A Benthic Study Examining the Relationship Between Sediment Properties and Faunal Groups Observed at Sir Edmund Bay, British Columbia

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A BENTHIC STUDY EXAMINING THE RELATIONSHIP BETWEEN SEDIMENT PROPERTIES AND FAUNAL GROUPS OBSERVED AT SIR EDMUND BAY, BRITISH COLUMBIA

by

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ABSTRACT

Sutherland, T.F., Levings, C.D., McPhie, R., Petersen, S.A. and Knapp, W. 2006. A benthic study examining the relationship between sediment properties and faunal groups observed at Sir Edmund Bay, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2631: vi + 49 p.

A benthic sampling survey was carried out in June 2003, at a finfish aquaculture site situated in Sir Edmund Bay located on the northeast shoreline of Broughton Island, Broughton Archipelago, British Columbia. Samples were also collected at reference stations in Penphrase Passage. A Van Veen grab was used to collect benthic organisms and sediment chemistry samples, while a gravity corer was used to collect sediment cores for *in situ* Total sediment sulphide analysis. Correlations between macrofauna and benthic variables are presented in this report.

RÉSUMÉ

Sutherland, T.F., Levings, C.D., McPhie, R., Petersen, S.A. and Knapp, W. 2006. A benthic study examining the relationship between sediment properties and faunal groups observed at Sir Edmund Bay, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2631: vi + 49 p.

Un relevé d’échantillonnage benthique a été réalisé en juin 2003 dans un site piscicole de la baie Sir Edmund, sur la côte nord-est de l’île Broughton, dans l’archipel Broughton, en Colombie-Britannique. Des échantillons ont également été prélevés dans des stations témoins situées dans le passage Penphrase. Une benne preneuse Van Veen a été utilisée pour prélever des organismes benthiques et des échantillons de sédiments à des fins d’analyse chimique, alors qu’un carottier à gravité a servi à prélever des carottes de sédiments à des fins d’analyse *in situ* des sulfures. Les corrélations entre la macrofaune et les variables benthiques sont présentées dans le rapport.

INTRODUCTION

BACKGROUND

The deposition of waste material on the benthic environment under and adjacent to salmon farm operations may have significant environmental effects. Waste material arising from netpens consists of both feed pellets and fish faeces and is thought to result in a feed pellet loss of 5 to 11% (Findlay and Watling, 1994) and a faecal material loss of 12.5% of feed weight (Brooks and Mahnken, 2003). The potential accumulation of this waste material and resulting organic enrichment can influence the abundance and diversity of an existing benthic community (Henderson and Ross, 1995). In order to carry out an assessment examining the potential impact of aquaculture operations on the benthic environment 3 key benthic sampling components are required: 1) a tracer of the waste feed material; 2) an indicator of organic enrichment; and 3) a faunal response to organic enrichment (Sutherland, 2004).

Tracers of waste material can be found using certain metals which make up the mineral component of feed material. Examples of such minerals are zinc and strontium which are added to feed pellets to prevent cataract formation in juvenile salmon (Richardson et al. 1986) and to trace the amount of calcium uptake within fish, respectively. Since zinc naturally occurs within the marine environment it is important to delineate the proportion of zinc that is derived from anthropogenic inputs. Yeats et al. (2005) describe a geochemical normalization technique that compensates for mineralogical changes and identifies sediments influenced by aquaculture operations. In terms of an indicator of organic enrichment, variables such as total sediment sulphide and redox potential have been used to classify sediments according to 4 categories: Normal, Oxic, Hypoxic, Anoxic outlined in Table 3 (Wildish et al. 1999). This report will examine the trends in the observed data set in context with the proposed tracers of waste material and indicators of organic enrichment as well as overall changes in other environmental variables. The faunal response to the observed sediment variables will also be examined.

Table 1. Characterizations of effect along an organic enrichment gradient (increasing from left to right) based on four types of environmental monitoring measures (Wildish et al. 2001).

Type of Measure	**Group**				**Reference**
Microbial	Normal	Oxic	Hypoxic	Anoxic	Poole et al. (1978)
Macrofaunal	Normal	Transitory	Polluted	Grossly polluted	Pearson and Rosenberg (1978)
*Sediment profiling imaging BHQ**	> 10	5 to 10	2 to 4	< 2	Nilsson and Rosenberg (1997)
Geochemical	Normal	Oxic	Hypoxic	Anoxic	Wildish et al. (2001)
Redox,, Eh, mV_{NHE}	> +100	0 to 100	-100 to 0	< -100	
Sulphides, S^{2-}, μM	< 300	300 to 1300	1300 to 6000	> 6000	

* = benthic habitat quality index

SITE CHARACTERISTICS

A benthic study was carried out at a fish farm located in Sir Edmund Bay on the south-central coast of British Columbia between June 24 and 27, 2003 (Figure 1). Sir Edmund Bay is located on the northeast border of Gilford Island within the Broughton Archipelago. The bay is approximately 1000 m long and 750 m wide with a maximum depth of 75 m. Nicholls Island is located at the entrance of the bay. The aquaculture lease site is located at the northeast shoreline of Sir Edmund Bay near the entrance to the bay. Two netpen systems were oriented in series and parallel to the shoreline for the recent growout cycle (March 2001 to March 2003) that occurred prior to the benthic field survey (Figure 2). During the sampling program only one empty netpen system along with an attached cluster of smaller pens remained in position. In the past different arrangements of netpen systems have been oriented perpendicular to the shoreline, although the exact position and duration of this mooring setup is not known.

METHODS AND MATERIALS

FIELD SAMPLING

A description of the sampling methods and laboratory analyses used in this study is outlined in detail in a data report by Sutherland et al. (2005). A square-shaped sampling grid comprised of 100 sampling stations arranged in a 10 x 10 pattern with a 30 m distance between stations was used as a template for station selection during the field sampling program. In addition, grab and core samples were also obtained from three reference stations in an adjoining passage (Penphrase Passage). A Van Veen grab (0.1 m^2) was used to collect benthic organisms and sediment chemistry samples, while a Pedersen gravity corer was used to collect sediment cores that were analyzed *in situ* for Total sediment sulphide concentration and redox potential. The locations of the grab and core deployments of various sediment variables can be seen Figure 2. The type of variables collected at each station is outlined in Table 1. While the intention was to sample every variable at each targeted station, difficulties in instrument deployments due to substrate type (boulder field) prohibited sample collection in certain cases.

The first Van Veen grab sample at each station was collected for macrofauna analysis using a deck hose fitted with a 0.5 mm screen and a sieve table consisting of a 1.0 mm screen mounted on top of a 0.5 mm screen. Ten percent formalin was used to preserve each sample in a labelled sample jar. The surface sediment (top 2 cm) from the second grab at each station was subsampled for sediment grain size, carbon, nitrogen and semi-trace metal analysis. The gravity corer contained modified core barrels drilled in a spiral pattern with sampling ports at 2 cm intervals. These ports were covered with duct tape in order to maintain suction throughout the corer upon deployment and retrieval and used to collect both Redox potential and total sediment sulphide measurements. The calibration of the Redox electrode (Orion 9678BN) and the Silver/sulphide electrode (Orion 6916BN) as well as the coring subsampling protocol are described in detail in Sutherland et al. (2005) after Wildish et al. (1999). The data collected as part of this study are presented in tabulated form in a published data report (Sutherland et al. 2005).

LABORATORY ANALYSIS

Macrofauna were enumerated to taxa levels of varying resolution. The surficial sediment subsamples were analyzed for trace-metal, total nitrogen, total carbon, organic carbon and particle size analysis. Trace metal analysis was carried out according to the PESC SEDMET Method V 6.0, using an Optima 4300 Inductively Coupled Plasma Emission Spectrometer (PerkinElmer Life and Analytical Science, Woodbridge, ON). This procedure tests for content of aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorous, potassium, selenium, silicon, silver, sodium, strontium, sulphur, tin, titanium, vanadium, and zinc. Sediment lithium was determined using Perkin Elmer Elan 6000 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) according to procedures outlined in PESC SEDICP-MS Method V 1.0.

The nitrogen concentration of the sediment samples was determined using the PESC TN Method V 2.0 automated, colorimetric, persulphate digest cadmium/copper reduction. Carbon analysis was conducted by ALS according to U.S. EPA Method 9060A. Total carbon was determined by high temperature oxidation of carbon to carbon dioxide which was then measured by means of a non-dispersive infrared analyzer. Inorganic carbon was determined by reaction with phosphoric acid to convert all carbonates to carbon dioxide which was then measured with the same infrared analyzer. Organic carbon was determined as the difference between total and inorganic carbon. The particle size analysis was carried out according to the Ocean Dumping Extra Points format (Soilcon, 2003). Each sample was first put through a 2.0 mm dry sieve. The samples were then wet sieved through 1.0 mm, 0.5 mm, 0.25 mm and 0.125 mm sieves and finally the remaining solution was stirred and 20 mL subsamples removed with a volumetric pipette at predetermined time intervals to determine the soil fractions less than 0.063 mm, 0.004 mm and 0.002 mm. The particle size data was also merged and presented in the standard Ocean Dumping format which consists of four broader categories: <0.004 mm, 0.004 - 0.63 mm, 0.63 - 2.00 mm and >2.00 mm.

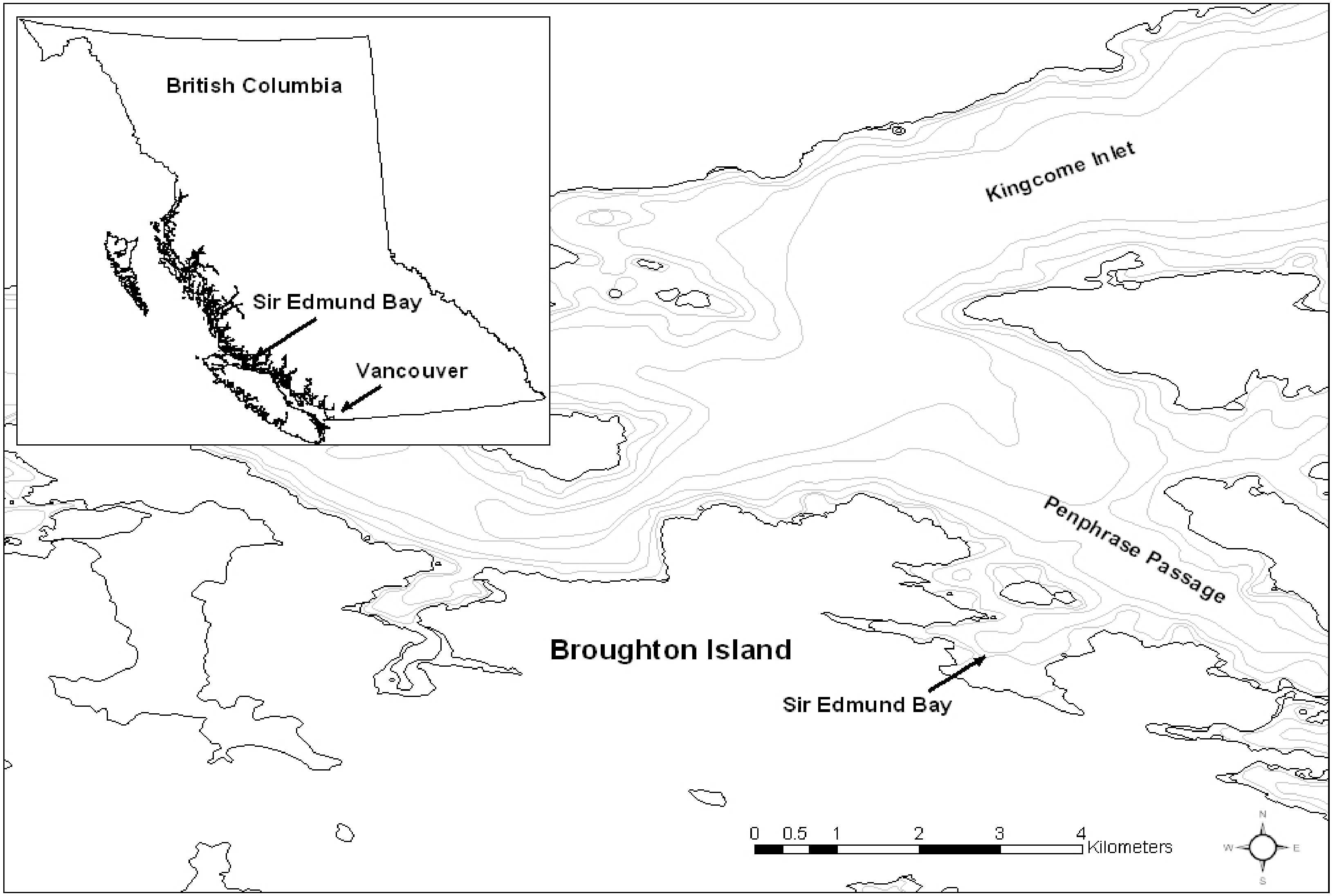

Figure 1. Location of Sir Edmund Bay, British Columbia.

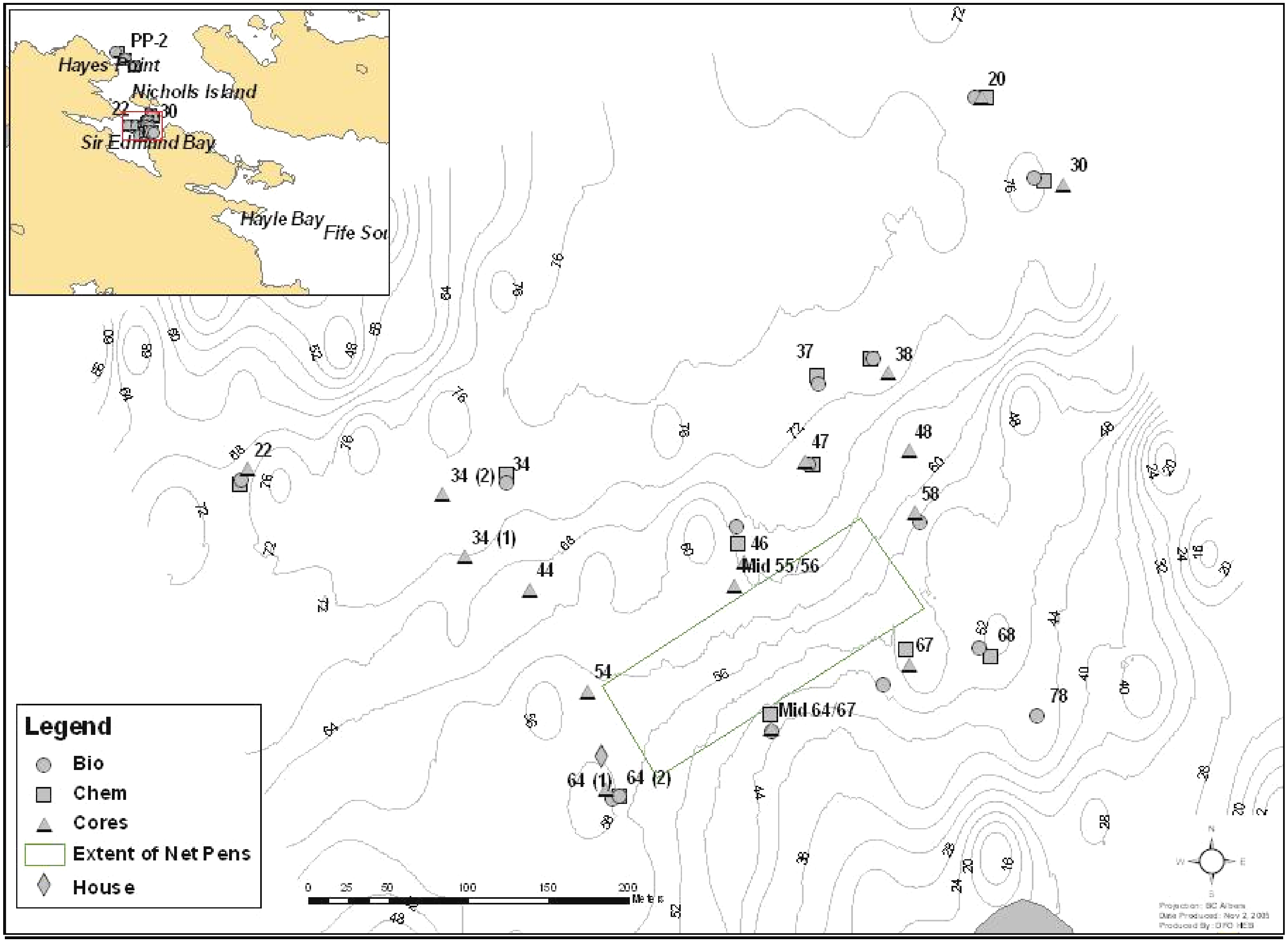

Figure 2. Location of sampling stations and netpen system at Sir Edmund Bay, British Columbia

RESULTS

STATISTICAL COMPARISONS OF SAMPLING VARIABLES BETWEEN REGIONS

The benthic data were pooled into four groups according to their distance from the netpen sustems in Sir Edmund Bay and their reference allocation in the adjoining channel, Penphrase Passage:

1) **Region I**: those samples located within 30 metres of the shoreward netpen perimeter (***shoreward perimeter stations***);
2) Region II: those samples located within 30 metres of the remaining netpen perimeter (***seaward perimeter stations***);
2) **Region III**: those samples beyond 30 metres of the netpen perimeter (***off-site stations***); and
3) **Region IV**: those samples located in Penphrase Passage (***reference stations***).

A 30-m division mark was chosen to distinguish between those stations located in perimeter stations and the off-site stations, since strong decays in sedimentation rates have been observed within the first 30 m from the perimeter of netpen systems in other studies (Stucchi et al. 2005). It is important to note that only one netpen system was in position during the sampling period (Figure 2). Although a second netpen system was not present during the sampling period (June, 2003) and does not appear in Figure 2, it was present for the recent growout cycle which occurred between March 2001 and March 2003. The perimeter stations that border both netpen systems were divided into two groups (shoreward and seaward) as outlined in Table 2. Statistical comparisons of the various sampling variables associated with a tracer of waste material, environmental variables of interest, evidence of organic enrichment, and faunal groups were carried out between the 4 regions (Table 3). A One-Factor ANOVA and post-hoc Tukey test was carried out on each variable of interest to distinguish differences between regions.

When considering a tracer of waste material, statistical tests were carried out on variables that included zinc content, a ratio of zinc and lithium contents (Yeats et al. 2005), as well as strontium content. A significant difference in zinc content was observed between Region I and the remaining regions (Table 3). Although no statistical difference was observed between regions for strontium and the zinc:lithium ratio, Figure 3 shows that higher mean values and standard deviations of these variables were observed in Region I (inshore perimeter stations) relative to the other regions.

When considering geotechnical and organic enrichment variables, statistical tests were carried out on sediment grain size (silt/clay contents), organic carbon content, nitrogen content, carbon: nitrogen ratio, calcium content, phosphorus content, particulate sulphur content, total sediment sulphide ($S^=$) content (dissolved fraction) and redox potential to determine region-specific differences (Table 3). A statistical difference in the mean cumulative silt content (< 63 µm) and clay contents (< 4 µm and <2 µm) was across the sampling regions. A post-hoc Tukey test revealed that the mean silt and clay contents observed in Penphrase Passage (reference stations) were different than those of the 3 Sir Edmund Bay sampling regions (perimeter and off-site stations). Both calcium and phosphorus contents, which have relatively high concentrations in feed pellets (Petersen et al. 2005) showed significant differences between Region I (shoreward perimeter stations) and the remaining stations. Figure A7 shows high concentrations of calcium and phosphorus at stations 64, 67, and 68. No statistical differences were observed between regions for the following variables: organic carbon content, carbon:nitrogen ratio, and total sediment sulphide concentration. It is important to note that the total sediment sulphide values measured in Region IV were not used in the statistical comparison, since they fell below the calibration threshold of the sulphide probe (< 50 µM). Figure 4 shows the range in total sediment sulphide and redox values observed across the regions. The below-threshold total sediment sulphide values that exist in Region IV that should be viewed with scepticism. Statistical tests were not carried out on redox values, since a recent study by Wildish et al. (2004) states that variations in redox potential values may be due to variations existing at the probe level, rendering redox estimates alone not entirely useful in terms of quantitative assessments. When considering faunal abundances, amphipods showed a significant difference between Region IV (reference stations) and the remaining regions, while bivalves showed a difference between Region III and the remaining regions.

