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DEPOSITION OF TRACE ELEMENTS IN THE TRAIL REGION, BRITISH COLUMBIA; AN ASSESSMENT OF THE ENVIRONMENTAL EFFECT OF A BASE METAL SMELTER ON LAND

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Teck Cominco's smelter compound, Trail, British Columbia (GSC Photo no. 4724-1).

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DEPOSITION OF TRACE ELEMENTS IN THE TRAIL REGION, BRITISH COLUMBIA; AN ASSESSMENT OF THE ENVIRONMENTAL EFFECT OF A BASE METAL SMELTER ON LAND

Abstract

This study was carried out to assess the spatial deposition and accumulation of trace elements on surface soil in the Trail area, British Columbia, site of a base metal smelter. Monitoring of the deposition was performed by strategically placing twenty-two flat moss-bags (moss-monitoring stations), in the study area and allowing them to be exposed to aerial deposition for 3-month periods over the course of the two-year study. The main goal of this research was to determine the cumulative deposition of the "settleable" portion of elements on land, the extent of influence from the point source, and the seasonal variations in the deposition pattern. The results of this study give a better understanding of the net increase of trace elements in surface soil over a given period of time. This is important in terms of the calculation of the element inventory of the soil and for long-term prediction of the future amounts of trace elements.

Résumé

La présente étude a été réalisée afin d'évaluer le dépôt et l'accumulation d'éléments traces dans le sol de surface, dans la région de Trail (Colombie-Britannique), à proximité d'une fonderie de métaux communs. On a effectué le contrôle du dépôt d'éléments traces en plaçant, en des endroits stratégiques de la zone d'étude, 22 sacs-filtres plats garnis de mousse végétale (des «stations de contrôle de mousse»). Au cours de l'étude biennale, ces stations de contrôle ont été exposées aux dépôts atmosphériques pendant des périodes de trois mois. L'objectif principal du projet de recherche consiste à déterminer les quantités cumulatives des dépôts composés de la portion «sédimentable» des éléments traces sur les sols, l'étendue des répercussions à partir de la source ponctuelle, et les variations saisonnières de la répartition des dépôts. Les résultats permettent de mieux comprendre l'augmentation nette de la teneur en éléments traces des sols pendant une période donnée, ce qui constitue un élément important des calculs de l'inventaire des éléments présents dans le sol et des travaux de prévision à long terme des quantités de futurs dépôts d'éléments traces.

Summary

The aerial deposition and accumulation of the elements As, Cd, Cu, Hg, Pb, and Zn on surface soil was assessed using the passive collection moss-monitoring method in the area surrounding the Trail smelter, British Columbia, Canada. Concentrations of the elements in moss bags exposed to atmospheric deposition for three months were corrected for elemental concentration of the moss matrix, geogenic input, and site-specific local background level, producing common background elemental concentrations for all monitoring stations.

After a two-year study period, the results show that the deposition of these elements is greatest in proximity to the smelter and decreases with an increase in distance. The pattern of deposition generally varies seasonally, with the magnitude of variation being dependent on the element being studied and the location of the monitoring station. Overall, the deposition of the studied elements appears to be a complex phenomenon involving various factors such as meteorological conditions (prevailing wind direction and precipitation), physiography (topography, valley shape, and orientation) and in-process activities at the smelter (production level, emission control efficiency, and the geochemistry of feed). It appears that, on an annual basis, in-process activities, particularly production levels of lead and zinc and the quantity of emissions from the stack, are more directly related to the observed aerial deposition of elements than any of the other factors.

The relative contribution of stack-emitted material and material originating from the secondary sources (e.g., windblown fugitive dust from storage piles and uncovered transportation of ore and slag, and historical dust) was estimated using a combined diffusion/distribution model.

The results indicate that secondary sources are the major contributor of lead and zinc deposited within a short distance from the smelter. The stack emissions become the main source of Pb and Zn at greater distances from the smelter. SEM/EDX photos show a marked difference in morphology and chemical composition of the typical material originating from each source.

The flux of elements into an unit area and the subsequent enrichment of elements in surface soil as a result of exposure to the atmospheric deposition was also calculated by extrapolating the concentration data obtained from the known dimensions of the moss bags to the measured elemental quantities of the surface soil. The net increase in existing quantity of the elements in a soil unit measuring 10 cm deep by one hectare of soil over a three-month time interval were estimated at 0.02%, 0.65%, 0.07%, 0.29%, 0.22%, and 0.65% for As, Cd, Cu, Hg, Pb, and Zn, respectively. These results can be used to predict the long-term degree of element accumulation in the soil assuming that the deposition rate persists over time and that all the elements accumulate on the soil surface with no postdepositional remobilization.

The significant correlation between the deposition rate of Pb, Zn, Cd, and Cu as registered by moss-monitoring stations and the quantity of these elements in surface soil indicate the possible effect of airborne material on the geochemistry of the soils in the study area. In contrast, the poor correlation for Hg and As indicates that the variation of these elements in soil samples are likely related to soil chemistry rather than atmospheric deposition. This demonstrates the importance of monitoring the atmospheric deposition of elements, since soil is not always a good indicator of depositional effects from a point source.

Sommaire

On a évalué le dépôt et l'accumulation des éléments As, Cd, Cu, Hg, Pb et Zn dans le sol de surface en utilisant la méthode de contrôle d'enregistrement passif par des sacs-filtres de mousse, dans la région voisine de la fonderie Trail, en Colombie-Britannique (Canada). On a appliqué des facteurs de correction aux concentrations des éléments présents dans les sacs-filtres de mousse, qui ont été déterminées après une exposition de trois mois aux dépôts atmosphériques. Les corrections ayant trait aux concentrations des éléments présents dans la matrice de mousse, à la contribution géogénique et aux concentrations de fond locales propres aux sites ont permis d'obtenir des valeurs de concentrations de fond des éléments qui sont communes à toutes les stations de contrôle.

Les résultats de l'étude biennale révèlent que le dépôt de ces éléments est maximal à proximité de la fonderie et qu'il décroît avec la distance. En général, la répartition des dépôts suit une variation saisonnière dont l'importance dépend de l'élément étudié et de l'emplacement de la station de contrôle. Dans l'ensemble, il semble que le dépôt des éléments étudiés est un phénomène complexe qui englobe différents facteurs tels que les conditions météorologiques (direction dominante du vent et précipitations), la physiographie (topographie, forme de la vallée et orientation) et les activités en cours d'exploitation à la fonderie (niveau de production, efficacité des mesures antiémissions et géochimie des matières d'alimentation). Les résultats semblent indiquer que la relation directe entre les divers facteurs susmentionnés et les valeurs observées de dépôts atmosphériques des éléments, établie pour une période de douze mois, est supérieure dans le cas des activités en cours d'exploitation, particulièrement les niveaux de production de plomb et de zinc et les quantités d'émissions de cheminée.

On a évalué, à l'aide d'un modèle combiné de diffusion/répartition, la contribution relative des substances émises à la cheminée et de celles provenant de sources secondaires (p. ex. les poussières fugitives déplacées par le vent, provenant des piles de stockage et du transport du minerai et des scories dans des contenants ouverts, ainsi que les poussières de nature historique).

Les résultats indiquent que la principale contribution au dépôt de plomb et de zinc à courte distance de la fonderie est celle des sources secondaires. Les émissions de cheminée deviennent la source principale de Pb et de Zn à de plus grandes distances de la fonderie. Les photographies obtenues par MEB/EDX montrent que la morphologie et la composition chimique des substances caractéristiques provenant de chaque source diffèrent nettement.

On a aussi calculé l'apport d'éléments dans une aire unitaire et l'enrichissement subséquent en éléments du sol de surface, suivant l'exposition aux dépôts atmosphériques. Pour ce faire, on a effectué une extrapolation des données qui tient compte des concentrations obtenues pour les sacs-filtres de mousse, de dimensions connues, et des concentrations mesurées des éléments présents dans le sol de surface. On a estimé que l'augmentation nette des concentrations initiales des éléments présents dans une unité pédologique, qui mesure un hectare de superficie et 10 cm de profondeur, pendant une période de trois mois, est respectivement de 0,02 %, 0,65 %, 0,07 %, 0,29 %, 0,22 % et 0,65 % pour As, Cd, Cu, Hg, Pb et Zn. On peut utiliser ces résultats pour prévoir le niveau d'accumulation à long terme des éléments dans le sol, en supposant que le taux de dépôt reste constant au fil du temps et que tous les éléments s'accumulent à la surface du sol sans subir une remobilisation après le dépôt.

La corrélation élevée qui existe entre les taux de dépôt de Pb, Zn, Cd et Cu, tels que déterminés à l'aide des données recueillies dans les stations de contrôle de mousse, et la concentration de ces éléments dans le sol de surface indique que les matières aéroportées ont probablement une incidence sur la géochimie des sols de la région à l'étude. Par contre, dans le cas de Hg et As, la faible corrélation indique que la variation de la concentration de ces éléments dans les échantillons de sol est probablement attribuable à la composition chimique du sol plutôt qu'aux dépôts atmosphériques. Ces résultats démontrent l'importance d'un programme de contrôle des dépôts atmosphériques d'éléments, puisque l'analyse du sol ne constitue pas toujours un indicateur fiable des incidences reliées aux dépôts provenant d'une source ponctuelle.

INTRODUCTION

Elements in the environment originate from various natural and anthropogenic sources. Naturally occurring elements may be derived from airborne dust particles (geogenic), volcanic activity, forest fires, and various biological processes, whereas anthropogenic releases of elements, particularly those of metals, result partially from the extraction amd smelting of metals, incineration of waste and sludge, metal fabrication plants, and fossil fuel combustion (Nriagu and Pacyna, 1988; Nriagu, 1990; 1994; Rasmussen, 1996).

The total world-wide emission of arsenic (As) from industrial sources in 1983 was approximately 19 000 tonnes (Nriagu, 1990). Of this, 12 350 tonnes (65%) were emitted through the smelting and refining of nonferrous metals. About 2280 tonnes (12%) resulted from fossil fuel combustion, which includes power generation, commercial, industrial and residential fuel combustion, and fuel wood combustion. According to Nriagu (1990), the ratios of industrial to natural emissions for arsenic (As), cadmium (Cd), mercury (Hg) and lead (Pb) were 1.6, 5.4, 1.4, and 28, respectively. In 1990, emissions of As, Cd, Hg and Pb in Canada were estimated at 371, 168, 2840 and 39 tonnes, respectively (Jacques, 1987). The atmospheric deposition of Pb in continental North America is estimated to be 0.02 gram per hectare per year (USEPA, 1986). Nriagu (1978) estimated the annual deposition of Pb to be 30 gram per hectare per year in rural areas of southern Ontario. However, the ambient levels of heavy metal fallout (except for Hg) from the atmosphere have declined in recent years (Reid et al., 1993; Rickert and Kaiserman, 1994).

Particles and elements emitted from an anthropogenic source may be deposited close to their origin or transported over great distances (Schroeder et al., 1987; Schroeder and Lane, 1988; Swaine, 1995; Rassmussen, 1998; Landsberger et al., 1990; Keeler et al., 1993). Schroeder et al. (1987) and Schroeder and Lane (1988) indicated that elements emitted from an anthropogenic source are subjected to prevailing atmospheric conditions, with the location and magnitude of deposition influenced ultimately by landscape ecology, wind characteristics, humidity, fog, clouds, precipitation, temperature, and solar irradiation. Metals can be transported globally through the atmosphere (Landsberger et al., 1990; Keeler et al., 1993).

In environmental studies, monitoring may be undertaken to assess the need for emission control around industrial sources of pollution (Reay, 1979). Monitoring refers to the relative assessment or measurement of exposure caused by natural and anthropogenic activities (Holdgate 1979; Preston 1975; Reay 1979). Monitoring an area or a source is a carefully planned exercise that provides a quantitative understanding of the impact of a point source on the environment at a given time. There are studies that determine the concentrations of elements in peat or humus in the vicinity of point sources or contaminated areas to show the possible source of contamination in the area, and to assess the range of atmospheric fallout and local impact (Reimann et al., 1997, Steinnes, et al., 1993; Parkarinen, 1981). Although these types of studies are good indicators of possible enrichment of elements in an area, they cannot be used for ongoing monitoring of the aerial deposition of elements (particles), as they report only the possible cumulative deposition since the start of an operation.

The deposition of particles and associated elements from a stationary source such as a smelter can be monitored using various biological media (e.g., transplanted lichen) and passive collection methods (e.g., deposit gauges, sticky tray, dust jar/bucket or an impactor) (Goodman and Roberts, 1971; Roberts, 1972; Groet, 1976; Parkarinen and Tolonen, 1976a, b; Little and Giffen, 1978; Pilegaard, 1979; Schroeder et al., 1987; Rhoades 1988; Godbeer and Swaine, 1995).

Useful results have been obtained using moss for monitoring the atmospheric deposition of particles and associated elements around point sources (Crump and Barlow, 1980; Goodman and Roberts, 1971; Goodman et al., 1975; Hall et al., 1975; Horler and Barber, 1975; Godbeer et al., 1981; Simmons and Pocock, 1987; Tripathi et al., 1993; Martin and Coughtrey, 1982; Temple et al., 1981). In this method, moss is collected from a remote natural environment and is cleaned and demineralized by treatment with acid. Although it uses moss, this passive collection approach for monitoring differs from biomonitoring, where live moss or other vegetation is used (Goodman and Roberts, 1971; Roberts, 1972; Pilegaard, 1979; Swaine, 1995).

There are a number of studies using acid-washed moss in bags to monitor the deposition of trace elements in the vicinity of point sources (Godbeer et al., 1981; 1984; Swaine et al., 1983; 1989; Swaine, 1994; Godbeer and Swaine, 1995). Moss has various physical and chemical characteristics that make it an ideal medium for capturing airborne particles and associated elements. Examination of *Sphagnum* moss using Scanning Electron Microscopy (SEM) indicates that structurally it is composed of small holes and folds, which retain particles (Fig. 1) (see also Swaine et al., 1983). Other characteristics of moss that make it useful in such studies are: 1) the cation exchange properties of *Sphagnum* moss allow it to retain metals deposited as ionic species (Martin and Coughtrey, 1982; Clymo, 1963; Ruhling and Tyler, 1970); 2) moss can retain significant quantities of water, therefore preventing the loss of captured particles through dripping or quick oversaturation (Martin and Coughtrey, 1982); and 3) moss can be placed into flat, square bags that facilitate the

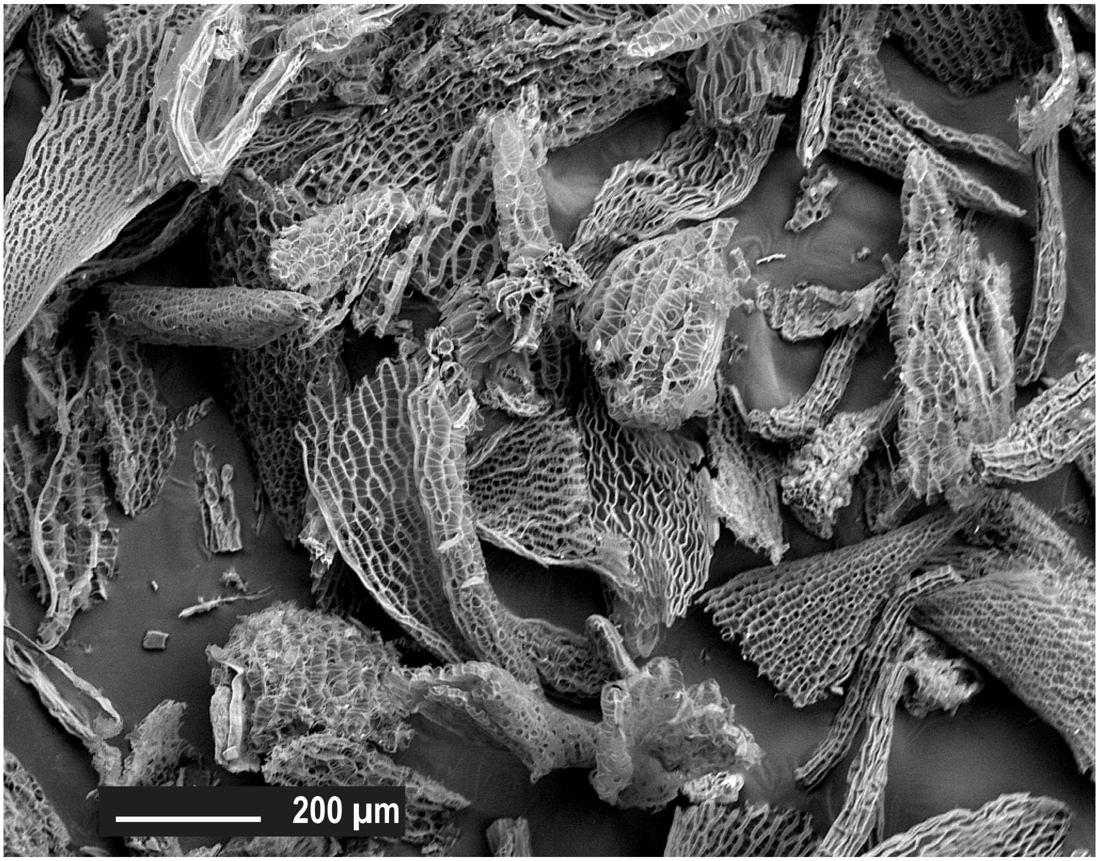

Figure 1. *Morphology of clean moss fragments before exposure to aerial deposition of particles (GSC Photo no. 4724-2).*

calculation of deposition rates per unit area (Martin and Coughtrey, 1982).

Overall, moss bags are an efficient monitoring device as they are convenient and inexpensive, especially for determining the extent of impact by a point source, the deposition pattern, and the parameters involved in the distribution and deposition of pollutants in the study area (Martin and Coughtrey, 1982; Godbeer and Swaine, 1995). The moss-monitoring method can be used to identify the so called “hot-spot” of impact, after which more detailed and precise monitoring by standard methods can be pursued (Goodman et al., 1975a, b).

In this study, the moss-monitoring method has been used to determine the quarterly (every 3 months) deposition and accumulation of As, Cd, Cu, Hg, Pb, and Zn at various distances from the Teck Cominco smelter at Trail, British Columbia.

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STUDY AREA

Smelting operation

Trail, British Columbia, is situated in the southern Kootenay Mountains (49°06.5'N; 117°42'W), on the west bank of the Columbia River, and is the site of a base metal smelter owned and operated by Teck Cominco Metal Ltd. (Fig. 2). The Trail smelter has been in operation since 1896, when the original was built as a copper-gold smelter. Early in the 20th century production quickly expanded to lead and then zinc. At present, the Trail operation is a zinc and lead smelting facility equipped with baghouses, electrostatic precipitators and scrubbers for all major stack and discharge sources. The Trail operation produces zinc, lead, silver, gold, cadmium, bismuth, indium, germanium, copper and sulphur products, as well as fertilizers. Zinc and lead production capacities are approximately 230 000 tonnes and 160 000 tonnes per year, respectively (Kenyon, 1998).

Climate

The study area falls within the intermontane physiographic region of British Columbia. The climate is mild with mean annual temperature of 8.3°C (Environment Canada, 1993).

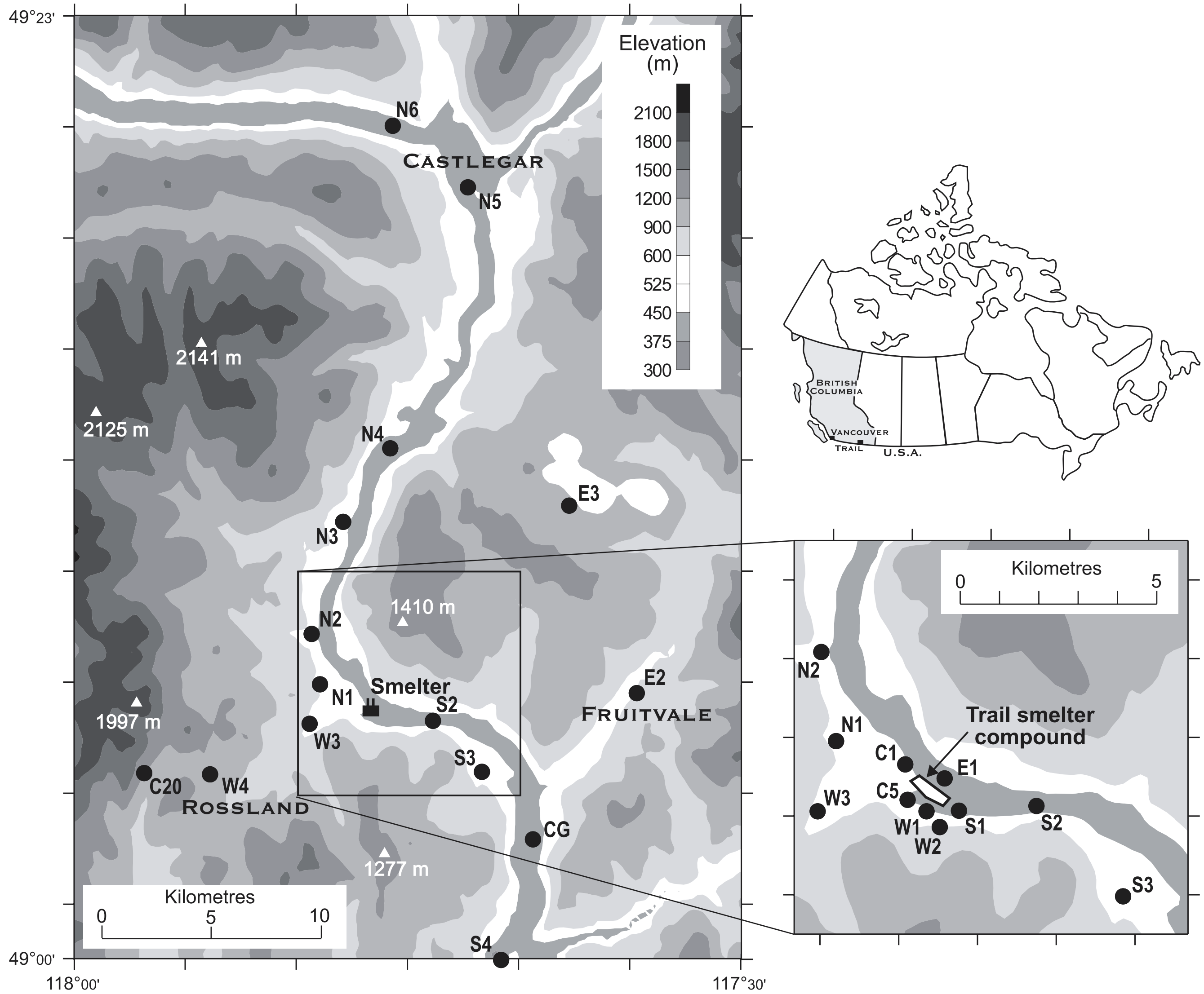


Figure 2. Map of Columbia River Valley, showing the site of the Teck Cominco zinc-lead smelting operation in Trail and locations of the moss-monitoring stations. Five groups of stations located in two major north-south and east-west transects are 1) northern stations (N6, N5, N4, N3, N2, and N1), 2) central stations (C1 and C5), 3) southern stations (S1, S2, S3, S4, and S5), 4) western stations (C20, W4, W3, W2, W1), and 5) eastern stations (E1, E2, and E3). Station CG is located at Columbia Gardens, approximately 11 km south of Trail. Note: the groupings are assigned based on the positions of the sampling sites in relation to the Columbia River Valley as opposed to the actual geographic coordinates. S5 is located outside the boundary of the map.

Total average precipitation is 731.9 mm per annum, with 533.2 mm falling as rain and 224.6 cm falling as snow according to the climate normals data for Castlegar region (Environment Canada, 1993). The prevailing wind direction is north-northwest to south-southeast with the stronger component to the southeast (Fig. 3), and is controlled largely by the orientation of the Columbia River Valley (Cominco, unpub. data, 2000). In a mountainous region such as Trail area, the wind speed and direction is strongly influenced by the elevation and topography of the terrain as well as the orientation of major features such as the Columbia River valley and tributary gorges.

