

Selenium Concentrations in Mine Refuse and Mist Mountain Rocks; Evaluation of Variations Laterally and Over Time

By Barry Ryan, Mike Fournier and Maggie Dittrick

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INTRODUCTION

The distribution of Selenium (Se) in the Jurassic-Cretaceous Mist Mountain Formation of southeastern British Columbia was documented in a previous study by Ryan and Dittrick (2001). As part of that study, complete sections of rock types, including coal seams were sampled, as well as various materials segregated by mining such as coarse refuse and solid tailings from tailings ponds. Preliminary results indicate that coal seams of the Mist Mountain Formation have Selenium concentrations similar to the world average for coal seams. The interburden rocks of the Mist Mountain Formation generally contain more Se than expected based on their composition but this is a function of their association with coal seams, which concentrate Se above the crustal average value. Selenium concentrations, within the Mist Mountain Formation, were higher in rocks with higher clay content and those closely associated with coal seams such as hanging wall, footwall and in-seam splits.

The present study deals with samples from mines in the Elk Valley and Crowsnest coalfields (Figure 1). The coal seams are contained in the Mist Mountain Formation, which is part of the Kootenay Group (Table 1). The formation outcrops extensively in the east Kootenays and varies in thickness from 25 to 665 metres (Gibsons, 1985). Typically 8% to 12% of the thickness of the formation is coal and in places this is distributed in over 30 seams. The rest of the formation is composed of non-marine siltstones, mudstones and sandstones. The Morrissey Formation, a sandstone unit that forms the footwall in most mines, underlies it. This formation is underlain by the Fernie Formation, composed predominantly of marine shales. The Elk Formation, a non-marine sandy formation containing thin sapropelic coal seams, overlies the Mist Mountain Formation.

Three aspects of Se distribution, not covered in the previous study are addressed here. These are:

- Changes in Se concentrations within refuse material over time;
- Lateral variations of Se within coal seams;
- Petrographic control on Se concentration in coal seams.

Coarse refuse material is dumped at various locations within the mine site and reclaimed. It is therefore possible to

get refuse samples of different, though not accurately defined, ages. Refuse samples, varying in age from over 15 years to less than five years, were collected from three mine sites. The fine refuse material (tailings) from three of the mines is pumped into tailing ponds where it settles and dewatered much like sediments in a lake. Core samples of tailings material from two mines were obtained. These cores provide stratigraphic sections through the tailings, though obviously, because of the way the tailings ponds are filled, it is not possible to assign exact ages to core samples.

During the previous study complete sections of seams and intervening lithology were sampled along the base of high walls. Because of active mining, the base of the high walls had migrated downward about 3 benches (45 metres) by the time the coal seams in the walls were re sampled in 2000. The 1999 and 2000 coal seam samples therefore pro-

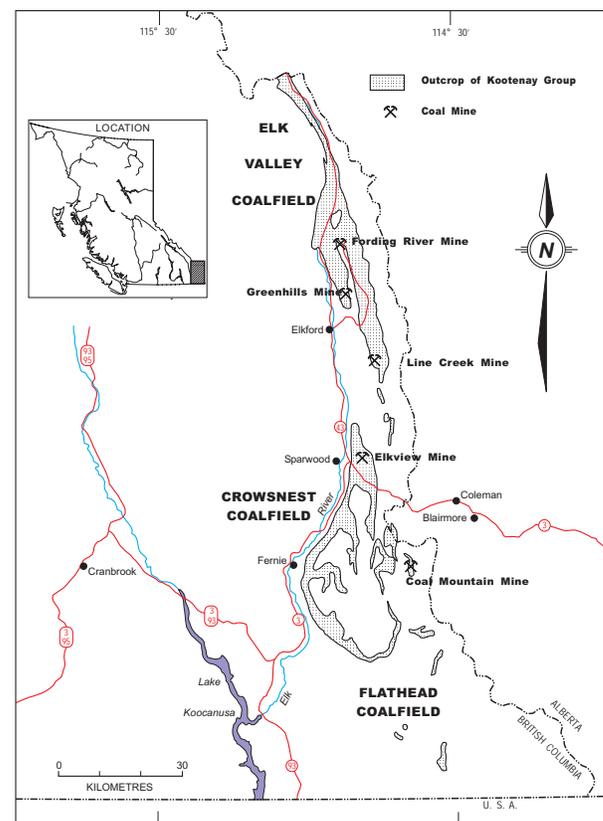


Figure 1. Coalfields and coal mines, southeastern British Columbia.

TABLE 1
KOOTENAY GROUP STRATIGRAPHY

LOWER CRETACEOUS	CADOMIN FORMATION		
JURASSIC AND CRETACEOUS	KOOTENAY GROUP	ELK FORMATION	
		MIST MOUNTAIN FORMATION coal seams	
		MORRISSEY FORMATION	MOOSE MOUNTAIN MEMBER
			WEARY RIDGE MEMBER
JURASSIC	FERNIE FORMATION	PASSAGE BEDS	

vide a good check of the lateral variation of Se concentrations within individual seams.

Fusinite and semi fusinite form as a result of fires in coal swamps. Selenium is very volatile and one would therefore expect concentrations in fusinite and semifusinite to be less than in vitrinite. In this study samples of bright and dull lithotypes were hand picked from a single seam. The samples are used in an attempt to better delineate a maceral influence on Se concentrations.

BACKGROUND

When a study of the Elk River and tributaries in southeast British Columbia (McDonald and Stroscher 1998) documented a trend of increasing Se concentrations over the last 15 years, mine operators in the area decided to study the Se distribution, mobility and effects on the environment in more detail. A number of studies are now under way or have been completed. Ryan and Dittrick (2001) studied the distribution of Se in the Mist Mountain Formation and this paper builds on their previous work, and in part details Se distribution in refuse material of variable age. Elevated concentrations of Se in stagnant water (lentic) can concentrate in the food chain and cause reproductive failure and die offs of fish and bird populations as documented in the Kesterton Reservoir in California (Weres, *et. al.*, 1989). In the case of the Kesterton reservoir, agricultural wastewater, enriched in Se, concentrated in the reservoir, which had no outflow. The ef-

fects of Se enrichment in flowing water have been less well documented.

DATA COLLECTION

Sampling of lake-bottom unconsolidated sediments has been undertaken using low-cost simple, though moderately labour intensive techniques for collecting cores of a few metres length. The method described in Reasoner (1993) was adapted for sampling in tailings pond areas not submerged by water. The process involved walking out on the near thixotropic material, putting a plywood floor on the tailings to support a stepladder (Photo 1). PCV pipe (7 cm diameter) with a catcher cone on the lower end was forced (with the aid of a sledge-hammer and block of wood held on the top of the pipe) through the plywood and into the tailings. The process was tiring for the sledgehammer operator and somewhat stressful for the person holding the block of wood, however it provided amusement for any passer-by.

Twelve cores with a cumulative length of 43.75 metres were obtained from 2 tailings ponds. Generally about 3 to 4 metres of pipe could be forced into the tailings before progress no longer warranted the effort. At that point the height of tailings in the pipe was measured with reference to the level of tailings outside the pipe. Forcing the pipe into the tailings caused some dewatering and compaction of the material entering the pipe. Consequently after the pipe was forced into the tailings, the level of the tailings in the pipe was always below the level of the tailings outside the pipe.

The core-filled pipes were extracted with the help of a come-along (Photo 1). The suction of the surrounding tailings on the pipe and its contents caused further compaction



Photo 1. Extracting a core from one of the tailings ponds.

of the core. Inspection of the core catcher at the base of the pipe indicated that little core was lost as the pipes were extracted. It is concluded the difference in core length between before and after extracting the core pipe is a result of dewatering and compaction. Total compaction averaged 24% and ranged from about 10% to 32%. The length of cores recovered ranged from 1.27 to 3.84 metres (Table2). Material in the top of the core may not be representative of surface material, because the process of setting up coring equipment inevitably disturbed the surface material around the coring site. Consequently, a surface sample was collected at a nearby locality.

**TABLE 2
TAILINGS PONDS CORE DATA SUMMARY**

core	length of pipe metres	length of core in pipe before recovery	length of core after recovery	percent total compaction
C00-1	2.7	ND	1.27	53
C00-2	2.7	ND	1.92	29
C00-3	2.7	ND	2.24	17
C00-8	2.7	2.4	2.4	11
C00-9	2.75	2.4	2.2	20
C00-10	4.27	3.67	3.63	15
C00-11	4.25	3.5	3.5	18
B00-45	4.24	3.21	2.88	32
B00-47	4.25	3.34	3.21	24
B00-49	4.26	3.32	3.13	27
B00-50	4.21	3.31	3.25	23
B00-52	4.72	3.77	3.84	19
average compaction				24

Cores were analyzed in Victoria. The filled pipe was placed in a horizontal cradle and cut along its length into two halves (Photo 2) using a bone saw with the blade set to just penetrate the plastic. The top half of the pipe with the tailings was separated from the lower half using a fine pull cord, before being carefully lifted off. The material was uniformly black with horizontal layering sometimes emphasized by changes in grain size, which ranged up to a few mm. A total of 114 (30 centimetre long) samples were collected by excavating a 1 centimetre by 0.5 cm deep channel along the center of the core. The tailings were dried, pulverized and sent for ICP-MS. Some samples were also sent for ash concentration, sulphur form analysis and major oxide analysis using XRF.

Surface samples were collected as channel or chip samples. Samples were crushed, pulverized and sent for ICP-MS analysis; some samples were also sent for ash, proximate and XRF analyses.



Photo 2. A bone cutter used to cut core tubes in preparation for sampling.

At one mine, a number of hand picked samples of bright and dull coal were collected from a single seam. These samples were prepared for petrographic analysis and sent for full proximate analysis.

ANALYTICAL TECHNIQUES

Most Se analyses were done using instrumental neutron activation analysis (INAA) in the previous study by Ryan and Dittrick (2001). The method requires no sample preparation other than pulverizing, consequently Se is not volatilized, as might be the case if the samples were subjected to hot dissolution. Selenium values were checked against a standard and duplicate samples were analyzed at separate laboratories. The data indicated that INAA was providing reliable Se concentration data as long as concentrations were safely above detection limits. However, INAA does have some disadvantages compared to induced coupled plasma mass spectroscopy (ICP-MS). ICP-MS is less expensive, has lower detection limits, and generally requires a smaller sample (1 gm, Table 3). In this study, ICP-MS results were compared to INAA results for samples analyzed previously (Figure 2). There is a tendency for ICP-MS to predict higher concentrations than INAA for concentrations above 4ppm and lower concentrations for samples with less than 4 ppm. On average INAA predicts concentrations 5% higher than ICP-MS.

