



GEOLOGICAL SURVEY OF CANADA

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**Biogeochemical survey using lodgepole pine bark:
Mount Milligan, Central British Columbia
(parts of 93N/1 and 93O/4)**

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1996



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CONTENTS

Introduction 1

Description of the Survey Area 2

Regional Geology and Mineralization 2

Surficial Geology 4

Sample Collection, Preparation and Analysis 5

Map Production and Data Handling 10

Element Distribution Maps 10

 Transparent Overlay 10

 Distribution Maps of Elements Determined by INAA 10

 Gold (Au) 10

 Arsenic (As) 11

 Barium (Ba) 11

 Bromine (Br) 11

 Calcium (Ca) 11

 Cerium (Ce) and Other Rare Earth Elements (Eu, La, Lu, Nd, Sm, Tb, Yb) 11

 Cobalt (Co) 12

 Chromium (Cr) 12

 Cesium (Cs) 12

 Europium (Eu) 12

 Iron (Fe) 12

 Hafnium (Hf) 12

 Potassium (K) 12

 Lanthanum (La) 13

 Lutetium (Lu) 13

 Sodium (Na) 13

 Neodymium (Nd) 13

 Rubidium (Rb) 13

 Antimony (Sb) 13

 Scandium (Sc) 13

 Samarium (Sm) 13

 Strontium (Sr) 13

 Thorium (Th) 14

 Uranium (U) 14

 Ytterbium (Yb) 14

 Zinc (Zn) 14

 Distribution Maps of Elements Determined by ICP-ES 14

 Aluminum (Al) 14

 Boron (B) 14

 Cadmium (Cd) 15

 Copper (Cu) 15

 Lithium (Li) 15

 Magnesium (Mg) 15

 Manganese (Mn) 16

 Molybdenum (Mo) 16

 Nickel (Ni) 16

 Phosphorus (P) 16

 Lead (Pb) 16

 Vanadium (V) 16

Discussion	16
Notes on the Data Listings (Appendices A and B)	17
Acknowledgements	17
References	18
Appendices	

FIGURES

Fig. 1	Survey Area with Respect to National Topographic System (NTS) Map Sheets	Facing p.1
Fig. 2	Simplified Geology of Mt. Milligan Survey Area	3

TABLES

Table 1	Standards V2 and V6c - Concentrations in Ash, Determined by INAA and ICP-ES	6
Table 2	Laboratory Duplicates - Concentrations in Ash, Determined by INAA and ICP- ES	7
Table 3	Determination Limits for Elements Analyzed by INAA and ICP-ES	9
Appendix A - Data Listings		A1
Appendix B - Statistical Summary		B1
Appendix C - Element Distribution Maps and Overlay of Sample Sites and Geology: (in envelope)		

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INTRODUCTION

This Open File contains data from a biogeochemical survey in the Mt. Milligan area of central British Columbia. Samples of outer bark from lodgepole pine (*Pinus contorta*) were collected on three occasions: as part of an orientation survey by one of us (CED) in 1991; in conjunction with a regional till sampling program (Sibbick *et al.*, 1996) in the summer of 1991; and a small follow-up survey in the Philip Lakes area in September, 1995 (CED).

Data listings, statistical summaries, a geology and sample location map, and element distribution maps are presented. The maps show element concentrations in the ash of outer bark scales from lodgepole pine. Instrumental neutron activation analysis (INAA) was used to determine 36 elements, of which 27 were in sufficient concentration to be detected and quantified. In addition, data are included for 12 elements determined by inductively-coupled plasma emission spectrometry (ICP-ES). All data reported are concentrations in ash remaining after controlled ignition at 470°C. For bark of lodgepole pine, the ashing process concentrates the elements with little or no loss of elements except for a few of high volatility (e.g. Br and Hg).

The interpretation of biogeochemical data should be undertaken with due consideration to chemical requirements and tolerances of plants. Plants require certain elements for their survival, and they have the ability to concentrate metals by scavenging them from the substrate. Zinc, for example, is needed for plant metabolism. Therefore, subtle differences in Zn concentrations between sample sites are more likely to reflect the health of the plant than significant differences in the chemistry of the substrate. However, major differences in Zn concentrations may reflect the presence of Zn mineralization. By contrast, plants also have the ability to exclude those elements that would have a detrimental effect on their growth or health. This 'barrier' mechanism (Kovalevskii, 1979) may result in only weak enrichment of an element in a tree from an environment where that element may be enriched in the substrate. As a consequence, for some elements there may be no simple relationship between the chemistry of a tree tissue and the chemistry of the soil and underlying parent material. Brief discussion is provided on the role of each element in plant function in order to assist in data interpretation. Biogeochemistry is a complex science involving the interaction of many organic and inorganic processes. However, careful and systematic collection and preparation of plant samples can provide cost-effective new insight into the chemistry of the substrate and its groundwaters.

This report presents data from the 134 sites at which lodgepole pine bark samples were collected. Except for close-spaced samples in areas of special interest (e.g. zones of known mineralization), samples were collected on as even a grid as was practically possible, attaining an average sample density of approximately 1 site per 1 km². The data listed in Appendix A are available in digital form on a CD-ROM as part of a multi-media data set (Williams, 1996), and can be obtained also as a separate MS-DOS (IBM-PC) 3.5" 1.44 Mb diskette, which can be read by any DBASE-compatible software, and as an ASCII comma delimited file. They can be obtained from:

GSC Bookstore
Geological Survey of Canada
601 Booth St.
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DESCRIPTION OF THE SURVEY AREA

The Mount Milligan survey area, centred at latitude 55° 07'N and longitude 124° 00'W, is located approximately 150 kilometres northwest of Prince George in central British Columbia (Fig. 1). The area has limited access by logging road from Fort St. James and from Windy Point on Highway 97. There is a network of exploration roads in the western third of the area near the Mount Milligan deposits (MBX and Southern Star), but access to the eastern two-thirds of the area is restricted to a few roads of limited extent.

Located on the Nechako Plateau, the study area is characterised by a relatively flat to hummocky plain at 1000 metres elevation, bounded on the west and east by north trending ridges of 1300 to 1500 metres elevation. Mount Milligan, eight kilometres northwest of the Mount Milligan deposits, rises to an elevation of 1508 metres.

