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WATER CHEMISTRY MEASUREMENTS ASSOCIATED WITH MINE WATER DISCHARGE INTO COASTAL WATERS OFF NOVA SCOTIA

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES	iv
ABSTRACT/RÉSUMÉ	v
INTRODUCTION	1
METHODS	1
DISCUSSION	2
Dissolved Metals.....	3
Particulate Metals.....	3
SPM.....	5
Nutrients	5
CONCLUSIONS	5
ACKNOWLEDGMENTS	6
REFERENCES	6

List of Tables and Figures

	Description	Page
Table		
1	Water Survey of the Plumes off #26 and Ligan - December 9, 1992	7
2	Dissolved Metal Data from the Plume Surveys	8
3	Particulate Metal Data from the Plume Surveys	9
4	Nutrient Data from the Plumes off #26 and Ligan	10
Figure		
1	Sampling Sites off David Head (Ligan) and Burnt Head (#26 Colliery)	11
2(A)	CTD data from Stations 1, 2, 3 and 4	12
2(B)	CTD data from Stations 5, 6, 9 and 10	13
2(C)	CTD data from Stations 11 and 12	14
3(A)	Dissolved Nickel, Zinc and Lead	15
3(B)	Dissolved Manganese, Iron and Copper	16
3(C)	Dissolved Aluminum, Cadmium and Cobalt	17
4(A)	Particulate Copper, Cadmium and Nickel	18
4(B)	Particulate Aluminum, Cobalt and Iron	19
4(C)	Particulate Manganese, Lead and Zinc	20
4(D)	SPM	21
5	Total SPM, Raw Water and Inorganic Grain Size Concentration with Distance from the Outfalls	22
6(A)	Ligan Outfall Raw Water Grain Size	23
6(B)	# 26 Outfall Raw Water Grain Size	24
7(A)	Ligan Outfall Inorganic Grain Size	25
7(B)	# 26 Outfall Inorganic Grain Size	26
8(A)	Silicate and Phosphate	27
8(B)	Nitrate+Nitrite and Ammonia	28

2124

ABSTRACT

Yeats P.A., J.A. Dalziel, and T.G. Milligan. 1998. Water Chemistry Measurements Associated with Mine Water Discharge into Coastal Waters off Nova Scotia. Can. Tech. Rep. Fish. Aquat. Sci. 2242: vi + 28 pp.

This report presents the data from November 1992 water chemistry surveys off #26 colliery near Glace Bay and the Lingan mine near New Waterford Cape Breton. These surveys were conducted to monitor the level of contamination in the plumes created by the discharge water from both mines into the adjacent coastal waters. Four stations in each plume were sampled to monitor the dispersal of contaminants. At each station water was sampled for dissolved and particulate metals (Fe, Al, Mn, Zn, Cd, Pb, Ni, Cu, Cd), salinity, nutrients, suspended particulate matter and particle size distributions. This data was compared to levels at a control site adjacent each plume and to the concentrations in the discharge water. The data showed the discharges from # 26 colliery and the Lingan mine had distinctly different chemical characteristics. The #26 discharge was characterized by low salinity, low pH and low SPM concentrations; very elevated levels of dissolved Fe, Al, Mn, Zn, Ni and Co; and very elevated particulate Cd and Cu. The Lingan discharge had higher salinity, pH and SPM concentrations; very high dissolved Fe and Mn; and particulate Fe. The chemical composition of particulates from the Lingan discharge was greater than 80% iron oxides, quite different from the composition at the # 26 colliery. Within the plumes, metal concentrations decreased rapidly as a result of dilution, chemical precipitation and settling of the metal rich particles. The concentration of dissolved and particulate metals were reduced to natural or near natural levels at the outer edge of the plumes. The particle size distribution studies also showed a decrease in concentration of the various size fractions with distance from each outfall but levels found at the outer edges of the plumes were still significantly higher than at the control site. The nutrient data showed elevated levels of silicate and ammonia off both outfalls decreased rapidly in the plumes to background levels.

RÉSUMÉ

Yeats P.A., J.A. Dalziel, and T.G. Milligan. 1998. Water Chemistry Measurements Associated with Mine Water Discharge into Coastal Waters off Nova Scotia. Can. Tech. Rep. Fish. Aquat. Sci. 2242: vi + 28 pp.

Notre rapport présente les données fournies par des analyses chimiques de l'eau effectuées devant la houillère n° 26, près de Glace Bay, et la mine de Lingan, près de New Waterford (Cap-Breton). Ces travaux avaient pour objet de surveiller le niveau de contamination dans les panaches créés par les effluents des deux mines dans les eaux côtières adjacentes. Dans chaque panache, on a établi quatre stations d'échantillonnage pour surveiller la dispersion des contaminants. À chaque station, on a dosé les métaux dissous et particuliers (Fe, Al, Mn, Zn, Cd, Pb, Ni, Cu, Cd) et mesuré la salinité, les éléments nutritifs, les matières particulières en suspension (MPS) et la granulométrie. Les données obtenues ont été comparées aux concentrations mesurées à un site témoin proche de chaque panache et dans l'effluent. Les données ont montré que les effluents de la houillère n° 26 et de la mine de Lingan présentaient des caractéristiques chimiques tout à fait différentes. L'effluent de la houillère

n° 26 se caractérisait par une faible salinité, un pH bas et des concentrations de MPS plus faibles, par des teneurs très élevées en Fe, Al, Mn, Zn, Ni et Co à l'état dissous, et par des teneurs très élevées en Cd et Cu sous forme particulaire. L'effluent de la mine de Langan présentait une plus forte salinité, un pH et des concentrations de MPS plus élevés, des teneurs très élevées en Fe et de Mg à l'état dissous, et du Fe sous forme particulaire. La composition chimique des matières particulaires dans l'effluent de la mine de Langan était représentée à plus de 80 % par des oxydes de fer, ce qui n'était pas du tout le cas dans l'effluent de la houillère n° 26. Dans les panaches, les concentrations de métaux baissaient très rapidement sous l'effet de la dilution, de la précipitation chimique et de la sédimentation des particules riches en métaux. La concentration des métaux sous forme dissoute ou particulaire retombait pratiquement au niveau naturel à la bordure externe des panaches. Les études granulométriques ont aussi montré une baisse de concentration des diverses fractions de taille en fonction de l'éloignement par rapport à chaque émissaire, mais les niveaux observés à la bordure extérieure des panaches étaient encore significativement plus élevés qu'au site témoin. Les données sur les éléments nutritifs ont montré que les concentrations élevées de silicate et d'ammoniac observées à la sortie des deux émissaires baissaient rapidement dans les panaches pour retomber aux niveaux de fond.

INTRODUCTION

During late November 1992, DEVCO coal mines at the #26 colliery near Glace Bay and the Lingan Mine near New Waterford began flooding. In an attempt to save the existing coal in these mines, the flood water was pumped into the adjacent coastal water. At one point the total discharge peaked at about 22,000 liters/min. The discharge from the mine sites caused very visible brown coloured plumes to form in the vicinity of the two discharge pipes off David Head (Lingan) and the one discharge pipe off Burnt Head (#26 Colliery). Depending on weather conditions, the plumes could either be contained within ~500 m offshore and follow the coastline to the east for several kilometres, or be dispersed offshore.

Chemical analyses of the water discharged from the two mine sites showed it to be anoxic, low in pH and high in several metals, especially iron and manganese. Concern was expressed by DFO Habitat Management that the turbid plume from the discharges, or the metals in the discharge water might be harmful to lobsters. The two plumes were forming in an area with an important lobster fishery.

In an attempt to improve our understanding of the extent of this contamination, members of the Marine Chemistry and Coastal Oceanography Divisions (Physical and Chemical Sciences Branch) conducted a marine sampling survey in the vicinity of the two discharges. This report describes the results of the measurements of dissolved and particulate metals (Fe, Al, Mn, Zn, Cd, Pb, Cu, Ni, and Co), nutrients, suspended particulate matter, and particle size distributions from this survey.

Results of this survey were provided to Habitat Management in January 1993. More recently, there has been an increase in mineral and offshore oil/gas exploration and production. Concerns about the effects of the produced and formation water from these operations on the marine environment has generated an interest in the chemistry of metaliferous discharges into marine waters. Therefore, the results of this survey are being documented here.

METHODS

CTD profiles were measured and water samples were collected on a twelve station survey of the coastal waters off the two discharge sites on December 9, 1992 using the FPV Cygnus and a modified Zodiac launch. The station locations for the survey are shown in Figure 1 and the sampling details for each station are described in Table 1. Sampling at stations 1 and 12 was conducted from the Cygnus while at all other stations work was done from the Zodiac launch.

Station 1 was the "control site" for the study of the plume off the #26 colliery. Station 2 was located near the discharge outfall off #26 colliery and station 6 at the outer edge of the plume. Station 12 was the "control site" for the survey off Lingan. Station 8 was located near the outfall off Lingan and station 11 was at the outer edge of this plume.

At each station, a vertical profile of salinity, temperature, depth, turbidity, and oxygen was measured using a Sea-Bird SBE-25 CTD and water samples were collected using a Niskin sampler modified to minimize trace metal contamination. The collected water sample was sub-sampled on-site for dissolved and particulate metals, suspended particulate matter (SPM), nutrients and salinity. The SPM samples were used for gravimetric determination of the suspended solid concentrations and for size fractionation of the samples. At stations 2, 8,

9 and 10, samples were collected from the surface water directly into the storage bottles because of the shallow depths and rough sea conditions. Sampling at the two discharge pipes (#1 and #2+4) from Lingan and the one discharge pipe from Mine #26 was conducted on December 10 with the water samples collected directly into the appropriate storage bottles.

The trace metal samples were processed at BIO on December 11, about 48 hours after collection. Each water sample collected for trace metals was filtered through an acid cleaned and tared 47 mm, 0.4 μm pore size Nuclepore filter. The filtrate was preserved with 1 ml/L of high purity HNO_3 (SeaStar) and analysed for the following dissolved metals; Zn, Cd, Pb, Cu, Ni, Fe and Co using the method of Danielsson et al. (1982), and for Mn and Al using a modification of Bewers et al. (1976). The outfall samples were analysed by the contract lab Fenwick Laboratories using ICP-MS. The particulate material on the Nuclepore filters was washed of residual salt and analysed for total particulate metals (Fe, Mn, Al, Zn, Cd, Pb, Ni, Cu, Co) using the method of Rantala and Loring (1989) and Loring and Rantala (1990).

The SPM concentrations were determined using standard gravimetric analysis as described in Winneberger et al. (1963). Samples were filtered using 47 mm, 0.8 μm HAWP Millipore filters. Eleven surface samples were also analysed for both raw and inorganic particle size distributions with a Coulter Multisizer IIe using the techniques described in Milligan and Kranck (1991). Coulter analysis of the unsonified raw water samples was completed within 48 hours of collection.

