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MINERAL RESOURCES DIVISION

TRACE ELEMENTS IN COALS OF THE EAST KOOTENAY AND PEACE RIVER COALFIELDS, BRITISH COLUMBIA

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ABSTRACT

Concentrations of 17 elements (Sb, As, B, Br, Cd, Cl, Cr, Co, Cu, F, Pb, Hg, Mo, Se, Th, U and Zn) have been determined in channel samples collected at all active mines in the Peace River (northeast British Columbia) and East Kootenay (southeast British Columbia) coalfields. Means in whole-seam samples from both regions, excepting those elements which are below detection limits in some samples, are as follows: Sb, 1.0 ppm; As, 1.6 ppm; Br, 1.0 ppm; Cl, 136 ppm; Cr, 21 ppm; Co, 2.3 ppm; Cu, 18 ppm; F, 518 ppm; Hg, 50 ppb; Th, 3.2 ppm; and U, 1.8 ppm.

By world standards, mean concentrations of fluorine in these coals are somewhat high. Concentrations of other elements are well within estimated ranges for most world coals, and some (As, Br, Cl, Co, Pb and Hg) appear to be in relatively low concentrations. Mean values of chlorine and thorium are significantly higher in Peace River coals than in East Kootenay coals. Variations in the concentrations of most elements with stratigraphic position are similar to variations in ash content of the samples, and are probably not stratigraphically controlled.

Based on these variations and statistical correlations, nine of the eleven elements with concentrations that consistently exceed detection limit (Sb, As, Cr, Co, Cu, F, Hg, Th and U) appear to have strong inorganic associations. The other two, bromine and chlorine, appear to be associated predominantly with the organic fraction.

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INTRODUCTION

The mining, upgrading, transportation, storage and utilization of coal all introduce waste material, including trace elements, to the environment (Gay, 1989). However, the potential for release of trace elements is by far most significant in the case of coal utilization, and probably the single "most important environmental aspect of trace elements in coal" (Swaine, 1989) is related to coal combustion for generation of electricity. With growing global emphasis on the use of thermal coal, and with consideration being given to construction of coal-burning power-generating facilities in British Columbia, it is timely to consider the trace element contents of coals currently being produced in the province. This study is aimed at determining trace element concentrations in raw British Columbia coal samples from producing mines, interpreting the manner in which trace elements are associated within the coals, and determining potential for removing trace elements through beneficiation. The first two subjects are addressed in this report. Conclusions are preliminary; a more definitive assessment must await further analyses.

There are currently eight producing coal mines in the province (Figure 1), and samples were collected in 1989 at seven of these (*see* Grieve, 1992 for a list of samples). These seven mines are all in the Foreland tectonic belt, five in southeastern and two in northeastern British Columbia. Coals produced from these mines are all low in sulphur (usually <0.5%), and, in the main, are medium-volatile bituminous in rank. The coal deposits of southeast British Columbia comprise the East Kootenay coalfields, and are hosted by the Mist Mountain Formation of the Jurassic-Cretaceous Kootenay Group. Coal mines in northeastern British Columbia are in the Peace River coalfield, and are hosted by the Lower Cretaceous Gates Formation. Other coal-bearing formations of Cretaceous age occur in the Peace River

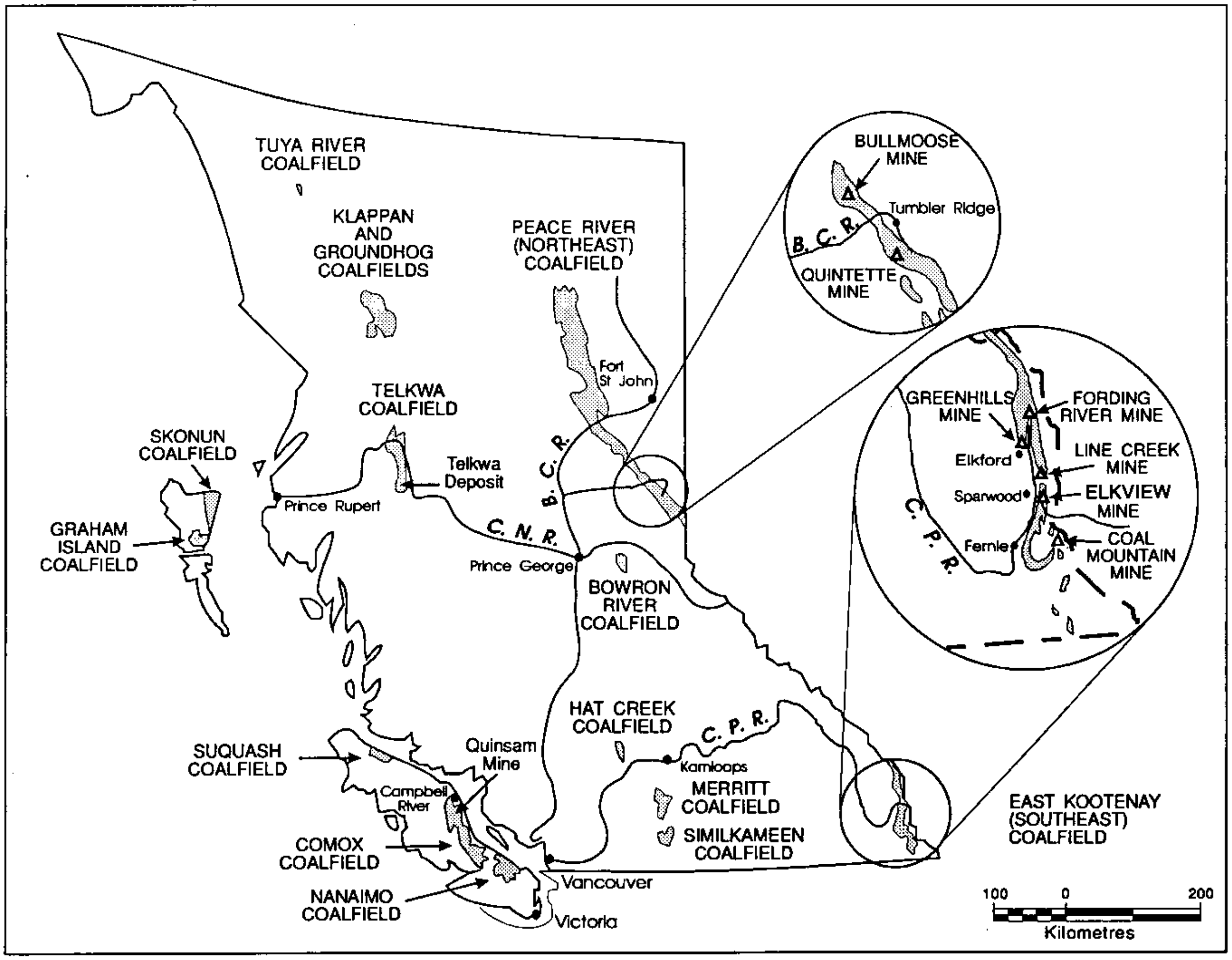


Figure 1. Outline of the province of British Columbia, Canada, with locations of all major coal basins and active coal mines.

coalfield, but were not sampled. The eighth coal mine in the province, the Quinsam mine on Vancouver Island, was also not included in the study.

Studies concerning the trace element contents of British Columbia coal deposits have been carried out on Insular Belt coals (Van der Flier-Keller and Dumais, 1988; Van der Flier-Keller and Goodarzi, 1991), Intermontane Belt coals (Dilles and Patrick, 1984; Goodarzi and Van der Flier-Keller, 1988, 1989; Goodarzi and Cameron, 1990), and Foreland Belt coals (Nichols and D'Auria, 1981; Goodarzi, 1987a, 1987b, 1988; Goodarzi *et al.*, 1985; Van der Flier-Keller and Fyfe, 1987).

To date, basic statistical analysis has been performed on trace element concentration data (*see* "Results" section, Figure 2 and Table 1). Means for the two regions have been compared using a t-test, to determine if there are significant differences in the concentrations of certain elements between the two regions (Table 1). Variations in element concentrations with change in stratigraphic position, both within formations and individual seams, have also been plotted (Figures 3 to 6). Relationships between element concentrations and ash contents have been established (Tables 2 to 4, Figures 7 to 9). These relationships provide a preliminary indication of the mode of association of the elements, that is, whether an element is dominantly associated with the inorganic or organic fraction of the coal. Correlations between different elements were also calculated (Tables 2 to 4), to provide further insight into their behaviour. The "Discussion" section of the report will provide preliminary interpretation of these analyses and comparisons between concentrations of the various trace elements in British Columbia coals and other coals, focusing on those from the United States and Australia.

It is important to note that the results given are not representative of clean coals, that is, those which have undergone coal preparation, and should not be considered typical of current or potential coal products from British Columbia. For the most part, trace element concentrations in product coals are expected to be lower than in raw coals, as most of the elements are associated with the mineral fraction of coals. However, where trace element bearing minerals are finely disseminated through an organic matrix, physical separation, and thus upgrading, may be difficult (Norton and Markuszewski, 1989).

A preliminary report on the occurrence of phosphorus in the same coal samples is given by Grieve (1992).

SAMPLING AND ANALYSIS

Channel samples of fresh coal were collected from working faces at seven open-pit coal mines in British Columbia in 1989 (Figure 1). The samples and their locations are listed in Grieve (1992). Each sample was intended to be representative of a seam or interval. Whole-seam samples were collected at six of the seven mines: Elkview, Fording River, Coal Mountain and Greenhills in southeast British Columbia, and Quintette and Bullmoose in the Peace River coalfield. In total, 30 whole-seam channel samples were collected, 22 from the southeast coalfields and eight from the northeast. At the seventh location, Line Creek mine in the Kootenay coalfields, four seams, named 10A, 10B, 9 and 8 in ascending stratigraphic order, were sampled in average 50-centimetre plies, for a total of 37 samples.

All element concentration determinations were made on raw coals. Ten elements were determined by neutron activation (Sb, As, Br, Cr, Co, Mo, Se, Th, U and Zn). Boron concentrations were determined by prompt gamma-ray spectrometry. Concentrations of copper, cadmium, lead and mercury were determined by atomic absorption, following digestion in $HCl/HNO_3/HF$. Fluorine concentrations were determined by the oxygen bomb digestion method (ASTM, 1979), known to give low results for many coals (Godbeer and Swaine, 1987; D.J. Swaine, personal communication, 1992). Chlorine values were determined by heating a mixture of coal and Eschka mixture in an oxidizing atmosphere (ASTM, 1978). The most reliable results were obtained for Sb, As, Br, Cl, Cr, Co, Cu, F, Hg, Th and U. There is more uncertainty in the results for B, Cd, Pb, Mo, Se and Zn, because some values are below detection limits. Statistical analyses of trace element data were carried out using the copyrighted software package CSS, produced by StatSoft.

RESULTS

CONCENTRATIONS OF TRACE ELEMENTS

Concentrations of elements in the whole-seam samples are displayed in Table 1 and Figure 2, and are listed individually below. For those elements for which all values are greater than the detection level, means and ranges are given, while for those elements for which some values are below detection limits, only ranges are given.

Mean concentrations of only two elements, chlorine and thorium, are significantly different in the two regions; both are higher in northeast coals than in southeast coals (Table 1).

ANTIMONY

Antimony concentrations in raw whole-seam samples range from 0.17 to 2.48 ppm, with a mean of 1.04. The mean in southeast coals is 1.13 ppm, compared with a mean of 0.77 ppm in northeast coals.

ARSENIC

Concentrations of arsenic in raw whole-seam samples range from 0.13 to 7.05 ppm, with a mean of 1.64. The mean arsenic concentration in northeast coals is 2.20 ppm, compared with a mean of 1.43 ppm in southeast coals.

BORON

Many of the samples contain less than detectable levels of boron. The range in boron contents in raw whole-seam Kootenay coals is less than 18 to 104 ppm, while boron values in Peace River coals range from 30 (or<31) to 56 ppm.

BROMINE

Concentrations of bromine in raw whole-seam samples range from 0.29 to 2.22 ppm, and the mean is 0.99. The mean in northeast coals is 1.23 ppm, compared with a mean of 0.90 ppm in southeast coals.