Factors influencing the outcome of these statistical tests include the 1) unequal number of replicates across the regions and 2) large variation in specific sampling variables observed within the perimeter stations. For example, Figure 3 outlines the mean concentrations of several minor metals measured across the 4 regions and shows higher mean values and standard deviations in both strontium and zinc in Region I relative to the other regions. The spatial presentation of sediment variables in relation to the netpen system location within Sir Edmund Bay (Appendix 1) allows one to examine the variation in estimates surrounding the netpen system and other areas.

Table 2. List of stations categorized according to sampling variable and grouped according to sampling region.

Region I : Shoreward Perimeter Stations

Sediment Grain Size	Sediment Organic C, N	Sediment Trace-metals	Sediment Sulphide-Redox	Fauna
	SEB64	SEB64	SEB64(1)	SEB64(1)
			SEB64(2)	SEB64(2)
SEB Midway 64-67	SEB Midway 64-67	SEB Midway 64-67	SEB Midway 64-67	SEB Midway 64-67
SEB67	SEB 67	SEB67	SEB67	SEB67
SEB68	SEB68	SEB68		SEB68
				SEB78

Region II: Seaward Perimeter Stations

Sediment Grain Size	Sediment Organic C, N	Sediment Trace-metals	Sediment Sulphide-Redox	Fauna
SEB34	SEB34	SEB34	SEB34(1)*	SEB34
			SEB34(2)	
SEB37	SEB37	SEB37		SEB37
SEB38	SEB38	SEB38	SEB38	SEB38
			SEB44	
SEB46	SEB46	SEB46	SEB46	SEB46
SEB47	SEB47	SEB47	SEB47	SEB47
			SEB48	
			SEB54	
			SEB Midway 55-56	
			SEB58	SEB58

Region III: Off-site Stations

Sediment Grain Size	Sediment Organic C, N	Sediment Trace-metals	Sediment Sulphide-Redox	Fauna
SEB20	SEB20	SEB20	SEB20	SEB20
SEB22	SEB22	SEB22	SEB22	SEB22
SEB30	SEB30	SEB30	SEB30	SEB30

Region IV: Reference Stations

Sediment Grain Size	Sediment Organic C, N	Sediment Trace-metals	Sediment Sulphide-Redox	Fauna
PP1	PP1	PP1	PP1	PP1
PP2	PP2	PP2	PP2	PP2
PP3	PP3	PP3	PP3	PP3

* (1) and (2) represent duplicate cores at the same station.

Table 3. Summary of statistical comparisons of sampling parameters across regions I, II, and III. The underline connects regions showing statistical similarity.

Sampling Variable	ANOVA P value	Tukey-Kramer test Pair-wise comparison
Tracer of waste material		
Zinc (μg g^{-1})	0.002	Region I Region II Region III Region IV
Zinc: Lithium	0.036	No statistical difference
Strontium (μg g^{-1})	0.025	Region I Region III Region IV Region III Region IV Region II
Environmental variables and Indicators of organic enrichment		
Percent clay (<0.002 mm)	0.003	Region I Region II Region III Region IV
Percent clay (<0.004 mm)	0.003	Region I Region II Region III Region IV
Percent silt (<0.063 mm)	0.013	Region II Region III Region I Region I Region IV
Carbon: Nitrogen	0.095	No statistical difference
Total Organic Carbon	0.056	No statistical difference
Total Nitrogen	0.025	Region I Region III Region IV Region III Region IV Region II
Calcium (μg g^{-1})	0.015	Region I Region II Region III Region IV
Phosphorus (μg g^{-1})	0.018	Region I Region II Region III Region IV
Particulate sulphur (μg g^{-1})	0.008	Region I Region IV Region IV Region II Region III
Total sediment sulphides S$^{=}$ (μM)	0.106	No statistical difference (Region IV not included due to values below calibration threshold).
Faunal Groups		
Arthropod abundance (No. m^{-2})	0.010	Region I Region II Region III Region III Region IV
Copepod abundance (No. m^{-2})	0.759	No statistical difference
Amphipod abundance (No. m^{-2})	0.006	Region I Region II Region III Region IV
Bivalve abundance (No. m^{-2})	0.000	Region I Region II Region IV Region III
Polychaete abundance (No. m^{-2})	0.386	No statistical difference

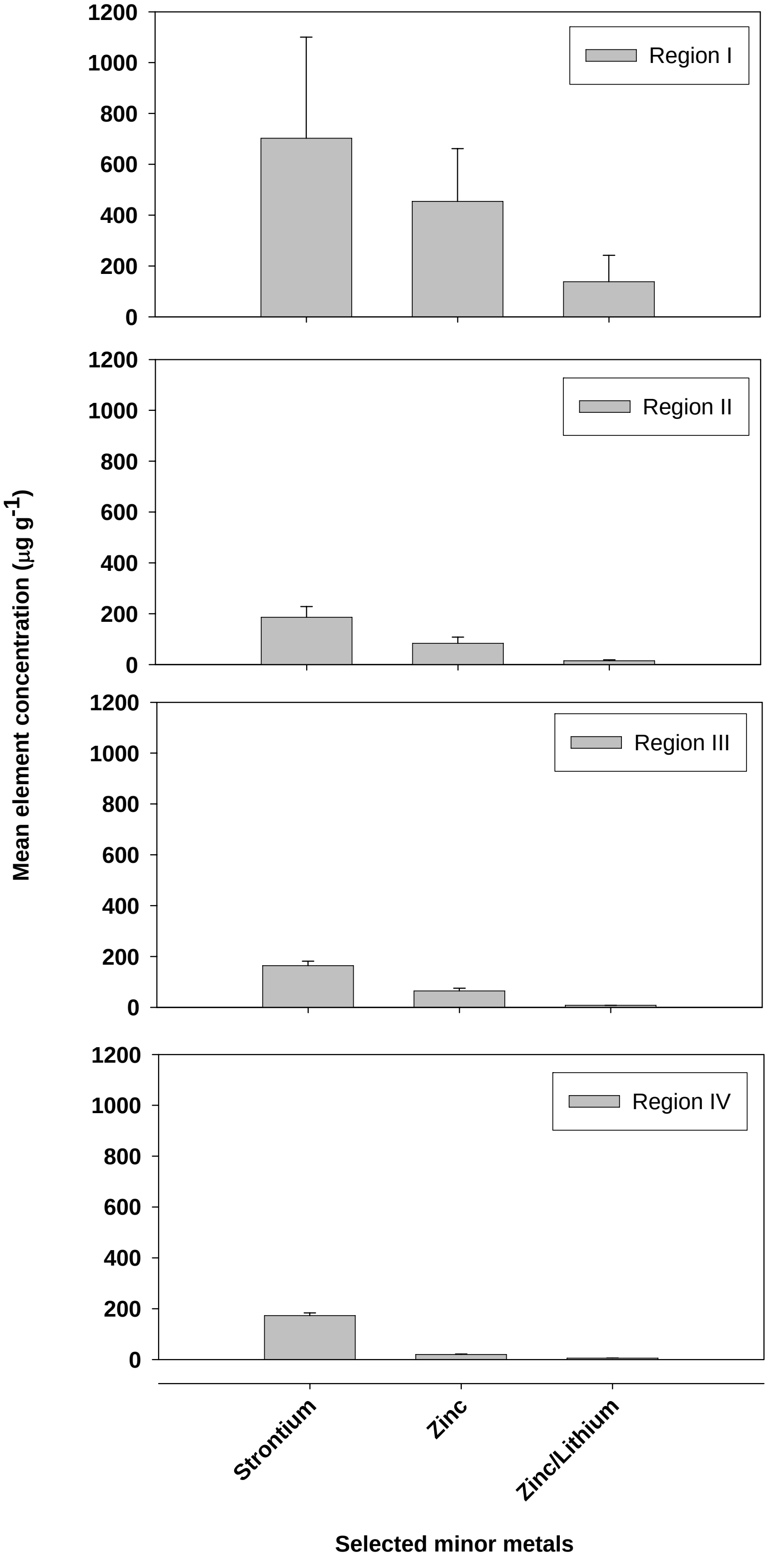

Figure 3. Mean concentration of minor metals observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations)

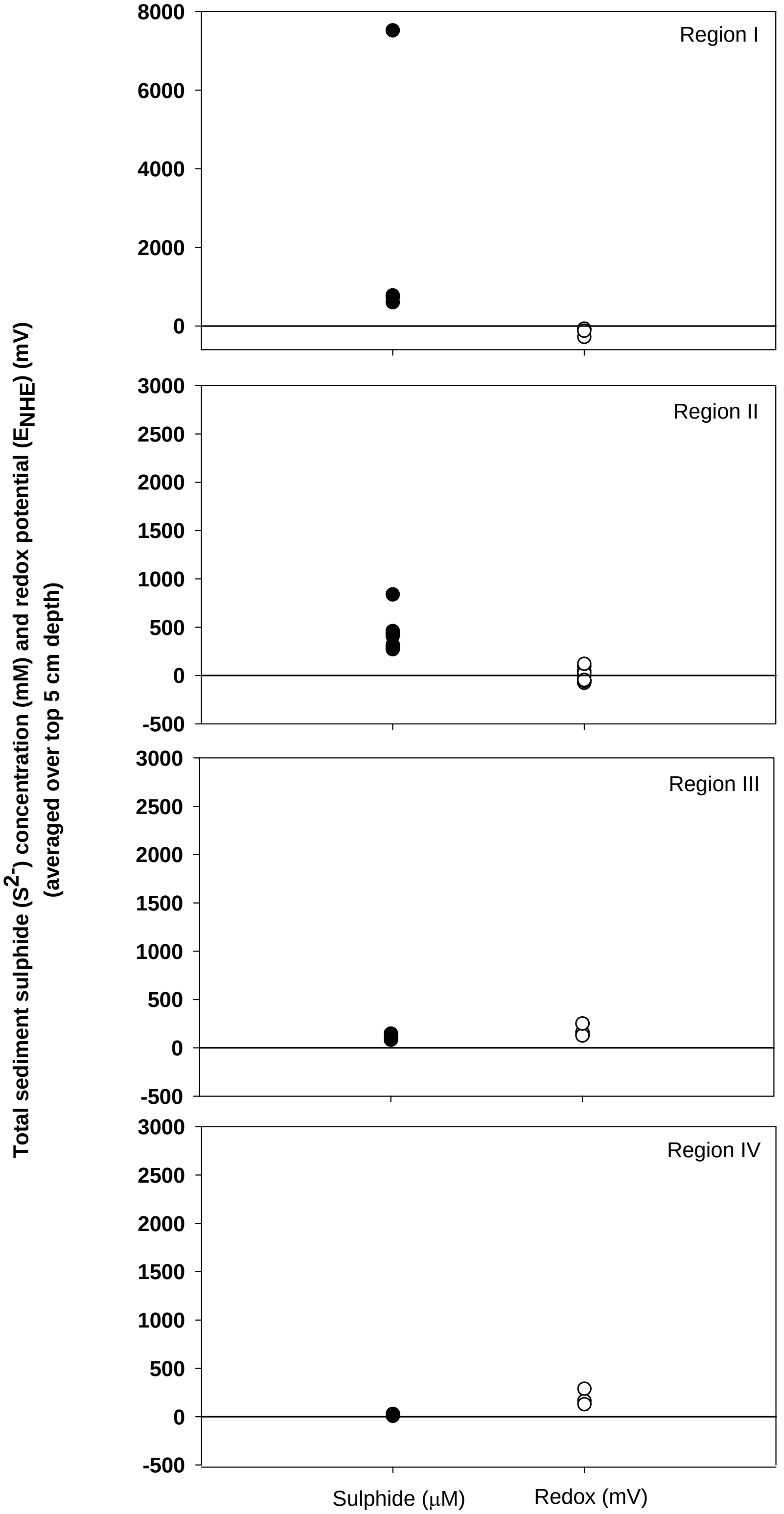

Figure 4. Total sediment sulphide concentrations and redox values (averaged over a sediment depth of 5 cm) observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations). Please note that the majority of sulphide values at the Penphrase Passage reference stations fell below the calibration threshold of the sulphide probe.

IDENTIFICATION OF TRACERS OF WASTE FEED PELLETS AND INDICATORS OF ORGANIC ENRICHMENT

Figure 5 shows the relationship between sediment zinc and lithium content for the current study (solid square symbols, dashed regression line) as well as for Retreat Passage (closed circle symbols, solid regression line), which serves as a far-field reference site within the Broughton Archipelago (Yeats et al. 2005). Three sediment zinc:lithium ratio data points sampled in this study (open square symbols) fall above the background regression line and, thus, were probably influenced by the presence of feed pellet material at Stations 64, 67, and 68 (shoreward perimeter stations).

Figure 6 shows the relationship between redox potential and total sediment sulphide concentration where total sediment sulphide concentrations increase with decreasing redox values. The majority of data points fall within the “Normal” and “Oxic” categories according to the total sediment sulphide levels associated with organic enrichment gradients outlined by Wildish et al. (1999) outlined in Table 1. Small-scale patchiness is evident when comparing the contrasting vertical profiles of total sediment sulphide concentrations of the two core deployments carried out at the same location at station 64 (Station 64(1): Oxic; Station 64(2): Anoxic). It is important to note that the open circle symbols represent those values which fall below the sensitivity threshold of the sulphide probe (50 µM).

THE RELATIONSHIPS BETWEEN FAUNAL GROUPS AND SEDIMENT CHEMISTRY

The relationships between faunal abundance and the 1) ratio of sediment zinc to lithium contents, 2) total sediment sulphide concentrations, and 3) sediment redox potentials are presented in Figures 7 (Arthropod richness), 8 (Arthropod abundance), 9 (Bivalve abundance), 10 (Polychaete abundance), and 11 (Nematode abundance). In general, the arthropod richness, arthropod abundance, and bivalve abundance decrease with increasing total sediment sulphide concentrations and ratios of sediment zinc to lithium contents. However, a similar trend is not observed for polycheate abundance where an increase in polychaetes is observed with increasing metal ratios and total sediment sulphide concentrations. It is important to note that the total sediment sulphide values at stations 34 and 64 are mean values of duplicate cores that were collected at these stations (Figure A12).

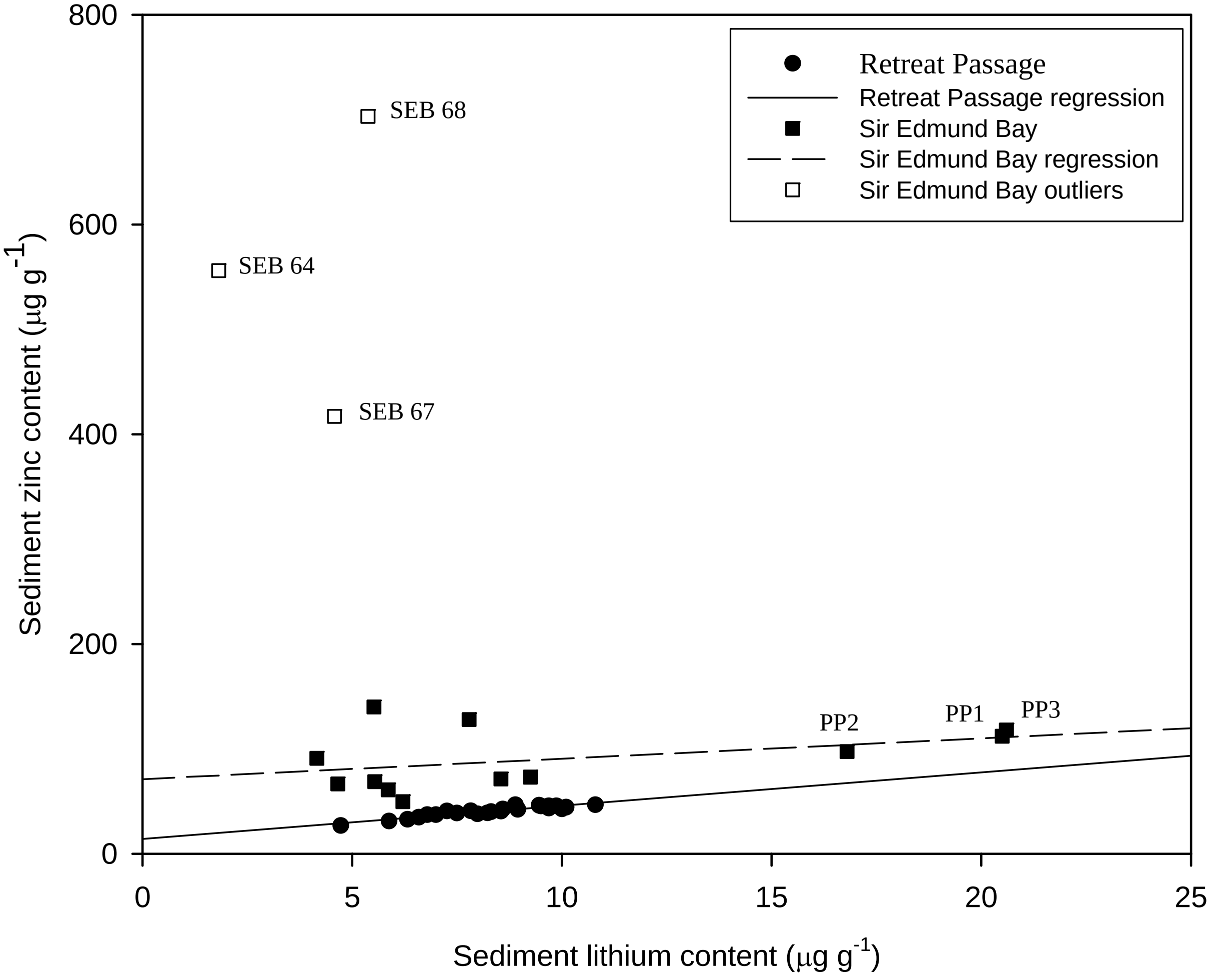

Figure 5. The relationship between sediment zinc and lithium content for two data sets collected in Sir Edmund Bay (solid square symbols) and and Retreat Passage (solid circle symbols). The Retreat Passage data set represent far-field background data from the Broughton Archipelago. The data points represented by open square symbols (Stations 64, 67, 68) reflect outlier points within the Sir Edmund Bay data set.