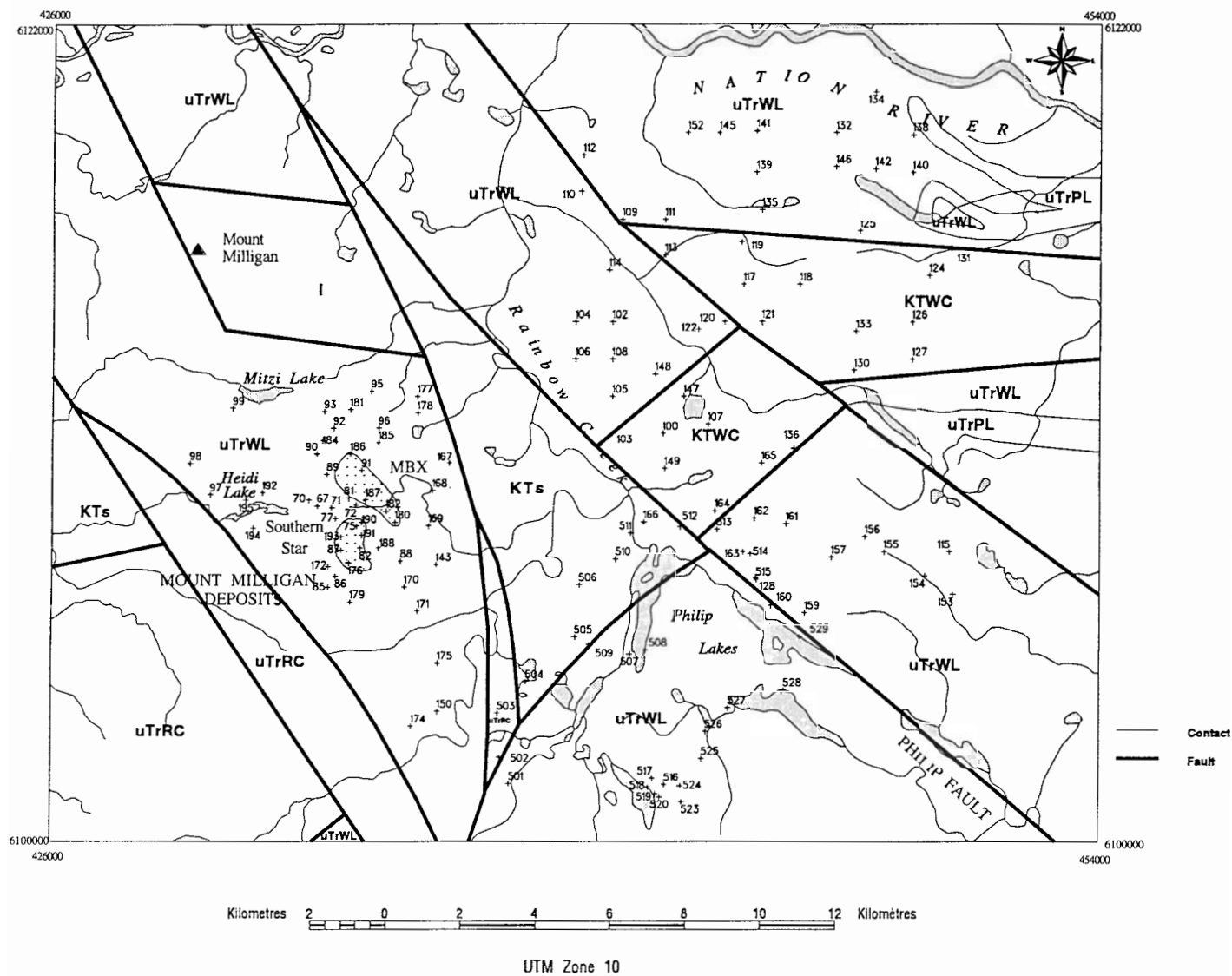
The area lies within the sub-boreal pine-spruce biogeoclimatic zone (Pojar *et al.*, 1987). The cold, dry climate supports a forest cover of generally low productivity. The extensive fire history of the area has resulted in many even-aged lodgepole pine stands. The dominant cover is lodgepole pine, with minor white spruce (*Picea glauca*), black spruce (*Picea mariana*), trembling aspen (*Populus tremuloides*), and paper birch (*Betula papyrifera*). In the understory there are sitka alder (*Alnus sinuata*), glandular birch (*Betula glandulosa*), various species of willow (*Salix spp.*), blueberries (*Vaccinium spp.*), lichens, feather mosses and grasses.

REGIONAL GEOLOGY AND MINERALIZATION (Fig. 2)

Takla Group rocks of the Quesnel Terrane underlie the Mount Milligan area (Nelson *et al.*, 1991). The Quesnel Terrane is an early Mesozoic island-arc sequence bounded on the west by oceanic rocks of the Cache Creek Terrane and on the east by oceanic rocks of the Slide Mountain Terrane. Metamorphic rocks of the Wolverine Complex are also in contact with the eastern boundary of the Takla Group/Quesnel Terrane (Struik, 1992). The Takla Group is Upper Triassic in age, consisting of rocks of sedimentary, extrusive volcanic, pyroclastic and epiclastic origin. Numerous coeval plutons, up to Early Jurassic age, intrude the Takla Group.

The Mount Milligan deposits are centred on Early Jurassic crowded plagioclase-porphyrific monzonite intrusions known as the MBX and Southern Star stocks (Nelson *et al.*, 1991). These, and numerous smaller stocks, intrude Upper Triassic Takla Group augite (+/- plagioclase) porphyry agglomerate, trachyte breccias and flows, and bedded epiclastic sediments of the Witch Lake Formation. Directly east of the intrusions, the Philip fault (also known as the Great Eastern fault) juxtaposes Takla Group rocks against Eocene continental sediments within an extensional basin (Nelson *et al.*, 1991). The eastern half of the study area is underlain by Witch Lake Formation, as well as basalt, diorite and locally limestone of the Philip Lakes succession (Struik, 1992). Quartzofeldspathic gneiss, schist and granite pegmatite of the Cretaceous-Tertiary Wolverine Metamorphic Complex outcrop in the east and northeast (Struik, 1992).

Alteration associated with the deposits comprises a crudely zoned potassic core centred on the intrusions (DeLong *et al.*, 1991), and surrounded by an east-west elongate 3.0 by 4.5 kilometre propylitic halo. Mineralization consists primarily of disseminated and fracture-filling chalcopyrite and pyrite. Lesser quantities of bornite are present within the potassic alteration zone. Approximately 70% of the mineralization is hosted by the Witch Lake volcanics with the remaining 30% in the monzonite intrusives. Gold is associated with chalcopyrite, pyrite and bornite and occurs as small grains up to 100 μm in diameter along sulphide grain boundaries and microfractures in pyrite (Faulkner *et al.*, 1990). Both gold and chalcopyrite are associated with the potassic alteration zone (DeLong *et al.*, 1991). Reserves of the deposit are estimated at 298.4 million tonnes grading 0.45 gram per tonne gold and 0.22% copper (Schroeter, 1994).



LEGEND

CRETACEOUS-TERTIARY

- KTs Eocene-Oligocene: basalt, volcanic wacke and fossiliferous volcanic ash-rich mudstone, sandstone
- KTWC Cretaceous-Tertiary Wolverine Complex: quartzo-feldspathic gneiss, schist, pegmatite, amphibolite, calc-silicate and marble

UPPER TRIASSIC (-JURASSIC?) - TAKLA GROUP

- uTrWL Witch Lake Formation and Philip Lakes succession correlatives: augite porphyry agglomerate, volcanic breccia, lapilli tuff and epiclastic sediments; local trachyte flows and tuff-breccias
- uTrPL Philip Lakes succession limestone
- uTrRC Rainbow Creek Formation: grey slate, thin-bedded siltstone, minor volcanoclastic sediments

INTRUSIVE ROCKS - (I)

Late Triassic-Early Jurassic: coarse grained, equigranular diorite/monzonite intruded by Late Cretaceous-Early Tertiary(?) equigranular, coarse grained granite with local rhyodacite and dacite.