CADMIUM

The range in cadmium contents in raw whole-seam southeast coals is less than 0.2 to 1.4 ppm, while that in northeast coals is less than 0.2 to 0.3 ppm. However, a large

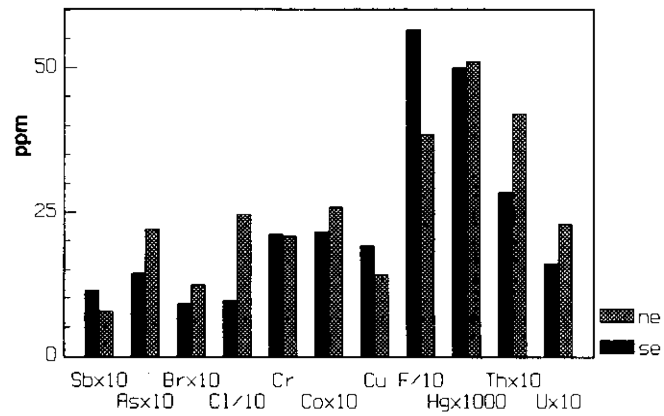


Figure 2. Comparisons of mean trace of element concentrations in the southeastern (se) and northeastern (ne) regions of British Columbia.

TABLE 1
TRACE ELEMENT CONCENTRATIONS (PPM) IN RAW COAL SAMPLES FROM NORTHEAST AND SOUTHEAST B.C.

	Southeast B.C.				Northeast B.C.				t	Both regions	
Element	Minimum	Maximum	Mean	s.d.	Minimum	Maximum	Mean	s.d.	(2-tailed)	Mean	s.d.
Sb	0.24	2.48	1.13	0.63	0.17	2.17	0.77	0.63	1.37	1.04	0.64
As	0.13	6.50	1.43	1.61	0.39	7.05	2.20	2.20	-1.05	1.64	1.78
Br	0.29	1.75	0.90	0.39	0.41	2.22	1.23	0.62	-1.76	0.99	0.47
B	<18	104	n/a	n/a	<31	56	n/a	n/a	n/a	n/a	n/a
Cd	<0.2	1.4	n/a	n/a	<0.2	0.3	n/a	n/a	n/a	n/a	n/a
Cl	40	220	96	45	150	400	246	94	-5.93	136	90
Cr	4.16	48.10	21.14	12.61	5.44	34.80	20.70	12.07	0.09	21.03	12.26
Co	0.92	3.70	2.14	0.71	0.72	4.02	2.59	1.17	-1.29	2.26	0.86
Cu	8	33	19	7.20	7	20	14	5.30	1.79	18	6.99
F	260	1090	566	230	190	690	385	191	1.99	518	232
Pb	<2	15	n/a	n/a	<2	12	n/a	n/a	n/a	n/a	n/a
Hg (ppb)	15	116	50	24	20	113	51	30	-0.10	50	25
Mo	<0.33	3.19	n/a	n/a	<0.40	1.10	n/a	n/a	n/a	n/a	n/a
Se	<0.60	3.43	n/a	n/a	<0.60	2.20	n/a	n/a	n/a	n/a	n/a
Th	0.89	5.74	2.86	1.20	1.89	7.24	4.21	2.04	-2.24	3.22	1.56
U	0.57	3.05	1.61	0.67	0.79	4.06	2.28	1.22	-1.92	1.79	0.88
Zn	<10	74	n/a	n/a	<10	53.6	n/a	n/a	n/a	n/a	n/a

n/a: not applicable

proportion of the samples contain levels of cadmium below the detection limit.

CHLORINE

Concentrations of chlorine in raw whole-seam samples range from 40 to 400 ppm, and the mean is 136 ppm. The mean in northeast coals, 246 ppm, is significantly higher than the mean in southeast coals, 96 ppm.

CHROMIUM

Chromium concentrations in raw whole-seam samples range from 4.16 to 48.10 ppm, with a mean of 21.03 ppm. The means in northeast and southeast coals are almost identical, at 20.70 and 21.14 ppm, respectively.

COBALT

Concentrations of cobalt in raw whole-seam samples range from 0.72 to 4.02 ppm, with a mean of 2.26 ppm. The mean concentration in northeast coals is 2.59 ppm, compared with the mean in southeast coals of 2.14 ppm.

COPPER

Copper contents in raw whole-seam samples range from 7 to 33 ppm, with a mean of 18. The mean value in southeast coals is 19 ppm, while the mean in northeast coals is 14 ppm.

FLUORINE

Fluorine concentrations in raw whole-seam samples range from 190 to 1090 ppm, and the mean is 518 ppm. Mean fluorine concentration in Kootenay coals is 566 ppm, compared with a mean of 385 ppm in Peace River coals.

LEAD

Some of the lead readings are below detection limit. Lead contents in raw southeast coals range from less than 2 to 15 ppm. The northeast coals contain from less than 2 to 12 ppm lead.

MERCURY

Mercury concentrations in raw whole-seam samples range from 15 to 116 ppb, with a mean of 50 ppb. In southeast coals the mean mercury concentration is 50 ppb, and the mean in northeast coals, at 51 ppb, is almost identical.

MOLYBDENUM

A large proportion of the molybdenum concentrations are below detection limit. The range in molybdenum concentrations in raw whole-seam samples from southeast British Columbia is less than 0.33 to 3.19 ppm. In northeast coals the range is less than 0.40 to 1.10 ppm.

SELENIUM

A large number of the selenium values are below detection limits. In raw whole-seam samples from southeast British Columbia selenium concentrations range from less than 0.60 to 3.43 ppm. In the northeast samples the range is from less than 0.60 to 2.20 ppm.

THORIUM

Mean thorium concentration in raw whole-seam samples is 3.22 ppm, and the range is from 0.89 to 7.24. In samples from the southeast the mean is 2.86 ppm, while in the northeast, the mean, at 4.21 ppm, is significantly higher.

URANIUM

Uranium concentrations in raw whole-seam samples range from 0.57 to 4.06 ppm, and the mean is 1.79. The mean in Kootenay coals is 1.61 ppm, and the mean in Peace River coals is 2.28 ppm.

ZINC

Some of the zinc concentrations are below detection limits. The range of zinc contents in raw whole-seam southeast coal samples is less than 10.0 to 74.0 ppm. In northeast samples the range is less than 10.0 to 53.6 ppm.

VARIATIONS WITH STRATIGRAPHIC POSITION

For the elements with concentrations consistently above detection limits, it is possible to display variations in element values with change in stratigraphic position, both for seams throughout the formations (Figures 3 and 6), and for individual ply samples within seams at Line Creek (Figures 4 and 5). These results are summarized below.

MIST MOUNTAIN FORMATION

There are no consistent stratigraphic trends in contents of any of the trace elements in whole-seam samples from the Mist Mountain Formation (Figure 3). However, several of the elements (Sb, Cr, Co, Cu, F, Hg, Th and U) show a distribution shaped like a backward letter "C". In other words, the lowest values are in samples from the base and top of the formation, while the highest values are in samples from roughly the middle one-third. The amount of variation at any stratigraphic position, especially the middle portion of the section, is high, however. This distribution is very similar to the distribution of the ash values in the samples (Figure 3L), suggesting that stratigraphic position *per se* is not a primary control on trace element concentrations.

INDIVIDUAL SEAMS

The apparent influence of ash content on the stratigraphic variations of certain trace elements is also seen within individual seams. The concentrations of several elements (Sb, Cr, Cu, Hg, Th and U) tend to increase up-section in seam 10A (Figure 4), for example, more or less mirroring the trend in ash contents within that seam. The pattern of ash contents within 8-seam is also reflected in the stratigraphic variations of the same six elements within that seam (Figure 5). The fluorine content profile in 8-seam is also similar to the ash profile, although an anomalous fluorine value occurs in a sample from between 5 and 6 metres above the base. This sample is known to contain fluorapatite (Grieve, 1992). The presence of ply samples with greater than 50 per cent ash at both the base of 8-seam and the top of 10A-seam is correlated with anomalously high concentrations of the elements listed above, as well as cobalt and arsenic. Similarities between ash and element profiles in 10B and 9-seam samples (not shown) are not as pronounced, but profiles of three elements, chromium, copper and thorium, appear to mirror the ash profiles in both seams.

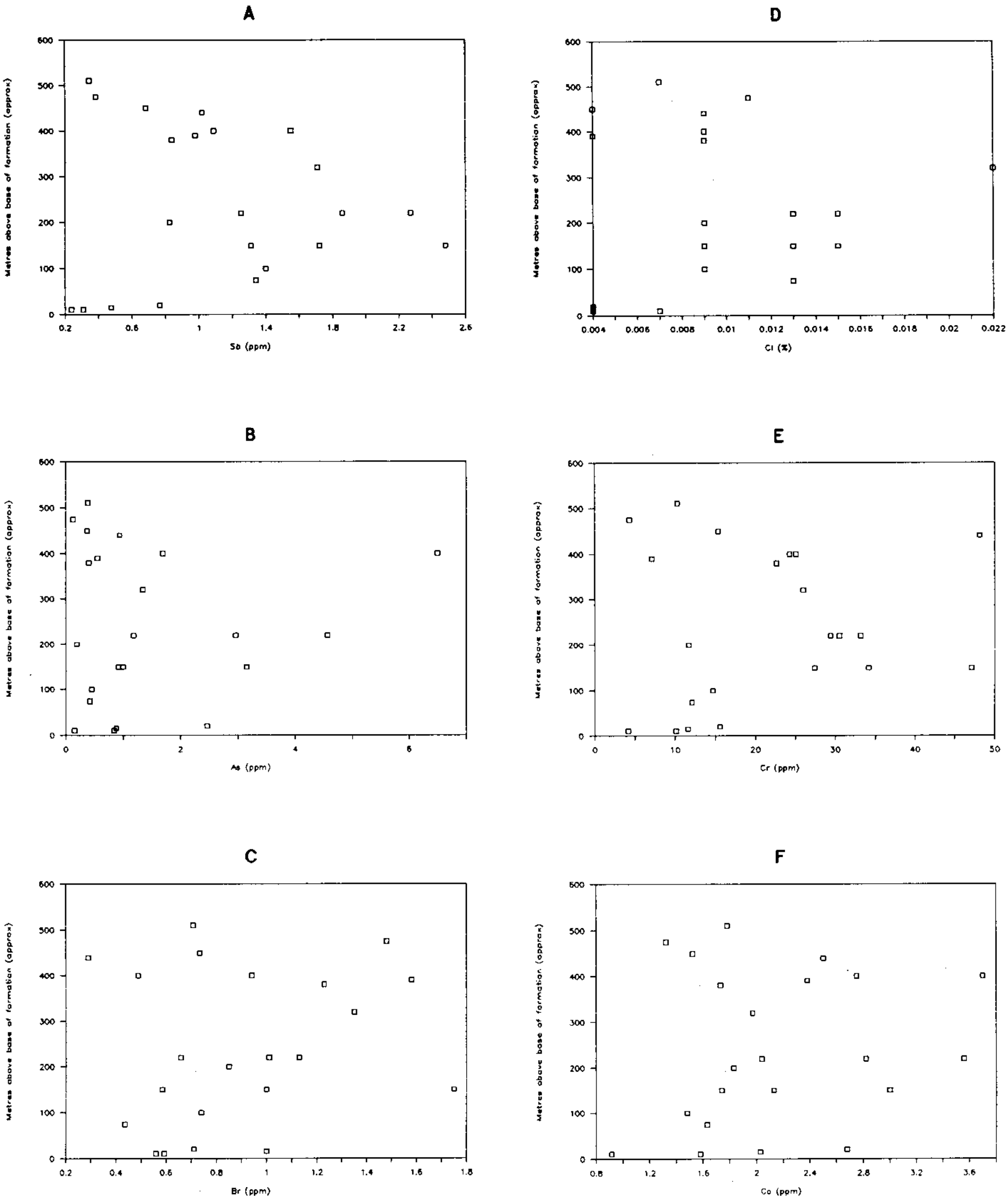


Figure 3. Variations in contents of ash and trace elements with relative stratigraphic position in whole-seam samples of Mist Mountain Formation coals (southeastern B.C.)

