ($p < 0.001$). Despite the differences in mean SL and size range, the overall SL-TDM relationship was

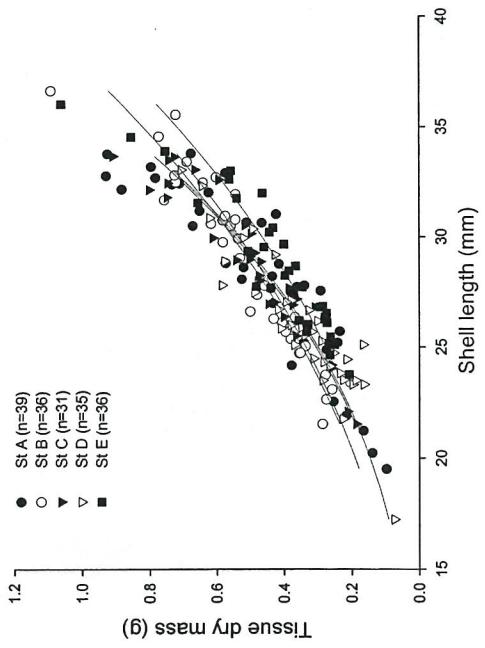


Fig. 3. Relationships between shell length (SL) and tissue dry mass (TDM) of *N. concinna* collected from different sites. There were no statistical differences in the SL-TDM relationships among the sites with the regression coefficients ranging from 2.55 to 3.71 (analysis of covariance [ANCOVA], $p > 0.5$). The regression equation of the pooled data was $TDM = 10^{-4.99} \text{ SL}^{3.19}$ with ($SE_b = 0.10$, $n = 93$, $r^2 = 0.86$, $p < 0.001$).

almost identical with no statistical differences (ANCOVA, $p > 0.5$) with the regression coefficients ranging from 2.55 to 3.71.

Metal concentrations in *N. concinna* tissue were therefore plotted against SL and comparisons of metal concentrations between the limpets from different sampling sites were directly made on regression analysis (Fig. 4). There were no significant concentration differences between the limpets from St. A and St. B, although most metal concentrations slightly decreased from St. A to St. B. The data from Sts. A and B were therefore pooled for clarity of statistical comparison. We found significant concentration differences of most metals between St. A-B (pooled), St. C, St. D and St. E. As in the seawater, tissue concentrations of Cu, Mn, Fe and Pb showed a strong tendency to increase towards the source of glacial discharge; Pb concentrations in the