The salinity samples were analysed using a Guildline Autosol salinometer to determine practical salinity as defined by the 1980 UNESCO/ICES/SCOR/IAPSO Joint Panel.

The unfiltered nutrient samples were collected in duplicate and frozen at -4°C within two hours of collection. The samples were thawed and analysed at our laboratory with a Technicon Auto Analyser II using modified Technicon procedures.

DISCUSSION

The seawater sampling was conducted on a day in which the winds increased through the day to moderate to strong onshore winds with seas up to a metre high. As a result of these wind conditions, the discharge plume was confined to within ~500 m offshore and extended alongshore several kilometres to the east of the discharges. Under these conditions, the water column at stations (#1-5, 9 and 10) were well mixed with the CTD results showing (Figure 2) uniform salinity and temperature distributions from top to bottom. At station 12, the control site off Lingan, there was a slight increase in salinity and temperature in the surface water while at station 1, the control site off #26 colliery, the increase was noted in the deep water below 12 m. The salinities change very little along the lengths of the plumes and are only ~0.5 lower in the plumes than at the control sites. This would indicate for the #26 colliery extensive dilution of the discharge before the sampling stations nearest the discharge pipes. For the Lingan discharge the salinity of the discharge and the receiving water are fairly similar, so dilution cannot easily be estimated from the salinity.

The chemical and physical characteristics of the two discharges were monitored in late November and early December 1992 by Environment Canada. The Lingan discharge was characterized (R. Parker, DOE, personal communication) as saline (25-30) and turbid (>300 NTU) with a pH of 5.5-6. The #26 colliery discharge was less salty (10-15), non-turbid (2

NTU) and had a lower pH (4.5-5). Both discharges had low levels of dissolved oxygen. Results for three samples collected for metal analysis on December 1, 1992 are very similar to those we report for Fe, Al, Mn, Zn, Ni and Co (Table 2).

DISSOLVED METALS

All the dissolved metal results are listed in Table 2 and illustrated in Figures 3A to 3C. Concentrations of dissolved Al, Zn, Ni and Co were much higher in the discharge from the #26 colliery than in the Langan discharge. This is consistent with the differences in pH of the discharges, #26 colliery has lower pH and higher metal concentrations. Fe, Al, Mn, Zn, Ni and Co concentrations in the #26 colliery discharge are 10^4 - 10^6 times the levels in seawater whilst concentrations of Cd, Pb and Cu are elevated by <100 times. Fe and Mn enrichments over seawater in the Langan discharge are similar to those in the #26 colliery discharge, Ni and Co are somewhat lower (10^3 - 10^4 times seawater) and Al, Zn, Cd, Pb and Cu levels are elevated by <100 times.

Within the marine waters, the dissolved concentrations of Fe, Mn, Zn (#26 colliery only), Co, and Ni showed rapid decreases with distance from the outfalls. Dissolved Cu and Cd concentrations also decreased but less drastically. Concentrations of dissolved Pb (and Zn from the Langan mine) were low and showed no indication of any trends. The trends for dissolved Al are unlike those for any of the other metals, concentrations increasing (most noticeably for the #26 colliery transect) with distance from the discharge. In both cases the downstream plume sample had higher dissolved Al concentrations than the control samples. This trend for increasing concentrations with distance was probably the result of significant release of Al from the suspended particles in the plume. The data from the Langan plume show lower salinity and higher dissolved metal concentrations at station 9 than at station 8 which was closer to the outfall. This observation was likely the result of sampling at a time when some cleaner coastal water had mixed with the plume water at station 8. The strong onshore wind and very heavy wave action at station 8 also made sampling difficult at this time and place. The progression for increasing salinity in the Langan transect is actually stn 9 < stn 8 < stn 11 < stn 10 < stn 12.

The concentrations of dissolved metals in the water from the two control sites - station 1 off #26 colliery and 12 off Langan - were similar to normal nearshore coastal water values. The concentrations of Al, Mn, Zn and Co were slightly higher at station 1 which might reflect some influence of the nearby discharge and plume. The sampling stations in the discharge plumes farthest from the outfalls showed Co and Mn concentrations from Langan (station 11) and Al, Co, Mn and Ni from #26 colliery (station 5) to be still significantly higher than the levels found at the control sites. These observations would indicate that the impacted area for these elements can extend beyond the visible plumes. Sub-surface sampling (stations 3, 4 and 11) shows that the elevated metal concentrations were not confined to the very near surface waters.

PARTICULATE METALS

The data for the particulate metals from both plumes and discharge outfalls are listed in Table 3 and illustrated in Figures 4A to 4D. The particulate concentrations of Al, Cd, Pb, Cu and Ni were higher in the outfall from mine #26, while SPM, Mn and Fe were higher in the discharge from Langan. The composition of the particles from the two discharges is evidently quite different. The Langan discharge had very high levels of Fe (iron compounds would appear to comprise at least 80% of the particulate matter), but lower levels of all the other metals. These differences are consistent with differences in the acidity of the discharges. The

Lingan discharge had higher pH and thus more precipitation of iron hydroxides. Precipitation of approximately 150 mg/L of iron hydroxides would decrease the dissolved Fe content of the Lingan discharge by approximately 80,000 mg/L.

The trends in the particulate metal data for the plume off the #26 mine are clearer than those off Lingan. The levels of particulate Fe and Zn (in terms of micrograms per gram of sediment) seen near the outfall off #26 mine are higher than in the mine discharge and decrease rapidly with distance from the source. An opposite trend is seen for Mn and Cu, where concentrations increase with distance from the source. Ni and Pb show an intermediate picture with a maximum in concentration within the plume. This distribution for Fe and Zn is explained by rapid precipitation of dissolved Fe and Zn, followed by dilution of the particulate matter by mixing with more normal oceanic particulate matter. For Co, Ni, and most notably Mn, uptake onto particles is more gradual with the result that highest concentrations are seen farther from the source. For Mn it is well known that the chemical oxidation of soluble Mn(II), to insoluble Mn(IV) is relatively slow. By the downstream edges of the two plumes (station 5 and station 11) the metal content of the particles was generally similar to that seen at the control stations and fairly representative of normal nearshore coastal water values.

The massive increases in particulate metal concentrations (in terms of micrograms of metal per liter of water) from the #26 colliery discharge to station 2 off the outfall and the very high iron content of the particles at station 2 can be described by a simple model of dilution of the discharge with precipitation of dissolved metals. Dilution of the discharge (a dilution factor of 25 is indicated by the changes in salinity) would produce a dissolved iron concentration of 44.8 mg/L at station 2 compared to the observed 2.2 mg/L. Precipitation of the excess dissolved iron would produce 42.6 mg/L of particulate iron, i.e. twice the observed particulate iron at station 2. This discrepancy could be accounted for by either a greater dilution factor or settling of some of the particulate iron. Hydrated iron oxide (or iron hydroxide) produced by this precipitation process would have an iron content of 52% if its chemical formula is $\text{Fe}(\text{OH})_3$ or $\text{FeO}_2 \cdot 3\text{H}_2\text{O}$. Similar calculations for Mn, Zn, Ni, and Co indicate that more than enough of all these metals is available from precipitation of dissolved metals in the discharge to account for the elevated particulate metal concentrations seen at station 2. The same conclusion does not apply for Al. Although the #26 discharge has a high dissolved Al concentration, precipitation of this material is insufficient to account for the particulate Al concentrations observed in the plume. Resuspension of 33 mg/L of bottom sediments with 8% Al is required to produce the observed particulate Al concentrations at station 2.

Dilution of the suspended particulate matter in the #26 colliery discharge would produce 2.0 mg/L of SPM at station 2. Precipitation of enough hydrated iron oxide to balance the iron would yield another 40.5 mg/L of SPM, and precipitation of manganese dioxide another 0.1 mg/L. Add to this the additional 33 mg/L from resuspension and we predict 75.6 mg/L for the SPM concentration at station 2, compared to the 82.12 mg/L that is observed. The predicted iron content would be 30% compared to the observed 25.9%, manganese 1060 mg/g compared to 590 mg/g, and aluminum 7.2% compared to 7.8%.

A similar description of dilution and precipitation between the Lingan discharge and station 9 cannot be calculated because the salinity of the Lingan discharge is essentially equal to that of the seawater. However, if the dilution factor is between 25 and 50, a reasonable prediction of the SPM and particulate Fe, Mn and Al concentrations results.

SPM

The water sampling reported here was conducted during a time of strong onshore winds that constrained the highly turbid discharge plumes. Mixing and settling of particles resulted in SPM distributions that were fairly uniform from top to bottom of the water column.

Total SPM, raw water grain size and inorganic grain size, show a decrease in concentration with distance from each of the outfalls (Figure 5). At the outer edges of the plumes, SPM concentrations were still significantly higher than those at the control sites. It is interesting to note that the SPM concentration at station 2, immediately off the #26 colliery discharge is far higher than that of the discharge. Precipitation of dissolved Fe, Al and Mn from the discharge undoubtedly contributes significantly to the high SPM concentrations observed at station 2.

Within the plumes, there was much less settling of the material from the Lingan outfall than that from the #26 colliery which was likely due to strong mixing on the wave cut terrace along this section of the coast. The plume at Lingan was held against the cliff face by the strong onshore wind, whereas the plume at #26 moved along the shore then dispersed off Table Head. Initial concentrations from the two outfalls (station 2 and 8) were similar despite the differences in discharge concentrations. The raw water grain size distributions show a large amount of flocculation of the material in suspension (Figure 6A, B). When compared to the disaggregated inorganic grain size distributions (Figure 7A, B), it can be seen that the typical flat distribution of the inorganic grains has been concentrated to a modal size of approximately 10 microns. This modal size is not the true in situ size of the particle aggregates, but represents what the Coulter Counter sees after an indeterminate amount of floc break up during sampling. Sample beakers containing the raw water samples had visible flocs in suspension, in the order of hundreds of microns in diameter. These flocs dispersed when the samples were screened during the Coulter analysis, but reformed in the beaker almost immediately. Similar sized flocs were observed in situ in the surface water at both locations.

NUTRIENTS

The nutrient data from the unfiltered samples collected from each survey site are listed in Table 4 and illustrated in Figure 8. None of the results indicate significantly elevated nutrient concentrations in either plume. The samples collected immediately off the two outfalls did have measurably higher concentrations of silicate and ammonia but levels rapidly decreased to background. Phosphate and nitrate concentrations were slightly lower in the discharge plume than at either of the control stations. DOE's sampling of the #26 colliery discharge indicated elevated levels of silicate, phosphate and ammonia but low nitrate+nitrite.