Geology of the Trail area

The Columbia River Valley bisects the sampling area, and is designated as the boundary between the Monashee (west side) and Selkirk (east side) mountains.

The geology of the area is complex, consisting of several rock units of varying age and origin (Fig. 4; Little, 1982; Simony, 1979). The surficial geology shows the effect of Pleistocene glaciation, and the area is predominantly covered by discontinuous ground moraine (Little, 1982). The major bedrock units are the Upper Jurassic to Cretaceous plutonic rocks (the Nelson Intrusives and the Rossland Monzonite), Lower Jurassic metavolcanic and metasedimentary rocks (the Elise Formation), upper Paleozoic (Pennsylvanian) sedimentary and metasedimentary rocks (the Mount Roberts Formation) and the pre-Pennsylvanian Trail Gneiss (precise age unknown) (Fig. 4; Little, 1982; Höy and Andrew, 1991; Simony, 1979).

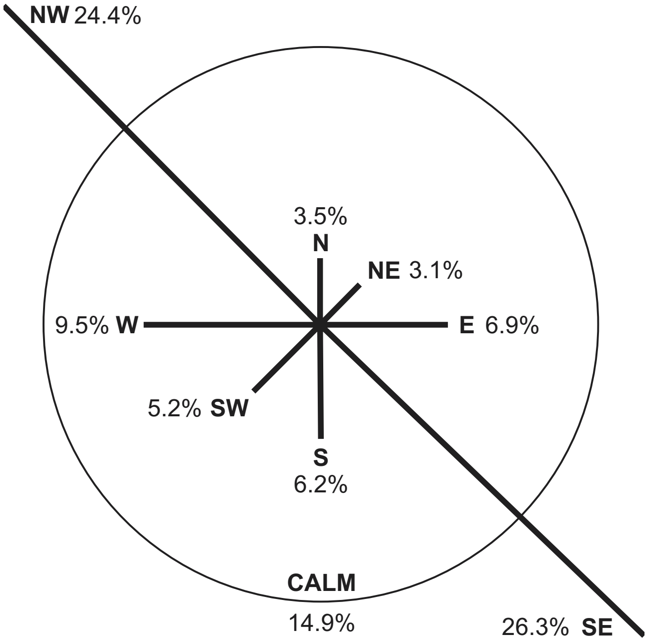


Figure 3. *Wind rose diagram for the Trail region showing the percentage of time wind occurs in each direction during the study period.*

The Nelson Intrusives

The town of Trail and most of the study area are situated over the Trail Pluton (Fig. 4) (Simony, 1979; Little, 1982). This pluton is part of the Upper Jurassic Nelson Intrusives, which also include the larger Bonnington and Nelson plutons. The Trail Pluton is a lacolith. Rock types consist predominantly of granodiorite, with quartz diorite, diorite, gabbro, and granite at the margins (Little, 1982; Sevigny, 1990). Molybdenum skarn and porphyry deposits occur along the margins (Höy and Andrew, 1989). The Trail Pluton is homogeneous and geochemically simple, compared to the nearby Bonnington Pluton. The Bonnington Pluton can be subdivided into two zones: a southern body ranging in composition from quartz gabbro to granite, and a northern body ranging from potassic tonalite to granodiorite (Sevigny, 1990). Table 1 contains a summary of the major and trace element geochemistry of the main phases of the Trail and Bonington plutons, as determined by Sevigny (1990). The geological setting, petrography and geochemistry indicate that the emplacement of the Nelson Intrusives was associated with the formation of the Kootenay Arc, which formed during the convergence of the North American plate with allochthonous oceanic terranes (Sevigny, 1990).

The Rossland Monzonite

The Rossland Monzonite (Fig. 4) is a grey to green, fine- to medium-grained stock, consisting of andesine, hornblende, orthoclase microperthite, augite, biotite, and quartz (Fyles, 1984). Although its age is unknown, it is cut by the Trail Pluton, which indicates an age older than Late Jurassic. The Rossland Monzonite hosts vein gold deposits.

The Elise Formation

Much of the area east and northeast of Trail (Montrose, Fruitvale, Champion Lakes) overlies the Lower Jurassic Elise Formation, part of the Rossland Group (Fig. 4). The lithology is characterized by flow breccia, massive lava, agglomerate, volcanic breccia, tuffs, tuffaceous conglomerate, andesite, basalt and augite porphyry, metamorphosed to the greenschist facies. Limestone xenoliths and calcite amygdules are found within the mafic flows. Clasts from the tuffaceous conglomerate are commonly limestone derived from the underlying Mount Roberts Formation (Little, 1982; Höy and Andrew, 1991).

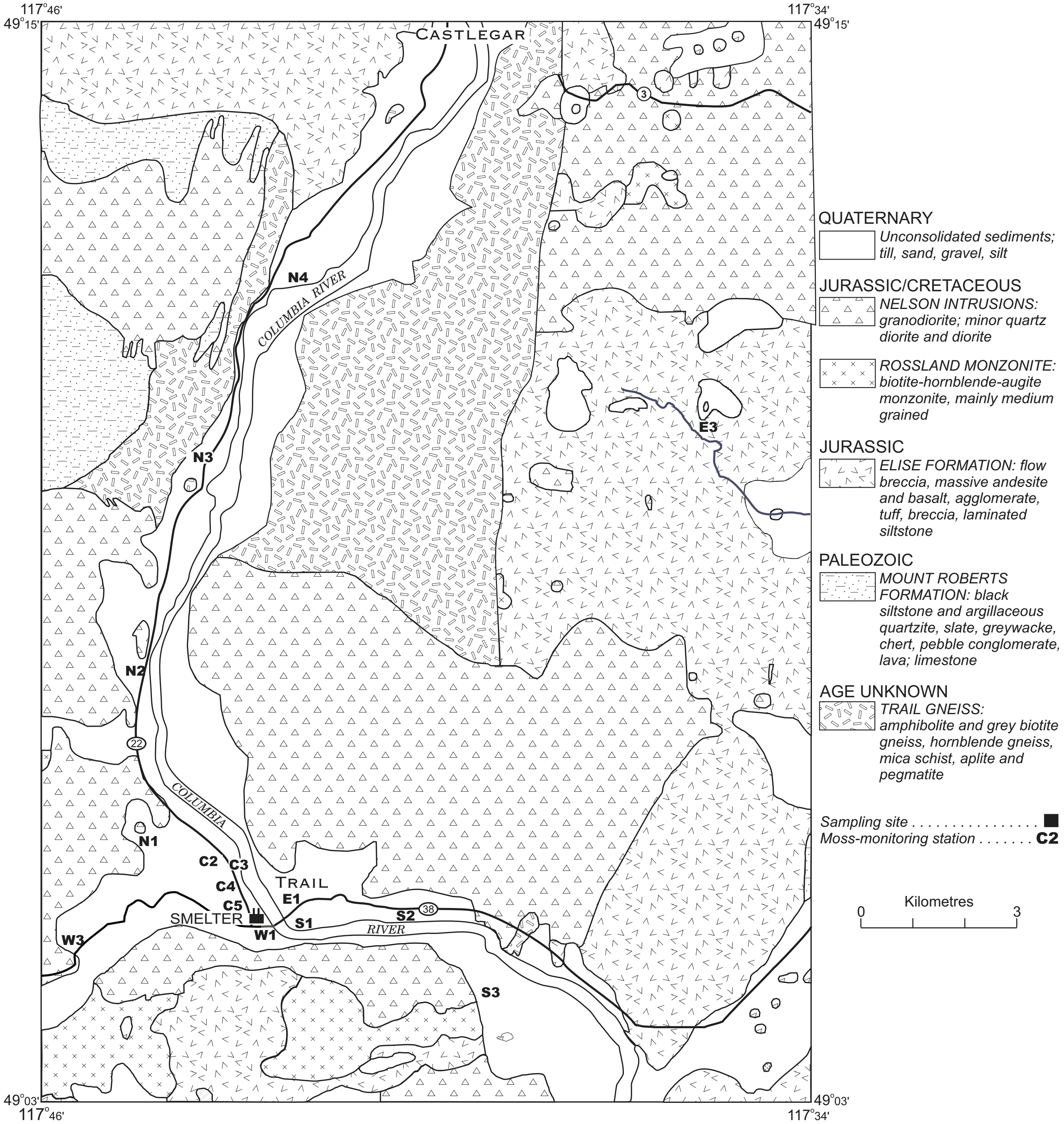


Figure 4. *Geological map of the Trail area, showing the locations of moss-monitoring stations (after Little, 1982).*

The Elise Formation hosts most of the gold and copper (pyrrhotite with chalcopyrite) vein deposits of the Rossland area (Höy and Andrew, 1991). Lead, zinc, and silver vein deposits are also associated with the contact of the Elise and the overlying Hall Formation. Associated minerals include sphalerite, galena, arsenopyrite, pyrite, chalcopyrite, and boulangerite.

Table 1
Average major and trace element concentration of the main phases of the Trail and Bonnington plutons (from Seveigny, 1990)

Major oxides (%)	Trail Pluton				Bonnington Pluton			
	Granodiorite		Quartz gabbro		Potassic tonalite		Granodiorite	
	%	sd	%	sd	%	sd	%	sd
SiO_2	64.2	1.39	54.25	1.17	60.51	0.9	66	2.17
TiO_2	0.57	0.08	0.92	0.08	0.64	0.11	0.38	0.09
Al_2O_3	16	0.22	17.49	0.75	16.88	0.61	16.47	0.47
Fe_2O_3	4.96	0.67	9.7	0.83	6.37	0.94	3.69	0.79
MnO	0.1	0.01	0.18	0.04	0.13	0.01	0.09	0.02
MgO	1.97	0.32	4.2	0.55	2.44	0.87	1.14	0.4
CaO	4.79	0.7	7.04	1.87	4.8	1.17	3.96	0.32
Na_2O	3.46	0.37	4.01	1.4	4.72	1.28	4.07	0.52
K_2O	3.09	0.35	1.83	0.56	2.91	0.35	3.45	0.41
P_2O_5	0.24	0.03	0.34	0.05	0.26	0.04	0.17	0.05
Trace elements (ppm)	**ppm**	**sd**	**ppm**	**sd**	**ppm**	**sd**	**ppm**	**sd**
V	100	18	223	50	130	38	59	19
Cr	20	7	32	12	22	16	10	12
Ni	5	1	13	2	7	3	5	2
Zn	69	8	126	11	82	15	54	11
Ga	18	1	21	1	19	1	17	1
Rb	93	8	72	32	96	22	102	21
Sr	654	29	744	285	700	187	782	132
Y	18	2	20	5	21	2	14	3
Zr	130	9	65	25	122	43	107	29
Nb	16	1	8	1	12	1	13	3
Ba	1039	112	809	107	1057	253	1418	286
Pb	13	5	9	2	9	4	12	2
Th	9	2	5	5	6	3	6	4

The Mount Roberts Formation

The Mount Roberts Formation (Fig. 4) consists of a succession of predominantly fine-grained siliciclastic rocks, argillite, carbonate, and minor greenstone, of Pennsylvanian and possibly Permian age (Little, 1982; Höy and Andrew, 1991). The Red Mountain molybdenum deposits are hosted by siltstone that has been tentatively assigned to the Mount Roberts Formation, based on lithological similarity (Höy and Andrew, 1991). However, Fyles (1984) suggested that these rocks belong to the Rossland Group, possibly the Elise Formation.

The Trail Gneiss

The Trail Gneiss (Fig. 4) is made up of hornblende gneiss, biotite, granodioritic gneiss, foliated aplite and pegmatite, massive pegmatite, quartzo-feldspathic mica schist, and amphibolite and garnet mica schist, and marble. Rock type compositions of the Trail Gneiss vary considerably and it is interpreted by Simony (1979) to be a reworked piece of the Precambrian North American craton.

METHODOLOGY

Preparation of moss media and the monitoring stations

Moss for this study (*Sphagnum fuscum*) was collected from a remote area of northern Canada (Mackenzie Delta area) by helicopter. This site was chosen with the goal of minimizing the potential influence by anthropogenic sources. Sampling was confined to the upper parts of beds to avoid contamination by soil materials.

Once collected, the moss was hand sorted to obtain long, clean strands, free of any extraneous material (e.g., leaves, debris, twigs). The moss was then soaked overnight in distilled water following which it was rinsed three times in distilled water. Subsequently the moss was soaked for six hours and 24 hours in 0.5 M nitric acid. After each soaking period, it was again rinsed three times in distilled water.

The resulting decontaminated moss was then air dried to a slightly damp state and then used to fill the moss bags, which are designed to allow air to continuously flow through the plastic mesh into the moss.

The moss washing process was conducted under strict conditions in a clean room specifically used for this purpose to avoid any contamination due to the airborne particles and other possible contamination. At all times, manipulation of the moss samples involved the use of sterile latex gloves, and working surfaces in contact with the moss were polyethylene-lined. All the containers used for washing, rinsing, and drying as well as the moss bags themselves were decontaminated by HNO_3-HCl solution. Before and after exposure, the moss bags were immediately sealed in clean polyethylene bags and transferred into cleaned containers for transportation. Subsequently, exposed moss was shipped under the same controlled conditions to the laboratories where sample analysis was carried out also in a controlled, clean-room environment.

Design of a moss-monitoring station

The moss-monitoring stations were constructed in a workshop located at the Geological Survey of Canada (Calgary). A monitoring station consists of a support frame, which holds two moss bags; a 2 m high pole on which the support frame rests to prevent mud splashing as the result of rain and to reduce contamination by wind-blown dust; and vertical bars to deter birds (Fig. 5).

Moss bags

The moss bag is a flat, fine-meshed plastic bag consisting of four, 8 x 8 cm compartments, each of which holds 2 g of moss. The bag is reinforced with extra layer of mesh in the bottom surface to reduce loss of moss during exposure in the field. Two moss bags held by a support frame are placed on each moss-monitoring station for replication purpose (Fig. 5). The known dimension of the moss bag allows extrapolation of the concentration of elements to the deposition rate expressed as grams per hectare for a given period of exposure.

Installation of moss-monitoring stations

Twenty-two moss-monitoring stations were placed in the area surrounding the smelter and up to a distance of 26 km north, 21 km south, 12 km west, and 14 km east of the smelter (Fig. 2). The location of each moss-monitoring station was determined after considering the topographic and meteorological conditions of the location, accessibility, area of health concern (e.g., hospital, school), and distance from roads, trees, and agricultural land. The exposed moss bags from these stations were collected every three months during the collection period of fall 1997 to winter 2000. This study however, focuses on 1998 and 1999 as the study period. The exposed moss bags were kept in sealed polyethylene bags and stored in a clean room until further processing was conducted. The exposed moss from all four sections of the moss bag was combined to represent the deposition experienced by the entire moss bag. This composite sample was then subjected to quantitative elemental analysis.

Sampling of surface soil

Surface soils around the Trail smelter were sampled prior to the beginning of the moss-monitoring study to determine the initial concentrations of elements in the soil. The soil samples were collected from the organic-rich, 0–10 cm upper part of the soil profile (~A-horizon), at the same locations as the moss-monitoring stations (Fig. 2). Two or three soil samples taken within a few metres of each other were mixed to serve as a composite sample for each site. The composite soil samples were air-dried and the less than

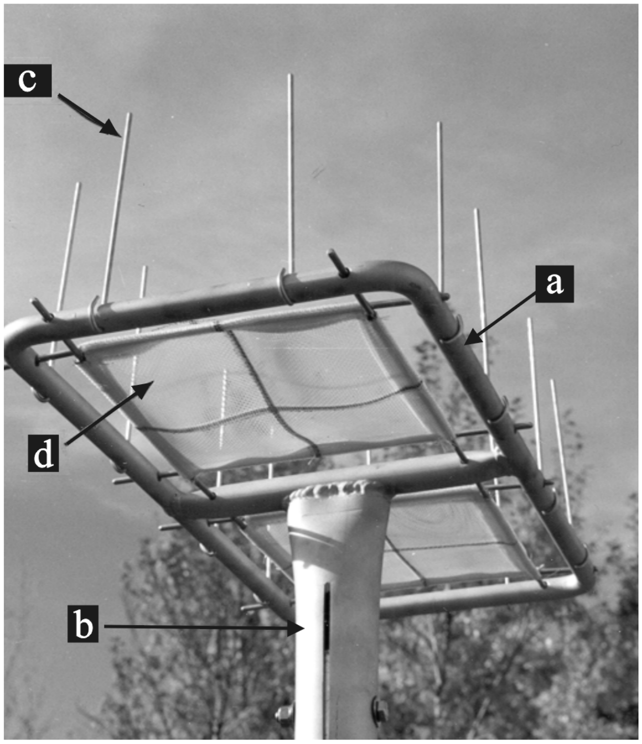


Figure 5. *A moss-monitoring station's components showing (a) support frame, (b) 2 m-high pole, (c) bird scare, and (d) moss bags (GSC Photo no. 4724-3).*

2 mm grain size fraction was recovered by dry sieving with a stainless steel sieve. The recovered materials were then ground and homogenized before analysis.

Analytical procedures

Exposed moss samples and samples of clean moss (before exposure) were shipped in sealed plastic containers to the Becquerel Laboratories Inc. (Mississauga, Ontario, Canada) for elemental analyses. The samples were tested for a suite of elements using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) followed by hot digestion with nitric, perchloric, and hydrofluoric acids. Instrumental Neutron Activation Analysis (INAA) was also used to determine the bulk concentration of elements using McMaster University's (Hamilton, Ontario) nuclear reactor followed by Gamma Spectrometry conducted by Becquerel Laboratories Inc. Concentrations of Hg were determined using Cold Vapor Atomic Absorption (CVAA) following digestion with Aqua Regia.

Geochemical analyses of the surface soil samples collected from the region were carried out using the same analytical techniques. The only difference was for arsenic, which was determined using Atomic Absorption hydride (AA hyd) after digesting the samples with Aqua Regia.

Analyses of duplicates, which represent laboratory splits of a single composite sample, were used in addition to laboratory standards to monitor analytical accuracy and precision of all analytical methods. For further information on analytical methods, see Stoppler (1992) and Sloss and Gardner (1995).

The morphology, mineralogy, and chemical compositions of particles were studied using Scanning Electron Microscopy/Energy Dispersive X-ray (SEM/EDX) at the Geological Survey of Canada, Calgary.

Data treatment

As-received data may contain elemental concentrations that are below the detection limit of the analytical instrument. The convention used in this case for the treatment of elemental data is that concentrations below the reported detection limit were assigned a value equivalent to one-half of the detection limit. This applies only for mathematical treatment of the data (EPRI, 1994). The resulting calculated value cannot be less than the lower limits of detection.

Correction for moss matrix

Concentrations of As, Cd, Cu, Hg, Pb, and Zn as registered by moss-monitoring stations were corrected for the moss matrix by subtracting elemental concentrations of blank moss samples (purified moss before exposure; Table 2). The resulting concentrations of the elements cannot be solely linked to atmospheric deposition from the Trail smelter since a portion of the elements deposited on the moss-monitoring stations could be traced to various natural and geogenic sources. Therefore, further corrections are required in order to differentiate the environmental effect of trace elements originating from smelting activities from those that are natural.

GEOGENIC AND NATURAL SOURCES OF TRACE ELEMENTS

Martin and Coughtrey (1982) stated that all trace elements occur, to a varying extent, within all components of the environment. Therefore, the environmental impact of trace elements is not a "unique occurrence", but rather an increase relative to the natural occurrence of trace elements. Unusual occurrences of trace elements in the environment can be attributed to natural events and industrial sources. In other words, "the primary source of trace elements into the

Table 2
Elemental concentrations of the blank moss samples (purified moss before exposure)

Blank moss samples	Al %	As mg/kg	Cd mg/kg	Cu mg/kg	Hg mg/kg	Pb mg/kg	Zn mg/kg
Fall 1997	0.03	0.2	0.05	2	0.06	1.8	3
Winter 1998	0.04	0.2	N/D	4	0.04	2.0	8
Spring 1998	0.03	0.2	0.08	3	0.05	1.9	6
Summer/Fall 98, Winter 99	0.01	0.4	0.12	3	0.04	4.0	18
Spring 1999	0.01	0.5	0.19	2	N/D	5.3	28
Summer 1999	0.01	0.3	0.10	4	0.04	5.0	15
Fall 1999, Winter 2000	0.01	0.3	0.07	2	0.09	1.7	11
Lower limit of detection	0.01	0.1	0.02	1	0.02	0.5	2
Method	INAA	INAA	ICP-MS	ICP-MS	CVAA	ICP-MS	ICP-MS

N/D: Not detected; ICP-MS: Inductively Coupled Plasma - Mass Spectrometry;
INAA: Instrumental Neutron Activation Analyses; CVAA: Cold Vapor Atomic Absorption

environment is from naturally occurring geochemical materials", which can be enhanced by human activity. Hence, anthropogenic activity is not the only source of trace elements, rather it is a cause of an elevated occurrence.

One of the most important parameters in an environmental study of atmospheric fallout from anthropogenic sources is to determine the variation in natural geological background data (Rasmussen, 1996; Lindberg, 1987). Geological processes, such as soil erosion and sediment deposition by wind (dust loading) contribute to the total (aerial) deposition of elements (particles) in the environment.

Another important factor in estimating natural geological sources of elements, such as Hg, is crustal degassing (Rasmussen, 1996). An example quoted by Rasmussen (1996) is the study of Crokett and Kinnison (1979) on the concentration of Hg in soils around a coal-fired power plant. They found that the concentration of Hg in the vicinity of the power plant was not significantly above background levels. In contrast, earlier studies of soil in the same location, based on a smaller sample set, and disregarding the natural background concentration of Hg, found a significant enrichment of Hg in the area and attributed this to atmospheric fallout.

It is estimated that the background concentration of elemental mercury (Hg^o) in the atmosphere is 1 to 4 ng/m^3 (Weiss et al., 1971; Lindqvist et al., 1991). According to Lindberg (1987), Hg degassing in global land areas ranges from 0.02 to 0.03 $\mu g/m^2/h$ (see also Weiss et al., 1971). The global Hg flux consisting of both particulate flux and crustal degassing is three times greater than that based on particulate flux alone (Lantzy and Mackenzie, 1979; Rasmussen, 1996).

Other natural sources that contribute to the aerial input of elements to the environment are forest fires, and volcanic oceanic emissions. Of the three natural sources, forest fires are the most important in an intensely forested region such as the Trail area.

Furthermore, input from other anthropogenic sources (non-point-source anthropogenic sources), such as pulp and paper mills, agricultural activities, and traffic, should also be taken into account while assessing a specific point source, in this case Trail smelter.

Critical gaps in information and uncertainties associated with attempts to quantify the natural and anthropogenic components of metals in soil, vegetation, and lake sediment samples exist (Rasmussen, 1996). In this study, attempts have been made to correct the elemental data for the geogenic and natural sources. However the approach used for this purpose has some shortcomings and is associated with errors. These shortcomings were dealt with by using a very conservative approach in evaluating the natural contribution of elements. This conservative approach minimizes any chances of underestimating the effect of the point source under investigation.

Geogenic contribution of elements

Elemental ratios have commonly been used for the differentiation of anthropogenic concentrations of elements from geologically induced (geogenic) elements in various sample media (Godbeer et al., 1984; Roulet et al., 2000; Ketterer et al., 2001). For this purpose, a conservative element such as Al (a lithophile element, associated with aluminosilicates) is often used, because concentrations of Al in the sample medium are influenced exclusively by crustal sources (Ketterer et al., 2001).

In this study, concentrations of Al registered by moss-monitoring stations (mean 0.07%, n=22; Table 3), versus those found in local soils (mean 7.72%, n=22; Table 3), were used to determine the contribution of geogenic sources. The results indicate that the estimated contribution of geogenic elements is low (0.002%–3.51%; mean 0.9%) perhaps because of the extensive vegetative coverage of land in the Trail area. Since the overall geogenic contribution of elements is low, the average geogenic contribution (0.9%) for the 22 monitoring stations was used regardless of the variation in geogenic contribution.

The concentrations of elements registered by the moss-monitoring stations were then corrected by subtracting the 0.9% geogenic portion from the total concentration of a given element. The resulting data reflect the remaining anthropogenic portion of 99.1%. This is a very conservative approach.