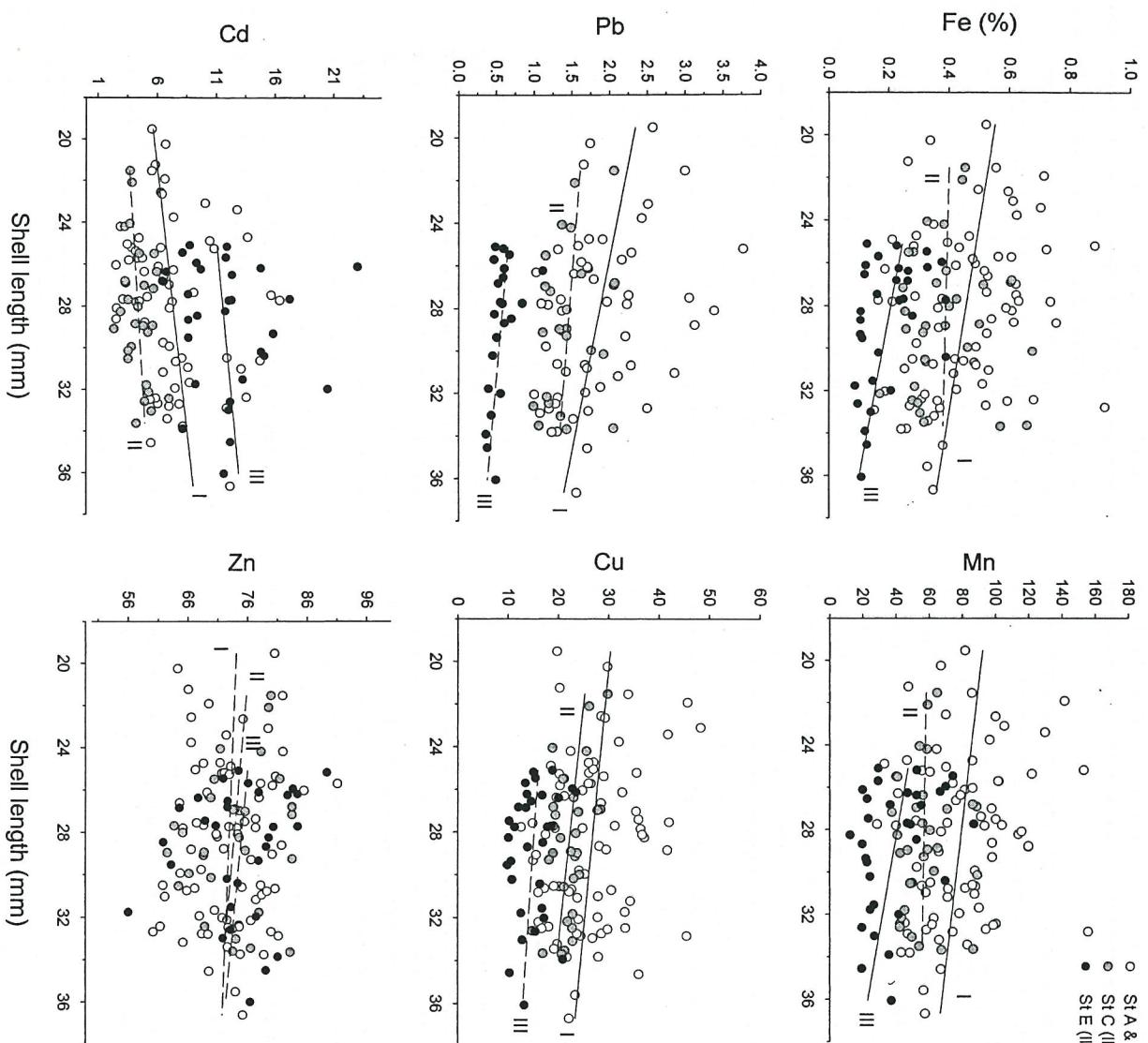


Fig. 4. Comparisons of metal concentrations ($\mu\text{g g}^{-1}$ TDM except Fe in %TDM) between *N. concinna* collected from different sampling sites. Data from St. A and St. B were shown to have no statistical difference with each other, and they were pooled for clarity of statistical analysis. The concentration values from St. D were intermediate between St. C and St. E, and not plotted for visual clarity of the comparisons. Solid regression lines are statistically significant; dotted lines, statistically insignificant, are plotted for clarity of comparisons.

limpet tissue were more than three times higher at St. A–B than at St. E, and Cu, Mn and Fe about twice as high at St. A–B than St. E. Thus, the concentrations of most metals in the limpet tissue reflected the background levels in the ambient seawater, and the spatial variation of Cu, Mn, Fe and Pb concentrations in the *N. concinna* tissue are likely to be related to glacier-melt water discharge during austral summer.

Unlike the other elements, the highest Cd values in the limpet tissue were found at St. E, where Cd concentrations in seawater were lowest. This indicates that Cd accumulation in the limpet tissue may be influenced

by other factors such as food availability and growth rate rather than the melt-water process. The density of microphytobenthos, which is considered as an important food source for *N. concinna* (Bréthes et al., 1994), could be highly variable over short distances, and the amount of Cd accumulated in *N. concinna* would be expected to be variable site to site depending on the food amount consumed. The Cd values from this study at St. E ($11.7 \mu\text{g g}^{-1}$ TDM) and St. C ($4.7 \mu\text{g g}^{-1}$ TDM) were similar to the values ($10.7 \mu\text{g g}^{-1}$ TDM and $4.9\text{--}5.0 \mu\text{g g}^{-1}$ TDM, respectively) reported in the corresponding period of previous years (Ahn et al., 1999, 2002).