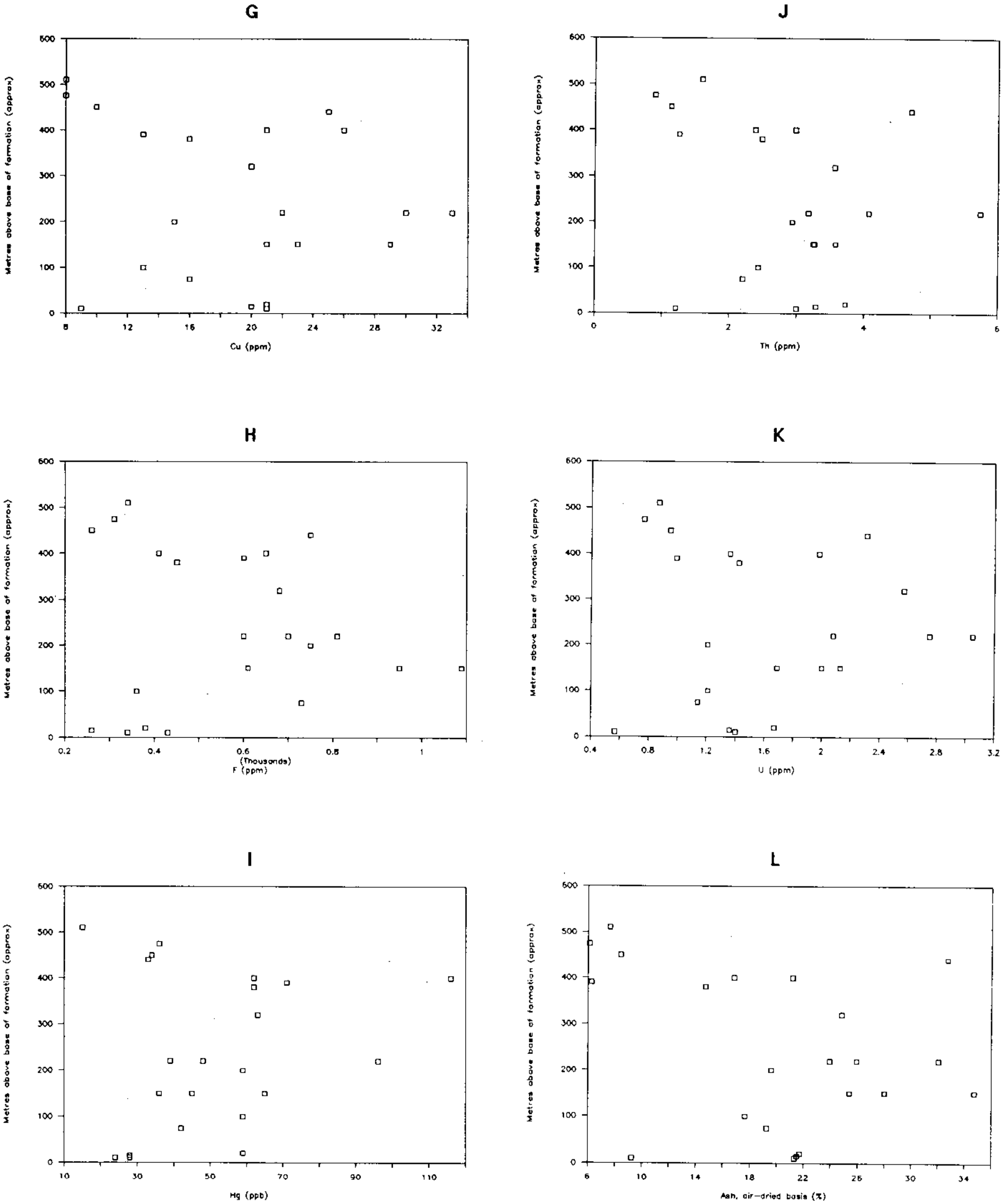


Figure 3 continued.

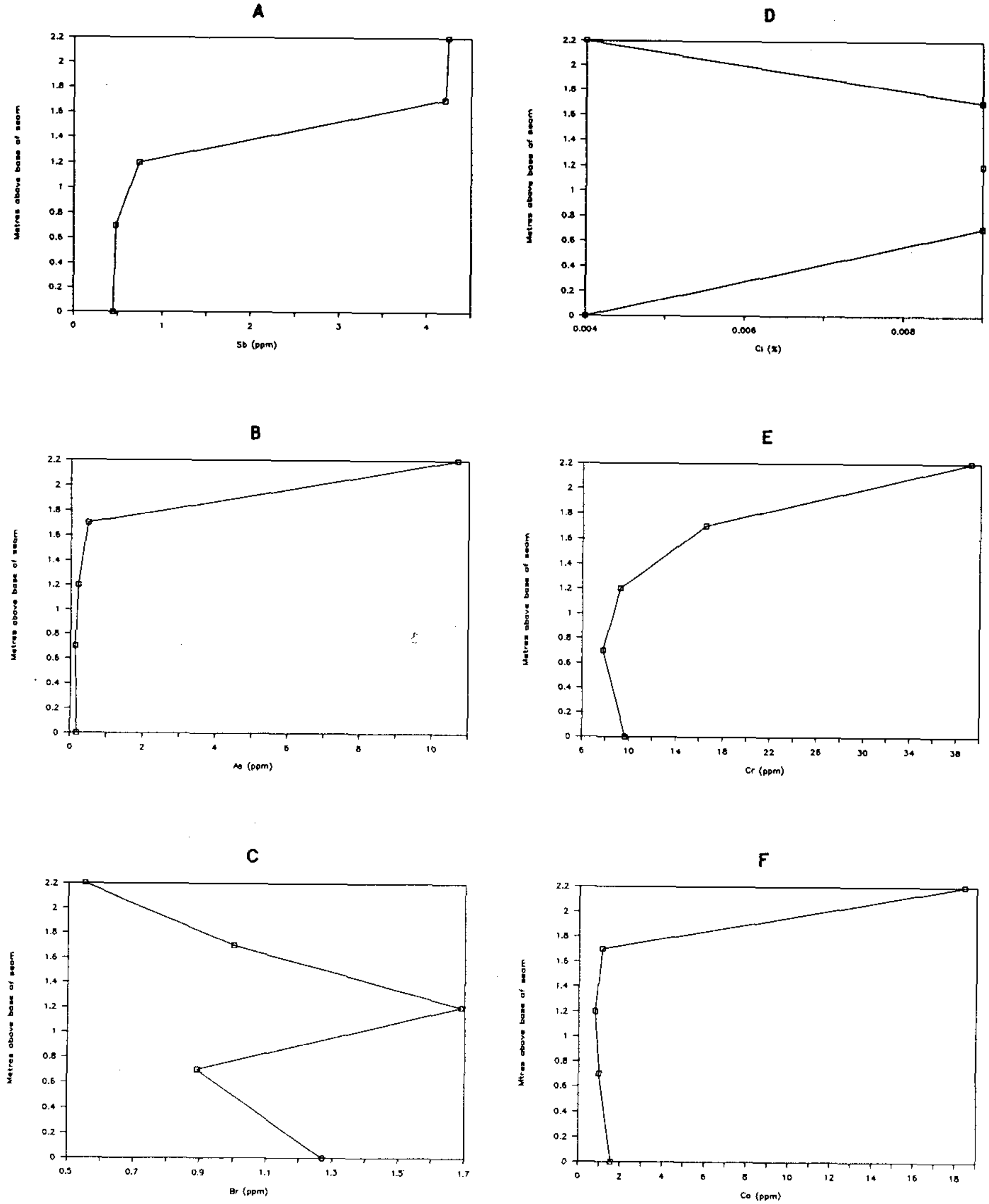


Figure 4. Variations in contents of ash and trace elements with stratigraphic position in ply-by-ply samples of 10A-seam at Line Creek mine (southeast B.C.)

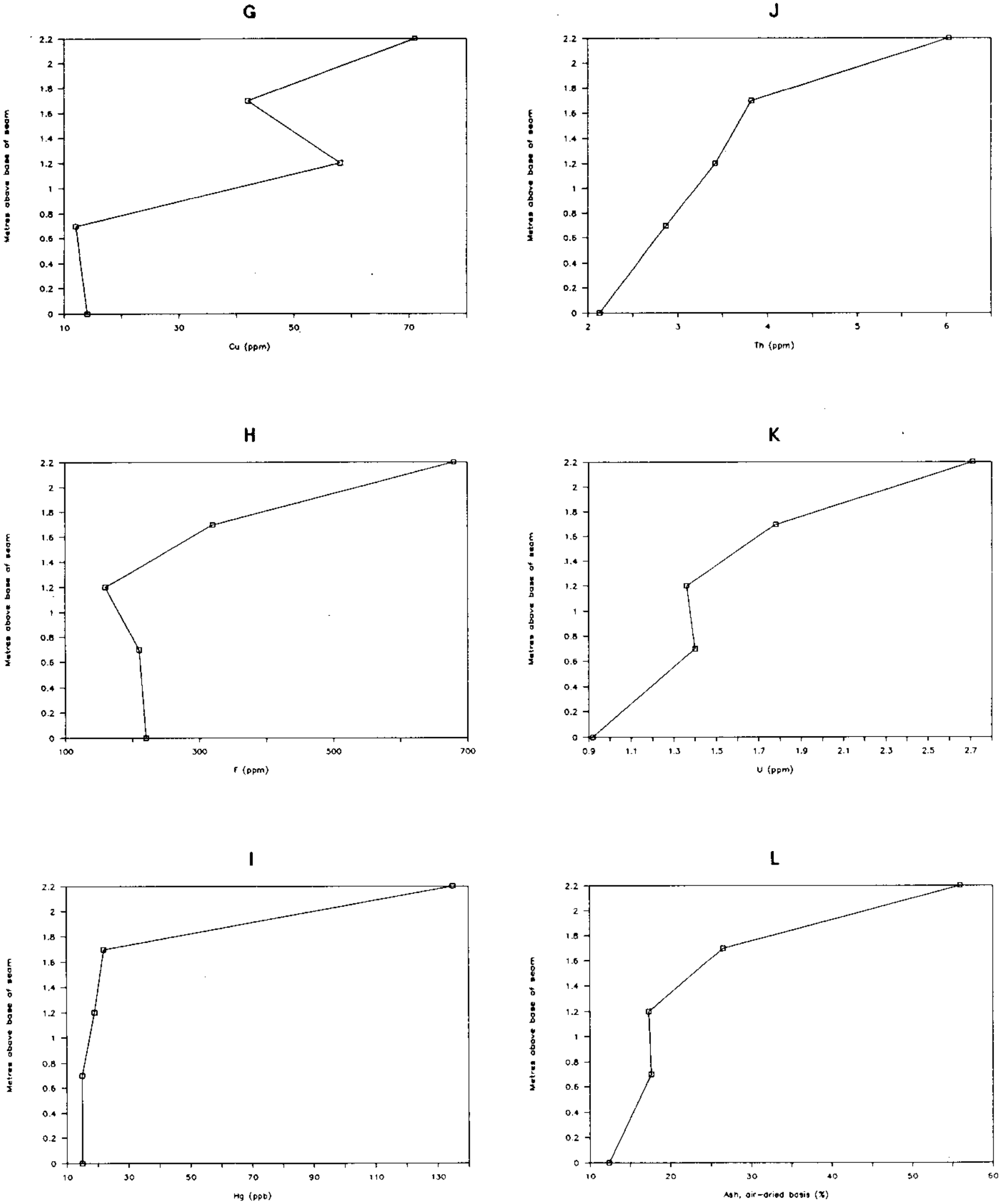


Figure 4 continued.