MBX and Southern Star stocks: crowded plagioclase porphyritic monzonite (Late Triassic-Early Jurassic)

Fig. 2: Simplified geology of Mt. Milligan survey area, compiled from Nelson *et al.* (1991), and Struik (1992), with modifications by J. Nelson (personal communication, 1994)

Subparallel polymetallic sulphide veins, containing disseminated to massive pyrite and chalcopyrite, radiate outward from the MBX stock in the propylitic alteration zone. The best-developed veins are 0.3 to 3.0 metres thick and contain 3 to 100 grams per tonne gold, 0.2 to 10% copper, 1 to 3% sphalerite, and traces of arsenopyrite and galena (Faulkner *et al.*, 1990).

SURFICIAL GEOLOGY

The last glacial event in the Mount Milligan region occurred during the Late Wisconsinan (Fraser Glaciation) between 25,940 \pm 380 years B.P. and 10,100 \pm 90 years B.P. (Clague, 1981). Regional ice movement during this event was primarily to the northeast, as interpreted from ice-flow indicators such as well-developed striae scoured into bedrock and drumlinoid features developed in unconsolidated sediments. This observation of regional flow is in accordance with earlier studies to the north, west and south of the Milligan area (Armstrong, 1949), and more recently by Plouffe (1991, 1992) in the Stuart and Fraser lakes area to the southwest. In the McLeod Lake region to the southeast, Struik and Fuller (1988) mapped the extent of glacial lake deposits and noted the presence of mineralized clasts in morainal deposits.

Surficial sediments of the study area include till, glaciofluvial and fluvial sand and gravel, glaciolacustrine sand, silt and clay, colluvium and organic materials (Kerr, 1991). Two surficial units predominate: an extensive morainal (till) blanket and large glaciofluvial outwash complexes. Till was deposited during the last glacial episode and is commonly hummocky and forms drumlins. It consists of a dense matrix-supported diamicton composed of very poorly sorted, angular to well-rounded pebbles to cobbles in a sand-silt-clay matrix. These sediments are more continuous in the eastern half of the map area, from south of Philip Lakes to north of Nation River. Flow was toward the northeast during full glacial conditions. South of Nation River, a gradual change in flow direction towards the east is indicated by drumlinoid features.

Large concentrations of glaciofluvial sand and gravel dominate the central part of the study area along the axis of Rainbow Creek, and the Nation River valley to the north and to the west of the Mount Milligan deposits. These outwash-sediment complexes consist of sinuous esker ridges up to 10 kilometres long, kame deposits and a series of broad overlapping outwash fans deposited by glacial meltwater during ice retreat. They represent the end product of a long period of glacial and fluvial erosion, transportation and reworking of many types of surficial sediments. Within the narrow Nation River valley, glaciofluvial sediments are locally overlain by up to 20 metres of glaciolacustrine silt and clay. During ice retreat, these sediments were deposited in a glacial lake with an elevation of approximately 850 metres. Colluvial sediments derived from till and weathered bedrock form a veneer over steep hill sides and valley walls in the highlands north and south of the Mount Milligan deposits. Highlands to the northeast of the Philip Lakes are also mantled by colluvial sediment.

Drift thickness is highly variable, ranging from less than 1 metre on rocky highlands to over 80 metres in the Rainbow Creek area (Kerr and Sibbick, 1992). Thicknesses in excess of 100 metres are common directly east of the Mount Milligan deposits (Kerr and Bobrowsky, 1991). Ronning (1989) has reported overburden depths in excess of 200 metres in the Nation Lakes area to the west.

Humo-ferric podzol is the main soil type of the region. Modifications of the original till substrate by soil-forming processes extend to an average depth of approximately 0.5 metre. Oxidation of the parent materials generally extends to a depth of 2 metres.

SAMPLE COLLECTION, PREPARATION AND ANALYSIS

The outer bark of lodgepole pine was collected by scraping about 50 g of loose scales into a standard 'kraft' paper soil bag. A paint scraper proved to be an effective tool for removing the bark scales. Care was taken not to include the inner bark because its composition is substantially different from that of the outer bark. Whereas there are seasonal variations in the chemistry of twigs and leaves, the chemistry of the outer bark does not change during the course of the year. This is because the bark is dead tissue, and therefore can be collected at any time, and samples from different survey periods can be integrated without the need to normalize data to a common time datum.

Approximately 50 g of dry bark was weighed into aluminum trays. The trays were placed in a pottery kiln, and the temperature slowly raised (over 2 - 3 hours) to 470°C. After a further 12 hours at this temperature, no charcoal remained and the bark was reduced to approximately 1 g of ash. Half was accurately weighed and compacted into small polyethylene vials, suitable for instrumental neutron activation analysis (INAA), and submitted for the determination of 36 elements at Activation Laboratories Ltd., Ancaster, Ontario. Maps are provided for 26 of these elements. Of the remaining 10 elements: the data for Mo were good, but not as precise as those obtained by ICP-ES, therefore data by the latter method were plotted; similarly, the data for Ni were better by ICP-ES; for Ag, Se and W only a few sites yielded concentrations slightly above the detection limit for these elements of 2 ppm, and the precision of the data was poor. A few sites yielded detectable levels of Ta (>0.5 ppm): these data are included in the elemental listings, but the precision was considered inadequate to warrant plotting distribution maps or generating statistics. Concentrations of Hg, Ir, and Tb were all below the detection levels of 1 ppm, 2 ppb, and 0.5 ppm, respectively. Detection levels for Sn by INAA vary with the matrix composition of the sample, and are commonly between 50 and 100 ppm Sn: no sample yielded concentrations above detection by this method.

The remaining half of the ash sample was submitted to Min-En Laboratories Ltd., Vancouver, British Columbia, for multi-element analysis by inductively coupled plasma emission spectrometry (ICP-ES), following an aqua regia digestion. For most elements this extraction is 'total', although for some (e.g. Al, B) it is only partial. The analytical precision was acceptable for the 12 elements for which data are provided (Tables 1 and 2).

Appropriate standards and duplicates were inserted to ensure quality control. The precision varied among elements and with element concentration. Standard V2 (GSC vegetation ash standard) was included with the first batches of samples, submitted for analysis in 1991. Subsequently this standard has all been used, and it has been replaced by GSC standard ash V6c - mostly pine twigs. From the data listings of Table 1, it is evident that there is consistently good precision for most elements. Also, from many similar analyses of these standard samples by several laboratories the data have been found to be accurate. Of the elements reported here, most samples contained levels substantially higher than detection limits, thereby providing analytical precision generally better than +/- 10%. Table 1 lists data obtained on standard ash samples inserted randomly within each batch of 20 samples. Table 2 lists analyses of duplicate pairs of ash samples, each pair inserted at random within each batch of 20 samples, and shows excellent replication for most elements in most samples. The classic 'nugget' effect of Au occurs in a few samples. Table 3 shows the determination (lowermost detection) limits quoted for each element by the analytical laboratories. In the few instances where element concentrations were not detectable, a value of half the determination limit was substituted for statistical calculations.