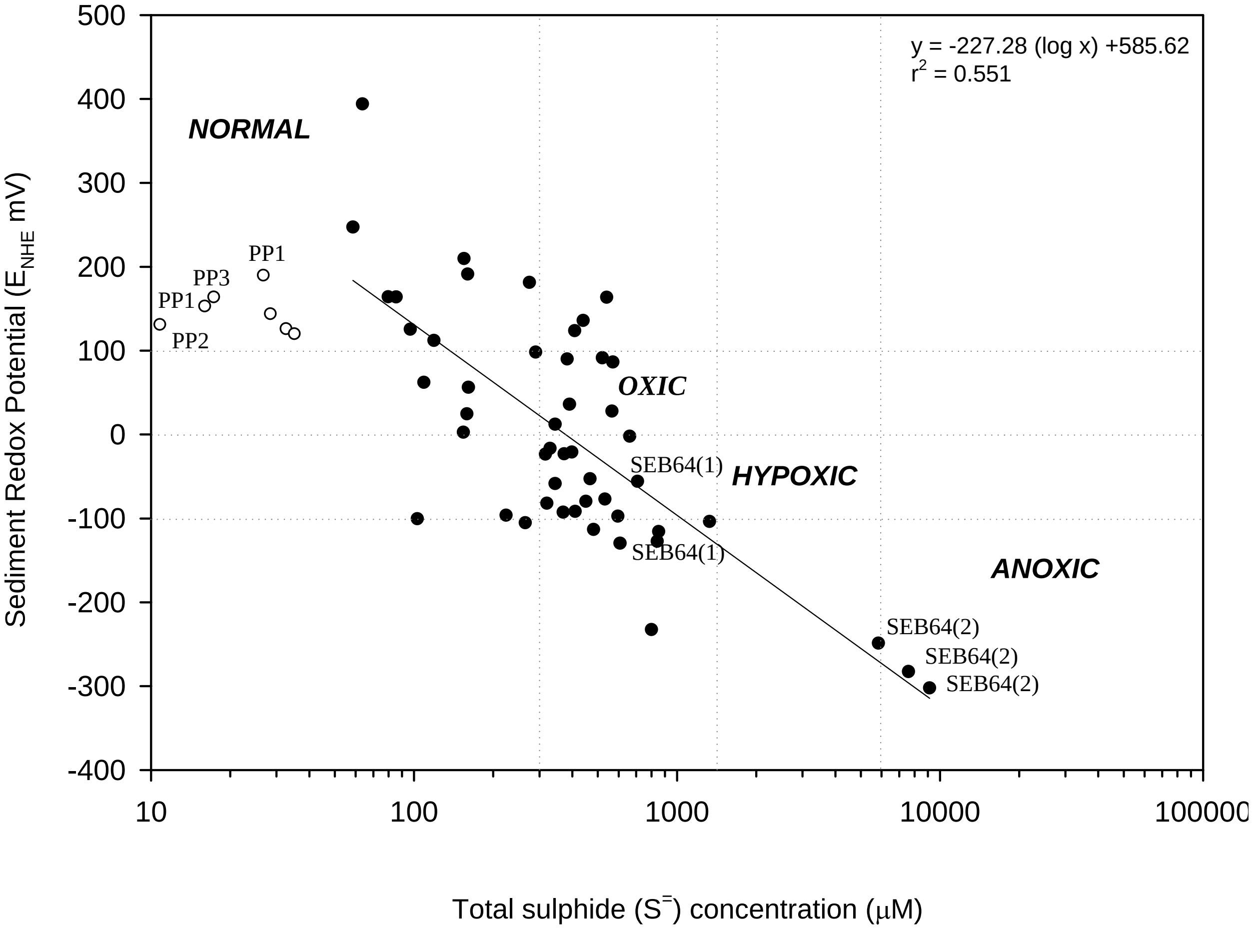

Figure 6. The relationship between sediment redox potential and total sulphide ($S^=$) concentration for Sir Edmund Bay and Penphrase Passage. Data points include those measured at 1 cm, 3 cm, and 5 cm depth intervals at each station. Organic enrichment gradient zones are marked using dashed lines and labelled according to Wildish et al. (1999). The open circles represent those values that fall below the sulphide calibration threshold that are not included in the regression.

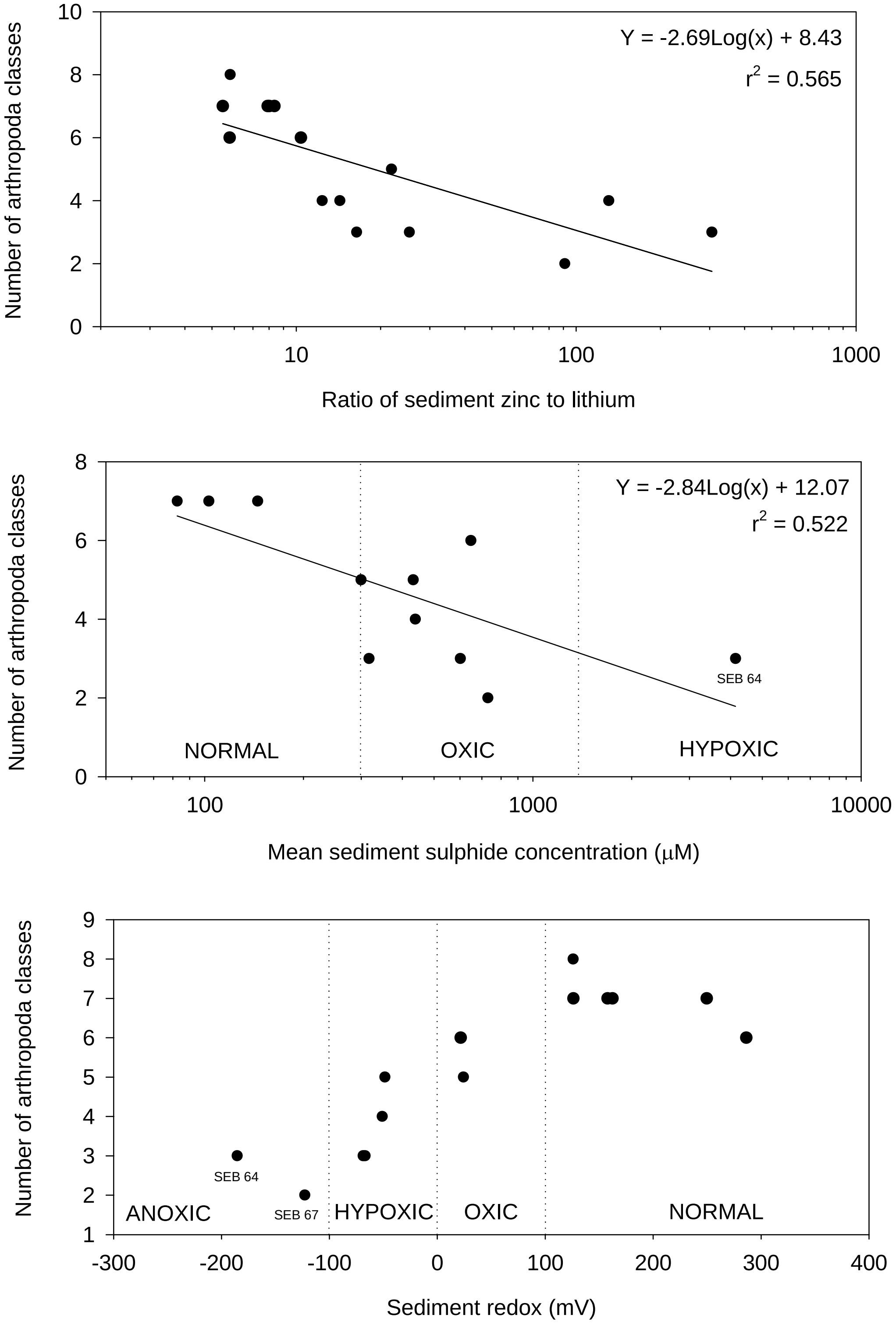

Figure 7. The relationship between arthropoda richness and the ratio of sediment zinc and lithium contents, total sediment sulphide concentration, and sediment Redox Potential. Sulphide and Redox estimates were averaged over the top 6 cm.

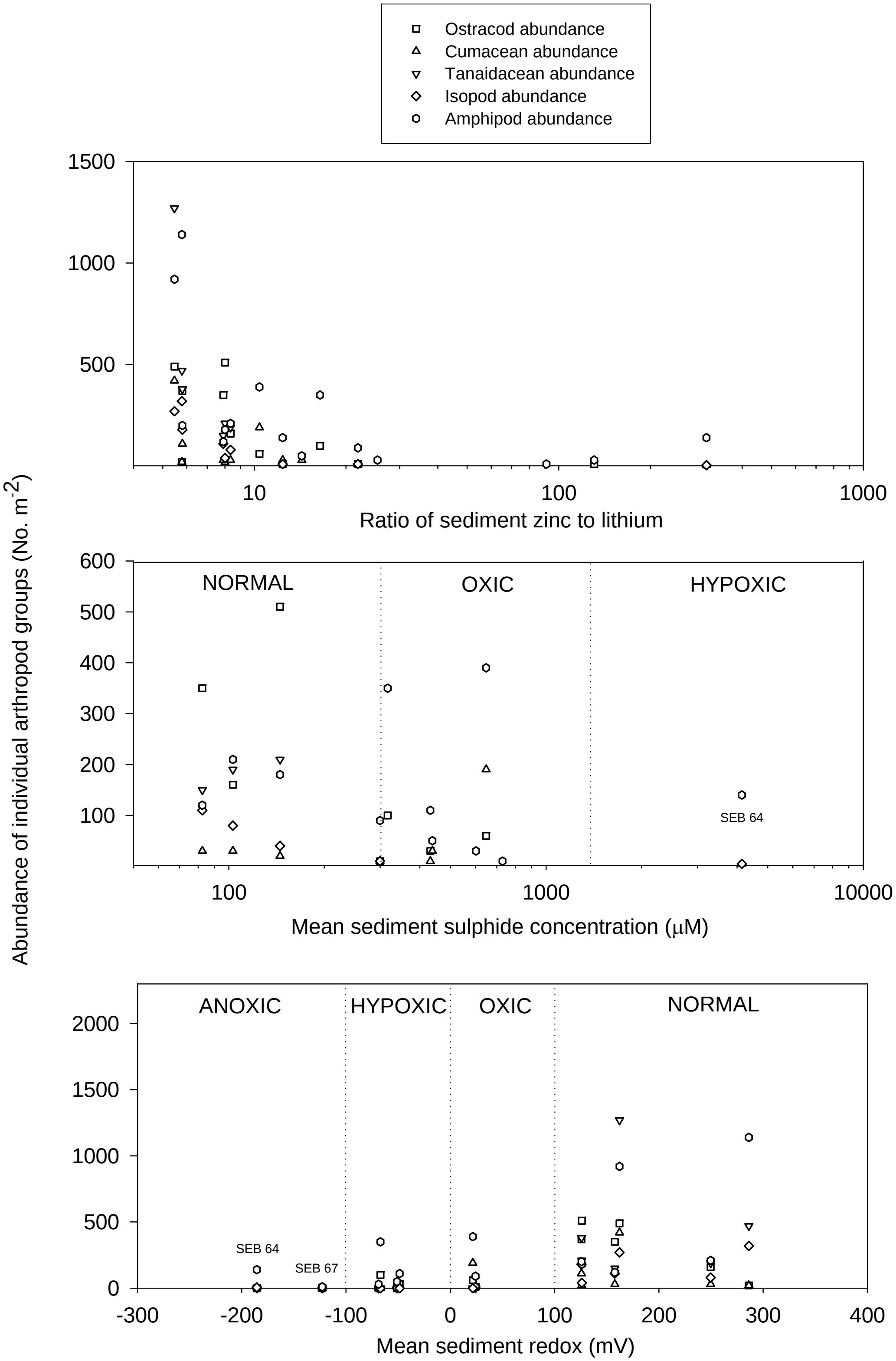

Figure 8. The relationship between the abundance of individual arthropod groups and the ratio of sediment zinc and lithium contents, total sediment sulphide concentration, and sediment Redox Potential estimates. The sulphide and redox data were averaged over the top 6 cm at each station.

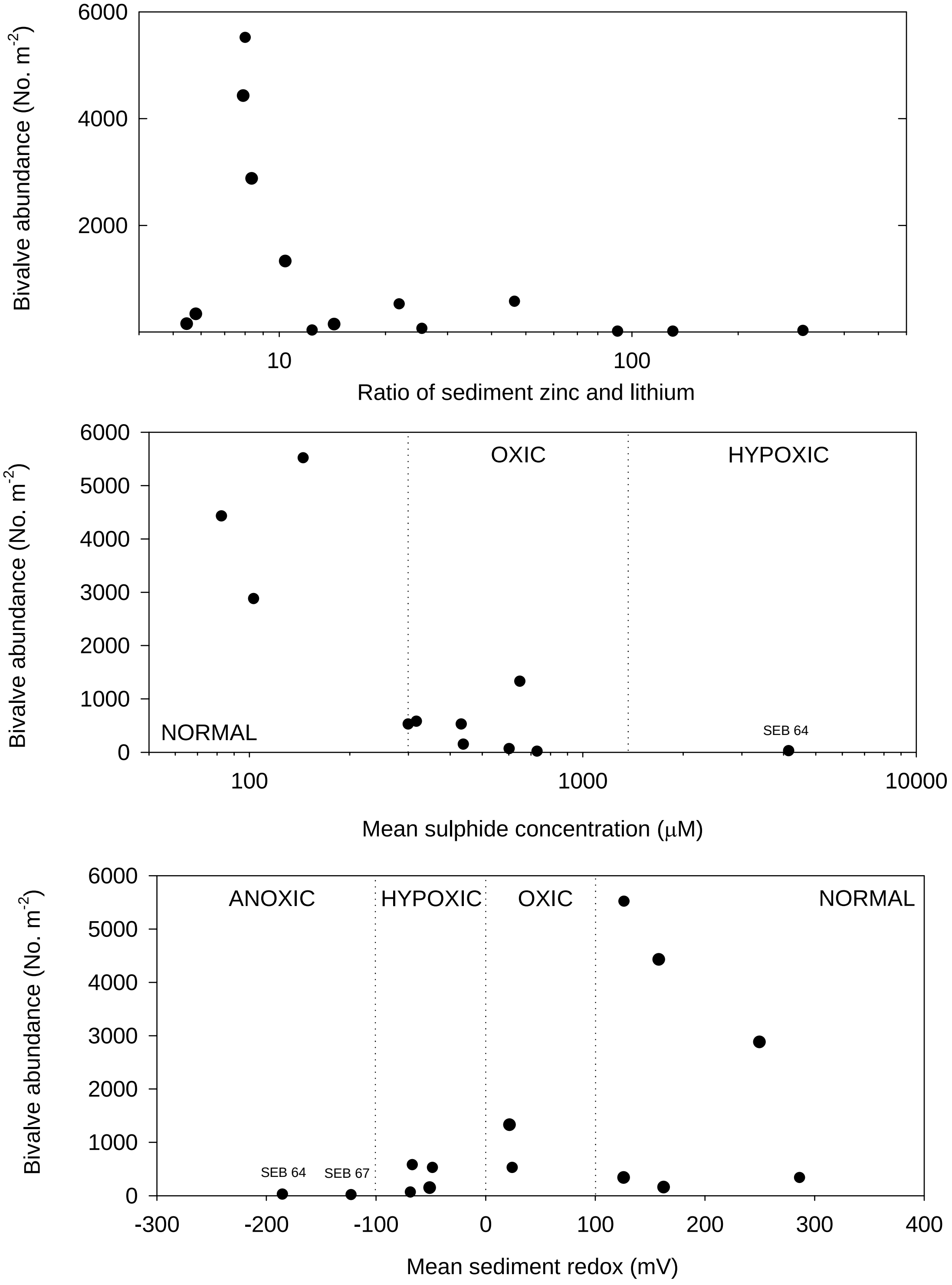

Figure 9. The relationship between bivalve abundance and the ratio of sediment zinc to lithium contents, mean sediment sulphide concentration, and mean sediment redox estimates. The sediment sulphide and redox data have been averaged over the top 6 cm at each station.

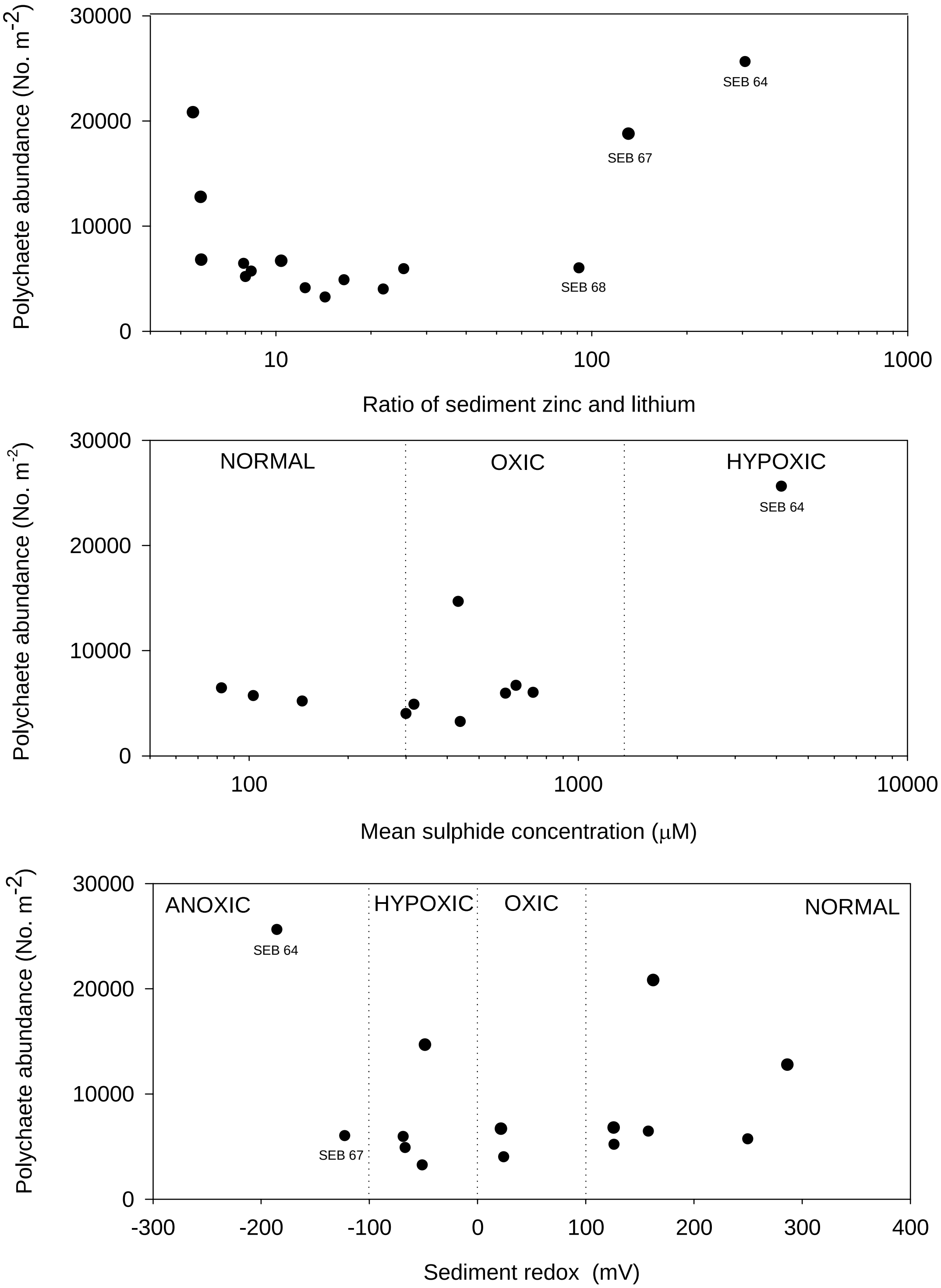

Figure 10. The relationship between polychaeta abundance and the ratio of sediment zinc and lithium contents, mean sulphide concentration, and mean sediment redox estimates. The sediment sulphide and redox data were averaged over the top 6 cm at each station.