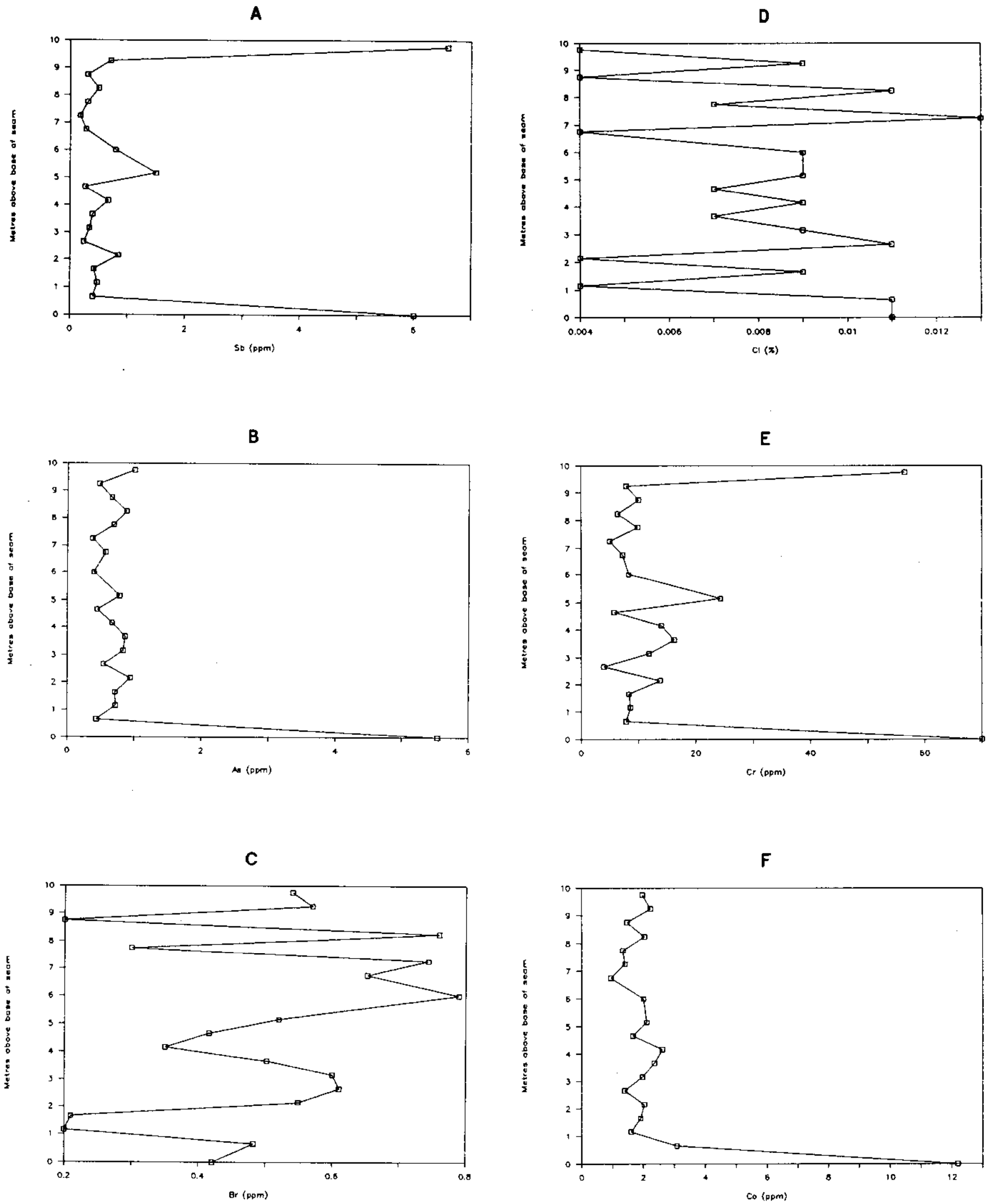


Figure 5. Variations in contents of ash and trace elements with stratigraphic position in ply-by-ply samples of 8-seam at Line Creek mine (southeastern B.C.).

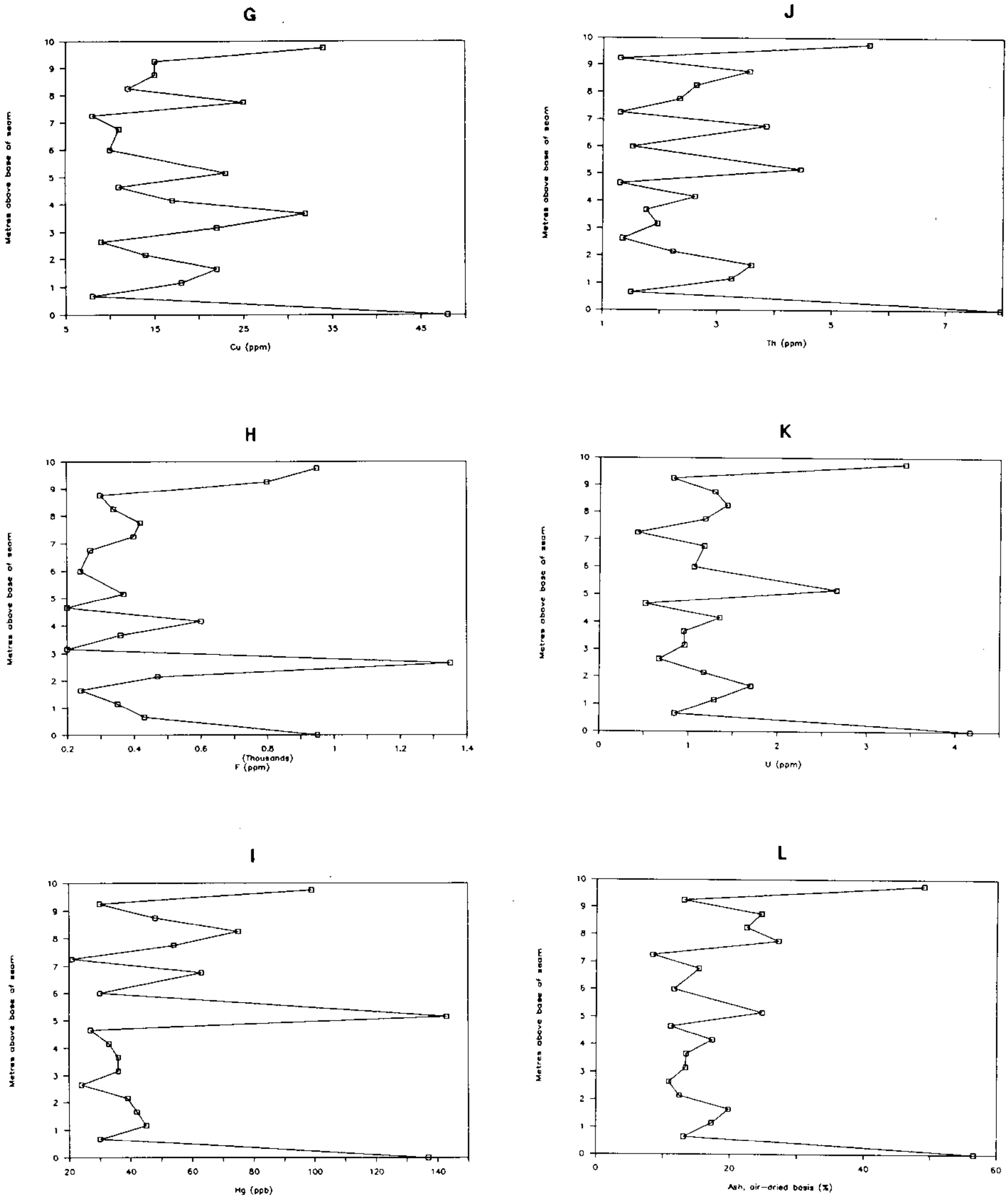


Figure 5 continued.

In summary, trace elements in the Mist Mountain Formation appear to be separable into two groups, those which tend to follow the ash contents of samples to a greater or lesser degree (Sb, As, Cr, Co, Cu, F, Hg, Th and U), and those with concentrations independent of relative ash contents (Br and Cl).

GATES FORMATION

As with the Mist Mountain Formation, trace elements in Gates Formation seams do not vary systematically with stratigraphic position (Figure 6). However, the stratigraphic profiles of some of the elements (Cr, Co, Cu, F, Th and U) are roughly parallel to the profile of ash contents of the samples. This generally results in most of the highest concentrations of these elements being in the upper half of the formation. All these elements display a similar relationship in southeast British Columbia.

CORRELATION ANALYSIS

Knowledge of the mode of association of an element in coal is as important as knowing the concentration of the element (Finkelman, 1980). This is because the mode of association determines the potential for upgrading the coal (with respect to the element in question), and the potential for release of the element during utilization. Correlation analysis provides a first impression of the association of an element in coal. Elements which are positively correlated with ash content, for example, are tentatively assigned to an inorganic association in coal (Swaine, 1990).

Correlation analysis of data here is somewhat hampered by the small number of samples from the Peace River coalfield, and by large numbers of samples with concentrations below detection limit for certain elements. Consequently, correlation analysis of cadmium, boron, lead, molybdenum and selenium is not attempted. For these reasons, only overall general trends in the data are noted below, and detailed comparisons between Peace River and Kootenay data are not made.

ELEMENT-ASH RELATIONSHIPS

Nine elements are correlated with ash at the 95 per cent confidence level in the southeast British Columbia whole-seam samples (Sb, As, Cl, Cr, Co, Cu, F, Th and U; Table 2; Figure 7). In the cases of the ply-by-ply samples from Line Creek, all these elements, together with mercury but excluding chlorine, are positively correlated to a significant degree with ash (Table 3; Figure 8).

In the Peace River samples five elements are positively correlated with ash (F, Cu, Cr, Th and U; Table 4; Figure 9).

INTER-ELEMENT RELATIONSHIPS

Not surprisingly, the elements which are positively correlated with ash tend to be positively intercorrelated (Tables 2 to 4). There are more significant positive correlations within the Kootenay whole-seam and Line Creek data than in the Peace River data. This could be related to the smaller size of the northeast data set. Some examples of strongly correlated pairs of elements in one or both regions include: thorium and uranium (both regions); chromium and copper (both); copper and cobalt (both); copper and thorium