Table 1: Standards V2 & V6c - Concentrations in Ash Determined by INAA & ICP-ES

Standard	INAA																										Zn ppm
	Au ppb	As ppm	Ba ppm	Br ppm	Ca %	Ce ppm	Co ppm	Cr ppm	Cs ppm	Eu ppm	Fe %	Hf ppm	K %	La ppm	Lu ppm	Na ppm	Nd ppm	Rb ppm	Sb ppm	Sc ppm	Sm ppm	Sr ppm	Ta ppm	Th ppm	U ppm	Yb ppm	
V2	15	1.0	2900	22	27.0	7	4	29	2.7	<0.02	1.50	1.5	7.40	4.5	0.07	5910	<5	200	1.0	1.1	0.5	1500	<0.5	1.0	0.6	0.26	2600
V2	14	2.0	2600	22	28.0	8	4	29	2.6	<0.02	1.68	1.7	7.92	4.7	<0.05	5960	<5	200	1.0	1.1	0.5	1400	<0.5	1.0	0.6	0.22	2600
V2	15	1.0	2700	22	27.3	7	4	29	2.6	0.14	1.17	1.7	7.26	4.2	0.05	6320	<5	210	1.0	1.1	0.6	1300	<0.5	1.0	0.8	0.25	2600
V2	15	1.0	2900	22	28.5	10	4	29	3.1	<0.02	1.03	1.5	8.69	4.4	<0.05	6000	<5	220	1.0	1.2	0.6	1300	<0.5	1.0	0.7	0.31	2600
V2	15	1.8	2700	19	25.3	7	5	38	2.8	0.18	1.86	1.3	6.81	4.0	<0.05	5710	<5	200	1.2	1.1	0.5	1500	<0.5	1.2	0.7	0.18	2400
V2	14	1.7	2700	17	26.0	7	4	30	2.7	<0.02	1.57	1.3	7.05	3.8	<0.05	5500	<5	180	1.3	1.2	0.5	1500	<0.5	1.0	0.5	0.16	2500
V2	14	2.7	2900	21	29.8	8	4	30	2.9	0.17	1.15	1.6	7.34	4.6	<0.05	5540	<5	230	1.2	1.2	0.6	1400	<0.5	1.2	0.8	0.33	2400
V2	14	1.8	2700	21	29.8	8	4	31	2.7	<0.02	1.10	1.6	7.79	3.8	0.06	5710	<5	200	1.2	1.1	0.5	1300	<0.5	1.1	0.5	0.23	2400
V2	12	2.0	2700	20	29.9	9	4	30	3.0	<0.02	1.72	1.3	7.58	4.5	<0.05	6360	<5	210	1.2	1.1	0.6	1500	<0.5	1.3	0.9	0.27	2400
V6c	13	6.6	400	13	15.7	44	9	61	<0.5	0.89	1.67	5.5	3.11	20	0.28	11600	23	45	1.1	4.4	3.0	890	<0.5	3.0	1.2	1.76	710
V6c	15	7.8	390	11	14.7	42	9	67	0.9	0.71	1.77	4.9	3.26	20	0.31	12000	24	43	1.2	4.4	3.0	1100	<0.5	3.0	1.5	1.62	790
V6c	20	6.4	420	11	15.1	40	8	63	0.7	0.73	1.63	5.2	4.28	19	0.31	11400	21	41	1.0	4.2	2.9	970	<0.5	3.3	1.0	1.66	890
V6c	17	6.4	400	11	14.5	41	7	67	1.3	0.81	1.71	5.2	3.22	19	0.30	11600	21	50	1.0	4.3	3.3	690	<0.5	2.6	0.9	1.41	640

ICP-ES

Standard	Al	B	Cd	Cu	Li	Mg	Mn	Mo	Ni	P	Pb	V
	pct	ppm	ppm	ppm	ppm	%	ppm	ppm	ppm	%	ppm	ppm
	0.01*	2	0.2	1	2	0.01	1	1	1	0.001	3	2
V2	1.923	168	<0.2	147	<2	3.148	17374	2	40	1.005	419	16.1
V2	0.792	169	2.4	129	<2	3.259	17861	3	45	1.047	421	15.4
V2	0.802	153	3.5	122	2	3.248	18054	3	44	1.061	479	15.7
V2	0.767	172	2.2	115	<2	3.145	17567	3	42	1.023	322	14.5
V2	0.703	166	2.3	115	<2	2.996	17054	3	40	1.002	273	13.9
V2	0.742	173	1.6	114	<2	3.117	17577	3	42	1.036	285	14.3
V2	0.724	175	1.5	122	<2	3.122	17663	2	36	1.018	272	14.4
V2	0.721	173	3.4	123	<2	3.127	17621	4	42	1.027	282	14.9
V2	0.712	166	2.8	110	2	3.067	16993	4	41	0.999	284	14.2
V6c	1.190	152	3.8	128	5	2.230	676	8	54	0.604	240	24.0
V6c	1.180	145	3.7	131	4	2.140	672	5	54	0.589	234	23.0
V6c	1.250	157	2.3	139	5	2.220	739	5	60	0.663	239	26.0
V6c	1.260	166	3.7	147	5	2.300	698	7	56	0.712	242	26.0

* First row of data shows determination limits

Table 2 (cont'd): Laboratory Duplicates - Concentrations in Ash Determined by INAA & ICP-ES