Thus, the spatial variation in Cd concentrations of *N. concinna* tissue appears to be somewhat consistent year to year.

The Cd levels found in the limpet tissue from St. E were highly elevated in comparison with those found in their related species from clean sites (Stenner and Nickless, 1975; Miramand and Bentley, 1992) and comparable to the values from polluted sites (Preston et al., 1972; Bryan and Hummerstone, 1977; Lande, 1977; Ramelow, 1985). The Cd elevation in the limpet tissue, however, seems natural rather than anthropogenic. Elevation of Cd is reportedly a unique feature among Antarctic marine organisms living in the naturally Cd-enriched Southern Ocean (Honda et al., 1987; Mauri et al., 1990; Berkman and Nigro, 1992; Ahn et al., 1996; Bargagli et al., 1996; Moreno et al., 1997). Cd seems to be taken up by phytoplankton along with phosphate, and as a result, accumulated in herbivores grazing on the phytoplankton and finally biomagnified through food webs. In King George Island, Cd elevation was also reported in the herbivorous bivalve *Laternula elliptica* (Ahn et al., 1996, 2001).

We also found the same trend in *N. concinna* feces with the highest Cu, Mn, Fe, Pb and Zn concentrations at St. A and the highest Cd at St. E (Fig. 5), indicating that these metals of lithogenic source were taken up mainly by feeding process, and excess metals were excreted with feces. A previous study on this species reported that the highest metal accumulation was found in the visceral organs, and suggested that metals accumulated in their tissues are taken up mostly from diet (Ahn et al., 2002). Microphytobenthos are reported to be the primary food source for *N. concinna* (Bréthes et al., 1994). However, data on metal concentrations in benthic algae or diatom in this area or any other areas in the

Antarctic are scarce, limited to a few species or taxa (Moreno et al., 1997; Bargagli et al., 1996, 1998; Farias et al., 2002). In most cases, browsing gastrropods like *N. concinna* feed on a variety of microalgae and diatoms, and therefore it seems difficult to draw any clear relationships between the metal concentrations of the benthic browsers and their diet (Miramand and Bentley, 1992).

In this study, we determined metal concentrations in two common macroalgae, the brown alga *Adenocystis utricularis* and the red alga *Iridaea cordata* collected from the two extreme sites (Sts. A and E), and found that Cu, Mn, Fe, Pb, Zn and Cd concentrations in these seaweeds were significantly higher at the site near the source of glacial-melt water input (Table 3). Thus, the concentrations of all the metals except Cd in the two seaweed species closely followed the trend shown in the tissue and feces of the limpet *N. concinna*; this may imply that the differences in metal concentrations in *N. concinna* are in part due to the differences in metal concentrations of algal food at their habitat, although this warrants further study as to assess whether these two seaweed species constitute the principal food items. Concentrations of most metals in the seaweed were one order of magnitude lower than the concentrations in the limpet tissue, but were one or two orders of magnitude higher than the concentrations in seawater (dissolved) (Fig. 6); this may suggest that biomagnification processes are operative through these food webs.

As shown in this study, however, substantial portions of most metals in seawater are associated with particles of organic matter in the environment.

Table 3

Comparisons of metal concentrations ($\mu\text{g g}^{-1}$ dry mass $^{-1}$) in the brown alga *Adenocystis utricularis* and the red alga *Iridaea cordata* between St. A (the nearest to the glacial input) and St. E (the farthest from the glacial input)

	St. A			St. E		
	Mean \pm SD			Mean \pm SD		
<i>Adenocystis utricularis</i>						
Al	688 \pm 57			220 \pm 15*		
Cu	6.5 \pm 0.23			6.11 \pm 2.9		
Mn	24.3 \pm 1.1			12.5 \pm 0.7*		
Fe	1730 \pm 154			481 \pm 71*		
Pb	0.44 \pm 0.03			0.104 \pm 0.018*		
Zn	23 \pm 3.9			10.8 \pm 3.1*		
Cd	4.50 \pm 0.06			1.50 \pm 0.19*		
<i>Iridaea cordata</i>						
Al	67 \pm 5			18 \pm 6*		
Cu	9.6 \pm 0.17			7.3 \pm 0.35*		
Mn	10.0 \pm 0.5			6.7 \pm 0.5*		
Fe	172 \pm 13			141 \pm 24		
Pb	0.14 \pm 0.015			0.12 \pm 0.021		
Zn	37 \pm 9.8			33 \pm 10.6		
Cd	1.5 \pm 0.05			0.24 \pm 0.004*		

