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PALEOENVIRONMENTAL AND ENVIRONMENTAL IMPLICATIONS OF THE BORON CONTENT OF COALS

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PALEOENVIRONMENTAL AND ENVIRONMENTAL IMPLICATIONS OF THE BORON CONTENT OF COALS

Abstract

The concentration of boron in Australian and Canadian coals was determined in order to assess the variation of boron in coal with respect to rank, age, geological setting and the degree of paleosalinity of the coal-forming environment.

The study indicates that relations between boron and rank are either very complex or non-existent, and the boron content of coals is not governed by the age of the coal. The boron content of seams is sensitive to the environment of deposition and may show the variation in the same seam laterally due to changes to the environment of deposition and/or the enrichment of boron by a secondary source.

It is proposed that the following ranges of values for boron in coal indicate the degree of marine influence during the early stages of coalification:

1. Up to 50 ppm boron — coal formed in a freshwater environment
2. 50 to 110 ppm boron — coal formed in a mildly brackish water environment
3. >110 ppm boron — coal formed in a brackish water environment.

The vertical variation of boron in a coal-bearing section or strata is related to the depositional environment. There is often little variation in boron content for coal layers as compared to the partings (dirt bands). The boron content of parting(s) in a coal-bearing strata may vary greatly as compared to the coal seams.

The variation of boron in heat-affected coal seams indicates that the behaviour of boron during the natural heating/burning of coal is dependent on the temperature of the system and the nature of the process.

Résumé

La concentration de bore dans les charbons canadiens et australiens a été déterminée afin d'évaluer les variations de la teneur en bore dans les charbons en fonction du rang, de l'âge, du milieu géologique et du degré de paléosalinité du milieu où ils ont été formés.

L'étude indique que les rapports entre le bore et le rang sont soit très complexes, soit inexistants et que l'âge des charbons ne contrôle pas la teneur en bore. La teneur en bore des filons est sensible au milieu de dépôt et sa variation latérale dans un même filon peut être causée par des changements dans le milieu de dépôt ou par un enrichissement en bore provenant d'une source secondaire.

Il est proposé que les intervalles de valeurs suivants de la teneur en bore des charbons indiquent le degré d'influence marine qui s'est manifesté durant les toutes premières étapes de la houillification :

1. jusqu'à 50 ppm de bore — charbon formé en milieu d'eau douce
2. de 50 à 110 ppm de bore — charbon formé en milieu d'eau légèrement saumâtre
3. plus de 110 ppm — charbon formé en milieu d'eau saumâtre.

La variation verticale de la teneur en bore des coupes ou strates houillères est liée au milieu de dépôt. Il y a souvent peu de variation de la teneur en bore dans les couches de houille comparativement aux passées stériles. La teneur en bore des passées stériles dans les strates houillères peut varier largement comparativement aux filons houillers.

La variation de la teneur en bore des filons houillers qui ont été soumis à des effets thermiques indique que le comportement du bore durant le chauffage ou la combustion naturels du charbon dépend de la température du système et de la nature du processus.

Summary

The concentration of boron in a number of Australian and Canadian coals was determined in order to assess the variation of boron content in coal with respect to rank, age, geological setting, stratigraphy, paleosalinity of the coal-forming environment, and the heating of coal seams, and to determine the amount of boron released during the combustion of coal. Data on the boron contents of coals from several other countries are provided for comparison.

Detailed studies of boron in Canadian coals do not show any relationship between boron content and rank (subbituminous coal to anthracite). The boron content of subbituminous coals (Ro_{random} 0.38-0.50%) from Western Canada is mainly dependent on the depositional environment. For example, the Hat Creek coals in British Columbia were deposited in a freshwater environment and have boron contents of <50 ppm, while the Vesta and Horseshoe Canyon coals in Alberta, both deposited in brackish water, have boron contents of 150 and 675 ppm, respectively.

Coals from Hat Creek, British Columbia (Oligocene–Eocene); Mount Allan, Alberta (Upper Cretaceous); Hoidahl Dome, Yukon Territories (Carboniferous); and Melville Island, Arctic Canada (Devonian) all have boron contents of <50 ppm, indicating that boron content is not related to the age of the coal deposits.

There is some evidence that boron content varies with maceral content in Canadian coals, particularly in relation to their inertinite content. The low boron content (25 ppm) of inertinite-rich bands in a brackish water coal seam (boron content 250 ppm) in Alberta (Seam 3, Vesta Mine) is probably related to micro-environments and geomorphology rather than the coal-forming environment, and may indicate a fluctuation in the water table, which resulted in the formation of inertinite under relatively drier, oxidizing conditions.

After a reappraisal of earlier work, and on the basis of work on Australian coals and recent work on Canadian coals, the following relationship is proposed between boron content and marine contamination of the original peat swamps:

1. Up to 50 ppm boron — coal formed in a freshwater environment
2. 50 to 110 ppm boron — coal deposited in a mildly brackish water environment
3. >110 ppm boron — coal deposited in a brackish water environment.

Using these criteria, the degree of marine influence on Canadian and Australian coals can be assessed.

The boron content of coal is either primary, resulting from the environment of deposition (a conclusion supported by independently derived sedimentological data), or is due to secondary enrichment.

High boron content in coals deposited in a freshwater environment is usually due to secondary enrichment and is typically related to the occurrence of evaporite deposits and diapirs, extensive fault systems associated with some coalfields, and the activity of groundwater. The high boron contents of some lignites from Saskatchewan and some bituminous coals from Springhill Coalfield, Nova Scotia are examples of secondary enrichment.

The boron content of coal seams remains relatively constant laterally and stays within the range of values designated for each depositional setting. However, where it does show some variation, this is attributed either to changes in the environment of deposition or to boron enrichment from a secondary source. Subbituminous coals in the Drumheller area of Alberta, deposited in slightly brackish to brackish water, show little variation in boron content laterally over a distance of 14 km. Medium to low volatile bituminous (nonmarine) coals (Seams 4, 10, and 11) from the Gates and Gething formations in northeastern British Columbia show little variation in boron content laterally over a distance of 6.5 km. The low Variance Ratio for the lateral variation of boron in western Canadian coal seams indicates a stable depositional environment during deposition of the coal.

Lateral variations in the boron contents of coal seams may result from secondary enrichment rather than variations in the depositional setting (primary boron). For example, boron in Seam 3 at Springhill, Nova Scotia, varies from 37 ppm (primary enrichment) to 210 and 280 ppm. The boron enrichment is due to the influence of brines, and this explains the high variance ratios of 5.7 and 7.6.

During the combustion of coal, boron is partitioned into bottom ash, fly ash retained by particle attenuation (usually electrostatic precipitation), and fine fly ash, some of which reaches the atmosphere with the stack gases. Hence, coal burning is a source of boron in the atmosphere, but it is not considered to be concentrated enough to have detrimental effects on vegetation, even close to power stations.

A comparative study of variations in the boron contents of heat-affected coal seams indicates that the controlling factors are the temperature of the system and the nature of the process involved. The boron content of the chars/coke is lower in the oxidation/combustion zone than that of the coal, possibly due to volatilization of the boron. Some enrichment of boron was noted in the carbonization zone. The high boron content of semi-coke containing coal tar pitch indicates that boron is concentrated in the liquid fractions of the carbonization byproducts during the natural heating of coal.

Sommaire

La concentration de bore dans un certain nombre de charbons canadiens et australiens a été déterminée afin d'évaluer la variation de la teneur en bore en fonction du rang, de l'âge, du milieu géologique, de la stratigraphie, de la paléosalinité du milieu de formation du charbon et de l'action de la chaleur sur les filons houillers, et de déterminer la quantité de bore qui est dégagée lorsque ces charbons sont brûlés. Sont fournies, pour fins de comparaison, des données sur les teneurs en bore de charbons de plusieurs autres pays.

Des études détaillées du bore présent dans les charbons canadiens n'indiquent aucun rapport entre le teneur en bore et le rang (du charbon sub-bitumineux à l'anthracite). La teneur en bore des charbons sub-bitumineux (Ro 0.38–0.50 %) de l'Ouest canadien dépend surtout du milieu de dépôt. Par exemple, les charbons de Hat Creek en Colombie-Britannique se sont accumulés en milieu d'eau douce et possèdent des teneurs en bore inférieures à 50 ppm, tandis que les charbons de Vesta et de Horseshoe Canyon en Alberta qui ont été déposés en eaux saumâtres ont des teneurs respectives en bore de 150 et de 675 ppm.

Les charbons de Hat Creek, Colombie-Britannique (Oligocène-Éocène); de Mount Allan, Alberta (Crétacé supérieur); de Hoidahl Dome, Yukon (Carbonifère) et de l'île Melville, Arctique canadien (Dévonien) ont tous des teneurs en bore inférieures à 50 ppm, ce qui indique que la teneur n'est pas liée à l'âge des dépôts houillers.

Certains indices montrent que la teneur en bore varie en fonction du contenu macéral des charbons canadiens, particulièrement leur contenu en inertinite. La faible teneur en bore (25 ppm) des bandes riches en inertinite dans un filon houiller formé en eau saumâtre (teneur en bore de 250 ppm) en Alberta (filon 3, mine Vesta) est probablement le résultat de micro-environnements et de la géomorphologie, plutôt que du milieu de formation du charbon, et elle pourrait indiquer une fluctuation du niveau de la nappe phréatique qui aurait causé la formation d'inertinite sous des conditions relativement plus sèches et oxydantes.

Après ré-évaluation de travaux antérieurs et sur la base d'études sur les charbons australiens et de travaux récents sur les charbons canadiens, les relations suivantes sont proposées entre la teneur en bore et la contamination marine des tourbières originales :

1. jusqu'à 50 ppm — charbon formé en milieu d'eau douce
2. de 50 à 110 ppm — charbon déposé en milieu d'eau légèrement saumâtre
3. plus de 110 ppm — charbon déposé en milieu d'eau saumâtre

À l'aide de ces critères, il est possible d'évaluer le degré d'influence marine sur les charbons canadiens et australiens.

La teneur en bore du charbon est soit primaire, résultant du milieu de dépôt (conclusion confirmée par des données sédimentologiques dérivées de façon indépendante), soit le produit d'un enrichissement secondaire.

Une forte teneur en bore dans des charbons déposés en un milieu d'eau douce est habituellement due à un enrichissement secondaire et est reliée typiquement à l'existence de dépôts d'évaporites et de diapirs, à la présence de grands systèmes de failles associés à certains bassins houillers, et à l'activité des eaux souterraines. Les fortes teneurs en bore de certains lignites de la Saskatchewan et de certains charbons bitumineux du bassin houiller de Springhill en Nouvelle-Écosse sont des exemples d'enrichissement secondaire.

La teneur en bore des filons houillers demeure relativement constante latéralement et se maintient dans la gamme des valeurs mentionnées pour chaque milieu de dépôt. Cependant, là où il y a des variations, elles sont attribuées soit à des changements dans les milieux de dépôt, soit à un enrichissement en bore de source secondaire. Les charbons sub-bitumineux de la région de Drumheller, en Alberta, qui se sont déposés en eau légèrement saumâtre à saumâtre, démontrent peu de variations latérales de la teneur en bore sur une distance de 14 km. Les charbons bitumineux (non marins) moyennement à peu volatils (filons 4, 10 et 11) des formations de Gates et de Gething, dans le nord-est de la Colombie-Britannique, présentent peu de variations latérales de la teneur en bore sur une distance de 6,5 km. Le faible rapport de variance pour la variation latérale du bore dans les filons houillers de l'Ouest canadien indique un milieu de dépôt stable au cours de l'accumulation du charbon.

Les variations latérales des teneurs en bore des filons houillers peuvent résulter d'un enrichissement secondaire plutôt que de variations dans le milieu de dépôt (bore primaire). Ainsi, la teneur en bore dans le filon 3 à Springhill, en Nouvelle-Écosse, varie de 37 ppm (enrichissement primaire) à 210 et 280 ppm. L'enrichissement en bore est attribué à l'influence des saumures, ce qui explique les hauts rapports de variance de 5,7 et de 7,6.

Pendant la combustion du charbon, le bore se répartit dans les cendres de fond, les cendres volantes retenues par des procédés d'atténuation des particules (habituellement par précipitation électrostatique) et les fines cendres volantes dont quelques-unes atteignent l'atmosphère avec les gaz brûlés. Par conséquent, la combustion du charbon constitue une source de bore dans l'atmosphère, mais la concentration n'est pas considérée suffisante pour avoir des effets dommageables sur la végétation même près des centrales électriques.

Une étude comparative des variations des teneurs en bore de filons houillers touchés par des phénomènes thermiques indique que les facteurs de contrôle sont la température du système et la nature du processus en cause. La teneur en bore des produits de combustion et des cokes est moins élevée, dans la zone d'oxydation/combustion, que celle des charbons, possiblement du fait que le bore s'est volatilisé. Un certain enrichissement en bore a été observé dans la zone de carbonisation. La forte teneur en bore du semi-coke contenant du brai de houille indique que le bore a été concentré dans les fractions liquides des sous-produits de carbonisation pendant le chauffage naturel du charbon.

INTRODUCTION

The geochemistry of coal is an integral part of any modern study dealing with coal characterization, owing to the possible presence in the coal of toxic and industrially undesirable elements that exceed the legal limits for emissions of such substances. A coal seam formed from material deposited in a brackish water environment may contain undesirable elements; for example, sulphur and elements that form sulphides and sulphates. Boron is an element that is sensitive to the environment of deposition and, therefore, can be used to delineate the area(s) of a coalfield influenced by brackish water conditions during deposition.

During the pioneering studies on trace elements in coal, carried out by V.M. Goldschmidt and co-workers at Gottingen, boron was found in ash from several coals (Goldschmidt and Peters, 1932). Data are available for a wide range of coals from Australia (CSIRO, 1960, 1966; Clark and Swaine, 1962; Brown and Swaine, 1964; Bone and Schaap, 1981; Knott and Warbrooke, 1983; Davy and Wilson, 1984; Swaine et al., 1984b), Canada (Hawley, 1955a; Goodarzi, 1987a,b, 1988; Goodarzi and Van der Flier-Keller, 1988, 1989; Goodarzi and Goodbody, 1990), New Zealand (Kear and Ross, 1961), South Africa (Kunstmann et al., 1963), and the U.S.A. (Zubovic et al., 1964, 1966; Swanson et al., 1976; Gluskoter et al., 1977; Zubovic et al., 1980; White et al., 1983; Chou, 1984; Affolter and Stricker, 1987). The content of boron in most coals "would probably be between 5 and 400 ppm boron" (Swaine, 1990). Concentrations are usually stated as parts per million (ppm) in coal (not ash) on an elemental basis. Modern analytical chemists tend to use $\mu g\ g^{-1}$ rather than ppm, but geochemists tend to favour ppm.

The contents of boron in coal are of interest for several reasons. It has been suggested that boron, presumably derived from coke, may affect the mechanical properties of certain steels (Borrowdale et al., 1959). Coal has been considered as a source of graphite for use as a moderator in nuclear reactors (Hutcheon, 1953), but the content of boron in the graphite must not exceed 2 ppm. The levels of soluble boron coming from washery wastes and fly ash disposal areas should be checked to ensure that undesirable amounts of boron are not being added to nearby rivers or lakes. Some fly ashes could be useful as soil supplements (Swaine, 1981), but plants should be monitored to ascertain whether the boron from fly ash is enhancing or retarding their growth. Similar effects should also be considered during reclamation projects after coal-mining. A process has been developed for the recovery of boron from fly ash (Tsuboi et al., 1990).

During the combustion of some coals using spreader stokers or chain-grate stokers, phosphatic deposits may form on superheater tubes or vertical riser tubes. Such deposits have been found to contain as much as five per cent boron and one to two per cent arsenic, mainly in the form of boron phosphate (BPO_4) (Brown and Swaine, 1964) and boron arsenate ($BAsO_4$) in solid solution in BPO_4 (Swaine and Taylor, 1970). Goldschmidt (1958) reported that Schulze (1934) believed that BPO_4 is related to SiO_2 (cristobalite). Natural occurrences of BPO_4 and $BAsO_4$ are not known. Phosphatic deposits have not been reported in boilers fired with pulverized coal, presumably because oxidizing conditions prevail. From a geochemical point of view, the content of boron in coal is interesting because it indicates whether the environment involved fresh, mildly brackish, or brackish water conditions during the early stages of coalification. Swaine (1962a, 1967, 1971) has investigated Australian coals from this point of view. The only other investigations of boron in coal as an indicator of the environment of deposition are those of Goodarzi (1987a, b, 1988), Goodarzi and Van der Flier-Keller (1988, 1989), Goodarzi and Goodbody (1990), Banerjee and Goodarzi (1990), and Gentzis et al. (1990) for Canadian coals.

DETERMINATION OF BORON CONTENT IN COAL

The amount of boron in coal generally has been determined through Atomic Emission Spectrometry (AES), using a direct current arc, or Inductively Coupled Plasma Emission Spectrometry (ICPAES), and by Spectrophotometry. It is also possible to use a special technique using Prompt Gamma-ray Spectrometry (GP) (Gladney et al., 1976) and Prompt-Gamma Neutron Activation Analysis (PGNAA), (Higgins, 1984). Most of the early work was done by direct current arc AES techniques using coal ash as the sample (Zubovic et al., 1961, 1964, 1966; Clark and Swaine, 1962; Brown and Swaine, 1964; Gluskoter et al., 1977), with ashing temperatures between 450°C and 815°C. Prior to ICPAES analysis, coal ash may be fused with sodium hydroxide (Pollock, 1975) or treated with nitric acid plus hydrofluoric acid at 130°C (Mills, 1986). Coal ash treated with sodium carbonate and then extracted with dilute sulphuric acid gives a solution suitable for the spectrophotometric determination using carminic acid (Pollock, 1975). A similar approach using coal ash prepared at 815°C, then mixed with sodium carbonate and heated at 875°C, prior to extraction and the addition of curcumin, is also used (AS, 1988).

The determination of boron by AES usually uses the lines B249.68 nm and B249.77 nm. Bugry and Shaw (1964) pointed out that there can be interference from nearby Fe lines at 249.65 nm and 249.78 nm, although the latter is a weak line. However, in the technique used at CSIRO by Clark and Swaine (1962), the determination of boron using the boron doublet at 249 nm was not affected (vitiated) by Fe interference, probably because of the favourable dispersion obtained by the large quartz prism. Also, most coal samples do not have a high iron content. The comment by Bugry and Shaw (1964) may well apply to low-boron, high-iron samples. According to Swaine (1990), "The usefulness of a particular line depends on the dispersion of the spectrograph, the conditions of excitation and the concentration of the element, usually a major constituent, that is suspected of causing interference. Hence, categorical statements about line interferences should not be made, but should only be based on experimental evidence." The competence of a spectrographer is based largely on a knowledge of the suitability of spectral lines for particular experimental conditions.

Consistent with the determination of any element at trace levels, care must be taken with sampling, and contamination must be kept to a minimum. If necessary, a "blank" determination may be carried out and used to correct for contamination. A specific source of contamination for boron is the paper used for some sample containers (Huffman, 1960). All aspects of the determination of trace elements in coal have been reviewed by Swaine (1985). The value of geochemical data is enhanced by checking analytical methods against reference standards; for example, the three South African samples, SARM 18, 19, and 20 (Ring and Hansen, 1984). Information on boron in various standard samples, including coal and fly ash, has been published by Gladney and Roelandts (1987).

MODE OF OCCURRENCE OF BORON IN COAL

All trace elements in coal are either associated with the organic coaly matter (macerals) or the mineral matter. Possible modes of occurrence of boron in coal are shown in Figure 1. Since plants require boron for proper growth, it is reasonable to postulate that the plants from which peat was formed contained boron. During coalification, all or part of this boron may have been released and lost from the swamp. Any boron that remained was probably organically combined, possibly by chelation with hydroxyl groups or associated with ester groups. This can be regarded as inherent boron. Another possibility is the presence of boron adsorbed to coal maceral or to organic-rich layers on inorganic matter, such as clay. Boron is commonly enriched in vitrinite macerals of coal and is more abundant in bright than in dull coal bands (Goodarzi et al., in press b).

The association of boron with clay (especially illite) is known, and perhaps anionic boron could be adsorbed by clays. Examination of clay-rich particles from the Upper Freeport coal (U.S.A.), by ion microprobe mass analysis, showed that boron was predominantly in detrital minerals (Finkelman, 1982). Tourmaline, which can contain up to about three per cent boron, has been reported in some coals and it would be worthwhile seeking it in others, keeping in mind that it is most likely to be very finely divided and hence difficult to detect. Although replacement cations and anions are found with some minerals, there is no evidence of this mode of occurrence for boron. For example, it was not found associated with pyrite, calcite, siderite, quartz or apatite in coals from the Sydney Basin, Australia (Swaine, 1971). The notion that boron is associated both organically and inorganically in coal is in keeping with Goldschmidt's suggestion that boron in rocks may be lithophile or biophile (Goldschmidt, 1937).