Local background concentration of elements

In environmental studies, the average composition of elements in the Earth's crust, or local bedrock, is often used as the natural background level in order to distinguish anthropogenically induced element concentrations from those occurring naturally in the environment (Reimann and de Caritat, 2000). However, there are serious flaws associated with this concept since the average composition of the Earth's crust or local bedrock is of limited relevance to the composition of naturally occurring dust particles in the Earth's lower atmosphere (Reimann and De Caritat, 2000).

Table 3
Concentration of aluminum (%) as registered by moss-monitoring stations during ten consecutive periods of study, and the concentation of Al (%) in surface soil (0–10 cm) collected from the same locations at the beginning of the study period

Stations	Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99	Winter 2000	Al (%) Soil
N6	25.7	N/D	0.04	0.08	0.07	0.05	0.09	0.16	0.07	0.02	0.05	7.33
N5	23.5	N/A	N/A	0.07	0.08	0.08	0.10	0.18	0.09	0.02	0.06	7.77
N4	11.3	0.01	0.03	0.11	0.14	0.06	0.12	0.10	0.07	0.05	0.10	7.14
N3	7.7	N/D	0.01	0.03	0.07	0.04	0.13	0.08	0.06	0.02	0.04	7.22
N2	2.9	N/D	0.04	0.04	0.06	0.05	0.08	0.08	0.05	0.01	0.06	7.30
N1	1.8	0.02	0.03	0.13	0.09	0.08	0.16	0.21	0.06	0.02	0.09	7.20
C1	1.5	N/D	0.02	0.07	0.04	0.07	0.23	0.08	0.04	0.02	0.06	7.26
C5	1.5	0.07	0.13	0.13	0.07	0.12	0.25	0.14	0.07	0.04	0.15	7.23
S1	2.7	0.03	0.07	0.07	0.07	0.07	0.15	0.10	0.08	0.03	0.10	7.43
S2	4.5	0.01	0.07	0.15	0.10	0.07	0.16	0.16	0.10	0.01	0.10	7.97
S3	7.4	0.01	0.03	0.05	0.07	0.05	0.07	0.09	0.07	0.03	0.05	7.99
CG	11	0.02	0.04	0.08	0.09	0.14	0.11	0.15	0.12	0.03	0.09	8.07
S4	14.1	N/D	0.02	0.08	0.05	0.08	0.07	0.11	0.06	0.01	0.05	7.18
S5	20.7	0.01	0.03	0.08	0.09	0.07	0.09	0.11	0.07	0.02	0.05	7.10
C 20	12	N/D	0.00	0.05	0.05	0.02	0.06	0.07	0.04	0.01	0.03	8.82
W4	6.8	N/A	N/A	0.09	0.06	0.10	0.28	0.16	0.03	0.01	0.16	8.13
W3	2.8	0.01	0.05	0.05	0.06	0.06	0.14	0.08	0.07	N/A	0.08	8.82
W2	2.6	N/D	0.05	0.06	0.06	0.06	0.10	0.08	0.05	0.01	0.06	7.01
W1	2	0.03	0.08	0.10	0.05	0.08	0.15	0.11	0.06	0.03	0.07	N/A
E1	2	N/A	N/A	0.08	0.07	0.08	0.14	0.10	0.05	0.02	0.09	7.42
E2	13.4	N/D	0.01	0.03	0.05	0.01	0.06	0.07	0.04	0.01	0.03	9.50
E3	13.5	N/A	N/A	0.08	0.07	0.07	N/A	0.11	0.08	0.01	0.07	8.31
Mean						0.07 (%)						7.72

* Reported concentration values are measured using Instrumental Neutron Activation Analyses (INAA);
Lower Limits of Detection (LLD) = 0.01 %; N/D: Not Detected; N/A: Not available

Ledin et al. (1989) also stated that the use of a single average background value in the interpretation of environmental components can be entirely misleading. The concept of constant background values is not supported by worldwide survey data, which indicate that the natural abundance of trace elements in many surface samples can vary remarkably over short distances (Darnley, 1995). This is due to such factors as the natural geochemical diversity of the Earth's surface and its underlying rock types, which influence the elemental composition of dust in a given location. For example, bedrock and glacial drift geochemistry influence the spatial variation in metal concentration (e.g., the contribution of metals from till to a surface environment) and should be taken into account when evaluating the relative contribution of atmospheric sources affecting an area.

The degree to which organic carbon influences spatial variation in metal concentrations is also important, because the variation in organic matter with climate and geographic setting influences the regional distribution of metals in the environment (Jeffrey, 1987; Garrett et al., 1990). In the biogeochemical cycle from crust to soils, elements undergo natural fractionation, which can significantly change the elemental content of the 'natural background' based on the average composition of the bedrock. Metal enrichment in organic forest soils commonly occurs because naturally occurring metals become concentrated in the upper few centimetres of undisturbed soils. This is a result of the metals being incorporated by living plants and accumulating in the decomposing remains in the humus layer (Rasmussen, 1998; Reimann and de Caritat, 2000). Henderson et al. (1999) confirmed this relationship between metals and organic matter in the surface layer of soils in the Trail area. This natural biogeochemical enrichment of elements is commonly misinterpreted as surface contamination by atmospheric fallout.

Therefore, in defining the natural background, geological and geographical variation must both be considered. Natural enrichment processes in variable geomorphological environments must be understood before an attempt is made to quantify the anthropogenic contribution of metals in the environment.

Because of the issues concerning defining a single global background level, a decision was made to establish the local background levels of elements specifically for the Trail area. As defined by the British Columbia Environment (1999), suitable areas for determining site-specific local background should be first found within a local geographic area and levels should represent the concentration of elements attributable to natural and anthropogenic non-point sources, not including any contribution from the point source under study.

In the Trail area, predominant wind flows are controlled by the Columbia River valley system, which is oriented north-northwest to south-southeast (Fig. 3). These wind flows, in turn, strongly influence the distribution of atmospheric emissions. Therefore, the areas least affected by airborne particles and elements in the Trail area have to lie outside the Columbia River Valley system, in a direction away from the path of the predominant, valley-controlled winds and relatively far away from the Trail smelter. Therefore, stations N6, S5, C20, E2, and E3 (Fig. 2; station S5 is located outside the boundary of the map in south) were chosen for determining site-specific local background concentrations of elements for the Trail study area, since they met the criteria for station selection outlined above (B.C. Environment, 1999). These stations are either sheltered from emissions by mountain ranges (stations C20, E2, and E3) or are located at a significant distance from the Trail smelter (stations N6 and S5) (Fig. 2). Furthermore, they represent the diversity of bedrock and surficial geology found within the study area, and the effects from natural and non-point-source anthropogenic activities. The influence of the Trail smelter on these monitoring stations was expected to be negligible; any possible influence could be the result of long-range atmospheric transport. Even so, long-range transport of particles and elements might not necessarily be attributable to the Trail smelter – it could be due to other intercontinental (or global) atmospheric fallout (Rasmussen, 1998).

Therefore, the concentrations of elements registered by stations N6, S5, C20, E2, and E3 during the collection periods were used to define a local background concentration level for the elements of interest within the study area (Table 4). The collected data were grouped on a semi-logarithmic scale, which are arbitrary divisions commonly used in Canada for geochemical mapping (Geological Survey of Canada, 1977). The concentration range of elements registered by these site-specific background stations was determined by frequency histogram plots for the collected data (Fig. 6a-f). The concentration range with the highest frequency data was chosen as the most probable local background range of elements for the Trail area (Table 5). Hence, observed elemental concentrations at all 22 moss-monitoring stations were then corrected using these local background values (Table 6a-f).

DISTRIBUTION OF DEPOSITED ELEMENTS IN THE TRAIL AREA

The concentration of the elements As, Cd, Cu, Hg, Pb, and Zn recorded by the moss-monitoring stations, after correcting for the moss matrix and natural and geogenic input, are presented in Table 6a-f. It should be noted that a large portion of the elements reported in Table 6 likely originate from "secondary sources" which contribute

Table 4
Concentrations of As, Cd, Cu, Hg, Pb, and Zn as recorded by moss-monitoring stations representing site-specific local background stations for the study area

As* (mg/kg)

Stations	Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99	Winter 2000
N6	25.7	0.4	0.1	0.2	0.0	0.0	0.0	N/D	0.1	0.3	0.1
S5	20.7	0.4	0.1	0.2	0.2	0.0	0.2	0.1	0.4	0.2	0.2
C 20	12	0.2	0.0	0.1	N/D	N/D	N/D	N/D	0.2	N/D	0.1
E2	13.4	0.1	0.1	0.1	N/D	N/D	N/D	N/D	0.0	N/D	0.1
E3	13.5	N/A	N/A	0.3	0.0	N/D	N/A	0.0	0.3	N/D	0.1
LLD = 0.1 mg/kg											
Cd(mg/kg)**											
N6	25.7	0.45	0.70	0.73	1.42	1.60	1.04	1.76	2.07	7.15	0.61
S5	20.7	0.95	0.70	0.73	0.76	1.18	2.07	0.65	2.19	1.30	0.54
C 20	12	0.45	8.90	0.53	0.54	0.41	0.51	0.47	1.32	0.26	0.20
E2	13.4	1.95	0.50	0.53	0.64	0.91	0.42	0.39	0.67	0.11	0.25
E3	13.5	N/A	N/A	0.53	0.64	0.89	N/A	1.39	4.85	1.17	1.18
LLD = 0.02 mg/kg											

Table 4 (Cont'd)
Concentrations of As, Cd, Cu, Hg, Pb, and Zn as recorded by moss-monitoring stations representing site-specific local background stations for the study area

Stations	Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99	Winter 2000
Cu** (mg/kg)											
N6	25.7	2	1	1	2	3	7	4	3	4	1
S5	20.7	3	2	2	5	10	15	4	9	9	3
C 20	12	2	N/D	0	2	3	6	2	18	5	N/D
E2	13.4	10	N/D	1	4	5	1	2	2	5	0
E3	13.5	N/A	N/A	1	2	4	N/A	21	13	4	1
LLD = 1 mg/kg											
Hg*** (mg/kg)											
N6	25.7	0.02	0.00	0.00	0.02	0.05	0.02	0.13	0.04	N/D	0.07
S5	20.7	0.03	0.00	0.02	0.07	0.07	0.12	0.10	0.06	0.01	0.00
C 20	12	0.02	0.00	N/D	0.02	0.01	0.07	0.13	0.06	N/D	0.00
E2	13.4	0.01	0.00	0.02	0.02	0.01	0.02	0.09	0.04	N/D	N/D
E3	13.5	N/A	N/A	0.02	0.02	0.05	N/A	0.09	0.04	N/D	N/D
LLD = 0.02 mg/kg											
Pb** (mg/kg)											
N6	25.7	44.2	14.0	16.1	15.2	31.8	24.5	16.3	23.0	18.7	14.6
S5	20.7	52.2	12.0	26.1	20.7	36.4	83.0	28.8	50.1	12.1	16.3
C 20	12	5.2	0.0	4.1	8.1	9.7	14.5	9.1	14.4	2.7	7.9
E2	13.4	6.2	4.0	6.1	8.5	27.2	6.6	10.2	3.6	2.2	5.0
E3	13.5	N/A	N/A	14.1	10.1	22.8	N/A	18.0	21.0	2.8	8.4
LLD = 0.5 mg/kg											
Zn** (mg/kg)											
N6	25.7	88	58	49	39	94	100	109	69	77	56
S5	20.7	128	50	89	76	78	310	80	162	37	54
C 20	12	20	2	18	43	16	76	40	185	9	14
E2	13.4	21	22	25	34	53	33	29	26	6	13
E3	13.5	N/A	N/A	55	47	53	N/A	54	67	13	22
LLD = 2 mg/kg											

*INAA: Instrumental Neutron Activation Analyses; **ICP-MS: Inductively Coupled Plasma - Mass Spectrometry; ***CVAA: Cold Vapor Atomic Absorption; N/A: Not Available; N/D: Not Detected; LLD: Lower Limits of Detection; Distance: The direct distance between a moss-monitoring station and the point source (Trail smelter installation)

Table 5
Estimation of site-specific local background levels of elements (As, Cd, Cu, Hg, Pb, and Zn) for the Trail area

	As	Cd	Cu	Hg	Pb	Zn
Concentration range with maximum frequency (mg/kg)*	0.1 to 0.5	0.5 to 1	2 to 5	0.02 to 0.05	10 to 20	50 to 100
Frequency**	29% and 27%	40%	33%	39%	33%	36%
Site-specific local background level (mg/kg)***	0.3	0.75	3.5	0.035	15	75

*The background concentration range was chosen from the data collected for stations N6, S5, C20, E2, and E3 during ten periods of the study (Fall 97 until Winter 2000). The concentration range with the highest frequency** was chosen as the most probable local background concentraion range for the Trail area. **Frequency represents the percentage of data, which fall within the given concentration range. ***Mean value of the concentration range with the highest frequency percentage (i.e., background level).

significantly to total particle deposition in the Trail area (Jennett et al., 1977). "Secondary sources" consist of fugitive dust from the uncovered transportation of ore concentrates and slag, and dust blown from storage piles located at the Trail smelter. Additionally, the historical dust resulting from past emissions from the smelter (i.e., prior to the collection period), which have become re-suspended in the environment, could also form a significant portion of the material detected by moss-monitoring stations.

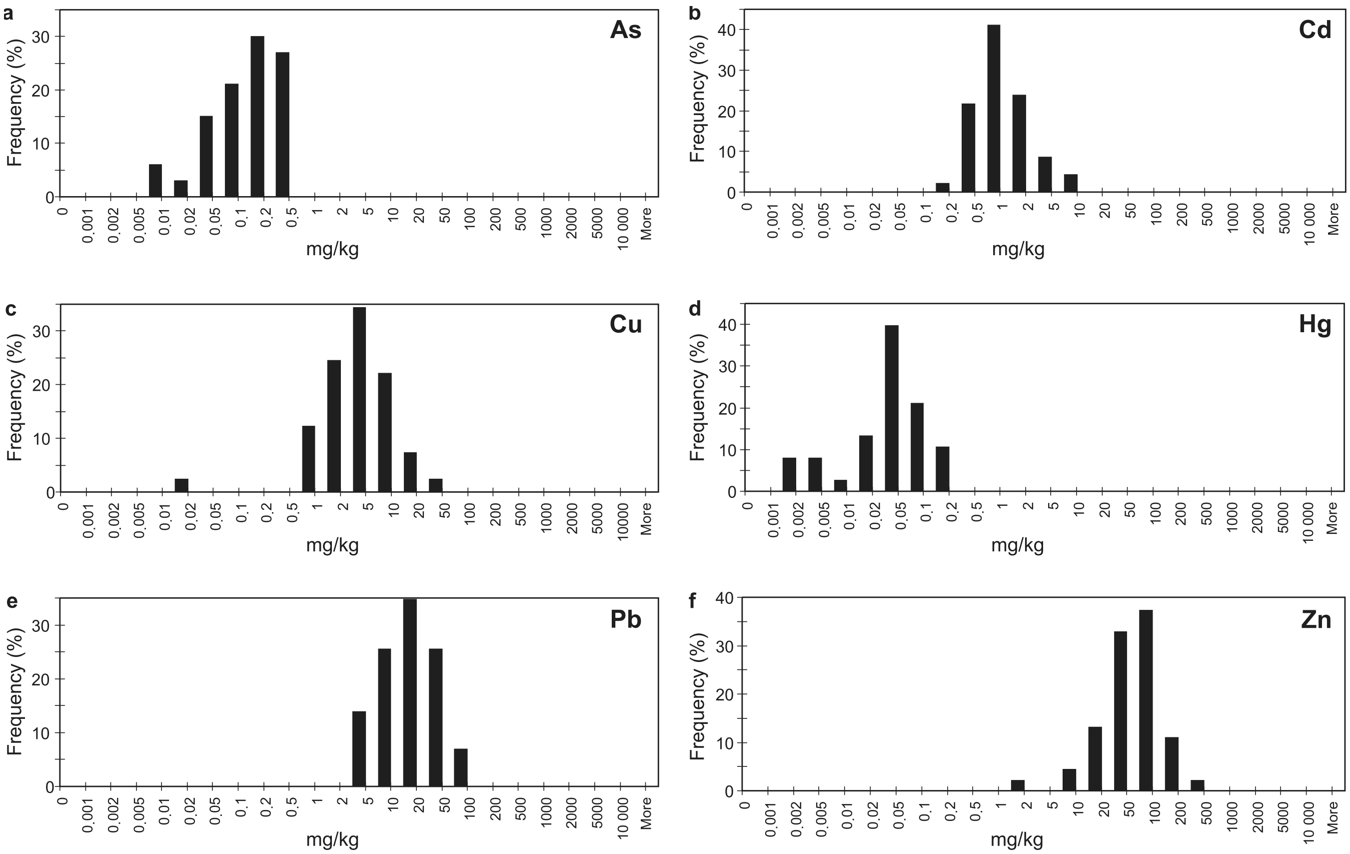


Figure 6 a–f. *Frequency histogram plots of the elements (a) As, (b) Cd, (c) Cu, (d) Hg, (e) Pb, and (f) Zn based on the data collected by the site-specific local background stations (N6, S5, C20, E2, and E3) during the study period. The concentration range with the maximum frequency is chosen as the most probable local background level for any given element.*

Table 6

Concentrations of As, Cd, Cu, Hg, Pb and Zn recorded by the moss-monitoring stations in the Trail area during nine consecutive periods of the study after correction for moss matrix, geogenic and local background level

As* (mg/kg)

	Stations	Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
North-Centre- South	N6	25.7	0.1	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	N5	23.5	N/A	N/A	N/D	N/D	N/D	N/D	N/D	N/D	0.3
	N4	11.3	1.0	0.3	0.3	0.6	0.9	0.1	0.5	0.6	2.0
	N3	7.7	0.4	0.2	0.0	0.1	0.4	N/D	0.3	0.4	0.8
	N2	2.9	1.6	0.8	0.4	0.7	1.0	0.2	1.0	0.7	2.2
	N1	1.8	3.8	3.1	7.0	4.6	3.4	2.9	7.0	2.0	3.0
	C1	1.5	3.3	5.0	17.5	3.9	4.6	10.3	8.0	2.5	10.7
	C5	1.5	13.2	11.6	15.3	5.7	5.2	10.6	12.8	9.2	6.6
	S1	2.7	10.5	4.9	5.7	2.8	3.7	3.5	7.3	8.1	6.5
	S2	4.5	3.8	3.8	3.5	2.1	1.9	1.6	4.3	4.1	2.2
	S3	7.4	0.5	0.6	0.7	N/D	N/D	N/D	0.4	0.3	0.0
	CG	11	2.4	1.4	1.8	0.7	1.2	0.7	2.0	1.5	0.8
	S4	14.1	0.9	0.3	0.2	N/D	0.2	N/D	0.1	0.3	0.3
	S5	20.7	0.1	N/D	N/D	N/D	N/D	N/D	N/D	0.1	N/D

Table 6 (Cont'd)

Concentrations of As, Cd, Cu, Hg, Pb and Zn recorded by the moss-monitoring stations in the Trail area during nine consecutive periods of the study after correction for moss matrix, geogenic and local background level

Stations		Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
West-East	C 20	12	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	W4	6.8	N/A	N/A	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	W3	2.8	0.2	0.5	0.9	N/D	0.3	0.2	0.4	0.1	N/A
	W2	2.6	1.4	1.5	2.4	0.6	0.6	0.8	1.6	1.2	1.5
	W1	2	5.2	6.0	7.2	1.3	2.3	5.4	8.4	3.6	3.7
	E1	2	N/A	N/A	3.0	1.6	2.1	2.1	3.2	3.5	2.8
	E2	13.4	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	E3	13.5	N/A	N/A	N/D	N/D	N/D	N/A	N/D	0.0	N/D
LLD = 0.1 mg/kg											
Cd (mg/kg)**											
North-Centre-South	N6	25.7	N/D	N/D	N/D	0.66	0.85	0.29	1.00	1.31	6.34
	N5	23.5	N/A	N/A	0.37	0.68	3.28	1.41	0.53	0.95	8.88
	N4	11.3	3.17	1.93	1.86	3.20	28.5	4.15	3.11	8.12	19.0
	N3	7.7	2.18	1.54	0.57	2.55	6.16	3.19	1.48	3.87	11.7
	N2	2.9	6.14	3.52	2.65	5.50	18.0	8.18	3.90	9.71	46.0
	N1	1.8	15.1	8.27	15.2	23.0	44.6	44.2	17.6	27.8	52.9
	C1	1.5	9.12	14.4	25.7	13.9	41.6	54.2	22.4	37.9	18.6
	C5	1.5	53.7	62.6	66.4	46.6	99.2	110	81.3	206	77.7
	S1	2.7	24.0	25.9	20.1	17.6	57.7	46.4	43.4	116	54.1
	S2	4.5	12.1	14.4	12.2	11.8	22.0	22.2	19.3	60.0	13.6
	S3	7.4	2.18	3.52	1.66	1.80	3.20	5.28	2.83	54.0	2.85
	CG	11	7.14	5.70	6.91	5.33	12.3	7.42	10.6	22.5	5.36
	S4	14.1	1.19	1.73	0.57	1.03	2.44	1.88	1.55	6.18	2.43
	S5	20.7	0.20	N/D	N/D	0.01	0.43	1.31	N/D	1.43	0.54
West -East	C 20	12	N/D	8.08	N/D	N/D	N/D	N/D	N/D	0.57	N/D
	W4	6.8	N/A	N/A	0.37	0.14	N/D	0.46	N/D	N/D	N/D
	W3	2.8	2.18	2.13	2.45	2.14	4.34	5.94	2.72	6.78	N/A
	W2	2.6	4.16	8.67	10.1	6.17	20.7	20.8	9.74	28.8	14.9
	W1	2	21.0	35.2	25.9	12.8	53.5	41.1	44.5	87.2	43.0
	E1	2	N/A	N/A	8.00	7.94	17.2	16.8	13.7	26.3	14.6
	E2	13.4	1.19	N/D	N/D	N/D	0.16	N/D	N/D	N/D	N/D
	E3	13.5	N/A	N/A	N/D	N/D	0.14	N/A	0.63	4.06	0.42
LLD = 0.02 mg/kg											
Cu (mg/kg)**											
North-Centre-South	N6	25.7	N/D	N/D	N/D	N/D	N/D	4	1	N/D	1
	N5	23.5	N/A	N/A	N/D	N/D	4	5	1	N/D	2
	N4	11.3	0	N/D	2	4	10	6	5	9	7
	N3	7.7	0	N/D	N/D	0	5	5	1	1	3
	N2	2.9	7	2	6	8	15	12	9	5	9
	N1	1.8	13	6	17	24	28	25	19	12	12
	C1	1.5	19	23	53	49	72	89	60	30	13
	C5	1.5	112	100	163	87	91	145	121	142	34
	S1	2.7	30	29	34	26	30	36	57	46	18
	S2	4.5	13	15	20	23	15	21	23	33	5
	S3	7.4	1	0	1	3	1	6	4	4	2
	CG	11	10	5	8	7	18	14	15	14	4
	S4	14.1	0	N/D	N/D	2	3	4	2	1	2
	S5	20.7	N/D	N/D	N/D	1	6	11	1	6	5

Table 6 (Cont'd)

Concentrations of As, Cd, Cu, Hg, Pb and Zn recorded by the moss-monitoring stations in the Trail area during nine consecutive periods of the study after correction for moss matrix, geogenic and local background level