ICP-MS samples were partially dissolved in aqua regia at a temperature of 90°C. If the wet chemistry sample preparation technique required for ICP-MS analysis was volatilizing Se from samples, or not extracting all the Se, then one would expect ICP-MS results to be consistently low compared to INAA results, which is not the case. It was felt,

TABLE 3
DETECTION LIMITS
(ICP-MS; ALL ELEMENTS ANALYZED. ONLY TOTAL DETERMINATIONS ARE SHOWN IN SUBSEQUENT TABLES)

element	detection	element	detection		
Au	0.2 ppb	T	Mo	0.01 ppm	T
Ag	2 ppb	T	Na	0.001 %	P
Al	0.01 %	P	Ni	0.1 ppm	P
As	0.1 ppm	V	P	0.001 %	P
B	1 ppm	P	Pb	0.01 ppm	T
Ba	0.5 ppm	P	S	0.02 %	P
Bi	0.02 ppm	T	Sb	0.02 ppm	V
Ca	0.01 %	P	Sc	0.1 ppm	P
Cd	0.5 ppm	T	Se	0.1 ppm	T
Co	0.1 ppm	T	Sr	0.5 ppm	P
Cr	0.5 ppm	P	Te	0.02 ppm	T
Cu	0.01 ppm	T	Th	0.1 ppm	P
Fe	0.01 %	P	Ti	0.001 %	P
Hg	5 ppb	T	Tl	0.02 ppm	T
Ga	0.02 ppm	T	U	0.1 ppm	P
K	0.01 %	P	V	2 ppm	P
La	0.5 ppm	P	W	0.2 ppm	P
Mg	0.01 %	P	Zn	0.1 ppm	T
Mn	1 ppm	P			

T total concentration

P partial concentration V some volatilization

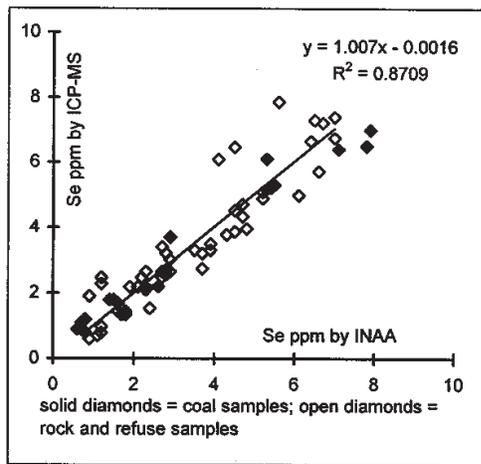


Figure 2. Comparison of Se analyses using INAA and ICP-MS.

therefore, that the ICP-MS method was providing accurate total Se concentrations and all Se analyses in this study were done using the technique. The comparison of methods was made using both coal and rock samples (Figure 2) because the Se has different mineralogy in the two sample types.

Partially dissolving samples in aqua regia at 90°C appears to produce complete extraction of some elements (for example Se) and partial extraction of others such as sulphur and especially rock forming elements such as iron. In these cases comparing ICP-MS data to total concentration data provides information on the partitioning of elements in sam-

ples. The relationship of S concentrations derived by ICP-MS and ASTM methods is discussed later.

DATA

The ICP-MS data for the 12 tailings-pond cores are summarized in Table 4, which only lists analyses reported as total concentrations and not those affected by partial extraction or volatilization. Data for some of the elements, which are only partially extracted by ICP-MS, are presented in the discussion. Samples from a hole from the mine B tailings pond were subjected to a number of leaches in an attempt to identify the way in which the Se and other metals are held in the tailings. The leach procedures are those employed by ACME laboratories. In all, 4 leaches each with a different level of aggressiveness, were used (Table 5). The least aggressive leach involved mixing 20 ml of distilled water with 1 g of solid for 1 hour to extract water-soluble components. A 1 M sodium acetate leach for 1 hour was employed to remove exchangeable cations adsorbed on clays. A 0.1 M hydroxylamine leach for one hour was used to remove elements adsorbed by amorphous Mn hydroxide. A 0.25 M hydroxylamine leach for one hour was used to remove elements adsorbed by amorphous iron hydroxide.

Coarse refuse samples were collected from three mines. It is difficult to collect a lot of coarse refuse samples because of the size of each sample, which is determined by the rock fragment size. Generally two, 10 Kg samples of refuse material were collected at each site. One sample of surface material and a second sample from a depth of about 0.7 metres were collected (Table 6). It was usually possible to find locations where the age of the material could be estimated to within a few years and ages ranged from 1 to 7 years to more than 15 years. Samples were analyzed by ICP-MS for Se and other elements; only those elements reported as total analyses are included in Table 6.

A number of outcrop coal samples were collected from Mines B and E. In the previous study the complete section was sampled; in this study only coal seams and some hanging walls and footwalls were sampled. Samples were analyzed by ICP-MS for a number of elements including Se. In addition the ash contents of samples were determined (Tables 7 and 8).

At mine A, a number of samples were hand picked from a single seam representing bright and dull lithotypes. These were analyzed for, proximate values, trace metals by ICP-MS, and for major oxides by XRF. In addition, basic petrography for the samples was recorded using standard microscope techniques and a 300 point count per sample (Table 9).

It is difficult to document the effect of weathering on Se concentrations in coal seams, primarily because of the variation in Se concentrations in the fresh seams. However, in order to better understand potential effects a number of samples of fresh and weathered coal from the same seam were collected and analyzed (Table 10). A few samples of sheared coal were collected (Table 11) to detect any abnormalities in the concentration of Se or any other elements.