Fig. 5. Comparisons of metal concentrations ($\mu\text{g g}^{-1}$ TDM except Fe in %TDM) in *N. concinna* feces between the sampling sites. Mean \pm 1 standard deviation bars ($n = 4$ at Sts. A & E, $n = 1$ at St. C) are represented. Significance: * $0.01 < p < 0.05$; ** $0.001 < p < 0.01$; *** $p < 0.001$.

Non-parametric Mann–Whitney *U*-tests were conducted to test significance of the differences between the two sites. Significance: * $0.01 < p < 0.05$, ** $0.001 < p < 0.001$, *** $p < 0.001$.

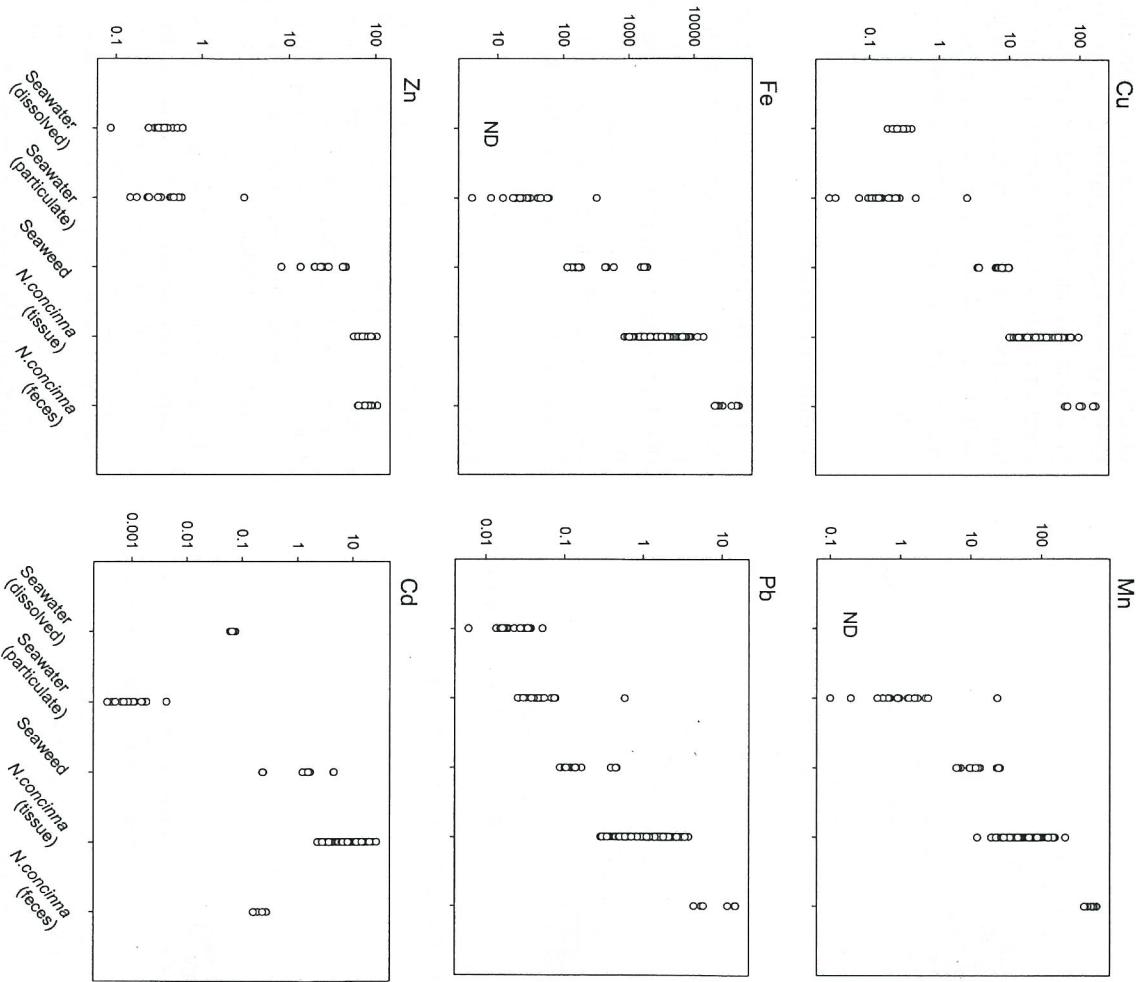


Fig. 6. Ranges of metal concentrations ($\mu\text{g l}^{-1}$ for seawater, $\mu\text{g g}^{-1}$ TDM for the others) in seawater, seaweed (*Adenocystis urticaris* and *Iridaea coriacea*) and *N. concinna* tissue and feces. All the data are presented as vertical points. ND: not determined.

ticulate matter, and the metal concentrations in the limpet tissue reflect their concentrations in the surrounding seawater. This may suggest that an alternative pathway of biomagnification is working; non-living particulate matter which sediments on algal mats or is attached on seaweed blades may be directly consumed by *N. concinna* when they browse algal food. The relative importance of biomagnification processes based on non-living particulate matter is yet to be resolved.

Tissue concentrations of Cu, Mn, and Pb correlated highly with those of Fe (Fig. 7), strongly suggesting that these metals of lithogenic sources accumulate in the limpet tissue in an unregulated fashion, and thereby, the tissue concentrations of these metals reflect changes in the environment. Previous studies in this area reported that Pb concentrations were elevated in some inshore waters adjacent to the station with a dramatic decrease

towards the offshore, and indicated that Pb originated from point sources at the station (Lee et al., 1990; KORDI, 1998). We, however, found that the overall Pb concentrations in the limpet tissues were very low, and they were linearly proportional with the Fe concentrations, indicating that the spatial variation was due to varying degrees of ice-melt water influence not due to contamination.

Thus, we have found little sign of contamination in seawater and in organisms, and the metal concentrations we observed can be considered as baseline levels. We have, however, found a wide range of spatial variation in the baseline concentrations in seawater, seaweed and limpet tissue with varying degrees of ice-melt water influence. Glacial-melt water runoff would be subject to change in amount and composition temporally as well as spatially, causing some fluctuations in natural