Stations		Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
West -East	C 20	12	N/D	N/D	N/D	N/D	N/D	3	N/D	14	2
	W4	6.8	N/A	N/A	N/D	N/D	1	3	N/D	N/D	2
	W3	2.8	0	2	7	5	4	8	6	6	N/A
	W2	2.6	2	7	14	9	12	19	14	14	5
	W1	2	29	37	46	18	35	49	56	44	15
	E1	2	N/A	N/A	11	11	10	23	16	14	5
	E2	13.4	6	N/D	N/D	0	2	N/D	N/D	N/D	2
	E3	13.5	N/A	N/A	N/D	N/D	0	N/A	17	9	1
LLD = 1 mg/kg											
Hg* (mg/kg)**											
North-Centre-South	N6	25.7	N/D	N/D	N/D	N/D	0.01	N/D	0.09	0.00	N/D
	N5	23.5	N/A	N/A	N/D	N/D	0.02	0.04	0.08	N/D	N/D
	N4	11.3	0.03	0.01	0.04	0.01	0.11	N/D	0.16	0.08	N/D
	N3	7.7	0.02	N/D	N/D	0.03	0.06	0.09	0.13	0.02	N/D
	N2	2.9	0.10	0.01	0.03	0.10	0.17	0.10	0.15	0.07	0.01
	N1	1.8	0.23	0.11	0.36	0.27	0.40	0.47	0.50	0.32	0.13
	C1	1.5	0.27	0.26	0.67	0.43	0.37	0.95	0.93	0.39	0.06
	C5	1.5	3.06	1.18	1.55	0.93	1.01	6.33	2.77	4.07	0.49
	S1	2.7	0.60	0.22	0.39	0.34	0.49	0.92	0.96	1.17	0.25
	S2	4.5	0.28	0.13	0.26	0.20	0.22	0.38	0.23	0.08	0.13
	S3	7.4	0.02	N/D	0.03	0.01	0.03	0.06	0.21	0.08	N/D
	CG	11	0.20	0.10	0.12	0.14	0.22	0.15	0.39	0.25	0.07
	S4	14.1	0.01	N/D	0.00	N/D	N/D	0.02	0.10	0.09	N/D
	S5	20.7	N/D	N/D	N/D	0.03	0.03	0.09	0.07	0.02	N/D
West -East	C 20	12	N/D	N/D	N/D	N/D	N/D	0.03	0.09	0.02	N/D
	W4	6.8	N/A	N/A	N/D	N/D	N/D	0.07	0.07	N/D	N/D
	W3	2.8	0.01	0.01	0.02	0.01	N/D	0.09	0.17	0.09	N/A
	W2	2.6	0.25	0.10	0.24	0.14	0.32	1.16	0.39	0.29	0.11
	W1	2	0.55	0.52	0.51	0.23	0.68	3.94	1.45	0.93	0.36
	E1	2	N/A	N/A	0.15	0.10	0.09	0.22	0.36	0.32	N/D
	E2	13.4	N/D	N/D	N/D	N/D	N/D	N/D	0.06	0.00	N/D
	E3	13.5	N/A	N/A	N/D	N/D	0.01	N/A	0.06	0.00	N/D
LLD = 0.02 mg/kg											
Pb (mg/kg)**											
North-Centre-South	N6	25.7	28.9	N/D	1.1	0.2	16.6	9.4	1.2	7.9	3.7
	N5	23.5	N/A	N/A	1.1	14.7	67.1	40.6	12.5	14.3	14.6
	N4	11.3	347	100	87.3	115	418	137	112	173	154
	N3	7.7	154	62.4	29.8	53.3	148	87.5	55.4	83.5	77.5
	N2	2.9	596	171	125.0	180	479	171	158	164	256
	N1	1.8	721	302	631.4	613	1010	610	568	422	462
	C1	1.5	995	740	1780	656	2122	2735	1424	908	518
	C5	1.5	2381	1870	2524	1081	1704	2702	2732	2646	772
	S1	2.7	1988	1034	818	684	1799	982	1729	2140	931
	S2	4.5	983	580	560	489	635	654	937	1500	177
	S3	7.4	150	140	87	59	67	96	162	140	15.4
	CG	11	287	170	177	112	382	209	316	366	51.6
	S4	14.1	99.3	60.5	24.9	27.9	98.6	71.7	74.6	104	18.2
	S5	20.7	36.9	N/D	11.0	5.7	21.2	67.4	13.7	34.8	N/D

Table 6 (Cont'd)

Concentrations of As, Cd, Cu, Hg, Pb and Zn recorded by the moss-monitoring stations in the Trail area during nine consecutive periods of the study after correction for moss matrix, geogenic and local background level

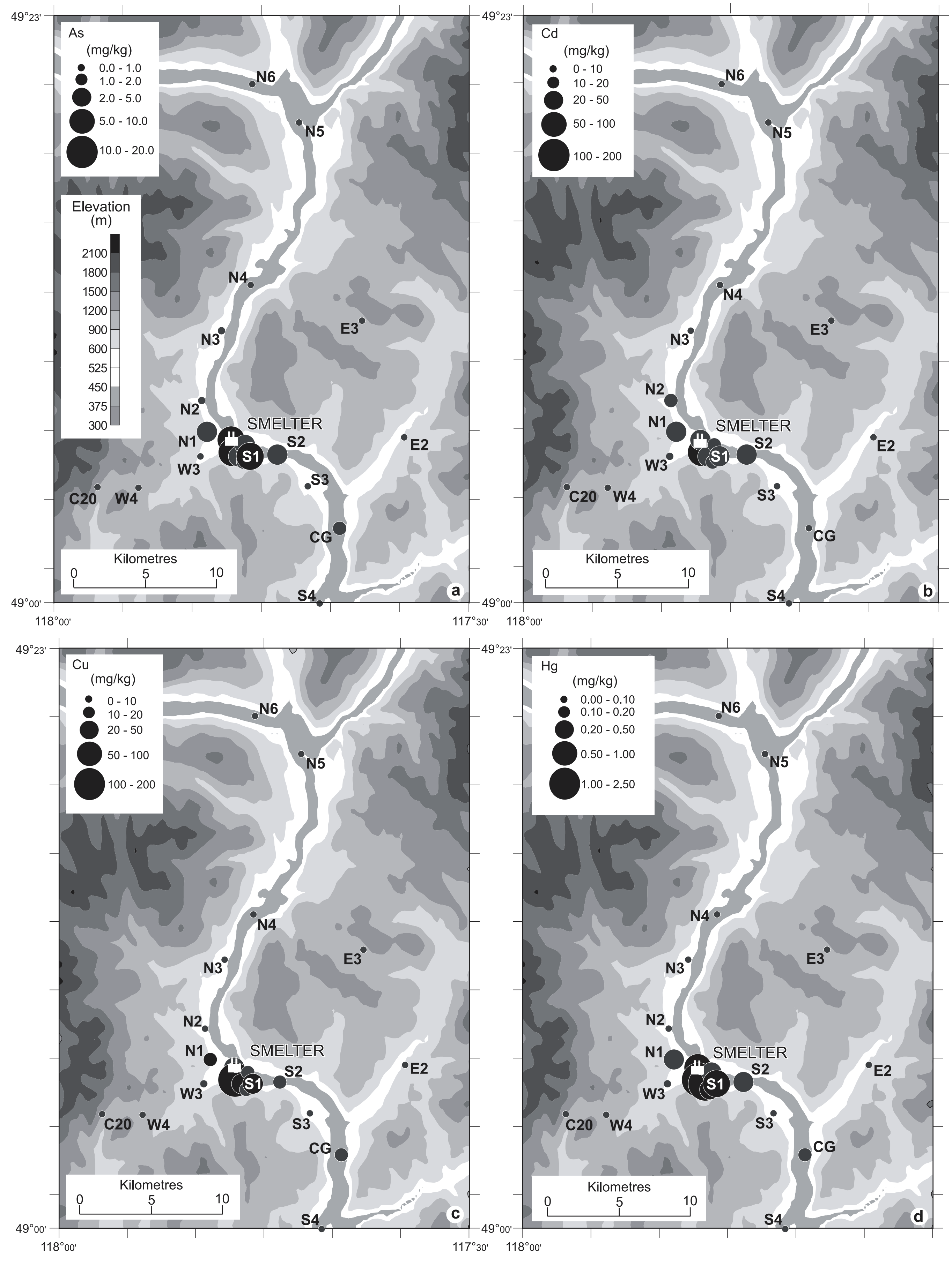
Stations		Distance km	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
West -East	C 20	12	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	W4	6.8	N/A	N/A	N/D	N/D	N/D	4.8	N/D	N/D	N/D
	W3	2.8	90.4	68.4	110	40.1	96.3	108	105	95.5	N/A
	W2	2.6	218	288	414	143	392	413	433	458	124
	W1	2	943	1178	1007	329	931	963	1663	1271	461
	E1	2	N/A	N/A	354	389	459	561	778	1059	198
	E2	13.4	N/D	N/D	N/D	N/D	12.1	N/D	N/D	N/D	N/D
	E3	13.5	N/A	N/A	N/D	N/D	7.8	N/A	3.0	6.0	N/D
LLD = 0.5 mg/kg											
Zn (mg/kg)**											
North-Centre-South	N6	25.7	13	N/D	N/D	N/D	19	25	33	N/D	2
	N5	23.5	N/A	N/A	N/D	2	161	167	24	62	68
	N4	11.3	609	328	374	438	910	551	439	604	501
	N3	7.7	383	182	85	157	419	253	135	248	254
	N2	2.9	1389	590	426	641	1485	660	428	803	893
	N1	1.8	4362	1592	2409	2806	4142	2913	2162	2426	2324
	C1	1.5	1557	1599	3714	1688	2416	3226	1817	1573	714
	C5	1.5	12805	8367	10821	6432	7866	9574	12066	14529	5937
	S1	2.7	4094	2658	3484	2410	4286	3377	4121	5951	2256
	S2	4.5	2489	1792	2290	1657	1802	2013	2280	3772	654
	S3	7.4	462	577	340	249	309	385	432	609	47
	CG	11	1409	852	1141	914	1382	862	1716	1973	409
	S4	14.1	294	264	93	126	171	223	213	397	60
	S5	20.7	52	N/D	14	1	3	233	5	86	N/D
West -East	C 20	12	N/D	N/D	N/D	N/D	N/D	1	N/D	109	N/D
	W4	6.8	N/A	N/A	N/D	5	N/D	11	N/D	N/D	N/D
	W3	2.8	344	359	443	283	405	601	408	490	N/A
	W2	2.6	1221	1448	1965	1191	2077	2023	1644	2503	1226
	W1	2	4907	4977	4806	2263	4902	3814	5914	5915	3813
	E1	2	N/A	N/A	1484	1341	1267	1766	1718	2068	427
	E2	13.4	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	E3	13.5	N/A	N/A	N/D	N/D	N/D	N/A	N/D	N/D	N/D
LLD = 2 mg/kg											

*INAA: Instrumental Neutron Activation Analyses; **ICP-MS: Inductively Coupled Plasma - Mass Spectrometry; ***CVAA: Cold Vapor Atomic Absorption; N/D: Not Detected; LLD: Lower Limits of Detection; N/A: Not Available; Distance: The radial distance between a moss monitoring station and the point source (Trail smelter installation).

The corrected elemental concentration data registered by moss-monitoring stations during the study period show a complex seasonal pattern (Table 6a-f). Overall, the distribution of elements extends in all directions, showing a gradual decrease with increasing distance from the point source (Fig. 7a-f, 8a-f). Generally, the highest deposition of elements occurred in central stations at a distance of approximately 1.5 to 3 km away from the boundary of the smelter compound, where major smelting activities occurred (e.g., location of stacks and ore and slag storage piles; Fig. 7a-f, 8a-f). Worth noting are the elemental concentrations observed at stations C1, C5, and S1, which received significant deposition of all elements during the study period (Table 6a-f). Deposition appears to level off at stations N5 and S5 (in a north-south transect) and E2 and W4 (in an east-west transect; Table 6a-f, Fig. 7a-f, 8a-f), which, based on the limited number of monitoring stations, likely represents a return to the local background level.

Factors influencing the deposition

There are a number of factors that control the seasonal and spatial distribution of elements deposited in the Trail area. Some of the most prominent factors are discussed in the following sections.


As
(mg/kg)
0.0 - 1.0
1.0 - 2.0
2.0 - 5.0
5.0 - 10.0
10.0 - 20.0
Elevation (m)
2100
1800
1500
1200
900
600
525
450
375
300
Cd
(mg/kg)
0 - 10
10 - 20
20 - 50
50 - 100
100 - 200
Cu
(mg/kg)
0 - 10
10 - 20
20 - 50
50 - 100
100 - 200
Hg
(mg/kg)
0.00 - 0.10
0.10 - 0.20
0.20 - 0.50
0.50 - 1.00
1.00 - 2.50
N6
N5
N4
N3
N2
N1
SMELTER
S1
S2
S3
S4
CG
E2
E3
W3
W4
C20
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49°23'
49°00'
118°00'
117°30'
a
b
c
d

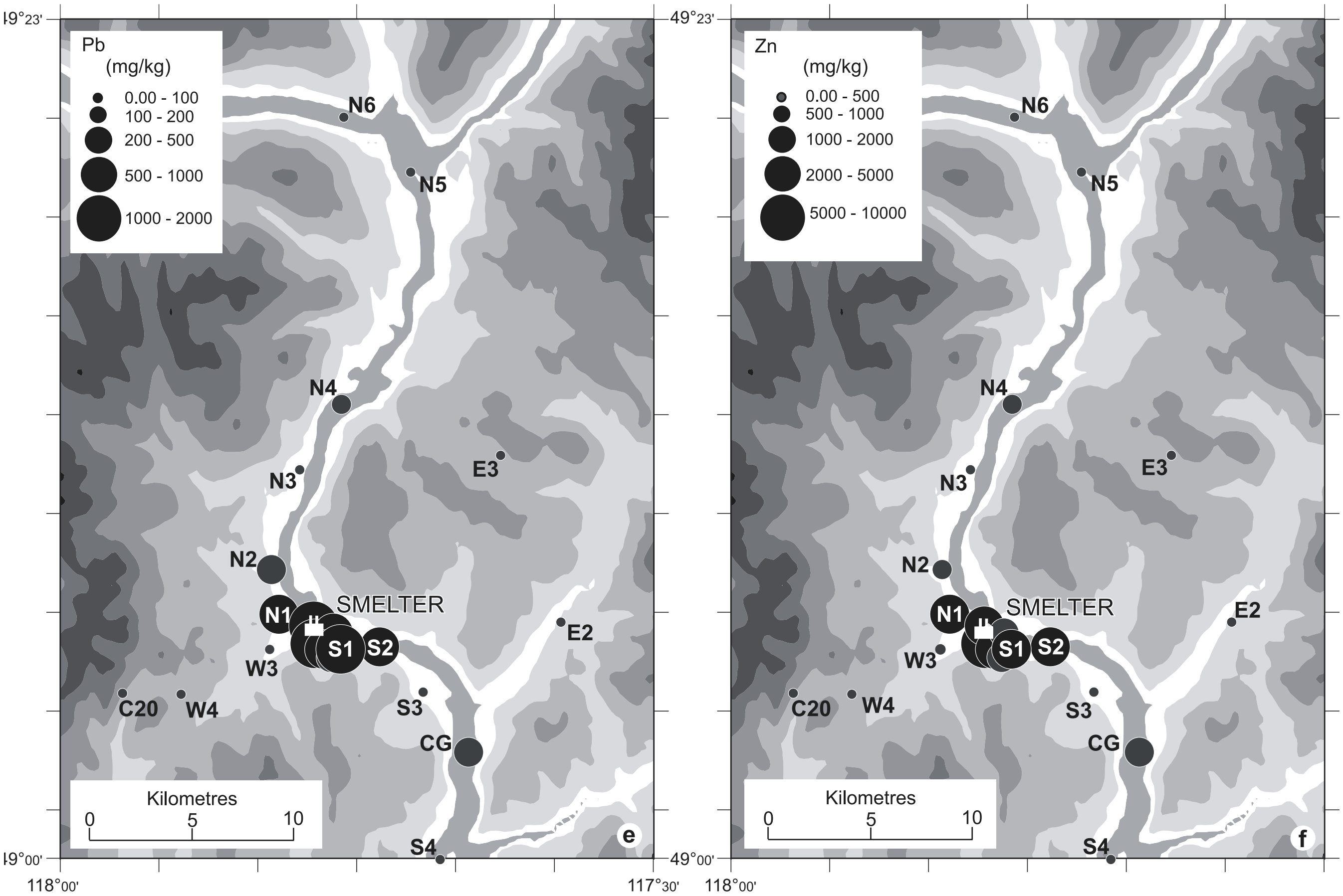


Figure 7 a–f. *Spatial distribution of the deposited elements (a) As, (b) Cd, (c) Cu, (d) Hg, (e) Pb, and (f) Zn as registered by moss-monitoring stations in the Trail area. The data is reported as the average concentration (mg/kg) over two years of sampling (winter 1998-fall 1999).*

Physiography and prevailing winds

The physiography of an area, in terms of terrain elevation (topography), and orientation and shape of valley systems, in conjunction with the direction of prevailing winds, dictates the distribution of airborne material emitted from a point source (Barry and Chorley, 1976; Harvey, 1976). In this study, deposition of the elements extended 11.3 km to the north-northwest (to station N4) and 14.1 km to the south-southeast (to station S4) of the Trail smelter (Table 6a-f). However, in an east-west transect, deposition extended only 2 km to the east (to station E1) and 2.8 km to the west (to station W3) of the Trail smelter (Table 6a-f). This indicates that the spatial distribution of elements is related to the northwest-southeast orientation of the Columbia River Valley system. This is due to the fact that deep and steep-sided valley walls conduct air flow within the valley system. Furthermore, the moss-monitoring stations located to the south-southeast of the smelter registered higher elemental concentrations than stations to the north-northwest throughout the study period (Table 6a-f, Fig. 7a-f). This is attributable to the prevailing southeasterly winds (Fig. 3).

Precipitation

The annual amount of precipitation in the Trail area was greater in 1998 (1237 mm/year) than in 1999 (975 mm/year) (Cominco, unpub. data, 2000). This is contrary to the annual average deposition of As, Cd, Pb, and Zn (as detected by the moss-monitoring stations), which in fact increased in 1999 (Fig. 8a-f). This indicates an inverse relationship between precipitation rates and deposition of elements on the moss-monitoring stations. This is despite the fact that precipitation scavenging of atmospheric particles and gases is an important factor in deposition of elements on land. Normally, higher precipitation often

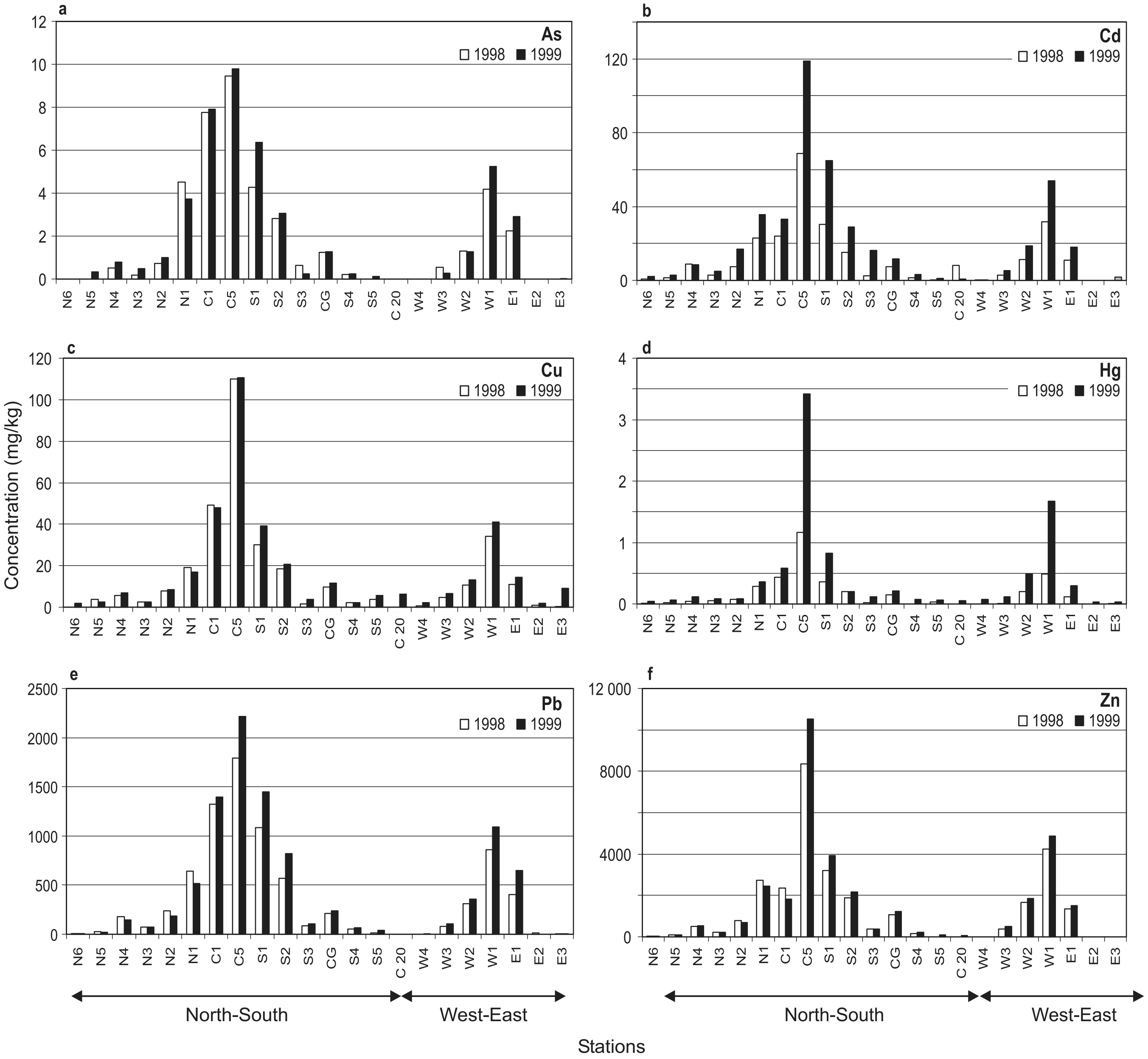


Figure 8 a–f. *Average annual (1998 and 1999) concentrations of the elements (a) As, (b) Cd, (c) Cu, (d) Hg, (e) Pb, and (f) Zn as registered by moss-monitoring stations located at two major north-south and west-east transects in the study area. The data are corrected for the moss matrix (blank moss sample), geogenic input, and local background level.*

results in higher deposition rates of airborne materials as a result of wet deposition processes. One explanation is that an increase in precipitation, especially in the form of snow, may have reduced dissemination of fugitive dust originating from the secondary sources, and hence decreased re-suspension of elements and particles on land. Additionally, leaching of elements out of the moss bags as the result of precipitation cannot be ruled out. However, studies have shown that leaching of elements out of moss bags is minimal because of the high water retention of moss (Martin and Coughtrey, 1982). Therefore, precipitation could have completely different effects on the distribution and deposition of particles and elements as determined by the moss-monitoring method.

In-process activities

The deposition of elements in the vicinity of a smelter could also be related to such in-process factors as production levels, the geochemistry of the feed, and the efficiency of the smelter's emission control systems, because they all influence the amount of elements emitted from the stacks. In this study, it was noted that the annual production and emission data (Fig. 9, 10a-c; Comico, unpub. data, 2000) vary proportionally to the annual average element concentrations as detected by the moss-monitoring stations (Fig. 8a-f). The increase in production of Pb and Zn during the second year of the study (1999) was associated with higher emissions of all the elements being studied except Cu and Hg (Fig. 8a-f, 9, 10a-c). It is interesting to note that Cu emissions were nearly consistent throughout both the first and second year of the study (Fig. 10c), and that annual average Cu concentrations recorded by the moss-monitoring stations are in agreement with this trend (Fig. 8c).

Mercury concentrations registered by the moss-monitoring stations increased in 1999 despite the decrease in emission levels of Hg at the smelter over the same period (Fig. 8d, 10c). Since the annual precipitation was lower in 1999 than 1998 (Comico, unpub. data, 2000), wet deposition can not explain the observed increase in Hg concentrations. The possible explanation is that a "secondary source" of mercury is responsible for the increase. The lower precipitation rates in this period may have intensified dissemination of particulate mercury as fugitive dust. A decrease in soil moisture could also cause degassing of mercury from soil with either a naturally high mercury content or soil that was previously contaminated by past high plant emission.