One approach to ascertaining the degree of association of a trace element with macerals or minerals (organic/inorganic) in coal is to plot the content in coal or ash against the ash yield (Clark and Swaine, 1962). Figure 2 shows such a plot for composite samples (i.e., samples representing a seam) from the southern and northern parts of the Sydney Basin, NSW, Australia. The inverse relationship led to the conclusion that boron "may be organically bound, at least in part, to the coal substance" (Brown and Swaine, 1964, based on Clark and Swaine, 1962).

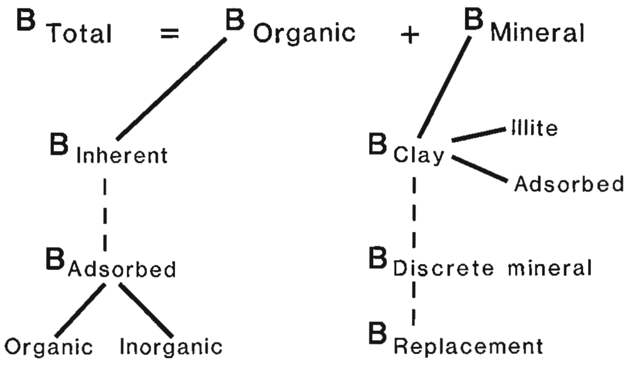


Figure 1. *Mode of occurrence of boron. (From Swaine, 1971.)*

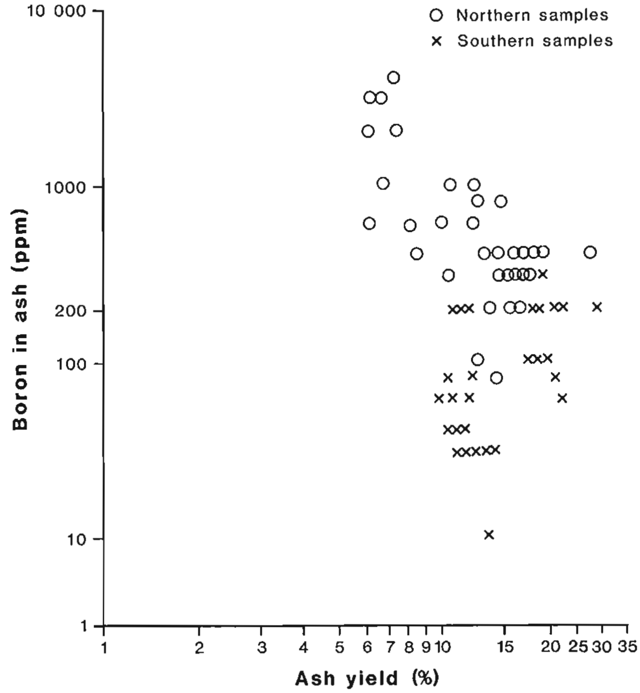


Figure 2. *Boron content of ash versus ash yield for composite samples of bituminous coals from the Sydney Basin, NSW, Australia. (From Clark and Swaine, 1962.)*

Nicholls (1968) plotted results from Clark and Swaine (1962) for boron in whole coal and ash against ash yield, the clearer relationship being for boron in ash. Other plots of boron contents in coal and in ash against ash yields for coals from the Lloyd Cove Seam, Sydney Coalfield, Nova Scotia, showed a clear relationship for the boron-in-ash plot, but an indeterminate scatter for the boron-in-coal plot (Nicholls, 1968, based on results in Hawley, 1955b). Nicholls (1968, p. 276) concluded that, "boron is largely, almost entirely, associated with the organic fraction in coals." Finkelman (1981) regarded boron as generally organically associated, but with illite and tourmaline as minor sources.

Studies of Illinois coals by Gluskoter et al. (1977) indicated a strong organic affinity for boron. On the basis of investigations of cores from some New Zealand coals, Gray (1983) concluded that, "boron is entirely associated with the coal" as distinct from the mineral matter. In another study, nuclear microprobe results of boron and calcium distributions in New Zealand coals from Waikato, by Vickridge et al. (1990), led to the statement that, "we favour the organo-borate anion complex mode of incorporation" of boron in the coal. However, preferential association with submicron-sized mineral particles was not ruled out.

The approach of plotting boron in coal against ash yield has been used on Canadian coals by Goodarzi (1988) for coals from Hat Creek, Fording Coal Mine (Greenhills, Eagle Mountain section) and Byron Creek Collieries (Fig. 3), and by Goodarzi and Van der Flier-Keller (1988) for coals from Hat Creek deposits No. 2 and No. 1, Zone A. These plots showed the inverse relationships characteristic of the organic association of boron. Similar plots for coals from the Sydney Basin, NSW, Australia (Clark and Swaine, 1962) (Fig. 2), and from the Theodore district, Bowen Basin, Queensland, Australia (Fig. 4) are the basis for favouring the organic association of boron in these Australian coals. An improvement in the inverse relationship was found when the coals from the northern part of the Sydney Basin were plotted (Fig. 5). Indeed, plotting the coals from the southern part (low-boron coals) tended to favour a direct relationship between boron content and ash yield, which indicates an inorganic association, at least in part. Also, the results for Hat Creek No. 2 coal (low values in Figure 6) do not show any definite trend that could be interpreted as indicating part organic, part inorganic associations for boron.

Perhaps the situation can be seen in terms of low and high contents of boron, assuming that total boron is made up of both organic boron and mineral boron as shown in Figure 1. When boron content is relatively high, say above 40 ppm, then organic boron predominates, and when boron is less than about

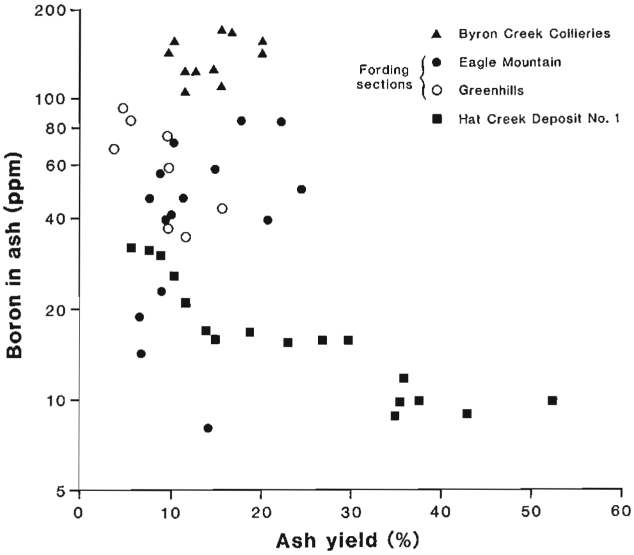


Figure 3. *Variation of boron versus ash yield in coals from Alberta (Byron Creek Collieries) and British Columbia (Hat Creek; Fording Coal Mine, Greenhills and Eagle Mountain sections). (After Goodarzi, 1988.)*

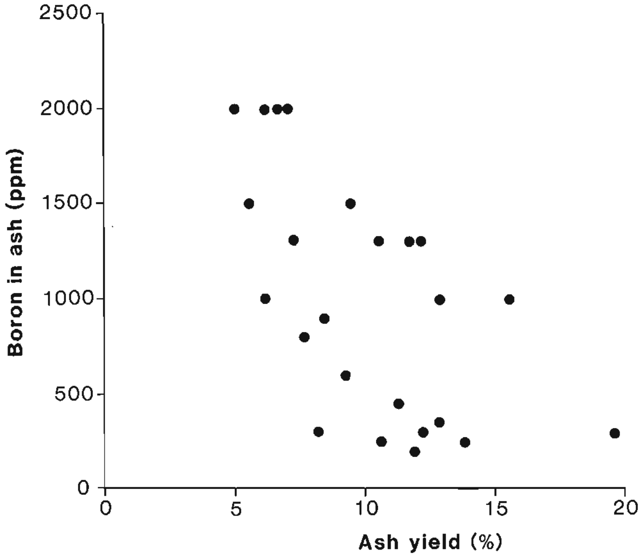


Figure 4. Boron contents of ash versus ash yields for coals from the Theodore District, Queensland, Australia. (After Swaine, 1971.)

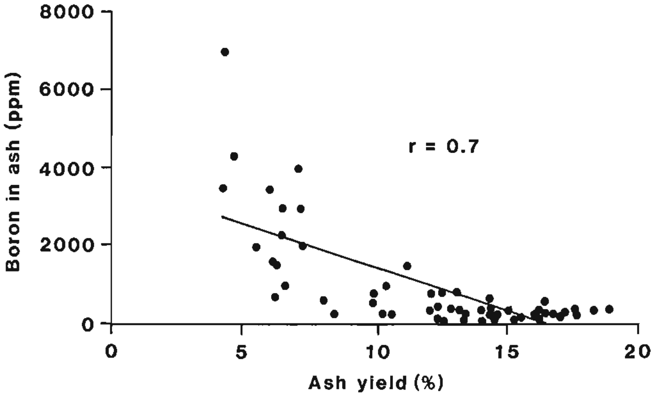


Figure 5. Boron contents versus ash yield of composite samples of ash from the northern part of Sydney Basin, NSW, Australia. (From Clark and Swaine, 1962.)

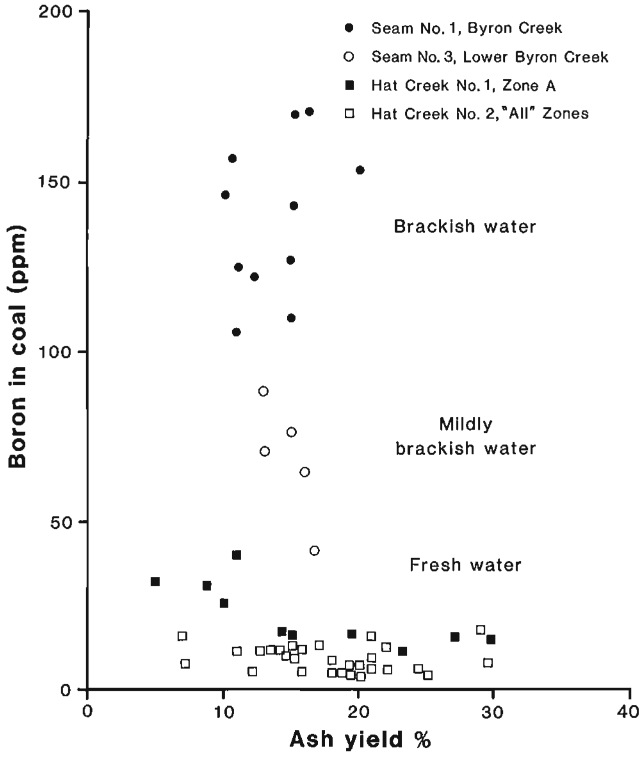


Figure 6. Concentration of boron in coal versus ash yield for the Byron Creek Collieries (Alberta) and Hat Creek (British Columbia) deposits. (After Goodarzi and Van der Flier-Keller, 1988.)
Byron Creek Collieries: Seam 1, and lower Seam 3
Hat Creek deposits: No. 1, and No. 2.

40 ppm, then perhaps the two forms are present in about the same proportions or the mineral boron predominates. Kaolinite from Sydney Basin coals contains up to 27 ppm boron (Swaine, 1971), which confirms this as a source of some boron. It should be stressed that the exact nature of the organic association of boron in coal is not known. It can be suggested that perhaps some of the total boron could be chelated with hydroxyl groups, probably phenolic hydroxyls, by analogy with the reactions of boric acid with polyhydric alcohols, notably mannitol. Indeed, Bouska (1981) stated that the "chelate-type bond . . . is highly probable" for boron in plants. In seawater, boron probably occurs in several forms, namely $B(OH)_3$, $B(OH)_4$, $NaB(OH)_4$, and a polyhydroxyl organic complex. It is postulated that contact between brackish water of varying salinity during the early stages of coalification, say up to the subbituminous stage (R_o 0.5%), could result in the intake of some boron by the coaly matter, probably by adsorption and due to the relatively high porosity of low-rank coal (Franklin, 1951; Hirsch, 1954).

Organic and inorganic associations of boron in coal have been put forward by several scientists who used float-sink fractionations; that is, separations based on density differences. Horton and Aubrey (1950) suggested that 75 to 100 per cent of boron in United Kingdom coals was organically associated, while Zubovic (1966) gave 77 per cent organic affinity for boron in U.S.A. coals, and Ruch et al. (1974) regarded boron as predominantly organically-bound in Illinois coals.

Leckie et al. (1990) studied the organic-rich radioactive marine shales of Cretaceous age from the basal Shaftesbury Formation, Alberta. These shales fall into three categories: 1) open marine, 2) restricted, marginal-marine, and 3) brackish water estuarine (Fig. 7a). The restricted, marginal-marine shales are radioactive, and contain higher marine algae (cf. *Lancettopsis lanceolata* Mädler, 1963) and higher Total Organic Carbon contents (TOC 6%) than the other two shale beds (Fig. 7b). The boron content of all shales is above 120 ppm. However, the organic-rich restricted shales have boron contents of 200 to 300 ppm, while the boron content for the other two shales is in the range of 120 to 200 ppm (Fig. 7c). These results indicate that there is a possible correlation between higher input of TOC and algal content in the marine environment and the boron content of these sediments, which points to a possible organic association for boron in these rocks.

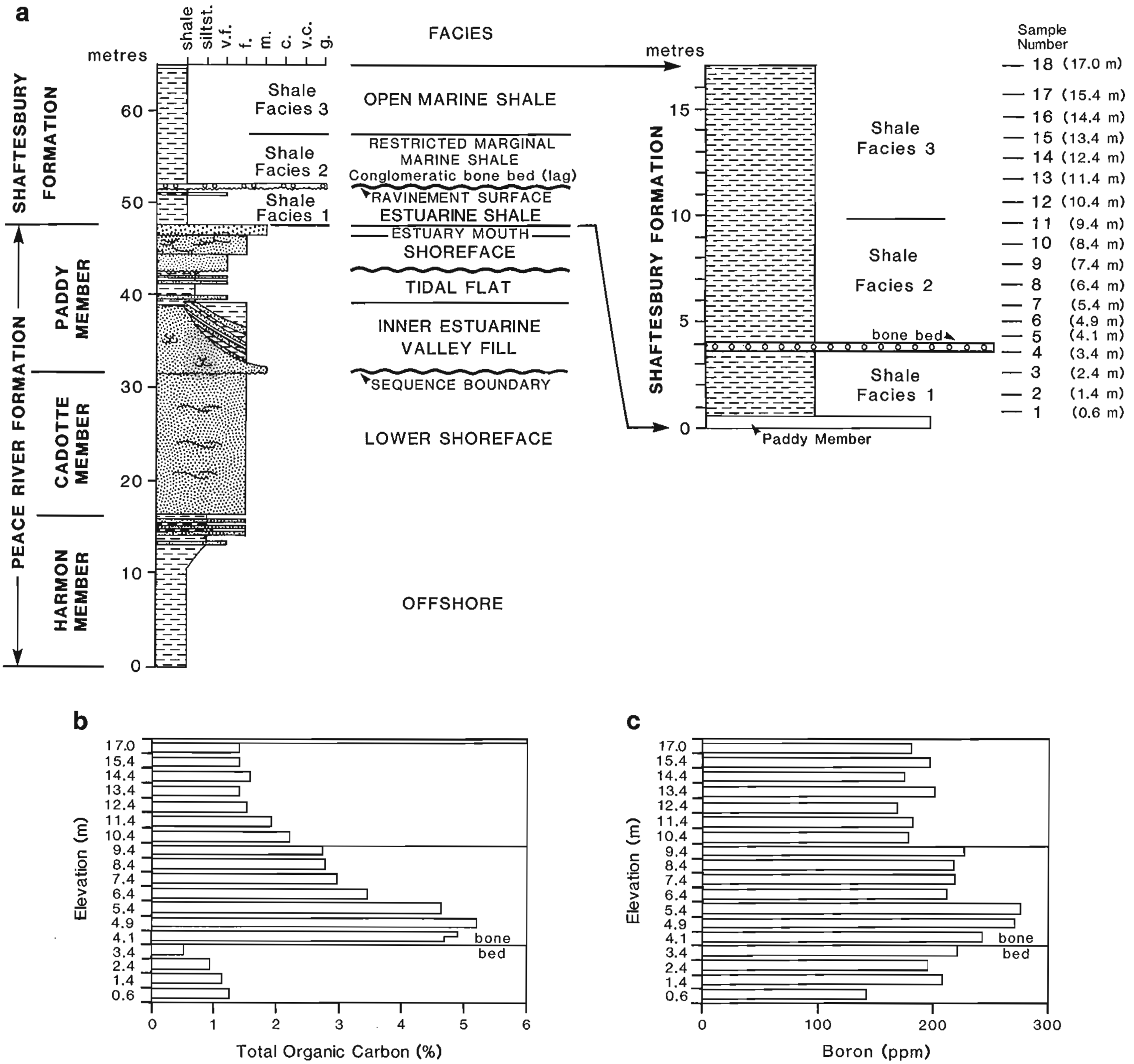


Figure 7. *Measured section of the Peace River Formation and the basal Shaftesbury Formation (from Leckie et al., 1990), showing the three shale facies and location of samples (**a**), the vertical variation of total carbon (**b**), and the vertical variation of boron (**c**) in the basal Shaftesbury Formation.*

BORON CONCENTRATIONS IN COAL

The boron contents of selected coals are given in Table 1. A complete compilation of the boron content in coals of different ranks from various countries has been provided by Swaine (1990). Low-rank coals from Hat Creek (Canada), East Germany, and Victoria (Australia) had low boron contents (2-32 ppm boron), but higher values were reported for some South Australian (Leigh Creek) and U.S.A. coals. A similar situation is found with bituminous coals, where low and high values may occur, even in one area. As will be suggested below, higher values are probably the result of marine incursions during the early stages of coalification. In some areas, boron contents are remarkably consistent. For example, 13 samples from 9 locations in the Lithgow Seam, in the western part of the Sydney Basin (Australia), contained 15 to 30 ppm boron with a mean of 20 ppm (for 90% of values). The samples were taken over a distance of about 100 km (Swaine, 1984).

Rank relationships

Somasekar (1972) stated that there is a relationship between boron content and rank of coals, and Lindahl and Finkelman (1986) suggested that, for coals in the U.S.A., the concentration of boron decreases with increasing coal rank, from about 100 ppm boron in lignite to about 10 ppm boron in anthracite. In contrast to these two studies, Banerjee and Goodarzi (1990) found no evidence of a relationship "between boron and rank of coals from different ages and geological settings."