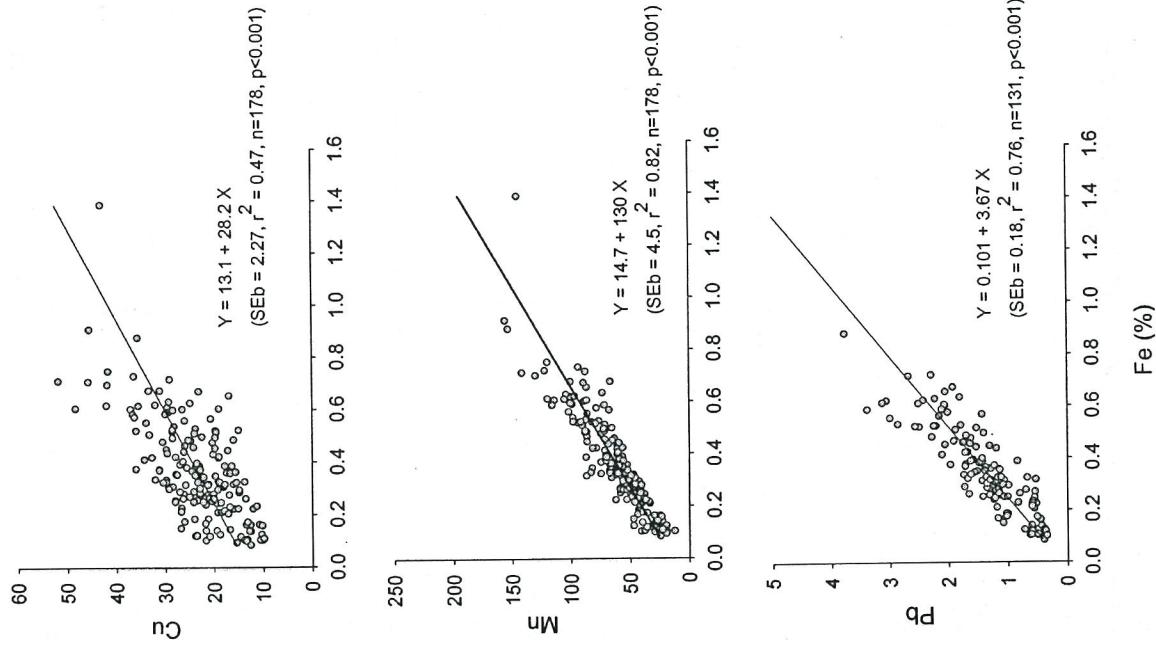


Fig. 7. Relationships between Fe (%TDM) and other metal concentrations ($\mu\text{g g}^{-1}$ TDM) in *N. concinna* tissue.

background levels in the surrounding seawater and subsequently in the baseline levels of biomonitor organisms. Normalization procedures should therefore be necessary to assess whether the concentrations observed represent background or contamination levels (Din, 1992; Balls et al., 1997; Knight and Paternack, 1999; Veinott et al., 2001). The strong correlations of Cu, Mn, Pb and Zn with Al and Fe in the particulate matter of seawater indicate that Al or Fe can be used to normalize variability in metal concentrations of seawater or sediment (Din, 1992; Balls et al., 1997). The good correlations of Cu, Mn and Pb with Fe in *N. concinna* tissue also indicate that Fe may be useful in identifying whether their elevated concentrations are anthropogenic or natural (Fig. 7). In addition, elevations of Cu and of some other metals of lithogenic sources are likely to be a

unique and regional feature of marine herbivores in King George Island related to local glacier-melt water processes, which should be taken into consideration in conducting future monitoring in this region. Whether introduction of some metals of lithogenic sources via melt-water runoff is a common process in many Antarctic bays during austral summer warrants further studies.

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References

- Ahn, I.-Y., 1994. Ecology of the Antarctic bivalve *Laternula elliptica* (King and Broderip) in Collins Harbor, King George Island: benthic environment and an adaptive strategy. Mem. Natl. Inst. Polar Res. (Special Issue) 50, 1–10.
- Ahn, I.-Y., Kang, J., Kim, D.-Y., 1999. A preliminary study on heavy metals in the Antarctic limpet, *Nacella concinna* (Strebel, 1908) (Gastropoda: Patellidae) in an intertidal habitat on King George Island. Korean J. Polar Res. 10, 1–8.