ICP-ES

Sample Number	Al pct 0.01*	B ppm	Cd ppm	Cu ppm	Li ppm	Mg %	Mn ppm	Mo ppm	Ni ppm	P %	Pb ppm	V ppm
		2	0.2	1	2	0.01	1	1	1	0.001	3	2
ICP91/1553	2.94	175	6.0	139	<2	1.45	15798	3	40	0.736	84	13
ICP91/1554	2.61	135	5.5	125	<2	1.26	13927	3	34	0.636	62	11
ICP91/1575	1.98	43	<0.2	46	4	9.46	4210	<1	747	0.147	<3	64
ICP91/1576	1.93	41	<0.2	47	4	9.37	4665	<1	751	0.154	3	62
ICP91/1598	2.56	56	5.5	107	6	1.18	9104	2	35	0.383	61	74
ICP91/1599	2.69	61	3.3	114	6	1.24	9879	2	37	0.420	65	76
ICP91/1624	2.72	53	6.8	197	4	1.39	5936	3	27	0.729	43	54
ICP91/1625	2.47	47	8.0	181	4	1.28	5503	2	25	0.667	40	50
ICP91/1644	1.11	46	20.7	87	<2	0.92	8222	2	24	0.612	44	14
ICP91/1645	1.11	47	16.3	89	<2	0.89	8118	3	23	0.624	43	15
ICP91/1684	1.93	43	1.1	104	6	1.14	2326	<1	20	0.344	31	71
ICP91/1685	2.01	45	1.3	106	6	1.16	2383	<1	21	0.342	30	75
ICP91/1717	2.77	64	4.0	173	10	1.77	5079	2	37	0.602	47	89
ICP91/1718	2.57	60	2.5	163	9	1.68	4765	<1	36	0.576	44	81
ICP91/1741	0.64	78	1.2	130	2	0.86	4529	2	20	0.375	30	34
ICP91/1742	0.60	78	1.1	124	2	0.85	4565	<1	19	0.371	30	32
ICP91/1761	0.44	119	4.0	96	<2	0.94	17565	2	39	0.661	51	17
ICP91/1762	0.41	126	3.4	93	<2	0.97	18586	3	39	0.638	54	15
ICP95/1329	1.24	113	15.2	123	4	1.19	1658	2	20	0.352	216	43
ICP95/1330	1.18	114	14.0	117	4	1.17	1624	<1	18	0.342	85	40
ICP95/1339	2.62	159	29.8	132	<2	1.17	7512	<1	8	0.543	16	<2
ICP95/1340	2.79	165	30.5	141	<2	1.24	8026	<1	8	0.583	6	<2

* First row of data shows determination limits

Table 3: Determination Limits for Elements Analyzed by INAA & ICP-ES

INAA

Element		Units of Measure	Determination Limit
Gold	Au	ppb	5
Arsenic	As	ppm	0.5
Barium	Ba	ppm	10
Bromine	Br	ppm	1
Calcium	Ca	%	0.2
Cerium	Ce	ppm	3
Cobalt	Co	ppm	1
Chromium	Cr	ppm	1
Cesium	Cs	ppm	0.5
Europium	Eu	ppm	0.02
Iron	Fe	%	0.05
Hafnium	Hf	ppm	0.5
Potassium	K	%	0.05
Lanthanum	La	ppm	0.1
Lutetium	Lu	ppm	0.05
Sodium	Na	ppm	10
Neodymium	Nd	ppm	5
Rubidium	Rb	ppm	5
Antimony	Sb	ppm	0.1
Scandium	Sc	ppm	0.1
Samarium	Sm	ppm	0.1
Strontium	Sr	ppm	300
Tantalum	Ta	ppm	0.5
Thorium	Th	ppm	0.1
Uranium	U	ppm	0.1
Ytterbium	Yb	ppm	0.05
Zinc	Zn	ppm	20

ICP-ES

Element		Units of Measure	Determination Limit
Aluminum	Al	pct	0.01
Boron	B	ppm	2
Cadmium	Cd	ppm	0.2
Copper	Cu	ppm	1
Lithium	Li	ppm	2
Magnesium	Mg	%	0.01
Manganese	Mn	ppm	1
Molybdenum	Mo	ppm	1
Nickel	Ni	ppm	1
Phosphorus	P	%	0.001
Lead	Pb	ppm	3
Vanadium	V	ppm	2

MAP PRODUCTION AND DATA HANDLING

The proportional dot maps for this Open File are all plotted using the Universal Transverse Mercator projection (NAD27 datum), with a central meridian of 123° (Zone 10). The hydrography bases (NTS 93N and 93O) for the dot maps were obtained in digital form from Surveys, Mapping and Remote Sensing Sector (SMRSS) of the Department of Natural Resources, Canada. The digital hydrography base was produced by splicing together the two 1:250 000 digital bases and then clipping the appropriate sub-area. The index map (Fig. 1) was also obtained from SMRSS and is presented using a Lambert Conformal Conic projection, Clarke 1866 spheroid, central meridian 95°, and standard parallels of 49° and 77°.

The geological base map is a compilation of those published by Nelson *et al.* (1991), and Struik (1992). The base was manually digitized and then transformed into the appropriate projection. Spatial point-in-polygon operations were then used to extract rock unit information for the individual sample sites. The rock unit attribute data were used in preparing the statistical summaries.

Map plots in this Open File were produced by ESRI's ARC/INFO software. Computations were performed on UNIX workstations, with output to a 600 dpi Hewlett-Packard Laserjet printer. The proportional dot maps were generated using AML (ARC/INFO Macro Language). The macro, with its corresponding input menu, prompts the user to input percentile break-points and an appropriate scaling exponent for each element to be mapped. Proportional dots are then generated, using the ARC/INFO SPOTSIZE, POINTSPOT and SPOT commands, with the user specifying an appropriate minimum and maximum dot size. For the purposes of this Open File, analytical values for a particular element that were greater than or equal to the 98th percentile were plotted at the maximum dot size; values less than the 98th percentile were scaled according to the user defined exponent. Exponents for individual elements were chosen to provide the best view of the analytical data. Accordingly, care should be exercised when attempting to compare different elements plotted with different exponents.

Element concentrations below analytical detection limits were reduced to half of the detection limit for data plotting and statistical calculations. For samples with duplicate analyses, data from the first of each duplicate pair were plotted.

ELEMENT DISTRIBUTION MAPS

Before interpreting the element distribution maps, the reader is advised to note the comments provided under each of the element headings. These notes are organized alphabetically by element symbol, dealing first with those elements determined by INAA, followed by those determined by ICP-ES. This sequence is the same as the element listings in Appendix A and the statistical summary in Appendix B.

Transparent Overlay

A transparent overlay at the same scale as the element distribution maps is provided to help locate individual samples and to relate their positions to bedrock geology and known mineral deposits.

Distribution Maps of Elements Determined by INAA

Gold (Au)

Gold is not known to be essential for plant growth and health. Consequently, patterns of Au distribution reflect zones of relative Au enrichment in soils, surficial deposits, groundwaters and near surface rocks. Background levels of Au in the ash of lodgepole pine bark are commonly < 5 ppb Au. The median value obtained for the current data set is < 5 ppb Au, and the 80th percentile is only 7 ppb (Appendix B, p.

B2) whereas the maximum reaches 185 ppb Au at site #187.

As might be expected, the highest concentrations are over the porphyry Cu/Au mineralization at the MBX and Southern Star deposits. Elsewhere concentrations are low, with the exception of a single site at the north end of Philip Lakes, near Rainbow Creek, with 147 ppb Au (site #166). The high ash yield of this sample (7.5%) may in part be due to its high Fe content, but may reflect also some contamination by airborne dust. Regardless, the high Au content is an indication of relative enrichment of Au in the immediate vicinity. To the southeast of this location a few samples yielded detectable Au. This area is of interest in that bark samples were also enriched in As.