CONCLUSIONS

The discharges from # 26 colliery and the Lingan mine had distinctly different chemical characteristics. The #26 discharge was characterized by low salinity, low pH and low SPM concentrations; very elevated levels of dissolved Fe, Al, Mn, Zn, Ni and Co; and very elevated particulate Cd and Cu. The Lingan discharge had higher salinity, pH and SPM concentrations; very high dissolved Fe and Mn; and particulate Fe. The chemical composition of particulates from the Lingan discharge was greater than 80% iron oxides, quite different from the

composition at the # 26 colliery. Within the plumes, metal concentrations decreased rapidly as a result of dilution, chemical precipitation and settling of the metal rich particles. The concentration of dissolved and particulate metals were reduced to natural or near natural levels at the outer edge of the plumes.

The SPM data showed uniform distributions from top to bottom in the water column throughout both plumes. The particle size distribution studies also showed a decrease in concentration of the various size fractions with distance from each outfall consistent with deposition by flocculation. Levels found at the outer edges of the plumes were still significantly higher than at the control site.

The nutrients data did not show any abnormally high levels within both plumes. The elevated levels of silicate and ammonia off both outfalls decreased rapidly in the plumes to background levels.

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Table 1

Water Survey of the Plumes off #26 and Ligan - December 9, 1992

Station	Depth(m)	Time (Atlantic)	Position	Sampling	Samples Collected				
				Depth(m)	DM	PM	Sal	Nut	SPM
1	15	07:50	Sampling off Mine #26 46-13.3N 59-55.9W ** off-shore **	1	o	o	o	o	o
				3					o
				6	o	o	o	o	o
				9					o
				12	o	o	o	o	o
2	2	09:20	46-13.3N 59-58.2W **off the outfall **	surf	o	o	o	o	o
3	6	09:36	46-13.2N 59-57.7W	surf					o
				1	o	o	o	o	o
				2.5					o
4	4	10:03	46-12.8N 59-56.9W	5	o	o	o	o	o
				surf					o
				1	o	o	o	o	o
5	6	10:26	46-12.3N 59-56.7W	4	o	o	o	o	o
				surf					o
				2	o	o	o	o	o
6	12	10:45	46-12.4N 59-56.0W	4					o
				surf					o
				5					o
7	6	11:15	CAMERA STATION 46-13.2N 59-57.7W	10					o
8	2	13:30	Sampling off Ligan ** off the out-fall **	surf	o	o	o	o	o
9	2	13:36	46-15.05N 60-02.75W	surf	o	o	o	o	o
10	2	13:46	46-14.8N 60-02.15W	surf	o	o	o	o	o
11	8	13:48	46-14.45N 60-01.5W	surf					o
				1	o	o	o	o	o
				2					o
				4	o	o	o	o	o
				6					o
				8	o	o	o	o	o
				1	o	o	o	o	o
				4					o
				8	o	o	o	o	o
				12					o
12	18	14:58	46-16N 60-03W ** off shore **	16	o	o	o	o	o
			Discharge Outfalls						
			Ligan 1		o	o			o
			Ligan(2+4) Combined		o	o			o
			Mine # 26		o	o			o

DM - dissolved metals

PM - particulate metals

Sal - salinity

Nut - nutrients

SPM - suspended particulate matter

Table 2

Dissolved Metal Data from the Plume Surveys

Station	Sampling Depth(m)	Fe	Al	Mn	Zn	Cd	Pb	Ni	Cu	Co
(conc. in µg/L)										
Mine #26										
Mine #26	outfall	1.12E6	89500	64800	2800	<0.5	<0.5	2900	<10	1640
2	surf-dip	2230	3.78	1000	22.1	0.100	0.013	37.6	0.42	9.63
3	1	26.1	9.2	288	3.04	0.036	0.009	11.1	0.27	6.40
3	5	51.5	10.5	295	2.70	0.041	0.005	11.1	0.29	6.50
4	2	0.96	21.8	230	2.98	0.033	-----	6.8	0.33	4.18
4	4	1.49	28.2	165	2.2	0.034	0.008	5.4	0.32	2.80
5	2	1.59	36.2	96	0.93	0.033	0.012	3.09	0.30	1.29
1-control	1	0.54	2.52	2.67	0.64	0.029	0.010	0.32	0.32	0.038
1-control	6	0.54	2.39	2.86	1.25	0.029	0.018	0.22	0.32	0.020
1-control	12	0.41	2.36	2.17	1.04	0.045	0.016	0.34	0.33	0.043
Lingan Mine										
Lingan 1	outfall	1.08E6	90	49300	25	<0.5	<0.5	220	22	290
Lingan 2+4	outfall	1.05E6	130	50900	25	<0.5	<0.5	240	27	300
8	surf-dip	3.65	1.71	301	0.37	0.059	0.015	1.74	0.45	1.55
9	surf-dip	154	1.06	775	0.26	0.098	0.002	3.76	0.51	3.19
10	surf-dip	6.13	2.47	221	0.38	0.048	0.008	1.00	0.40	0.95
11	1	0.22	1.05	329	0.32	0.040	0.020	1.79	0.35	1.41
11	4	0.39	1.73	205	0.33	0.036	0.012	1.07	0.42	0.83
11	8	0.42	2.67	107	0.12	0.034	0.009	0.69	0.31	0.40
12-control	1	0.40	1.50	1.01	0.24	0.029	0.014	0.40	0.28	0.015
12-control	8	0.44	1.52	1.12	0.62	0.028	0.018	0.31	0.28	0.013
12-control	16	0.37	1.51	1.03	0.52	0.029	0.012	0.49	0.31	0.019

Table 3

**Particulate Metal Data from the Plume
Surveys**

Station	Sampling Depth(m)	SPM mg/L	Fe %	Al %	Mn	Zn	Cd (conc. in mg/Kg)	Pb	Ni	Cu	Co
Mine #26											
Mine #26	outfall	2.70	14.40	8.95	190	66	31.6	81	65	298	10
2	surf-dip	82.12	25.90	7.82	590	586	0.10	30	37	35	17
3	1	22.96	28.40	6.37	620	553	0.11	4	42	31	24
3	5	28.92	23.50	7.22	680	456	0.11	6	43	31	23
4	2	20.37	19.70	7.39	890	463	0.20	5	47	42	25
4	4	27.53	12.40	8.10	1340	283	0.25	4	52	39	21
5	2	15.21	11.30	8.78	1220	250	0.18	5	50	39	19
1-control	1	2.00	5.22	8.14	1720	138	1.24	73	40	58	15
1-control	6	2.41	3.71	7.07	1340	210	0.60	52	30	41	11
1-control	12	2.27	5.05	6.61	1440	113	0.59	57	42	38	19
Lingan Mine											
Lingan 1	outfall	148.7	55.30	0.13	230	36	0.08	2	14	8	6
Lingan 2+4	outfall	173.8	53.50	0.43	290	165	0.13	3	30	12	12
8	surf-dip	68.75	9.90	8.62	1220	124	0.18	38	47	38	19
9	surf-dip	78.00	15.50	8.39	1010	138	0.11	25	45	35	20
10	surf-dip	25.67	12.20	8.62	1240	133	0.23	3	47	39	17
11	1	40.87	11.10	9.72	990	126	0.12	33	48	38	20
11	4	39.62	11.30	9.37	1130	136	0.16	37	49	40	20
11	8	35.57	10.10	9.66	1130	122	0.15	32	48	34	18
12-control	1	1.93	3.77	7.53	1510	75	1.37	54	33	45	13
12-control	8	1.72	3.58	8.20	1340	91	0.97	60	30	45	19
12-control	16	1.40	3.05	6.09	1180	39	0.76	48	48	28	16

Table 4

**Nutrient Data from the Plumes off #26 and
Lingan**

(conc. in $\mu\text{moles/L}$)

Station	Sampling Depth (m)	Salinity	Silicate	Phosphate	Nitrate + Nitrite	Ammonia
Sampling off # 26 mine						
2	surf-dip	28.752	7.19	0.13	1.73	5.68
3	1	28.871	5.49	0.08	1.81	2.64
3	5	28.929	5.51	0.06	1.81	2.79
4	2	28.959	5.27	0.06	1.83	2.34
4	4	29.032	5.16	0.13	1.90	2.30
5	2	29.237	4.71	0.21	1.89	2.20
1-control	1	29.301	5.03	0.62	2.44	2.26
1-control	6	29.292	5.05	0.61	2.45	2.31
1-control	12	29.619	4.49	0.57	2.41	2.38
Sampling off Lingan mine						
8	surf-dip	28.758	5.96	0.11	1.71	4.65
9	surf-dip	28.643	6.03	0.08	1.61	9.47
10	surf-dip	28.844	5.12	0.18	1.67	3.11
11	1	28.809	5.47	0.09	1.63	4.49
11	4	28.862	5.17	0.16	1.68	3.19
11	8	29.157	4.72	0.27	1.80	2.76
12-control	1	29.454	5.08	0.64	2.64	2.08
12-control	8	29.440	5.02	0.64	2.66	2.08
12-control	16	29.472	5.01	0.62	2.67	2.14

Figure 1

Sampling sites off David Head (Lingan) and Burnt Head (#26 Colliery)

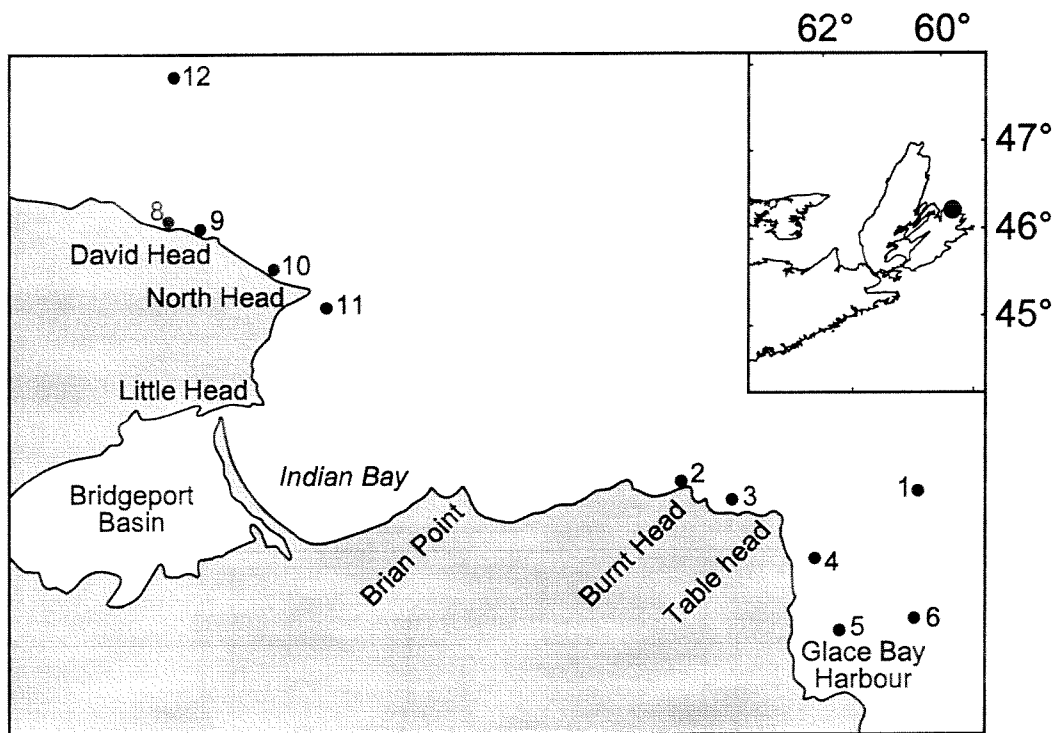


Figure 2 (A)