TABLE 4
ICP-MS ANALYSES OF TAILINGS POND
CORE SAMPLES

Interval	Ash	Se	Mo	Cu	Pb	Zn	Ag	Ni	Co	Au	Cd	Bi	P	La	Hg	Ga
	%	ppm	ppm	ppm	ppm	ppm	ppb	ppm	ppm	ppb	ppm	ppm	%	ppm	ppb	ppm
B00-45																
surface	71.04	4.5	4.46	35.61	14.95	151.4	271	20	5.3	0.7	1.58	0.26	0.089	6.3	163	1.9
0.0-0.3		6.3	5.23	32.42	16.09	194.9	265	21.6	6.1	0.6	1.93	0.28	0.092	6.6	214	1.8
0.3-0.6		4.9	3.97	30.69	14.73	135	229	18.9	5.2	0.2	1.4	0.27	0.085	6.6	120	1.7
0.6-0.9		4.4	4.4	30.26	14.45	167	232	20.9	5.6	0.9	1.6	0.26	0.079	6.2	165	1.9
0.9-1.2		3.5	3.42	31.87	13.75	122	212	17.8	4.6	1	1.36	0.27	0.078	6.1	108	1.5
1.2-1.5		3.4	3.47	32.83	12.89	112.5	197	16.8	4.5	0.8	1.27	0.26	0.079	5.9	112	1.3
1.5-1.8		3.7	3.47	32.64	14.74	135.6	218	18.7	4.8	0.8	1.42	0.26	0.093	6.1	123	1.5
1.8-2.1		3.2	3.32	30.61	12.84	108	198	16.9	4.1	0.4	1.29	0.24	0.091	6.4	106	1.3
2.1-2.4		3.5	3.37	29.47	13.81	140	227	19.2	4.8	0.6	1.54	0.25	0.082	6.3	140	1.7
2.4-2.7		4.2	4.01	32.8	14.95	161.3	257	20.3	5.1	0.3	1.84	0.28	0.085	6.1	161	2.1
B00-47																
surface	77.21	4.7	4.4	35.03	16.2	156.9	280	20	5.7	0.8	1.69	0.27	0.09	6.3	157	2.1
0.0-0.3		6.6	5.37	32.02	16.95	220	269	24.3	6.4	0.5	2.12	0.27	0.082	5.9	242	2
0.3-0.6		5.1	4.64	30.06	14.83	165.8	250	21.4	5.6	0.3	1.68	0.27	0.085	6.4	170	2
0.6-0.9		4.5	3.89	31.84	14.44	140.7	242	19	5.4	0.4	1.42	0.27	0.081	6	148	1.7
0.9-1.2		4.3	4.26	30.29	14.6	167.7	235	19.4	5.3	0.5	1.56	0.26	0.081	6.2	160	1.9
1.2-1.5		3.6	3.22	31.63	13.73	92.2	194	17	4.1	0.2	1.04	0.25	0.079	6	103	1.2
1.5-1.8		3.3	3.22	30.43	12.65	120	191	15.8	4.1	0.4	1.24	0.24	0.096	6.7	124	1.2
1.8-2.1		4.3	4.08	33.2	15.52	180.8	269	20.7	5.3	0.5	1.93	0.27	0.09	5.9	191	1.9
2.1-2.4		3.2	3.14	29.25	11.8	100.8	210	16.7	3.8	0.3	1.12	0.23	0.082	6	102	1.3
2.4-2.7		4.4	3.98	33.1	14.57	194.8	257	21.1	5.2	0.3	1.99	0.26	0.077	6.1	194	1.8
2.7-3.0		4.3	4	31.49	15.6	187.4	262	20.2	5.1	0.5	1.96	0.27	0.083	6.4	194	1.9
bottom		3.9	3.38	30.71	12.99	338.6	221	17.9	4.5	0.2	1.35	0.24	0.077	6	126	1.4
B00-49																
surface	54.79	3.9	3.59	30.42	13.33	120	217	16.5	4.6	0.7	1.29	0.21	0.089	6.3	113	1.5
0.1-0.4		5.2	4.44	31.18	14.24	138.4	258	19.6	5.4	0.4	1.44	0.27	0.077	5.8	154	2.1
0.4-0.7		4.5	4.14	31.54	14.03	139	248	19.8	5.2	0.2	1.58	0.27	0.074	5.8	159	2.3
0.7-1.0		4.3	4.14	29.2	13.57	137.6	236	19.2	5.1	0.2	1.4	0.26	0.073	5.8	152	2
1.0-1.3		3.2	3.23	29.84	12.56	104.8	195	16.7	4.2	1	1.11	0.24	0.078	5.9	100	1.4
1.3-1.6		3.5	3.68	29.29	12.79	126.3	203	17.4	4.4	0.4	1.25	0.24	0.076	6	126	1.8
1.7-2.0		4.1	4.22	30.87	13.52	182.5	245	20.7	5.4	0.6	1.85	0.24	0.093	5.9	185	2.1
2.0-2.3		4.1	4.15	33.35	14.27	197.7	262	20.3	4.9	0.6	1.84	0.25	0.086	6.3	213	2.3
2.3-2.6		3.8	3.59	32.69	14.15	165.9	269	20.7	5.1	0.4	1.68	0.27	0.075	6.2	175	2
2.6-2.9		3.9	4.13	31.75	14.87	189.6	266	19.8	5.1	0.4	1.77	0.26	0.076	5.7	209	2
bottom		3.8	3.71	31.04	15.17	270.8	251	20.3	4.9	0.3	1.78	0.27	0.076	5.8	177	1.9
B00-50																
surface	76.73	4.5	4.23	34.43	16.59	158.5	275	19.6	5.5	0.7	1.69	0.27	0.087	5.8	185	2.1
0.1-0.4	79.26	5.4	5.61	31.05	14.75	192.5	276	22.1	5.8	0.4	1.93	0.26	0.086	6	224	2.6
0.4-0.7	77.31	5.1	4.55	31.22	14.53	162.4	262	20.3	5.5	0.5	1.76	0.26	0.077	5.6	202	2
0.7-1.0	73.55	3.9	4	30	14.41	132.4	229	17.9	5.1	0.6	1.3	0.26	0.076	5.4	161	2.4
1.0-1.3	67.1	3.4	3.32	30.92	12.94	117	198	16.4	4.3	0.6	1.19	0.24	0.072	5.7	109	2.2
1.3-1.6	58	3.3	3.35	28.65	13.09	114.1	186	14	3.9	0.5	1.05	0.22	0.078	6.3	106	1.6
1.6-1.9	75.51	4.1	4.36	30.57	15.41	187.8	274	20.6	5.1	0.6	2	0.26	0.093	6.6	187	2.8
1.9-2.2	78.19	3.7	3.99	29.3	13.9	172.2	259	18.7	4.5	0.4	1.62	0.26	0.077	6.5	151	2.8
2.2-2.5	72.02	3.4	3.27	31.58	13.85	126.3	250	17.7	4.3	0.2	1.4	0.26	0.066	6.2	119	2
2.5-2.8	75.72	3.7	4.27	30.5	14.44	147.8	253	19.1	4.9	0.4	1.58	0.26	0.068	6.1	142	2.4
2.8-3.1	69.18	3.2	3.09	30.38	13.53	128.1	235	16.6	4.1	0.3	1.37	0.26	0.061	5.8	120	2
bottom	55.92	3.3	3	28.68	12.16	376.9	205	15.2	3.9	0.2	1.14	0.24	0.07	6.7	90	1.3
B00-52																
surface	74.56	4.7	5.22	34.15	16.92	185	313	23.2	6.6	0.3	2.02	0.27	0.094	6	189	2.2
0.1-0.4	79.52	5.6	5.25	31.45	16.19	244.4	298	22.8	5.9	0.4	2.2	0.26	0.077	5.9	316	2.5
0.4-0.7	78.48	4.8	4.19	29.96	15.07	181.1	256	19.8	5.1	0.2	1.77	0.25	0.064	5.8	188	2.4
0.7-1.0	80.08	5	4.98	28.32	16.48	201.8	276	21.7	5.7	0.2	1.88	0.26	0.07	6.1	227	2.5
1.0-1.3	72.17	3.4	3.52	28.77	13.09	142.6	218	15.6	4.2	<.2	1.34	0.25	0.063	6	124	2
1.3-1.6	72.22	3.5	3.48	30.48	13.5	138.3	229	16.4	4.7	0.2	1.4	0.26	0.07	6.5	142	2.1
1.6-1.9	74.63	4.1	4.26	31.33	15.01	198.5	259	19	4.9	0.2	1.88	0.26	0.078	6.4	220	2.6
1.9-2.2	74.99	5.2	5.44	28.3	16.74	326	290	22.8	5.7	0.3	2.82	0.24	0.088	6.6	402	2.7
2.2-2.5	76.81	4.5	4.41	27.92	15.07	239.4	262	20.1	5.1	0.3	2	0.24	0.075	6.2	263	2.5
2.5-2.8	80.03	4.1	4.03	30.4	14.9	186	268	19.6	5	<.2	1.92	0.26	0.07	6	239	2.5
2.8-3.1	73.71	4.2	3.8	28.86	15.44	164.8	255	19.1	4.5	<.2	1.68	0.27	0.068	6.2	188	2.3
3.1-3.4	77.78	3.9	3.46	31.47	15.6	147.7	259	21.1	5.1	0.2	1.55	0.29	0.064	5.4	214	2.5
3.4-3.7	74.6	3.6	4.01	27.82	13.76	140.7	238	19.4	5	0.3	1.49	0.25	0.068	5.6	179	2.4
bottom	75.69	3.6	3.51	29.23	14.08	507.5	256	19.6	4.6	0.4	1.56	0.27	0.073	5.9	165	2.1

**TABLE 6
COARSE REFUSE DATA**

	Age years	Ash %	Se ppm	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Au ppm	Cd ppm	P %	Hg ppb	Te ppm	Ga ppm
Mine A	recent		3.7													
L bnch D	15+	75.18	2.5	2.04	28.04	11.82	90.9	265	15.1	3.3	0.3	1.24	0.113	80	0.05	1.3
L bnch S	15+	74.56	1.8	1.55	27.54	11.54	101.1	263	15	3	0.5	1.41	0.093	94	0.06	1.4
U bnch D	15+	74.31	2	1.82	33.02	12.37	140.2	308	14.5	3	0.4	1.76	0.079	131	0.06	1.4
U bnch S	15+	75.91	2	2.09	31.64	12.94	121.1	275	18.5	4.3	<.2	1.68	0.08	121	0.06	1.4
U bnch D	15+	77.74	3.4	3.44	27.14	11.42	116.7	323	14.9	2.6	0.2	1.88	0.452	160	0.08	2.4
U bnch S	15+	77.33	2.4	1.93	27.82	12.36	120.6	377	15.4	3.2	0.2	2.06	0.196	109	0.07	1.7
Mine B	recent		3.5													
pile D	1 to 7	63.26	3.5	2.52	27.32	11.24	96.4	272	13.7	3.2	<.2	1.37	0.07	137	0.05	1
pile D	1 to 7	62.23	3.5	2.43	27.5	11.03	109.3	275	14.7	3.3	<.2	1.48	0.086	126	0.04	1.1
S	1 to 7	68.37	2.2	1.86	29.3	11.14	112.3	224	12.1	3.2	0.2	1.42	0.065	92	0.06	1.2
S	1 to 7	65.42	1.9	1.83	27.52	11.13	83.7	212	9.9	3.1	<.2	1.19	0.06	81	0.05	1.3
Mine C	recent		2.1													
L bnch D	15 +/-	54.02	2.1	1.32	26.48	11.07	77.2	215	9.2	2.6	<.2	1.45	0.076	244	0.05	0.7
U bnch D	15 +/-	59.66	1.8	1.37	31.29	12.12	76.8	207	8.2	3.6	<.2	1.3	0.058	107	0.06	0.9
U bnch S	15 +/-	63.83	1.8	1.39	28.36	11.6	75.8	233	11.3	3.1	<.2	1.24	0.071	151	0.06	1.2
Pile D	5+/-	55.36	2.1	1.77	28.06	10.57	66.6	202	16.9	3.8	<.2	1.03	0.041	85	0.05	1

U=Upper, L=Lower; Bnch = Bench S = surface sample D= sample about 70 cm depth

**TABLE 7
SURFACE COAL, HANGING WALL AND FOOTWALL MATERIAL MINE B
SEAM 1 IS LOWEST IN SECTION**

Seam	ash %	thick ppm	Se ppm	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Co ppm	Cd ppm	P %	Hg ppb	Te ppm	Ga ppm
14 coal	14.1	1	1.4	1.17	13.2	5.3	11.8	109	7.3	1.3	0.38	0.084	7	0.03	0.5
13 coal	5.4	1.5	0.7	0.7	5.4	2.2	8.3	26	5	1	0.1	0.062	< 5	0.02	0.2
12 coal	25.7	1.5	1.4	1.44	16.8	6.2	44.9	114	4.6	1.8	0.71	0.024	18	0.03	0.3
11 HW	64.1	0.5	2.5	3.05	20.8	14.3	98.7	192	26.8	5.1	1.04	0.024	270	0.06	1.3
11 coal	6.4	1.5	0.4	0.65	5.0	1.9	6.2	32	1.6	0.4	0.07	0.129	< 5	0.03	0.2
10 coal	11.1	1.5	0.9	1.02	6.1	3.5	8.5	37	3.7	0.8	0.11	0.081	11	0.03	0.3
10 coal	53.1	1	2.1	1.48	19.6	10.4	56.6	207	5.2	1.7	1.31	0.04	20	0.06	0.8
9 HW	68.5	0.15	3.4	1.95	36.2	19.2	199.1	285	40.4	8.4	2.79	0.142	122	0.12	1.6
9 HW	86.5	0.15	3.1	3.46	28.9	17.8	151.7	259	46.5	9.1	1.49	0.142	93	0.07	3.2
9 coal	8.9	1	0.6	1.49	11.1	3.2	9.4	58	5.6	2.1	0.1	0.1	< 5	0.05	0.3
9 HW	73.7	0.2	2.5	1.69	24.8	14.2	73	431	6.9	1.2	0.96	0.01	33	0.02	1.4
8 coal	18.0	2.5	1.8	1.73	8.4	3.3	52.2	93	4	0.4	0.36	0.054	88	0.03	0.5
8 parting	76.6	2.5	3.7	2.18	31.8	13.5	164.9	547	20.3	5.4	2.56	0.065	53	0.07	1.6
8 coal	16.9	3	1.2	1.65	10.4	4.2	33	108	5.1	0.6	0.51	0.044	14	0.02	0.3
7 HW	82.7	0.2	4.8	4.13	34.0	21.7	185.9	326	65.6	15.9	1.93	0.125	84	0.04	2.1
7 coal	18.4	1.5	1.4	1.09	9.0	4.6	23.4	56	4.2	1.3	0.34	0.012	14	0.02	0.4
7 parting	82.9	0.1	1.7	0.56	20.5	8.5	11.8	139	3.7	1.4	0.42	0.003	9	0.05	1.5
7 coal	18.4	1.5	0.6	1.72	10.7	2.3	25	33	3.4	0.7	0.3	0.008	43	< .02	0.6
7 FW	71.3	0.3	3.7	4.99	26.7	16.9	117.4	156	45.4	11.1	1.08	0.025	263	0.05	1.7
7 FW	44.8	0.5	3.5	6.35	24.7	13.2	150.2	145	30.4	5.7	1.32	0.128	121	0.07	1.3
6 coal	20.8	4	1.6	1.59	25.5	8.9	20.1	75	7	2.1	0.33	0.05	38	0.05	0.3
5 HW	70.1	0.5	2.8	1.34	26.0	16.7	121.2	265	28.1	17.3	0.81	0.051	62	0.07	1.3
5 coal	8.4	1.5	0.4	0.78	5.6	2.6	4.6	19	2	0.2	0.05	0.218	< 5	0.03	0.3
5 FW	63.7	1.5	1.4	1.27	17.0	8.4	96.8	129	7.5	2.5	0.6	0.042	24	0.03	1.6
4 coal	14.2	2	1.2	0.5	10.1	5.4	13.3	38	5.1	1.6	0.22	0.034	12	0.03	0.2
3 coal	21.2	1	1.7	2.21	16.6	6.1	57.5	98	6.7	1.5	0.7	0.029	23	0.03	0.2
3 coal	39.1	2	2.7	1.57	18.8	8.6	61.1	161	10.3	1.6	1.2	0.034	19	0.04	0.3
2 coal	21.3	2	0.5	0.22	5.0	4.0	4.6	21	3.1	0.7	0.04	0.12	< 5	< .02	0.1
1 coal	57.0	3	3.3	4.26	37.3	11.1	98.4	262	21.3	5.1	1.35	0.067	101	0.06	0.9