Arsenic (As)

Arsenic is known for its toxicity, yet some tree species can accumulate extraordinary amounts without exhibiting any visible harmful affects (Warren *et al.*, 1964; Dunn and Scagel, 1989). Arsenic is an essential element for the metabolism of carbohydrates in fungi and algae, and a few ppm As in most conifer tissues is to be expected. The median value of 3.25 ppm As for the data set is a typical background concentration for lodgepole pine bark. The map of As distribution shows two areas of interest: around the MBX and Southern Star deposits and adjacent to the northeastern limit of Philip Lakes. The latter area has coincident enrichment of Fe and several elements commonly associated with Fe in plant tissues - Hf, Sc, REE, Na, and Th. This 'iron factor' in plants (Dunn, 1995, p.407) has been found in gold-rich areas to have an additional association with As, Sb, Cr and Au. Sample of twigs from white and black spruce collected from this area in September, 1995, confirm that there is enrichment of As, with above background levels of Au, Ag, Sb, Cu, U, and Th. The implication for the Philip Lakes area is that there may be a zone of concealed mineralization. Gossans are reported from this area (L. Struik, personal communication, 1996).

Barium (Ba)

All samples yielded substantially more barium than the INAA detection limit of 10 ppm Ba. The median value of 590 ppm Ba is similar to the 560 ppm Ba obtained from the same sample medium collected around the Nickel Plate mine in southern British Columbia (unpublished data). It is noteworthy that there appears to be a spatial relationship among distributions of Ba, As and Au. Highest Ba concentrations are not coincident with those of As and Au, but are peripheral to them. This observation is consistent with that noted around Au mineralization in the boreal forest of northern Saskatchewan (Dunn, 1984).

Bromine (Br)

Bromine is a volatile element, present in most, if not all terrestrial plants, but it is not known to be an essential element. It can form many different complexes within plants. Some complexes volatilize during the ashing process, causing losses of 30 - 90 percent of the Br contained within the plant tissues. However, it has been noted (Dunn, 1986) that where gold mineralization exists, there is sometimes enrichment of Br in plant ash, indicating that a stable Br compound is retained. Within the survey area the range of Br values is small and there are no notable concentrations of Br.

Calcium (Ca)

Calcium is a major 'building block' element, essential for the rigidity of cell walls in most plants. The variations in Ca content of the bark may influence the distribution of some trace elements. For example, a statistical analysis of multi-element data sets commonly reveals a strong association of Ca with Ba and Zn. Comparison of the distribution patterns of Ca and Ba shows some positive correlations in the western part of the survey area, but no clear relationship with Zn.

Cerium (Ce) and other Rare Earth Elements (Eu, La, Lu, Nd, Sm, Tb, Yb)

The 36 element INAA scan includes data for eight rare earth elements (REE): lanthanum (La), cerium (Ce), neodymium (Nd), samarium (Sm), europium (Eu), terbium (Tb), ytterbium (Yb), and lutetium (Lu). Of these elements, only Tb consistently yields

concentrations below the detection level of 0.5 ppm and therefore no map of Tb is included. Because of the geochemical coherence of the REE they are all considered together in this section. Maps of distribution patterns are very similar, with relatively high concentrations over the Mount Milligan deposits and in the Philip Lakes area. The iron factor discussed above (under arsenic) is probably the dominant control on the content of REE in the pine bark.

Cobalt (Co)

Traces of Co are required by some plants to assist in the fixation of major nutrients (Kabata-Pendias and Pendias, 1984). One ppm Co in ash is sufficient for growth of most plants, but conifer bark usually contains 5 - 10 ppm Co. Plant tissues commonly contain elevated levels of Co over ultramafic rocks, and it has been observed that some plants exhibit Co enrichment in the vicinities of gold mineralization in northern Saskatchewan (Dunn, 1986). In the survey area it is noteworthy that the highest Co concentrations occur over the Mount Milligan deposits, and at sites east of Philip Lakes where there is also enrichment of As and Fe-related elements.

Chromium (Cr)

Chromium is a non-essential element for which precise INAA data are obtained at low ppm levels. Concentrations in 25 percent of the samples are higher than the 10 - 20 ppm Cr that is characteristic of pine bark ash. The sites with the higher levels reflect relatively high abundances of soluble Cr in the substrate. The mechanisms of absorption and translocation of Cr in plants (especially as the soluble Cr^{2+} and Cr^{6+}) are similar to those of Fe, giving rise to a fairly stable Cr/Fe ratio in plant tissues (Cary *et al.*, 1977). This association is apparent from comparison of the Cr and Fe maps. The trees are unlikely to reflect any enrichment of Cr^{3+} (e.g. in chromite) in the substrate because root tissues are not capable of reducing the poorly soluble Cr^{3+} to the soluble Cr^{2+} .

Cesium (Cs)

This alkali metal performs no known essential function in plant tissues, and is usually present at less than 3 ppm Cs in ash of conifer bark. The median value for this data set is 1.3 ppm Cs and, although no sites of unusual enrichment are present, clusters of relative enrichment occur in bark samples from sites near Heidi and Philip Lakes. Near some gold deposits there is a spatial relationship of Cs in plant tissue with highest concentrations peripheral to zones of Au enrichment (Dunn, 1995).

Europium (Eu) - see cerium

Iron (Fe)

Iron is essential for photosynthesis and is a major constituent of chlorophyll. In addition, there is a residual content of Fe which reflects the composition of the substrate. Iron that is in a soluble form in soils and waters, or can become soluble in the acidic micro-environment around roots, is easily taken up in large amounts by plants. Therefore, the inference from the map of Fe distribution is that Fe is present in a readily soluble form near the Mount Milligan deposits, and to the east of Philip Lakes. There is a notable association of several elements at these sites, which are collectively referred to as the 'Fe factor' (see section on As).

Hafnium (Hf)

The content of Hf in the ash of lodgepole pine bark is commonly less than 1 ppm, and it is not known to perform any useful role in plant growth. Hafnium in plants commonly exhibits a close relationship to Fe, and within the survey area the pattern of Hf distribution is almost identical to that of Fe. The uptake of Hf by plants may also be linked to Zr, due to their close geochemical affinities.

Potassium (K)

Potassium has no structural role in plants, but it serves a number of catalytic roles and is required in large amounts (Bidwell, 1979). It is very important in the overall metabolism of plants. Lower concentrations are present in bark than in most other plant

tissues, with just over 4% as the median value. In environments where there is an abundance of K, trees may excrete unwanted amounts into the outer bark. If this is the case, sites with relatively high levels of K in bark may reflect a potassic-rich substrate (e.g. K-rich clays or felsic rocks). It should be noted, however, that interactions with other elements (e.g. Al) can complicate the picture. Consequently, unless the substrate is moderately uniform (i.e. similar lithology) and there are similar environmental conditions within a survey area, variation in K content of trees is likely to be difficult to interpret, and therefore not of great value for mineral exploration.

Lanthanum (La) - see cerium

Lutetium (Lu) - see cerium

Sodium (Na)

Sodium concentrations between 0.1 and 1 percent are common in conifer tissues and may reach several percent over zones of Na enrichment in the substrate. Some Na enrichment commonly occurs in association with Fe, and in the survey area there is a strong correlation between these elements. Highest concentrations occur near the Mount Milligan deposits and Philip Lakes.