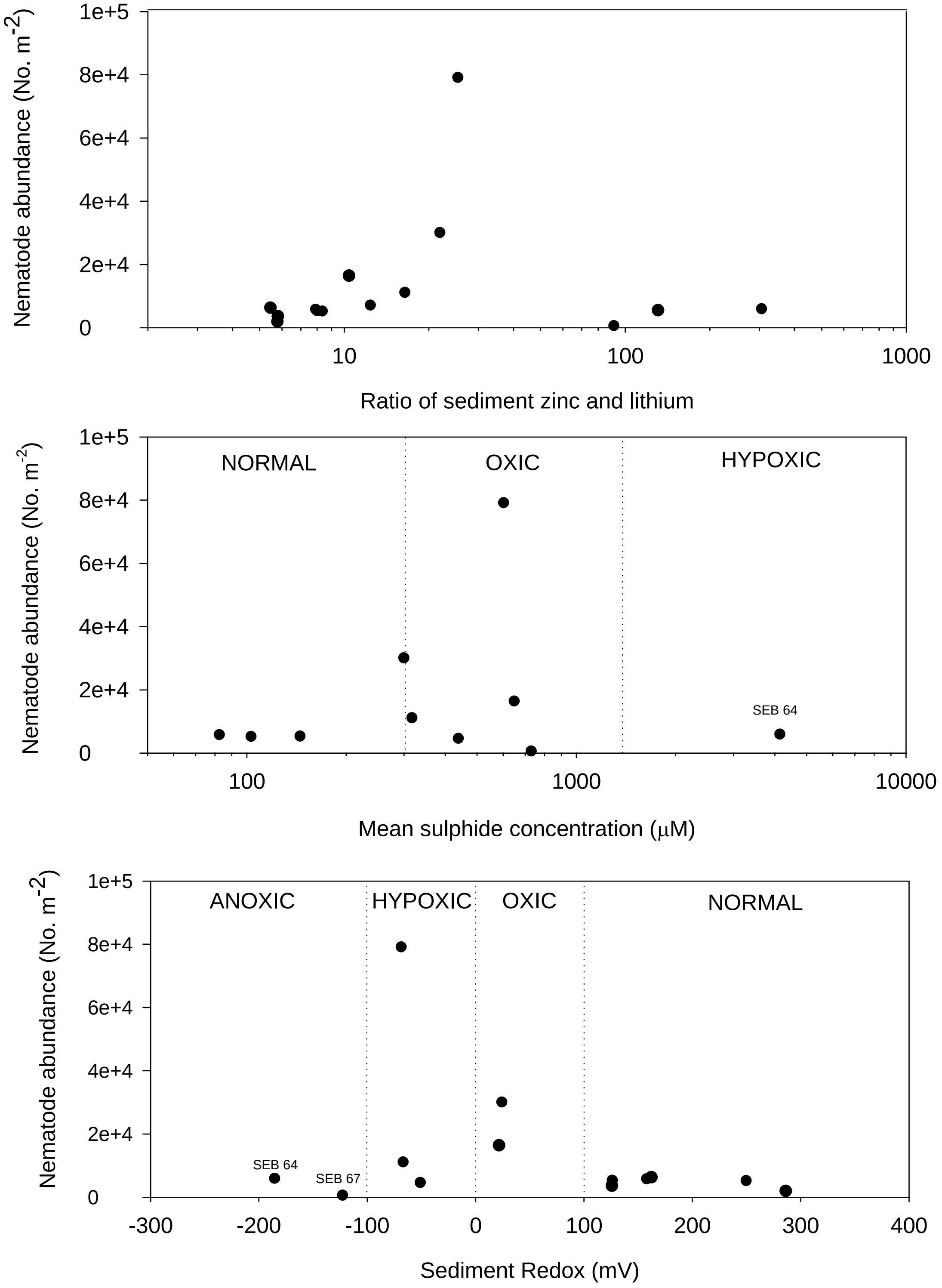

Figure 11. The relationship between nematode abundance and the ratio of sediment zinc and lithium contents, mean sulphide concentration, and mean sediment redox potential estimates. Sediment sulphide and redox data were averaged over the top 6 cm.

DISCUSSION

Three key benthic sampling components are examined to carry out an assessment associated with the potential impact of aquaculture operations on the benthic environment in this study. These components include 1) a tracer of the waste feed material (ex. zinc:lithium ratio); 2) an indicator of organic enrichment (ex. total sediment sulphide concentration); and 3) a faunal response to organic enrichment (ex. polychaete abundance) (Sutherland, 2004). This discussion outlines the trends in the observed data set in context with these three sampling components.

When considering a zinc:lithium ratio tracer, the values observed at stations 64, 67, and 68 (Figure 5) fall well above a regression line describing a naturally-occurring trend of background ratios following the application of a lithium normalization technique (Yeats et al. 2005). Since these three outliers fall outside the confidence limits of this regression line, it is likely that these stations were influenced by the presence of waste feed pellet material. Zinc has been observed to accumulate within organic-rich sediments located near other aquaculture operations (Chou et al. 2002). Relatively high concentrations of both zinc and strontium were observed at these 3 stations (64, 67, and 68) located within the shoreward border of the netpen system which may favour depositional conditions due to netpen baffling effects on waves and currents when compared to that of the seaward border of the netpen system (Figure A10). A significant difference in sediment zinc content was observed between Region I (inshore perimeter stations) and the other Regions (II:seaward perimeter stations; III:off-site stations; IV:reference stations). The high variance in strontium observed in Region I was probably responsible for a lack of statistical difference between regions and suggests that patchy conditions exist within the shoreward perimeter stations. It is interesting to note that calcium and phosphorus concentrations, which exist in high quantities within feed pellets (Petersen et al. 2005), showed a similar trend to that of zinc and strontium with relatively higher concentrations at stations 64, 67, and 68 (Figures A7 and A9). In terms of trace-metal toxicity, the zinc concentrations observed at Stations 64, 67, and 68 fall above the Canadian Council of Ministers of the Environment (CCME) probable effects level (PEL) for zinc (271 mg kg^{-1}) suggesting potential harm to fauna. However, the bioavailability of the zinc present in the sediment needs to be considered when evaluating the toxicity of zinc on the local faunal populations (DFO, 2005).

When considering an indicator of organic enrichment, trends in total sediment sulphide concentrations and ratios of carbon and nitrogen were examined. In terms of the total sediment sulphide ($S^{=}$) concentrations, the values observed in this report were compared to organic enrichment classifications outlined by Wildish et al. (2001) in Table 1. Figure 6 shows that the surface total sediment sulphide values analyzed from the second core deployment at Station 64(2) fall into the Anoxic category according to the organic enrichment criteria. Data falling into the Anoxic category are considered to be potential candidates for a HADD (Wildish et al. 1999). However, the surface total sediment sulphide profiles observed during the first coring attempt at Station 64(1) fell into organic enrichment category level of Oxic. This contrast in total sediment sulphide ($S^{=}$) profiles within one station location reveals a highly patchy benthic environment and results in difficulties when determining an overall zone of impact. It is important to note that it was not possible to retrieve a core for total sediment sulphide ($S^{=}$) analysis at station 68, since the loose, sulphidic-anoxic material would not form a plug in the core barrel. Furthermore, the patchy nature of the benthic environment would be influenced by the presence of boulders as seen by the ROV survey where waste material could accumulate within boulder crevices. Additional evidence for a heterogeneous benthic substrate exists due to the large gap in total sediment sulphide values observed between the second deployment at Station 64 (6000 – 9000 µM) and the remaining stations (< 1300 µM) across the sampling grid.

When considering spatial trends in other environmental variables, the mean sediment chemistry values, such as carbon and nitrogen, (Figures A5 and A6) tended to be higher in Region I (shoreward perimeter stations) than those observed in the other Regions. The trends in carbon and nitrogen distribution are similar to those described above where the carbon and nitrogen concentrations are higher along the inshore perimeter netpen stations relative to the remaining stations (Appendix A5). In addition, pairwise regional comparisons in nitrogen content showed statistical differences between Regions I and II (Table 3).

When considering the faunal response to waste or organic enrichment factors, correlations were observed between the various faunal groups and a tracer of the feed waste material (ex. sediment zinc to lithium ratios) as well as an organic enrichment indicator (ex. total sediment sulphide concentration). In general, the arthropod richness/abundance and bivalve abundance were observed to decrease with an increasing ratio of sediment zinc to lithium contents and an increasing total sediment sulphide concentration (Figures 7, 8, and 9). In addition, linear relationships were observed for arthropod richness and zinc:lithium ratio as well as sediment sulphide concentrations. Brooks and Mahnken (2003) observed a linear relationship between all macrofaunal taxa and total sediment sulphide concentrations in British Columbia.

In terms of the polychaete group, linear correlations between polychaete abundance and the zinc to lithium tracer as well as the sulphide organic enrichment indicator were not evident (Figure 10) as higher values of polychaete densities were observed for at relatively high levels of these sediment variables. This trend is probably due to the fact that two different groups of polychaetes dominated at the stations classified within the Normal and Anoxic categories, exhibiting different responses to the correlated sediment variables (zinc to lithium, sulphide). Capitellids have been shown to dominate in near-field stations characterized by sulphidic-anoxic conditions (Weston, 1990) and were likely present at Stations 64 and 67 contributing to the higher polychaete values. In the future, more taxonomic resolution is required within this faunal group to determine the effects of organic enrichment on non-tolerant species. In summary, although it appears that the benthic environment at stations 64, 67, and 68 was influenced by the presence of waste feed pellet material through geochemical-normalization of zinc concentrations, evidence for organic enrichment according to the sulphide classification system (Table 1) is limited to one of two deployments at Station 64 and likely at 68 where cores were not retrievable. With the exception of polychaetes, faunal groups tended to have relatively low concentrations at stations 64, 67, and 68.

The concentrations and abundances of the sampled benthic variables are presented in relation to the station locations and netpen position in Appendix 1. It is difficult to contour map the benthic variables in this study due to the non-uniform density of the stations located within the proposed systematic grid pattern as the potential to over- or underestimate the variables is high with the sampling pattern (McGrew and Monroe, 1993). As a result a description of the overall spatial trends in benthic variables is also located in Appendix 1.

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APPENDIX 1: SPATIAL DISTRIBUTIONS OF SAMPLING VARIABLES

Data representing benthic sediment, chemical, and faunal properties have been plotted in relation to their position within a proposed sampling grid (Figure 2) and to an empty netpen cluster moored at the time of the study (June 2003). A systematic, aligned grid pattern consisting of 100 stations was designed to serve as a sampling template across the aquaculture lease site in Sir Edmund Bay. As described in the report, stations were focused around the netpen perimeter (Regions I and II), far-field sites within Sir Edmund Bay (Region III), and reference sites in Penphrase Passage (Region IV). Although the intention was not to sample 100 stations within this grid pattern, less than 25% of these stations sampled due to budget and time constraints, netpen obstructions, and logistical difficulties associated with grab/core deployments on a mixed substrate (boulder-field). The unevenness of the spatial layout and density of sampled stations was not conducive for contour mapping which may result in the under- or over-representation of certain areas (McGrew and Monroe, 1993). Thus, data are presented in this appendix according to their position in the proposed sampling grid and in relation to the existing netpen system to help provide an overall picture of spatial trends within these variables. Trends of those variables not discussed in the text are described below.

The sediment grain size distributions observed at stations located in Sir Edmund Bay and Penphrase Passage are presented in Figures A1 and A3 according to the Ocean Dumping Protocol categories and the Ocean Dumping Protocol Extrapoints categories, respectively. It appears that the gravel fraction is relatively low at those stations (22, 34, 37, and 38) located in the deepest part of the basin of Sir Edmund Bay and higher at the remaining stations associated with sloping substrates. Stations sampled side-by-side show similarity in grain size distribution while differences in grain size distribution tend to appear between “station pairs” located more than 30 metres apart, suggesting a patchy environment. In addition, the mean distribution of sediment grain size at Penphrase Passage appears to be different from those observed in the three regions in Sir Edmund Bay (Figures A2 and A4). This finding may be due to the fact that one of the replicates in Penphrase Passage (Region IV) has a different sediment grain size distribution (skewed towards fine sediments) relative to those of the other two replicates in this reference region.

The spatial distribution of sediment metal content is presented in Figure A7 (major elements: calcium, phosphorous, potassium, silicon, and sulphur) and Figure A10 (minor elements: copper, lithium, strontium, and zinc). These elements were analyzed as they have linkages to aquaculture activities through feed inputs, antifouling agents, or benthic enrichment products. In terms of the major elements, the calcium and phosphorous distributions are similar to that of carbon, nitrogen, zinc, and strontium as the major elements are higher at the shoreward perimeter stations 64, 67, and 68 (Figure A7). A statistical difference in both calcium and phosphorus contents was observed between Region I and the remaining Regions.

LIST OF APPENDIX I FIGURES

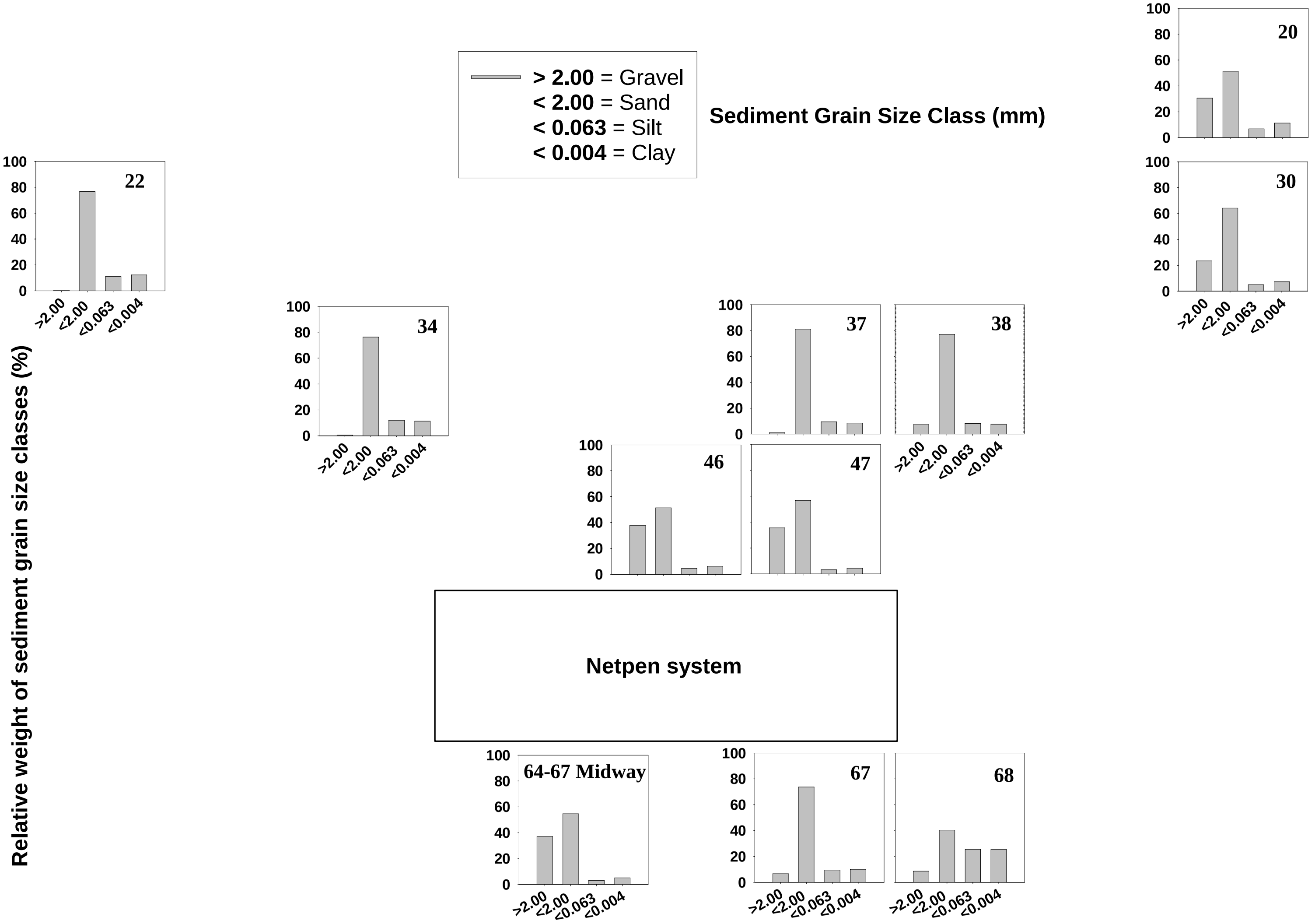

Figure A1. Spatial distribution of sediment grain size fractions (Ocean Dumping categories) observed at stations sampled in Sir Edmund Bay.

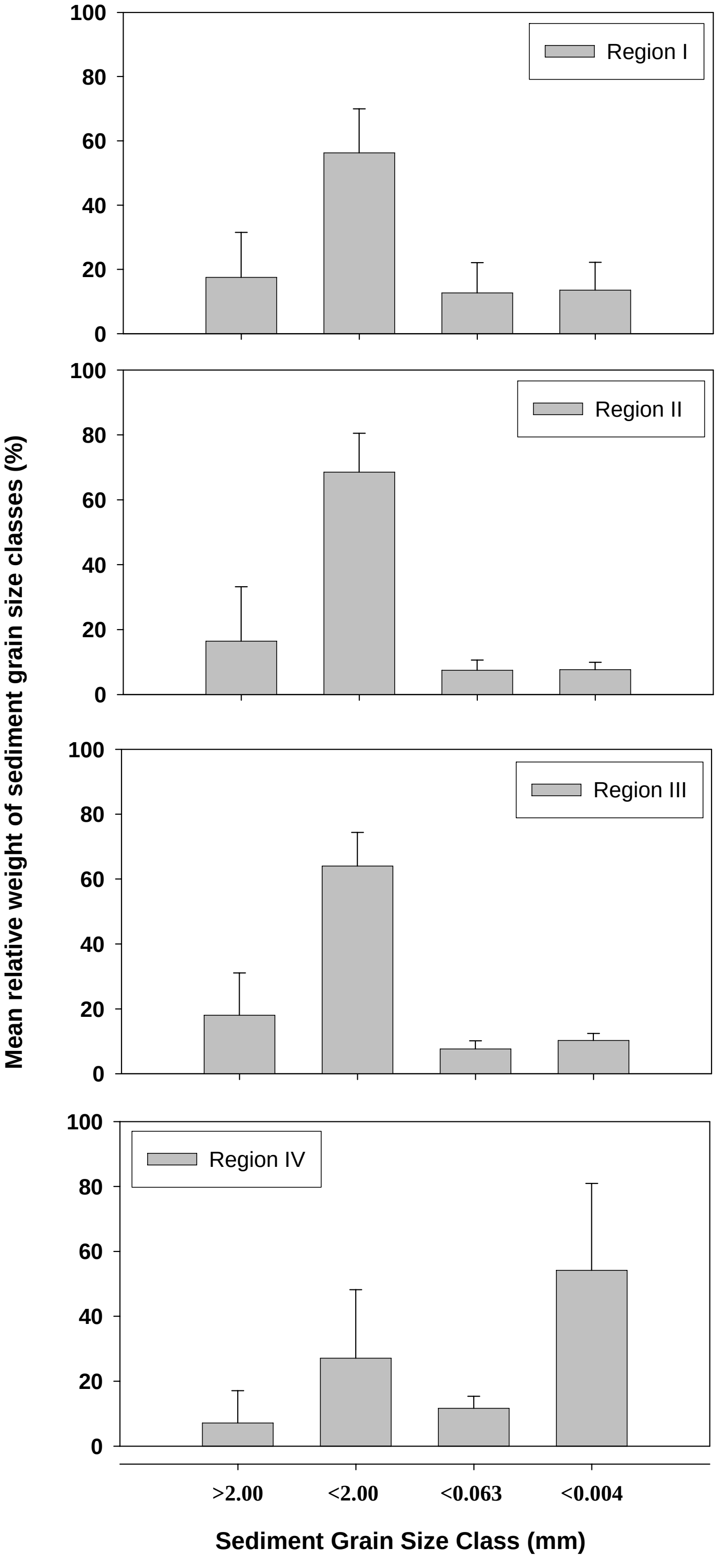

Figure A2. Mean sediment grain size fractions (Ocean Dumping categories) observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations).