- Ahn, I.-Y., Chung, H., Choi, K.-S., 2001. Some ecological and physiological features of the Antarctic clam, *Laternula elliptica* (King and Broderip) in a nearshore habitat on King George Island. Ocean Polar Res. 23, 419–424.
- Ahn, I.-Y., Kim, K.-W., Choi, H.-J., 2002. A baseline study on metal concentrations in the Antarctic limpet *Nacella concinna* (Gastropoda: Patelidae) on King George Island: variations with sex and body parts. Mar. Pollut. Bull. 44, 421–431.
- Ahn, I.-Y., Lee, S.H., Kim, K.T., Shim, J.H., Kim, D.-Y., 1996. Baseline heavy metal concentrations in the Antarctic clam, *Laternula elliptica* in Maxwell Bay, King George Island, Antarctica. Mar. Pollut. Bull. 32, 592–598.
- Alam, I.A., Sadiq, M., 1993. Metal concentrations in Antarctic sediment samples collected during the Trans-Antarctica 1990 Expedition. Mar. Pollut. Bull. 26, 523–527.
- Balls, P.W., Hull, S., Miller, B.S., Pirie, J.M., Proctor, W., 1997. Trace metal in Scottish estuarine and coastal sediments. Mar. Pollut. Bull. 34, 42–50.
- Bargagli, R., Monaci, F., Sanchez-Hernandez, J.C., Cateni, D., 1998. Biomagnification of mercury in an Antarctic marine coastal food web. Mar. Ecol. Prog. Ser. 169, 65–76.
- Bargagli, R., Nelli, L., Ancora, S., Focardi, S., 1996. Elevated cadmium accumulation in marine organisms from Terra Nova Bay (Antarctica). Polar Biol. 16, 513–520.
- Beaumont, A.R., Wei, J.H.C., 1991. Morphological and genetic variation in the Antarctic limpet *Nacella concinna* (Strebel, 1908). J. Moll. Stud. 57, 443–450.
- Berkman, P.A., Nigro, M., 1992. Trace metal concentrations in scallops around Antarctica: extending the mussel watch programme to the Southern Ocean. Mar. Pollut. Bull. 24, 322–323.
- Brethes, J.-C., Ferreyra, G., de la Vega, S., 1994. Distribution, growth and reproduction of the limpet *Nacella (Patinigera) concinna*