Neodymium (Nd) - see cerium

Rubidium (Rb)

Although Rb may substitute for K in rock-forming minerals, there is an antagonism between K and Rb in plants (Kabata-Pendias and Pendias, 1984). This results from their competition for the same binding sites, thereby causing different distribution patterns for the two elements. Cesium is also involved and differences between the Cs and Rb maps indicate that the strong geochemical affinity commonly shown by these elements does not occur universally throughout the survey area, and that some partitioning has taken place.

Antimony (Sb)

Excellent analytical precision is obtained for traces of Sb by INAA, so that variations in the sub-ppm concentrations are real, and not an artifact of the analytical technique. Although Sb can be readily taken up by plants in soluble forms, it is considered a non-essential element (Kabata-Pendias and Pendias, 1984) and is usually present at low ppm levels. The median value for the present data set is 1.1 ppm Sb. Higher concentrations (maximum of 5 ppm) occur in samples from the area of the Mount Milligan deposits, and at several sites east of Philip Lakes where there is coincident enrichment of arsenic and other elements. As noted above, there is a good correlation with Fe and Fe-related elements.

Scandium (Sc)

Data on the essentiality of Sc in biologic systems are inconclusive (Horovitz, 1988). If required, Sc is needed only in 'ultra-trace' amounts, and therefore its presence in bark is controlled essentially by the chemistry of the substrate and by the distribution of other elements. In particular, there is commonly a near perfect correlation between Sc and Fe in plant tissues and a comparison of the maps of these two elements clearly demonstrates this association.

Samarium (Sm) - see cerium

Strontium (Sr)

INAA has poor sensitivity to traces of Sr, and analytical precision is inferior to that for most other elements considered in this study. However, Sr concentrations are significantly above detection limits in over 80 percent of the samples, such that the areas of Sr enrichment depict significant regional variations.

Strontium is known to be essential for some plant species, but its general

essentiality still needs confirmation. It performs a function similar to Ca in plants, and may be incorporated into their structural components. However, interactions between Ca and Sr are complex and, as demonstrated by the distribution maps, there is not a close relationship between these elements in bark samples from the survey area.

Thorium (Th)

Thorium has low solubility and is not essential for plant growth. Its concentration in plant ash is typically < 2 ppm Th, and even over zones of Th-rich mineralization (e.g. allanite with > 5000 ppm Th in northern Saskatchewan) only a few ppm accumulate in the tissues (Dunn and Hoffman, 1986). The median value in the survey area is 0.6 ppm Th, with a maximum of only 2.5 ppm Th. However, although the range of concentrations is small, the excellent precision of the analytical data permits resolution of the subtle regional differences. Of note is the strong similarity of the Th and Fe distributions. However, the relationship is not linear, since there is an 8-fold increase from the median to maximum values of Fe, yet only a 4-fold increase in Th over the same statistical range.

Uranium (U)

Although U_3O_8 has high solubility, it rarely exceeds concentrations of more than 2 ppm in plant ash. There are a number of notable exceptions, particularly in northern Saskatchewan where enrichments in spruce twigs are locally more than three orders of magnitude (Dunn, 1983). The maximum in the survey area is 1.6 ppm U, and more than 50% of the samples yielded <0.1 ppm U. In a relative sense, the highest values are over the Southern Star zone, and at a few isolated sites to the east. The Fe/U association that occurs in some biogeochemical data sets is not present in the survey area.

Ytterbium (Yb) - see cerium.

Zinc (Zn)

Because Zn is essential for carbohydrate and protein metabolism, differences of a few 100 ppm Zn in ash are probably related to the health of the tree rather than subtle changes in substrate chemistry. In general, concentrations of Zn in bark samples from the survey area are moderately high. Typical background concentrations in pine bark from elsewhere in British Columbia are approximately 1500 ppm Zn, whereas the median value for this data set is 2300 ppm. Slightly elevated levels occur peripheral to the Mount Milligan deposits, but the highest concentrations are at sites on the Wolverine Complex in the northeast, and south of Philip Lakes.

Distribution Maps of Elements Determined by ICP-ES

Aluminum (Al)

All dry vegetation samples were placed in Al trays for ashing. Therefore a certain amount of contamination from this source is inevitable. However, the wide range in Al concentrations, and the high levels of Al in the samples suggest that areas of *relative* Al enrichment are significant. The aqua regia extraction used is not 'total', but good precision was obtained for duplicate samples. Tests to compare data obtained from a total analysis with those by ICP-ES (aqua regia digestion) indicate that the acid digestion releases approximately 50% of the Al. There is no obvious relationship of Al concentrations in the pine bark to underlying lithologies or known zones of mineralization. Most of the highest concentrations are isolated occurrences.

Boron (B)

Borosilicate test tubes were used for the acid digestion of the ash samples, from which the analysts suggest 5 - 10 ppm B may be released. This is an insignificant amount in comparison with the concentrations of B present in the ash. Tests indicate that the analytical procedure used provides data which represent about 50% of the true concentrations of B in the samples. Precision, however, is excellent.

Boron is an element that is essential for plant growth, and it is believed to play an important role in the translocation of sugars (Bonilla *et al.*, 1980). In general, B uptake is low from Ca-rich soils. Comparison of the maps of Ca and B distributions shows that there is a generally an inverse relationship between the two elements.

Cadmium (Cd)

Cadmium is extremely easily absorbed by plants and can therefore be expected to reflect relative Cd concentrations in the soils and groundwaters. However, it can be captured by a variety of organic compounds in cell walls and therefore not all will be transported to the tree extremities. Pine bark commonly contains higher levels of Cd than tissues from most other tree species, with the notable exception of birch.

Although there is a strong geochemical association between Cd and Zn in many geochemical environments, this is not always evident in plant tissues because of the *requirement* that plants have for Zn but not for Cd and therefore partitioning may take place. There are similarities in distribution patterns of Zn and Cd, but the correlation is far from perfect. Cadmium concentrations are remarkably high, reaching a maximum of 160 ppm Cd. The background level for the area is approximately 16 ppm Cd, which is higher than the usual level <10 ppm Cd in bark of pines from a wide range of geological terranes. Highest concentrations occur in samples from the northeast over rocks of the Wolverine Complex and the Witch Lake Formation. Elsewhere, high levels of Cd in plant tissues have been found to reflect concealed base-metal mineralization (Dunn, 1995).

Copper (Cu)

Data obtained for Cu by ICP-ES from the aqua regia leach are both precise and accurate. Copper plays a fundamental role in a plant's metabolism. It assists in such processes as respiration, photosynthesis, nitrogen fixation and valence changes, and is present in many micro-components of plants (small and large molecules, chloroplasts, mitochondria etc.). As a consequence, the 'background' concentration of Cu in ash of the bark (median value of 174 ppm Cu) is high compared to many trace elements.