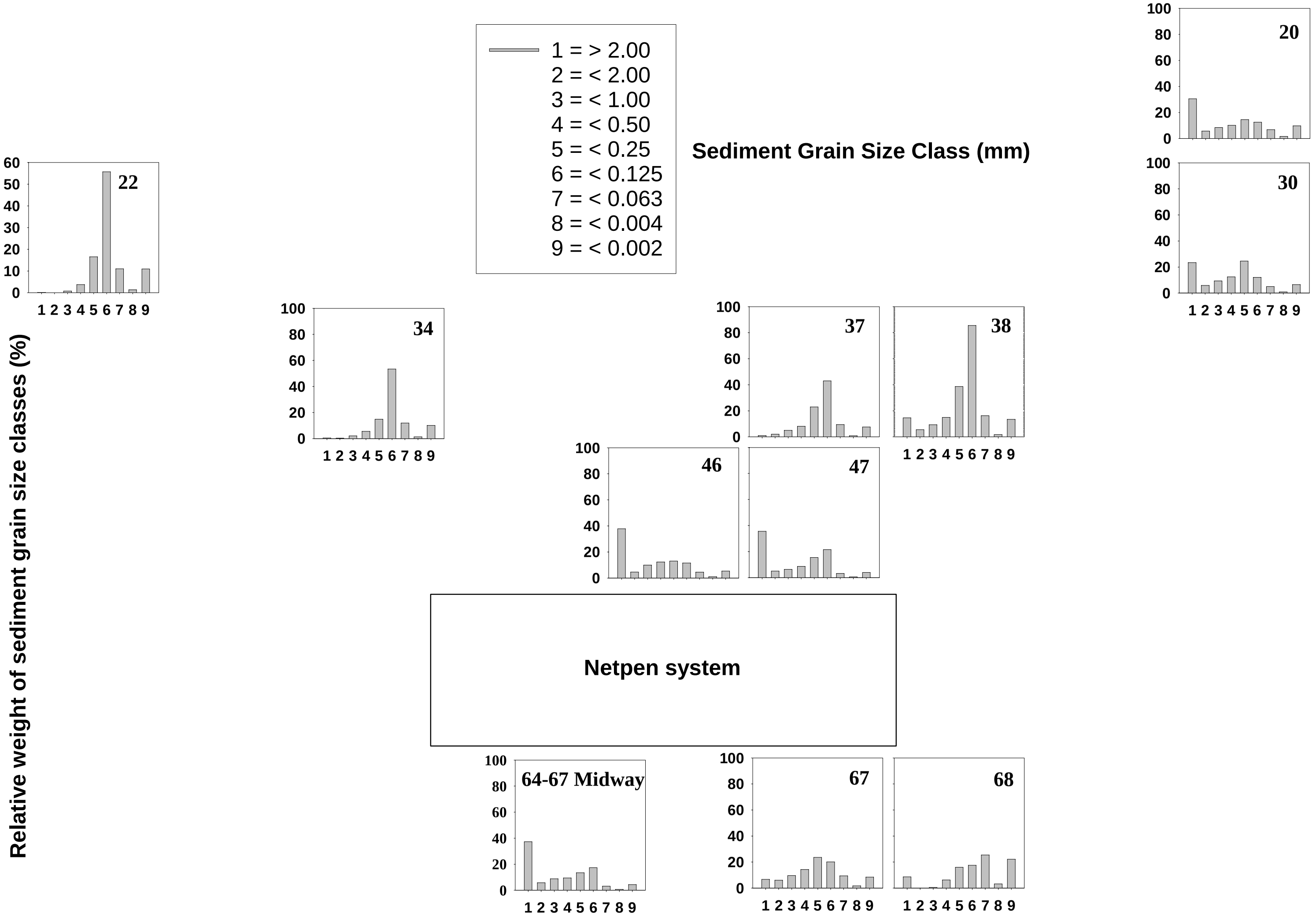

Figure A3. Spatial distribution of sediment grain size fractions (Ocean Dumping Extrapoints categories) observed at stations sampled in Sir Edmund Bay.

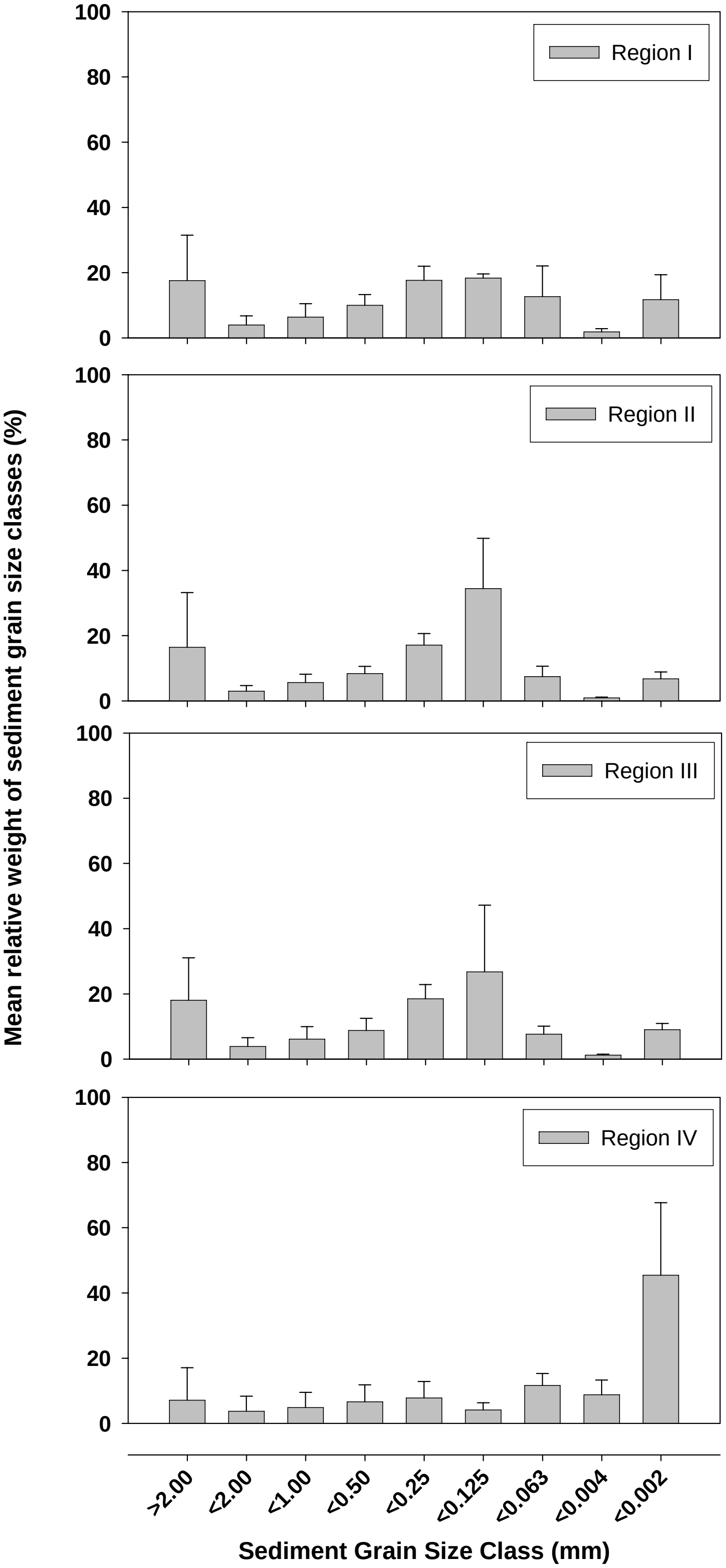

Figure A4. Mean sediment grain size fractions (Ocean Dumping Extrapoints categories) observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-sit stations) and Region IV (reference stations).

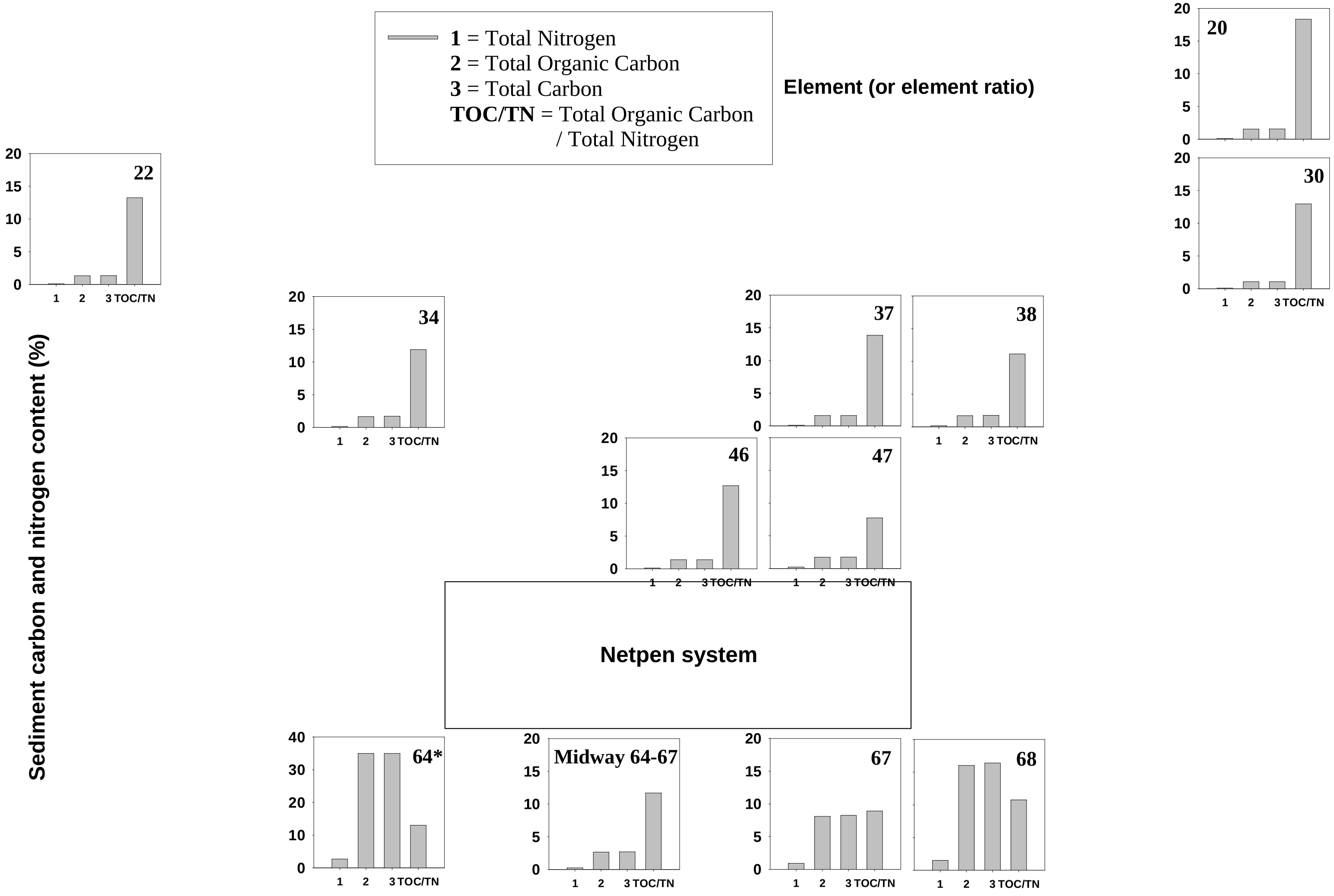

Figure A5. Spatial distribution of sediment carbon and nitrogen estimates observed at stations sampled in Sir Edmund Bay. *Note: all scales standardized except SEB64.

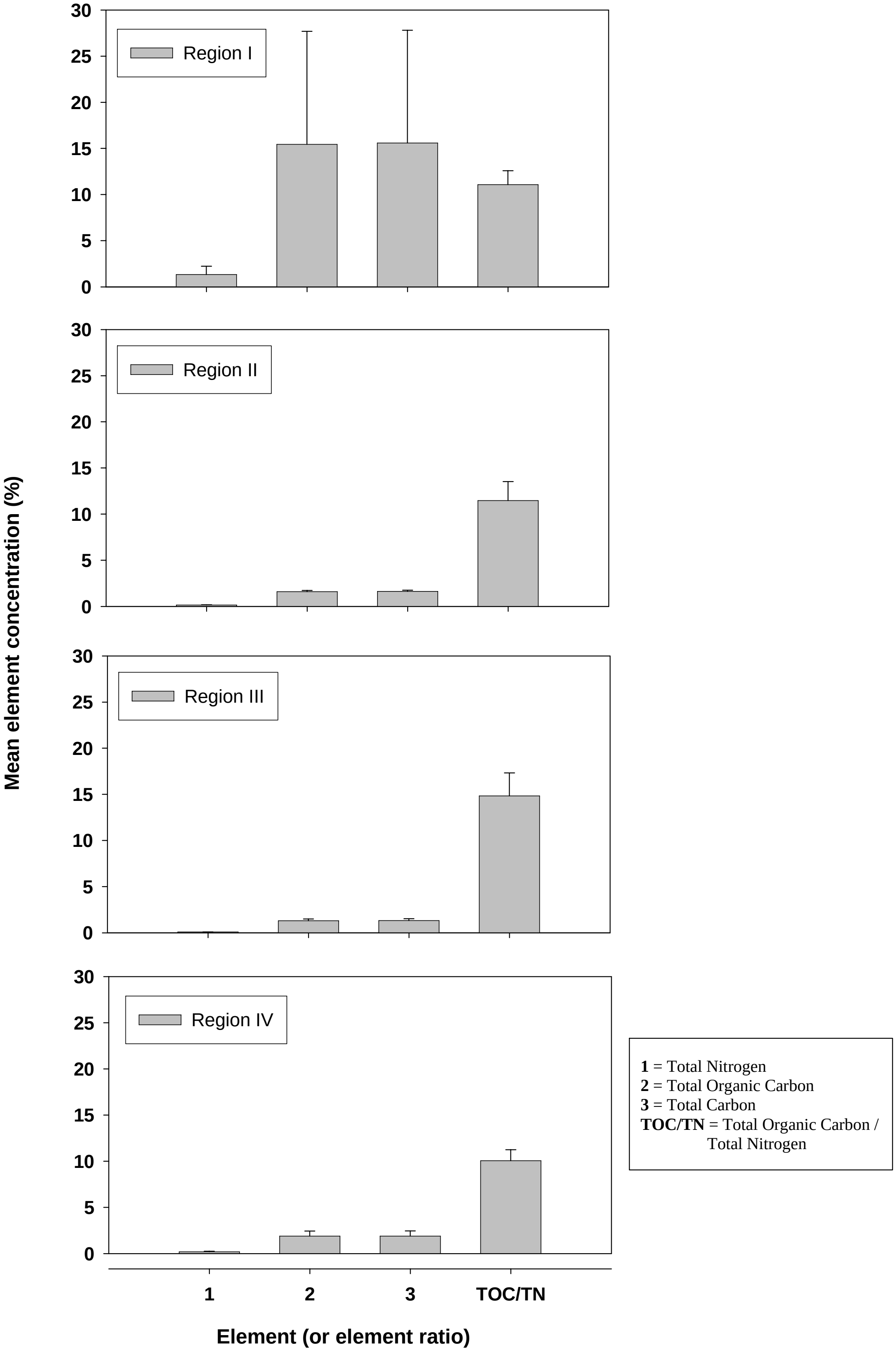

Figure A6. Mean carbon and nitrogen estimates observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations)

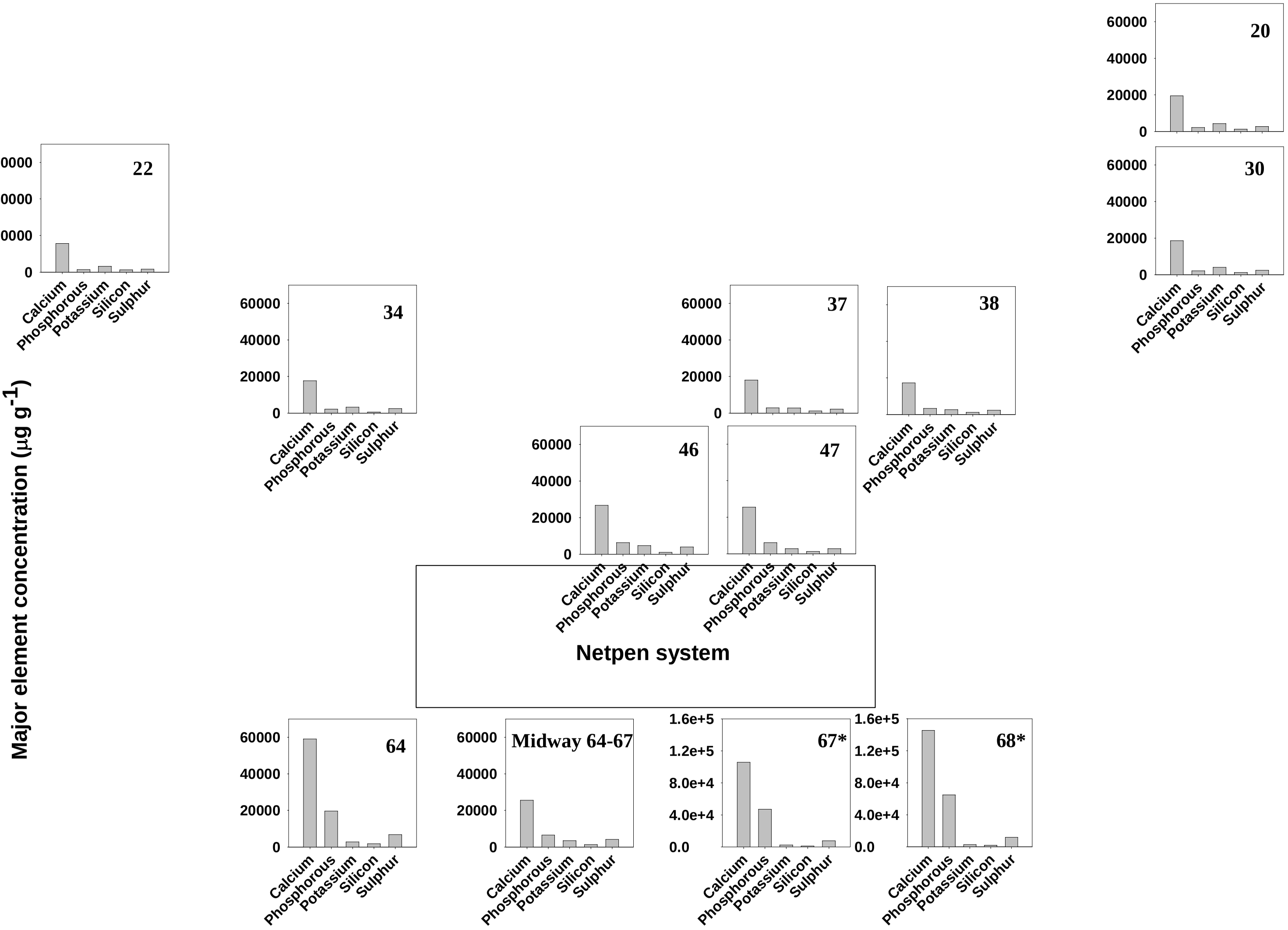

Figure A7. The spatial distribution of sediment metal contents (major elements) observed at stations sampled in Sir Edmund Bay. *Note: all scales standardized except SEB67 and SEB68.