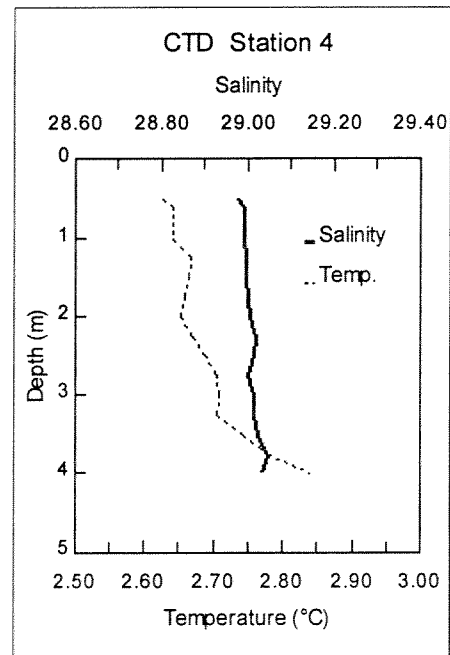
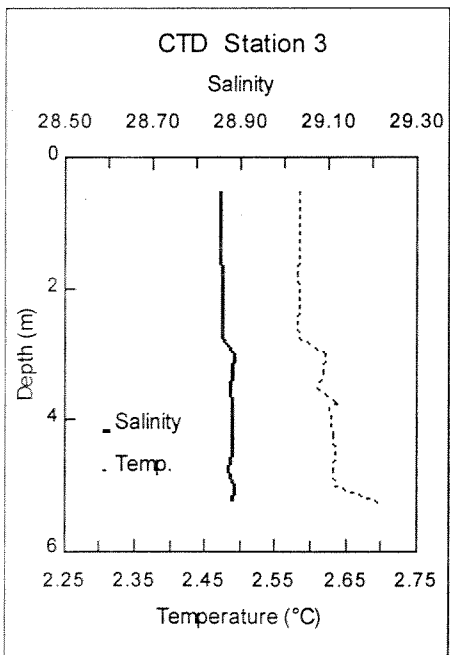
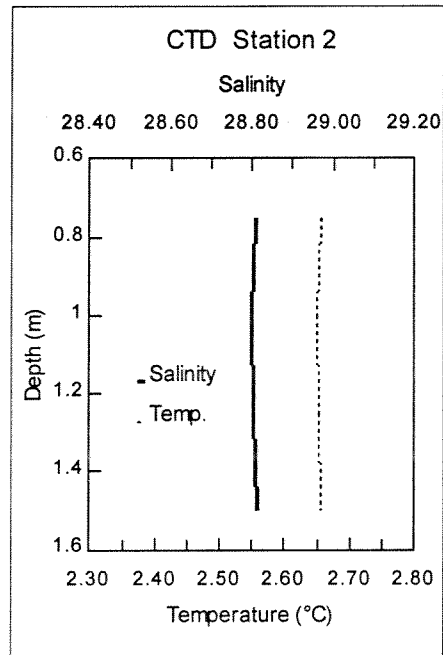
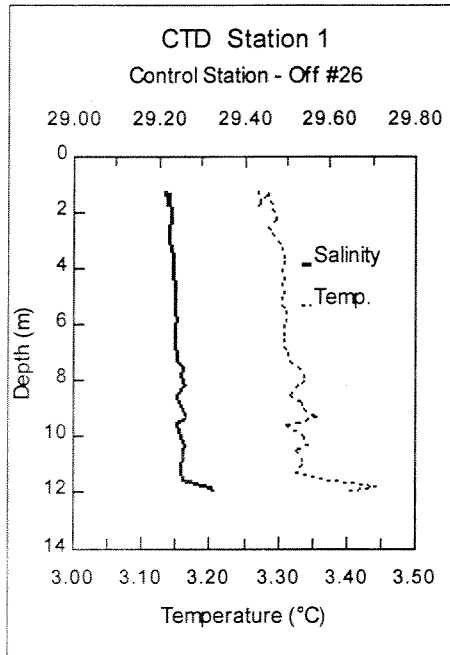


Figure 2 (B)

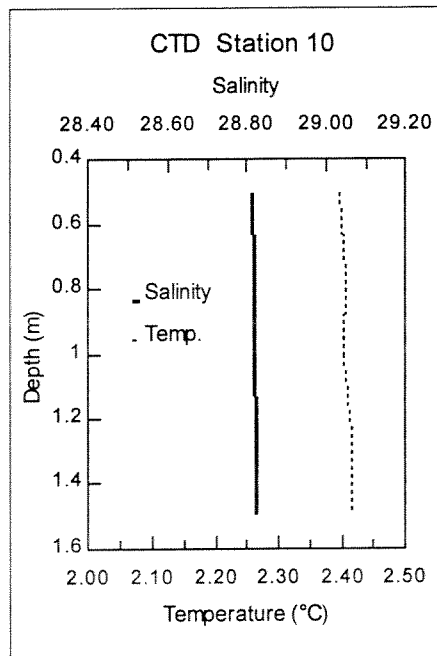
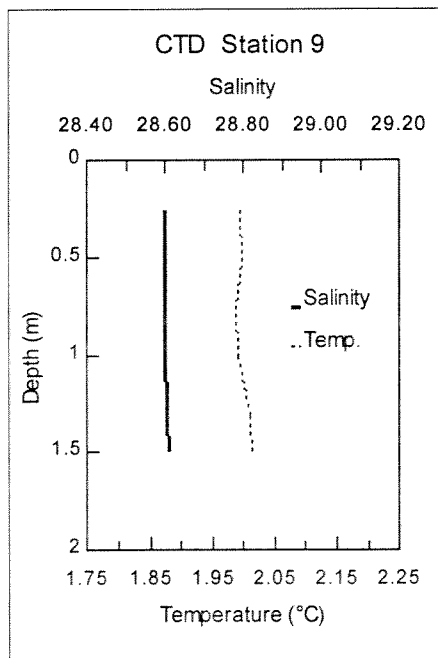
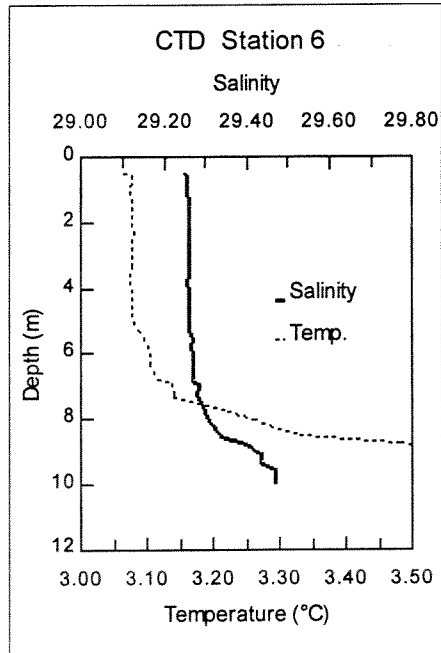
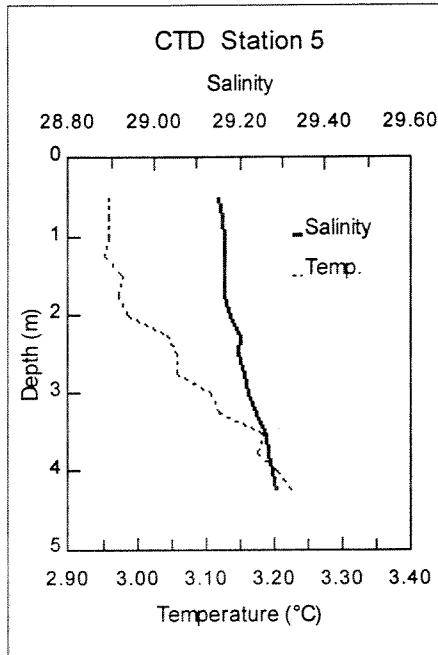


Figure 2 (C)

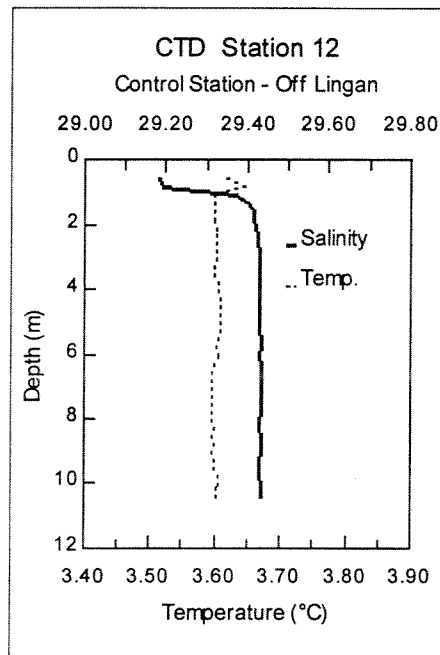
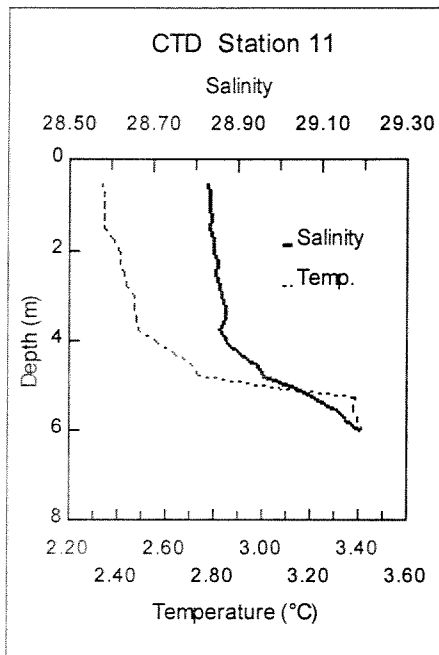


Figure 3 (A)