The interpretation of Cu distribution patterns in tree tissues should be approached with caution, since laboratory studies report numerous antagonistic and synergistic interactions with both major and minor elements. These are reviewed briefly by Kabata-Pendias and Pendias (1984). However, despite the essentiality of Cu and the complex metabolic roles that it may play, substantial differences among the survey samples are more likely to reflect major differences of Cu in the substrate than the relatively small differences attributable to micronutrient functions. As would be expected, there are anomalous concentrations in some samples from above the MBX zone and at a number of sites to the northeast. Several sites at the south end of Philip Lakes yielded relatively high Cu concentrations.

Lithium (Li)

Lithium commonly follows Rb and Cs in nature. In conifer bark it is less abundant than Rb but commonly enriched with respect to Cs. It is not known to be essential to plant metabolism. Its high solubility (except where firmly bonded to clay minerals) causes Li enrichment in soils and waters to be readily reflected in plant tissues. In the survey area there is weak enrichment of Li in the Heidi and Philip Lakes areas at sites where there are also anomalous levels of the 'Fe factor' elements (see section on As).

Magnesium (Mg)

Magnesium is a macronutrient which plays several important roles in plant health, including photosynthesis and numerous enzymic reactions. From a biogeochemical prospecting perspective, major differences in Mg concentrations in plants can indicate significant differences in the underlying lithology, but smaller differences are not known to be of value in delineating zones of mineralization. The relatively high Mg content to samples in the northern half of the survey area suggests a higher mafic component to the

substrate.

Manganese (Mn)

Manganese is an essential element which is readily taken up by plants, especially where the acidity of the ground is high (e.g. boggy areas). In acidic environments there is a Mn/Fe antagonism, which is extended to elements with a broad affinity for Fe.

Molybdenum (Mo)

Molybdenum is required in trace amounts by most plants for nitrogen fixation and nitrate reduction. Concentrations are usually <2 ppm Mo in lodgepole pine bark, although over highly alkaline soils the trees more readily absorb Mo and therefore slightly higher levels may be expected. In view of the Cu/Mo association with Mt. Milligan porphyry deposits, it is of interest to note the close correspondence between Cu and Mo elsewhere in the survey area.

Nickel (Ni)

The presence of Ni may assist in the translocation of nitrogen in some plants, but its general essentiality is unproven. When in solution, Ni is readily taken up by plants, therefore it may be expected that the Ni content of the bark may be positively correlated with Ni concentrations in groundwaters.

INAA has low sensitivity to Ni (detection limit of 50 ppm Ni in ash). In contrast, excellent precision and accuracy are obtained by ICP-ES down to the minimum level (4 ppm) recorded for this data set. The pattern of Ni distribution is similar to that of Mg and P, and, to a lesser extent, Cu and Mo.

Phosphorus (P)

Phosphorus plays a vital role in plant energy metabolism, and it is extremely important as a structural part of many organic compounds. Its uptake by trees may be antagonized by excess Ca but, from the maps showing distribution patterns of Ca and P, this antagonism is not apparent in the pine bark. Similarly, high levels of P may influence the uptake of numerous trace metals, although this effect appears to be subordinate to the over-riding effect of the substrate chemistry. In the present data set the strongest association with P is among Mg, Cu, and Mo.

Lead (Pb)

Despite the known toxic effects of Pb, it occurs naturally in all plants, and in small traces Pb may even be an essential element (Broyer *et al.*, 1972). It is taken up mainly by root hairs and stored as a pyrophosphate in cell walls. Within lodgepole pine, Pb is stored mostly in the roots with lesser amounts in the outer bark and lower twigs. Concentrations are moderately high at a few sites, notably around Philip Lakes. At the south end of Philip Lakes a single high value for Pb is close to the site of enrichment in Zn, Cu, and Mo.

Vanadium (V)

Although V is detectable in all but one of the bark samples, its essentiality for plants other than green algae has not been proven. Soluble V is easily taken up by roots, and it may play a similar role to Mo in fixing nitrogen. In acidic soils, such as those in the Mt. Milligan area, the soluble VO^{2+} species is more rapidly absorbed by roots than the VO_3^- and HVO_4^{2-} that predominate in neutral and alkaline environments (Welch, 1973). In the survey area the almost identical patterns of Fe and V distribution show that V is closely related to the 'Fe factor' (see As section).

DISCUSSION

A companion geochemical study to this Open File report displays and discusses the element content of till samples, most of which were collected at the same time and at the same sites as the lodgepole pine bark samples (Sibbick *et al.*, 1996). There are some

similarities, but also some significant differences in the element distribution patterns which require some explanation.

Firstly, analysis of a till sample involves sieving and selection of one size fraction from a bulk sample commonly weighing approximately 5 kg, dug from a single small pit. The tree roots, however, may extend through several cubic metres of soil (all horizons) and till, on occasion reaching and penetrating joints and fractures in bedrock. The tree, therefore, extracts elements from a large volume of material of diverse composition, including groundwater. Some elements dissolved in groundwater and readily extracted by the tree roots may not precipitate on till and soil particles.

A second factor of importance is the barrier mechanism established at the root/sediment interface by some plants for some elements (Kovalevskii, 1979). Because each species of plant has a different requirement for and tolerance to a range of chemical elements, some partitioning of elements takes place and there is selective absorption and translocation into the plants. For biogeochemical exploration, conifers are good sample media because they are primitive plants that have a wide tolerance to many trace elements. The outer bark may, by analogy, be equated with biotite in rocks, in that it is something of a repository for many elements that do not fit elsewhere or are not required for the metabolic function of the tree.

A third factor is that slight enrichments of metals in till samples are unlikely to be reflected in the vegetation as weak biogeochemical anomalies. This is especially true in the ppb (Au) and ppm ranges of concentration common in till samples. Some of these metals may not be present in a chemical form *available* for uptake (e.g. Cr structurally bound in chromite); some may be excluded from uptake at the roots or only partially absorbed; and some may be taken up but dispersed among tree tissues to the extent that inter-site variations are so small that they cannot be detected.

The net result of these factors is that the geochemical information supplied by the vegetation is different from that of the till. Just as two methods of geophysical survey will provide totally different information, so will two methods of geochemical survey. A high correlation between distribution patterns of two geochemical sample media is the exception rather than the rule. In geological environments where there is sufficient concentration of metals to form a mineral deposit, such a 'critical mass' of elements may be sufficient to generate biogeochemical anomalies above (by upward diffusion) or close to (by movement in electrochemical cells) the mineral source. Tills, however, usually have geochemical anomalies displaced down-ice from the mineralized source. Such factors need to be taken into consideration when interpreting geochemical results. Valuable exploration information can be obtained from the analysis of till samples. When this information is coupled with analysis of vegetation samples, a powerful combination is provided for assisting in the exploration for mineral deposits.

NOTES ON DATA LISTINGS (APPENDICES A and B)

Appendix A lists all analytical data obtained for the lodgepole pine bark ash. Appendix B provides some simple statistical analyses of the data by treating the data set as a whole, and by dividing the data according to the underlying bedrock geology (according to stratigraphic unit). Abbreviations used in the appendices are explained in Fig. 2.

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