Detailed studies of boron in Canadian coals indicate that in coals from: a) the same geological setting and of the same age (Goodarzi and Cameron, 1987; Goodarzi, 1988), b) different geological settings but the same age (Banerjee and Goodarzi, 1990), and c) different geological settings and ages (Goodarzi, 1987a; Goodarzi and Van der Flier-Keller, 1989), there is either no relationship between boron content and the

TABLE 1

Contents of boron in selected coals from Canada, U.S.A., Australia, U.K., Greece, and Germany

Location	Boron (ppm)	Source of data
Low rank coals (lignite-subbituminous)		
Latrobe Valley, VIC, Australia	2–30	Bone and Schaap (1981)
Leigh Creek, SA, Australia	40–300	CSIRO (1966)
Hat Creek No.1, BC, Canada	9–32	Goodarzi (1987a)
Hat Creek No. 2, BC, Canada	1–18	Goodarzi and Van der Flier-Keller (1988)
Saskatchewan, Canada	15–234	Beaton (1990)
Niederrhein, E. Germany	6–21	Pietzner and Wolf (1964)
Gulf Province, United States	<10–200	Swanson et al. (1976)
Fort Union region, United States	15–300	Hatch and Swanson (1976)
Greece	8–444	Foscolos (1989)
Bituminous coals		
Sydney Basin, NSW, Australia	1–300	Clark and Swaine (1962)
Bowen Basin, QLD, Australia	<1.5–150	Brown and Swaine (1964)
Fording Mine, BC, Canada	9–94	Goodarzi (1988)
Byron Creek, BC, Canada	25–200	Goodarzi and Van der Flier-Keller (1989)
Telkwa, BC, Canada	18–40	New data, this study
Vesta Mine, AB, Canada	171–265	Gentzis et al. (1990)
Mannville, AB, Canada	18–1144	Banerjee and Goodarzi (1990)
Melville Island, Arctic Canada	14–69	Goodarzi and Goodbody (1990)
Ruhr, W. Germany	9–92	Kautz et al. (1975)
South Africa	11–109	Kunstmann et al. (1963)
N. and S. Wales, U.K.	0.5–50	Swaine, unpublished data
Eastern United States	<0.6–160	Zubovic et al. (1980)
Western United States	16–140	Gluskoter et al. (1977)
Alaska, North Slope	20–200	Affolter and Stricker (1987)

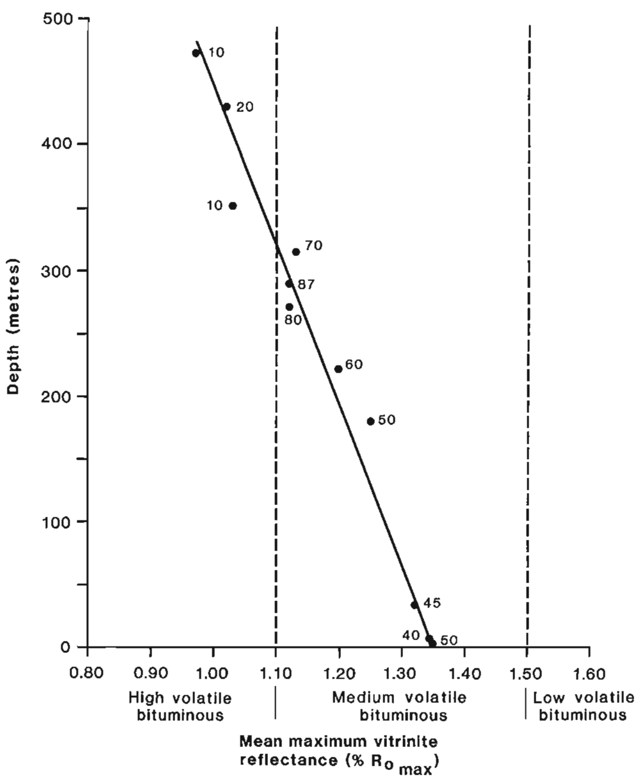


Figure 8. Variation of boron content in high to medium volatile bituminous coals in the Eagle Mountain section, Fording Coal Mine. (The rank/depth relationship is from Goodarzi et al., 1991.) The number beside each black circle represents ppm boron.

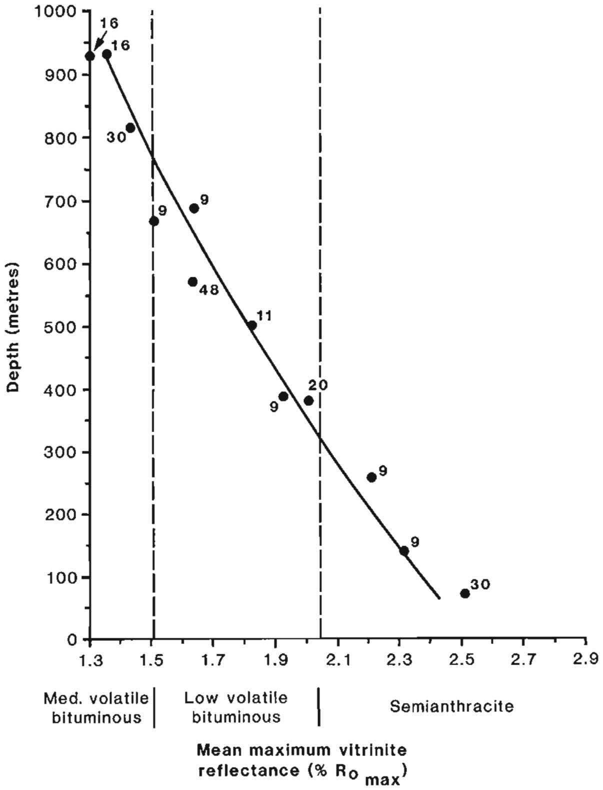


Figure 9. Variation of boron in medium volatile to semianthracitic coals from Mount Allan, Alberta. (The rank/depth relationship is from Hughes and Cameron, 1985.) The number beside each black circle represents ppm boron.

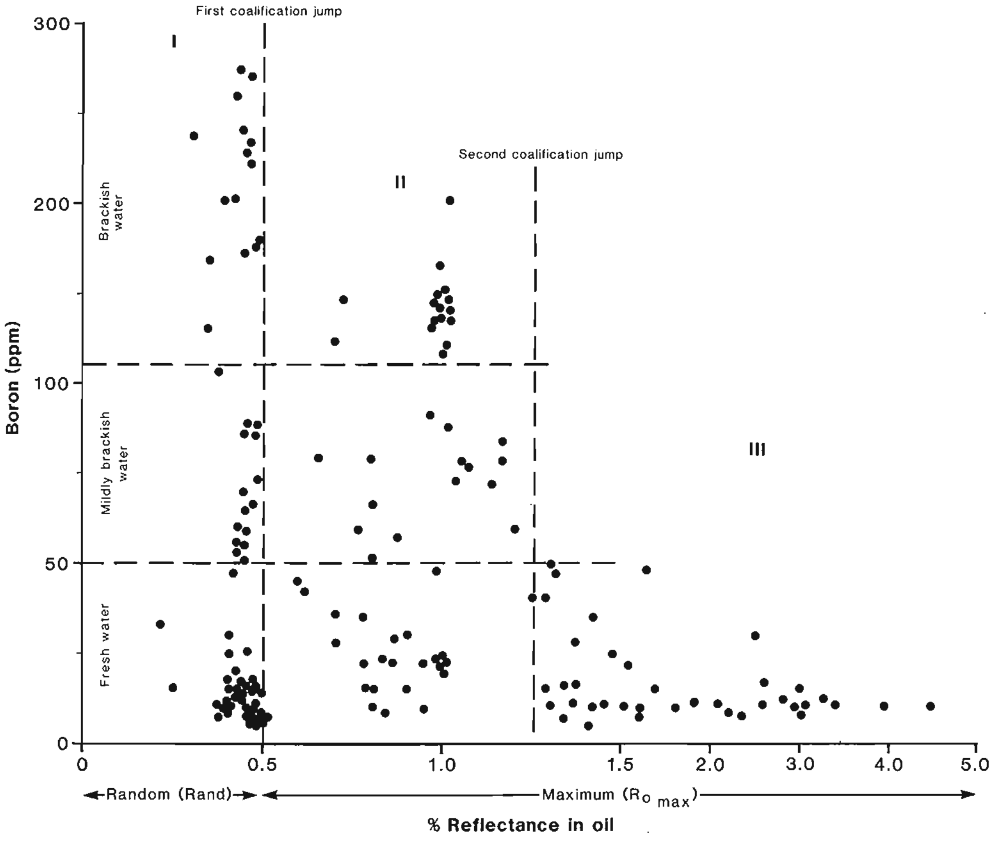


Figure 10. Variation of boron with rank as determined by the reflectance (%R_{omax}) of coals from Western Canada.

reflectance and rank of coals or a very complex relationship (Goodarzi and Swaine, 1992) (see Figures 8 and 9). Figure 10 shows the variation of boron content with rank (lignite-meta-anthracite: Ro_{random} 0.25 to 0.60%, Ro_{max} >0.60 to 5.00%) for Canadian coals (ash <25%) from different depositional environments and of different ages. The variation of boron with rank for this large set of coal samples again indicates that the relationship between boron content and rank is rather complex. There appear to be three populations based on boron/rank relationship, but these are related to the coalification stages rather than the rank of the coal. The first group comprises coals that are in the diagenetic stage of formation and consists of lignite to high volatile C bituminous coals. As shown in Figure 2, these coals have no relation with rank. Variation of boron in this group is only related to the depositional environment (as supported by geological evidence). Hat Creek coal (Zone A), from British Columbia, and coals from Seam 3 in the Vesta Mine and Seam 0 of the Horseshoe Canyon Formation (Drumheller coal area, Alberta), are subbituminous (Ro_{random} 0.38-0.50%) (Goodarzi, 1985a; Gentzis et al., 1990). However, coals in the Hat Creek deposit, which were deposited in a freshwater environment, have boron contents of <50 ppm, while Vesta and Drumheller coals, both of which were influenced by brackish water conditions during deposition, have boron contents of 150 and 675 ppm, respectively. It is clear that there is no relationship between boron content and this rank level (Fig. 10). The second group is in the early catagenetic stage and within the bituminous coal range. There is no boron/rank relationship for this group (Fig. 10). The third group includes coals with ranks above the second coalification jump (Ro_{max} >1.25%). This third group comprises mainly bituminous coals that are geographically restricted to Western Canada (coals from the Kootenay Group, and the Gates and Gething formations, and anthracite and meta-anthracite from the Groundhog and Hoidahl Dome coalfields). There is no clear-cut relationship between boron and rank for this group either (Fig. 10).

Age relationships

The variation of boron content with ash content for Canadian coals of different ages (Devonian to Oligocene-Eocene) is shown in Figure 11. It is apparent that the boron content of coals is not governed by the age of coal. For example, coals from

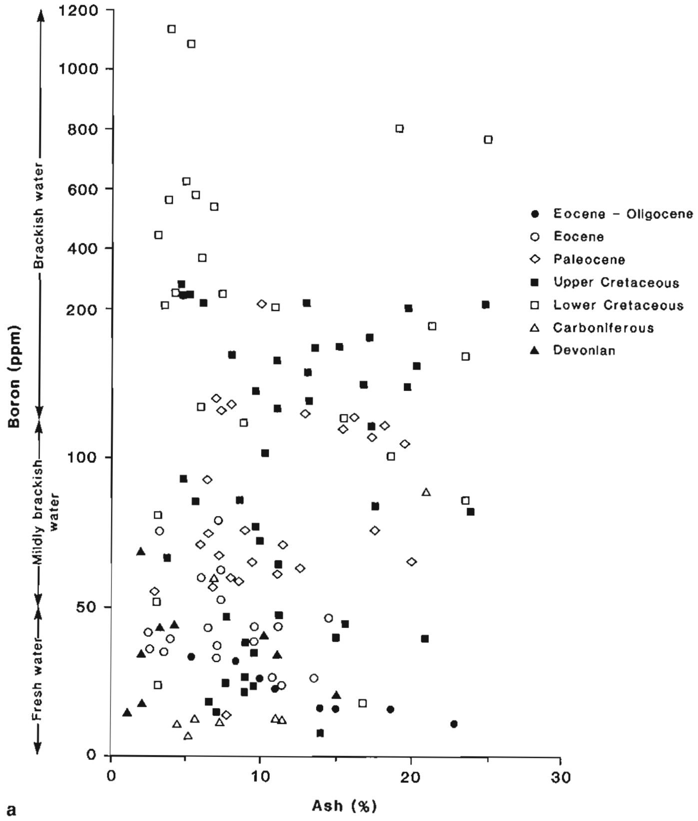


Figure 11a. Variation of boron versus %ash for Canadian coals of different ages.

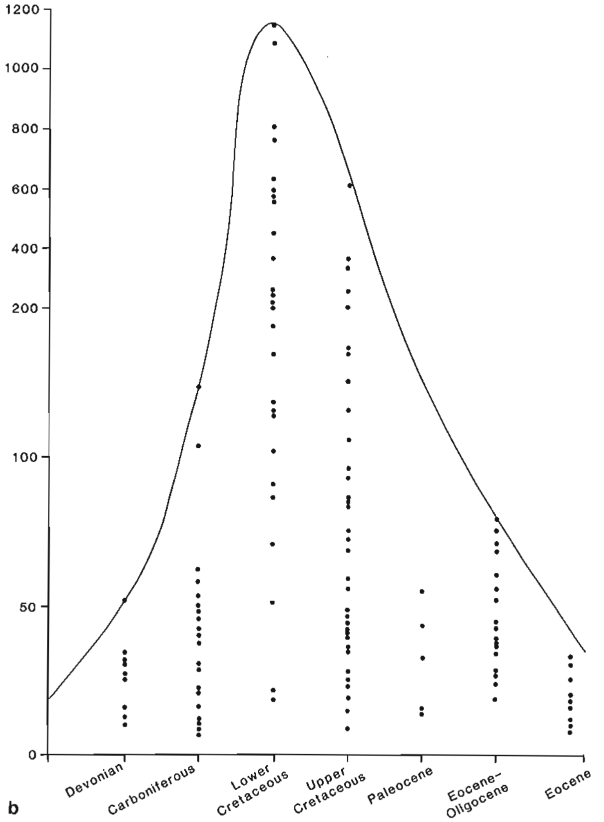


Figure 11b. Variation of boron versus age of coals from Canada.

Hat Creek, British Columbia (Oligocene–Eocene), Mount Allan, Alberta (Jurassic–Lower Cretacous), Hoidahl Dome, Yukon Territories (Carboniferous), and Melville Island (Devonian) all have boron contents of <50 ppm, reflecting their freshwater depositional settings rather than their age.

Compositional relationships

An important factor that influences the maceral composition of Canadian coals is the age of the coal. Coals of differing ages may have different maceral compositions, owing to the various types of peat-forming plant communities that are age related (Teichmüller and Teichmüller, 1982). In Canada, the Devonian coals from the Arctic are sporinite-rich (Goodarzi and Goodbody, 1990); in contrast, Cretaceous and younger coals are commonly resinite-rich (Hat Creek coals, British Columbia; Goodarzi 1985a). Unlike the Australian Gondwana coals, which are rich in inertinite (Chandra and Taylor, 1982) (the inertinite content of entire coal seams may amount to 85 per cent of the coal; Taylor and Cook, 1962), the Canadian coals occasionally may contain up to 35 per cent inertinite (Cameron, 1984).

There is some evidence of variation of boron with maceral content in Canadian coals, particularly as related to the inertinite content of coals. For example, Seam 7 from Drumheller was formed from material deposited in a mildly brackish water setting and has a boron content of 70 ppm, while an inertinite band occurring at the top of this seam has a boron content of 27 ppm. The carbonaceous shale (ash content 43%) occurring immediately beneath this inertinite layer also has a boron content of 35 ppm. The lower boron content for this inertinite layer is accompanied by low sulphur and volatile matter contents and a higher fixed carbon content as compared to the whole coal (Table 2). A similar situation was observed in the detailed study of Seam 3 from the Vesta Mine, Alberta (Table 2).

The low boron contents (25 and 27 ppm) of inertinite-rich bands in Seam 7 (formed under mildly brackish water conditions) from Drumheller (boron content of the whole seam is 70 ppm), and Seam 3 (formed under brackish water conditions) from the Vesta Mine (boron content of the whole seam is 250 ppm) are probably related to the geomorphology of the coal forming environment. The inertinite-rich bands may reflect a change in depositional

TABLE 2

Variation of boron and sulphur with macerals in western Canadian coals

Location	Rank	Depositional environment	% Weight			
			Ash yield	Sulphur	Fixed carbon	Boron (ppm)
Line Creek	Medium volatile bituminous	Fresh water				
Seam 6						
a. Vitrinite-rich layer			9.2	0.72	67.4	54
b. Inertinite-rich layer			6.2	0.65	71.5	23
c. Whole seam			27.0	0.64	54.0	47
Seam 8						
a. Vitrinite-rich layer			6.0	0.33	70.1	78
b. Whole seam			14.2	0.34	65.0	46
Drumheller	Subbituminous	Mildly brackish water				
Seam 7						
a. Inertinite-rich layer			7.0	0.16	62	27
b. Carbonaceous shale			14.0	0.31	52	70
c. Whole coal			14.0	0.31	52	70
Vesta Mines	Subbituminous	Brackish water				
Seam 3						
a. Inertinite-rich layer			9.0	0.19	56	25
b. Whole coal			10.0	0.45	48	210

environment (pH of water), a relatively drier, oxidative condition, and/or a drop in the level of the water table.

Goodarzi et al. (in press, a) reported a higher concentration of boron (78 ppm) in a vitrinite-rich band (ash yield 6.0%), as compared to the whole coal (average of 11 samples: 46 ppm), in Seam 8 at the Line Creek Mine, British Columbia (Table 2). The relatively higher boron content of the vitrinite-rich layer possibly indicates an organic association of boron.

Seam 6 from Line Creek contains vitrinite-rich and inertinite-rich bands. The vitrinite-rich band has a higher boron content (54 ppm) than either the whole coal seam (47 ppm), or the inertinite-rich band (27 ppm). Inertinite bands in coal are indicative of a drop in water table level and, therefore, dryness, oxidation, and possible peat fires (Goodarzi, 1985b), while vitrinite bands indicate a higher water table level. The low boron contents of inertinite-rich bands in Seam 3 in the Vesta Mine and Seam 6 in the Line Creek Mine simply indicate that these two bands formed above the water table and, therefore, had less contact with water containing boron.

Summary (boron concentrations in coal)

It has been established that there is little relationship between the boron content and rank and/or age of Canadian coals, but there is a relationship between boron content and the composition of the coal. Low rank coal (high volatile C-B subbituminous) will favour secondary enrichment of boron.

Comparisons of boron values for coals with mean boron values for rocks and soils (Table 3) indicate that many coals contain more boron than limestones and sandstones but that their boron contents are similar to those of many shales and some soils. In general, the boron contents in sediments associated with coal-bearing strata and most coals are variable. For example, for coals that show secondary enrichment of boron (Saskatchewan lignites) the associated sedimentary rocks contain less boron than the coal (see below), while in coals that absorbed boron during their deposition, or immediatly afterward, the boron content of the partings is commonly variable and may be higher than that of the associated coal layers.

TABLE 3

Boron contents of rocks and soils

	Boron (ppm)	Source
Earth's crust	13	Bowen (1979)
Shale (mean)	10	Bowen (1979)
Limestone (mean)	20	Bowen (1979)
Sandstone (mean)	30	Bowen (1979)
Sediment (mean)	100	Bowen (1979)
Soil	2-100	Swaine (1955)
Tonstein	25-66	Goodarzi et al. (1990)
Most coals	5-400	Swaine (1990)
Most coals (probable mean)	30-60	Swaine (1990)

MARINE INFLUENCE ON THE AMOUNT OF BORON IN COAL

Goldschmidt and Peters (1932) reported that argillaceous sediments of marine origin contain relatively high concentrations of boron compared to terrestrial clays. This is the basis for the use of boron as a salinity indicator. Further work on Swedish sediments by Landergren (1945) indicated that the boron concentrations in marine and nonmarine sediments differ significantly. This conclusion was confirmed by Landergren and Manheim (1963). Much work on the association of boron with clays in relation to paleosalinity confirmed the claims of Goldschmidt and Peters (1932) and Landergren (1945), although there have been some dissenting views. The situation has been reviewed succinctly by Couch (1971) who decided that "the validity of boron as a salinity index has been established by numerous studies over the past two decades." Geochemical methods, including the assessment and interpretation of the amount of boron in clays, have been discussed by Bouska (1981), especially in relation to paleosalinity.

The basis for using the amount of boron in clays, coals, or other materials as an indicator is that seawater contains 4.6 ppm boron compared with less than about 0.1 ppm boron in most rivers and other terrestrial waters. The question is, do clays and coals assimilate boron from the waters in which they are deposited and retain it during diagenesis and later processes? There is experimental evidence that clays remove some boron from aqueous solutions. For example, Hingston (1964) showed that kaolinite, montmorillonite, and illite extract boron from solutions, but not to the same extent. Lerman (1966) carried out experiments on the intake of boron by clays from artificial seawater solutions, and found that the intake was proportional to the concentration of boron in solution, the process following the Freundlich adsorption isotherm.

Another experimental study (Fleet, 1965) showed that the removal of boron from natural waters depended on both the salinity and the boron content of the solution. These experiments confirmed that adsorption is the mechanism for the initial intake of boron. Other studies by Harder (1961) and Couch and Grim (1968) showed that fixation of boron is rapid and that desorption does not occur when the concentration of boron in solution is reduced.

In general, illites fix more boron than kaolinites or montmorillonites, depending mainly on the boron concentration in solution, but also on pH, ionic strength, and temperature. As Couch (1971) pointed out, the boron content in clays depends on some properties of the sediment; namely, the amount of boron retained from earlier sedimentary cycles, the clay mineralogy, grain size, surface area, and crystallinity of the clay. It is not easy to ascertain the amount of boron retained from earlier sedimentary cycles. For a particular clay mineral, boron intake would be expected to be enhanced in poorly ordered specimens. On the basis of a study of some kaolinitic Tertiary shales, Couch (1971) concluded that "paleosalinities calculated from boron and clay-mineral data . . . are consistent with paleoenvironments independently determined from the fauna." He suggested that "samples of similar clay mineralogy, or corrected for mineralogic changes" should be used. Perhaps the use of whole-rock concentrations is the reason for some of the doubts expressed by some authors about the boron method.