HW=hanging wall and FW= footwall

TABLE 8
SURFACE COAL, HANGING WALL AND FOOTWALL MATERIAL MINE E
SEAM 1 IS LOWEST IN SECTION

Seam	thick	ash	Se	Mo	Cu	Pb	Zn	Ag	Ni	Co	Cd	P	La	Cr	Hg	Te	Ga	
		%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	%	ppm	ppm	ppb	ppm	ppm	
15	coal	2	13.4	4	0.53	6.0	2.1	13.2	49	7.7	0.4	0.25	2.9	9.1	12	0.02	0.2	
14	coal	1.5	25.3	2.8	0.71	14.0	6.6	11.5	133	3.2	0.7	0.19	6.6	5.5	11	0.06	0.2	
13	coal	1	29.6	5.5	1.25	23.2	8.7	47.3	90	9.9	3.4	0.48	14	12	51	0.09	0.5	
12	coal	1.5	11.7	1	0.67	18.5	3.5	5.5	50	2.2	0.8	0.23	0.199	10.4	2.6	10	0.07	0.2
11	coal	1	11.5	1.9	1.34	9.7	7.0	14.3	58	5.5	1.1	0.18	0.13	8.3	2.3	17	0.04	0.2
10	HW	2	54.4	3.3	2.44	25.5	11.5	109.5	332	18.3	4.9	2.08	6.3	12.6	59	0.07	0.8	
10	coal	6	25.4	2.4	1.69	18.6	7.1	24.4	153	5.6	1.1	0.64	7.7	10.6	16	0.06	0.3	
10	FW	0.3	52.7	3.7	2.89	25.2	10.1	99.5	318	21.6	3.4	2.02	0.062	4.8	15.8	44	0.04	0.5
	interB	6	86.7	3.2	3.11	25.0	15.8	152.1	410	32.6	5.2	1.95	0.123	9.8	31.8	66	0.05	2.3
9	coal	3	40.6	3.5	2.9	20.2	9.9	100.2	173	12.5	3.7	1.36	0.096	10.4	9.2	48	0.07	0.6
	interB	15	87.6	2.5	2.07	24.4	12.0	106.4	375	27.3	5.6	1.52	0.098	9.5	32.6	60	0.06	1.9
8	HW	0.4	32.1	4.7	2.6	20.3	8.1	34.0	188	16.8	2.2	0.87	0.035	2.6	7.7	22	0.03	0.7
8	HW	0.4	88.1	5.1	1.85	34.0	15.5	114.4	384	26.4	4.4	1.9	0.093	5.1	15.2	81	0.08	1.6
8	coal	3	20.2	2.1	1.77	15.1	5.6	43.8	93	6.5	1.5	0.46	0.117	6.9	9.5	19	0.04	0.4
8	coal	0.1	50.6	1.6	1.66	15.4	12.3	6.7	86	3	0.8	0.26	0.006	3.3	<.5	90	0.07	0.6
8	coal	0.3	53.9	5.9	4.12	29.3	14.3	142.4	254	18.9	5.3	1.55	0.003	1.9	9.4	147	0.06	0.4
7	coal	1.5	22.5	5.5	2.82	12.7	6.6	63.6	99	16	1.6	0.38	0.142	10.1	9.5	45	0.08	0.5
6	coal	2	64.0	3.8	3.1	30.2	10.4	95.7	420	12.2	1.6	2.17	0.091	12	20.9	51	0.06	0.9
5	HW	0.2	86.0	4.9	3.58	51.3	17.4	292.3	472	51.2	9.6	4.83	0.145	7.8	22.9	186	0.07	2.2
5	HW	0.2	88.8	3.9	2.27	40.4	15.7	194.3	430	41	6.9	3.37	0.163	8.6	24.8	101	0.07	2.5
5	coal	1.5	20.4	1.8	1.91	16.6	4.8	34.9	101	11.1	2.3	0.69	0.13	10.8	6	31	0.04	0.4
5	FW	1.5	74.6	4.8	3.02	37.4	14.8	216.7	433	26.2	5.5	2.69	0.102	8.4	18.2	146	0.08	1.4
4	coal	3	67.3	2.7	2.49	28.1	12.8	118.9	212	21.9	4.4	1.1	0.06	10.3	10.9	80	0.03	1
3	coal	2.5	14.1	0.7	1.19	14.5	4.8	21.7	58	3.1	1.1	0.6	0.145	8.8	8.1	75	0.03	0.2
	interB	6	85.6	4.7	2.79	37.5	15.8	243.6	553	43.2	6.6	3.87	0.188	17.8	32.8	131	0.07	2.5
2	coal	0.3	42.6	1.5	5.96	20.8	6.2	12.8	296	12.7	1.4	0.23	0.041	8.3	12.6	30	0.04	0.4
	interB	2	84.4	3.9	2.96	30.2	14.9	217.6	525	40.8	8.2	2.65	0.143	14.4	23.9	248	0.06	2.4
	interB	6	87.4	4.8	2.7	39.7	17.0	238.5	548	36.7	6.7	4.11	0.195	14.1	29.9	229	0.08	2.6
1	HW	4	78.5	3.2	2.43	37.8	20.0	193.6	350	28.4	7.5	2.46	0.071	8.3	18.2	122	0.07	1.4
1	coal	2.5	18.1	1.3	1.05	25.1	10.4	28.2	34	3.6	2.2	0.18	0.124	13.4	0.6	22	0.05	0.4
1	parting	0.3	72.3	2.8	2.05	18.1	9.5	230.0	346	25	4.2	2.55	0.049	4.6	24	97	0.05	1.2
1	coal	5	29.8	1.7	4.61	19.8	7.1	34.2	109	5.8	1.3	0.27	0.122	8.9	3.2	26	0.05	1.1
1	FW	4	73.3	5.3	3.62	42.1	14.6	176.7	653	31.8	5	3.62	0.117	9.7	18.9	147	0.08	1.4

TABLE 11
ICP-MS, PROXIMATE AND OXIDE ANALYSES ON
SHEARED COAL

	Se	Mo	Cu	Pb	Zn	Ag	Ni	P
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	%
Mine B seam 1								
F	2	0.48	2.65	1.94	17.4	11	1.7	0.02
S	1.3	0.92	10.62	5.68	31	67	2.5	0.083
Mine E seam 8								
F	2.1	1.77	15.1	5.6	43.8	93	6.5	0.12
S	1.6	1.66	15.44	12.33	6.7	86	3	0.006
S	5.9	4.12	29.34	14.26	142.4	254	18.9	0.003
S	5.5	2.82	12.66	6.58	63.6	99	16	0.142
	M% ad	VM% ad	Ash% ad	FC% ad	B/A			
F			6.54					
S	0.35	22.89	22.01	54.75	0.083			
F			20.2					
S	0.25	19.48	51.92	28.35	0.017			
S	0.32	15.62	54.24	29.82	0.089			
S	0.36	20.56	23.74	55.34	0.052			

B/A ratio of base to acid oxides. F=Fresh S=Sheared

DISCUSSION

TAILINGS POND DATA

Cores were collected from 2 ponds. Seven cores were collected from the pond C (Figure 3), which has been inactive for about 20 years, although it is periodically flooded to stop it from drying out and generating dust. Five cores were collected from pond B, which is active. Tailings enter the ponds via spigots, which are periodically moved. It is therefore impossible to document a detailed and consistent pond stratigraphy. However, based on annual clean coal production, yield and size of the pond it is possible to estimate average accumulation rates, which probably range from 20 to 50 cm per year in compacted material. This means that a 3 metre core probably represents from 5 to 10 years of accumulation.