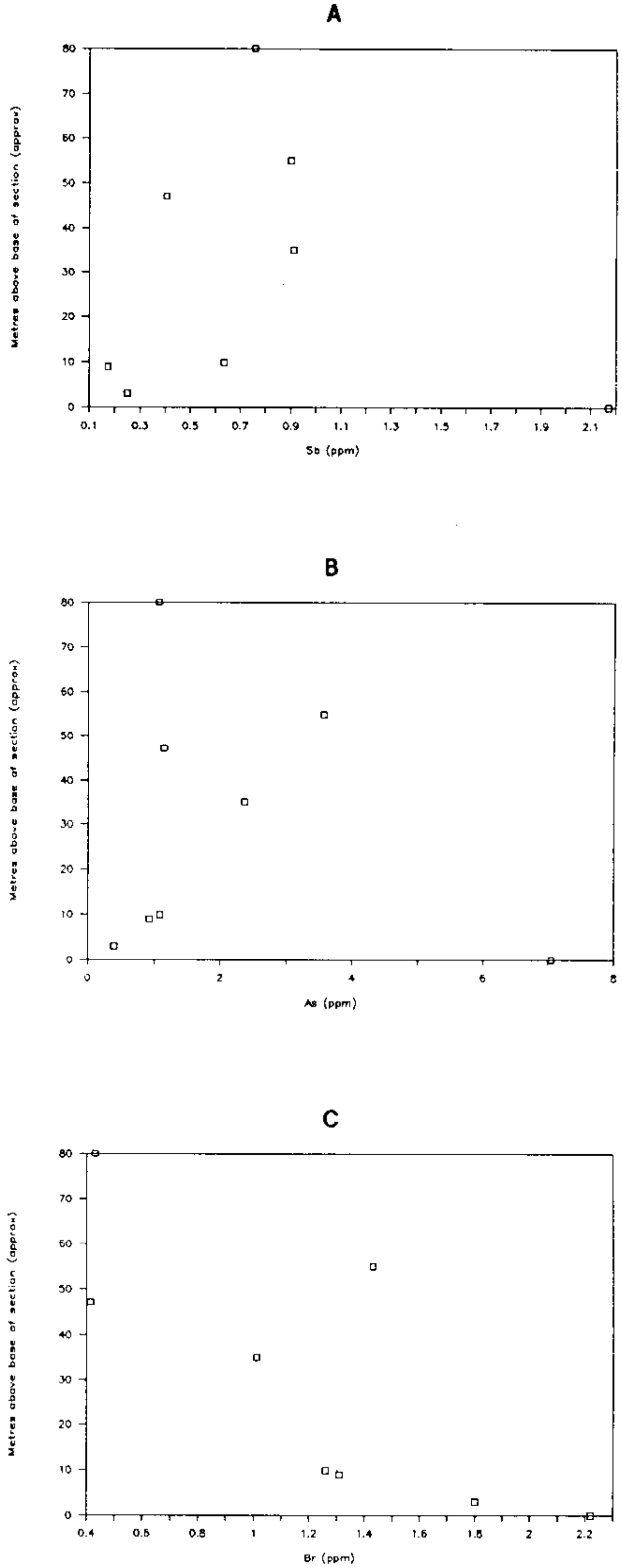
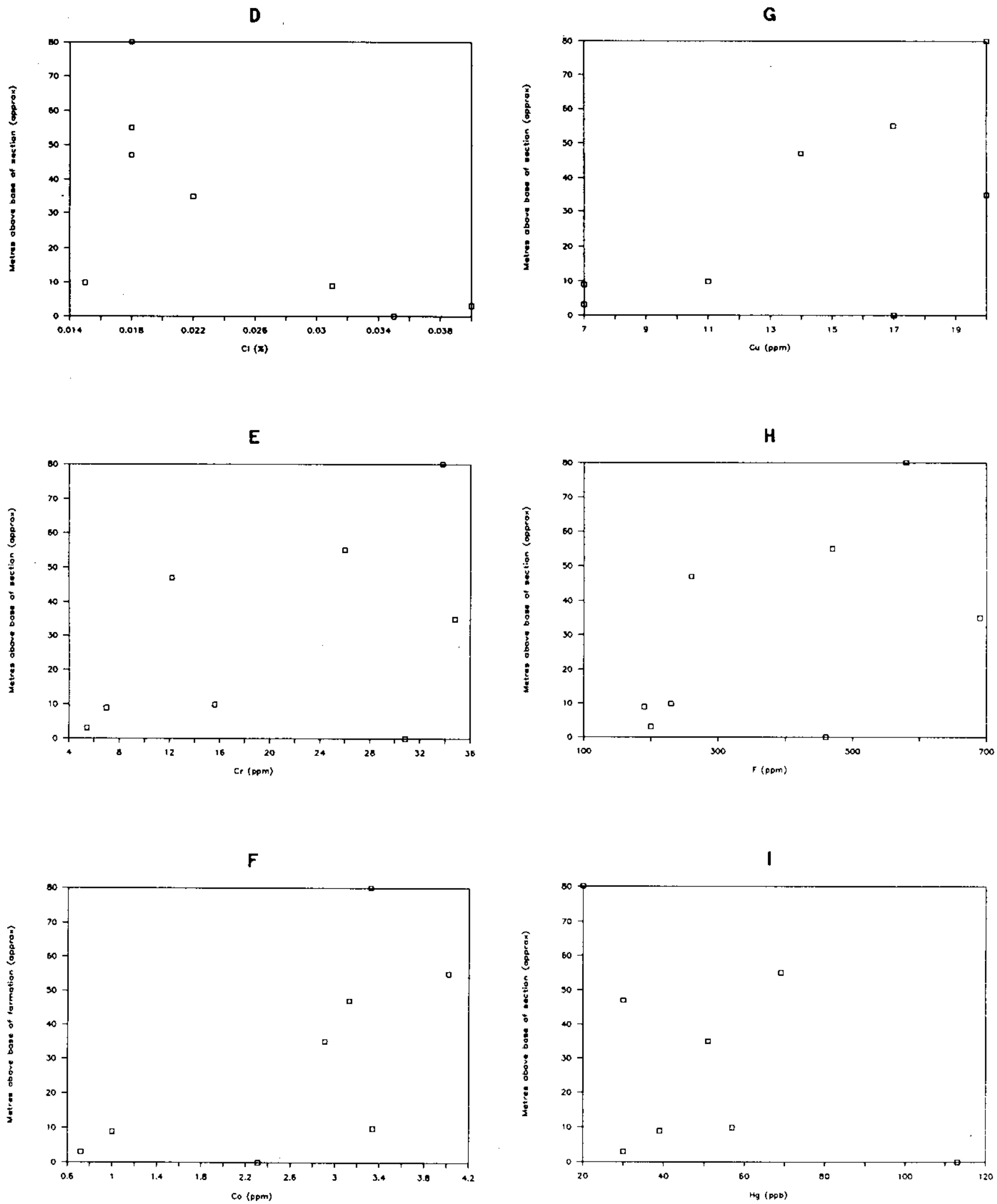


Figure 6. Variations in contents of ash and trace elements with relative stratigraphic position in whole-seam samples of Gates Formation coals (northeastern B.C.).



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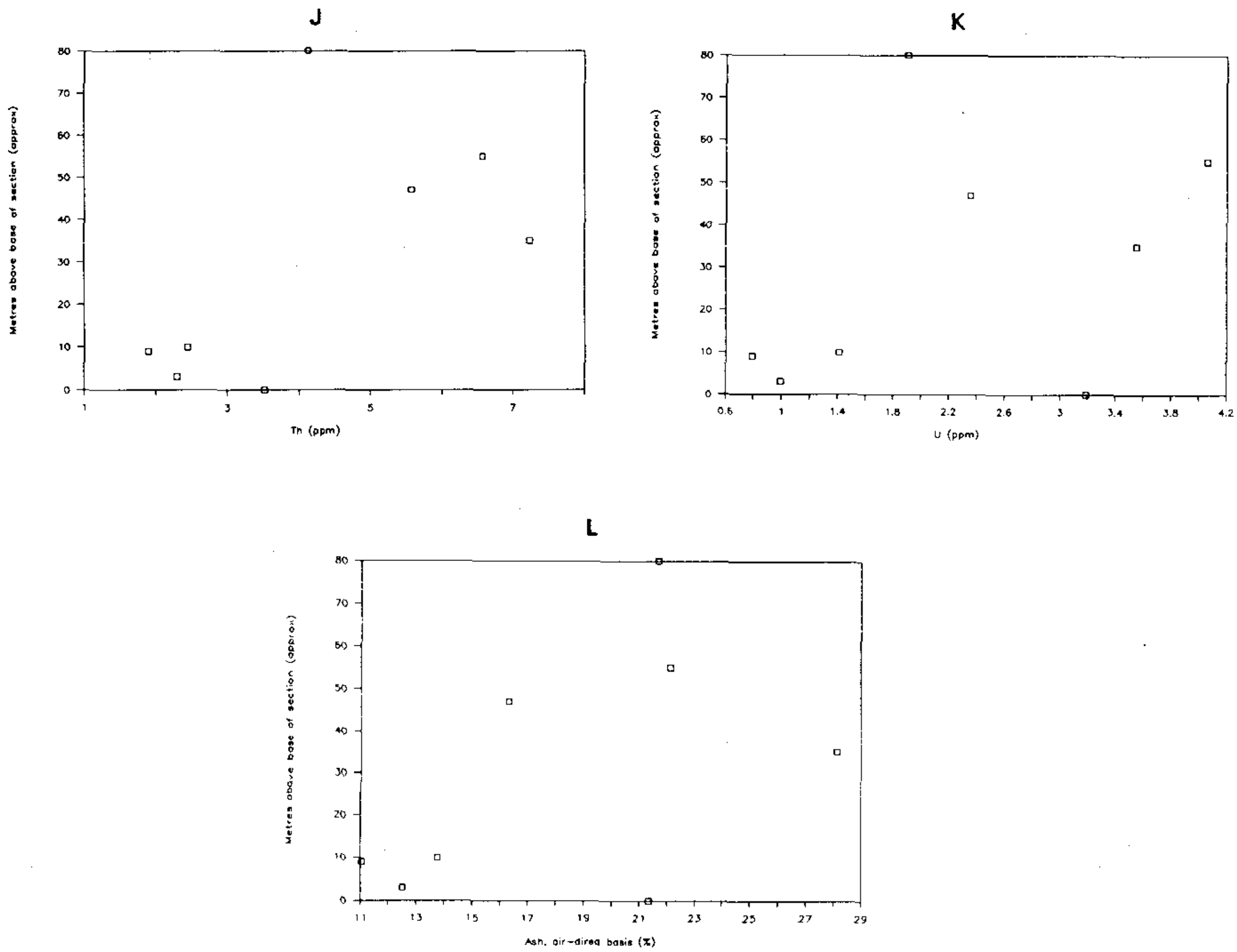


Figure 6 continued.

TABLE 2
CORRELATION COEFFICIENTS BETWEEN ELEMENTS AND ASH CONTENT IN WHOLE SEAM SAMPLES FROM SOUTHEASTERN B.C.

	Ash	Sb	As	Br	Cl	Cr	Co	Cu	F	Hg	Th
Sb	.69										
As	.46	.38									
Br	-.10	.14	.07								
Cl	.54	.69	.27	.28							
Cr	.83	.73	.43	-.05	.53						
Co	.52	.49	.76	.21	.21	.51					
Cu	.85	.60	.64	.07	.43	.70	.80				
F	.66	.71	.30	-.03	.55	.67	.26	.46			
Hg	.17	.48	.32	.09	.19	.18	.54	.38	.22		
Th	.89	.57	.40	-.10	.42	.68	.62	.88	.42	.35	
U	.80	.69	.50	.11	.67	.77	.62	.86	.47	.39	.87