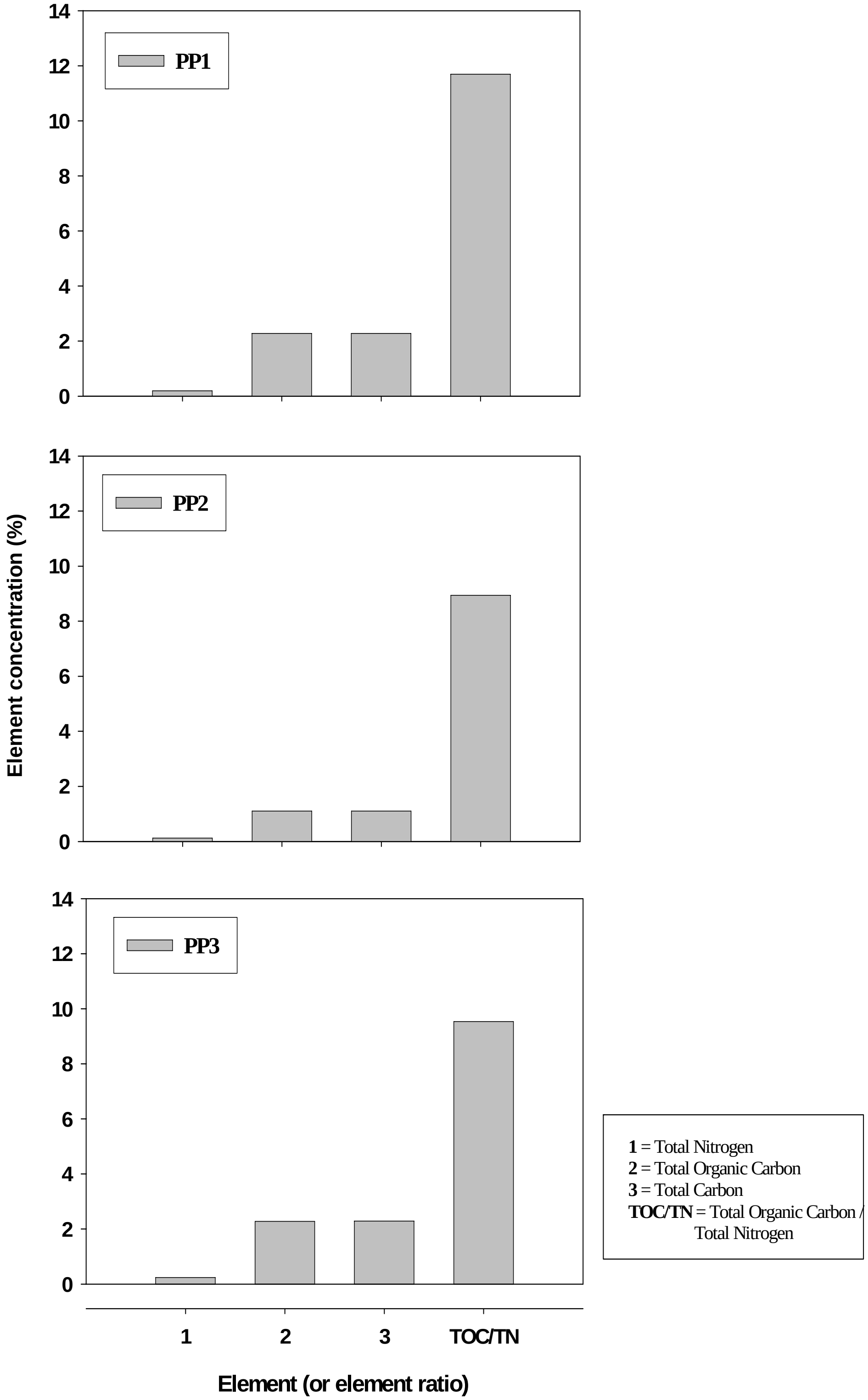

Figure A8**.** Sediment carbon and nitrogen estimates observed at reference stations located in Penphrase Passage.

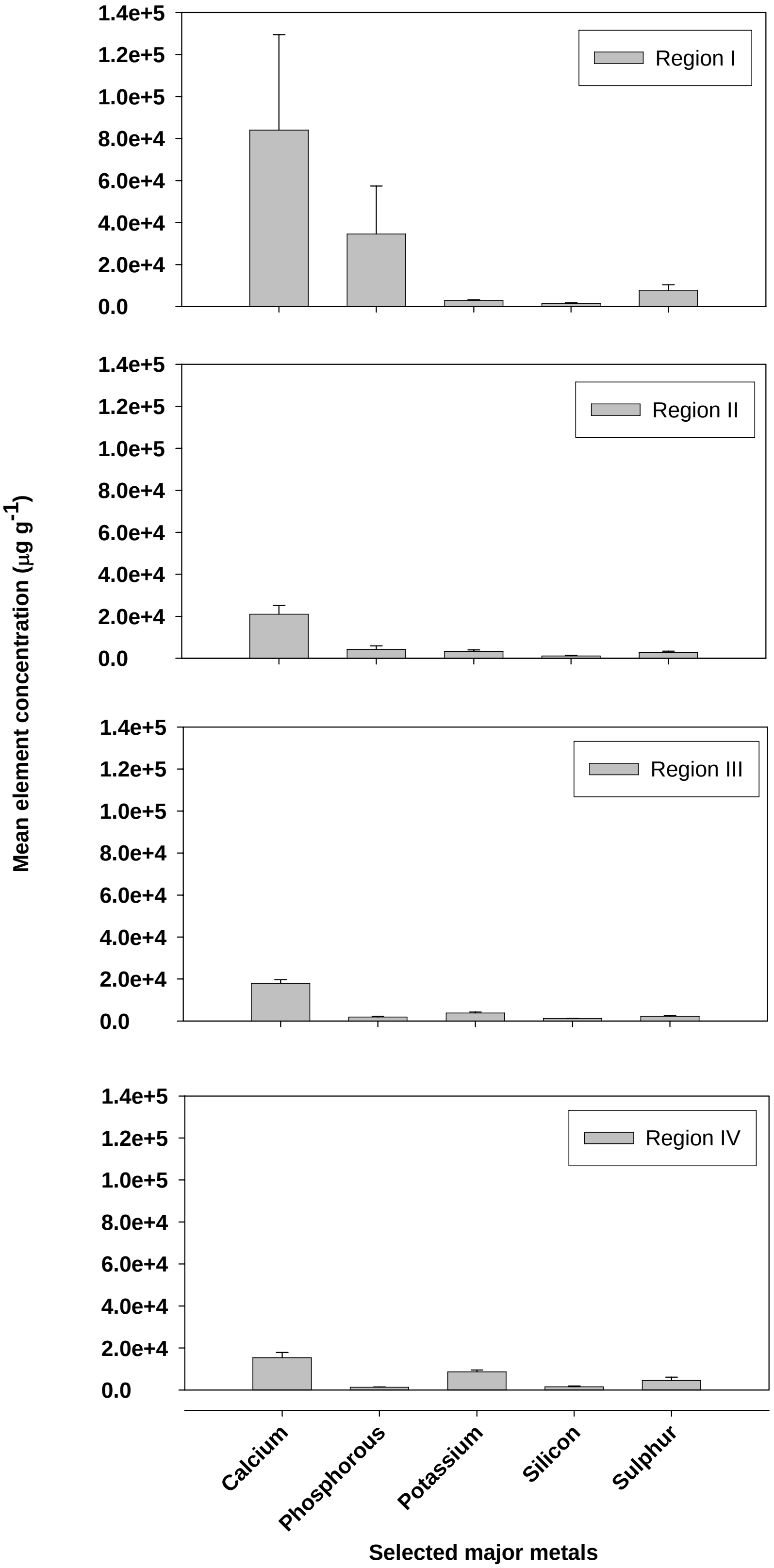

Figure A9. Mean concentration of major metals observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations)

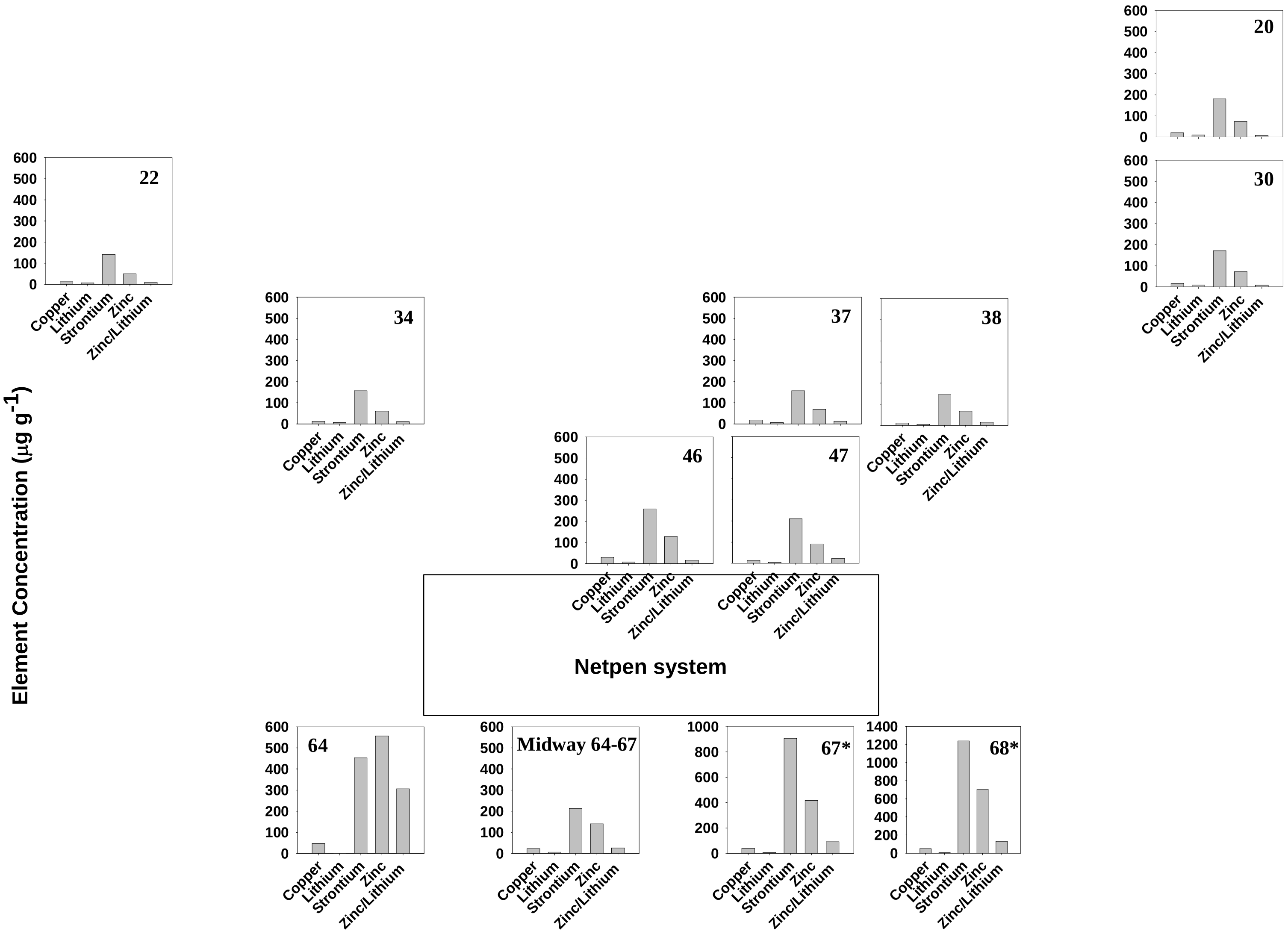

Figure A10. Spatial distribution of sediment metal contents (minor elements) observed at stations sampled in Sir Edmund Bay. *Note: all scales standardized except SEB67 and SEB68.

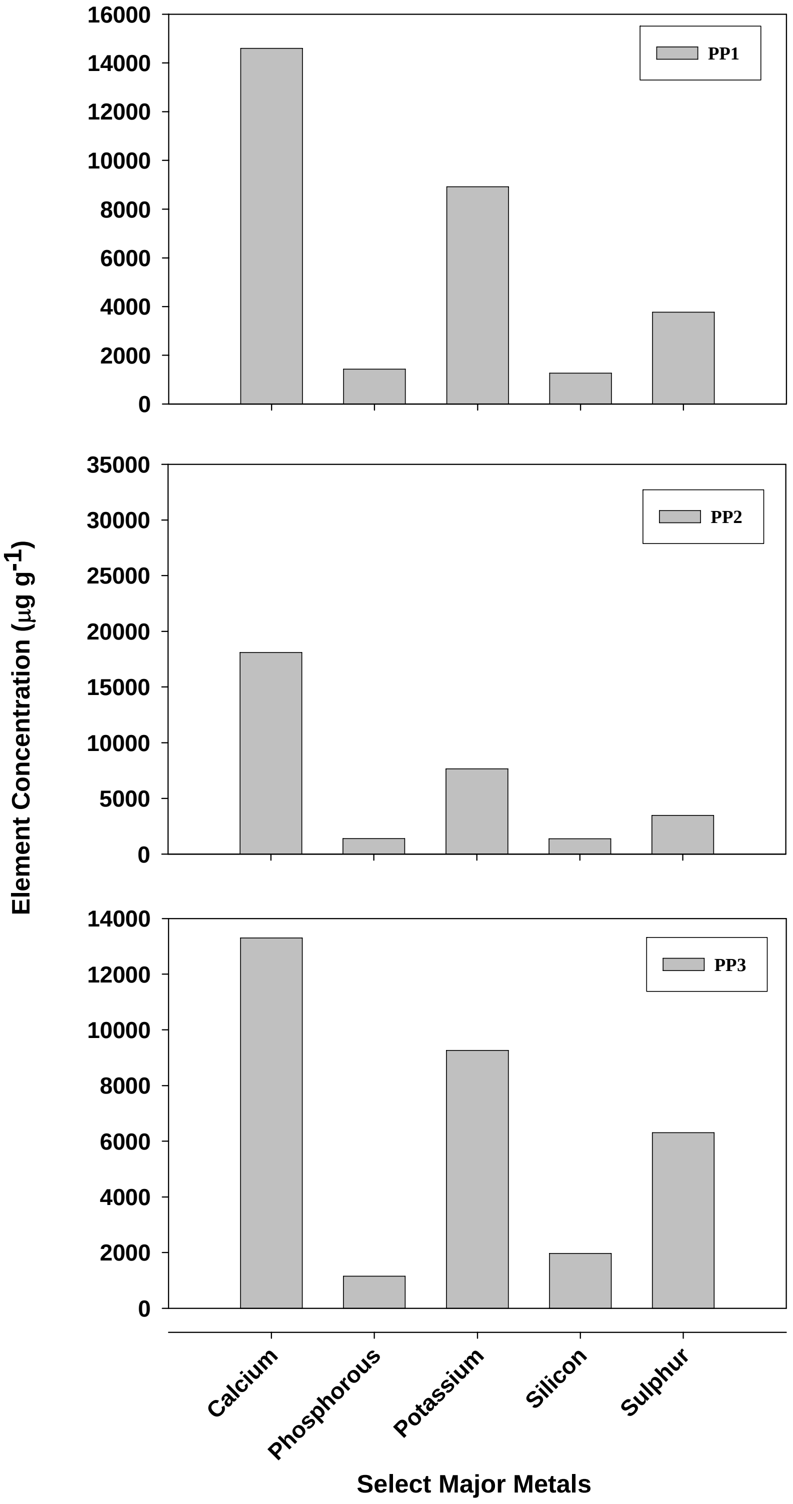

Figure A11. Concentrations of major metals observed at reference stations located in Penphrase Passage.

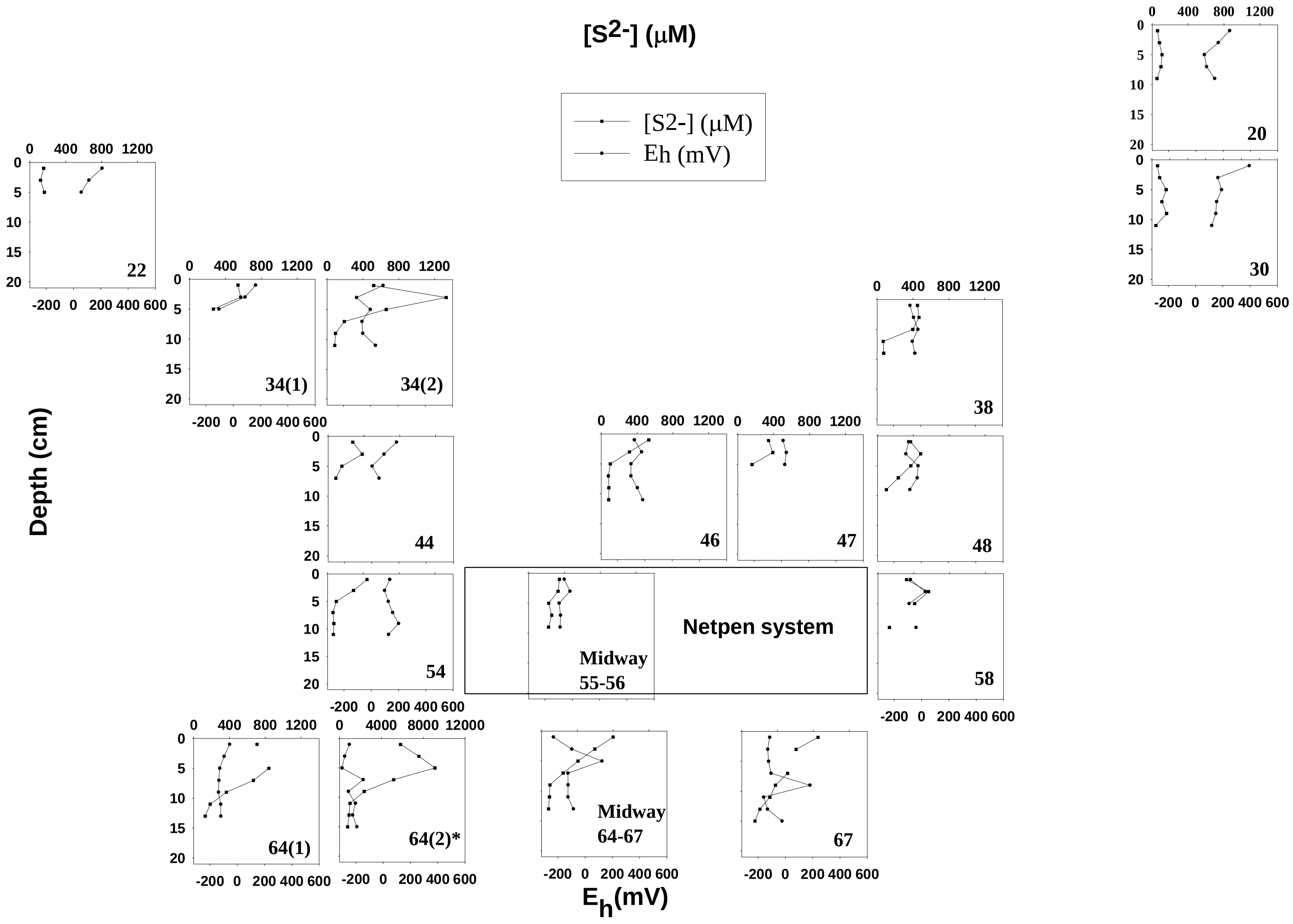

Figure A12. Vertical profiles of sulphide concentrations and redox (E_h) observed at stations sampled in Sir Edmund Bay. *Note: the scales are standardized with the exception of station SEB 64(2).