Tailings pond material consists of the solid tailings and interstitial water. The material has the consistency of wet mud 10 cm below the surface. It is difficult to estimate the water content but core recovery results provide sufficient data to make an informed estimate. The cores experienced an average compaction of 24% (Table 2) as they were ex-

TABLE 9
ANALYTICAL DATA FOR COAL SAMPLES COLLECTED FOR SE VERSUS PETROGRAPHY STUDY

B/A	Se	Mo	Cu	Pb	Zn	Ag	Ni	Co	Cd	P	La	Cr	Hg	Te	Ga	
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	%	ppm	ppm	ppb	ppm	ppm	
T	4.2	2.3	25.7	11.0	130.3	178	11.4	3.2	1.32	0.059	7	9.2	85	0.03	0.3	
1D	1.4	1.61	14.1	5.0	4.1	70	1.6	0.5	0.28	0.051	8.6	2.9	12	0.05	0.1	
2B	2.3	1.7	7.0	7.9	5.1	40	2.8	0.7	0.19	0.044	4.7	3.5	5	0.03	0.1	
3D	0.027	2.2	1.87	17.7	7.8	4.2	136	2.7	0.5	0.11	0.004	1.1	7	7	0.04	0.1
4B	0.020	2.6	1.8	18.3	9.4	2.5	87	5.2	1.1	0.03	0.003	1.8	5.5	6	0.02	0.1
5D	0.011	1.4	1.69	11.8	4.8	3.7	56	3.2	1.4	0.15	0.002	1.8	3.5	< 5	0.03	0.1
6B	0.015	1.2	1.41	10.6	3.8	2.6	29	1.9	1.5	0.14	0.008	8.1	< .5	< 5	0.02	0.1
7D	0.030	6.5	8.9	10.4	7.9	6.9	40	9.6	4.4	0.21	0.067	14.9	1.7	321	0.06	0.3
8B	0.035	2.5	3.36	6.9	3.7	3.4	17	5.9	2.2	0.07	0.074	15.3	2.7	86	0.03	0.4

	coal analyses					Petrography Volume %		
	M% ad	Ash% ad	VM% ad	VM% daf	FC% ad	Reactives	Inerts	Mineral matter
A T	0.3	36.4	17.3	27.3	46.0	70	10	20
A 1D	0.32	23.5	18.8	24.7	57.4	43	39	18
A 2B	0.37	5.8	24.5	26.1	69.4	85	14	2
A 3D	0.37	31.1	17.5	25.6	51.0	44	36	20
A 4B	0.46	5.0	26.2	27.7	68.4	93	4	3
A 5D	0.39	12.1	23.3	26.6	64.2	73	20	6
A 6B	0.44	5.9	26.7	28.5	67.0	92	4	5
A 7D	0.44	11.1	21.5	24.3	67.0	53	39	8
A 8B	0.4	4.6	25.1	26.4	70.0	83	15	2
G 1T	0.93	1.8	12.7	13.0	85.5	62	33	5
G 2T	0.81	12.7	12.4	14.2	74.9	61	28	10
G 3T	0.75	2.4	12.5	12.8	85.1	47	51	2
G 1B	0.73	1.7	14.9	15.2	83.4	76	22	1
G 2D	0.7	1.4	13.1	13.3	85.4	58	40	2
G 3B	0.67	13.2	14.8	17.0	72.1	81	6	13
G 4D	0.6	3.8	12.7	13.2	83.5	53	44	3

A samples from Mine A G samples from Gething Formation

T=total seam B= bright lithotypes D=dull lithotypes. B/A ratio of base oxides to acid oxides

tracted, and once at surface they retained water filling intergranular porosity. The measure of compaction using the compression resulting from driving the pipe into the tailings materials vary based on length of core and pond character. In the active pond B, cores of 3 to 4 metres length compacted 22%. In the inactive pond C, cores varying from 2.7 to 3.7 metres length compacted 16%. These compaction amounts are estimates of the water, which was expelled as the cores were forced into the barrel. The resulting cores probably contained 5% to 25% water. After recovery of the core, most of this water was evaporated and the dry tailings held any trace metals that may have originally been held in solution. There are therefore three samples to consider, the expelled water, which was not sampled, the included water, which in

terms of dissolved solids, was probably combined with the final tailings sample, and finally the solid tailings sample.

The distilled water leaches for core B00-50 (Table 5) indicate concentrations of elements in the included and expelled water phases as well as any easily leached phase pre-existing on the solid sample. Elements originally in solution were probably precipitated on the solid tailings in a water-soluble form, as the tailings cores dried. Therefore, these elements should be extractable by a distilled water leach.

The different leaches applied did not remove significant Se from the dried samples, and in fact most samples were below detection limits (Table 5). This is not the case

TABLE 10
ICP-MS PROXIMATE AND OXIDE ANALYSES ON WEATHERED COAL

	M% ad	Ash% ad	VM% ad	VM% daf	FC% ad	B/A	Se ppm	Mo ppm	Cu ppm	Pb ppm	Zn ppm	Ag ppm	Ni ppm	Cd ppm	Bi ppm	P %
Seam 1																
weathered	1.5	6.5	26.3	28.6	65.7	0.53	2	0.48	2.65	1.94	17.4	11	1.7	0.1	0.03	0.017
↓	1.3	7.3	26.5	29.0	65.0	0.25	1.1	0.35	2.94	3.42	3.8	11	1.6	0.08	0.03	0.034
↓	0.9	10.0	26.4	29.6	62.8	0.06	5.7	0.51	5.75	2.15	53.3	27	18.4	0.28	0.07	0.008
fresh	0.5	56.6	14.6	34.1	28.3	0.09	3.6	1.23	25.13	12.55	105.8	224	24.3	1.18	0.22	0.055
seam 2																
weathered	2.6	9.5	31.6	36.0	56.2	1.22	1.5	0.4	11.96	1.52	31.8	30	22.6	0.88	0.03	0.044
↓	0.6	20.8	26.1	33.1	52.6	0.03	8.4	1.83	15.14	7.6	34.5	60	9.9	0.63	0.18	0.05
↓	0.4	17.1	27.3	33.1	55.1	0.09	2.1	2.38	10.82	7.49	25.5	53	8.8	0.16	0.11	0.336
fresh	0.6	4.9	29.0	30.7	65.5	0.14	0.6	0.89	5.44	2.23	2.8	12	2.4	0.04	0.02	0.003

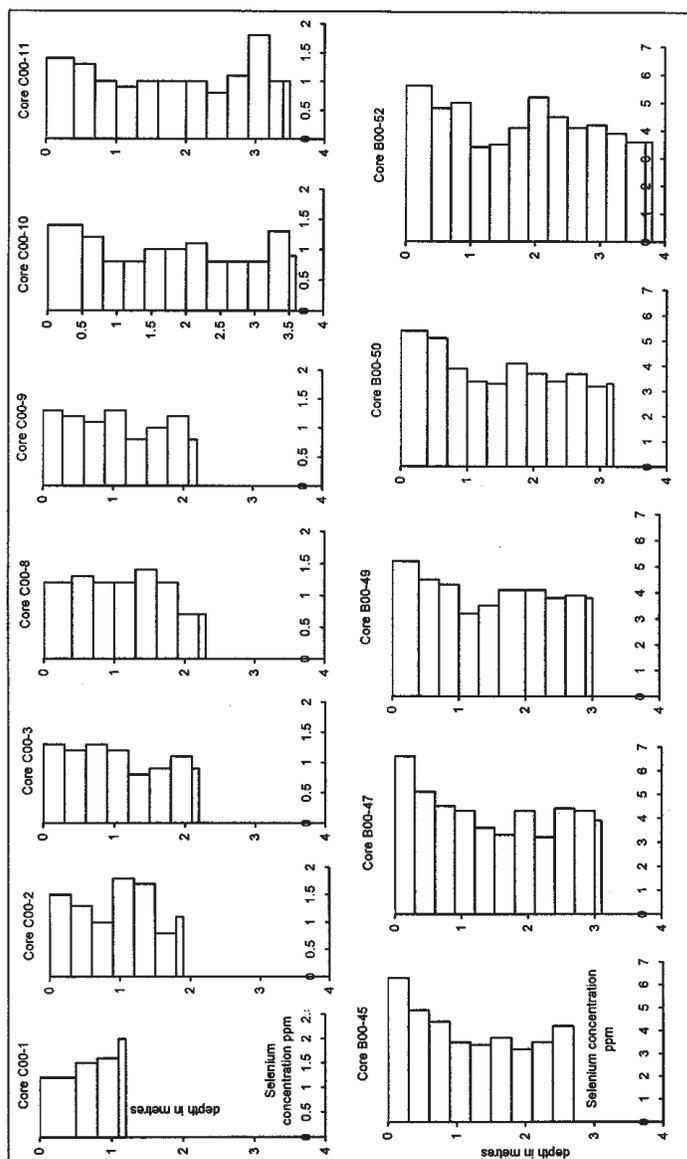


Figure 3. Se stratigraphy for the tailings ponds cores.

TABLE 12
COMPARISON OF RECENT AND OLDER REFUSE MATERIAL
DATA SEMI QUANTATIVE BASED ON LIMITED NUMBER OF ANALYSES

	A mine				C mine				B mine			
	Se	ash	N	yr	Se	ash	N	yr	Se	ash	N	yr
contact material	3.5			0	2.9			0	2			0
raw coal					1.9	24.6						
HW + FW	4.3		13	0	1.8		12	0	3.8		5	0
refuse+tails recent	3.1	61.4	7		2.4		4	0	3.5	48.6	4	0
old refuse	2.45	75.8	6	15 +	2	58.2	4	15+/-	2.8	64.8	4	1--7
old tails					1.1	22.1	59	15+	4.1	74	54	0--10

contact material values from Ryan and Dittrick (2001)

N = number of samples

for the distilled water leach, in part because of increased instrument sensitivity. The water leach removed, on average, 2.6% of the Se in the dried sample. The pH and Eh conditions determine which Se species are in solution. In lower pH environments Se is reduced to Se⁰ or Se⁺⁴ and is more readily adsorbed onto Fe and Mn oxyhydroxides (Belzile *et al.*, 2000). Some of this Se would reenter solution in the distilled water leach, especially considering the proportions of solid to liquid (1 g solid to 20 ml distilled water). The water-leach Se therefore represents Se, which was in the pore water but precipitated onto the tailings as they dried. Se that in the tailings pond was adsorbed onto the tailings but was released into solution in the neutral pH distilled water leach.