- (Strebel, 1908) in relation to potential food availability, in Esperanza Bay (Antarctic Peninsula). *Polar Biol.* 14, 161–170.
- Bryan, G.W., Hummerstone, L.G., 1977. Indicators of heavy-metal contamination in the Looe Estuary (Cornwall) with particular regard to silver and lead. *J. Mar. Biol. Ass. UK* 57, 75–92.
- Chang, K.I., Jun, H.K., Park, G.T., So, Y.S., 1990. Oceanographic conditions of Maxwell Bay, King George Island, Antarctica (Austral Summer 1989). *Korean J. Polar Res.* 1, 27–46.
- Clarke, A., 1989. Faecal production and an estimate of food intake in the wild of the Antarctic limpet *Nacella concinna* (Strebel). *J. Moll. Stud.* 55, 261.
- Clarke, A., 1990. Faecal egestion and ammonia excretion in the Antarctic limpet *Nacella concinna* (Strebel, 1908). *J. Exp. Mar. Biol. Ecol.* 138, 227–246.
- Danielsson, L., Magnusson, B., Westerlund, S., 1978. An improved metal extraction procedure for the determination of trace metals in seawater by atomic absorption spectrometry with electrothermal atomization. *Anal. Chem. Acta* 98, 47–57.
- Davenport, J., 1988. Tenacity of the Antarctic limpet *Nacella concinna*. *J. Moll. Stud.* 54, 355–356.
- Din, Z.B., 1992. Use of aluminium to normalize heavy-metal data from estuarine and coastal sediments of Straits of Melaka. *Mar. Pollut. Bull.* 24, 484–491.
- Farias, S., Arisnaharreta, S.P., Vodopivec, C., Smichowski, P., 2002. Levels of essential and potentially toxic trace metals in Antarctic macroalgae. *Spectrochimica Acta Part B* 57, 2133–2140.
- Honda, K., Yamamoto, Y., Tatsukawa, R., 1987. Distribution of heavy metals in Antarctic marine ecosystem. *Proc Natl. Inst. Polar Res. Symp. Polar Biol.* 1, 184–197.
- Hong, S., Kang, C.Y., Kang, J., 1999. Lichen biomonitoring for the detection of local heavy metal pollution around King Sejong Station, King George Island, Antarctica. *Korean J. Polar Res.* 10, 17–24.
- Jwa, Y.-J., Lee, J.-I., 1992. Geochemistry of the volcanic rocks from the Fildes Peninsula, King George Island, Antarctica. *J. Korean Earth Sci. Soc.* 13, 200–211.
- Knight, M.A., Paternack, G.B., 1999. Sources, input pathways, and distributions of Fe, Cu, and Zn in a Chesapeake Bay tidal freshwater marsh. *Environ. Geol.* 39, 1359–1371.
- KORDI, 1998. Annual report of environmental monitoring on human impacts at the King Sejong Station. Korea Ocean Research and Development Institute Report, No. BSPP 98001-02-1151-7, p. 407 (in Korean with English abstract).
- KORDI, 2001. Annual report of environmental monitoring on human impacts at the King Sejong Station. Korea Ocean Research and Development Institute Report, No. EC PP 01 001-B2, p. 504 (in Korean with English abstract).
- Lande, E., 1977. Heavy metal pollution in Trondheimsfjorden, Norway, and the recorded effects on fauna and flora. *Environ. Pollut.* 12, 187–198.