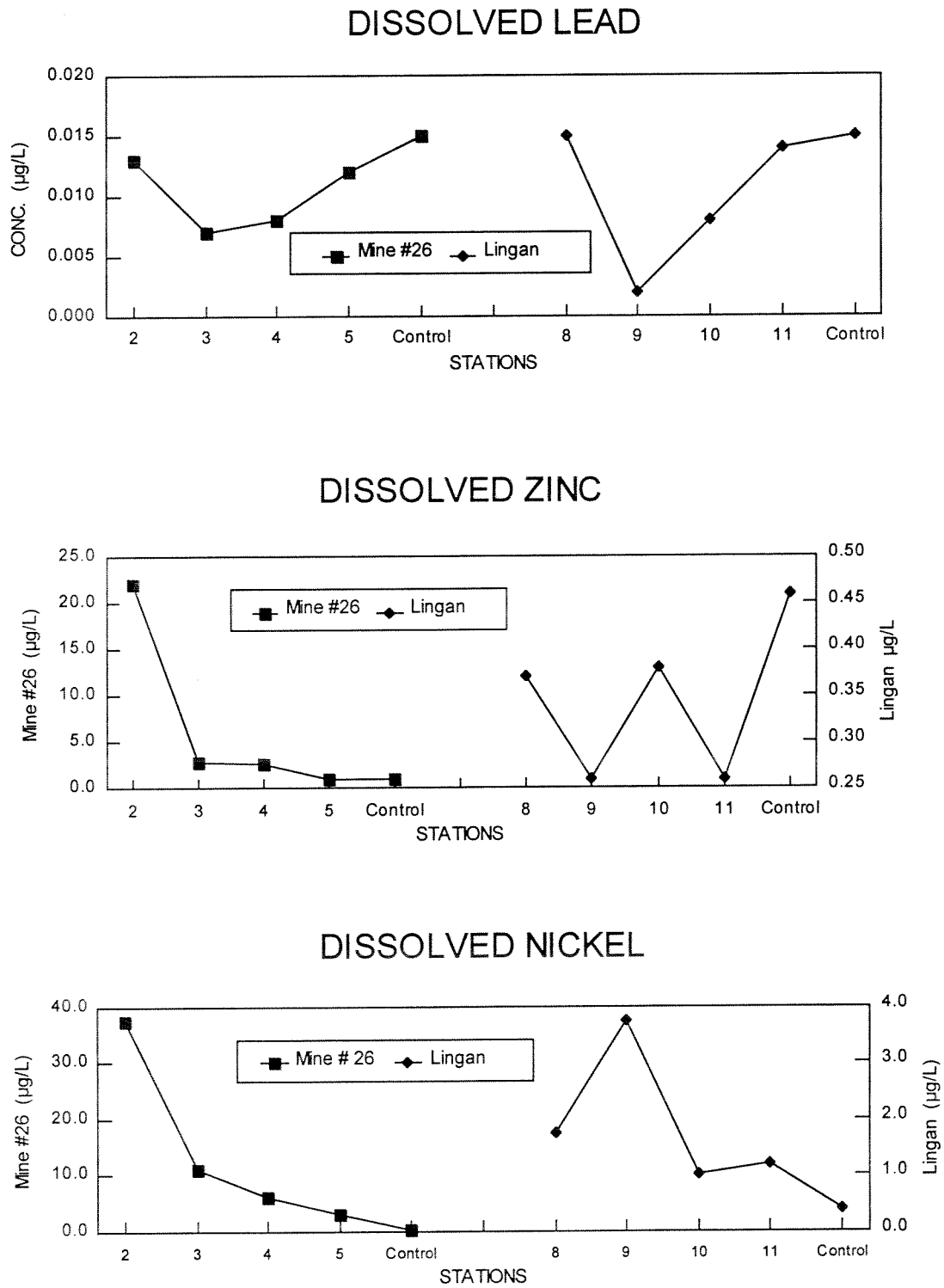
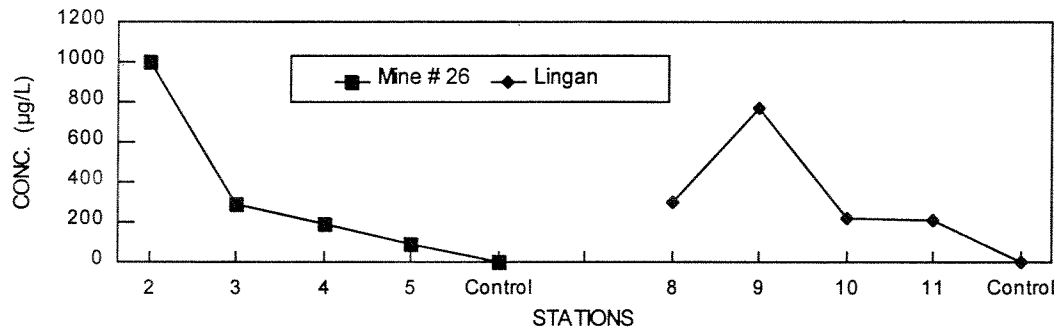
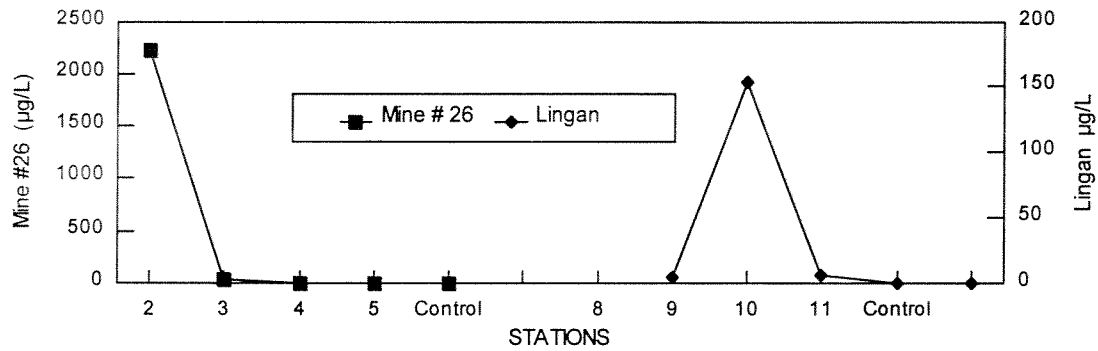


Figure 3 (B)

DISSOLVED MANGANESE



DISSOLVED IRON



DISSOLVED COPPER

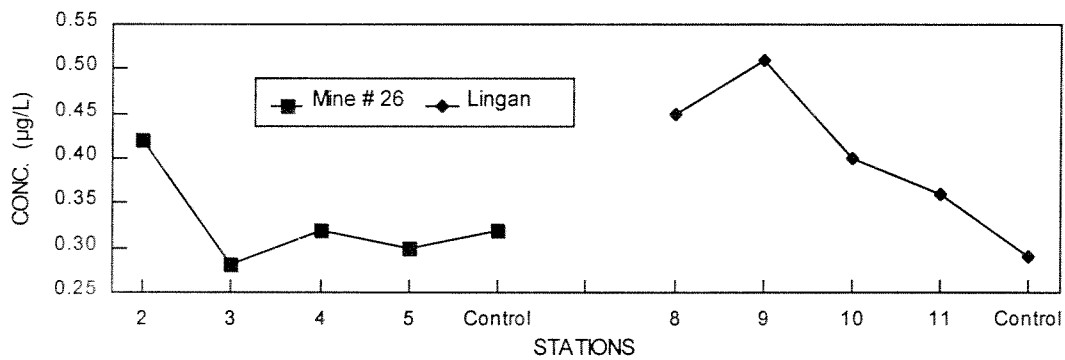
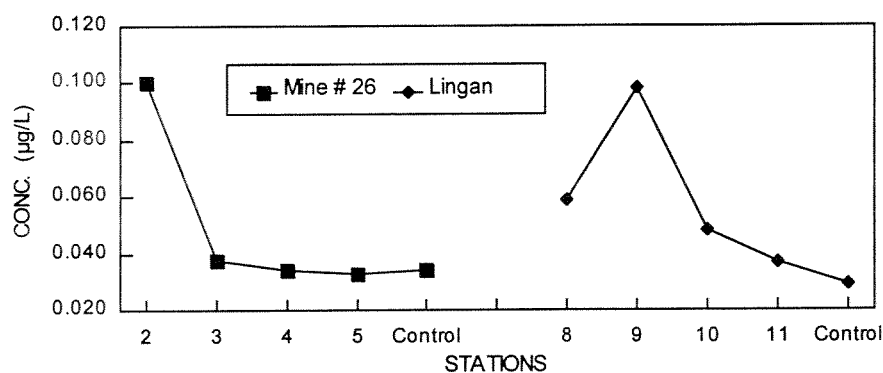
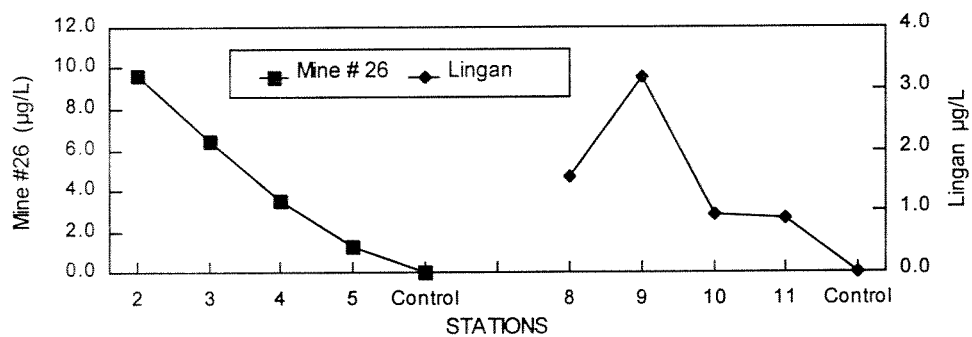


Figure 3 (C)