In view of the usefulness of the boron content of clays for indicating, at least approximately, the degree of salinity in terms of marine, brackish water, and fresh water, several attempts have been made to use the boron content of sediments associated with coals. Degens et al. (1957) and Keith and Degens (1959) investigated shales from part of the Appalachian Coal Basin in Pennsylvania, U.S.A., and found the following mean values for boron content: 44 ppm boron (fresh water), 92 ppm boron (brackish water), and 115 ppm boron (marine). Ernst et al. (1958), on the basis of work on some sediments in the Ruhr region of Germany, suggested values of 15 to 45 ppm boron for freshwater conditions and 90 to 190 ppm boron for marine conditions, and concluded that "boron contents seem to offer possibilities for correlation in non-fossiliferous sequences of changes in salinity, as well as a means for diagnosis of the environment of non-fossiliferous sediments." Several hundred samples of dirt bands (that is, coaly material with an ash yield of more than 35%) from four coal measures (Illawarra, Newcastle, Tomago, and Greta) in the Sydney Basin, NSW, Australia, were analysed for boron (Swaine, 1962a). Mean values were 43 ppm boron (Illawarra, fresh water), 64 ppm boron (Newcastle), 107 ppm boron (Tomago), and 164 ppm boron (Greta, marine), as shown in Figure 12. However, the ranges of values, even for 90 per cent of values, were wide. Similar wide ranges were also found for clay-rich dirt bands. It was not considered worthwhile trying to separate the clays for further examination. Bohor and Gluskoter (1973) used boron in illite as an indicator of paleosalinity for Illinois coals, and suggested that better results would probably be gained by using samples from vertical sequences of cyclothemic units. On the basis of boron in Carboniferous sediments (claystone and siltstone) from coal basins in Central Bohemia, Bouska and Pesek (1976) "confirmed sedimentation in a freshwater environment." Goodarzi et al. (1990) found 25 to 66 ppm with a mean of 37 ppm boron in 15 kaolinitic tonsteins from the East Kootenay Coalfield of southeastern British Columbia, in keeping with the freshwater environment proposed for the coal bearing strata (Gibson, 1985).

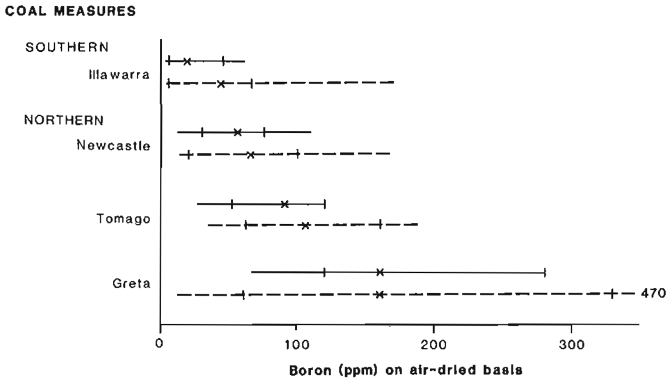


Figure 12. *Contents of boron in clean coal composites (—) and dirt bands (--) from the Sydney Basin, NSW, Australia. Mean values (x) and ranges for 90% of the values (+ – +) are shown. (From Swaine, 1962a.)*

The Emma Fiord oil shales in arctic Canada were formed in a lacustrine environment subjected to a marine influence and mainly consist of recessive weathering, black marlstone and shale with interbedded thin coal seams and algal and oolitic limestones (Davies and Nassichuk, 1988). The boron content of these shales is between 62 and 197 ppm (Fig. 13), in agreement with the organic petrological (Goodarzi et al., 1987) and sedimentological (Davies and Nassichuk, 1988) evidence, indicating the mildly brackish to brackish nature of the water in which the shales were deposited.

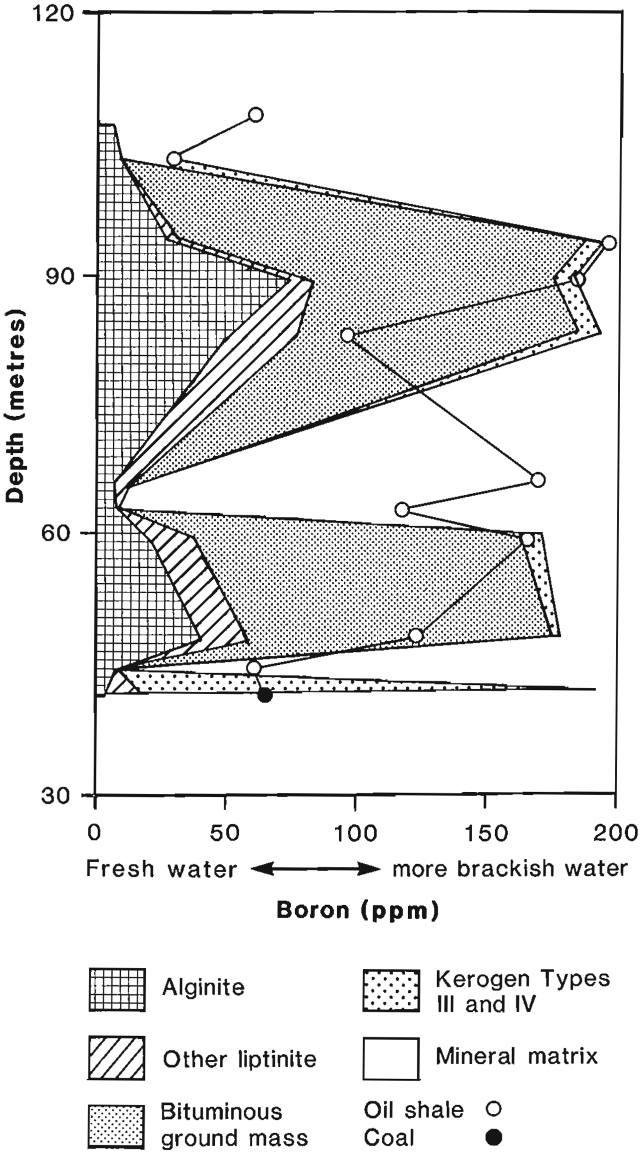


Figure 13. *Variation of boron content with depth and environment in coal and oil shales of Lower Carboniferous age from the Emma Fiord Formation, Arctic Archipelago.*

The above two studies support the use of boron along with other parameters for the determination of the depositional environments of sediments.

It seemed logical to assess the relationship between the amount of boron in coal and the degree of marine influence. Hence, Swaine (1962a) determined the boron contents of hundreds of samples of coal (samples with an ash yield of less than 35%). On the basis of the results (Fig. 13) it was suggested that the Illawarra Coal Measures were freshwater-influenced and the Greta Coal Measures were marine-influenced, there being some independent geological evidence for these conclusions; for example, marine fossils are associated with *Glossopteris* in the upper beds of the Greta Coal Measures. The results for the Tomago Coal Measures indicate some influence from brackish water conditions (Swaine, 1967), a finding that has some support from tonstein studies (Diessel, 1965) and other geological evidence (Diessel, 1980). On the basis of these results and further work, it was suggested that the following scale of values is applicable (Swaine, 1971):

1. Up to 40 ppm boron: *freshwater-influenced coals*
2. 40-120 ppm boron: *brackish-water-influenced coals*
3. >120 ppm boron: *marine, seawater-influenced coals*

The term 'marine' could be misunderstood and could be taken to imply that the coal was formed in seawater, even where the salinity was intermediate between seawater and fresh water; that is, brackish water. As pointed out by Goodarzi (1987a), "It is difficult to visualize a coal seam of any lateral extent or thickness developing in a true marine environment." However, some peat swamps were located close to the sea. Wanless et al. (1969) suggested that "many coal swamps were near sea level and were subject to drowning with a slight rise in sea level." They cited examples of marine transgressions in some parts of the U.S.A. which would have produced brackish water conditions during the early stage of coalification. It is important to understand the history of marine water trapped in sediments below peat beds; what was its migration path and did it traverse the overlying peat beds (coal seams) when the entire sequence of strata was being compacted?

Following a reappraisal of earlier work and taking into account recent work by Goodarzi and co-workers on Canadian coals and by Swaine and co-workers on Australian coals, it is proposed that the terms identifying the degrees of salinity and their associated boron concentrations should be changed to fresh water (F), mildly brackish water (MB) and brackish water (B). The new ranges and categories are:

1. Up to 50 ppm boron: *freshwater-influenced coals* (F)
2. 50-110 ppm boron: *mildly brackish-water-influenced coals* (MB)
3. >110 ppm boron: *brackish-water-influenced coals* (B)

In a study of coals from the Illinois Basin, Gluskoter et al. (1977) found generally enhanced values for boron content (12–230 ppm boron, with a mean of 110 ppm boron), possibly representing "a greater marine influence during and immediately following the time of the coal swamp in the basin." This is in keeping with other criteria; for example, "coals of the Illinois Basin are generally more closely associated with marine strata than are coals in the Appalachian (eastern) or in the Rocky Mountain (western) areas" (Gluskoter et al., 1977, based on Wanless et al., 1969 and Weimer, 1970).

Since the original suggestion by Swaine (1962a, 1967, 1971), the relationship between the boron content of coal and paleosalinity has been recognized by Timofeev et al. (1967) and Gluskoter et al. (1977). However, the only extensive use of variations in boron contents in coal to assess the degree of marine influence on coals has been by Goodarzi, who has studied a wide range of Canadian coals of different ranks and ages. Hat Creek No. 1 coals (Goodarzi, 1987a) and Hat Creek No. 2 coals (Goodarzi and Van der Flier-Keller, 1988) were deposited in freshwater environments. Values for boron contents of Byron Creek Collieries coals indicated that "the coal from Seam 1 was deposited in a more marine (brackish water) environment than the other seams" (Goodarzi, 1987b). Seam 1 was classified as brackish water, while Seam 3 was classified as semi-brackish water (Goodarzi, 1987a). Coals from the Fording Coal Mine in British Columbia were assessed as influenced by freshwater to mildly brackish water conditions (Goodarzi, 1988). A detailed study of the Tulameen coal deposit in British Columbia, using samples from the Blakeburn Mine, indicated formation in a freshwater environment (Goodarzi and Van der Flier-Keller, 1989). The Canadian results are interesting because the conclusions drawn from the boron contents seem to be compatible with information about the environmental conditions derived from other, mainly geological, sources.

Seawater contains 4.6 ppm boron, compared to less than 0.1 ppm in most river and other terrestrial waters. It is suggested that, at the early stages of coalification, organic matter assimilates some boron from swamp waters affected by influxes of seawater. The boron could be retained in the peat through adsorption or by a more direct chemical fixation. The nature of the relationship between the organic matter and boron is unknown, but it could be through hydroxyl or ester groups, perhaps by the formation of a boron-chelation complex. Some support for this hypothesis is the stable boron complex formed with mannitol. Nicholls (1963) stated that "the relative bond strength between boron–oxygen suggests that this bond would be very stable against weathering hydrolysis and no significant boron would be released until the lattice . . . was almost entirely disintegrated." Perhaps the boron/coal bonding is similarly stable. Contacts between volcanic rocks and coal deposits may be a factor in the boron enrichment of some coals, through the migration of boron into seams adjacent to the volcanic rocks. Contact metamorphism of this type has been reported for some coals (Bouska, 1981).

It has been pointed out that coals are unlikely to have formed in a seawater environment. The mineable coal beds in the U.S.A. are derived from freshwater environments with little or no marine influence during their deposition. Good quality coal cannot develop under continuous influence of marine or brackish water, because of the resultant high ash and sulphur contents (Cecil et al., 1982). Since the transformation of peat to coal results in a net organic matter loss, which results in the concentration of mineral matter, the transformation of Okefenokee peat to a level of medium volatile coal under laboratory conditions has resulted in a net loss of 50% organic matter. A 10 cm thick peat layer with 10% ash will become a 1 cm thick bituminous coal bed with 18% ash, while a peat with 25% ash results in a bituminous coal with 40% ash. Therefore, coal partings frequently represent a high mineral matter content, and are coalified peat layers rather than true detrital sedimentary partings (Cecil et al., 1982).

Goodarzi (1987a) stated that "most coals described as marine are formed under brackish water conditions; for example, the marine-influenced coals of the Illinois Basin were probably formed under deltaic conditions close to the sea (Wanless et al., 1969); however, some of them were influenced by marine conditions immediately after deposition because of transgression of the sea in the particular deltaic setting (Wanless et al., 1969)." Perhaps the presence of too much seawater would severely restrict continued peat formation. At most, brackish water conditions, produced by contamination of swamp waters by seawater, are envisaged. It seems that increased subsidence during a period of peat accumulation (Taylor and Warne, 1960) could allow incursions of seawater, especially during storms. Dilution of the invading seawater by swamp water would leave a concentration of up to a few parts per million of boron, some of which could be removed and fixed by the peat. Indeed, Timofeev et al. (1967) stated that high boron contents in brown coals from the Angara–Chulym depression, U.S.S.R., "could be due to the penetration of B-containing sea water into the peat bog during the ingression of epicontinental sea basins."

A possible reason for variations in the boron contents of coals from a restricted area, where the concentration of boron in the swamp waters was relatively constant, is the hummocky terrain found in raised swamps (McCabe, 1984). In such cases, less boron would be available at the tops of the hummocks above the water level. An example of this type of variation in boron concentration is found in a coal seam at the Vesta Mine, Alberta. The details of boron and sulphur contents, and the proximate and maceral composition of this coal seam are presented in Figure 14. The boron contents of all coal layers with ash contents of 5.0 to 8.6% is high (171-265 ppm). The sulphur content of these layers is 0.31 to 0.50%, while their volatile matter content is 41.1 to 42.9%. However, a coal layer near the top of the seam has surprisingly low boron (25 ppm), sulphur (0.19%), and volatile matter (35%) contents. In contrast, the same coal layer has the highest fixed carbon (56.8%) and inertinite content (36%) compared to other coal layers (Fig. 14). The presence of a high content of inertinite in this coal layer indicates that the coal was exposed at the surface, since inertinite in coal is formed either by the process of weathering/oxidation or fire (Teichmüller and Teichmüller, 1982). This coal layer also contains pyrolytic carbon, confirming the exposure to air and the possibility of a peat fire (Goodarzi, 1986a). The evidence outlined suggests that this coal layer in this location was deposited in the raised area of the swamp and above the water level, and therefore assimilated less boron from the brackish swamp water.

Perhaps the most interesting and potentially useful aspect of the concentration of boron in coal is its relevance to the assessment of the degree to which coal seams were subjected to a marine influence. Additional research is required to extend existing studies of this aspect of Australian and Canadian coals.

BORON CONTENT AND THE DEGREE OF MARINE INFLUENCE ON CANADIAN COALS

The coal resources of Canada are found from west (coastal British Columbia) to east (Atlantic Provinces) and from south (southern Alberta) to north (Yukon Territory and the Arctic Archipelago) (Fig. 15). Canadian coals range in age from Middle Devonian to Eocene and Oligocene (Smith, 1989). The western Canadian economic coals are mainly in Upper Jurassic to Paleocene strata, while the eastern Canadian coals are mainly in the Upper Carboniferous. Northern Canadian coals occur in Carboniferous strata in Yukon and in the Devonian of the western Arctic Islands.

Goodarzi and co-workers have published results showing the boron content of several coals from various Canadian coal deposits and/or coalfields. These results will be assessed in terms of the freshwater (F), mildly brackish water (MB), and brackish water (B) criteria outlined above.

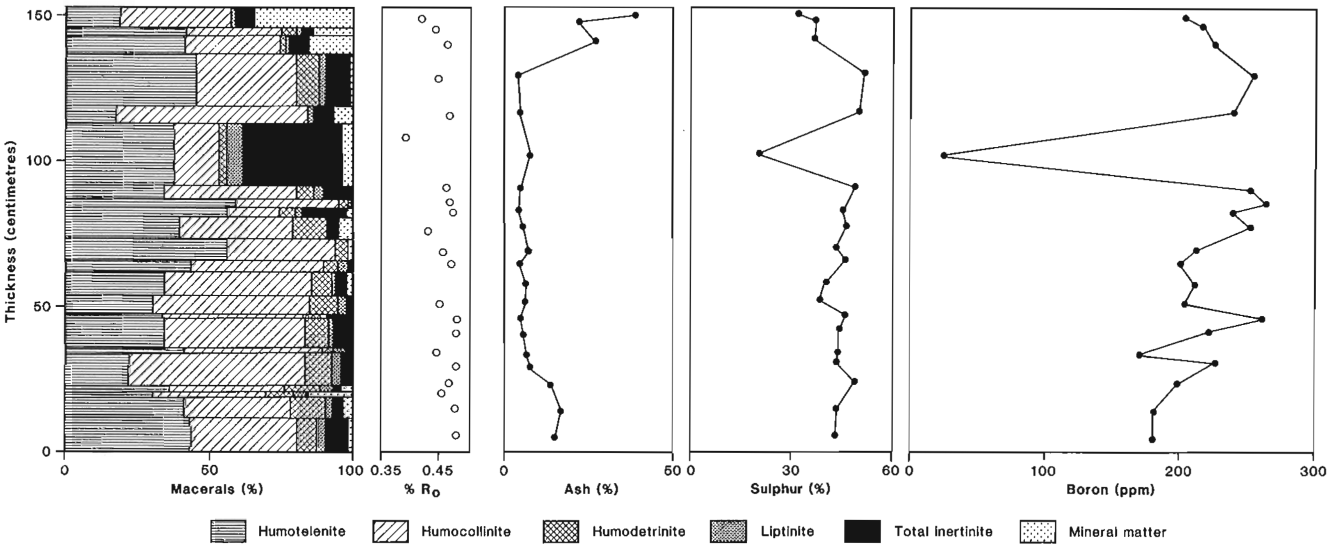


Figure 14. In-seam variation of percentages of macerals (with %Ro), ash, sulphur, and boron (ppm) in a coal seam at the Vesta Mine, Alberta.

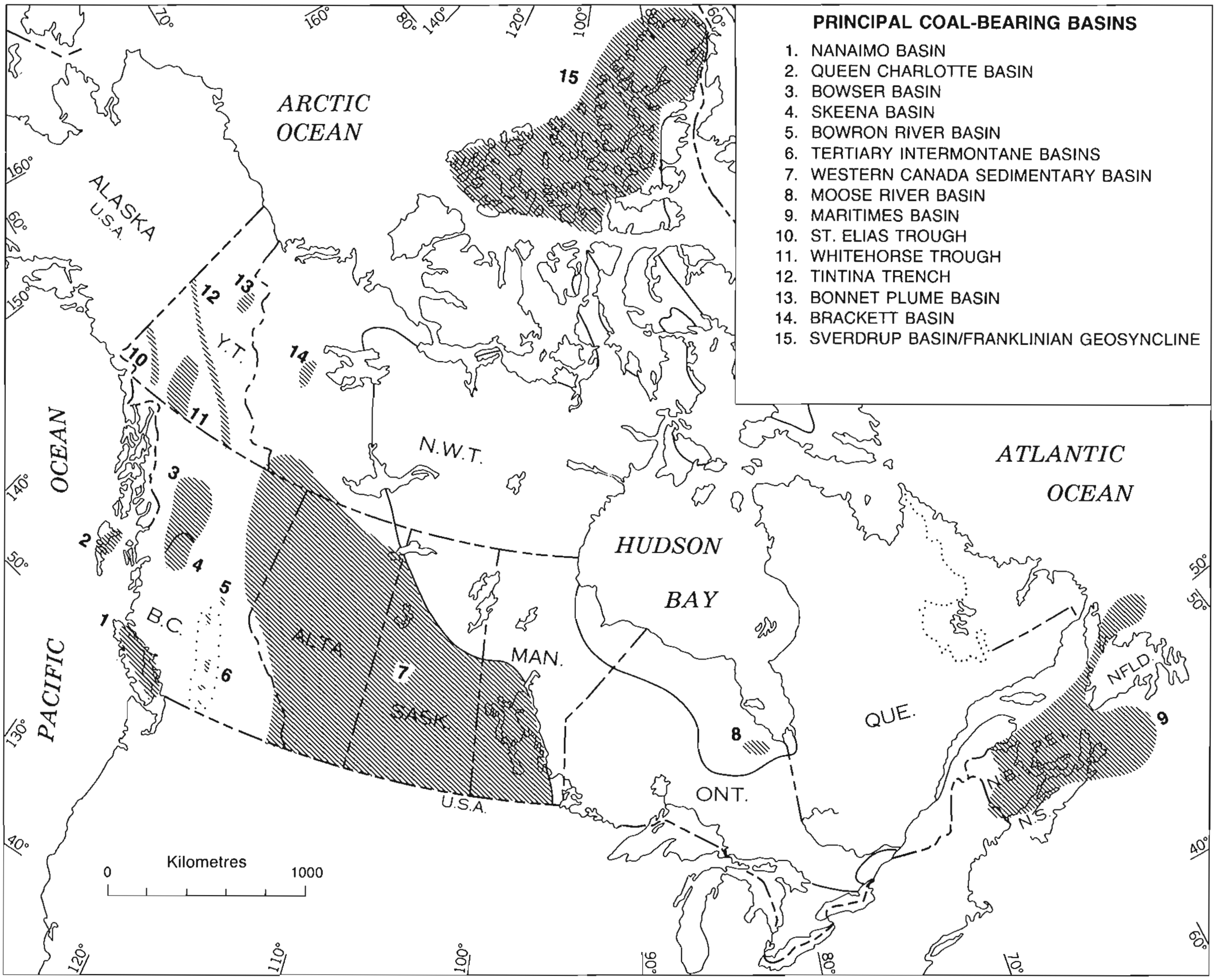


Figure 15. Coalfields of Canada. (From Smith, 1989.)