Note:
n=22; r=0.42 is significant at 95% confidence

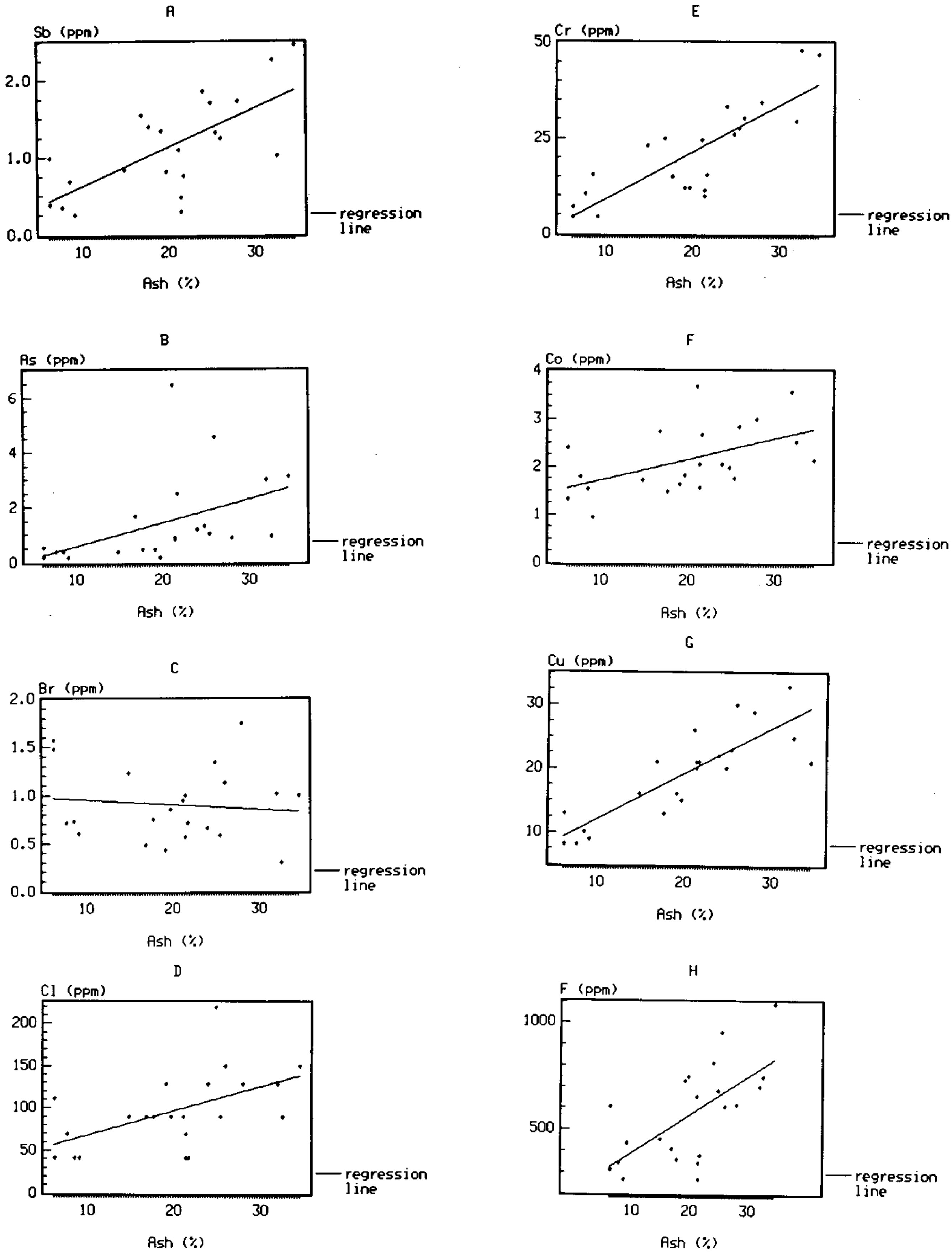
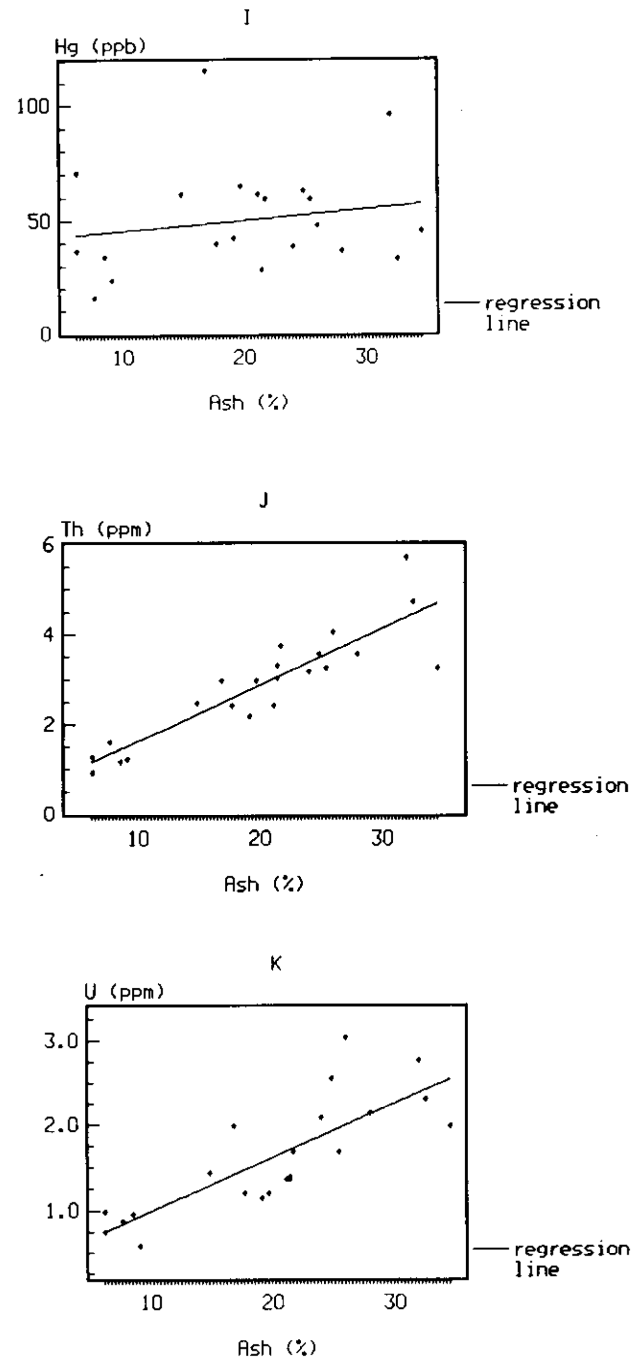


Figure 7. Graphs of trace elements versus ash contents in whole-seam samples of Mist Mountain Formation coals (southeastern B.C.). For correlation coefficients *see* Table 2.



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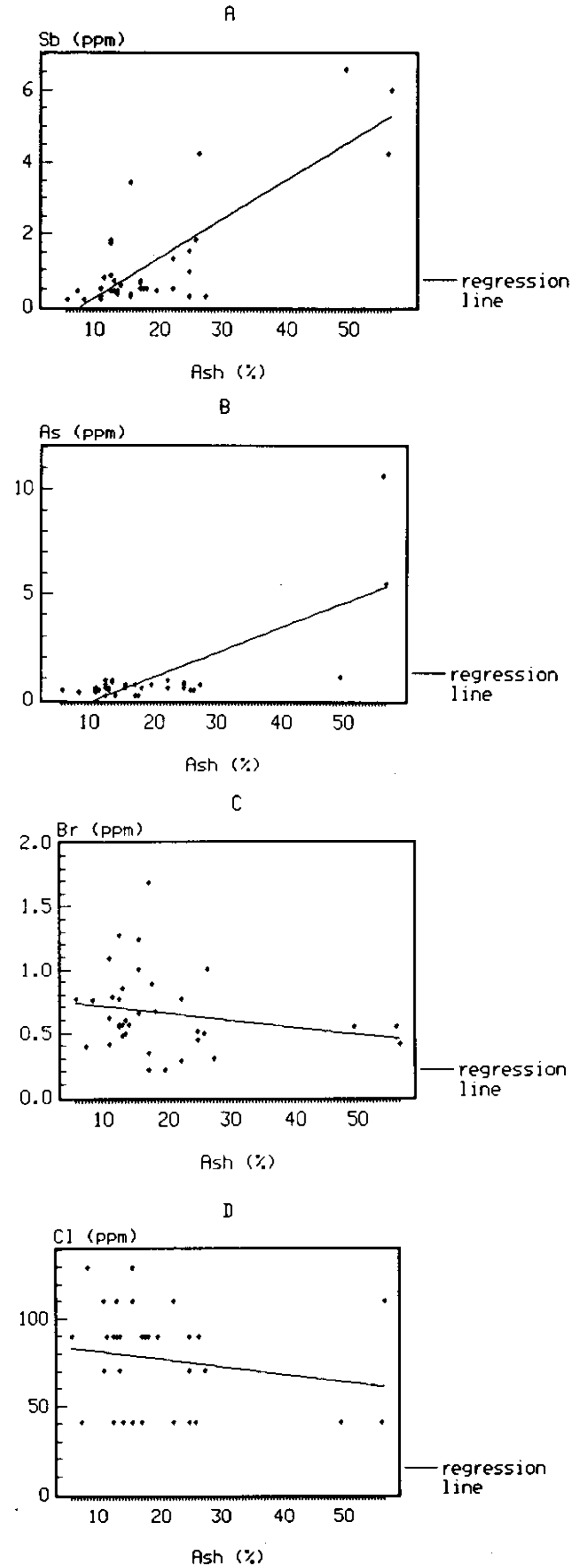

Figure 8. Graphs of trace elements versus ash contents in ply-by-ply samples of four coal seams (10A, 10B, 9 and 8) at Line Creek mine (southeastern B.C.). For correlation coefficients *see* Table 3.

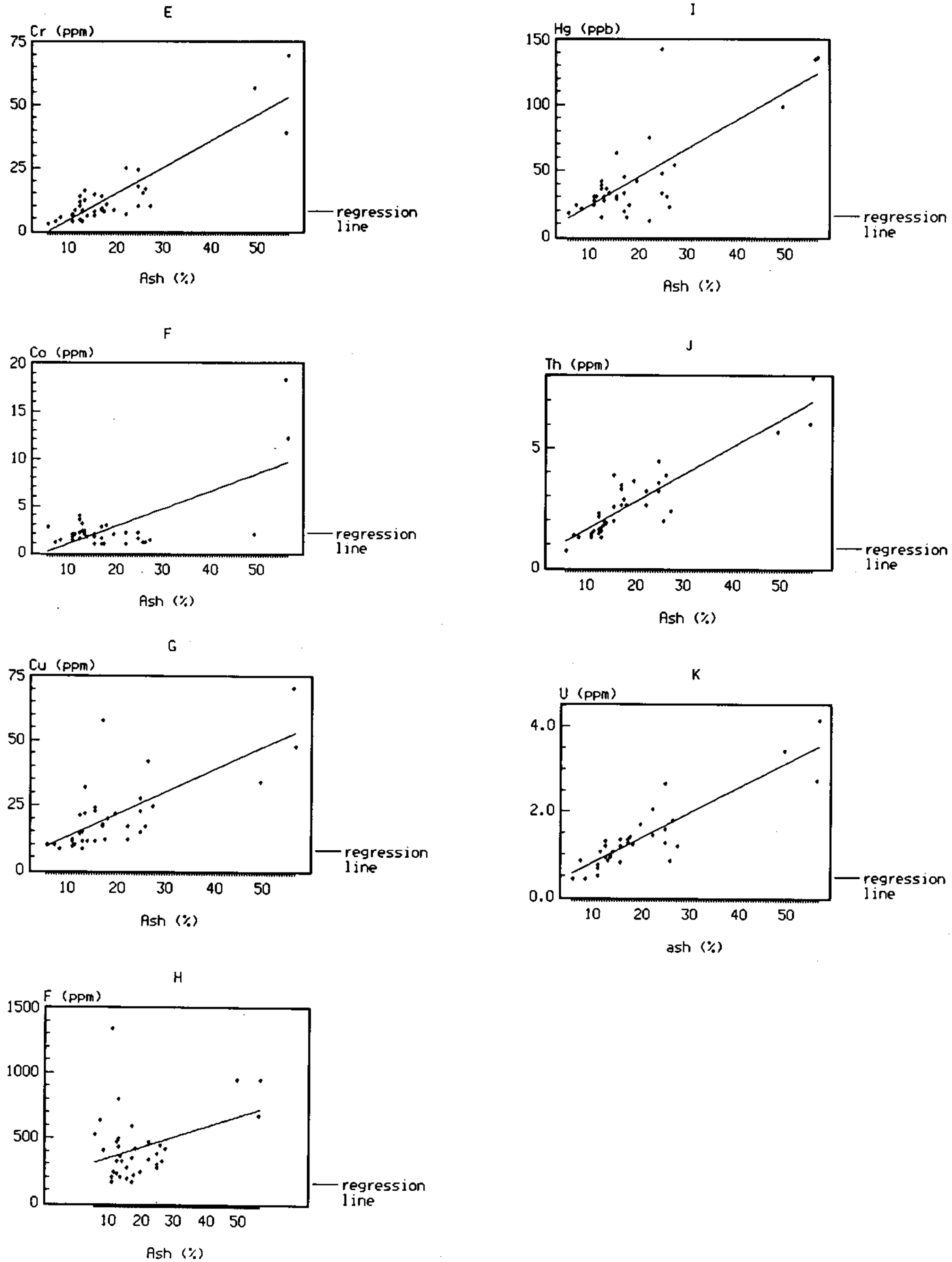

Figure 8 continued.

TABLE 3
CORRELATION COEFFICIENTS BETWEEN ELEMENTS AND ASH CONTENT IN LINE CREEK MINE PLY-BY-PLY SAMPLES FROM SOUTHEASTERN B.C.

	Ash	Sb	As	Br	Cl	Cr	Co	Cu	F	Hg	Th
Sb	.81										
As	.74	.54									
Br	-.21	-.04	-.17								
Cl	-.18	-.06	-.14	.30							
Cr	.89	.87	.61	-.22	-.14						
Co	.69	.53	.97	-.15	-.02	.60					
Cu	.73	.63	.70	.18	-.05	.63	.64				
F	.38	.39	.34	-.34	.02	.46	.33	.12			
Hg	.78	.60	.68	-.27	-.08	.73	.66	.51	.32		
Th	.91	.74	.64	-.14	-.17	.86	.58	.70	.26	.78	
U	.89	.82	.57	-.21	-.11	.92	.56	.63	.34	.79	.93

Note:
n=37; r=0.33 is significant at 95% confidence

TABLE 4
CORRELATION COEFFICIENTS BETWEEN ELEMENTS AND ASH CONTENT IN WHOLE-SEAM SAMPLES FROM NORTHEASTERN B.C.