DISSOLVED CADMIUM



DISSOLVED COBALT



DISSOLVED ALUMINUM

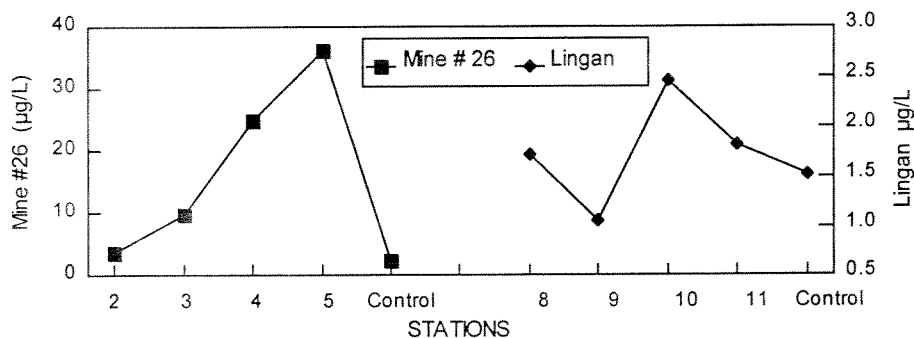
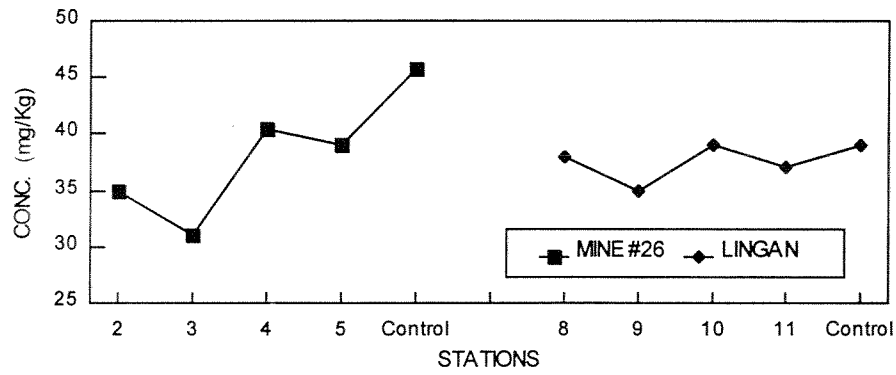
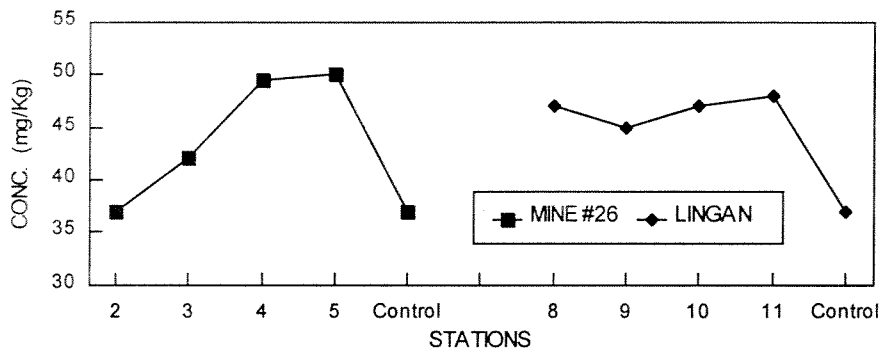


Figure 4 (A)

PARTICULATE COPPER



PARTICULATE NICKEL



PARTICULATE CADMIUM

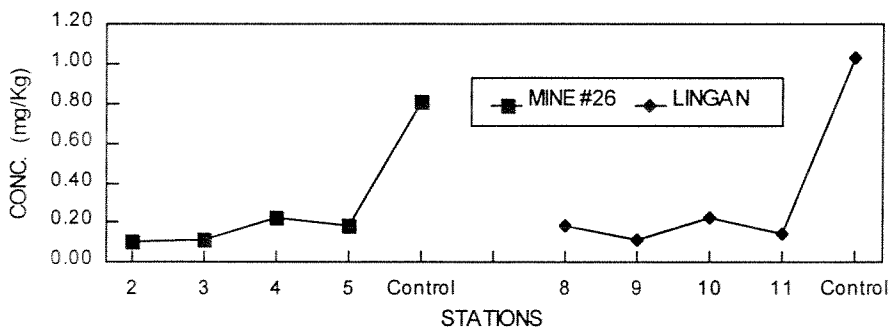
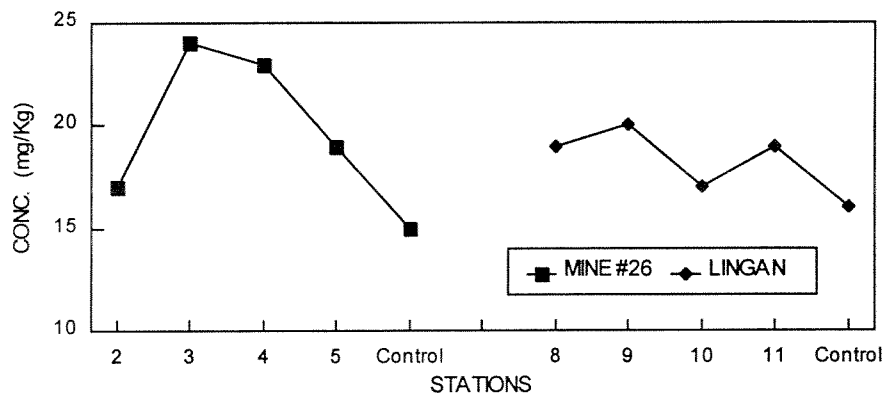
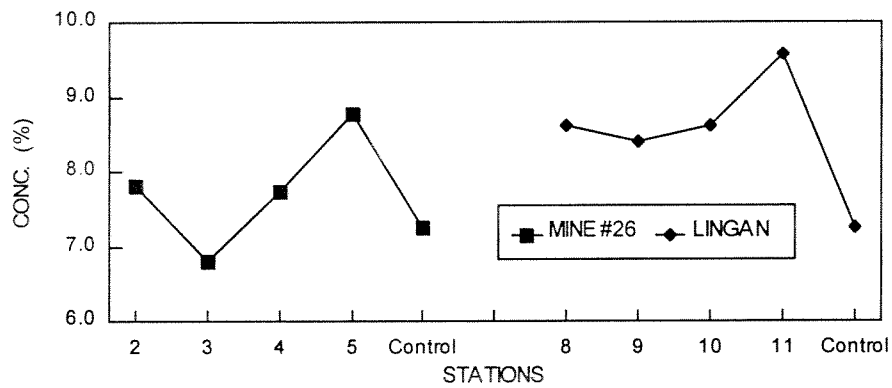


Figure 4 (B)

PARTICULATE COBALT



PARTICULATE ALUMINUM



PARTICULATE IRON

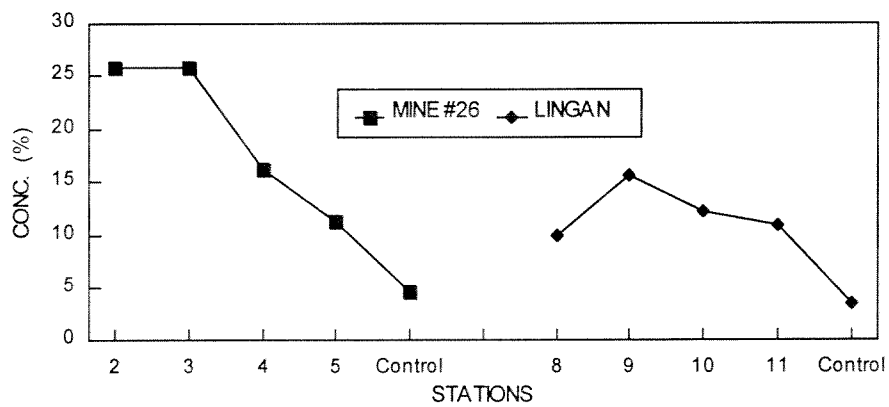
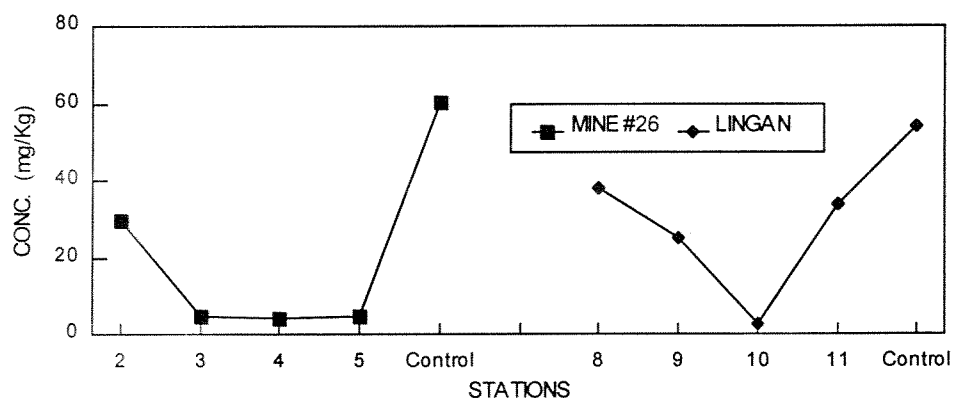
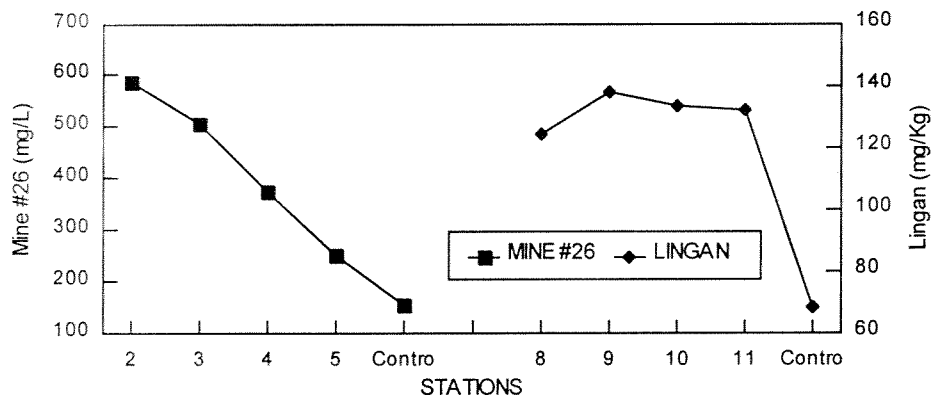


Figure 4 (C)

PARTICULATE LEAD



PARTICULATE ZINC



PARTICULATE MANGANESE

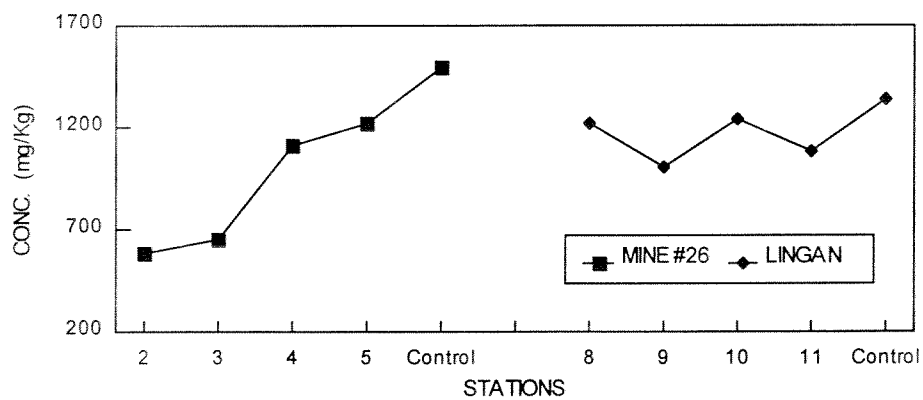


Figure 4 (D)