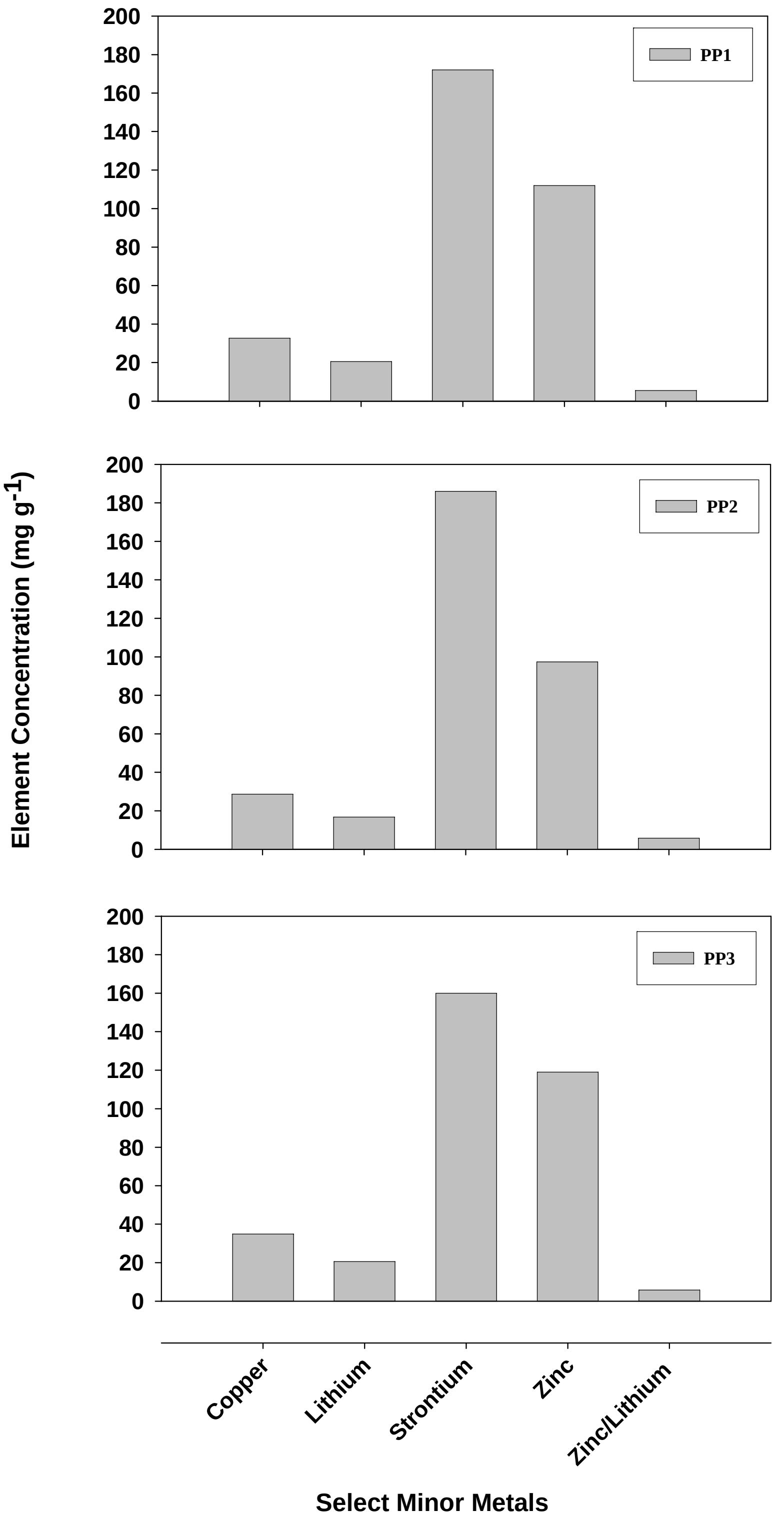

Figure A13. Concentrations of minor metals observed at reference stations located in Penphrase Passage

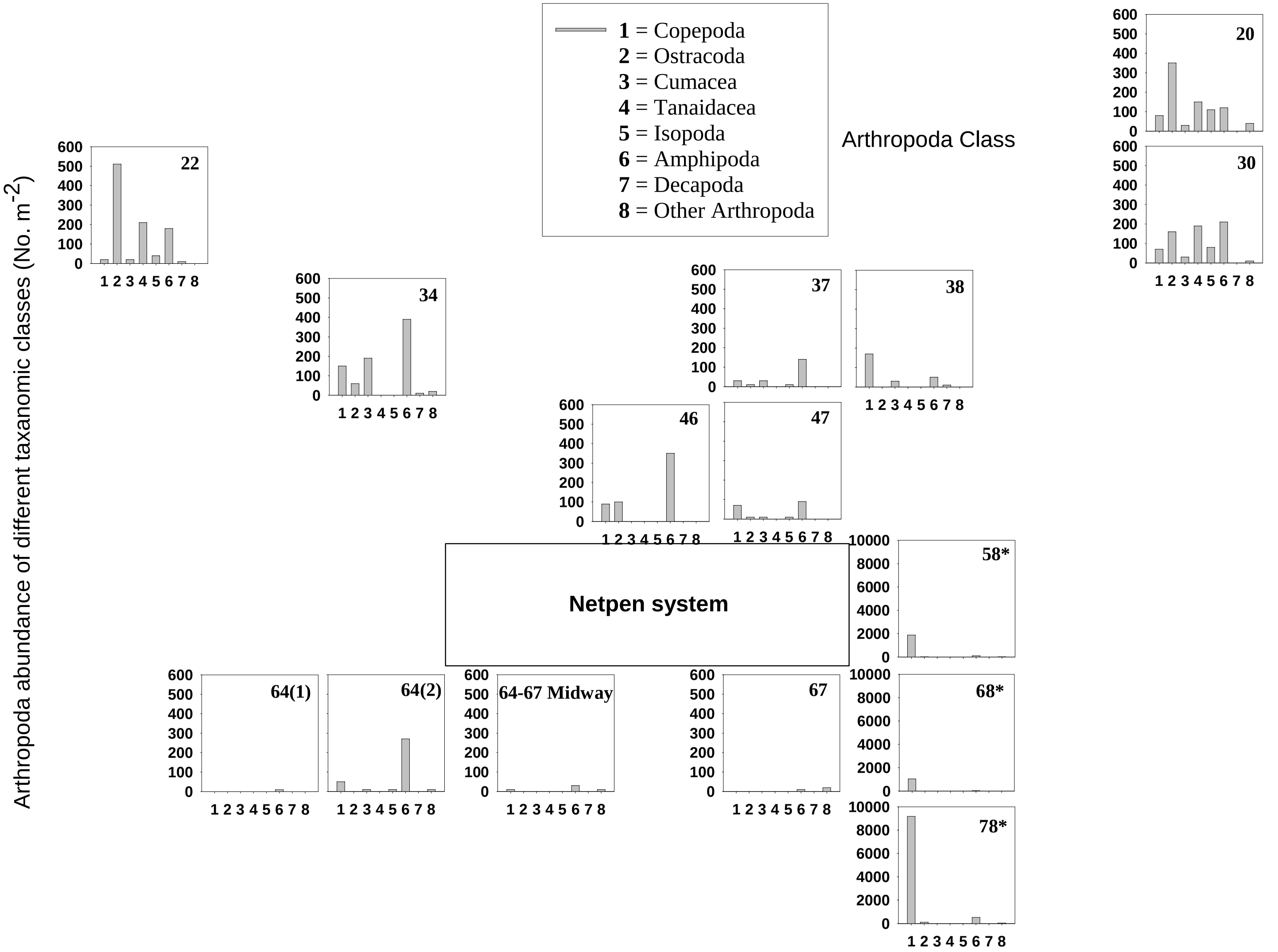

Figure A14. Spatial distribution of arthropoda abundance for different taxanomic classes observed at stations sampled in Sir Edmund Bay. *Note: Scales for stations SEB58, SEB68, and SEB78 standardized to 10,000 to accomodate a larger range of data.

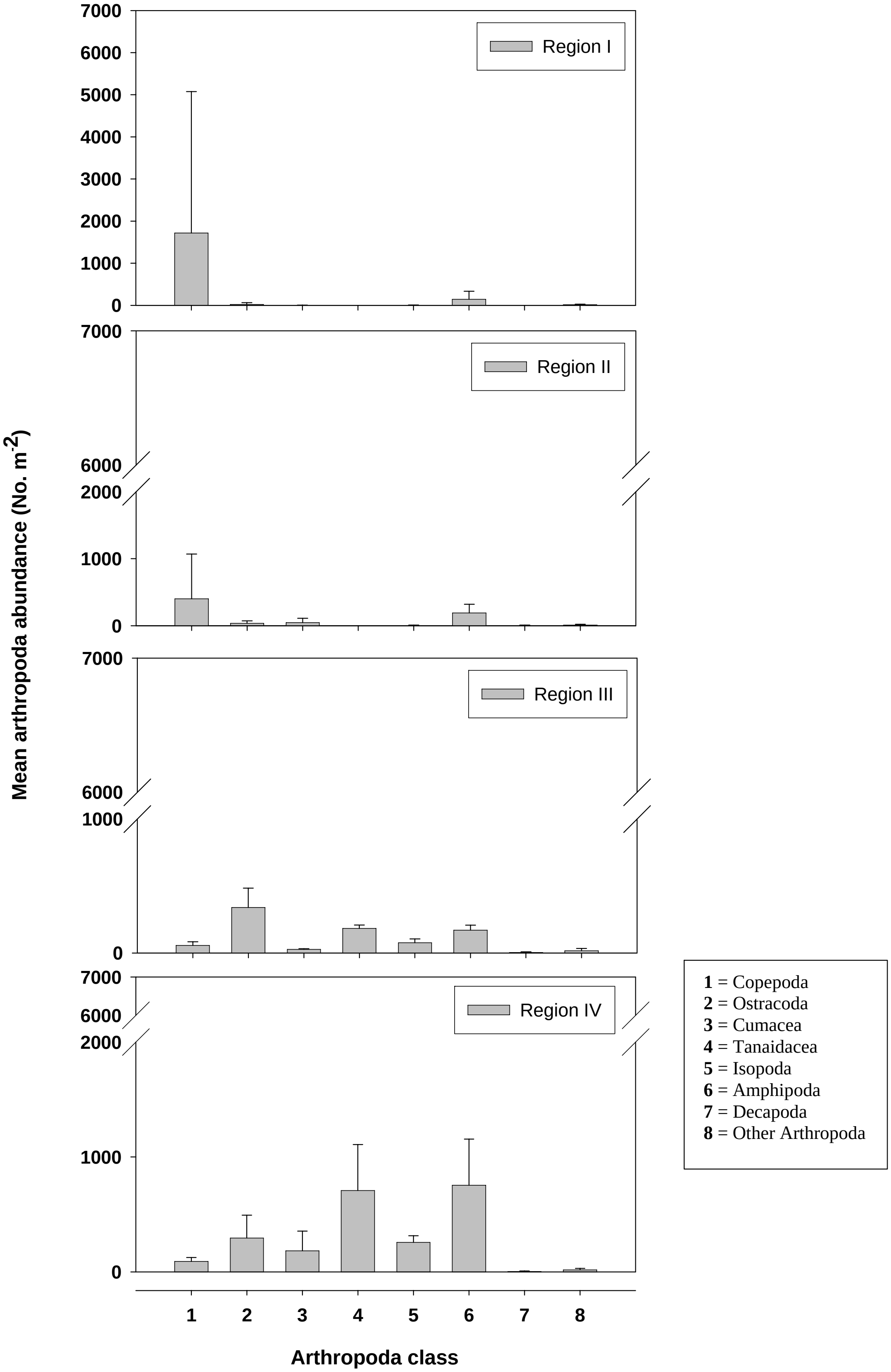

Figure A15. Mean arthropoda abundance for classes observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations).

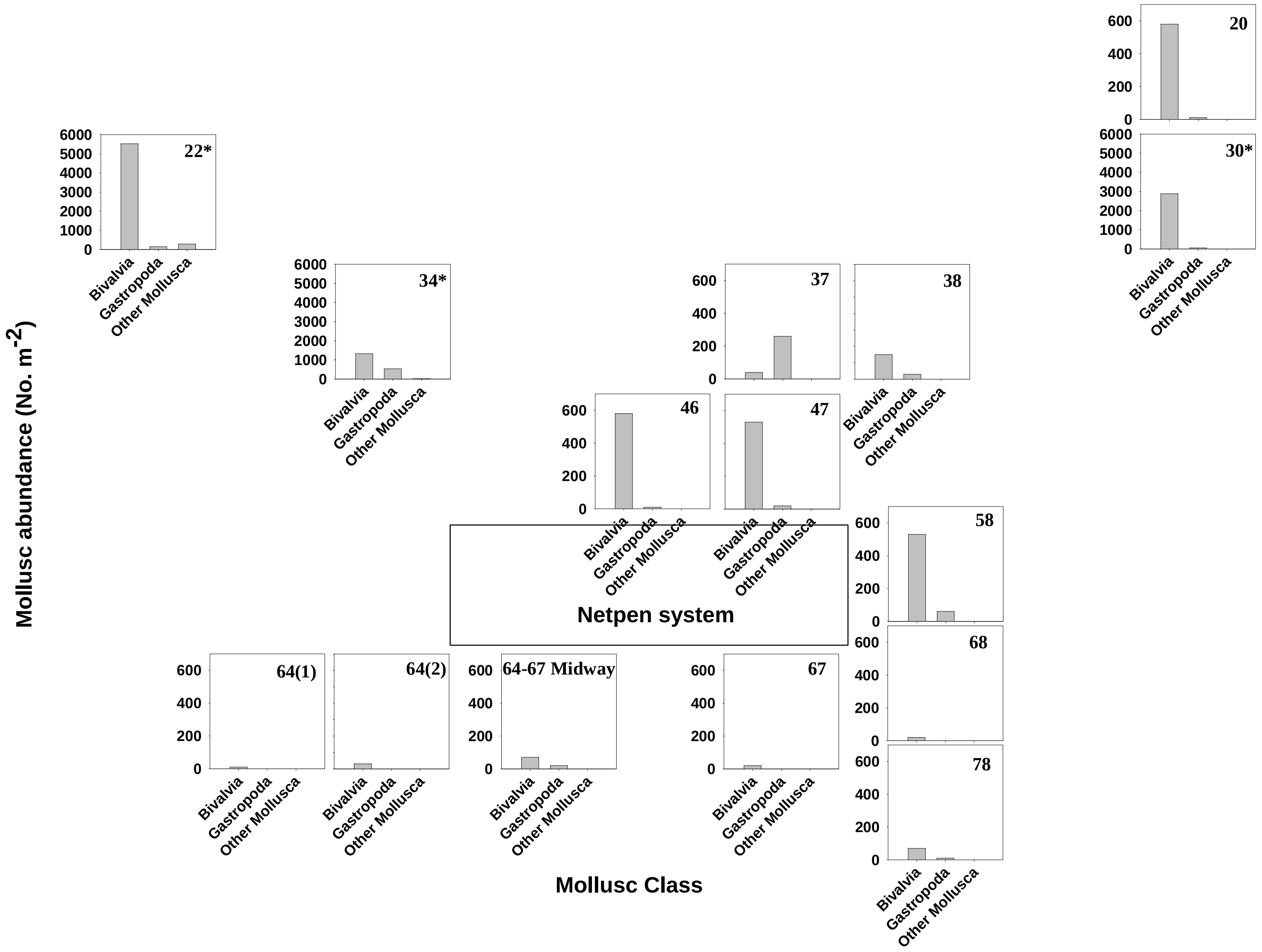

Figure A16. Spatial distribution of mollusca abundance for each class observed at stations sampled in Sir Edmund Bay.
*Note: Scales for stations SEB22, SEB30, and SEB34 standardized to 6000 to accommodate a larger range.

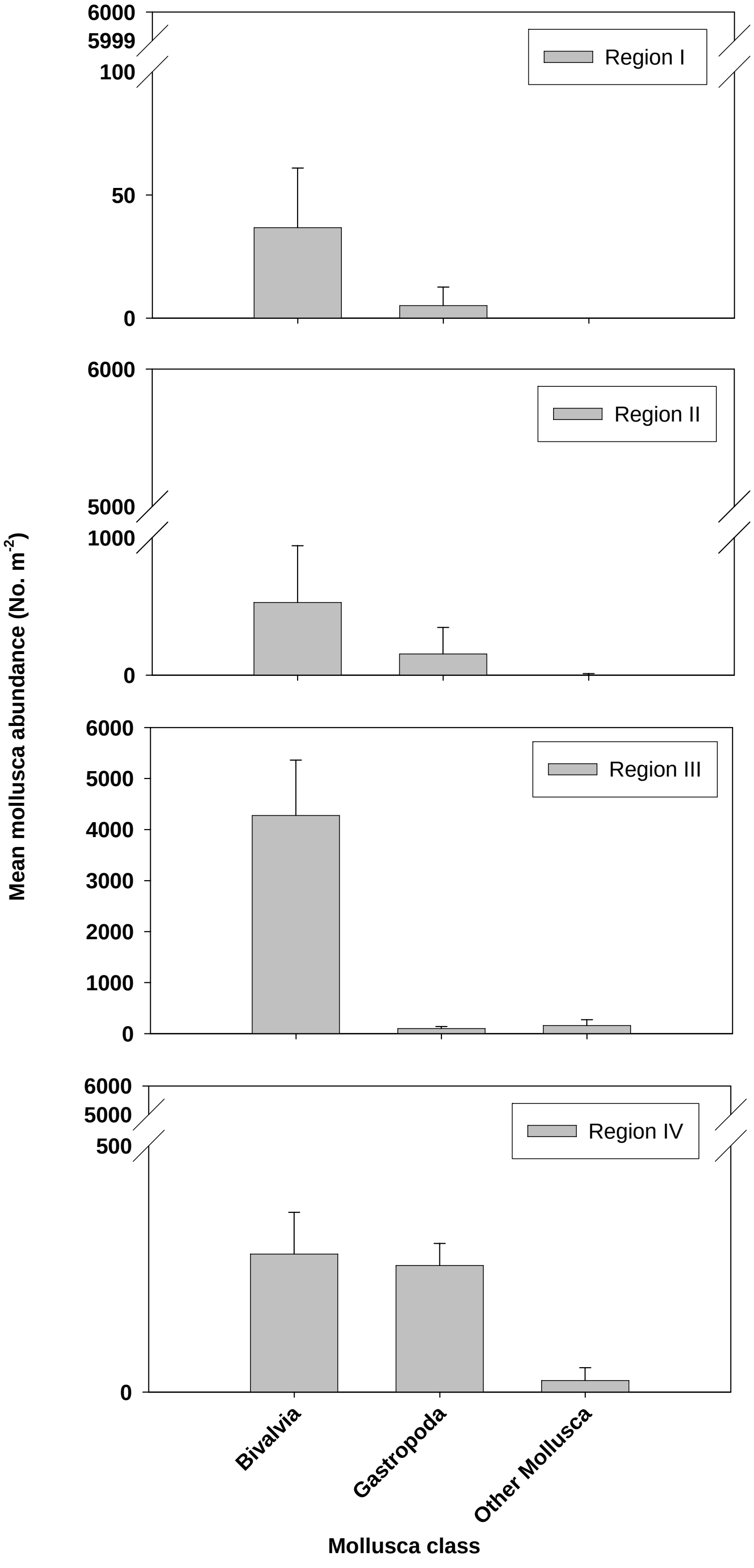

Figure A17. Mean mollusca abundance for classes observed at stations located in Region I (shoreward perimeter stations), Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations).