British Columbia

Coal deposits in British Columbia occur in three regions: Coastal, Intermontane, and Rocky Mountain (Fig. 16). The results of boron analyses for Rocky Mountain coal from Alberta and British Columbia will be discussed together. Analytical results are given in Tables 4 to 8.

Coastal region

Deposition of coal in the Comox and Nanaimo basins on Vancouver Island occurred during a series of four or five marine transgressions and regressions with facies generally progressing from fluvial, through coal-bearing lagoonal/deltaic to marine environments (Muller and Jeletzky, 1970).

The boron contents of coals (22 samples) from Vancouver Island are in the range of 10 to 130 ppm with an average of 70 ppm for Comox coals, and between 10 and 270 ppm with a mean of 106 ppm for Nanaimo Basin coals (Van der Flier-Keller and Dumais, 1987; Van der Flier-Keller and Goodarzi 1991), which indicate freshwater to brackish water conditions as proposed by Muller and Jeletzky (1970).

Intermontane region

The Intermontane coal basins of British Columbia contain some of the thickest low-rank coal deposits in the world (Goodarzi, 1985a; Duff, 1987). The coal deposits in this region (Fig. 16) were deposited in a fluvial to lacustrine environment (Kim, 1979; Wilson, 1979). The following coalfields or deposits were examined for their boron content: in the north, Telkwa, Mt. Klappen, Groundhog, and Bowron River coalfields, and, in the south, the Hat Creek coal deposits, the Merritt and Quilchena coalfields, and the Princeton and Tulameen coalfields (Fig. 16).

The northernmost intermontane region coalfield examined in this study is the Groundhog Coalfield (Fig. 16). There, the coal occurs in an Upper Jurassic sequence of transitional marine and nonmarine coal measures (Bustin and Moffat 1983). Only 7 out of 57 samples examined for their boron content were coal (<35% ash). The mean boron contents are 10 ppm for the coal and 19 ppm for the carbonaceous shale (Table 4). There is no evidence of a brackish water influence on the coal, based on these boron values.

The Lower Cretaceous Telkwa Coal Measures of the Skeena Group are located in west-central, intermontane British Columbia (Fig. 16), and consist of interbedded marine and nonmarine sediments (Koo, 1984). The Telkwa coal measures are about 400 m thick and ten major coal seams have been recorded (Matheson and van den Bussche, 1989). Boron contents of Telkwa coals were determined for seams from drillhole GSB-89-01. Figure 17 shows the simplified stratigraphic log of this drillhole, along with the boron and ash contents of the coal seams. Boron contents are between 18 and 40 ppm for coal and up to 60 ppm for the interbedded sediments, similar concentrations to those found in the other intermontane coals (Table 4).

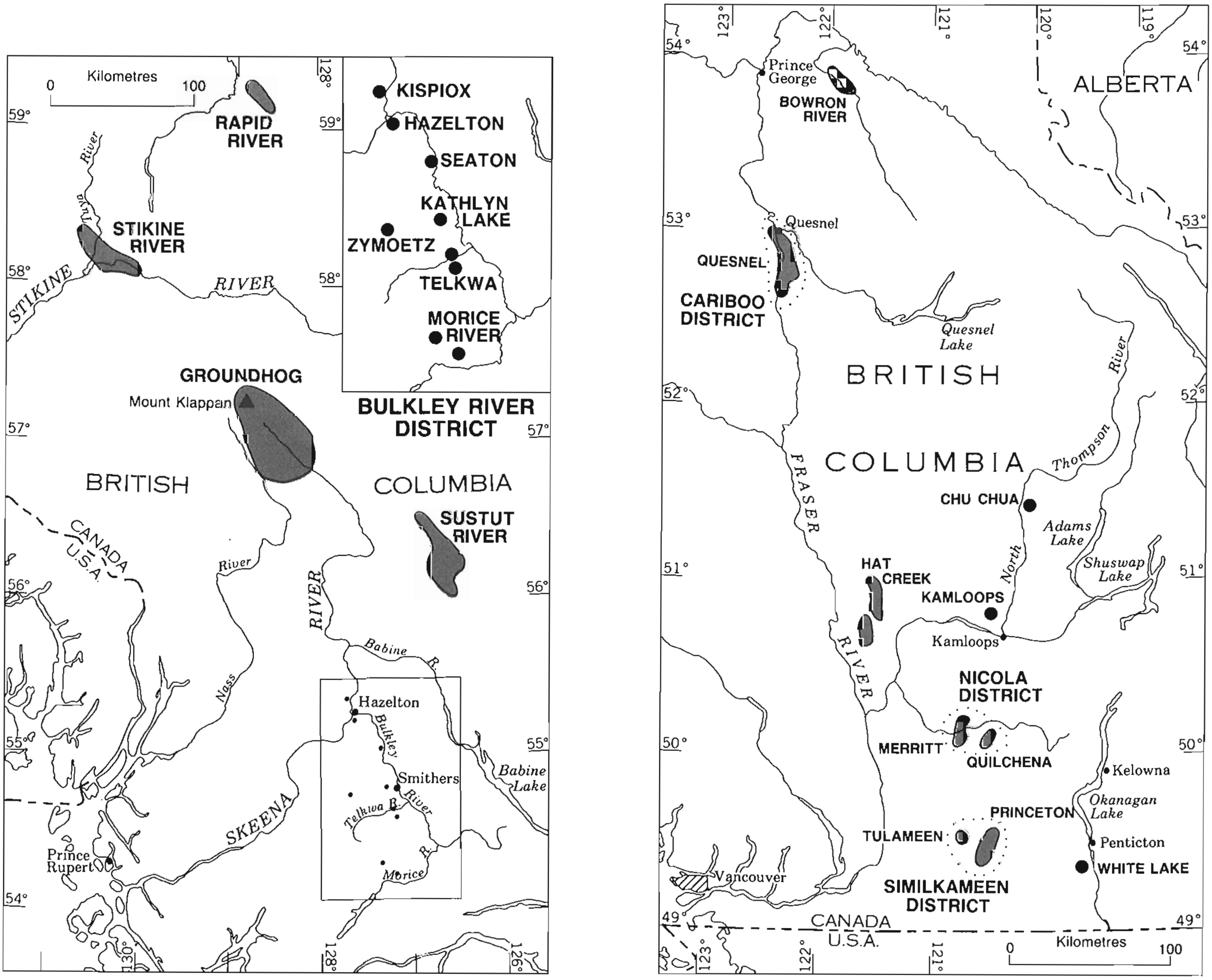


Figure 16. *Coal districts, coalfields, and coal deposits of the Intermontane Region of British Columbia. • = location of coal referred to in this study.*

TABLE 4

Assessment of the degree of marine influence on coals from the Intermontane Region, British Columbia, based on boron content

Location	Lithology	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Groundhog Coalfield	coal carb. shale	8 50	10 50	F F	This study, new data
Telkwa Coalfield	coal carb. shale		18–40 60	F F	This study, new data
Bowron River Deposit	coal		65–125*	F	This study, new data
Hat Creek Deposit					
No. 1, Zone A	coal	17	9–32	F	Goodarzi (1987a) Goodarzi and Van der Flier-Keller (1988)
No. 2, Zone A	coal	10	9–14	F	Goodarzi (1987a) Goodarzi and Van der Flier-Keller (1988)
No. 2, Zones B and C	coal	12	6–18	F	Goodarzi (1987a) Goodarzi and Van der Flier-Keller (1988)
No. 2, Zone D	coal	10	5–7	F	Goodarzi (1987a) Goodarzi and Van der Flier-Keller (1988)
Merritt Coalfield	coal carb. shale argill. shale	11	19–68	F	This study, new data
Quilchena Deposit	coal	2	36–37	F	This study, new data
Blakeburn strata, Tulameen	coal (upper 14 m) coal (lower 4 m)	19 8	27–46 34–79	F MB	Goodarzi and Van der Flier-Keller (1989) Goodarzi and Van der Flier-Keller (1989)
Princeton	coal	6	24–84	MB	This study, new data

*The high boron content is due to secondary enrichment
F = Freshwater environment; MB = Mildly brackish water environment

TABLE 5

Assessment of the degree of marine influence on coals from the Rocky Mountain Front Ranges region

Location	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Gates Formation				This study, new data
Seam 4 – Five different locations	18	7–61	F	
Seam 10 – Two different locations	5	6–23	F	
Seam 11 – Nine different locations	24	5–17	F	
Fording Mine				Goodarzi (1987b)
Greenhills seams				
Uppermost	3	35–44	F	
Lowermost	4	68–94	MB	
Eagle Mountain seams				
Uppermost	4	9–23	F	
Middle	6	57–85	MB	
Lower	4	40–48	F	
Byron Creek Colliery (Kootenay Group)				Goodarzi (1988)
Uppermost	2	25–50	F	
Middle	5	40–90	F–MB	
Bottom	24	85–200	MB–B	
Mount Allan (Kootenay Group)				Goodarzi and Cameron (1987)
Coal	12	2–22	F	
Carbonaceous shale	2	20–48	F	
Elk Valley drillholes				This study, new data
Drillhole 3	7	25–59	F	
Drillhole 2	10	17–56	F	
Drillhole 1	12	15–68	F–MB	

F = Freshwater environment; MB = Mildly brackish water environment; B = Brackish water environment

TABLE 6

Boron content of coals from the Elk Valley Coalfield, British Columbia

Location	No. of samples	Boron (ppm)	Environment of deposition
Greenhills, Fording Mine	8	57	MB
Eagle Mountain, Fording Mine	14	45	F
Mount Michael, lower section	11	19	F
Mount Michael, upper section	15	24	F
North Line Creek section	7	21	F
Burnt Ridge extension	16	16	F
Ewin Pass section	3	23	F
Burnt Ridge section	8	13	F
Teepee Mountain	4	15	F
Crown Mountain	2	24	F
Horseshoe Ridge	16	18	F
Weary Ridge	16	29	F
Elk Valley, Core 1	22	38	F
Elk Valley, Core 2	23	39	F

F = Freshwater environment; MB = Mildly brackish water environment

TABLE 7

Boron content of coals from the Crowsnest, Flathead, and Tent Mountain coalfields, British Columbia

Location	No. of samples	Boron (ppm)	Environment of deposition
Crowsnest Coalfield			
Sparwood Ridge	11	24	F
Razor Ridge	2	10	F
Parcel 13	7	16	F
Wheeler Ridge	3	35	F
Martin Ridge	8	20	F
Hosmer Ridge	8	20	F
Martin Creek	2	22	F
Morrissey M-4	11	27	F
Morrissey M-10	10	24	F
Morrissey M-15	10	24	F
Morrissey M-20	8	27	F
Flathead Coalfield			
Flathead Ridge	16	20	F
Flathead Ridge pipeline	9	20	F
Lodgepole	5	31	F
Mt. Taylor	10	35	F
Sage Creek	3	41	F
Tent Mountain Coalfield	23	44	F

F = Freshwater environment

TABLE 8

Boron content of "needle coals" from the Elk Formation, Elk Valley, British Columbia

Section	Lithology	Ash (%)	Thickness (m)	Boron (ppm)	Environment of deposition
EV1	coal	3.4	15	14	F
EV2	coal	11.0	8	15	F
EVA2	coal	26.0	8	39	F
EV3A	coal	23.0	70	26	F
EV3B	coal	16.6	50	28	F
EV3C	coal	6.7	180	29	F
EV3	coal	4.6	entire section	12	F
EV4A	carb. shale	47.0	10	82	F
EV4B	coal	6.4	10	19	F
EV4C	coal	9.4	10	14	F
EV4AI	coal	5.0	18	18	F
EV4BII	coal	6.4	20	19	F

F = Freshwater environment

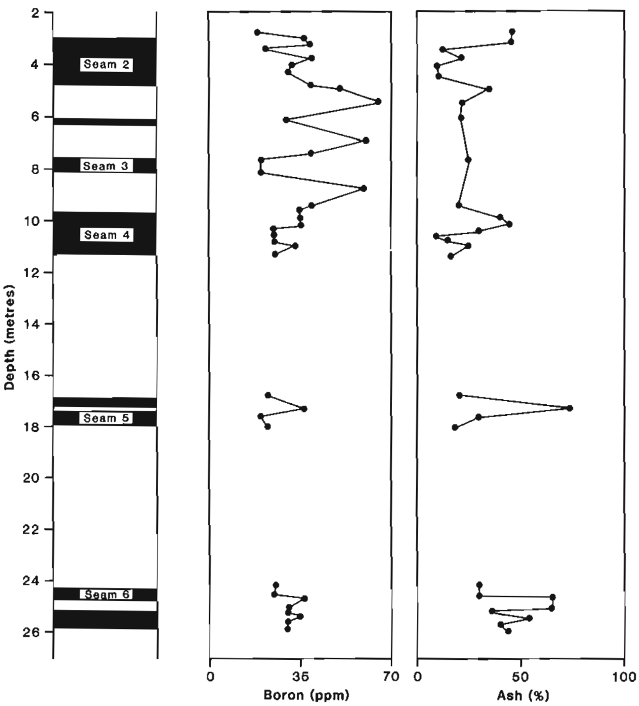


Figure 17. Simplified stratigraphic log of seams, with boron and ash contents, from drillhole GSB-89-01, Telkwa Coalfield, British Columbia.

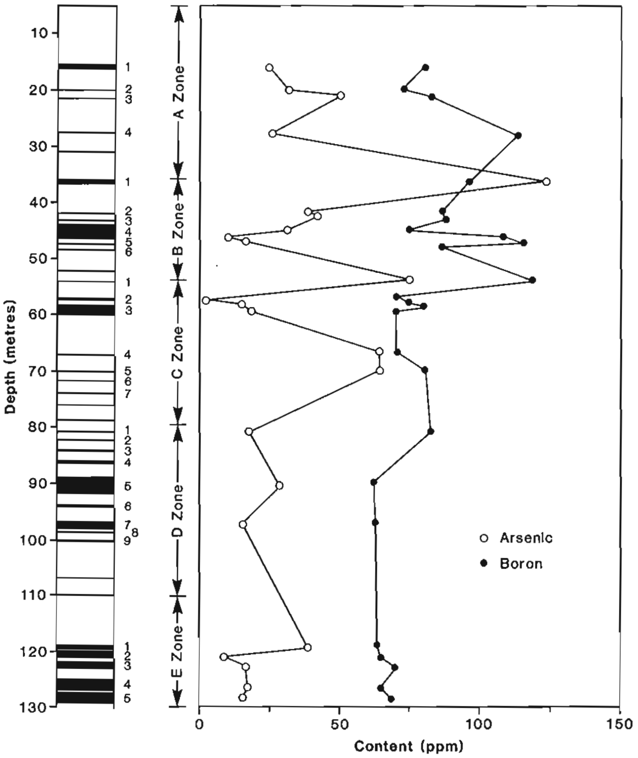


Figure 18. Variation of boron and arsenic contents (ppm) for coals in drillhole GSB-90-01, Bowron River Coal Deposit, British Columbia.

The Bowron River deposit is located in east-central British Columbia in the intermontane region (Fig. 16). The coal measures are Tertiary in age, occur in the Bowron River graben, and are bounded by Mississippian volcanic rocks (Matheson and Sadre, 1990). The boron contents of this deposit, as determined for coal seams and other sedimentary layers in drillhole GSB-90-01, are between 65 and 125 ppm, with the higher values occurring in the upper part of the deposit. Variations in the boron and arsenic contents of coal from this hole are shown in Figure 18. The high boron contents noted do not reflect the depositional environment of this coal deposit, which was limnic swamps near the shores of a shallow lake (Smith, 1989). The concentrations are possibly related to the removal and mobilization of arsenic, boron, and sulphur from the adjacent Mississippian volcanic rocks by groundwater, which flowed along the faults and into the coal beds (Goodarzi et al., 1992). The mobilization of arsenic is reflected in the high but variable arsenic content of the Bowron River coals (Fig. 18). The arsenic content of these coals is between 2 and 123 ppm with an average value of 27 ppm, which is higher than the averages for intermontane coal deposits such as Hat Creek (12.7 ppm) or Tulameen (2.7 ppm) (Van der Flier-Keller and Goodarzi, 1989).

The Hat Creek coals in south-central British Columbia consist of three deposits. Deposits No. 1 and No. 2 contain up to 600 m of coal and interbedded sediments (Kim, 1979). They are two of the thickest subbituminous coal deposits in the world, and were formed in a freshwater, lacustrine environment (Goodarzi, 1987a; Goodarzi and Van der Flier-Keller, 1989). They contain 5 to 32 ppm boron, which indicates freshwater conditions consistent with other evidence (Kim, 1979; Goodarzi, 1985a; Goodarzi and Gentzis, 1987).

The Merritt and Quilchena coalfields are located in the Nicola Coal District (Fig. 16). Coals from the Merritt Coalfield have an average boron content of 43 ppm, in agreement with their freshwater fluvial origin (Hills, 1965). The boron contents of seams in this area fall within a narrow range (19–68 ppm) for coal, a wider range (84–124 ppm) for high-ash carbonaceous shale (ash content 35–70%), and an even wider range (24–312 ppm) for argillaceous shale. The average boron contents of high-ash coal, carbonaceous shale, and argillaceous shale are similar (Table 4). Subbituminous coal in the Quilchena Coalfield is located in the Nicola Coal District. The boron contents of these coals is within the range for freshwater coal (36–37 ppm) (Table 4). The coals in both coalfields were formed in a freshwater fluvial environment (Hills, 1965).