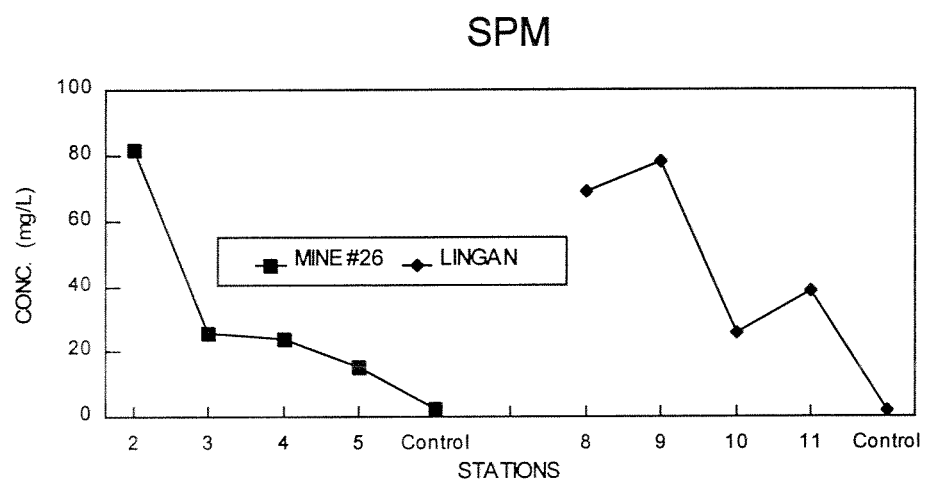


Figure 5

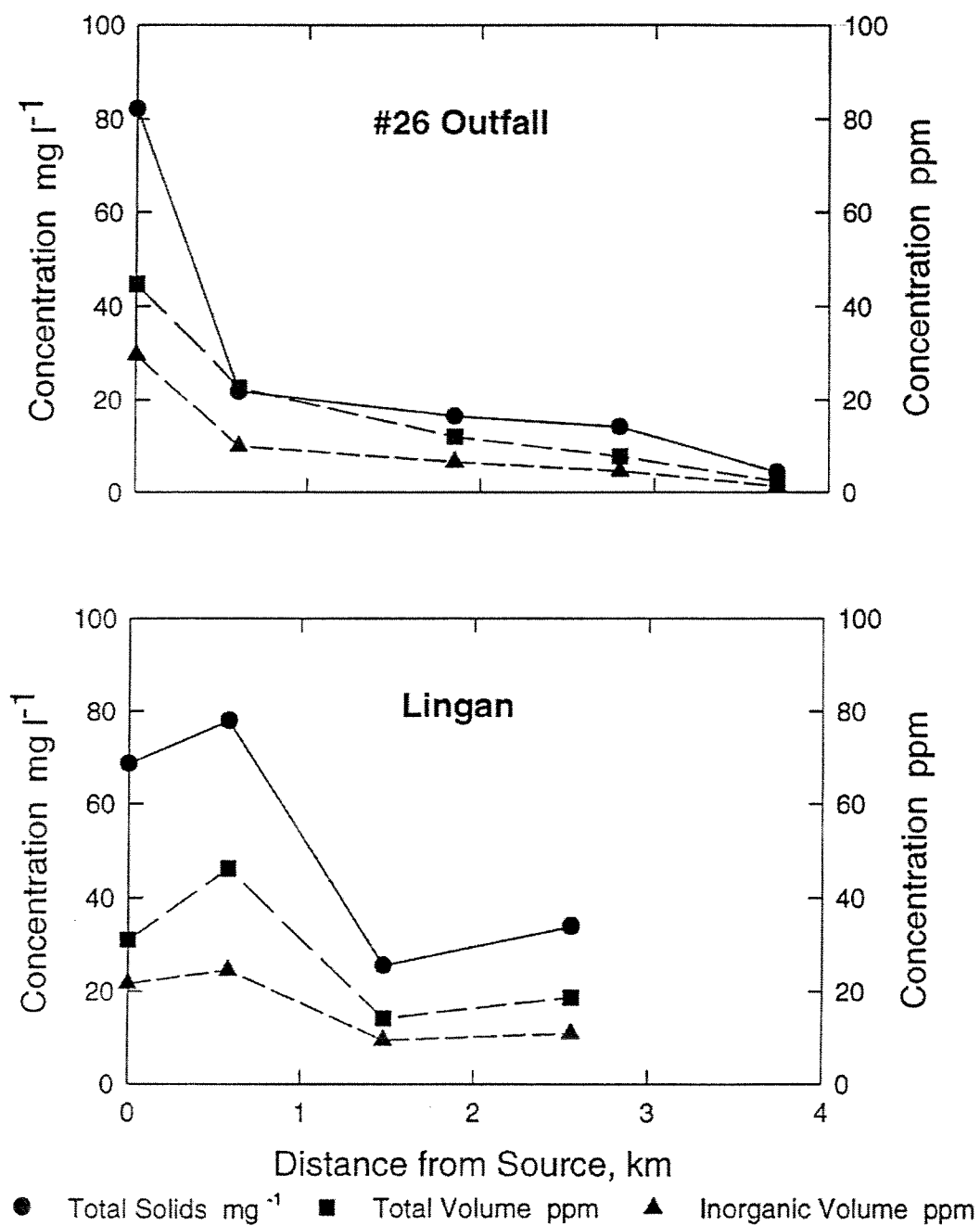


Figure 6(A)

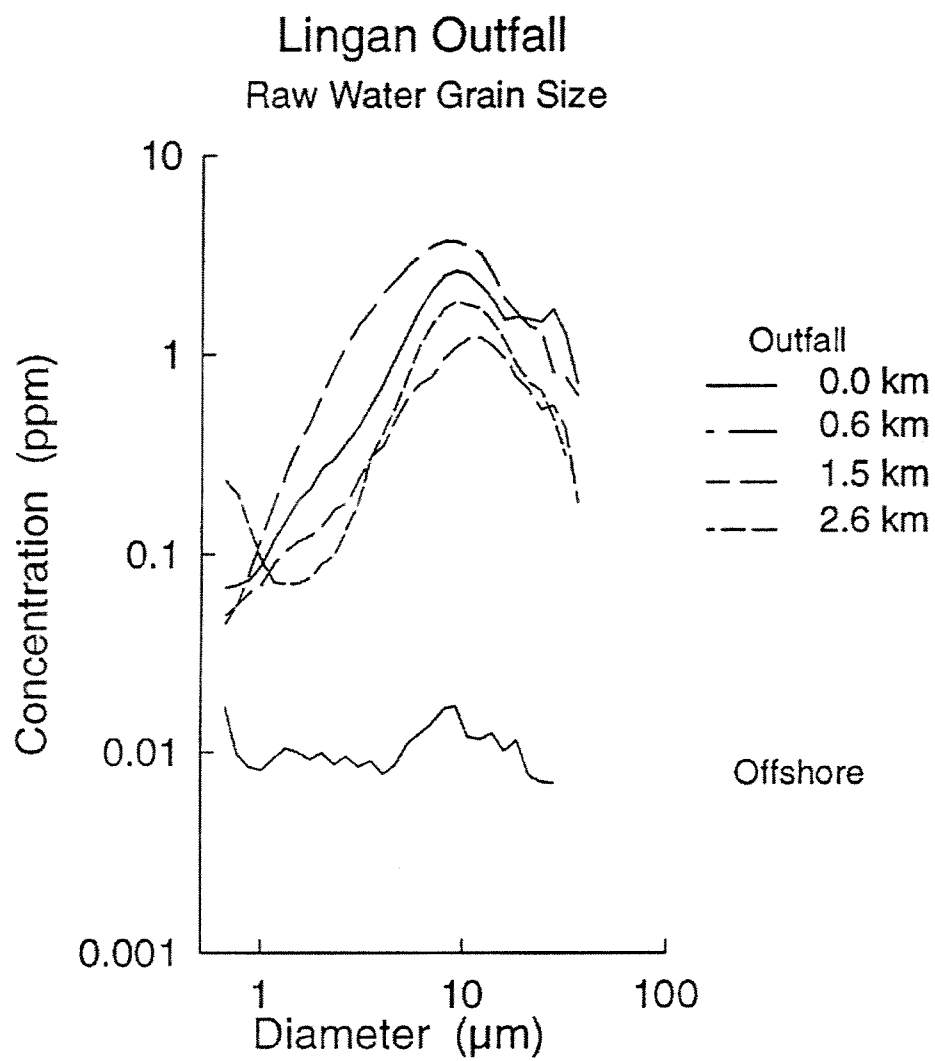


Figure 6(B)

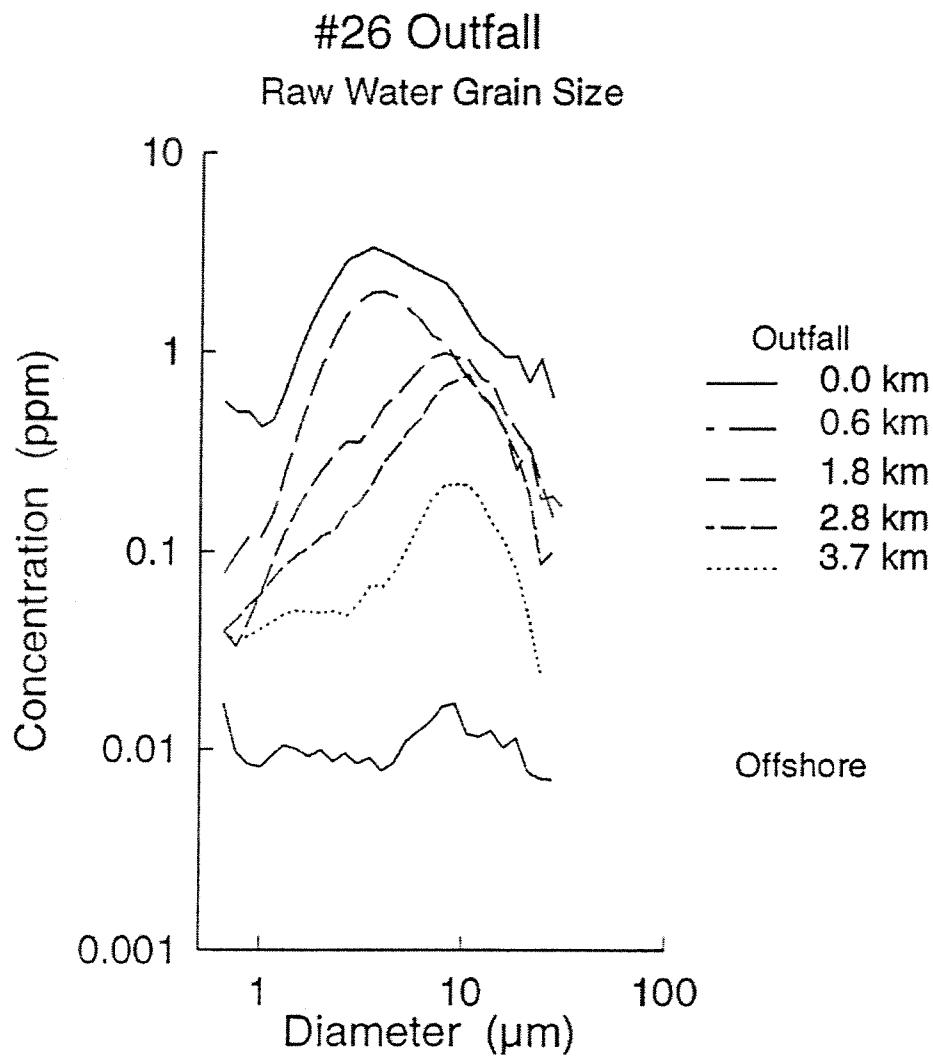


Figure 7(A)