It is not possible to differentiate pore water Se from Se adsorbed onto the tailings. However, the maximum amount of Se possible in solution can be estimated by assuming all the leach Se was originally in the pore water. Because leach results are reported in terms of the solid sample some assumptions are made. If the water leach phase represents material that was in the included water associated with the samples after compaction and before drying, then based on an assumed water content of 10% by volume and an assumed dry specific gravity of the tailings of 2, the concentrations reported have to be increased by a factor of about 18. This means that a Se water leach concentration of less than 0.2 ppm (ranges up to 0.153 ppm) removed from the solid could represent a concentration in the pore water of 2.7 ppm. This is much higher than concentrations generally reported for pore waters in sediments (Velinsky and Cutter, 1991), Belzile *et al.*, 2000) (Weres *et al.*, 1989) and indicates that a significant amount of the leach Se must be adsorbed in the tailings pond and not in solution in the pore water. The distilled water leach did not remove high concentrations of any of the elements noted in Table 5, indicating that concentrations reported for tailings approximate those of dry tailings with little influence from pore water material.

It is important to determine if the tailings ponds data indicate:

1. Any substantial loss of Se over time.
2. Any remobilization of Se.
3. Changes in the mineralogical association of Se compared to fresh samples.

It appears that the older tailings pond C (15 years+) has lost Se compared to the younger pond B. However, much of the difference in Se contents can be explained by the difference in ash contents between the two ponds. Cores from pond C average 22.1% ash and those from pond B average 79.4% ash. There is no indication of Se decreasing with depth in the cores (Figure 3). Most of the variations in concentration with depth can be explained by changes in ash content. The average Se concentrations of the tailings are broadly similar to the concentrations of fresh equivalent rock types.

Se concentrations appear to be a bit higher in older material within tailings pond B than for younger, surface materials (Table 12). This is explained by the addition of pyrite to the tailings. In tailings pond C, average Se concentrations are lower than for surface rocks. Part of the reason is the low ash content of the tailings, which should be compared to raw coal rather than hanging wall or footwall material. As a further complication, the tailings represent material from the lower seams in the section that have below average Se concentrations and the raw coal Se and ash data in Table 12 are average values calculated using the full section. Consequently, it cannot be proven that the low Se contents in tailings pond C represent loss of Se over a fifteen-year period, because it is difficult to know what bench mark fresh Se concentration to use for comparison. The pyrite concentration in the tailings pond C is about 0.2% (Figure 4) and there is no correlation of Se with pyrite. If there has been any addition of pyrite to the tailings and formation of a Se pyrite mineral (as discussed later) for pond B, then the pyrite has been removed over the years and this could be reflected in a loss of Se.

The 12 cores from the 2 tailings ponds have a remarkably consistent stratigraphy (Figure 3) The Se concentra-

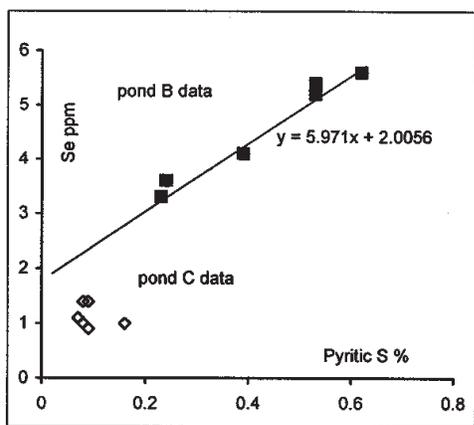


Figure 4. Pyritic S *versus* Se for tailings material from ponds B and C.

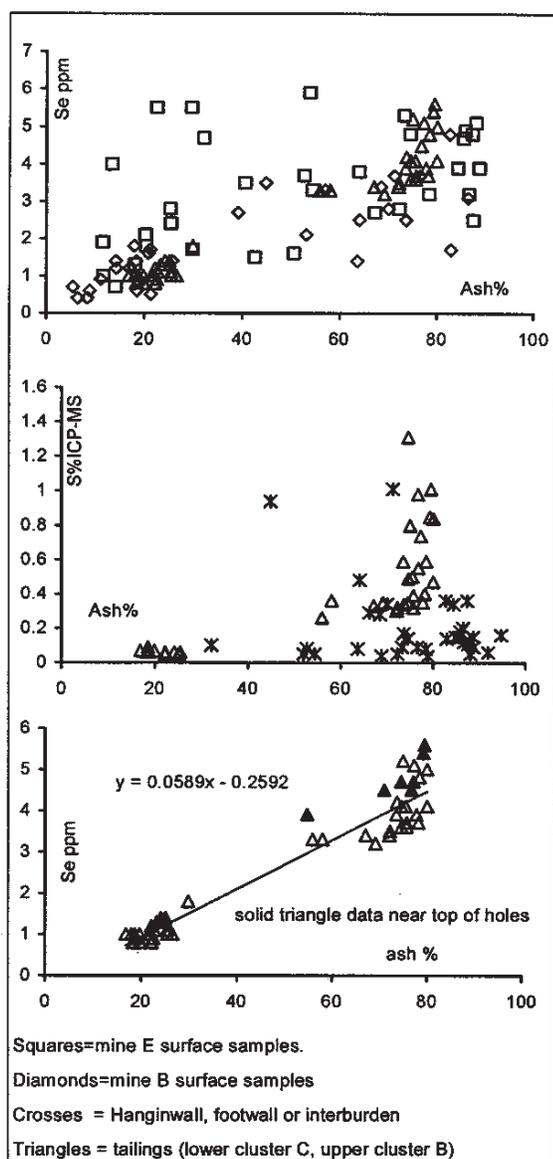


Figure 5. Ash *versus* Se and Ash *versus* Sulphur plots for surface and tailings samples.

tions peak at the surface and at a depth of about 1 to 2 metres in both ponds. This may indicate an upward migration of Se caused in part by changing pH and Eh with depth in the water column. Any migration of Se will change the inter element correlations and the ash *versus* Se relationship seen in fresh samples. Ash content data are available for four holes and Se *versus* ash data correlate (Figure 5), and have a similar distribution to that seen in fresh samples. Also, the ash and Se stratigraphic profiles for the 4 tailings cores (Figure 6) are similar, indicating that, if Se has been mobilized, then it has retained an ash relationship. However, if the data points from the top of the core holes are identified on an ash *versus* Se plot (Figure 5) they appear enriched in Se relative to ash. This could indicate upward migration of Se probably into higher pH environments in the tailings pore water or the effects of evapo-concentration as the tailings are repeatedly flooded.

Changes in the mineralogical association of Se may effect the correlation of Se with other elements. The data in Table 13 are linear correlation coefficients (R) for Se against other elements. In coal, hanging wall and footwall samples, the most obvious conclusion from the data is an absence of any correlation with S. This may indicate that Se is not associated with organic sulphur or pyrite in these rock types and may occur adsorbed onto clays or as selenides. In Interburden rocks there is a better correlation of Se with S and a number of trace metals. This is compatible with a selenide and/or sulphide association. In the coarse refuse of variable age and tailings pond B there is a strong correlation of Se with S and an increased correlation with Fe and Mn (Table 13).

Tailings material contains higher sulphur, at a given ash content, than fresh hanging wall, footwall or interburden material (Figure 5), probably because it is enriched in pyrite liberated from the raw coal during washing. The Fe concentration of tailings is also higher than for hanging wall and footwall material (Figure 7), probably because of the addition of pyrite and siderite liberated from raw coal. Both of these minerals have been identified in coal and in partings associated with the coal. The sulphur-form data (Table 14) for samples from pond B indicate a pyrite content of about 0.8% (calculated assuming $\text{pyrite\%} = \text{Pyritic Sulphur\%} \times 1.87$). There may have been removal of some pyrite by oxidation, but a lot of the increase in Fe content may be caused by the addition of siderite. An addition of about 0.8% pyrite to tailings material would increase the average Se concentration above that of the hanging wall, footwall and parting material in the pit, which is the source of much of the tailings. If the concentration of Se in pyrite is in the range of 25 ppm, then this would increase the Se concentration in the tailings by about 0.25 ppm and this is about the increase seen in comparing hanging wall and footwall material to the average Se content of the tailings in pond B (Table 12).

It is important to try to determine the concentration of Se in pyrite associated with the coal seams and with pyrite in the tailings ponds. Some analyses and data from the literature discussed in Ryan and Dittrick (2001) indicate that the Se content in massive pyrite in the Mist Mountain Formation and in coal is low, generally less than 50 ppm. An analy-

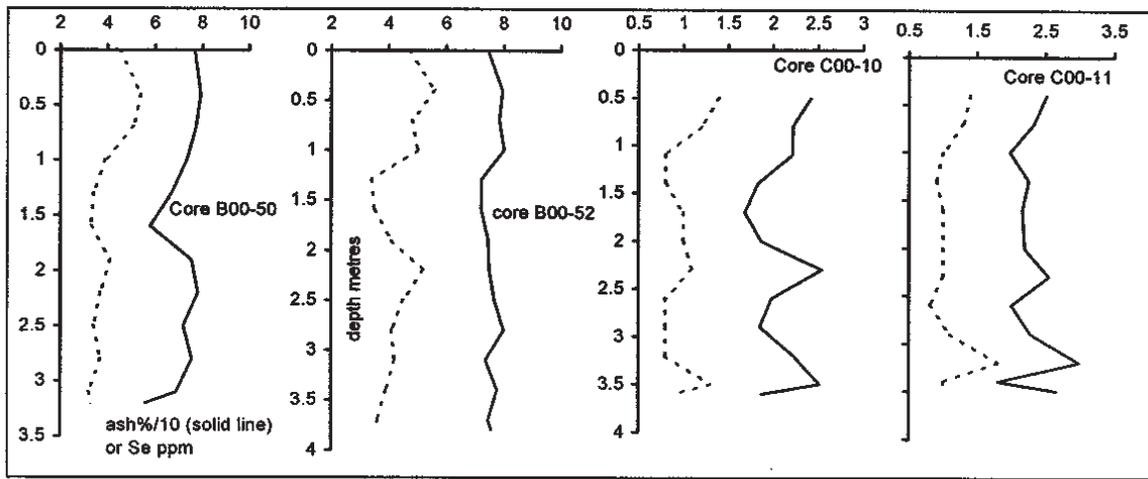


Figure 6. Se and Ash profiles in 4 holes. The X axes are ppm Se or percent ash divided by 10.