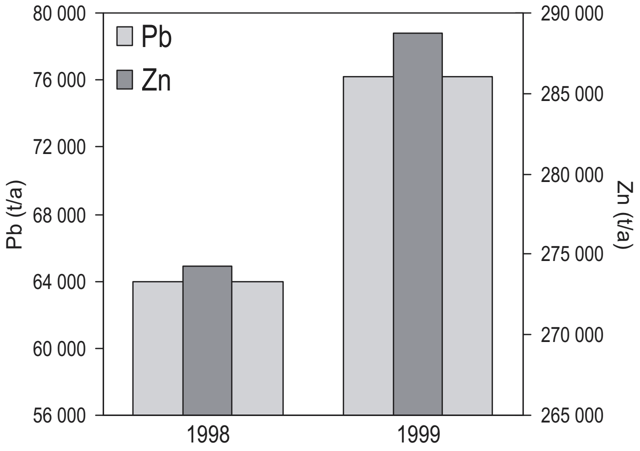


Figure 9. *Annual production (tonnes per year) of Pb and Zn by the Trail smelting operation during 1998 and 1999.*

It should be noted that the moss-monitoring method is designed to simulate the net increase of elements on surface soil. In the case of volatile elements such as Hg the post-depositional volatilization from the moss bags has not been taken into account (volatilization could occur in both soil and moss surfaces).

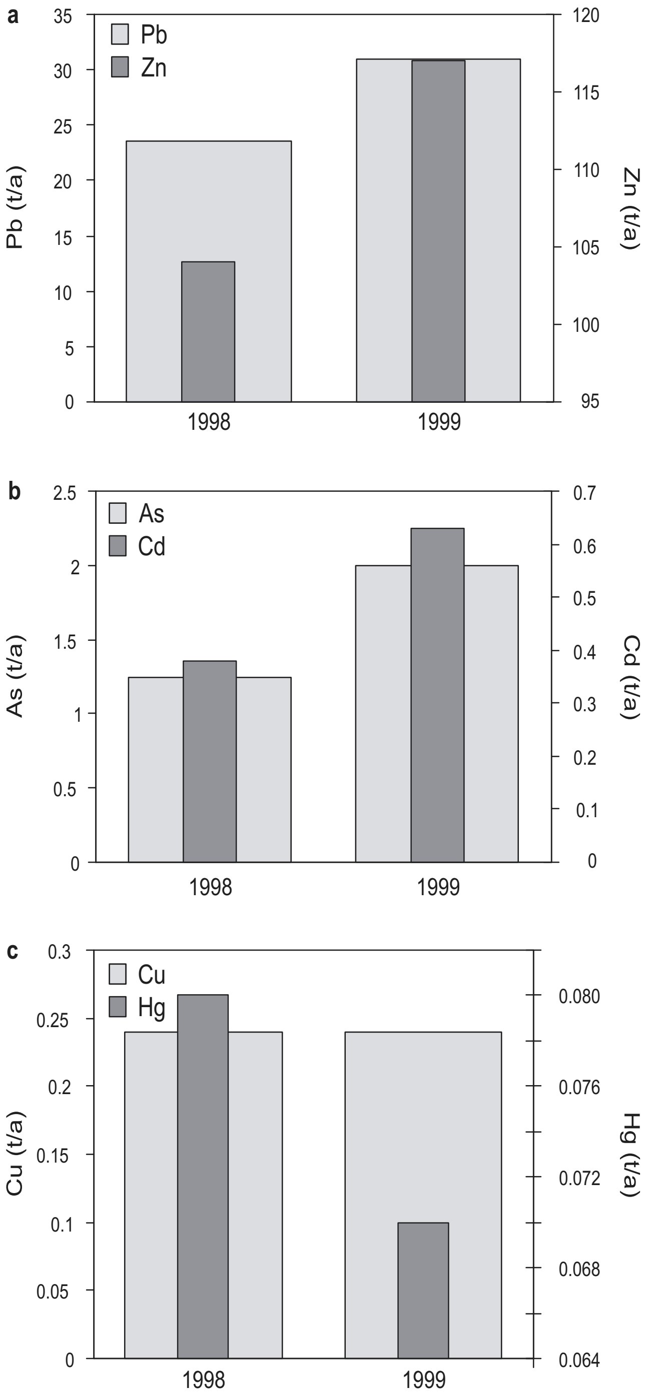


Figure 10 a–c. *Annual atmospheric emission (tonnes per year) of the elements (a) Pb and Zn, (b) As and Cd, and (c) Cu and Hg by the Trail smelting operation during 1998 and 1999 (Cominco, unpub. data, 2000).*

SOURCES OF TRACE ELEMENTS ASSOCIATED WITH SMELTING ACTIVITIES

Jennett et al. (1977) studied smelters in Missouri, U.S.A. and found that the presence of metals such as Pb, Zn and other trace metals in the environment was partly a result of metal smelting activity. The main sources were stack emissions and secondary sources, which are summarized in Figure 11.

Stack emissions

The prime sources of trace metals associated with smelting activities are the main stacks of the smelter. The stacks discharge thermally altered metal particulates to the atmosphere (Jennett et al., 1977).

Secondary sources

'Secondary source' is a broad term that includes all the possible sources of elements that indirectly relate to the smelting activities. Secondary sources have a significant role in the total contribution of elements to the environment (Jennett et al., 1977). The materials from these sources have a mineralogy and chemical composition that distinguishes them from the thermally processed material emitted from the stack.

The relative contributions of the secondary-source materials versus the material emitted from the stack are of interest primarily because emissions from these sources can be reduced by applying the appropriate measures. Also, the contribution of material from secondary sources can cause a problem in evaluating the impact of stack emissions from metal smelters and consequently the mass balance of elements in the system. For instance, dissemination and resuspension of the historical dust within the system may result in an overestimation of the environmental impact of recent emissions from the stack of the smelter, which recently have been significantly reduced by new technology in the smelting process.

Secondary-source origins

The secondary sources of metals can be grouped into three major components: 1) fugitive dust, 2) historical dust, and 3) other smelter omissions.

Fugitive dust

Fugitive dust is a less obvious, but very important source of metals in the area. It comprises dust from truck and railroad transport, and loading and unloading of ore concentrates, and windblown dust from piles of metal concentrate. Metal concentrates contain approximately 70% Pb or Zn by weight and are not only blown onto soil and plants, but may also be washed away to soil and streams. Transport in open vehicles and railroad cars aids in disseminating these materials (Jennett et al., 1977).

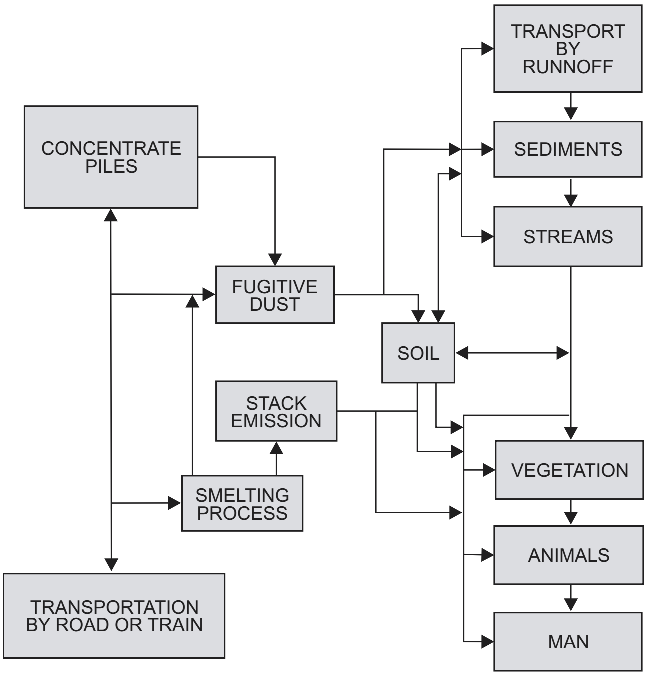


Figure 11. *Potential sources of trace elements in the environment as related to the smelting activities (modified after Jennett et al., 1977).*

Historical dust

The input of trace elements to the environment can be related to the past activities of the smelter. These materials are also classified as secondary sources since they are not directly related to present activities. The Trail smelter has operated since 1896, and has certainly contributed to the input of trace elements in this area. Historical dust can be the result of redundant operations (e.g., roasting of metals) or old dust from past, higher emissions of the smelter (Ketterer et al., 2001). These materials can be re-suspended within the region and are not considered as new material in the elemental inventory of the system.

Other smelter emissions (process)

Another possible secondary source, apart from the concentrate ores and slag piles, is the start-up stack of the zinc roaster, from which thermally unaltered particles of zinc sulphide (ZnS) are discharged (M. Edwards, pers. comm., 2000).

Monitoring the contribution of the secondary sources

Lead and zinc deposition data along the north-south transect were used to determine the contribution of secondary-source material versus material emitted from the stack. As discussed previously, the north-south orientation of the Columbia River Valley, in conjunction with the prevailing wind direction gusting in the same direction, causes element distribution to be confined within the valley system. This allowed for one-dimensional distribution modelling of emissions from the point source along a north-south line.

In addition to the stations along the north-south transect, a number of moss-monitoring stations were also installed adjacent to the areas where input from the secondary sources was expected to be the highest and their effects could be evaluated. These stations, such as C2, C3, and C4, are located within the boundary of the smelter compound (Fig. 12), and are likely to receive high emissions from secondary sources, including windblown particles from metal-rich dust covering the smelter floor, concentrate and slag piles, trucking activities, and other manipulations of feed and waste material within the smelter compound.

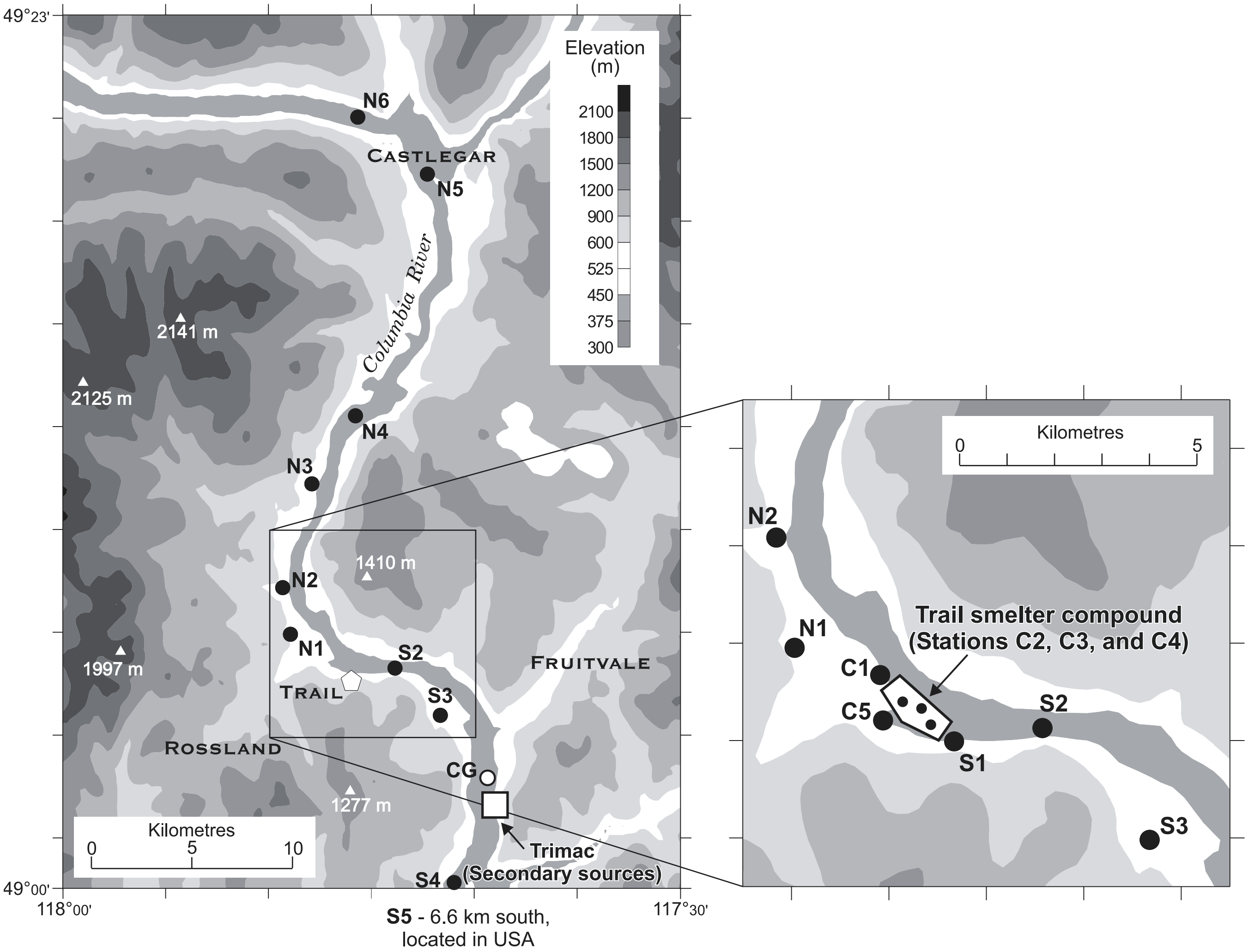


Figure 12. The locations of the moss-monitoring stations along the north-south transect of the Columbia River Valley system. Stations C2, C3, and C4 located inside the smelter compound and station CG near the Trimac ore and slag storage are specifically considered for evaluation of the secondary-source contribution.

Spatial distribution of Pb and Zn

The data shown in Table 7 indicate the high concentration of Pb and Zn registered by stations located within the boundary of the smelter. This was expected because these stations were intentionally located close to the area influenced by re-suspended particles and secondary sources inside the smelter compound. Hence, records from stations C2, C3, and C4 therefore do not represent the actual deposition of elements from the Trail smelter's stacks.

Table 7

Concentrations of Pb and Zn as registered by the moss-monitoring stations along the north-south transect (Columbia River Valley direction). Stations C2, C4, and C3 were added (bold) to monitor the contribution of secondary sources (fugitive dust) within the Trail smelter compound

Pb (mg/kg)

	Stations	Distance km	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99	Average*	Cumulative**
North- Centre-South	N6	25.7	N/D	1.1	0.2	16.6	9.4	1.2	7.9	3.7	5.7	40.2
	N5	23.5	N/A	1.1	14.7	67.1	40.6	12.5	14.3	14.6	23.6	165
	N4	11.3	100	87.3	115	418	137	112	173	154	162	1297
	N3	7.7	62.4	29.8	53.3	148	87.5	55.4	83.5	77.5	74.7	598
	N2	2.9	171	125	180	479	171	158	164	256	213	1704
	N1	1.8	302	631	613	1010	610	568	422	462	577	4619
	C1	1.5	740	1780	656	2122	2735	1424	908	518	1360	10882
	C2	0	792	986	908	1871	990	976	704	1043	1034	8270
	C3	0	7198	9893	5860	12382	10406	11929	10683	3312	8958	71663
	C4	0	2302	3860	2056	3152	3662	4007	3294	1969	3038	24302
	C5	1.5	1870	2524	1081	1704	2702	2732	2646	772	2004	16030
	S1	2.7	1034	818	684	1799	982	1729	2140	930.9	1265	10116
	S2	4.5	580	560	489	635	654	937	1500	177	691	5530
	S3	7.4	140	87.3	58.7	66.8	95.6	162	140	15.4	95.6	765
	CG	11	170	177	112	382	209	316	366	51.6	223	1783
	S4	14.1	60.5	24.9	27.9	98.6	71.7	74.6	104	18.2	60.1	481
	S5	20.7	N/D	11.0	5.7	21.2	67.4	13.7	34.8	N/D	25.6	154

Method: ICP-MS, Lower Limits of Detection = 0.5 mg/kg

Zn (mg/kg)

	Stations	Distance km	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99	Average*	Cumulative**
North- Centre-South	N6	25.7	N/D	N/D	N/D	19	25	33	N/D	2	20	79
	N5	23.5	N/A	N/D	2	161	167	24	62	68	81	485
	N4	11.3	328	374	438	910	551	439	604	501	518	4144
	N3	7.7	182	85	157	419	253	135	248	254	217	1732
	N2	2.9	590	426	641	1485	660	428	803	893	741	5926
	N1	1.8	1592	2409	2806	4142	2913	2162	2426	2324	2597	20774
	C1	1.5	1599	3714	1688	2416	3226	1817	1573	714	2093	16747
	C2	0	2289	3349	4451	6653	4210	3450	4139	3602	4018	32142
	C3	0	22710	23703	22061	23078	31260	24782	24042	5190	22103	176825
	C4	0	10734	18748	9559	4753	8975	20307	14775	14779	12829	102631
	C5	1.5	8367	10821	6432	7866	9574	12066	14529	5937	9449	75592
	S1	2.7	2658	3484	2410	4286	3377	4121	5951	2256	3568	28543
	S2	4.5	1792	2290	1657	1802	2013	2280	3772	654	2032	16259
	S3	7.4	577	340	249	309	385	432	609	47	369	2948
	CG	11	852	1141	914	1382	862	1716	1973	409	1156	9249
	S4	14.1	264	93	126	171	223	213	397	60	193	1548
	S5	20.7	N/D	14	1	3	233	5	86	N/D	57	343

Method: ICP-MS, Lower Limits of Detection = 2 mg/kg

*Average concentration from two years of sampling (winter 1998 - fall 1999). **Sum of the concentration from two years of sampling (winter 1998 - fall 1999). N/D = not detected.N/A = not available. Distance: The radial distance between a moss-monitoring station and the smelter compound.

The maximum deposition was recorded by station C3 adjacent to the feed and slag piles (Table 7). Although stations C2 and C4 are also within the smelter compound and have the same radial distance from the stacks, they register less impact than station C3 (Table 7) because they are somewhat farther from the uncovered feed and slag storage piles. Furthermore, outside the smelter boundary, stations show a rapid decrease in concentrations of Pb and Zn, which can be attributed to the reduced effects of secondary sources.

This rapid decrease in deposition can be represented by normalizing the Pb and Zn deposition data registered in all the stations to the maximum deposition recorded by station C3. The results are then presented as a percentage deposition of Pb and Zn relative to their maximum concentration in C3 (Table 8). The results indicate that deposition of Pb and Zn detected by stations C2, C4, and also the stations just outside the boundary of the smelter compound (C1 and C5) are only a small fraction of the maximum deposition detected by C3 station (Table 8). For example, stations C1 and C5, located 1.5 km away from the smelter compound, show an up to 85% decrease relative to the maximum deposition of Pb registered for station C3 (Table 8). This significant decline in deposition of Pb and Zn is attributed to the stations being at greater distances from secondary sources, leading to the conclusion that secondary sources are responsible for the high deposition within the boundary of the smelter compound.

The majority of the material released from secondary sources is not passed through any filtering process and consists of larger particles in comparison to the material emitted from the stack. This results in more gravitational deposition, and also results in a significant decrease in the deposition of elements outside the boundary of smelter operations (van der Grift et al., 1971; Duprey, 1972; Corrin and Natusch, 1977). In contrast, the thermal treatment of feed material (ore concentrate) through the smelter results in the fractionation, volatilization and condensation of a portion of elements among the various dust and stack-emitted gases. The more volatile elements condense preferentially on the surface of smaller particles in the flue gas, as a result of their higher surface area. These elements tend to pass through the filtration system and are more likely to be emitted from the stack. (Clarke and Sloss, 1992). Therefore, the distribution of the smaller particles in stack-emitted material will be more widespread, with a low fallout rate and more long-range transport (van der Grift, 1971; Duprey, 1972; Corrin and Natusch, 1977). Similar conclusions were drawn from the results of studies of smelters in Missouri, U.S.A by Lowsley (1977), Wixson and Jennett (1974), Hemphill (1977), and Jennett et al. (1977). They concluded that fugitive emissions, or those from non-point sources, such as transportation routes and smelter floors, are major sources of particulate matter, even exceeding stack emissions, but only within the smelter confines. Beyond the smelter boundary, stack emissions become the prime anthropogenic contributors of Pb to the environment.

Site-specific secondary sources

The significance of the secondary sources within the boundary of the smelter was discussed in the prior text. The limited effect of secondary sources is also evident in the proximity of the feed and slag piles beyond the smelter compound. One of the most remarkable examples of a site-specific secondary-source outside the Trail smelter boundary is found 11 km from the smelter complex, at the Columbia Gardens station (CG) (Fig. 12). This station is located 1.2 km north of Trimac, where Zn-Pb-rich ore and slag is stored (Fig. 12). The direction of the prevailing winds (northwest-southeast), suggests the windblown fugitive dust from the stored material in this area is likely to contribute to the amount of Pb and Zn registered in station CG.

If stations S3, CG and S4 received emissions only from the stack of the Trail smelter, then theoretically, the deposition of particulate elements in these stations would decrease as the distance from the smelter increased. Since

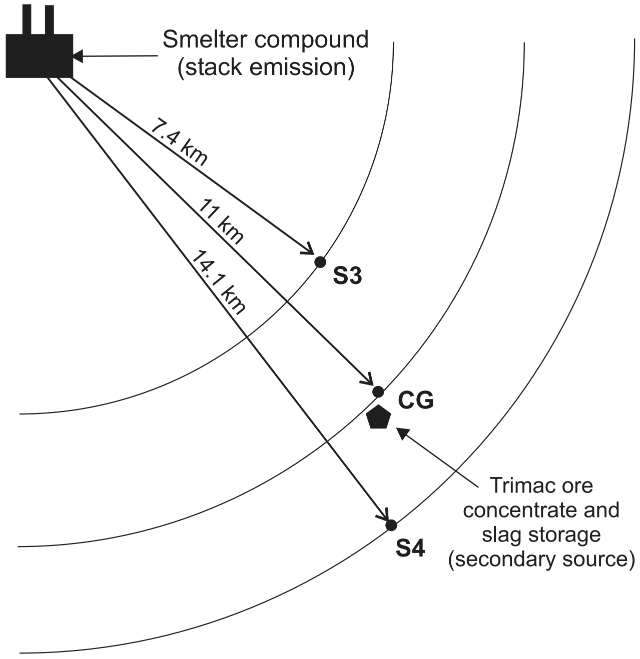
Table 8
Per cent deposition of lead and zinc in various stations along the north-south sampling transect relative to the maximum deposition recorded by station C3* [The values in bold refer to the stations located within the boundary of the smelter (zero distance)]

Stations	Distance (km)	Pb	Zn
N6	25.7	0%	0%
N5	23.5	0%	0%
N4	11.3	2%	2%
N3	7.7	1%	1%
N2	2.9	2%	3%
N1	1.8	6%	12%
C1	1.5	15%	9%
C2	0	**12%**	**18%**
C3	0	**100%**	**100%**
C4	0	**34%**	**58%**
C5	1.5	22%	43%
S1	2.7	14%	16%
S2	4.5	8%	9%
S3	7.4	1%	2%
CG	11	2%	5%
S4	14.1	1%	1%
S5	20.7	0%	0%

*Average from two years' sampling (winter 1998 - fall 1999).

the CG station is almost equidistant to both S3 and S4 (Fig. 12, 13), the anticipated concentration of Pb and Zn registered by CG station would be approximately the mean of the value registered by S3 and S4. This is if we assume that at a distance of 11 km from the smelter, the effect of the stack emissions from the Trail smelter decreases linearly as a function of the inverse distance (The Sutton (1953) and Csanady (1973), model is used to infer that an approximately linear projection can be made for the deposition of stack-emitted material at a distance of 11 km away from the smelter source; see the following text).

However, higher concentrations of Pb and Zn were recorded for CG as compared to S3 and S4 during all periods of the study (Table 7). The windblown dust originating from the feed and slag piles (and their manipulation) is likely to have caused the higher depostion of Pb and Zn in station CG, whereas the deposition of metals in stations S3 and S4 are mainly attributable to smelter stack emissions, as no major secondary sources were identified in the proximity of these stations.



T = *Total concentration of elements as registered by the moss- monitoring stations* S3, S4, *and* CG

Stck_{CG} = *Contribution of stack emission in* CG *station*

Scnd_{CG} = *Contribution of secondary source (Trimac feed/slag storage piles)*

$\text{Stck}_{CG} \sim (T_{S3}+T_{S4})/2 \quad \% \, \text{Scnd}_{CG} = (T_{CG} - \text{Stck}_{CG})/T_{CG} \times 100$

Figure 13. *Location of Columbia Gardens station (CG) relative to the Trail smelter (source of stack emission), and adjacent stations (S3 and S4). Also shown is the calculation applied for determining the site-specific secondary-source contribution (see Table 9).*

This elevated deposition of Pb and Zn at CG station relative to stations S3 and S4 can be estimated by calculating the difference between the deposition values for the CG station from the mean of the values for stations S3 and S4 and conversion of the value to a percentage (Fig. 13 and Table 9). If we attribute the elevated deposition in CG station to the contribution of secondary sources, the results indicate that the secondary source contribution for Zn and Pb ranges between 41 and 87%, showing seasonal variations (Table 9).