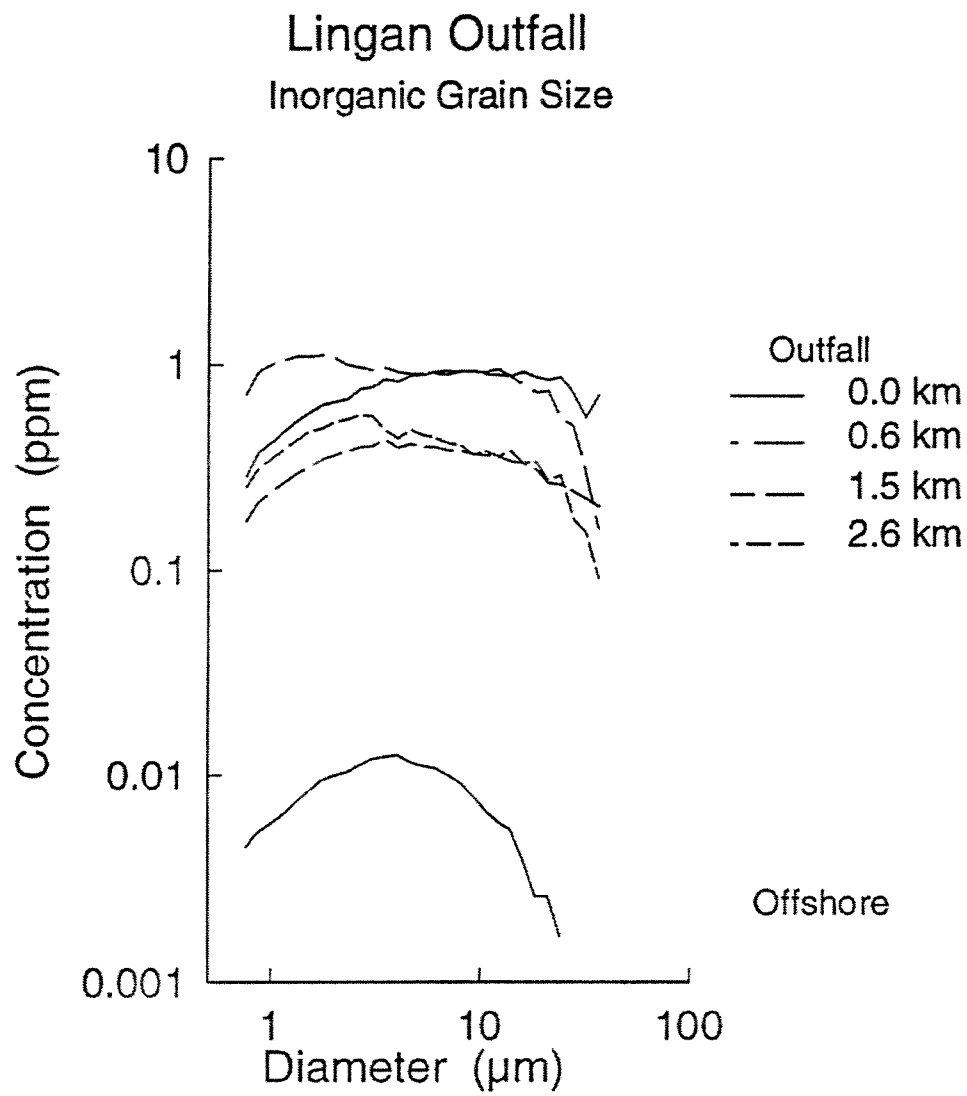


Figure 7(B)

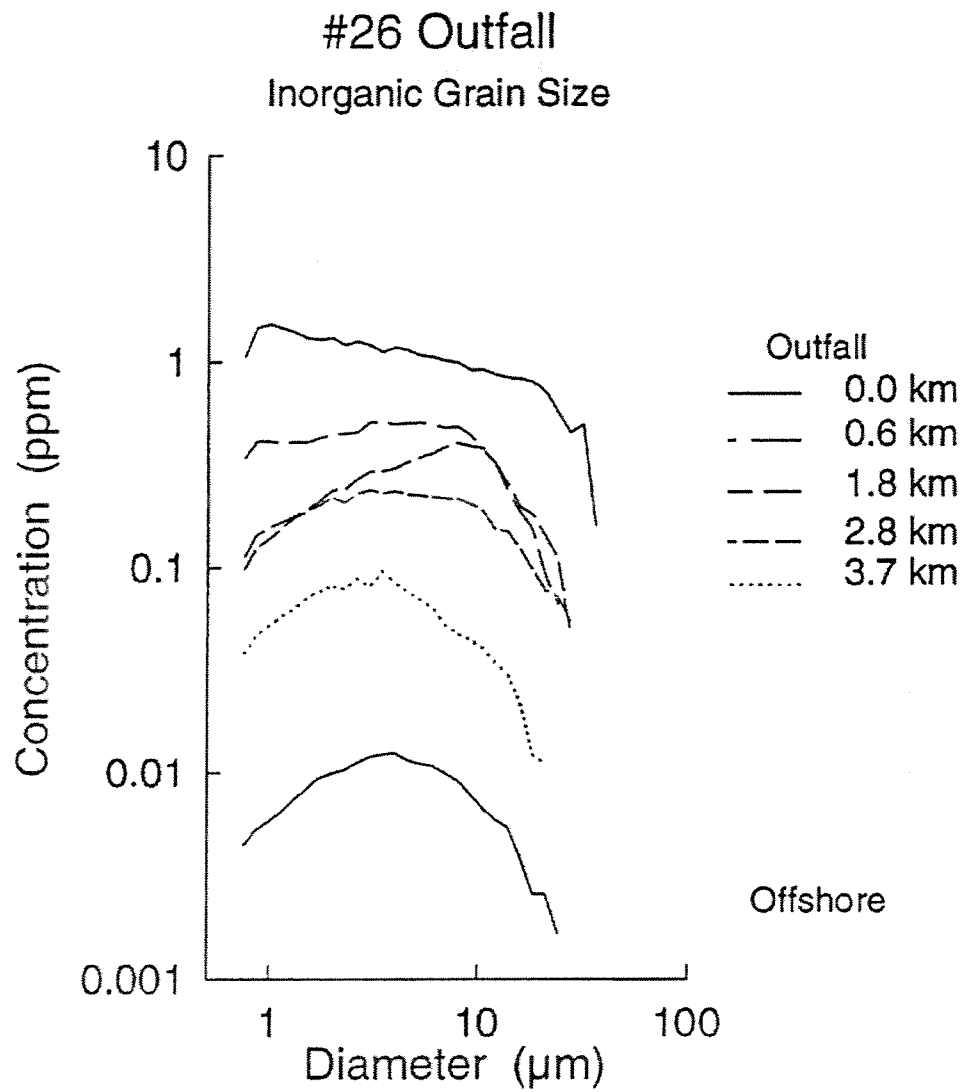


Figure 8 (A)

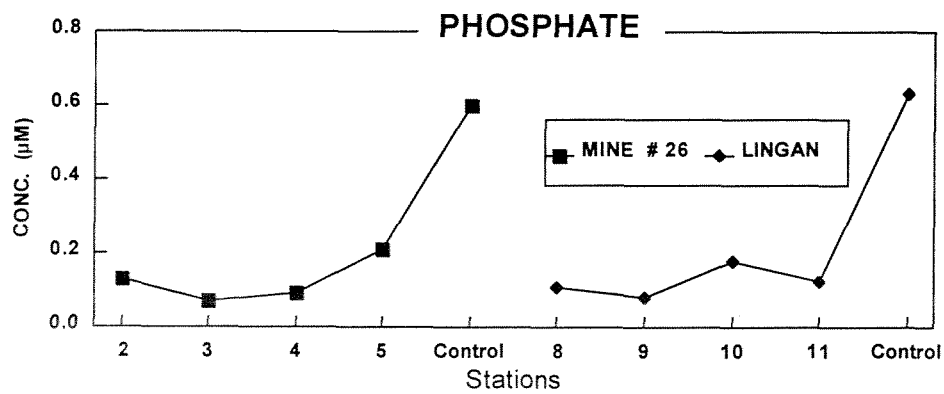
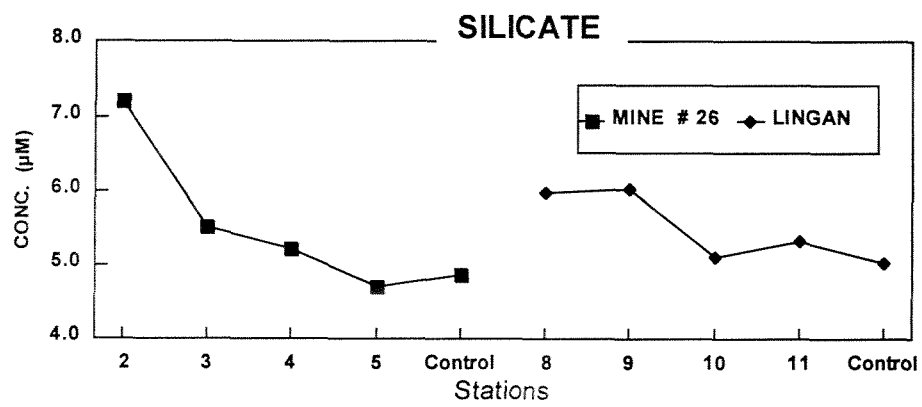


Figure 8 (B)