The Similkameen coals are of fluvial-lacustrine origin, as exemplified by the coals of the Blakeburn Mine (Tulameen Field), which have a boron content of 20 to 80 ppm with an average of <50 ppm (Goodarzi and Van der Flier-Keller, 1989), indicating a freshwater environment (Table 4). On the basis of boron contents (27 to 46 ppm, mean 37 ppm), the lower 14 m of the Blakeburn strata at Tulameen are within the range for freshwater conditions. However, coal in the upper part (4 m) with 51 to 79 ppm (mean 65 ppm) boron falls at the lower end of the mildly brackish water category (Fig. 19), as suggested by Goodarzi and Van der Flier-Keller (1989). Results for the upper and lower parts of the dirt bands do not show as much variation; boron contents are 15 to 45 ppm (mean 25 ppm) for the lower 14 m and 12 to 55 ppm (mean 27 ppm) for

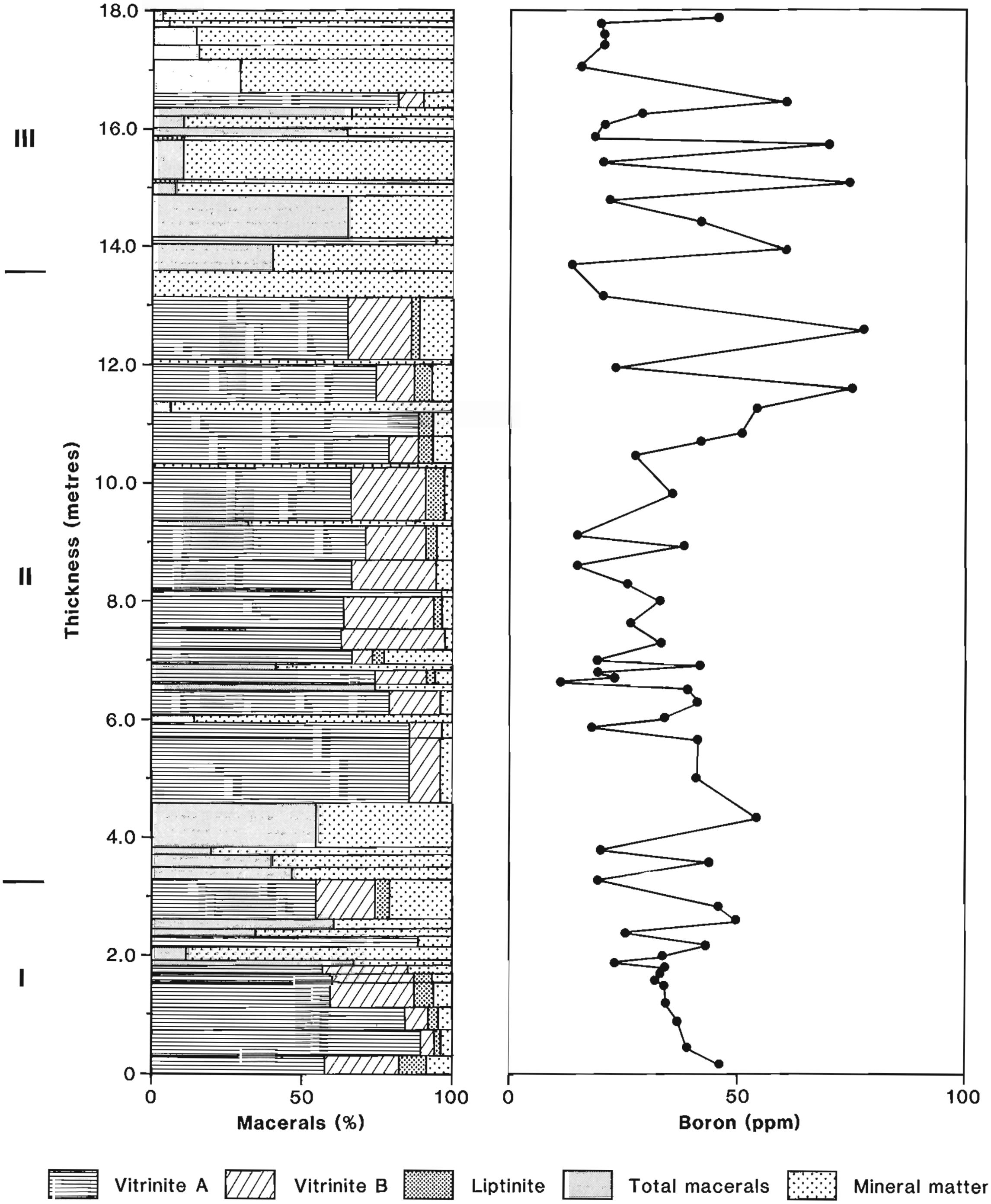


__Figure 19.__ Variation of coal macerals, reflectance (% Ro), and boron, for coal layers and partings in the Blakeburn Mine, British Columbia.

the upper 4 m. Coals from the Princeton Coalfield have boron contents in the range of 24 to 84 ppm with an average of 63 ppm, similar to the upper part of the Tulameen coal, and are at the boundary between the freshwater and mildly brackish water environments.

Generally, the boron contents of coals in the intermontane coalfields or deposits are within the range for a freshwater coal deposited in a fluvial to lacustrine environment. However, some coals or parts of coal deposits, particularly in the Similkameen coal district, have boron values slightly above (63 ppm) the freshwater range (<50 ppm). The geological setting and the nature of the country rocks — for example, the occurrence of volcanic rocks and faults in coal-bearing strata — also have influenced the level of boron concentration which, in some cases (e.g., the Bowron River deposit), has resulted in an elevated boron content in the coal.

The Rocky Mountain Front Ranges and Foothills, British Columbia and Alberta

This is the most productive coal region of Canada and more than 95 per cent of the country's bituminous coal resources are located within this area. Coal is found in three regions: the southern Rocky Mountain Front Ranges, the Rocky Mountain Inner Foothills Belt, and the Rocky Mountain Outer Foothills Belt.

Southern Rocky Mountain Front Ranges region

In this region coal occurs in the Kootenay Group which is one of the major sources of metallurgical coal in Western Canada. Almost half of the medium and low volatile bituminous coals of Mesozoic age in Canada are within this region, which consists of four coal districts: Panther River/Clearwater, Cascade, Crowsnest, and East Kootenay (Fig. 20). The coals were deposited under fresh to brackish water conditions, as determined from their boron contents (Tables 5-8). Goodarzi (1988) examined the coal seams at the Fording Coal Mine, and the Elk Valley Coalfield (East Kootenay coal district). The uppermost seams in the Eagle Mountain section at the Fording Mine contain 10 to 20 ppm boron, which is in the range for deposition in a freshwater environment. This assessment is consistent with the statement by Dunlop and Bustin (1987) that "the entire sequence is interpreted as non-marine." The lower seams in the Eagle Mountain section are also in the range of boron content for freshwater conditions. However, the upper and middle seams at the Greenhills section and the middle seams in the Eagle Mountain section have boron contents that indicate mildly brackish water conditions (Fig. 21).

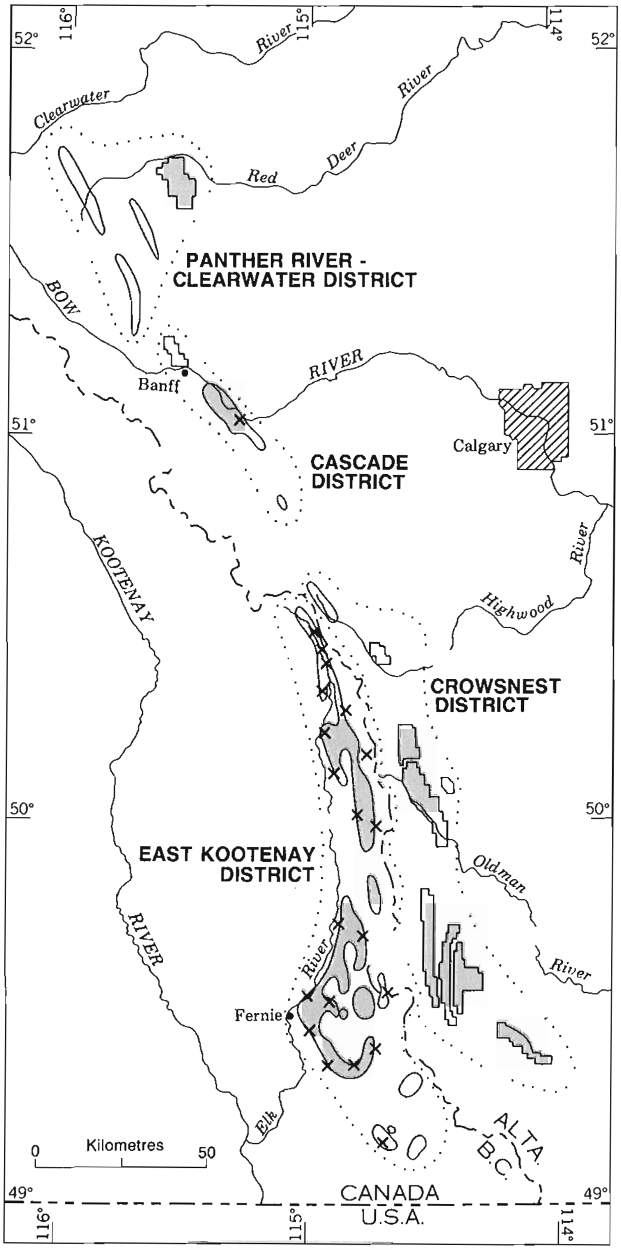


Figure 20. *Coal districts and coalfields of the southern Rocky Mountain Front Ranges, Canada. X = location of coal discussed in this study.*

The Byron Creek Collieries mine is also located in this region. Results of boron analysis for coal in this mine indicate a gradation from brackish- to freshwater conditions from deeper to shallower stratigraphic levels (Fig. 22), in accordance with the statement by Goodarzi and Cameron (1987) that "the lower seams of the Kootenay Group accumulated in environments relatively close to marine conditions. In any given

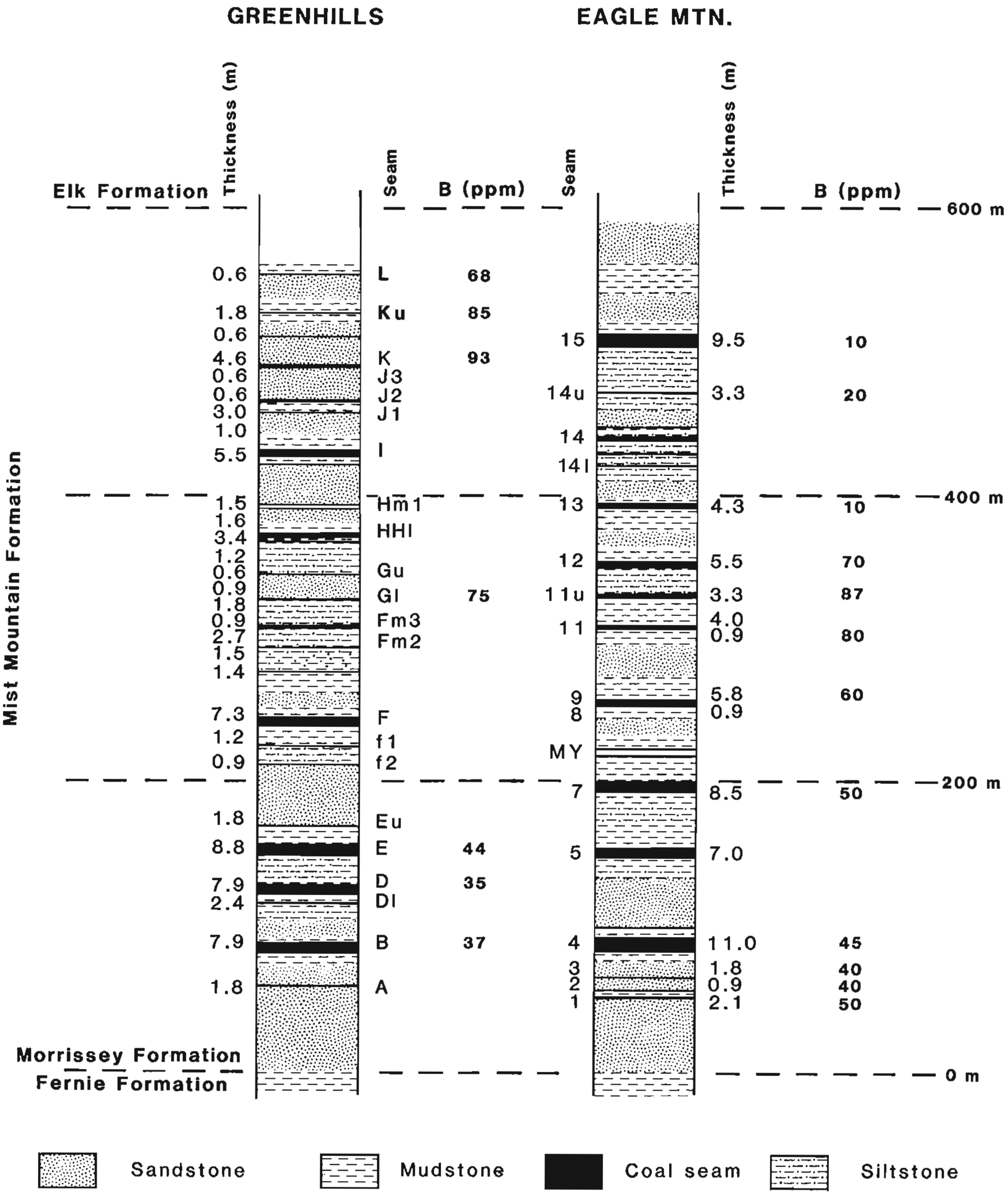


Figure 21. Generalized composite columnar sections of the Kootenay Group (Morrissey and Mist Mountain formations) at the Greenhills and Eagle Mountain sections, Fording Coal Mine, British Columbia, showing the major coal seams, their thickness, boron content (ppm), and nomenclature. (Courtesy of Fording Coal Mine.)

section, seams at successively higher stratigraphic levels would have been formed under conditions farther and farther removed from marine influence."

A number of coal seams in three drillholes in the northern part of the Elk Valley Coalfield were examined for their boron content (Fig. 23). Boron contents of the coal seams (Table 6) is in the range for a freshwater depositional environment (<50 ppm), in agreement with the geological setting of these coal seams (Gibson, 1985). However, some boron contents, associated with carbonaceous shale (ash 37-63%), are higher, in the range of 66 to 93 ppm, indicating that only coal (<25% ash) should be used for the determination of the depositional setting based on boron content.

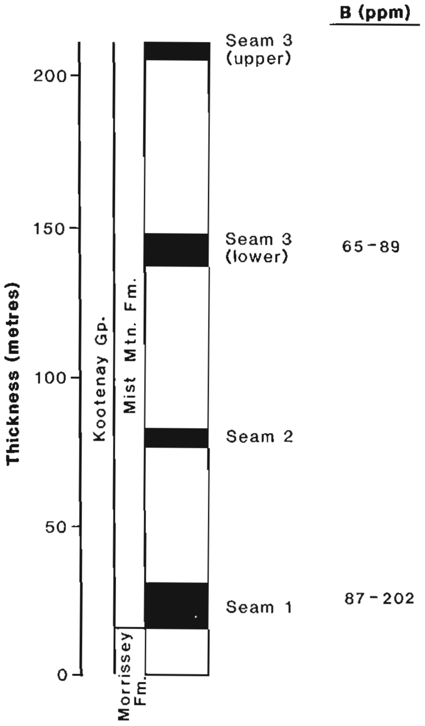


***Figure 22.** Boron contents of Kootenay Group coal seams at Byron Creek Collieries, Alberta.*

A regional study of coals from the Elk Valley Coalfield, constructed from 16 stratigraphic sections (Fig. 24) and based on analyses of 160 coal seams, indicates a F to MB environment of deposition (Goodarzi et al., in press b). The other major coalfields in this region include the Crowsnest, Tent Mountain, and Flathead coalfields (Fig. 20). Boron contents of coals from these coalfields are low, ranging from 10 to 44 ppm (based on 120 samples of coal) (Table 7), supporting a continental, freshwater origin for these coals, as postulated by Gibson (1985).

An unusual type of coal occurs in the Elk Formation in this region and consists of a "compact mass of rod-like needles, in beds which rarely exceed a thickness of 15 cm" (Gibson, 1985). Newmarch (1953) first described this type of coal as "needle coal". Needle coals are rich in liptinite macerals (Pearson and Grieve, 1980; Kalkreuth, 1982; Snowdon et al., 1986). The concentration of boron in needle coals collected from the Elk Valley Coalfield is low (12-39 ppm, Table 8) and is indicative of a freshwater environment, as suggested by Snowdon et al. (1986).

The boron content of coals from the Crowsnest District is low (19-42 ppm), indicating a freshwater setting, although one sample from Ridge Creek has a boron content of 55 ppm, indicating a slightly brackish water setting.

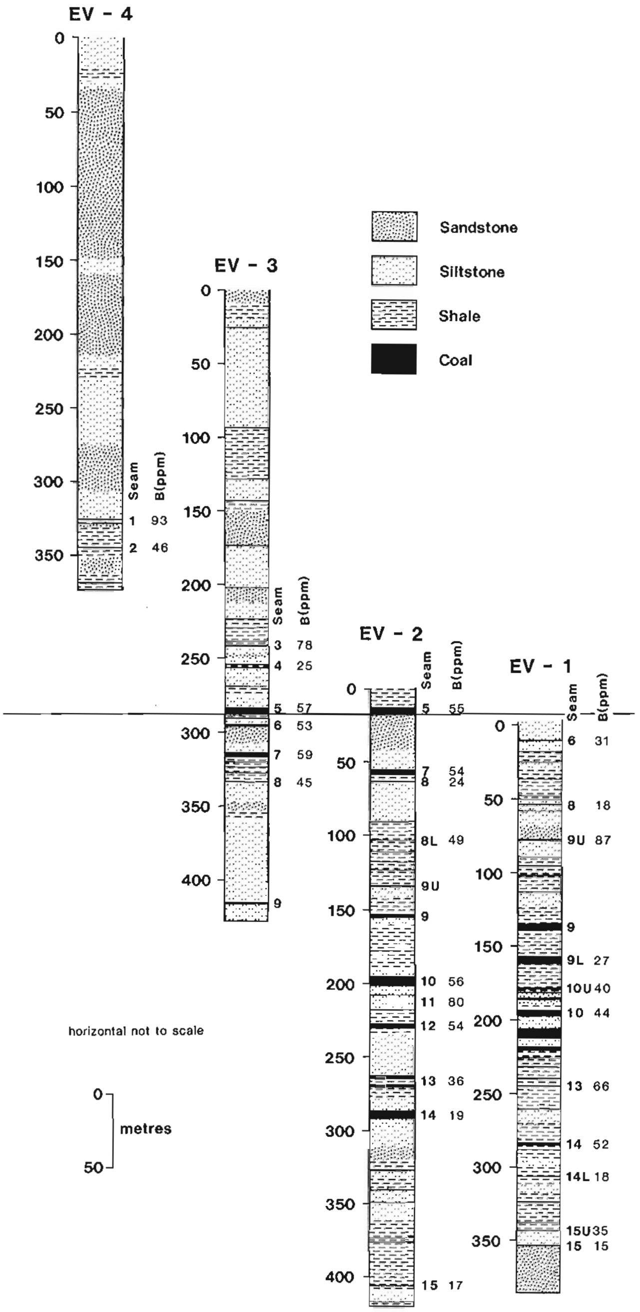


***Figure 23.** Variations in the boron contents of Kootenay Group coals in the Elk Valley Coalfield, British Columbia, from drillhole cores.*

Medium volatile bituminous to semianthracitic coal is found in the section at Mt. Allan, Alberta, which is in the Cascade District (Fig. 20). This section contains 13 coal seams (Hughes and Cameron, 1985). Goodarzi and Cameron (1987) examined the elemental content of the coal seams. The average boron content of these coal seams is 12 ppm, indicating a freshwater origin for the coal in this section (Table 9). However, one sample of carbonaceous shale from Barrier Mountain has a

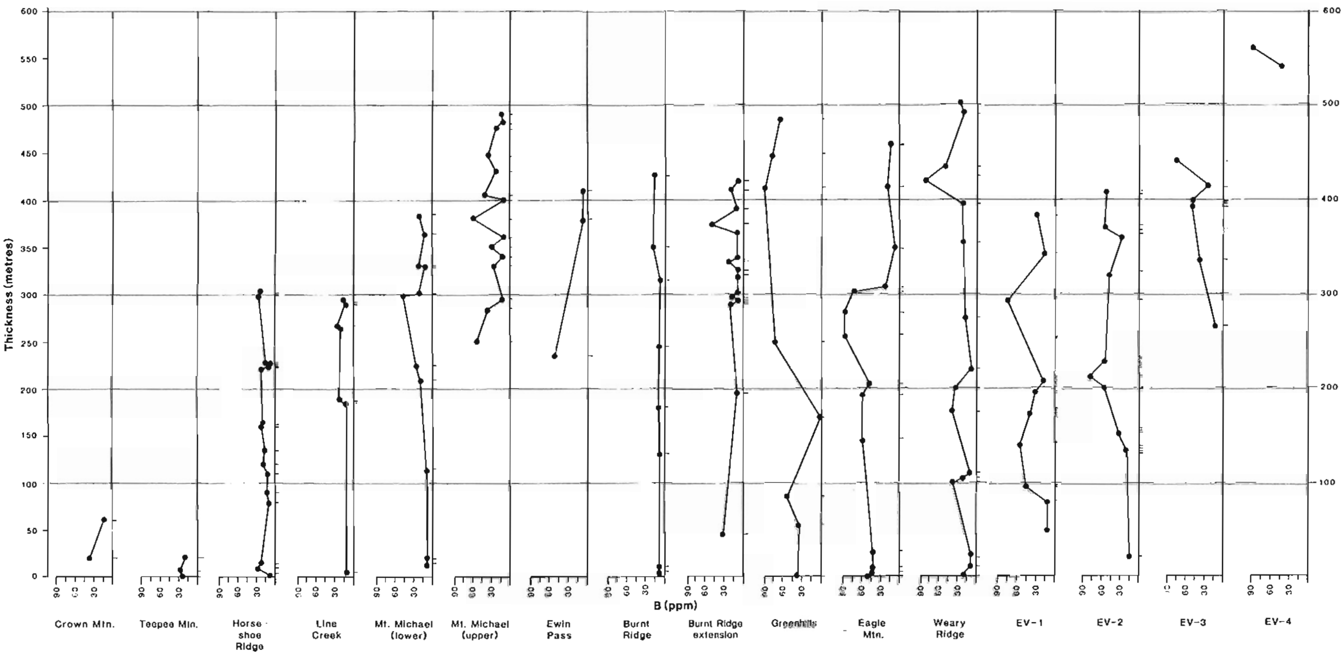


Figure 24. The regional variation of boron concentrations (ppm) in coals from the Elk Valley Coalfield.