Estimation of the relative contribution of stack and secondary sources using statistical diffusion models

A combined diffusion model is used for depicting the distribution and deposition of Pb and Zn within the smelter boundary and its vicinity, based on the data obtained from the moss-monitoring stations. This combined model consists of two individual diffusion models, which are complementary, and represent various sources of emissions as related to the smelting activities around the point source. These models are as follows:

1. Diffusion of particles from a stack. The theoretical diffusion model inferred from work by Sutton (1953), Csanady (1973), and Carras (1995), which is a function of the distance from the stack, is capable of simulating the deposition of particulate elements originating from a continuously emitting point source (e.g., stack of the smelter). This model is expressed by the following equation:

$$\chi(x,0,0) = \frac{q}{\pi U \sigma z \sigma y} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \tag{1}$$

Where: χ[1] is the ground level concentration (g/cm^3) of an element along the plume axis position of x (y and z are set to zero[2]); “x” is the distance (m) from the base of the stack along the plume axis at ground level; “q” is the amount of emissions (g/sec) from the stack (source strength). In the present study, the q value is given as tonnes per year (t/a) (Cominco, unpub., 2000), which was converted to grams per second (g/sec); “U” is the average wind speed (8 km/hr;

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[1] χ is the solution to the differential equation presented by Sutton (1953) regarding the diffusion from a continuous point sources.

[2] The reason for setting y and z coordinates to zero is to determine the ground level concentration in one dimension along the axis “x” (distance from the point source).

Table 9
Relative contribution of secondary sources versus stack emission for Pb and Zn registered in Columbia Gardens (CG) station using the site-specific secondary-source concept

	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99	Average*
Secondary-sources contribution									
Pb	41	68	61	78	60	63	67	67	65
Zn	51	81	80	83	65	81	75	87	76
Stack contribution									
Pb	59	32	39	22	40	37	33	33	35
Zn	49	19	20	17	35	19	25	13	24

* Average from 2 years of study (winter 1998 - fall 1999).

Environment Canada, 1993); "h" is the average stack height (main stacks), set at ~100 m (Cominco, unpub., 2000); and σ_z and σ_y are the dispersion factors as related to size of the plume in the axis z and y.

Given a simplification proposed by Csanady (1973), the size of the plume in each axis is calculated by the following equation:

$$\sigma_z = i_z \cdot x$$
$$\sigma_y = i_y \cdot x \qquad (2)$$

Where: "$i_z = 0.104$" is a turbulence intensity factor in the z direction (the height of the plume); and "$i_y = 1.76\, i_z$" is a turbulence intensity factor in the "y" direction (the width of the plume) as obtained from Csanady, (1973).

The deposition of elements on the ground is proportional to the concentration in the air immediately above the ground level as expressed by equation [1] (Csanady, 1955; 1973). The location at which the maximum deposition occurs along the "x" axis (maximum ground level concentration) is expressed where the argument in the exponential of equation [1] is equal to –1 (i.e., where $\sigma_z = h/\sqrt{2}$; Csanady 1973). The falling rate is proportional to the resulting particle speed, which is a vector sum of the wind speed, falling speed (Stoke's formula), and plume buoyancy (Sutton, 1953).

This model holds only for idealized and stable wind conditions. Other factors, such as the topography of the region and meteorological parameters (amount and type of precipitation), obviously have some effect.

2. Diffusion of particles from secondary sources within the smelter boundary

The deposition of trace elements originating from a secondary source within the boundary of the smelter is well represented by the Gaussian curve (Hall et al., 1997), which has its peak at center and rapidly declines over a short distance from the center. This is correlated with the actual distribution of secondary-source trace elements in Trail area as discussed previously, which is at a maximum level within the boundary of the smelter and declines rapidly over increased distance from the smelter.

Combined-diffusion model

The theoretical combined-diffusion model for particulate and element dispersion in a one-dimensional system (along a sampling line) is shown in Figure 14. Two side components (2 and 3) show the stack emission effects to the north and south with the maximum ground level (χ) occurring at the distance estimated by equation [1] (Csanady, 1973; Carras, 1995). Additionally, the deposition from the secondary sources within the smelter compound is presented by a Gaussian curve in the center (component 1) as explained previously (Fig. 14).

A moss-monitoring station registers the combined deposition from both secondary and stack sources at a given point. Our theoretical combined model can be fitted to the empirical deposition data obtained from the moss-monitoring stations in order to estimate the relative contribution of each component (as related to the stack and secondary sources).

Estimating the relative contribution of secondary sources versus stack source

Deposition of Zn and Pb as registered by moss-monitoring stations (cumulative concentration for the two years 1998 and 1999) were plotted versus distance from the smelter along the north-south transect (Fig. 15a) (only data for Zn is shown since Pb shows the same deposition pattern). The result shows a nonsymmetrical, complex curve, which is skewed toward the south as a result of the prevailing wind (Fig. 15a). This complex curve is believed to be a

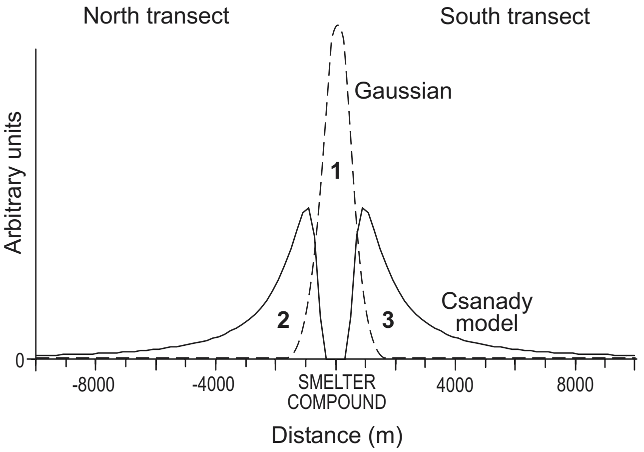

Figure 14. *The theoretical combined-diffusion model for particulate elements emitted from stack and secondary sources in a one-dimensional sampling line and as a function of distance from the smelter compound. Component 1 is a Gaussian model representing the deposition from secondary sources within the smelter compound; Components 2 and 3 show the diffusion from the stack(s) as presented by equation [1] in the text (Csanady, 1973; Carras, 1995).*

combination of a number of individual diffusion curves for various sources around the smelter.

Dividing the deposition curve into the individual diffusion sources

The "fitting" process is applied to the empirical data obtained from moss-monitoring stations by matching the combined theoretical model to the empirical curve along the north-south transect. As a result, the complex curve obtained from the empirical data is divided into a set of four individual curves (components 1–4) (Fig. 15b). Each component represents the quantity of the deposition by either stack or secondary sources at various locations around the Trail smelter and are as follows:

Component 1

Deposition from secondary sources within the boundary of the smelter (composed of the data from stations C2, C3, and C4), which is fitted by a Gaussian curve in the center (Fig. 15b).

Component 2

Deposition from the stack in a north-northwest direction, which is composed of data from stations C1, N1, N2, N3, N4, N5, and N6. The maximum ground level for the deposition of material from the stack in this direction is approximately 1 km away from the center of the smelter compound where stacks are located (Fig. 15b).

Component 3

Deposition from the stack in a south-southeast direction, which is composed of the data from stations C5, S1, S2, S3, S4, and S5 (Fig. 15b). The maximum ground level in a southern direction occurs at a greater distance of

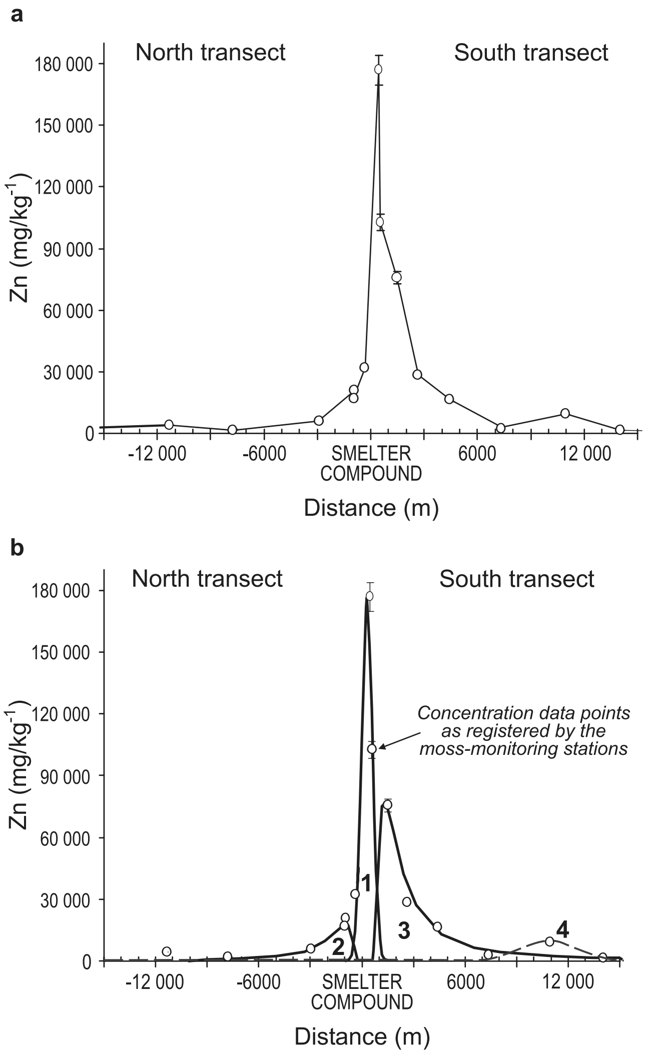

Figure 15. *(a) Cumulative concentration of Zn over two years of monitoring (winter 1998 – fall 1999) as registered by the moss-monitoring stations along the north-south sampling transect in the Trail smelter's surrounding area. (b) Empirical deposition data (e.g., a two-year cumulative concentration of Zn) divided into the fitted diffusion models (Components 1-4) as related to the stack and secondary sources. For descriptions of the components refer to the text.*

approximately 1.8 km as compared to the north side (component 1) (Fig. 15b). This is accompanied by a greater magnitude of the curve in this direction (Fig. 15b) attributable to the southward direction of the prevailing wind in Trail area.

Component 4

Site-specific secondary sources representing the local deposition of material from the secondary sources at the CG station (composed of the data from stations S3, CG, and S4). The Columbia Gardens (CG) station registers higher deposition than its neighboring stations S3 and S4 as discussed previously. The secondary source's contribution in this station is defined by a Gaussian curve based on three points: stations S3, CG, and S4 (Fig. 15b).

The transformation of Figure 14 to Figure 15b via Figure 15a in which the theoretical model is tuned to fit the empirical data, can be described mathematically by the use of conformal mapping as explained by Fisher (1999). In this approach, the transformation can be described intuitively by noting that the north and south lobes of the model (components 2 and 3) can be modified in magnitude by considering that a different depositional regime is present in each direction, possibly due to the prevailing wind direction. This is clearly shown in Figure 15b, where the north lobe (component 2) has a reduced magnitude, reflecting a lesser deposition due to the fact that the plume spends less time in the north side than the south direction.

Calculation of the area under the curve

The areas under each component represent the relative magnitude of contribution from the source they correspond to. The areas under the components were calculated using Simpson's rule. The estimated areas were then reported as a percentage of the total area under all four components covering the entire north-south transect in the Trail area (Table 10). This approach is used to calculate the proportion of each component as it relates to the contribution of stack and secondary sources.

The results indicate that the input from secondary sources form a relatively large portion of the total deposition over the entire study area (Table 10). Secondary sources within the boundary of the smelter and the CG station together contribute up to 42% and 45% of the total Zn and Pb, respectively, deposited in the study area. It should be noted that the percentage values reported in Table 10 represent the relative contribution of secondary sources within our full-size one-dimensional system, which extends 15 km north and south of the smelter (Fig. 15b).

The influencing factors

The relative contribution of stack-emitted versus secondary sources may vary as a result of numerous factors, such as seasonal variation in meteorological conditions, efficiency of emission control systems (e.g., baghouses), and the degree that secondary-sources are involved (e.g., feed and slag manipulations). Each factor can affect the magnitude of emissions from both the stack and secondary sources.

Meteorological conditions may influence the effect of the secondary source. For instance, high winds can cause the re-suspension of particles from uncovered concentrate/slag storage piles or of historical dust. On the other hand, precipitation can increase the deposition of airborne particles emitted from stack. Furthermore, precipitation, especially in the form of snow, reduces re-suspension of particles and hence increases the relative contribution of stack emissions as compared to the secondary sources.

The efficiency of the filtering mechanisms as well as the production level of the plant can also directly influence the degree to which the stack emissions contribute to the amount of elements deposited in the area.

Table 10
Approximate percentage contributions of various sources in total deposition of Pb and Zn deposited in the study area (window of 15 km away from the Trail smelter along the north-south line; see Fig. 15b) during eight consecutive periods of study (winter 1998–fall 1999)

	Pb (1998)	Pb (1999)	Zn (1998)	Zn (1999)
Component 1*	36%	33%	33%	26%
Component 2**	16%	12%	15%	12%
Component 3***	38%	46%	43%	53%
Component 4†	9%	9%	10%	9%

*Secondary sources contribution within the smelter compound; **Stack contribution north of the smelter; ***Stack contribution south of the smelter; †Site-specific secondary-source contribution at Columbia Gardens (CG) station.

It should be noted that the resolution of this statistical model for analyzing the spatial distribution of elements and particles depends largely on the number of monitoring stations installed in the study area. The additional stations planned for the continuation of this study will increase the resolution of the data.

Characteristics of deposited material

The morphology and chemical composition of particles as characterized by SEM/EDX show that the particles originating from secondary sources, such as the material deposited in the CG station (site-specific secondary-source station), are characterized mainly by large, angular fragments with a chemical composition similar to material present in the sulfide ore (e.g., ZnS) (Fig. 16a). In contrast, stack-emitted particles that are thermally altered and have undergone the filtering process are usually small, subangular to rounded, fluffy particles (Fig. 16b). Their chemistry indicates that they have been subject to oxidation. A typical stack-emitted Pb particle contains mostly small and rounded particles of PbO (Fig. 16b). This result is consistent with work by Bolter (1977), who found lead

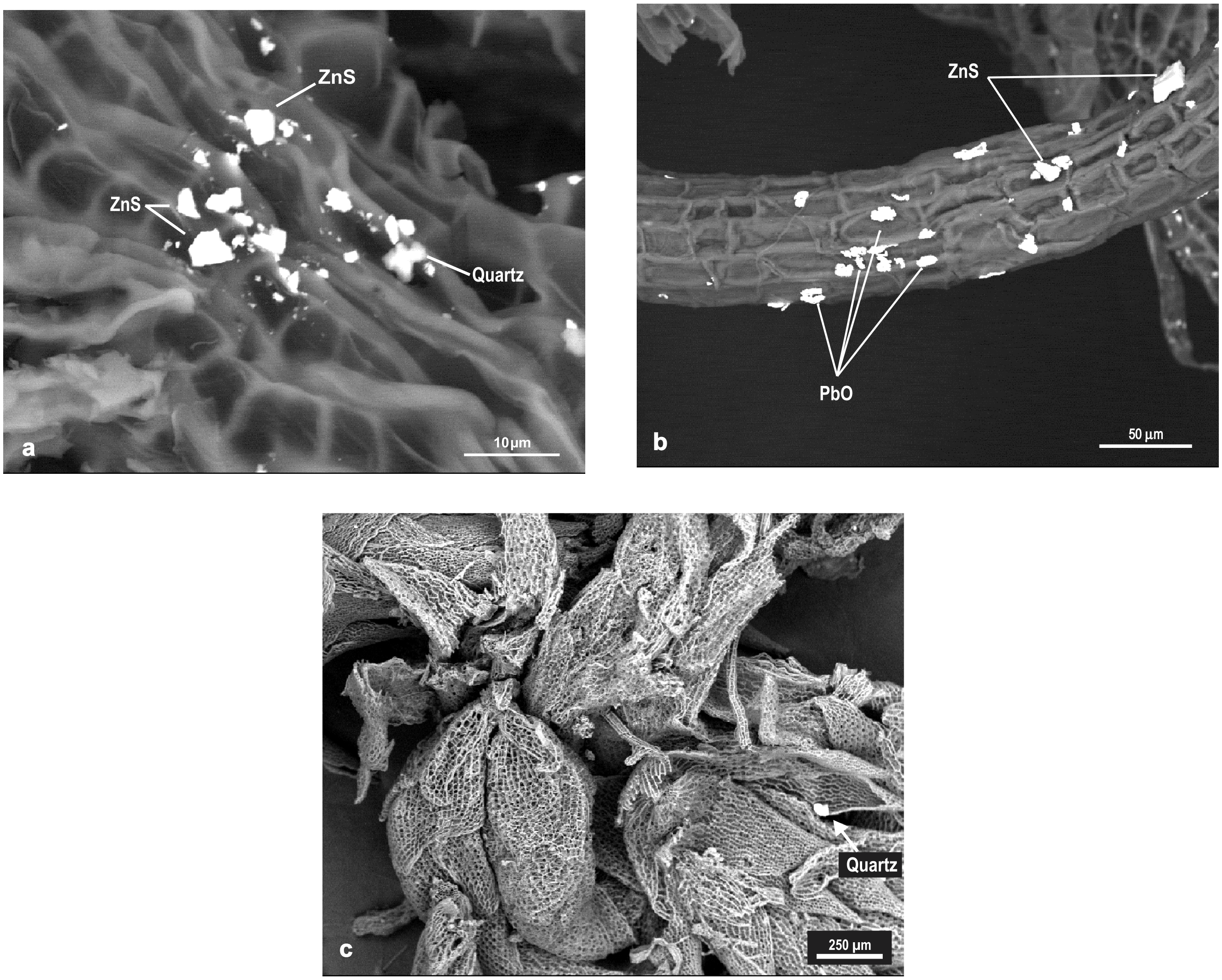

Figure 16. *SEM/EDX photos, showing morphology and chemical composition of typical particles collected at: (a) the site-specific secondary-source monitoring station at Columbia Gardens (CG). The particles are mainly angular and have a chemical composition of similar to sulfide ore (e.g., ZnS); (b) moss-monitoring stations close to the smelter compound. Angular particles of ZnS are typical of particles originating from the secondary sources, whereas the rounded, fluffy-shaped particles of PbO indicate thermally altered material emitted from the stack; (c) geogenic particles collected at the moss-monitoring station in Castlegar (Station N6) characterized by angular quartz particles (GSC Photo no. 4724-4).*

compounds emitted from the lead smelter stack are mainly in the form of Pb, $PbSO_4$, and PbO-$PbSO_4$, in contrast with the mainly PbS form emitted from the secondary sources.

Furthermore, particles of geogenic dust are commonly angular to subangular and consist of silicate compounds (Fig. 16a, c). These materials are more common in background stations located at greater distances from the smelter activities, where natural sources are the major contributor of elements (e.g., station N6; Fig. 16c).

ACCUMULATION OF TRACE ELEMENTS ON THE SURFACE SOIL

Moss-monitoring provides valuable information on the flux and deposition rate of airborne particulate matter and elements on land by using an artificial deposition surface, which simulates deposition on the soil surface. Flat, square moss bags of known dimensions facilitate calculating deposition rates on a unit area basis (Martin and Coughtrey 1982), which can be extrapolated to larger areas. Cross-calibrations between flat moss bags and several types of standard deposition gauges show good correlation, which enhances confidence in extrapolating from moss-monitoring data to deposition units (Ratcliffle, 1975; Goodman et al., 1975a, b). However, it is prudent to calibrate the estimation of deposition rate obtained by moss-monitoring stations with standard deposition monitoring methods (Martin and Coughtrey, 1982).

To that end, prior to the moss-monitoring study, the concentrations of trace elements in surface soil were measured. Subsequently, the accumulation rates of the trace elements on the surface soil were estimated using the concentration data obtained from the moss-bag survey (Table 6a-f).

Quantity of trace elements in surface soil

The bulk concentrations of the elements (As, Cd, Hg, Cu, Pb, and Zn) in the soil samples around the Trail smelter were determined as shown in Table 11. These elements can

Table 11
Bulk concentrations (mg/kg) of As, Cd, Cu, Hg, Pb, and Zn in surface soil samples from the Trail area

	Station	Distance (km)	As	Cd	Cu	Hg	Pb	Zn
North-Centre-South	N6	25.7	7.2	1.4	16	0.06	92	133
	N5	23.5	4.6	1.3	15	0.04	57	115
	N4	11.3	11.2	3.1	21	0.05	242	166
	N3	7.7	12.0	1.6	14	0.06	127	162
	N2	2.9	6.2	2.2	16	0.05	100	263
	N1	1.8	8.0	2.9	22	0.06	518	220
	C1	1.5	17.4	2.5	21	0.06	182	183
	C5	1.5	45.2	11.5	92	0.51	1279	858
	S1	2.7	50.8	16.0	106	0.66	1139	1632
	S2	4.5	20.2	5.6	32	0.26	354	495
	S3	7.4	65.8	2.8	20	0.04	95	138
	CG	11	18.6	4.7	24	1.39	391	366
	S4	14.1	15.4	3.1	35	0.21	191	247
	S5	20.7	11.8	1.3	31	0.04	109	101
West-East	C 20	12	156.7	0.6	36	0.02	112	85
	W4	6.8	13.8	0.6	45	0.13	47	93
	W3	2.8	23.6	3.0	53	0.27	552	220
	W2	2.6	28.4	4.4	101	0.37	679	1039
	W1	2	N/A	N/A	N/A	N/A	N/A	N/A
	E1	2	14.6	1.8	28	0.08	218	234
	E2	13.4	18.4	2.6	30	0.06	53	335
	E3	13.5	9.6	1.7	32	0.06	75	164
Selected methods			AA-hyd	ICP-MS	ICP-MS	CVAA	ICP-MS	ICP-MS
Lower limit of detection (mg/kg):			0.5	0.20	1	0.02	0.5	2

AA-hyd: Atomic Absorption-hydride analyses; ICP-MS: Inductively Coupled Plasma - Mass Spectrometry; CVAA: Cold Vapor Atomic Absorption; N/A: Not Available all occur naturally in the soil (Rasmussen, 1996; Reimann and de Caritat, 2000). The local background levels for As, Cd, Cu, Hg, Pb, and Zn are reported as 19.7, 1.67, 51.5, 0.07, 37.9, and 168 mg/kg, respectively (Goodarzi, unpublished data) and 10, 1.5, 45, 0.025, 75, and 200 mg/kg, respectively (B.C. Environment, 1999) for the Trail area and Kootenay region (southeastern British Columbia)[1]. Both studies present the 95th percentile of their data set after excluding the outliers. The analysis is conducted using ICP-MS after hot digestion with $HCl-HNO_3$. The relatively high background soil concentrations of metals and trace elements in this region are due to the fact that the soils are influenced by the presence of underlying mineralized bedrock, which is enriched in chalcophilic elements (Little, 1982; Sevigny, 1990).

In order to translate the concentration data to the mass of elements distributed per unit of land, the following procedures were applied.

Defining the "soil unit"

Each soil sample obtained from a given location around the smelter is assumed to represent a larger unit of land, which is referred to as a "soil unit" in this paper. Soil unit is defined as a box of soil 10 cm (0.1 m) deep extending over an area of 1 hectare (10^4 m^2). Using this assumption, the volume of the soil unit can be estimated as follows:

$$V=(0.1)\ \mathrm{m} \times (10^4)\ \mathrm{m}^2 = (10^3)\ \mathrm{m}^3 \qquad (3)$$

If the soil density is assumed to be 1.5 g/cm^3 (1.5 x 10^3 kg/m^3), then the mass of the soil unit (M) can be calculated using the following equation:

$$M=(10^3)\mathrm{m}^3 \times (1.5 \times 10^3)\ \mathrm{kg/m}^3 = (1.5 \times 10^6)\ \mathrm{kg} \qquad (4)$$

Soil scientists consider the bulk density of soil to range from 1.30 to 1.35 g/cm^3 (Hillel, 1980). However, several factors suggest that a larger value should be used. First, the presence of quartz may increase bulk soil density to as much as 1.6 g/cm^3 (Hillel, 1980). In this case, because much of the study area is underlain by a granodiorite pluton, the presence of significant amounts of quartz within the soil is anticipated (Little, 1982; Sevigny, 1990). Secondly, the presence of iron sulphides in the exposed country rocks of the Trail area can increase the particle density of soil (Sevigny, 1990; Hillel, 1980). Based on these factors, a decision was made to set the average soil bulk density to 1.5 g/cm^3.