- Latouche, Y.D., Mix, M.C., 1982. The effects of depuration, size and sex on trace metal levels in bay mussels. *Mar. Pollut. Bull.* 13, 27–29.
- Lee, S.H., Kim, K.T., Kim, S.H., 1990. Trace metals in the surface waters of Maxwell Bay, King George Island, Antarctica. *Korean J. Polar Res.* 1, 11–15.
- Lee, J.I., Hwang, J., Kim, H., Kang, C.Y., Lee, M.J., Nagao, K., 1996. Subvolcanic zoned granitic pluton in the Barton and Weaver Peninsulas, King George Island, Antarctica. *Proc. NIPR Symp. Antarct. Geosci.* 9, 76–90.
- Mauri, M., Orlando, E., Nigro, M., Regoli, F., 1990. Heavy metals in the Antarctic scallop *Adamussium colbecki*. *Mar. Ecol. Prog. Ser.* 67, 27–33.
- Miramand, P., Bentley, D., 1992. Heavy metal concentrations in two biological indicators (*Patella vulgata* and *Fucus serratus*) collected near the French nuclear fuel reprocessing plant of La Hague. *Sci. Total Environ.* 111, 135–149.
- Moreno, J.E.A., de Gerpe, M.S., Moreno, V.J., Vodopivec, C., 1997. Heavy metals in Antarctic organisms. *Polar Biol.* 17, 131–140.
- Nolan, C.P., 1991. Size, shape and shell morphology in the Antarctic limpet *Nacella concinna* at Signy Island, South Orkney Islands. *J. Moll. Stud.* 57, 225–238.
- Pecherzowski, K., 1980. Distribution and quantity of suspended matter in Admiralty Bay (King George Island), South Shetland Islands. *Polish Polar Res.* 1, 75–82.
- Peck, L.S., Baker, A.C., Conway, L.Z., 1996. Strontium labelling of the shell of the Antarctic limpet *Nacella concinna* (Strebel, 1908). *J. Exp. Mar. Biol. Ecol.* 42, 71–85.
- Preston, A., Jefferie, D.F., Dutton, J.W., Harvey, B.R., Steele, A.K., 1972. British Isles coastal waters: the concentrations of selected heavy metals in sea water, suspended matter and biological indicators—a pilot survey. *Environ. Pollut.* 3, 69–82.
- Ramelow, G.J., 1985. A study of heavy metals in limpets (*Patella* sp.) collected along a section of the Southeastern Turkish Mediterranean coast. *Mar. Environ. Res.* 16, 243–253.
- Steiner, R.D., Nickless, G., 1975. Heavy metals in organisms of the Atlantic Coast of SW Spain and Portugal. *Mar. Pollut. Bull.* 6, 89–92.
- Veinott, G., Perron-Cashman, S., Anderson, M.R., 2001. Baseline metal concentrations in coastal Labrador sediments. *Mar. Pollut. Bull.* 42, 187–192.
- Walker, A.J.M., 1972. Introduction to the ecology of the Antarctic limpet *Patinigeria polaris* (Hombron & Jacquinot) at Signy Island, South Orkney Islands. *British Antarct. Surv. Bull.* 28, 49–69.
- Windom, H.L., Byrd, J.T., Smith Jr., R.G., Huan, F., 1991. Inadequacy of NASQAN data for assessing metal trends in the Nation's Rivers. *Environ. Sci. Technol.* 25, 1137–1142.
- Yoo, K.-C., Yoon, H.I., Oh, J.-K., Kim, Y., Kang, C.Y., 1999. Water column properties and dispersal pattern of suspended particulate matter (SPM) of Marian Cove during austral summer, King George Island, West Antarctica. *The Sea (The Korean Society of Oceanography)* 4, 266–274 (in Korean).