	Ash	Sb	As	Br	Cl	Cr	Co	Cu	F	Hg	Th
Sb	.57										
As	.49	.95									
Br	-.14	.49	.59								
Cl	-.31	.13	.21	.72							
Cr	.93	.69	.56	-.11	-.34						
Co	.58	.28	.21	-.44	-.88	.61					
Cu	.94	.58	.46	-.31	-.48	.95	.73				
F	.97	.52	.41	-.19	-.29	.95	.52	.93			
Hg	.31	.87	.94	.73	.21	.38	.15	.24	.20		
Th	.83	.21	.24	-.36	-.49	.61	.66	.76	.72	.07	
U	.85	.62	.67	.07	-.31	.73	.66	.78	.73	.55	.86

Note:
n=8; r=0.71 is significant at 95% confidence

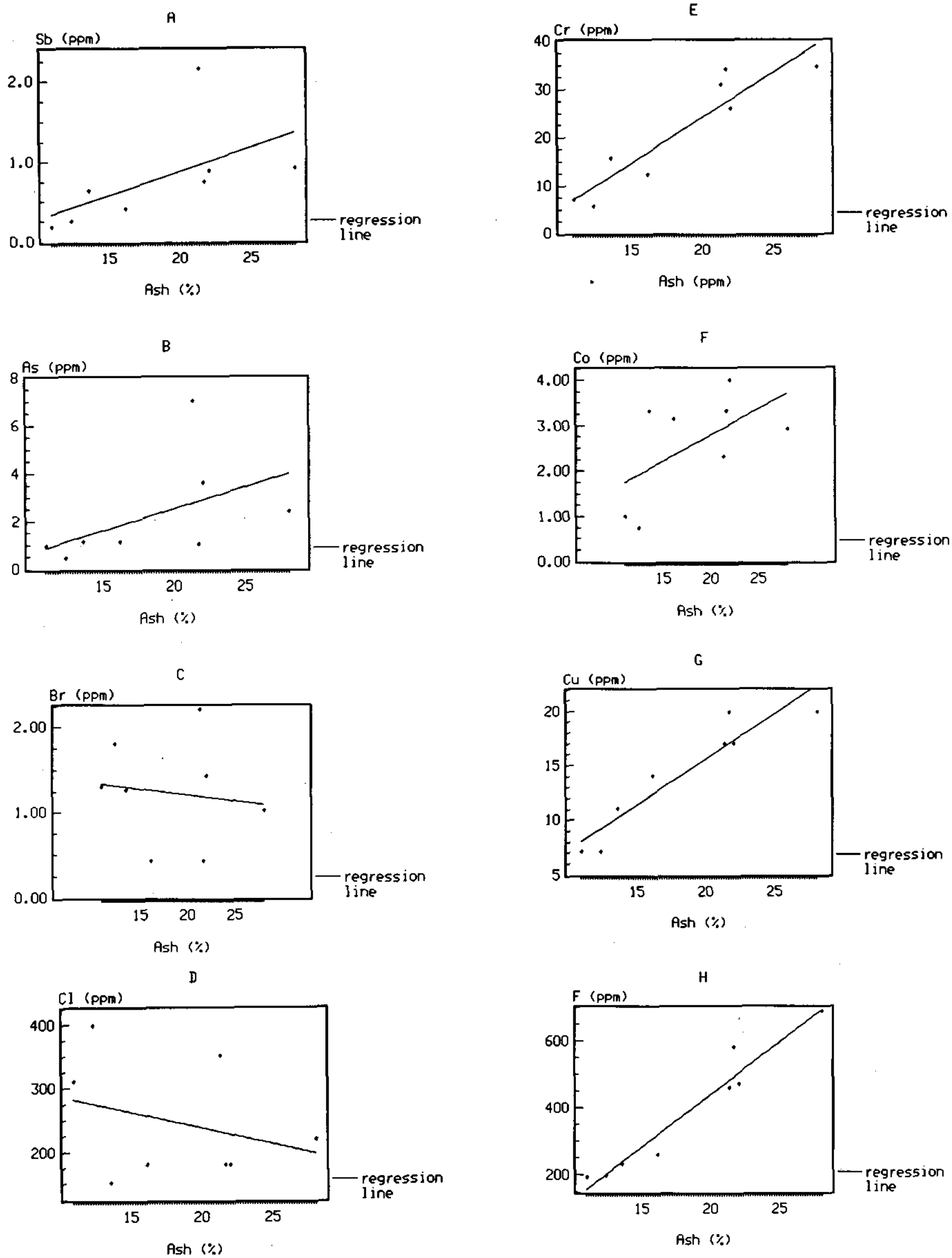

Figure 9. Graphs of trace elements versus ash contents in whole-seam samples of Gates Formation coals (northeastern B.C.). For correlation coefficients *see* Table 4.

(both); chromium and antimony (southeast); arsenic and cobalt (southeast); fluorine and chromium (northeast). Chlorine and bromine are the least frequently positively correlated with other elements, but can be correlated with each other.

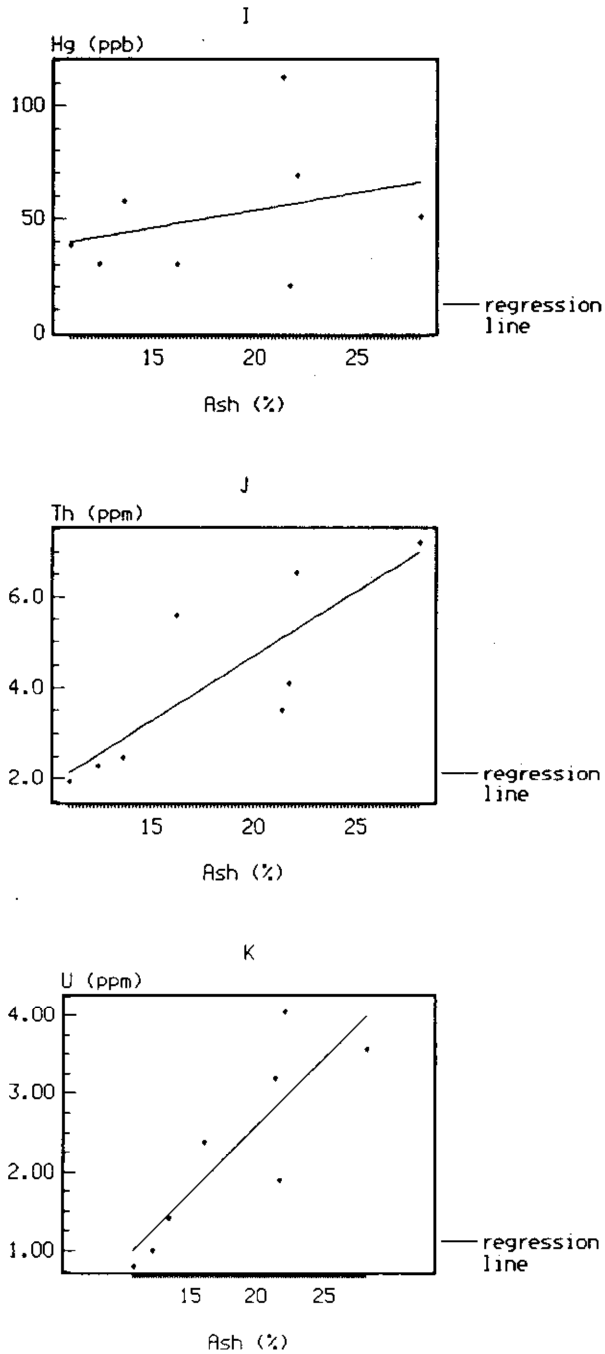

Figure 9 continued.

DISCUSSION

In very general terms, elements in this study tend to fall into two groups. One group is comprised of elements which follow ash content stratigraphically, and tend to be positively correlated with ash content and positively intercorrelated (Sb, As, Cr, Co, Cu, F, Hg, Th and U). The other group consists of chlorine and bromine, and represents those elements which are generally not correlated with either the ash contents of samples or with the other elements. It is tentatively concluded that the first group is primarily associated with the inorganic fraction of coals, while the second is ascribed to the organic fraction. Interpretations from the literature are cited below to describe the association of the elements which fall below detection limits in some samples.

Elements are discussed separately below. Comparisons between values of elements in British Columbia coals and world coals are included, and British Columbia coals are subjectively classified as being relatively "low", "average" or "high" in each trace element. Data on world coals and the general behaviour of specific elements in coal are taken from Swaine (1990), Finkelman (1980), Clarke and Sloss (1992), and other references, as noted. Estimates of the environmental significance of specific elements in coal are also given. These are taken from two sources: Swaine (1989) classifies elements into one of three levels of environmental significance: "prime," "lesser" and "insignificant"; Clarke and Sloss (1992) group trace elements, excepting halogens and radioactive elements, into three categories of environmental concern, "greatest", "moderate" and "minor".

One important positive factor, which is not elaborated on here, is the high calorific value, due to the high rank, of these coals, in comparison with many thermal coals traded on the world market. This translates into a need to use less coal, and consequently a tendency to produce less waste, to generate a given amount of energy.

ANTIMONY

Antimony values in British Columbia coals fall well within the range for most world coals (0.05 to 10 ppm according to Swaine, 1990) and the mean corresponds almost exactly with the mean in United States coals, which is 1.1 ppm (Finkelman, 1980). The mean in Australian coals is given as 0.5 ppm (Swaine, 1990), but the concentration of antimony in British Columbia coals in comparison with world coals can be classified as "average". Results here suggest a probable inorganic (mineral) association, which is generally consistent with interpretations in the literature (Finkelman, 1980), although Swaine (1990) ascribes some antimony in coal to an organic association. A positive correlation between antimony and sulphur in Peace River B.C. coals may reflect an association in sulphides, which has been noted elsewhere.

Antimony from coal is considered to be environmentally "insignificant", partly because of the low concentrations in most coals, by Swaine (1989, 1990), and of "minor" environmental concern by Clarke and Sloss (1992).

ARSENIC

Arsenic concentrations in British Columbia coals fall at the low end of the estimated range for most world coals (0.5 to 80 ppm, Swaine, 1990). The mean corresponds very closely with the mean in Australian coals (1.5 ppm, Swaine, 1990), and is low in comparison with means from some other regions (for example, roughly 15 ppm in United States coals, according to Swaine, 1990, and Finkelman, 1980). Our coals are therefore classified as being "low" in arsenic. The results of this study suggest a probable inorganic association in British Columbia coals, which is consistent with the general interpretation of Swaine (1990). Arsenic concentration is usually low in low-sulphur coals, consistent with a sulphide relationship (Finkelman, 1980; Swaine, 1990).

Arsenic in coal is classified as being of "prime" environmental significance by Swaine (1989), and of "greatest" environmental concern by Clarke and Sloss (1992). The low mean level of arsenic in British Columbia coals is a favourable characteristic.

BORON

The range in concentrations of boron in British Columbia coals falls well within the estimated range for most world coals (5 to 400 ppm, Swaine, 1990) and these coals are classified as "average" in a global context. Boron is generally ascribed to organic association in coal (Vickridge *et al.*, 1990; Swaine, 1990), although some argue for a partial inorganic affiliation (Burchill *et al.*, 1990).

Boron in coal is considered to be of "prime" environmental significance by Swaine (1989) and of "greatest" concern by Clarke and Sloss (1992).

BROMINE

Bromine concentrations in these samples are at the low end of the estimated range for most world coals (0.5 to 90 ppm) and most Australian coals (0.4 to 30 ppm, Swaine, 1990). The mean is also below the means for various regions of the United States (Finkelman, 1980). These coals are thus classified as "low" in this element. Bromine in the samples studied here is believed to be in predominantly organic association, which is consistent with Swaine's (1990) and Finkelman's (1980) interpretations of the literature.

Bromine, being a halogen, is volatile. However, bromine in coal is considered to be of "lesser" environmental significance (Swaine, 1989).

CADMIUM

The range in cadmium concentrations in British Columbia coals is within the estimated world coal range (0.1 to 3.0 ppm, Swaine, 1989, 1990), although much of our data are below the detection limit of 0.2 ppm. An estimated range in most Australian coals is given as 0.01 to 0.2 ppm (Swaine, 1990), with a mean of 0.08 ppm, while the mean in United States coals is 1.3 ppm (Finkelman, 1980). Cadmium contents in our coals are tentatively classified here as "average", although they may be lower, depending on the non-detectable concentrations. Cadmium in coal is widely believed to be associated with sulphides, including sphalerite, and its concentration is usually low in low-sulphur coals (Swaine, 1990; Finkelman, 1980).