Mass of elements in the soil unit

The mass of a given element distributed in a soil unit (ME) can be estimated using the concentration data (E mg/kg) of a representative soil sample as expressed by the following equation:

$$ME = (1.5 \times 10^6)\ \mathrm{kg} \times (E)\ \mathrm{mg/kg} \qquad (5)$$

Equation [5] assumes that the mass of the studied element (ME) is evenly distributed throughout the soil unit. Therefore, the mass of elements (ME) can be reported in milligrams per 10-centimeter hectare of land (soil) by multiplying the concentration data (E) by a value of 1.5 x 10^6 kg, which equals the mass (M) of the soil unit. Milligrams per hectare are subsequently converted to kilograms per hectare (kg/ha) by multiplying the results by 10^{-6} (Table 12a-f).

Incremental accumulation of trace elements in the surface soil

The accumulation of elements on the surface soil over a given period of time can be estimated using the atmospheric deposition rates measured by moss-monitoring stations. The deposition of elements measured by flat moss bags can be extrapolated over a larger unit of area. This approach is used to determine the possible enrichment of metals and other trace elements (incremental accumulation) in the vicinity of the Trail smelter.

Calculating the deposition rate per unit of land (hectare)

A moss bag is subdivided into four 8 x 8 cm compartments (64 cm^2 = 64 x 10^{-8} ha each). Each compartment was filled with 2 g (0.002 kg) of moss. In order to convert the measured elemental concentration data obtained from the monitoring station into a quarterly (three months) deposition rate (kg/ha), the following equation can be used:

$$d = \frac{0.002\ \mathrm{kg} \times E\ \mathrm{mg/kg} \times 10^{-3}\ \mathrm{g/mg}}{64 \times 10^{-8}\ \mathrm{ha}} \qquad (6)$$

where "E" is the measured concentration of the element in mg/kg registered by a moss-monitoring station after a three-month exposure period; and "d" is the deposition rate in g/ha for that three-month period.

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[1] Both studies present the 95th percentile of their data set after excluding the outliers. The analysis is conducted using ICP-MS after hot digestion with $HCl-HNO_3$.

This equation assumes the moss bag has a flat surface, regardless of its thickness. However, the thickness of the moss bag was minimized to reduce the error associated with this assumption.

The deposition rates (g/ha) of As, Cd, Cu, Hg, Pb, and Zn for the three-month periods over the course of study have been calculated (Table 12a-f) using the concentration data registered by moss-monitoring stations at various sites around the Trail smelter (Table 6a-f). However, this calculation utilizes the total amounts of elements, including re-suspended elements, which may overestimate the amount of newly deposited material on the land due to the stack emission.

Accumulation of elements on the soil unit

The ratio of the deposition rate of an element to the total existing mass of that element in the soil unit (represented by the soil samples) is used to derive the per cent addition of the element to the soil unit (one hectare land) over a given period of time (in this case, three months). For example, the deposition of 4 kg/ha of Pb applied to the 10 cm notional layer per 3 months for a site in which the soil contains 200 kg/(10 cm) ha Pb, results in addition of 2% Pb into the soil (see equation 7).

$$\text{Addition (\%)} = \frac{4\ \text{kg/ha}}{200\ \text{kg/(100 cm) ha}} \times 100 \qquad (7)$$

Table 13 shows the per cent increase in the quantity of the six studied trace elements in soil over each period of study using the above calculation. The results indicate an arithmetic mean accumulation of 0.02%, 0.65%, 0.07%, 0.29%, 0.22%, and 0.65% for As, Cd, Cu, Hg, Pb, and Zn, respectively, on the soil unit over period of three months. Maximum accumulation was observed at the stations located near the point source (Table 13a-f).

The same principle can be applied to predict the accumulation of the elements over a longer period of time assuming that the metal source processes remain unchanged and the deposition rate persists over time.

It should be noted that the above approach assumes that the deposited elements remain within the 10 cm thick hectare. However, because of the mobility of elements within the soil as a result of various factors, the situation can be more complicated. Processes such as soil erosion,

Table 12
The estimated masses of As, Cd, Cu, Hg, Pb, and Zn distributed in a soil unit [kg/ha (10 cm)] and their aerial deposition rates (g/ha/3 months) as registered by the moss-monitoring stations around the Trail smelter

As*												
			kg/ha/10 cm	**g/ha/3 months**								
Station		**Distance (km)**	**Masses per soil unit**	**Fall 97**	**Winter 98**	**Spring 98**	**Summer 98**	**Fall 98**	**Winter 99**	**Spring 99**	**Summer 99**	**Fall 99**
North -Centre - South	N6	25.7	10.8	0.20	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	N5	23.5	6.9	N/A	N/A	N/D	N/D	N/D	N/D	N/D	N/D	1.03
	N4	11.3	16.8	3.24	0.93	1.09	1.90	2.70	0.28	1.61	1.98	6.13
	N3	7.7	18.0	1.15	0.68	0.10	0.35	1.09	N/D	0.84	1.19	2.51
	N2	2.9	9.3	4.91	2.42	1.30	2.21	3.17	0.50	3.13	2.14	6.72
	N1	1.8	12.0	12.00	9.58	21.86	14.22	10.60	9.21	21.96	6.22	9.26
	C1	1.5	26.1	10.30	15.62	54.63	12.24	14.50	32.34	24.96	7.96	33.57
	C5	1.5	67.8	41.33	36.34	47.81	17.88	16.15	33.27	39.92	28.62	20.66
	S1	2.7	76.2	32.97	15.40	17.68	8.81	11.50	11.00	22.82	25.36	20.28
	S2	4.5	30.3	12.00	11.87	11.05	6.48	5.93	5.09	13.56	12.79	6.84
	S3	7.4	98.7	1.50	1.81	2.10	N/D	N/D	N/D	1.24	1.05	0.05
	CG	11	27.9	7.51	4.25	5.48	2.12	3.76	2.30	6.35	4.80	2.38
	S4	14.1	23.1	2.71	0.94	0.55	N/D	0.62	N/D	0.26	1.02	1.03
	S5	20.7	17.7	0.39	N/D	N/D	N/D	N/D	N/D	N/D	0.37	N/D
West -East	C 20	12	235.1	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	W4	6.8	20.7	N/A	N/A	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	W3	2.8	35.4	0.69	1.44	2.69	N/D	0.98	0.70	1.33	0.41	N/A
	W2	2.6	42.6	4.44	4.81	7.52	1.96	1.96	2.64	4.89	3.69	4.58
	W1	2	N/A	16.24	18.71	22.57	4.13	7.04	16.73	26.17	11.30	11.43
	E1	2	21.9	N/A	N/A	9.35	5.06	6.48	6.45	10.00	11.06	8.70
	E2	13.4	27.6	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	E3	13.5	14.4	N/A	N/A	N/D	N/D	N/D	N/A	N/D	0.10	N/D

Table 12 (Cont'd)

The estimated masses of As, Cd, Cu, Hg, Pb, and Zn distributed in a soil unit [kg/ha (10 cm)] and their aerial deposition rates (g/ha/3 months) as registered by the moss-monitoring stations around the Trail smelter

Cd												
			kg/ha/10 cm	g/ha/3 months								
Station		Distance (km)	Masses per soil unit	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
North -Centre - South	N6	25.7	2.10	N/D	N/D	N/D	2.06	2.64	0.91	3.11	4.10	19.82
	N5	23.5	1.95	N/A	N/A	1.16	2.12	10.25	4.39	1.64	2.97	27.76
	N4	11.3	4.65	9.91	6.04	5.81	9.99	88.91	12.95	9.72	25.39	59.41
	N3	7.7	2.40	6.81	4.80	1.78	7.98	19.26	9.98	4.64	12.09	36.48
	N2	2.9	3.30	19.20	10.99	8.28	17.19	56.33	25.56	12.20	30.35	143.69
	N1	1.8	4.35	47.07	25.86	47.61	71.94	139.34	138.18	54.86	87.00	165.32
	C1	1.5	3.75	28.49	45.06	80.44	43.44	130.04	169.44	69.90	118.42	58.19
	C5	1.5	17.25	167.85	195.57	207.41	145.58	310.07	344.67	254.03	643.95	242.84
	S1	2.7	24.00	74.94	80.98	62.79	54.94	180.22	145.08	135.61	363.18	168.99
	S2	4.5	8.40	37.78	45.06	38.01	36.78	68.83	69.31	60.26	187.38	42.44
	S3	7.4	4.20	6.81	10.99	5.19	5.62	10.00	16.49	8.85	168.60	8.90
	CG	11	7.05	22.30	17.81	21.60	16.67	38.39	23.19	33.17	70.29	16.73
	S4	14.1	4.65	3.72	5.42	1.78	3.22	7.62	5.86	4.85	19.31	7.58
	S5	20.7	1.95	0.62	N/D	N/D	0.03	1.34	4.08	N/D	4.46	1.69
West -East	C 20	12	0.90	N/D	25.24	N/D	N/D	N/D	N/D	N/D	1.77	N/D
	W4	6.8	0.90	N/A	N/A	1.16	0.43	N/D	1.42	N/D	N/D	N/D
	W3	2.8	4.50	6.81	6.66	7.66	6.69	13.57	18.56	8.51	21.19	N/A
	W2	2.6	6.60	13.01	27.10	31.51	19.28	64.59	65.13	30.43	90.11	46.42
	W1	2	N/A	65.65	110.09	81.06	39.94	167.24	128.36	139.05	272.42	134.28
	E1	2	2.70	N/A	N/A	25.01	24.83	53.59	52.61	42.81	82.13	45.59
	E2	13.4	3.90	3.72	N/D	N/D	N/D	0.49	N/D	N/D	N/D	N/D
	E3	13.5	2.55	N/A	N/A	N/D	N/D	0.43	N/A	1.97	12.68	1.30
Cu*												
North -Centre - South	N6	25.7	24.0	N/D	N/D	N/D	N/D	N/D	11.74	2.42	N/D	2.78
	N5	23.5	22.5	N/A	N/A	N/D	N/D	11.56	14.97	2.26	N/D	6.21
	N4	11.3	31.5	1.55	N/D	7.74	11.43	32.44	18.83	16.39	27.81	23.18
	N3	7.7	21.0	1.55	N/D	N/D	1.24	14.89	15.20	2.28	4.17	9.36
	N2	2.9	24.0	23.23	7.74	20.13	24.40	46.56	36.39	26.74	14.40	27.17
	N1	1.8	33.0	41.81	20.13	54.20	75.57	87.98	77.37	60.53	37.73	36.85
	C1	1.5	31.5	60.39	72.78	165.68	153.58	224.44	277.84	187.00	95.22	40.00
	C5	1.5	138.0	351.50	311.24	509.44	270.40	283.81	454.11	379.29	444.42	104.85
	S1	2.7	159.0	94.45	91.36	106.84	81.69	94.91	111.79	177.83	144.57	57.21
	S2	4.5	48.0	41.81	48.00	63.49	71.68	46.56	66.71	70.68	104.21	16.41
	S3	7.4	30.0	4.65	1.55	4.65	8.28	4.60	18.40	12.47	10.98	6.01
	CG	11	36.0	32.52	17.03	26.32	21.34	56.21	42.88	46.57	44.13	12.97
	S4	14.1	52.5	1.55	N/D	N/D	4.92	8.28	11.63	5.70	4.29	6.08
	S5	20.7	46.5	N/D	N/D	N/D	4.42	18.78	35.83	2.33	17.71	16.33
West -East	C 20	12	54.0	N/D	N/D	N/D	N/D	N/D	8.37	N/D	44.20	5.93
	W4	6.8	67.5	N/A	N/A	N/D	N/D	1.71	8.00	N/D	N/D	6.03
	W3	2.8	79.5	1.55	7.74	23.23	14.07	12.97	25.73	19.72	17.58	N/A
	W2	2.6	151.5	7.74	23.23	44.90	29.42	36.08	60.18	43.50	44.49	16.33
	W1	2	N/A	91.36	116.13	144.00	57.18	108.91	153.03	174.39	138.93	47.00
	E1	2	42.0	N/A	N/A	35.61	34.28	32.38	70.46	50.65	44.28	16.22
	E2	13.4	45.0	20.13	N/D	N/D	0.81	4.73	N/D	N/D	N/D	6.03
	E3	13.5	48.0	N/A	N/A	N/D	N/D	1.35	N/A	53.93	27.92	2.85

Table 12 (Cont'd)

The estimated masses of As, Cd, Cu, Hg, Pb, and Zn distributed in a soil unit [kg/ha (10 cm)] and their aerial deposition rates (g/ha/3 months) as registered by the moss-monitoring stations around the Trail smelter

Hg												
			kg/ha/10 cm	**g/ha/3 months**								
Station		**Distance (km)**	**Masses per soil unit**	**Fall 97**	**Winter 98**	**Spring 98**	**Summer 98**	**Fall 98**	**Winter 99**	**Spring 99**	**Summer 99**	**Fall 99**
North -Centre - South	N6	25.7	0.10	N/D	N/D	N/D	N/D	0.03	N/D	0.29	0.00	N/D
	N5	23.5	0.06	N/A	N/A	N/D	N/D	0.06	0.13	0.25	N/D	N/D
	N4	11.3	0.08	0.09	0.03	0.11	0.03	0.34	N/D	0.50	0.24	N/D
	N3	7.7	0.08	0.07	N/D	N/D	0.10	0.20	0.27	0.42	0.07	N/D
	N2	2.9	0.08	0.32	0.02	0.08	0.33	0.52	0.31	0.46	0.20	0.03
	N1	1.8	0.09	0.73	0.34	1.11	0.84	1.24	1.47	1.55	1.01	0.40
	C1	1.5	0.09	0.83	0.82	2.11	1.35	1.15	2.97	2.92	1.21	0.20
	C5	1.5	0.77	9.57	3.68	4.83	2.92	3.16	19.77	8.65	12.73	1.52
	S1	2.7	0.99	1.87	0.70	1.20	1.07	1.52	2.86	3.00	3.64	0.78
	S2	4.5	0.38	0.88	0.39	0.81	0.63	0.69	1.20	0.73	0.23	0.40
	S3	7.4	0.06	0.06	N/D	0.09	0.03	0.10	0.20	0.66	0.24	N/D
	CG	11	2.08	0.63	0.31	0.37	0.43	0.68	0.48	1.20	0.77	0.23
	S4	14.1	0.32	0.05	N/D	0.01	N/D	N/D	0.06	0.32	0.27	N/D
	S5	20.7	0.06	N/D	N/D	N/D	0.10	0.10	0.27	0.22	0.07	N/D
West -East	C 20	12	0.03	N/D	N/D	N/D	N/D	N/D	0.10	0.29	0.07	N/D
	W4	6.8	0.20	N/A	N/A	N/D	N/D	N/D	0.23	0.22	N/D	N/D
	W3	2.8	0.40	0.02	0.03	0.06	0.02	N/D	0.27	0.53	0.27	N/A
	W2	2.6	0.55	0.79	0.31	0.75	0.45	1.00	3.63	1.21	0.91	0.33
	W1	2	N/A	1.71	1.64	1.58	0.72	2.11	12.31	4.52	2.89	1.12
	E1	2	0.11	N/A	N/A	0.47	0.32	0.27	0.69	1.11	1.00	N/D
	E2	13.4	0.09	N/D	N/D	N/D	N/D	N/D	N/D	0.18	0.00	N/D
	E3	13.5	0.09	N/A	N/A	N/D	N/D	0.03	N/A	0.18	0.00	N/D
Pb*												
North -Centre - South	N6	25.7	138	90	N/D	3	1	52	29	4	25	11
	N5	23.5	86	N/A	N/A	3	46	210	127	39	45	46
	N4	11.3	363	1085	313	273	359	1306	428	351	541	481
	N3	7.7	191	481	195	93	167	463	273	173	261	242
	N2	2.9	150	1862	536	391	563	1497	534	494	511	800
	N1	1.8	777	2252	945	1973	1915	3156	1905	1776	1319	1444
	C1	1.5	273	3110	2313	5562	2051	6630	8548	4449	2837	1617
	C5	1.5	1919	7439	5844	7888	3378	5324	8444	8536	8268	2412
	S1	2.7	1709	6213	3230	2555	2138	5622	3069	5402	6686	2909
	S2	4.5	531	3073	1812	1750	1527	1983	2043	2928	4688	551
	S3	7.4	143	468	437	273	183	209	299	506	436	48
	CG	11	587	896	530	552	350	1192	654	989	1143	161
	S4	14.1	287	310	189	78	87	308	224	233	326	57
	S5	20.7	164	115	N/D	34	18	66	211	43	109	N/D
West -East	C 20	12	168	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	W4	6.8	71	N/A	N/A	N/D	N/D	N/D	15	N/D	N/D	N/D
	W3	2.8	828	282	214	344	125	301	337	329	298	N/A
	W2	2.6	1019	682	901	1295	445	1224	1291	1354	1431	387
	W1	2	N/A	2946	3682	3147	1027	2910	3011	5196	3973	1439
	E1	2	327	N/A	N/A	1106	1216	1433	1752	2433	3309	618
	E2	13.4	80	N/D	N/D	N/D	N/D	38	N/D	N/D	N/D	N/D
	E3	13.5	113	N/A	N/A	N/D	N/D	24	N/A	9	19	N/D

Table 12 (Cont'd)

The estimated masses of As, Cd, Cu, Hg, Pb, and Zn distributed in a soil unit [kg/ha (10 cm)] and their aerial deposition rates (g/ha/3 months) as registered by the moss-monitoring stations around the Trail smelter

Zn*												
			kg/ha/10 cm	g/ha/3 months								
Station		Distance (km)	Masses per soil unit	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
North -Centre - South	N6	25.7	200	40	N/D	N/D	N/D	58	79	105	N/D	6
	N5	23.5	173	N/A	N/A	N/D	7	503	523	74	195	211
	N4	11.3	249	1903	1025	1168	1370	2843	1721	1371	1886	1565
	N3	7.7	243	1197	570	264	490	1310	791	421	773	794
	N2	2.9	395	4341	1843	1333	2003	4642	2062	1336	2510	2789
	N1	1.8	330	13631	4974	7529	8768	12945	9103	6756	7580	7263
	C1	1.5	275	4867	4998	11605	5275	7550	10081	5680	4916	2230
	C5	1.5	1287	40017	26147	33816	20099	24582	29920	37706	45402	18553
	S1	2.7	2448	12795	8306	10886	7530	13395	10553	12879	18596	7050
	S2	4.5	743	7778	5599	7155	5177	5631	6291	7124	11789	2044
	S3	7.4	207	1445	1802	1063	778	967	1204	1351	1902	146
	CG	11	549	4403	2663	3565	2856	4318	2695	5364	6165	1279
	S4	14.1	371	919	824	292	393	535	698	667	1240	188
	S5	20.7	152	163	N/D	44	5	10	727	14	270	N/D
West -East	C 20	12	128	N/D	N/D	N/D	N/D	N/D	3	N/D	341	N/D
	W4	6.8	140	N/A	N/A	N/D	17	N/D	34	N/D	N/D	N/D
	W3	2.8	330	1076	1121	1385	884	1266	1878	1276	1530	N/A
	W2	2.6	1559	3814	4525	6142	3722	6492	6321	5139	7823	3830
	W1	2	N/A	15334	15553	15018	7071	15318	11920	18482	18484	11917
	E1	2	351	N/A	N/A	4637	4191	3958	5518	5369	6462	1333
	E2	13.4	503	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
	E3	13.5	246	N/A	N/A	N/D	N/D	N/D	N/A	N/D	N/D	N/D

*Calculated deposition rates are obtained from the extrapolation of moss-monitoring concentration data.

N/D: Not detected

N/A: Not Available

Table 13

Per cent accumulation (or increase in initial mass) of As, Cd, Cu, Hg, Pb, and Zn in a soil unit (1 ha x 10 cm depth) determined at various sampling sites around the Trail smelter over the study period

As											
Station		Distance (km)	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
North-Centre-South	N6	25.7	-	-	-	-	-	-	-	-	-
	N5	23.5	-	-	-	-	-	-	-	-	0.01
	N4	11.3	0.02	0.01	0.01	0.01	0.02	-	0.01	0.01	0.04
	N3	7.7	0.01	-	-	-	0.01	-	0.00	0.01	0.01
	N2	2.9	0.05	0.03	0.01	0.02	0.03	0.01	0.03	0.02	0.07
	N1	1.8	0.10	0.08	0.18	0.12	0.09	0.08	0.18	0.05	0.08
	C1	1.5	0.04	0.06	0.21	0.05	0.06	0.12	0.10	0.03	0.13
	C5	1.5	0.06	0.05	0.07	0.03	0.02	0.05	0.06	0.04	0.03
	S1	2.7	0.04	0.02	0.02	0.01	0.02	0.01	0.03	0.03	0.03
	S2	4.5	0.04	0.04	0.04	0.02	0.02	0.02	0.04	0.04	0.02
	S3	7.4	-	-	-	-	-	-	-	-	-
	CG	11	0.03	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.01
	S4	14.1	0.01	0.00	-	-	-	-	-	0.00	0.00
	S5	20.7	-	-	-	-	-	-	-	-	-

Table 13 (Cont'd)

Per cent accumulation (or increase in initial mass) of As, Cd, Cu, Hg, Pb, and Zn in a soil unit (1 ha x 10 cm depth) determined at various sampling sites around the Trail smelter over the study period

Station		Distance (km)	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
West - East	C 20	12	-	-	-	-	-	-	-	-	-
	W4	6.8	-	-	-	-	-	-	-	-	-
	W3	2.8	-	0.00	0.01	-	-	-	-	-	-
	W2	2.6	0.01	0.01	0.02	0.00	0.00	0.01	0.01	0.01	0.01
	E1	2	-	-	0.04	0.02	0.03	0.03	0.05	0.05	0.04
	E2	13.4	-	-	-	-	-	-	-	-	-
	E3	13.5	-	-	-	-	-	-	-	-	-
Cd											
North -Centr e -South	N6	25.7	-	-	-	0.10	0.13	0.04	0.15	0.20	0.94
	N5	23.5	-	-	0.06	0.11	0.53	0.23	0.08	0.15	1.42
	N4	11.3	0.21	0.13	0.12	0.21	1.91	0.28	0.21	0.55	1.28
	N3	7.7	0.28	0.20	0.07	0.33	0.80	0.42	0.19	0.50	1.52
	N2	2.9	0.58	0.33	0.25	0.52	1.71	0.77	0.37	0.92	4.35
	N1	1.8	1.08	0.59	1.09	1.65	3.20	3.18	1.26	2.00	3.80-
	C1	1.5	0.76	1.20	2.15	1.16	3.47	4.52	1.86	3.16	1.55
	C5	1.5	0.97	1.13	1.20	0.84	1.80	2.00	1.47	3.73	1.41
	S1	2.7	0.31	0.34	0.26	0.23	0.75	0.60	0.57	1.51	0.70
	S2	4.5	0.45	0.54	0.45	0.44	0.82	0.83	0.72	2.23	0.51
	S3	7.4	0.16	0.26	0.12	0.13	0.24	0.39	0.21	4.01	0.21
	CG	11	0.32	0.25	0.31	0.24	0.54	0.33	0.47	1.00	0.24
	S4	14.1	0.08	0.12	0.04	0.07	0.16	0.13	0.10	0.42	0.16
	S5	20.7	0.03	-	-	-	0.07	0.21	-	0.23	0.09
West - East	C 20	12	-	2.80	-	-	-	-	-	0.20	-
	W4	6.8	-	-	0.13	0.05	-	0.16	-	-	-
	W3	2.8	0.15	0.15	0.17	0.15	0.30	0.41	0.19	0.47	-
	W2	2.6	0.20	0.41	0.48	0.29	0.98	0.99	0.46	1.37	0.70
	E1	2	-	-	0.93	0.92	1.98	1.95	1.59	3.04	1.69
	E2	13.4	0.10	-	-	-	0.01	-	-	-	-
	E3	13.5	-	-	-	-	0.02	-	0.08	0.50	0.05
Cu											
North -Centr e -South	N6	25.7	-	-	-	-	-	0.05	0.01	-	0.01
	N5	23.5	-	-	-	-	0.05	0.07	0.01	-	0.03
	N4	11.3	0.00	-	0.02	0.04	0.10	0.06	0.05	0.09	0.07
	N3	7.7	0.01	-	-	0.01	0.07	0.07	0.01	0.02	0.04
	N2	2.9	0.10	0.03	0.08	0.10	0.19	0.15	0.11	0.06	0.11
	N1	1.8	0.13	0.06	0.16	0.23	0.27	0.23	0.18	0.11	0.11
	C1	1.5	0.19	0.23	0.53	0.49	0.71	0.88	0.59	0.30	0.13
	C5	1.5	0.25	0.23	0.37	0.20	0.21	0.33	0.27	0.32	0.08
	S1	2.7	0.06	0.06	0.07	0.05	0.06	0.07	0.11	0.09	0.04
	S2	4.5	0.09	0.10	0.13	0.15	0.10	0.14	0.15	0.22	0.03
	S3	7.4	0.02	0.01	0.02	0.03	0.02	0.06	0.04	0.04	0.02
	CG	11	0.09	0.05	0.07	0.06	0.16	0.12	0.13	0.12	0.04
	S4	14.1	-	-	-	0.01	0.02	0.02	0.01	0.01	0.01
	S5	20.7	-	-	-	0.01	0.04	0.08	0.01	0.04	0.04