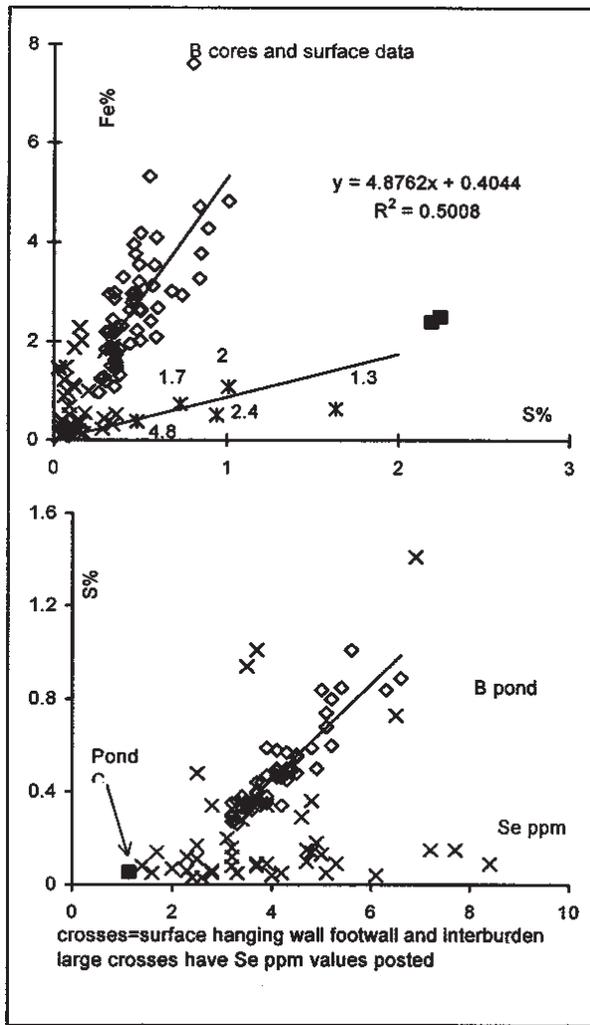


Figure 7. S versus Fe plot with pyrite line.

TABLE 13
LINEAR CORRELATION (R) FACTORS OF SE WITH
OTHER ELEMENTS FOR DIFFERENT ROCK TYPES

	coal	HW + FW	interB	weathered coal samples	refuse mixed age	B pond cores	C pond cores
number	53	31	14	8	14	53	58
ash%	32.8	76.6	83.9	16.0	67.7	73.9	22.1
S*	.04	.13	.44	.36	.95	.91	-.29
Mo	.42	.43	.89	.35	.84	.90	.46
Cu	.33	.53	.92	.36	-.42	.19	.46
Pb	.45	.30	.91	.33	-.28	.76	.55
Zn	.49	.41	.84	.41	.26	.22	.03
Ag	.30	.56	.92	.22	.42	.67	.58
Ni*	.56	.34	.87	.36	.27	.80	.25
Co	.54	.39	.34	.33	-.23	.90	.17
Mn*	-.14	.05	-.51	.01	.34	.52	.29
Fe*	-.12	-.04	-.35	-.04	.38	.65	.25
As**	.09	.19	.27	.08	.50	.62	.55
U*	.43	.50	.93	-.13	.37	.73	.30
Th*	.13	.35	.53	.46	.20	.27	.34
Sr*	.13	-.12	-.02	.09	.49	-.05	.53
Cd	.39	.40	.89	.32	.27	.68	.73
Sb**	.30	.43	.92	.33	.13	.75	.47
Bi	.33	.37	.79	.60	-.27	.42	.41
V*	.23	-.13	.23	.48	.26	.17	.39
P*	-.07	.34	.46	-.11	.49	.24	.26
La*	.20	.17	.58	.07	.45	.02	.44
Cr*	.28	-.36	-.40	.15	.24	.14	.26
B*	-.32	.11	.56	.15	-.11	-.32	-.36
Na*	.08	.25	-.63	-.18	.17	.57	-.04
Sc*	.41	.03	.42	.67	-.21	.53	.03
Hg	.47	.24	.76	-.01	.17	.67	.31
Te	.40	.43	.77	.24	-.06	.36	.17
Ga	.24	-.19	.25	.51	.29	.37	.60

* partial extraction

** possible loss by volatilization

sis of massive pyrite from a coal seam in this study provided a concentration of 25 ppm. There is, however, always the possibility that the finely disseminated pyrite in coal seams, hanging wall and footwall material has higher Se contents. Some outcrop data in the Fe versus S plot (Figure 7) appears to scatter along a pyrite line. The Se contents are posted next to these points and do not indicate any trend of increasing Se with increasing pyrite content making it unlikely that there are higher concentrations of Se in pyrite.

Sulphur-form data in the tailings ponds indicate the presence of some pyrite (Table 14). A pyritic S versus Se plot (Figure 4) indicates that pyrite in pond B contains 319 ppm Se (5.971×53.4 , the slope of the line in Figure 4 is 5.971 and 53.4% S=100% pyrite). This assumes that the ASTM method for identifying pyrite works on tailings material. If the method is appropriate, there is strong evidence for the formation of diagenetic Se-rich pyrite. The Y (Se) intercept in Figure 4 indicates that about 2 ppm Se is not associated with sulphides. There is very little (about 0.2%) pyrite in tailings in pond C and no Se versus pyritic S relationship. If this secondary mineral was present it has been removed over the years.

Belzile *et al.* (2000) studied the distribution of Se in lake sediments. They found that in sediments near the water interface higher pH environments increased Se solubility. Within the sediments, reduced pH favoured the adsorption of Se as Se^{+4} onto Fe-Mn oxyhydroxides, with a preference for Fe oxyhydroxides, (Balistrieri and Chao, 1990). Further reduction of pH deeper into the sediments favoured the formation of Se^0 and precipitation of diagenetic minerals such as achavalite ($FeSe$) and ferroselite ($FeSe_2$) or the incorporation of Se into pyrite to form Se-pyrite. In tailings pond B there is evidence for the formation a diagenetic Se pyrite. There is also some evidence for the formation of Fe oxyhydroxides. The 0.1 molar and 0.25 molar hydroxylamine leaches, designed to remove Fe and Mn hydroxides, together remove on average 44% of the Fe reported in the unleached samples. Fe and Mn hydroxides have been shown to adsorb Se (Belzile *et al.*, 2000). In tailings pond B, there is no clear evidence of a Se rich Fe hydroxide. However, though most of the leaches reported Se concentration below detection limit of 0.2 ppm, the 0.25 molar hydroxylamine leach designed to remove Fe hydroxides reported 4 samples with Se concentrations of 0.2 ppm. These samples correspond to samples with higher total Se and on average could imply a removal of about 4.5% of the total Se as a Se Fe-oxyhydroxide. Low concentrations of Se in the leach samples may be caused by readsorption of Se by the organic phase during the leach experiments. In pond C, in contrast to pond B, there is no correlation of Se with Fe or S (Table 13) and consequently there is no evidence for any Se pyrite.

The ASTM sulphur form analysis reports pyritic sulphur based on the amount of Fe removed by nitric acid. Pyritic-S will therefore not include sulphur in other sulphides. This will be reported as organic S, which is determined by difference after total sulphate and pyritic sulphur have been determined. This may help to explain why S measured by ICP-MS is greater than pyritic S measured by the ASTM

TABLE 14
SULPHUR FORM ANALYSES AND ICP-MS SULPHUR ANALYSES

Mine	rock type	ash %	Se ppm	S% ICP-MS	S% total	S% pyrite	S% sulphate	S% organic
C	T	24.2	1.4	0.06	0.27	0.08	0.07	0.12
C	T	25.4	1.1	0.06	0.24	0.07	0.04	0.13
C	T	18.7	0.9	0.06	0.27	0.09	0.03	0.15
C	T	25.1	1.4	0.04	0.28	0.09	0.03	0.16
C	T	21.6	1	0.03	0.27	0.08	0.02	0.17
C	T	26.5	1	0.07	0.27	0.16	0.07	0.04
B	T	79.3	5.4	0.85	0.99	0.53	0.06	0.4
B	T	75.5	4.1	0.5	0.62	0.39	0.04	0.19
B	T	55.9	3.3	0.26	0.46	0.23	0.04	0.19
B	T	79.5	5.6	1.01	1.17	0.62	0.05	0.5
B	T	75.0	5.2	0.8	0.98	0.53	0.04	0.41
B	T	75.7	3.6	0.32	0.42	0.24	0.05	0.13
B	T	ND	4.5	0.98	1.2	0.62	0.07	0.51
A	T	ND	4.7	1.31	1.42	0.64	0.07	0.71
A	R	ND	ND	0.08	0.2	0.14	0.06	0.01
A	R	ND	ND	0.29	0.42	0.28	0.07	0.07
B	C	ND	ND	0.39	0.8	0.2	0.05	0.55
B	C	ND	ND	0.46	0.9	0.35	0.03	0.52
B	C	ND	ND	0.05	0.42	0.05	0.09	0.28
B	FW	ND	ND	1.1	1.28	0.55	0.04	0.69
B	HW	ND	ND	0.34	0.62	0.22	0.07	0.33
E	C	ND	ND	0.1	0.62	0.12	0.04	0.46
E	IB	ND	ND	0.34	0.43	0.22	0.04	0.17

T=tails R=coarse refuse C=coal IB=interburden

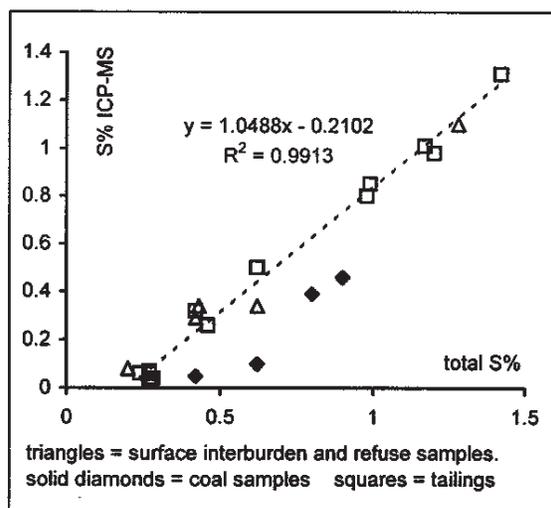


Figure 8. A comparison of S analyses by ASTM and ICP-MS methods.

method. Interpretation of S and Fe ICP-MS data is confused by the fact that the hot aqua regia extraction may not remove all the Fe or S or there may be volatile loss during the digestion. It removes a lot more Fe than that present in pyrite based on a plot of pyritic S versus Fe (ICP-MS). A comparison of total S and ICP-MS S analyses (Figure 8) indicates that the ICP-MS S measurement is a constant 0.2% low for rocks and somewhat lower for coal samples. It appears, based on S-form data (Table 13), that ICP-MS extraction measures all the pyritic S and some of the organic S, though it appears to extract less of the organic S in coal.