Swaine (1990) classifies cadmium as being of "prime" environmental significance, and similarly Clarke and Sloss (1992) consider it to be of "greatest" concern. The nature of cadmium occurrence in coal is a good argument for the use of low-sulphur coals in coal-fired power plants.

CHLORINE

Concentrations of chlorine in both the Kootenay and Peace River coalfields are toward the low end of the estimated range for most world coals (50 to 2000 ppm, Swaine, 1990). For example, the mean in United States coals is given as 580 ppm (Finkelman, 1980). Our coals are therefore classified as "low" in chlorine compared to world coals. Chlorine in the coals studied here is believed to be organically associated, which is consistent with the general view of chlorine in coal (Swaine, 1990).

Swaine (1989) classifies chlorine in coal as being of "lesser" environmental significance, but it is a very undesirable element because it can cause fouling and corrosion in thermal power plants. Low chlorine content in British Columbia coals makes them attractive as thermal coals.

CHROMIUM

Chromium contents in British Columbia coals are well within the estimated range in most world coals (0.5 to 60 ppm), and the mean corresponds almost exactly with an estimated general world mean of about 20 ppm (Swaine, 1990). It is very reasonable, therefore, to classify our coals as "average" in their chromiun contents. Data here suggest that the mode of occurrence of chromium in our coals is predominantly inorganic, and an inorganic association in coal is generally ascribed to chromium (Swaine, 1990; Finkelman, 1980).

Swaine (1989) considers chromium in coal to be of "lesser" environmental significance, and Clarke and Sloss (1992) rate it as being of "moderate" concern.

COBALT

Cobalt concentrations in British Columbia coals are toward the low end of the estimated range for most world coals (0.5 to 30 ppm) and the mean is below an estimated mean for most coals (from 4 to 8 ppm, Swaine, 1990). Our coals are therefore classified as being "low" in cobalt. Data suggest an inorganic association for most of the cobalt, while review of the literature led Finkelman (1980) to conclude that cobalt in coal is dominantly associated with inorganic matter, including sulphides. Swaine (1990), on the other hand, appears to ascribe both an inorganic and organic association to cobalt.

Swaine (1989) classifies cobalt in coal as being environmentally "insignificant", and Clarke and Sloss (1992) rate it as being of "minor" concern.

COPPER

Copper concentrations in British Columbia coals fall safely within the estimated range of most world coals (0.5 to 50 ppm), and the mean corresponds closely with a mean for copper in coal of 19 ppm (Finkelman, 1980). Means in Southern Hemisphere coals (8 to 10 ppm) are lower than in American coals (15 ppm, Swaine, 1990). Our coals are therefore classified as "average" in copper. The data here strongly suggest that copper in British Columbia coals is associated with the inorganic fraction. This is consistent with the well-accepted occurrence of copper in chalcopyrite in coal (Finkelman, 1980; Swaine, 1990).

Swaine (1989) classifies copper as being of "lesser" environmental significance, and Clarke and Sloss (1992) describe it as being of "moderate" concern.

FLUORINE

Fluorine contents in British Columbia coals appear to exceed the estimated range of fluorine in most world coals (20 to 500 ppm) and the mean is above the estimated world mean of about 150 ppm (Swaine, 1990). The means for United States (74 ppm, Finkelman, 1980) and Australian coals (about 110 ppm, Swaine, 1990) are below the British Columbia mean and the estimated world mean value. Our coals are therefore classified as being relatively "high" in fluorine. The fluorine is believed to be inorganically associated, probably mainly in fluorapatite, which has been detected in low-temperature ashes derived from these samples (Grieve, 1992). This is consistent with the thinking of both Swaine and Finkelman.

In a separate study concerned with phosphorus in British Columbia coking coals (Grieve, 1992), it was determined that this element is predominantly associated with fluorapatite. The two main factors controlling phosphorus concentrations in raw coals are the amount and mineralogy of the mineral matter. Given a strong correlation between fluorine and phosphorus in these coals (Grieve, 1992), probably related to their common occurrence in fluorapatite, it seems reasonable to suggest that fluorine concentrations are also determined to some extent by mineralogy. In order to demonstrate a possible dependence, F/ash versus ash for Line Creek 8-seam (southeast B.C.) samples has been plotted (Figure 10), and the samples in which fluorapatite was positively identified by x-ray diffraction in low-temperature ash have been highlighted. Clearly, variations in the contents of fluorapatite have the ability to create anomalous concentrations of fluorine in coals.

Fluorine in coal is volatile, and is classed as being an element of "prime" environmental significance (Swaine, 1989). The fluorine content of British Columbia coals would appear to be a negative factor. The potential for reduction of fluorine by beneficiation is therefore an important subject for future study. Grieve (1992) noted that the phosphorus content in East Kootenay coals tends to be lower in the light fraction of sink-float separates, than in the original sample. This suggests that a significant portion of the fluorapatite can be liberated and removed with relative ease.

LEAD

The range of lead values in British Columbia coals is toward the low end of the estimated range for most world coals (2 to 80 ppm, Swaine, 1990). An estimated mean for most Australian, South African and American coals is 10 to 15 ppm, while for European coals it is somewhat higher (Swaine, 1990). British Columbia coals are therefore considered to be relatively "low" in their lead contents. Lead is thought to be exclusively associated with mineral matter in coal (Swaine, 1990; Finkelman, 1980).

Lead is of "prime" environmental significance according to Swaine (1989), and of "greatest" concern according to Clarke and Sloss (1992). Low lead concentrations in raw British Columbia coals are therefore a favourable characteristic.

MERCURY

Mercury contents in British Columbia coals are near the low end of the estimated range for most world coals (20 to 1000 ppb, Swaine, 1990), and the mean is below estimated means for Australian (100 ppb, Swaine, 1990) and United States coals (180 ppb, Finkelman, 1980). Our coals are therefore classified as being "low" in mercury. The mercury is thought to be associated with the inorganic fraction. This is consistent with a generally accepted association of mercury with sulphide minerals (Swaine, 1990; Finkelman, 1989), and the observation that mercury is usually low in low-sulphur coals (Swaine, 1989).

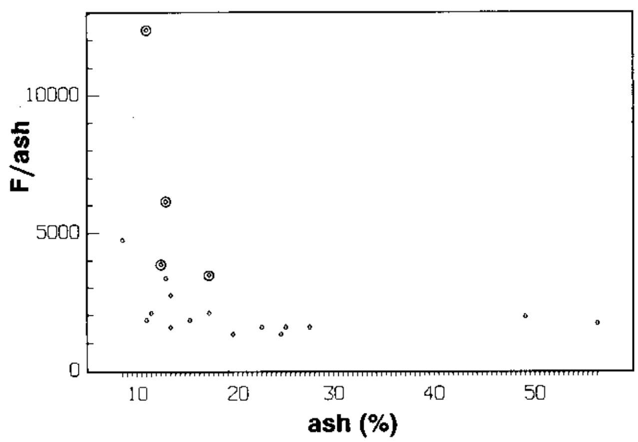

Figure 10. Graph of normalized fluorine concentrations (F/ash) versus ash contents in ply-by-ply samples of 8-seam at Line Creek mine (southeastern B.C.). Highlighted samples contain fluorapatite in low-temperature ash.

The high toxicity of mercury, in combination with its volatility, make it an element of "prime" environmental significance (Swaine, 1989) and of "greatest" concern (Clarke and Sloss, 1992). Most mercury emitted by coal-burning power plants is in the vapour state (Clarke and Sloss, 1992) and can be carried large distances from its point of discharge. Low mercury contents, as in these British Columbia coals, is an attractive coal quality attribute.

MOLYBDENUM

The range of molybdenum concentrations in British Columbia coals compares favourably with the estimated range in most world coals (0.1 to 10 ppm) and an estimated approximate world mean (1 to 2 ppm, Swaine, 1990). Our coals are therefore classified as "low to average" in molybdenum, with the Peace River samples being at the lower end of this range. Molybdenum is generally thought to be inorganically associated in coal (Finkelman, 1980).

Molybdenum is classified as having "lesser" environmental significance by Swaine (1989), but Clarke and Sloss (1992) rank it as being of "greatest" concern.

SELENIUM

The range in selenium concentrations in British Columbia coals places them within the range of most world coals. For example, Swaine (1990) gives an estimated range for several regions of 0.2 to 1.6 ppm, and a mean in Australian coals of 0.9 ppm. Finkelman (1980) cites 4.1 ppm as the mean concentration of selenium in United States coals. Our coals are therefore classified as being of "average" selenium concentration. Selenium is thought to be both organically and inorganically bound in coal (Swaine, 1990; Finkelman, 1980).

Selenium in coal is classed as being of "prime" environmental significance by Swaine (1989), and of "greatest" concern by Clarke and Sloss (1992).

THORIUM

Thorium values in British Columbia coals are within the estimated range of most world coals (0.5 to 10 ppm, Swaine, 1990), and their means compare favourably with the mean in United States coals (4.7 ppm, Finkelman, 1980). Thorium is classified as having "average" abundance in our coals; the evidence concerning its mode of occurrence points to an inorganic association. This is consistent with both Swaine's (1990) and Finkelman's (1980) interpretations of the literature.

Thorium in coal is classed as having "lesser" environmental significance by Swaine (1989). Most of the concern over thorium is due to its radioactivity, and radioactivity emanating from coal-burning power plants is generally acknowledged not to be a significant problem (Clarke and Sloss, 1992).

URANIUM

Uranium concentrations in British Columbia coals are within the estimated range for most world coals (0.5 to 10 ppm), and the mean compares very closely with an estimated world mean of 2 ppm (Swaine, 1990). Our coals are therefore classed as "average" in terms of their uranium contents. The data here strongly suggest that uranium is inorganically associated, although Swaine (1990) and Finkelman (1980) both concluded that organic association also occurs.

As with thorium, Swaine (1989) classes uranium as being of "lesser" environmental significance. Most of the concern over uranium is related to radioactivity, and comments concerning this issue made with respect to thorium are valid.

ZINC

The range in zinc concentrations in British Columbia coals is classified as "average" in comparison with other world coals. For example, Swaine (1990) cites 5 to 300 ppm as the estimated range for most world coals, and 25 ppm as an estimated mean for some American and Australian coals. Finkelman (1980) gives 39 ppm as the mean zinc concentration in United States coals. Zinc is generally thought to be associated with the inorganic fraction of coal (Finkelman, 1980; Swaine, 1990), including accessory sphalerite.

Swaine (1989) classifies zinc in coal as being of "lesser" environmental significance, and Clarke and Sloss (1992) classify it as being of "moderate" concern.

SUMMARY

- Among elements which are consistently above detection limits, trace elements in raw coals from producing mines in southeast and northeast British Columbia appear to belong to two groups, based on their apparent mode of association in coal. The first group (Sb, As, Cr, Co, Cu, F, Hg, Th and U) is primarily inorganically associated, while the second group (Br and Cl) is organically bound.
- Concentrations of trace elements do not vary systematically with stratigraphic position. The ash contents of specific samples appear to exert more control than does stratigraphic position. In the case of the Mist Mountain Formation (southeast B.C. or East Kootenay coalfields) this control results in most of the elements in the first group having their highest concentrations in samples from the middle one-third of the formation, and their lowest values from near the base and top. In the Gates Formation (northeast B.C. or Peace River coalfield) concentrations of a similar set of elements are highest in the upper half of the formation.
- Compared with world coals, raw coals from the Peace River and East Kootenay coalfields in British Columbia tend to have relatively "high" concentrations of fluorine, "average" concentrations of ten trace elements (Sb, B, Cd, Cr, Cu, Mo, Se, Th, U and Zn) and relatively "low" concentrations of six (As, Br, Cl, Co, Pb, and Hg). Among trace elements of "prime" environmental significance, as defined by Swaine (1989), raw British Columbia coals contain below average mean concentrations of arsenic, lead and mercury, and "high" concentrations of only one element, fluorine.

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