Table 13 (Cont'd)

Per cent accumulation (or increase in initial mass) of As, Cd, Cu, Hg, Pb, and Zn in a soil unit (1 ha x 10 cm depth) determined at various sampling sites around the Trail smelter over the study period

Station		Distance (km)	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
West - East	C 20	12	-	-	-	-	-	0.02	-	0.08	0.01
	W4	6.8	-	-	-	-	-	0.01	-	-	0.01
	W3	2.8	-	0.01	0.03	0.02	0.02	0.03	0.02	0.02	-
	W2	2.6	0.01	0.02	0.03	0.02	0.02	0.04	0.03	0.03	0.01
	E1	2	-	-	0.08	0.08	0.08	0.17	0.12	0.11	0.04
	E2	13.4	0.04	-	-	-	0.01	-	-	-	0.01
	E3	13.5	-	-	-	-	-	-	0.11	0.06	0.01
Hg											
North -Centre -South	N6	25.7	-	-	-	-	0.03	-	0.30	-	-
	N5	23.5	-	-	-	-	0.11	0.23	0.44	-	-
	N4	11.3	0.12	0.05	0.15	0.04	0.46	-	0.66	0.32	-
	N3	7.7	0.08	-	-	0.12	0.24	0.33	0.50	0.08	-
	N2	2.9	0.42	0.03	0.11	0.44	0.69	0.42	0.62	0.27	0.04
	N1	1.8	0.77	0.36	1.17	0.89	1.32	1.56	1.64	1.06	0.43
	C1	1.5	0.88	0.87	2.23	1.43	1.21	3.14	3.09	1.28	0.21
	C5	1.5	1.25	0.48	0.63	0.38	0.41	2.58	1.13	1.66	0.20
	S1	2.7	0.19	0.07	0.12	0.11	0.15	0.29	0.30	0.37	0.08
	S2	4.5	0.23	0.10	0.21	0.17	0.18	0.31	0.19	0.06	0.11
	S3	7.4	0.11	-	0.17	0.05	0.17	0.35	1.15	0.41	-
	CG	11	0.03	0.01	0.02	0.02	0.03	0.02	0.06	0.04	0.01
	S4	14.1	0.01	-	-	-	-	0.02	0.10	0.09	-
	S5	20.7	-	-	-	0.16	0.16	0.44	0.35	0.11	-
West - East	C 20	12	-	-	-	-	-	0.40	1.12	0.27	-
	W4	6.8	-	-	-	-	-	0.12	0.11	-	-
	W3	2.8	0.01	0.01	0.02	0.01	-	0.07	0.13	0.07	-
	W2	2.6	0.14	0.06	0.14	0.08	0.18	0.66	0.22	0.17	0.06
	E1	2	-	-	0.41	0.28	0.24	0.60	0.98	0.88	-
	E2	13.4	-	-	-	-	-	-	0.20	-	-
	E3	13.5	-	-	-	-	0.03	-	0.21	-	-
Pb											
Station		**Distance (km)**	**Fall 97**	**Winter 98**	**Spring 98**	**Summer 98**	**Fall 98**	**Winter 99**	**Spring 99**	**Summer 99**	**Fall 99**
North-Centre-South-	N6	25.7	0.07	-	-	-	0.04	0.02	-	0.02	0.01
	N5	23.5	-	-	-	0.05	0.25	0.15	0.05	0.05	0.05
	N4	11.3	0.30	0.09	0.08	0.10	0.36	0.12	0.10	0.15	0.13
	N3	7.7	0.25	0.10	0.05	0.09	0.24	0.14	0.09	0.14	0.13
	N2	2.9	1.24	0.36	0.26	0.38	1.00	0.36	0.33	0.34	0.53
	N1	1.8	0.29	0.12	0.25	0.25	0.41	0.25	0.23	0.17	0.19
	C1	1.5	1.14	0.85	2.04	0.75	2.43	3.13	1.63	1.04	0.59
	C5	1.5	0.39	0.30	0.41	0.18	0.28	0.44	0.44	0.43	0.13
	S1	2.7	0.36	0.19	0.15	0.13	0.33	0.18	0.32	0.39	0.17
	S2	4.5	0.58	0.34	0.33	0.29	0.37	0.38	0.55	0.88	0.10
	S3	7.4	0.33	0.31	0.19	0.13	0.15	0.21	0.36	0.31	0.03
	CG	11	0.15	0.09	0.09	0.06	0.20	0.11	0.17	0.19	0.03
	S4	14.1	0.11	0.07	0.03	0.03	0.11	0.08	0.08	0.11	0.02
	S5	20.7	0.07	-	0.02	0.01	0.04	0.13	0.03	0.07	-

Table 13 (Cont'd)
Per cent accumulation (or increase in initial mass) of As, Cd, Cu, Hg, Pb, and Zn in a soil unit (1 ha x 10 cm depth) determined at various sampling sites around the Trail smelter over the study period

Station		Distance (km)	Fall 97	Winter 98	Spring 98	Summer 98	Fall 98	Winter 99	Spring 99	Summer 99	Fall 99
West - East	C 20	12	-	-	-	-	-	-	-	-	-
	W4	6.8	-	-	-	-	-	0.02	-	-	-
	W3	2.8	0.03	0.03	0.04	0.02	0.04	0.04	0.04	0.04	-
	W2	2.6	0.07	0.09	0.13	0.04	0.12	0.13	0.13	0.14	0.04
	E1	2	-	-	0.34	0.37	0.44	0.54	0.74	1.01	0.19
	E2	13.4	-	-	-	-	0.05	-	-	-	-
	E3	13.5	-	-	-	-	0.02	-	0.01	0.02	-
Zn											
North -Centr e -South	N6	25.7	0.02	-	-	-	0.03	0.04	0.05	-	-
	N5	23.5	-	-	-	0.00	0.29	0.30	0.04	0.11	0.12
	N4	11.3	0.76	0.41	0.47	0.55	1.14	0.69	0.55	0.76	0.63
	N3	7.7	0.49	0.23	0.11	0.20	0.54	0.33	0.17	0.32	0.33
	N2	2.9	1.10	0.47	0.34	0.51	1.18	0.52	0.34	0.64	0.71
	N1	1.8	4.13	1.51	2.28	2.66	3.92	2.76	2.05	2.30	2.20
	C1	1.5	1.77	1.82	4.23	1.92	2.75	3.67	2.07	1.79	0.81
	C5	1.5	3.11	2.03	2.63	1.56	1.91	2.32	2.93	3.53	1.44
	S1	2.7	0.52	0.34	0.44	0.31	0.55	0.43	0.53	0.76	0.29
	S2	4.5	1.05	0.75	0.96	0.70	0.76	0.85	0.96	1.59	0.28
	S3	7.4	0.70	0.87	0.51	0.38	0.47	0.58	0.65	0.92	0.07
	CG	11	0.80	0.49	0.65	0.52	0.79	0.49	0.98	1.12	0.23
	S4	14.1	0.25	0.22	0.08	0.11	0.14	0.19	0.18	0.33	0.05
	S5	20.7	0.11	-	0.03	-	0.01	0.48	0.01	0.18	-
West - East	C 20	12	-	-	-	-	-	-	-	0.27	-
	W4	6.8	-	-	-	0.01	-	0.02	-	-	-
	W3	2.8	0.33	0.34	0.42	0.27	0.38	0.57	0.39	0.46	-
	W2	2.6	0.24	0.29	0.39	0.24	0.42	0.41	0.33	0.50	0.25
	E1	2	-	-	1.32	1.19	1.13	1.57	1.53	1.84	0.38
	E2	13.4	-	-	-	-	-	-	-	-	-
	E3	13.5	-	-	-	-	-	-	-	-	-

groundwater leaching of elements, and removal in surface runoff, can transport elements from their initial site of deposition (Henderson et al., 1998). The physical chemistry of the elements under investigation and the depositional conditions will cause some redistribution of elements (e.g., mobility under the given Eh/pH conditions, interactions with other elements, organic affinity, and susceptibility to sequestration by clays; Rose et al., 1979). For this reason, monitoring the postdepositional fate of elements in specific environments is necessary to assess the environmental impact in full.

Deposition of elements versus concentration of elements in soil

The relationship between the deposition data obtained from the moss-monitoring study and existing concentrations of elements in the soil from the same location was investigated by estimating the correlation coefficient between both data sets. Table 14 shows a good correlation between the two data sets for Pb, Zn, Cd, and for some periods, Cu. This indicates the possible effect of the airborne material on the surface soil in the study area. In contrast, there is a poor correlation between the moss and surface soil data for Hg and As. This indicates that the variation of Hg and As in soils is more closely related to soil type and other local factors than it is to the atmospheric deposition of elements due to the recent Trail smelter emissions. This is to be expected, since Hg and As are volatile elements and are least likely to deposit around the point source – they tend to remain in the atmosphere where they are subject to long-range transport (Rasmussen, 1998; Schroeder and Lane, 1988). In particular, the quantity of arsenic in soil may have been largely influenced by the presence of arsenopyrite in the country rocks of the region (Little, 1982; Höy and Andrew, 1991). For example, moss-monitoring station C20 experienced low atmospheric deposition of As throughout this study. However, the soil sample from the same location contained high concentrations of As, likely due to the

Table 14
Correlation coefficient* between the bulk concentrations of elements in the surface soil and elements deposited on moss-monitoring stations during the various study periods

	As	Cd	Cu	Hg	Pb	Zn
Fall 1997	-	0.79	-	-	0.84	-
Winter 1998	-	0.77	0.58	-	0.84	0.58
Spring 1998	-	0.67	-	-	0.69	0.55
Summer 1998	-	0.68	-	-	0.76	0.56
Fall 1998	-	0.77	-	-	0.67	0.64
Winter 1999	-	0.69	-	-	0.58	0.56
Spring 1999	-	0.82	0.57	-	0.81	0.58
Summer 1999	-	0.84	0.59	-	0.83	0.64
Fall 1999	-	0.69	0.54	-	0.79	0.59

* Only correlation coefficients significant at the 99% confidence limit (0.542; *n=21*), or higher, are reported.

natural chemistry of the soil, surficial deposits, and underlying geology of the area, or past mining and smelting activities in the region (Table 12a-f).

This indicates that in order to determine input from anthropogenic sources, examining soil samples alone, without additional supporting evidence from atmospheric deposition monitoring (moss-monitoring, mechanical filters), can result in erroneous interpretations.

COMPARING THE MOSS-MONITORING DATA WITH OTHER MONITORING SYSTEMS

The ambient level of metals in atmosphere in the vicinity of the Trail smelter is being monitored by a high-volume air sampler (mechanical filters) as part of Teck Cominco's environmental study. The available data for elements captured by mechanical filters at seven different locations around the Trail smelter were compared to the data obtained by the moss-monitoring stations at the same locations.

The comparison between these two methods was carried out by plotting the regression line and subsequently calculating the correlation coefficient between the two data sets. The results of such a comparison for Pb and Zn are shown in Figures 17a-f and 18a-f, respectively. A good correlation exists between the mechanical filter data and the moss-station data, as evidenced by a linear relationship with a relatively high correlation coefficient for some of the study periods. Mechanical filter data for summer periods were not available.

The quality of the relationship between the mechanical filter data and that from moss-monitoring varies seasonally. This is because of the different nature of each measurement. Mechanical filters measure the ambient level of elements (particles) in air, including those that settle and those that do not settle, whereas the moss-monitoring system determines only the deposition of settleable portion of elements (particles) in the region. Hence, a factor such as meteorological conditions can result in the two types of monitoring giving different results. For example, higher precipitation will cause higher deposition of suspended aerosol particles present in the atmosphere by wet deposition process. The suspended particles are leached out of the atmosphere and result in a reduction of the ambient level of particles and associated elements in the air. In this case, the moss-monitoring stations will record higher deposition of settleable elements, while the mechanical filters record less ambient levels of elements in air.

CONCLUSIONS

This study investigated the aerial deposition and accumulation of As, Cd, Cu, Hg, Pb, and Zn on surface soil in the vicinity of a major lead-zinc smelter in Trail, British Columbia. The following conclusions may be drawn.

In general, deposition of the elements studied is greatest in the vicinity of the smelter complex, and decreases with an increase in distance. Deposition of the elements extends to greater distances north-northwest and south-southeast of the smelter than to the east or west, correlating well with prevailing wind direction and the orientation of the valley in which the smelter is located.

The depositional pattern of the studied elements in the study area is controlled by a number of factors, such as meteorological conditions (prevailing wind direction and annual precipitation), physiography (topography, valley shape, and orientation) and in-process activities at the smelter (production level, emission control efficiency, and the geochemistry of feed). Production levels at the smelter and emissions from the stack (as related to emission control efficiency), are however, the most significant contributors to the observed concentrations of these elements around the smelter.

A theoretical diffusion model for evaluating the contribution of particulate elements originating from the stack emissions and secondary sources indicates that Pb and Zn deposition in the study area has been largely affected by secondary sources. The effects of the secondary sources decrease significantly outside the boundary of the smelter as indicated by the rapid decline of the elemental profile. Hence, at a distance of more than 1.5 km, stack-emitted material becomes the major contributor to elemental deposition. There are number of in-process and meteorological factors that may affect the relative contribution of stack versus secondary sources as is

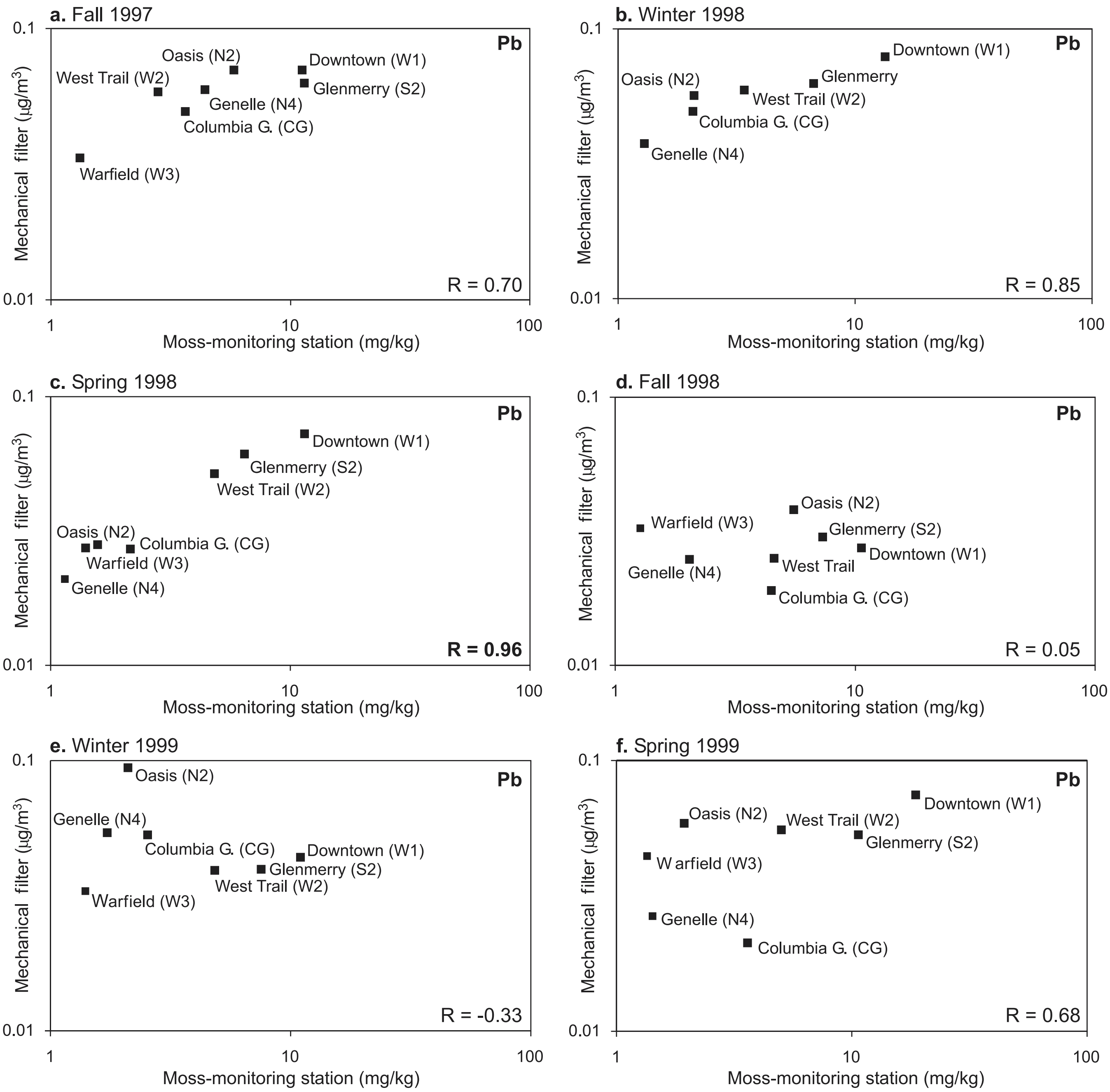

Figure 17 a–f. *Relationship between the Pb data collected at moss-monitoring stations in the Trail area and mechanical filters at the same locations during (a) fall 1997, (b) winter 1998, (c) spring 1998, (d) fall 1998, (e) winter 1999, and (f) spring 1999. Correlation coefficients (R) significant at the 95% confidence limit, or higher, are bolded.*

indicated by the seasonal variation in their per cent contribution.

The morphology and chemical composition of the stack-emitted particles were found to be remarkably different from the particles originating from secondary sources. This difference, which results from the in-process activities of the smelter, might be a factor in determining the distribution behavior of the elements from each source.

The results of this study also provide a better understanding of trace element fluxes in surface soils in the vicinity of a base metal smelter. This approach can be used to determine accumulation and subsequently the increase in quantity of trace elements in soil over a given period of time, regardless of the postdepositional remobilization of elements due to biological activities, hydrological effects, or any other interaction between the deposited emissions and the surface soil.

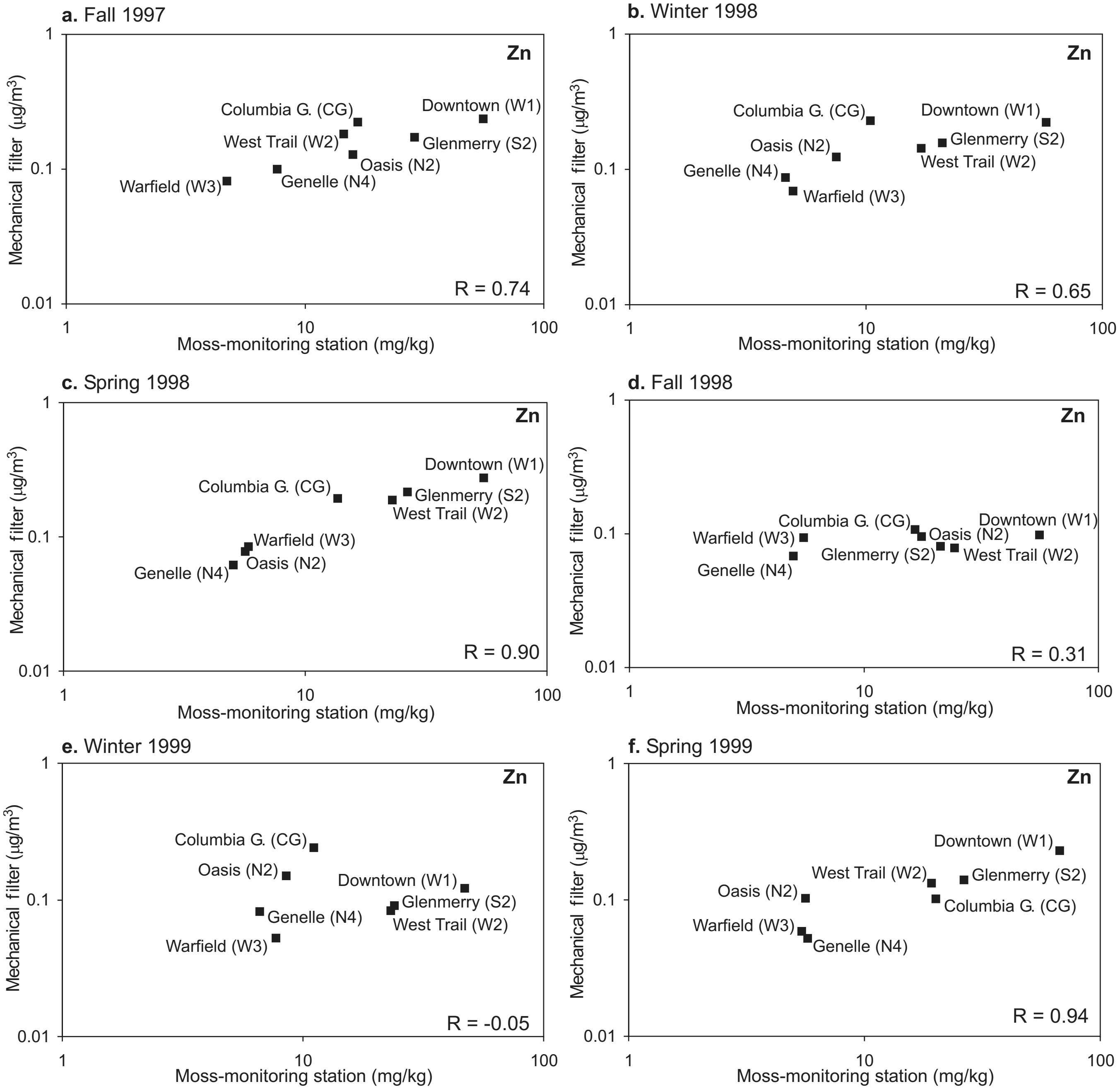

Figure 18 a–f. *Relationship between the Zn data collected at moss-monitoring stations in Trail area and mechanical filters at the same locations during (a) fall 1997, (b) winter 1998, (c) spring 1998, (d) fall 1998, (e) winter 1999, and (f) spring 1999. Correlation coefficients (R) significant at the 95% confidence limit, or higher, are bolded.*

The good correlation between Cd, Cu, Pb, and Zn in the surface soil and their atmospheric deposition rates around the smelter suggest the possible effect of the airborne particulate elements on the geochemistry of the soil in the Trail region. Hg and As do not show a good correlation between deposition rates and soil concentrations, implying that the quantity of these elements is controlled by local soil factors rather than aerial deposition.

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