TABLE 9

Boron content of coals from the Outer Foothills Belt of the Rocky Mountains, Alberta

Location	Lithology	No. of samples	Boron (ppm)	Environment of deposition
Crowsnest District				
Oldman Gap	coal	1	23	F
Wilkinson Summit	coal	4	19	F
Cabin Ridge	coal	7	22	F
Ridge Creek	coal	1	55	MB
Bragg Creek	coal	2	42	F
Cascade District				
Barrier Mountain	coal	6	20	F
	carb. shale	2	109	
Mount Allan	coal	12	2-22	F
	carb. shale	2	20-46	F
Coalspur Coalfield	coal	12	21	F

F = Freshwater environment; MB = Mildly brackish water environment

boron content of 109 ppm (boron content of the coal is 20 ppm). This high boron content is possibly due to enrichment by boron-bearing minerals.

Inner Foothills Belt

This region contains half of Canada's measured medium and low volatile bituminous coal resources and is divided into northern and southern regions (Smith, 1989).

Kalkreuth and McMechan (1984) and Kalkreuth and Langenberg (1986) have studied coals throughout the area of occurrence of the Gates and Gladstone formations in terms of their coalification patterns and depositional environments. The coal seams occur mainly in nonmarine strata (Fig. 25). All coal seams from these two formations generally have low boron contents (10-39 ppm, Table 10), which is in agreement with their nonmarine depositional environment (Kalkreuth and Langenberg, 1986). Coal from the Nikanassin Formation has a boron content of 122 ppm, indicating a brackish water environment, in agreement with the stratigraphic and sedimentological interpretation by Stott (1984) and Gibson (pers. comm., 1992). This variation is similar to that observed in the Kootenay Group coals (e.g., coal seams from Byron Creek Collieries), where the lowermost seam was deposited under brackish water conditions and the environment became less brackish with increasing distance from the shoreline (Goodarzi, 1987b).

The Coalspur coal zone is one of the most important sources of low-sulphur coal in the Alberta Foothills (Gentzis et al., 1989). The Coalspur Formation was deposited in an alluvial plain environment during the early Paleocene (Jerzykiewicz and McLean, 1980). The boron contents of the Arbour and Val D'Or coal seams from the Coalspur section (15-44 ppm) (Fig. 26) indicate a freshwater setting, in agreement with the freshwater depositional setting suggested by Jerzykiewicz and McLean (op. cit.).

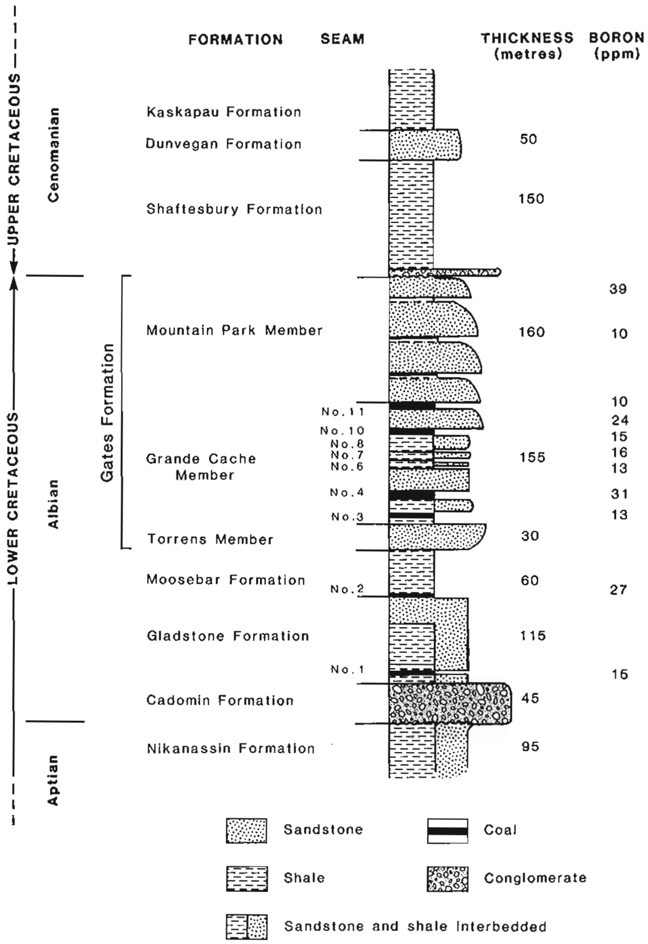


Figure 25. Diagrammatic columnar stratigraphic section, showing the positions and boron contents of coal seams and associated sedimentary rocks in the Grande Cache area, Alberta. (Section courtesy of W.D. Kalkreuth.)

TABLE 10

Variations in the boron contents of coals from the Inner Foothills Belt of the Rocky Mountains, Alberta

Formation	Member	Environment	Seam	No. of samples	Average Boron (ppm)
Gates[1]	Mountain Park	nonmarine	B	3	39
			A	1	10
	Grande Cache	nonmarine	11	12	10
			10	2	24
			8	5	15
			7	2	16
			6	6	13
			4	9	31
			3	3	13
	Torrens	nonmarine	–	–	–
Moosebar[1]		marine	–	–	–
Gladstone[1]		nonmarine	2	9	27
			1	1	15
Nikanassin[2]		marine	–	11	92

Seam identifications are from Kalkreuth and Langenberg (1986)

[1] Cretaceous

[2] Jurassic–Cretaceous

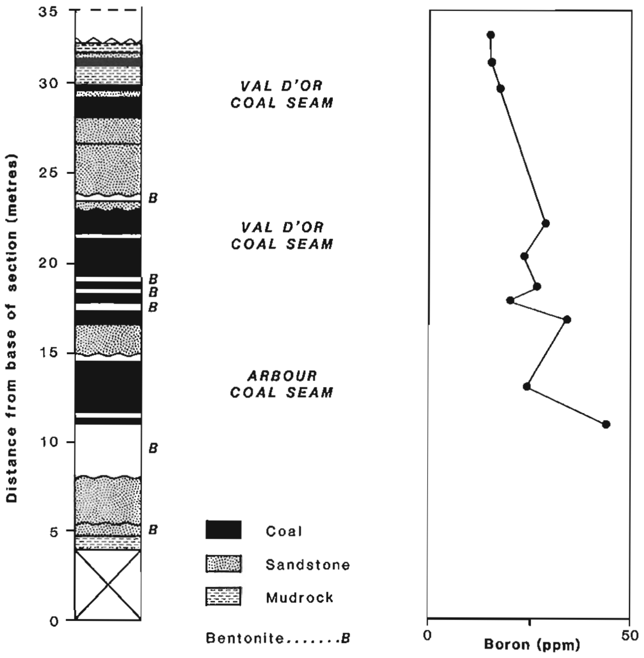


Figure 26. Coalspur Formation, showing coal seams and boron contents.

Coalfields of the Interior Plains of Alberta and Saskatchewan

Alberta Plains

There are 49 coalfields in the Alberta Plains, in stratigraphic sequences ranging in age from Upper Cretaceous to Tertiary (Fig. 27). Results of boron analyses of coals from Alberta are given in Table 11.

The environments in which the Mannville Group coals were deposited varied from fresh, to mildly brackish, to brackish water. Data on the boron contents of coals in the Mannville Group (Lower Cretaceous) are also included in Table 11. Other evidence quoted by Banerjee and Goodarzi (1990) indicates that "most of the coals from the Lower Cretaceous Mannville Group of southern Alberta, Canada, were deposited in a paralic environment." A detailed study of the Mannville Group coals led Banerjee and Goodarzi (1990) to conclude that the coals containing the highest levels of boron (256-1144 ppm) "belong to a 'stacked shoreline' sequence,

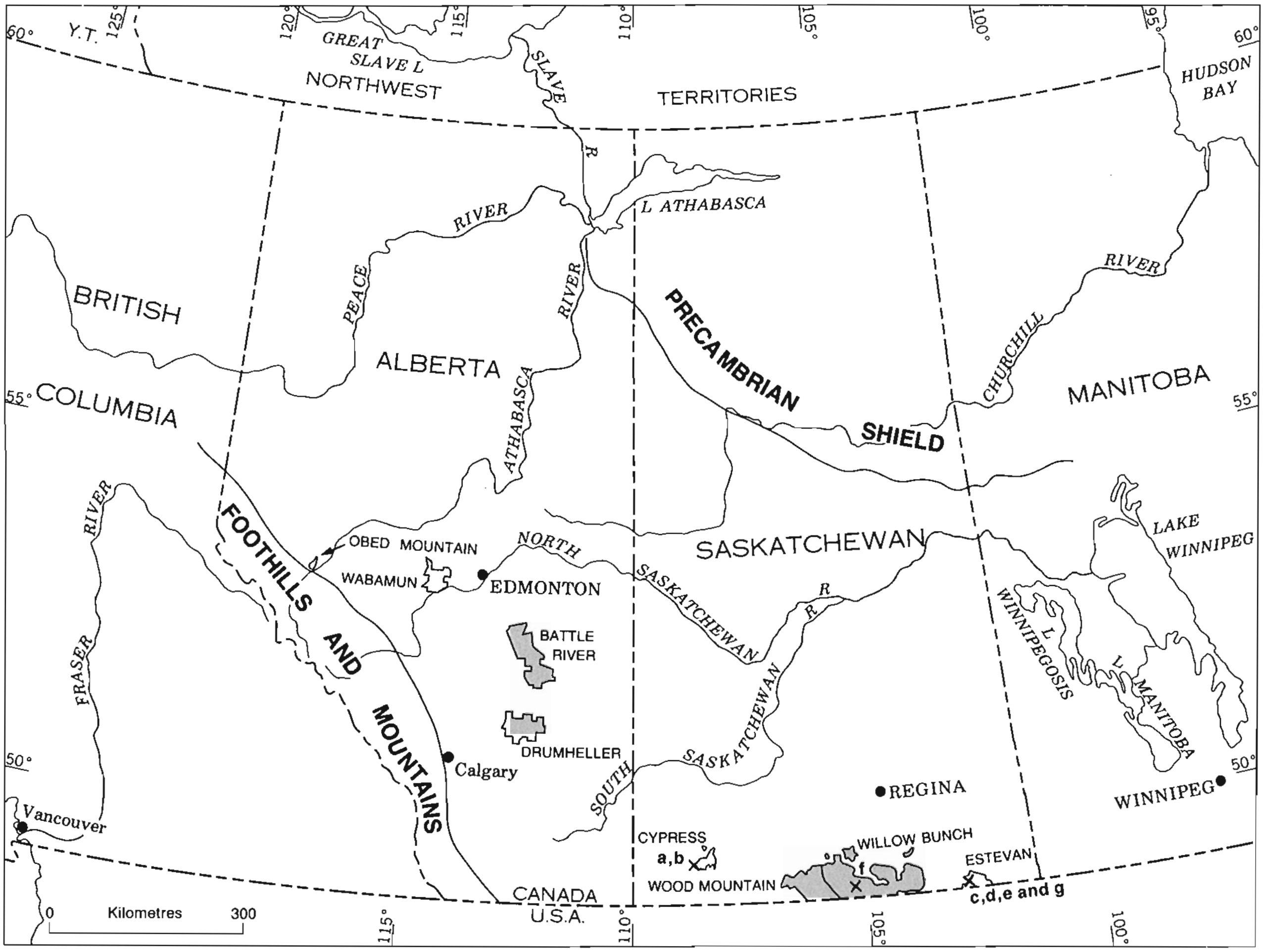


Figure 27. The coalfields of the Interior Plains of Alberta and Saskatchewan showing locations of coals reported in this study. (After Smith, 1989.) See Figure 48, in-seam variations.

where each coal is directly overlain by marine transgressive sediments, which caused the anomalously high boron'' (Fig. 27). The other coals with low to moderate boron contents are encased by lagoonal/tidal flat sediments. They are not overlain by transgressive sediments (Figs. 28, 29). The salinity fluctuated in this environment to produce the low to moderate boron contents (18–247 ppm) of these coals.

The coals of the Battle River Coalfield and Drumheller area (Table 11) occur in the Upper Cretaceous Horseshoe Canyon Formation. Dawson et al. (1989) stated that deposition of the Battle River coals was influenced in part by brackish waters. They believed that the coal seams in the Battle River Coalfield were deposited in an interdistributary bay, and commented that ''the nature of the interdistributary bay (coastal lake?, lagoon?) cannot be defined on a sedimentological basis alone. Further paleontological studies are needed to establish the upper limit of the marginal marine conditions of deposition in the Battle River Coalfield section.'' Gentzis et al. (1990) examined the petrology and boron content of coals from the Vesta Mine, which is located within the Battle River Coalfield. Boron contents of these coals are in the range of 150 to 270 ppm, which places them within the range of brackish water coal.

Rahmani and Hills (1982) stated that the depositional environment of ''the transition zone between the Bearpaw and Horseshoe Canyon formations in the Drumheller area was a prograding deltaic complex fed by river(s) draining the Cordillera and debouching their load into the shallow and warm epicontinental Bearpaw Sea.'' Shepheard and Hills (1970, 1979) stated that the depositional setting of coal-bearing sequences in the Drumheller area is comparable to that of the Mississippi Delta. However, Rahmani and Hills (1982) stated that the coal-bearing sequence ''was probably deposited along an embayed shoreline, in estuaries and barrier island complexes, where tidal energy was the dominant process in estuaries, inlets and back barrier settings'' (Fig. 30).

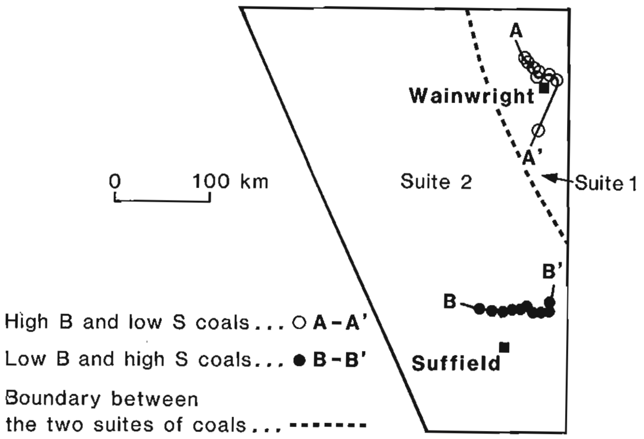


Figure 28. *Locations of wells in southern Alberta containing Mannville Group coals and the locations of stratigraphic cross-sections A–A', and B–B'. (From Banerjee and Goodarzi, 1990.)*

The variation in the amount of boron contained in the coal-bearing strata in the Drumheller–Ardley Region, Red Deer Valley, Alberta is shown in Table 12. There are 15 coal seams in 18 sections, and these were sampled by Gibson (1975). The average boron content of the coal seams from Gibson's

TABLE 11

Assessment of the degree of marine influence on coals from the Plains region, Alberta

Location	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Obed Marsh Mine	24	44–55	F	This study, new data
Highvale Mine	33	30	F	This study, new data
Battle River Coalfield Vesta Mine	16	150–270	B	Gentzis et al. (1990)
Battle River Coalfield	1	245	B	Swaine (1982 and unpublished data)
Drumheller area	43	144	B	This study, new data
Mannville Group	2	18, 22	F	Banerjee and Goodarzi (1990)
	5	51–102	MB	
	21	121–1144	B	

F = Freshwater environment; MB = Mildly brackish water environment; B = Brackish water environment

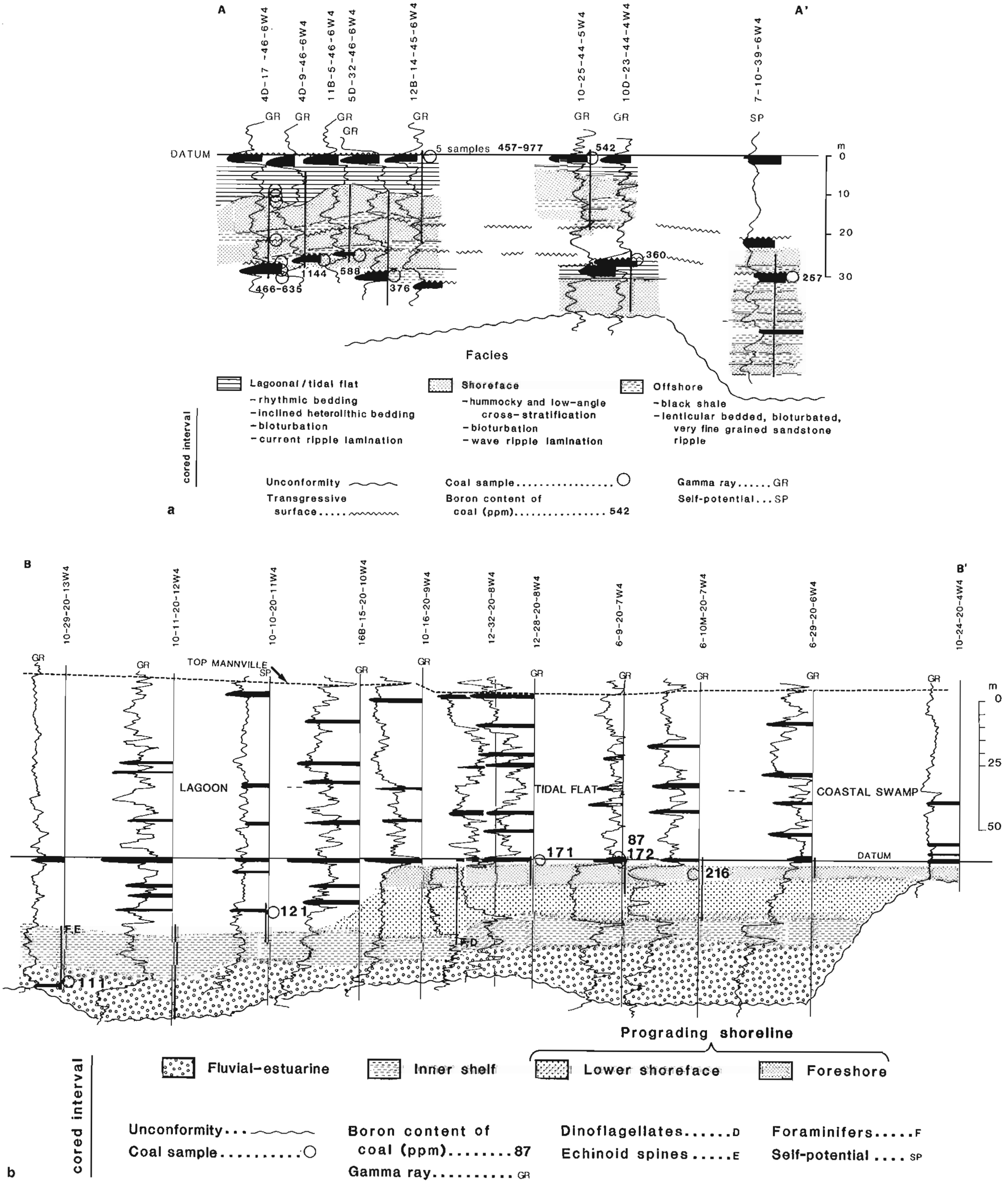


Figure 29. *Stratigraphic cross-sections A–A′ and B–B′ of the Mannville Group. (See Figure 28 for locations.)*

a. *Stratigraphic cross-section A–A′, of wells containing Suite 1 Mannville Group coals in southern Alberta, showing the paleoenvironmental setting of the coal in "stacked shoreline" sequences. (From Banerjee and Goodarzi, 1990.)*

b. *Stratigraphic cross-section B–B,′ of wells containing Suite 2 Mannville Group coals in southern Alberta, showing the paleoenvironmental setting of the coal in "lagoonal/tidal flat" sediments. (From Banerjee and Goodarzi, 1990.)*

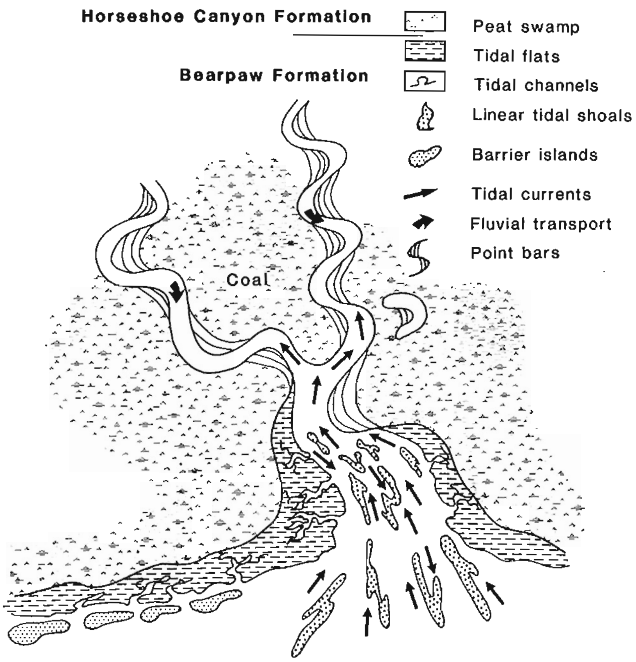


Figure 30. The areal relationships of depositional environments of the lower coal beds of the Bearpaw/Horseshoe Canyon transition, Drumheller, Alberta. (After Rahmani, 1983).

collection is between 16 and 628 ppm (Table 12), indicating fresh to brackish water depositional environments, in agreement with the marine influence in this area as established from sedimentological evidence by Shepheard and Hills (1970, 1979) and Rahmani and Hills (1982). The coal seams at the base of the coal-bearing strata (i.e., seams 0, 1, and 2) were deposited in a brackish water setting, as indicated by a schematic portrayal of areal relationships of depositional environments (Rahmani and Hills, 1982). The boron content is 170 ppm for Seam 0, and is between 97 and 628 ppm for Seams 1, 2, and 3 at three different locations. The average boron contents are 290 ppm for Seam 1 (with a range of 97–625 ppm), 218 ppm for Seam 2 (with a range of 112 to 370 ppm), and 112 ppm for Seam 3 (with a range of 73 to 146 ppm), indicating the brackish water origin of these coal seams. The coal with the highest boron content in the Drumheller area (Seam 1) was deposited behind a barrier island/tidal inlet (Rahmani and Hills, 1982).