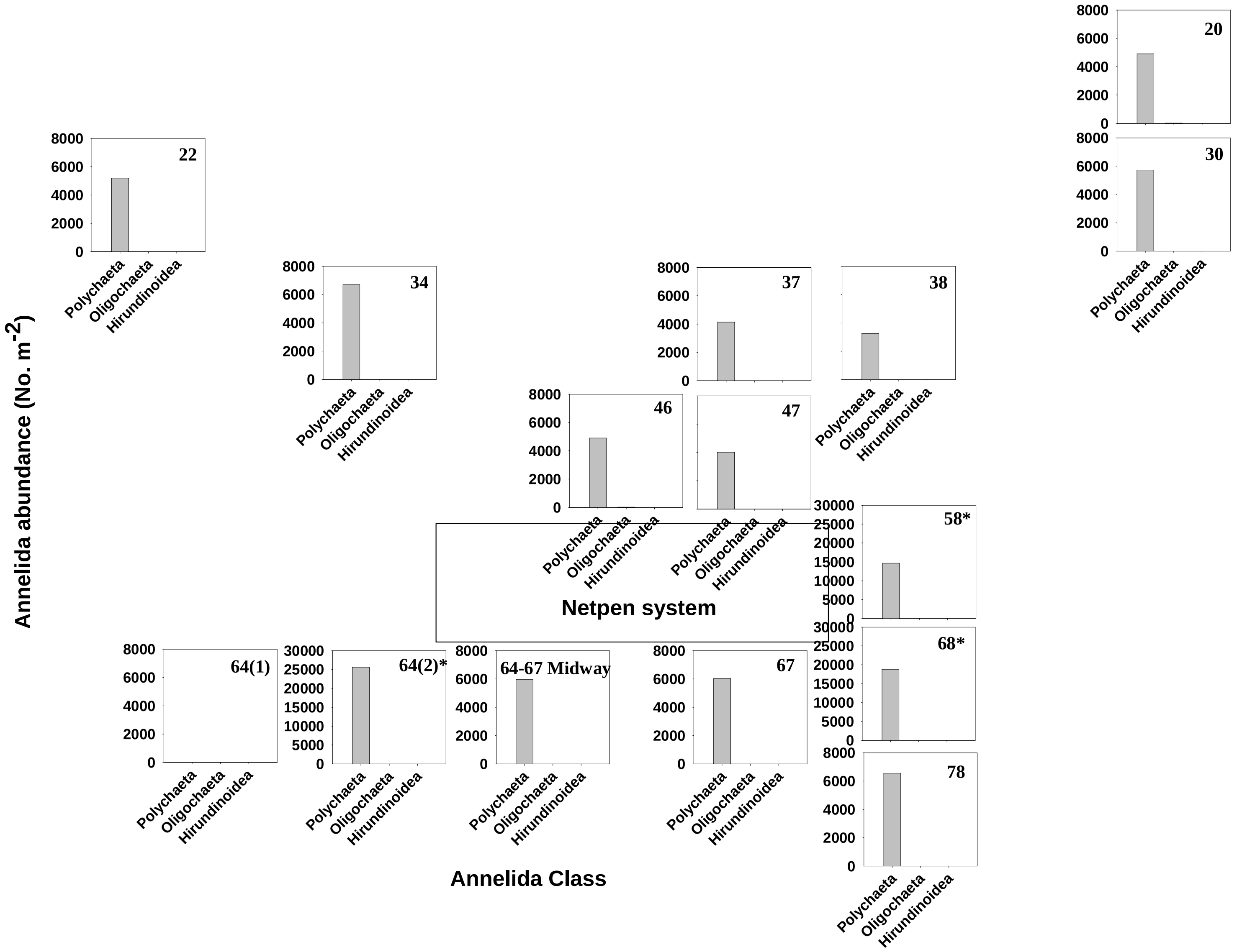

Figure A18. Spatial distribution of annelida classes observed at stations sampled in Sir Edmund Bay.
* Note: Scales for stations SEB58, SEB64 and SEB68 standardized to 30,000 to accommodate a larger range.

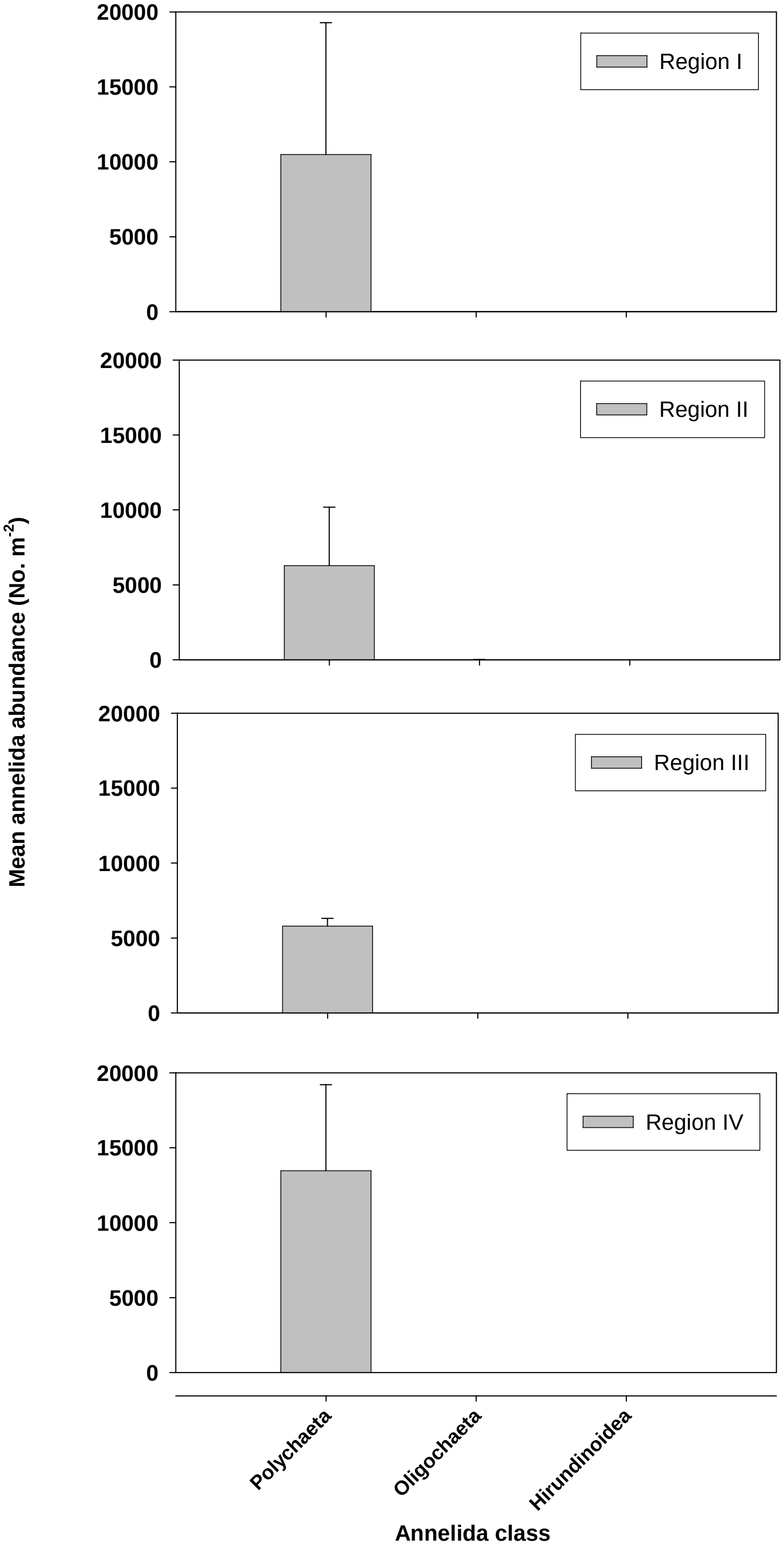

Figure A19. Mean annelida abundances for classes observed at stations located in Region I (shoreward perimeter stations, Region II (seaward perimeter stations), Region III (off-site stations) and Region IV (reference stations).

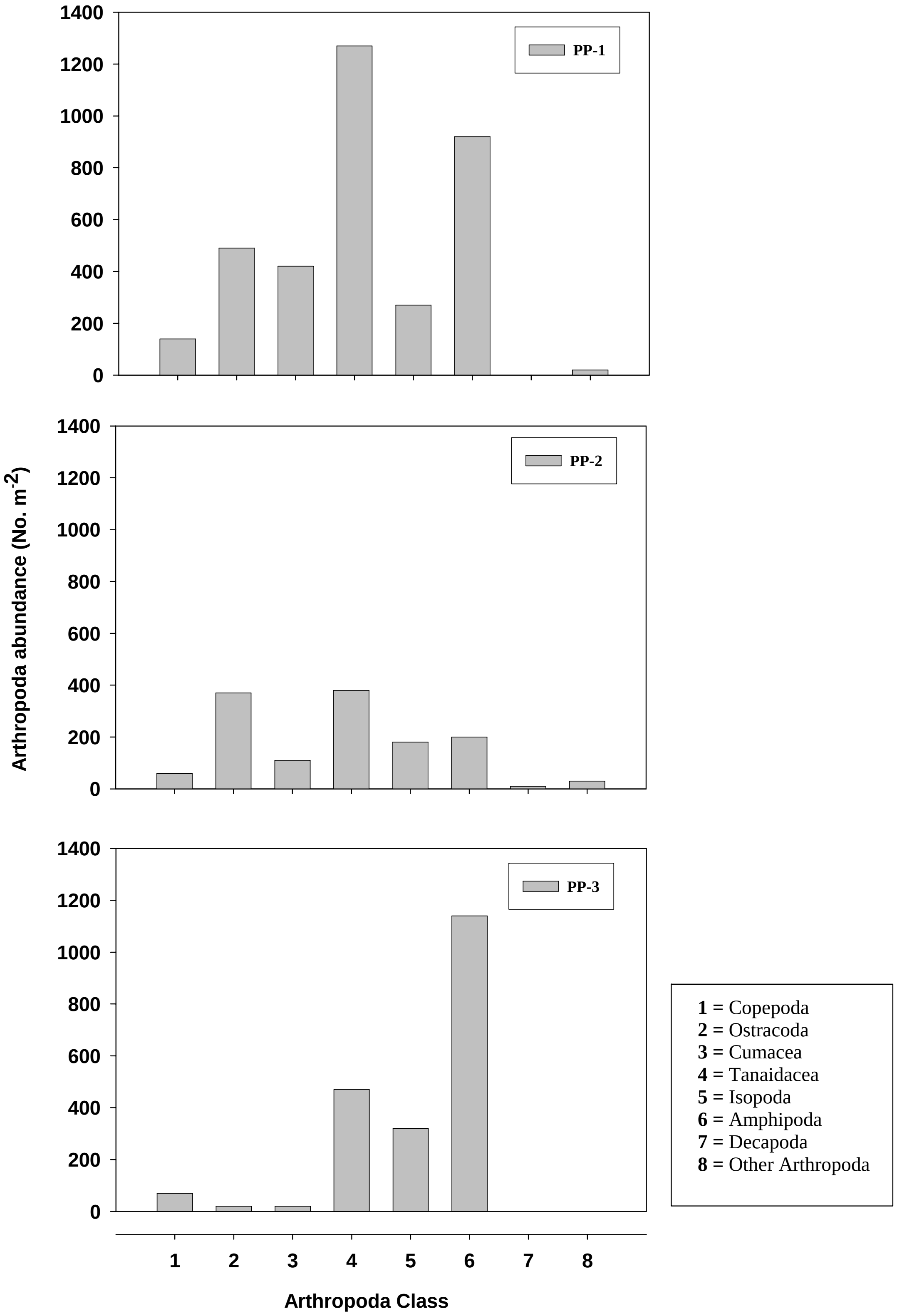

Figure A20. Arthropoda abundance for classes observed at reference stations located in Penphrase Passage

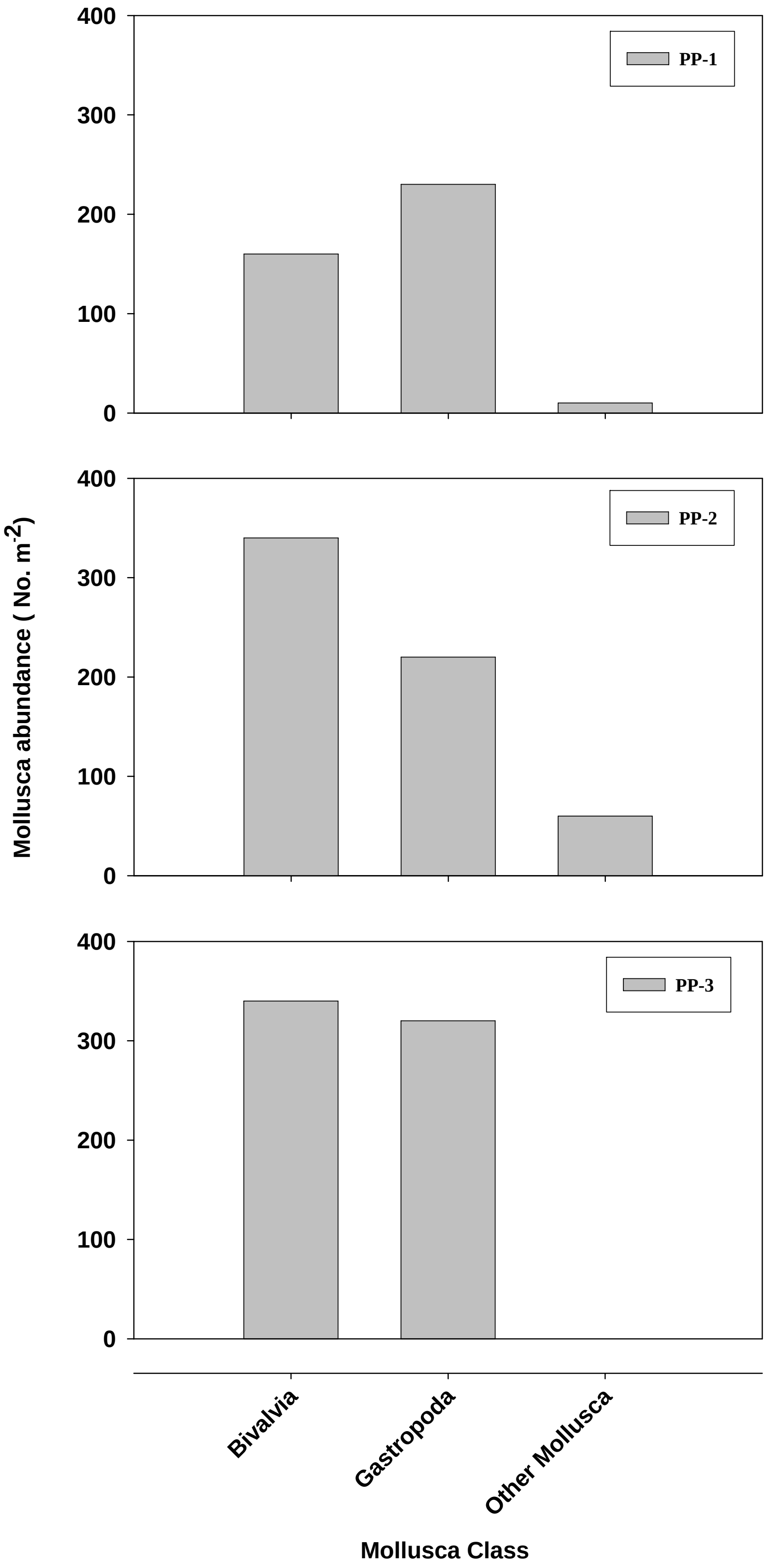

Figure A21. Mollusca abundance for classes observed at reference stations located in Penphrase Passage

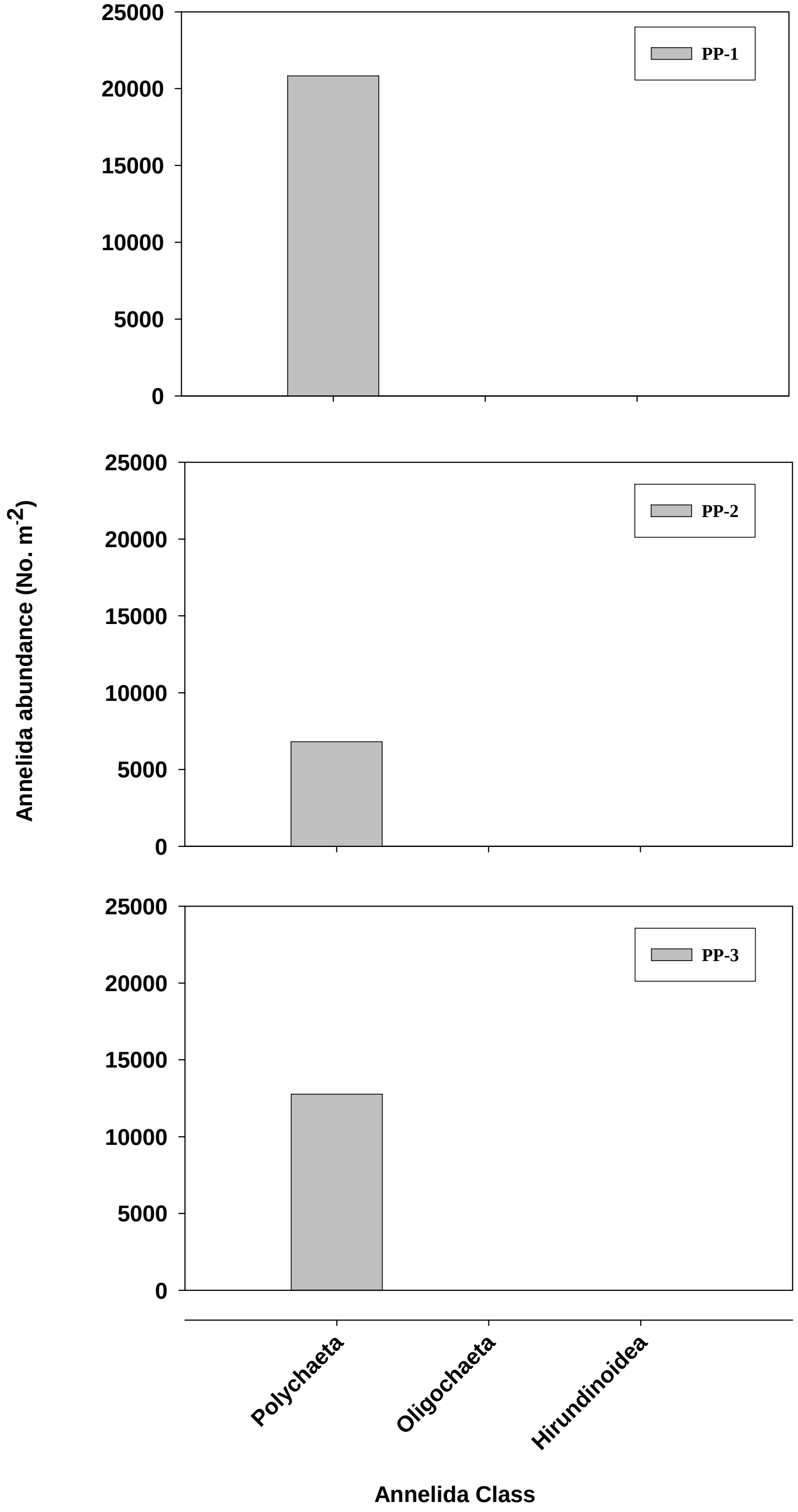

Figure A22. Annelida abundance for classes observed at reference stations located in Penphrase Passage