COARSE REFUSE MATERIAL

It is difficult to collect a lot of coarse refuse samples because of the size of each sample, which is determined by the rock fragment size. The size range of the material is determined by the processing plants and usually has a maximum size of 5 cm. A lot more samples would need to be collected for a comprehensive study. At most mines it was only possible to estimate the age of the refuse material. Though it was possible to collect material ranging in age from recent to about 15 years old.

It is impossible to compare the Se concentrations of old refuse material to those of fresh refuse material because Se concentrations of the material prior to any weathering have probably changed over time. The Se concentration of the old refuse material is not significantly lower than that of recent material (Table 6). However in most cases the older refuse has similar or lower Se concentrations than the average value for recent refuse material. These comparisons should be treated with caution because they are based on only a few samples. There does not appear to have been a major remobilization of Se out of refuse material. The data also appear to indicate some removal of Se from near surface material, though this may be caused by downward migration of fine material. Surface samples have similar or lower Se concentrations than samples collected at the same location but 70 cm below surface (Table 6). The only safe conclusion is that large amounts of Se are not leached out of bulk coarse refuse material over time. This conclusion might not hold for finer material which makes up a small percentage of the total refuse samples. The coarse refuse material is stored above the water table and therefore experiences a different environment from the tailings, which are constantly submerged and probably in a lower pH environment. The constant wetting and drying and oxidizing environment may make coarse refuse material more susceptible to removal of Se, because the conditions are more likely to produce the soluble oxidized forms of Se.

SURFACE DATA

Regional Variation

In 1999 stratigraphic sections were sampled at the five mines and the Se concentrations measured for all rock types, including coal seams (Ryan and Dittrick, 2001). In this study, coal seams in stratigraphic sections previously sampled at two of the mines were resampled. Because of the pro-

gression of mining samples in this study (2000) were collected from lower benches, and sample sites (1999 versus 2000) for particular seams were probably in the order of 50 metres apart. Comparison of the data (Figure 9) indicates very little lateral consistency of Se concentration within seams. The Se concentration in seams is controlled by ash content and petrography. Both can change markedly along strike within a single seam. It is unlikely, therefore, that individual seams can be characterized by a single Se concentration.

Petrography Data

Nine samples were collected from a single seam at Mine A. In addition, data are used from a study of the Gething Formation from northeastern British Columbia. In that coal quality and petrography data were already available it was only necessary to analyze the samples for Se. Four of the samples from MINE A were handpicked bright

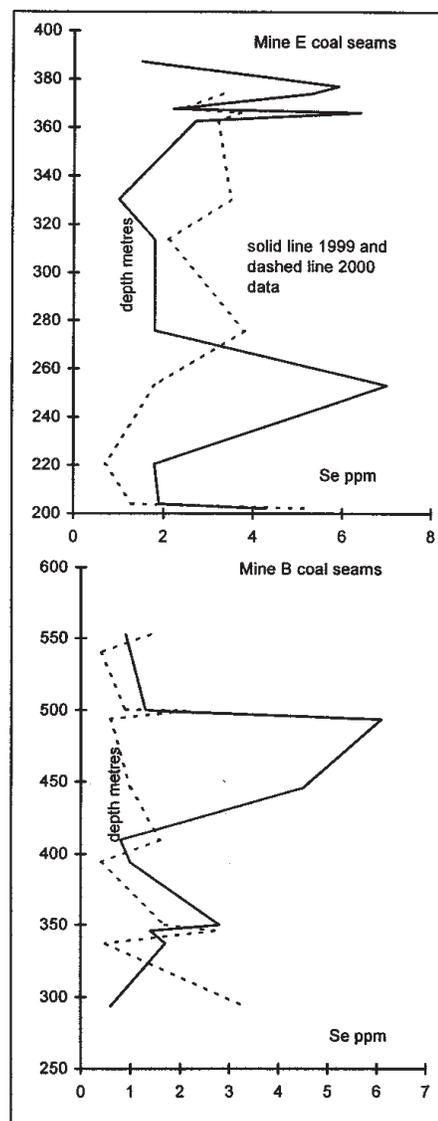


Figure 9. Lateral consistency of Se in coal seams.

coal, four were handpicked dull coal and the last was a channel sample across the whole seam. Similarly, for the Gething samples the first three samples (Table 9) are channel samples and the others are handpicked samples of bright or dull coal. The proximate analyses of the samples (Table 9) indicate dull samples from Mine A have higher ash contents than the bright samples. The volatile matter contents on a dry ash free basis are consistently higher for the bright samples than for the dull samples indicating a high reactivities content in the former. This is supported by the petrography summarized in Table 9. In the previous paper washability data was used to support the conclusion that, within the coal, Se concentrates in the reactive macerals. This is because Se is volatile and would be volatilized by forest fires responsible for charring the vegetation and initiating the formation of the inertinite. In this study based on a triangular plots of volume percentages of mineral matter inerts and vitrinite with posted Se concentrations (Figure 10) it appears that the Se is concentrated in the inert coal macerals and mineral matter.

Weathered Samples

Goodarzi, (1987) has documented the effect of weathering on Se concentrations. In this study two sets of samples were collected at Mine B going from bloom coal to fresh coal within the same seam. There is no clear pattern of deletion of Se in the samples (Figure 11). There does seem to be a decrease in S% as measured by ICP-MS, which probably indicates a removal of trace amounts of pyrite during weathering. One of the more striking changes is the increase in base/acid ratio for weathered coal. This appears to be caused by the precipitation of Mg, Fe and Ca carbonates in the weathered coal. Many trace metals seem to decrease in the weathered coal (Table 10), but there is no consistent trend.

Sheared Coal

A lot of seams have highly fractured zones or are cut by shear zones. At mines E and B, shear zones and non sheared coal from the same seam were sampled (Table 11). Sheared coal is characterized by an increase in ash content, but no major changes in trace chemistry. The base/acid ratios for the sheared coal remain low indicating that the increase in ash was the result of mixing in ground-up country rock and not the introduction of secondary carbonates. If there was a lot of water movement during shearing it does not appear to have precipitated carbonates or removed trace elements.

CONCLUSIONS

Cores of tailings material up to 4.7 metres long (before compaction) were recovered from two tailings ponds using minimal equipment. The dried tailings were analyzed for a number of elements including Se with the intention of documenting any loss of Se from the tailings ponds, mobility of Se within the tailings ponds and the mineral association of Se in the tailings ponds.

There is no clear evidence for a substantial loss of Se from the tailings. Average Se concentrations for the length

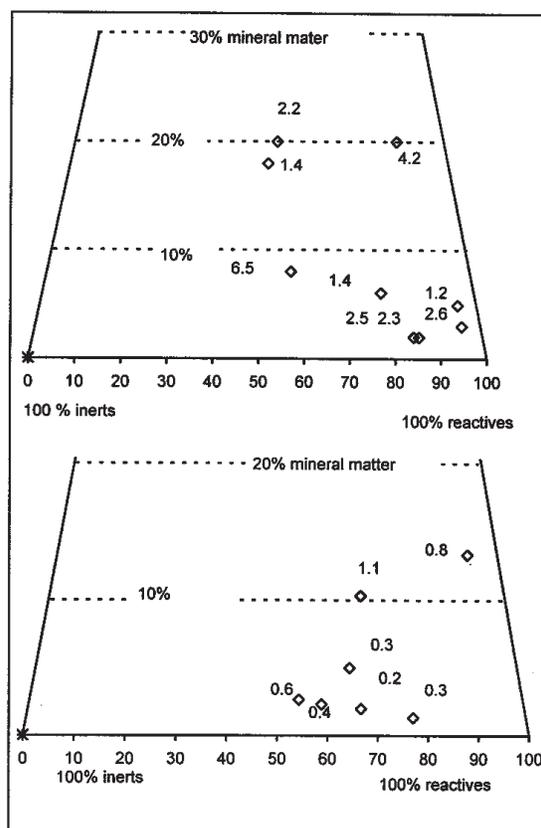


Figure 10. Triangular plot of volume percents of mineral matter, inert and reactive macerals with posted.

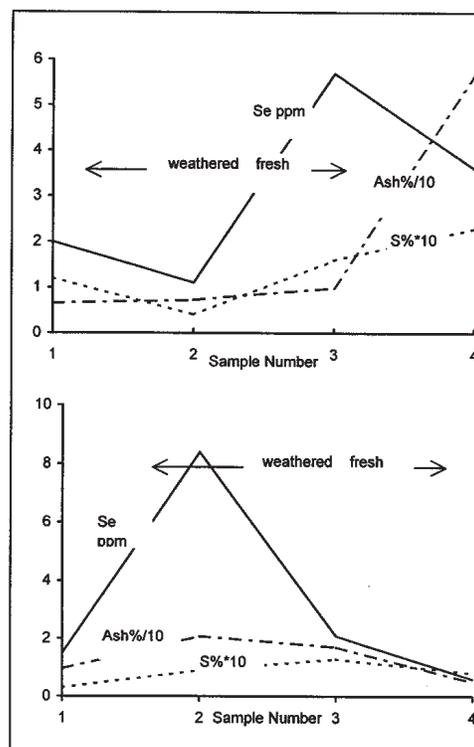


Figure 11. Profiles of Se ppm, S%*10 and Ash%/10 for 2 weathered seams Mine B.

of cores recovered are not markedly lower than what would be expected based on the Se contents of the materials being mined.

There is some evidence of movement of Se within the tailings towards the sediment water interface. Unlike Se in outcrop rocks and coal, Se in the tailings ponds seems to be in part associated with a Se rich pyrite and Fe oxyhydroxides.

There is some indication that small amounts of Se are removed from near surface coarse refuse material but more samples are required to confirm this.

A comparison of Se contents from different locations within the same seams did not reveal any strong lateral consistency in Se concentrations.

Weathering does not markedly decrease Se contents probably because there is not much pyrite in the coal and it has low Se contents. The main change is the introduction of secondary carbonates that increase the base/acid ratio.

Shearing of coal appears to be largely a mechanical process, which produces little change in the seam chemistry but does increase the ash content.

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