The Obed Marsh coal deposit is subbituminous B to high volatile C bituminous (R_O 0.43-0.52%) and of Late Paleocene age. Examination of the in-seam profiles indicates undisturbed peat accumulation over long periods of time (Gentzis and Goodarzi, 1990).

TABLE 12

Variations in the boron contents (ppm) of coals in the Drumheller-Ardley region of the Red Deer River Valley, Alberta

	Sections																
Seam	6	7	8	13	15	17	21	27	28	30	34	35	39	40	41	53	55
15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	31*	–
14	–	–	–	–	–	–	–	–	–	–	–	–	–	–	94	124	–
13	–	–	–	–	–	–	–	–	–	–	–	–	–	34	68	–	–
12	–	–	–	–	–	–	–	–	–	–	–	149	–	86	110*	–	68
11U	–	–	–	–	–	–	–	–	–	–	–	–	–	–	87	–	–
11	–	–	–	–	–	–	–	–	–	–	–	34*	75	119	126*	–	–
10	–	–	–	–	–	–	–	52	76*	–	16	57*	72	–	–	–	–
9	–	–	–	–	–	–	–	93	95	55	68	–	–	–	–	–	111
8	–	–	–	–	–	–	–	90	50	74*	125	–	–	–	–	–	70
8L	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	84
7	–	–	–	–	–	78	77	–	–	–	–	–	–	–	–	103	–
6	–	–	–	–	80	94	34*	–	–	–	–	–	–	–	–	81	–
5	249	133	–	118*	–	100	–	–	–	–	–	–	–	–	–	–	–
4	100	133	33*	106	–	–	–	–	–	–	–	–	–	–	–	–	–
3	118	146	73	52*	–	–	–	–	–	–	–	–	–	–	–	–	–
2	370	173	112	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1	628	150	97	–	–	–	–	–	–	–	–	–	–	–	–	–	–
0	170	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

*High ash content (more than 30%)

This coal deposit is associated with fluvial sediments. Fining-upward point bar sequences as well as fine grained overbank sediments are present, indicating a meandering river environment of deposition (Jerzykiewicz, pers. comm., 1989). Boron content of this coal deposit, based on three seam profiles, averages 44 to 55 ppm (Table 11), although an individual sample from one coal layer had a boron content as high as 89 ppm. The low boron contents of the Obed Marsh coal seams are in agreement with their freshwater origin, as indicated by the sedimentological evidence.

Saskatchewan lignites

The Paleocene Ravenscrag Formation of southern Saskatchewan contains vast quantities of lignite in the Cypress, Wood Mountain, Willow Bunch, and Estevan coalfields (Fig. 31a). Coals were deposited in an alluvial plain/fluvial environment (Whitaker et al., 1978). The continental nature of the depositional environments, in which the ancestral peat of these coals was deposited, have been confirmed by the palynological studies of Blackburn (1982) and Nambudiri (1987). The concentrations of boron and sodium increase from west to east in the coalfield. Boron is most abundant in the Willow Bunch Coalfield (Table 13). Beaton et al. (1991) stated that boron and sodium were probably introduced into the coal from circulating groundwater. The formation of low-lying subbasins by the dissolution of deep, underlying evaporites may have contributed to the accumulation of peat in the Cypress and Willow Bunch coalfields in southern Saskatchewan (Broughton, 1985).

The sources of boron and sodium in lignites of the Ravenscrag Formation are probably: a) the deep, underlying Prairie Evaporite Formation of Devonian age, which has undergone much dissolution (Meijer Drees, 1986), b) the underlying Upper Cretaceous Bearpaw Formation shales containing barite and gypsum (Brown, 1967), and c) the bentonite and volcanic ash that are present within the Ravenscrag Formation (Fraser et al., 1935; Crawford, 1955). The dissolution of the Prairie Evaporite Formation is partly related to water circulation at deep levels within Williston Basin (Garven and Vigrass, 1985; McTavish and Vigrass, 1987) (Fig. 31). According to Garven and Vigrass (op. cit.), water enters recharge zones in the southern part of the basin, travels laterally through the formations, and is partly diverted upward at the edge of salt dissolution. The Estevan Coalfield currently lies above the salt dissolution edge and some discharge from the deep waters appears in the coalfield, in the vicinity of the Souris River (Garven and Vigrass, op. cit.). The boron content of the Estevan coal is 140 ppm. The Willow Bunch Coalfield is located in the central area of Saskatchewan and was formed over a salt dissolution trough (Broughton, 1985). The high concentration of boron (234 ppm) in the coal from this coalfield is also due to its contact with deeper, upwelling waters in the past. Coals of the western (Cypress) coalfield have the lowest boron content (27 ppm), and are located in the recharge zone. Here, since the groundwater flows downward, the coal does not encounter the deep basin upwelling waters (Beaton and Goodarzi, 1989).

The above results indicate that anomalously high boron concentrations in coals are commonly due to secondary sources, such as the occurrence of evaporites in the country rock and the activities of groundwater, rather than the environment of deposition.

Yukon and Northwest Territories

Vast quantities of coal of lignite to anthracite rank occur on both the mainland and Arctic Archipelago of northern Canada (Smith, 1989) (Fig 32).

Cameron et al. (1988) reported the occurrence of an anthracitic coal seam of Early Carboniferous age in the Hoidahl Dome area, Yukon Territory (Fig. 32). A detailed analysis of this seam for ash, sulphur, and boron is presented in Figure 33. The coal layers have very low ash, sulphur, and boron contents (Table 14). Hoidahl Dome coals occur in the Kayak Formation and Richards et al. (in press) state that, "The coal-bearing siliciclastics of basal Kayak were deposited in shoreline and coastal plain environments that succeeded the fluvial and deltaic(?) environments represented by the underlying Kekiktuk Formation." The average boron content of the coal is 10 ppm, indicating a freshwater environment of deposition, in agreement with the proposed upper delta depositional setting. However, the boron content of the only parting in this seam is 148 ppm and that of the sediment near the floor of the seam is 88 ppm, indicating possible occurrences of illite in these two layers within the coal seam.

A coal seam occurs near the base of the Lower Carboniferous Emma Fiord Formation in Sverdrup Basin, arctic Canada. The depositional setting for this seam was lacustrine and the coal contains *Botryococcus* algae so that the coal is similar to the Carboniferous coals of Atlantic Canada (see below). The boron content of this coal seam is 63 ppm, in keeping with a mildly brackish water, lacustrine environment of deposition (Davies and Nassichuk, 1988).

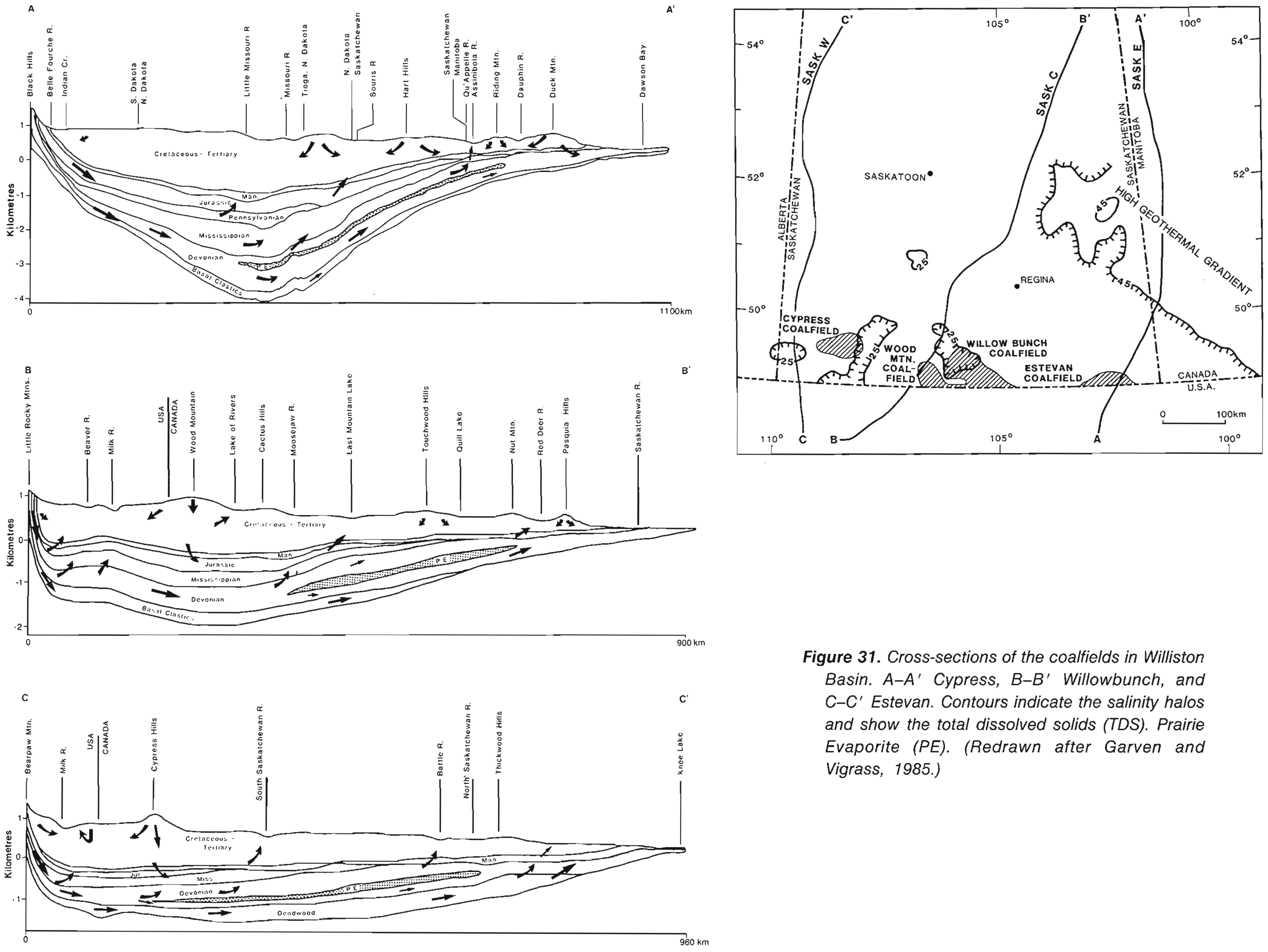


Figure 31. *Cross-sections of the coalfields in Williston Basin. A–A' Cypress, B–B' Willowbunch, and C–C' Estevan. Contours indicate the salinity halos and show the total dissolved solids (TDS). Prairie Evaporite (PE). (Redrawn after Garven and Vigrass, 1985.)*

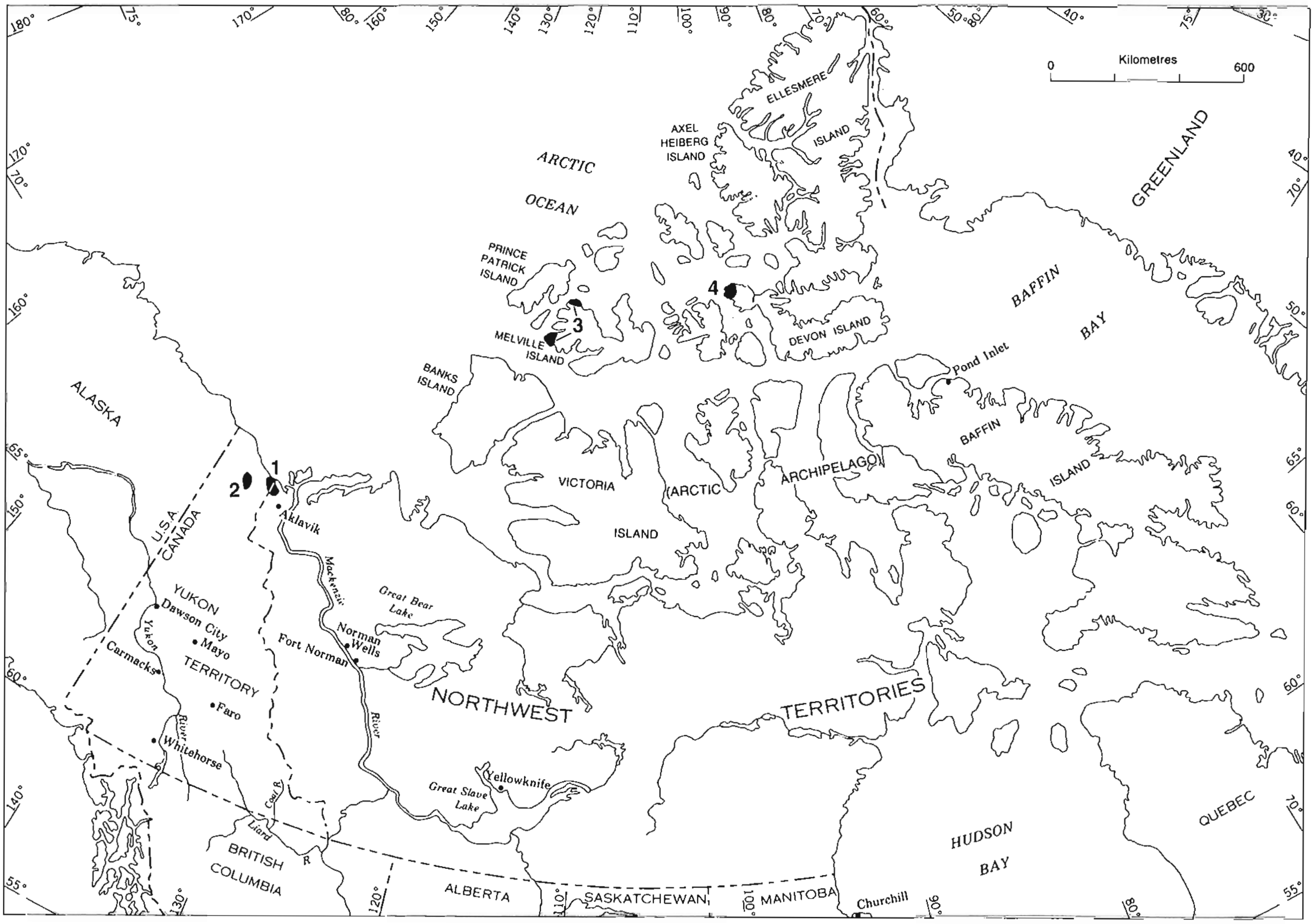


Figure 32. Coal districts and prospective coal areas in Yukon and the Arctic Islands. (After Smith, 1989.) 1 = Mount Granger and Division Mountain, 2 = Hoidahl Dome, 3 = Devonian coals of Melville Island, and 4 = Carboniferous coal, Grinnell Peninsula.

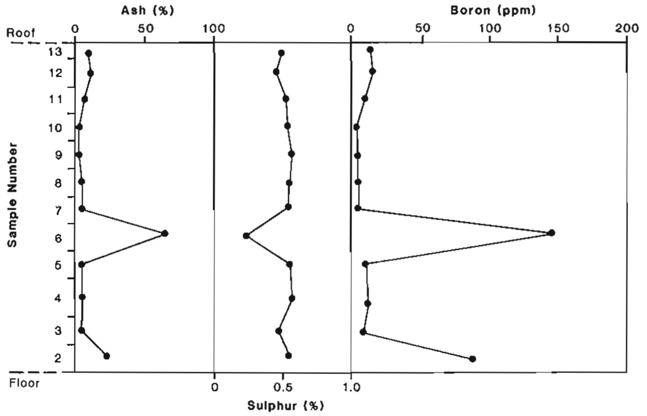


Figure 33. In-seam variation of boron (ppm), sulphur (%), and ash content (%) through Hoidahl Dome, Yukon Territory. (Sulphur and ash data are from Cameron et al., 1988.)

The oldest coal deposit in Canada is located in the western Arctic and in the Middle to Upper Devonian Clastic Wedge (Embry and Klovan, 1976). The coals occur in the Weatherall, Hecla Bay, and Beverley Inlet formations (Figs. 34, 35) on Melville Island. They are mainly spore-rich cannel coals, formed toward the margins of small lacustrine complexes associated with a coastal plain, and in interdistributary/interdelta lobe bays in a lower delta-plain setting (Goodarzi and Goodbody, 1990). The boron content of the cannel coals (8 samples) is 9 to 41 ppm with an average of 33 ppm, while the boron content of the associated humic and liptinite-rich coals (9 samples) ranges from 16 to 69 ppm, with an average of 28 ppm (Goodarzi and Goodbody, 1990). The boron contents indicate a freshwater depositional environment.

TABLE 13

Assessment of the degree of marine influence on coals from Saskatchewan

Location	Lithology	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Estevan Coalfield (Estevan Seam)					Beaton et al. (1991)
Bienfait section	coal	1	14	F	
	coal	10	*169	F	
	carb. shale	3	*79	F	
Boundary Dam section	coal	1	14	F	
	coal	10	*109	F	
	carb. shale	6	*90	F	
Utility section	coal	11	*120	F	
	carb. shale	3	*69	F	
Costello Mine	coal	9	*130	F	
	carb. shale	5	*100	F	
Willowbunch Coalfield					Beaton (1990)
	coal	10	*234	F	
	carb. shale	7	*135	F	
Cypress Coalfield (Ferris Seam)					Beaton and Goodarzi (1990)
Shaunavon section	coal	3	14	F	
	carb. shale	10	49	F	
South Fork	coal	3	33	F	
	carb. shale	3	70	F	

*The high boron content is due to secondary enrichment
F = Freshwater environment

TABLE 14

Assessment of the degree of marine influence on coals from the Arctic Archipelago and Yukon Territory

Location	Lithology	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Arctic Archipelago					
Melville Island	coal	17	15–41	F	Goodarzi and Goodbody (1990)
	coal	1	69	MB	
Grinnell Peninsula	coal	1	63	MB	Goodarzi et al. (1987)
Yukon Territory					
Hoidahl Dome	coal	10	9	F	This study, new data
	carb. shale	2	116	F	
Mount Granger	coal	2	28	F	Beaton (pers. comm., 1991)
	carb. shale	15	38	F	
Division Mountain	coal	19	50	F	Beaton (pers. comm., 1991)
	carb. shale	13	68	F	

F = Freshwater environment; MB = Mildly brackish water environment

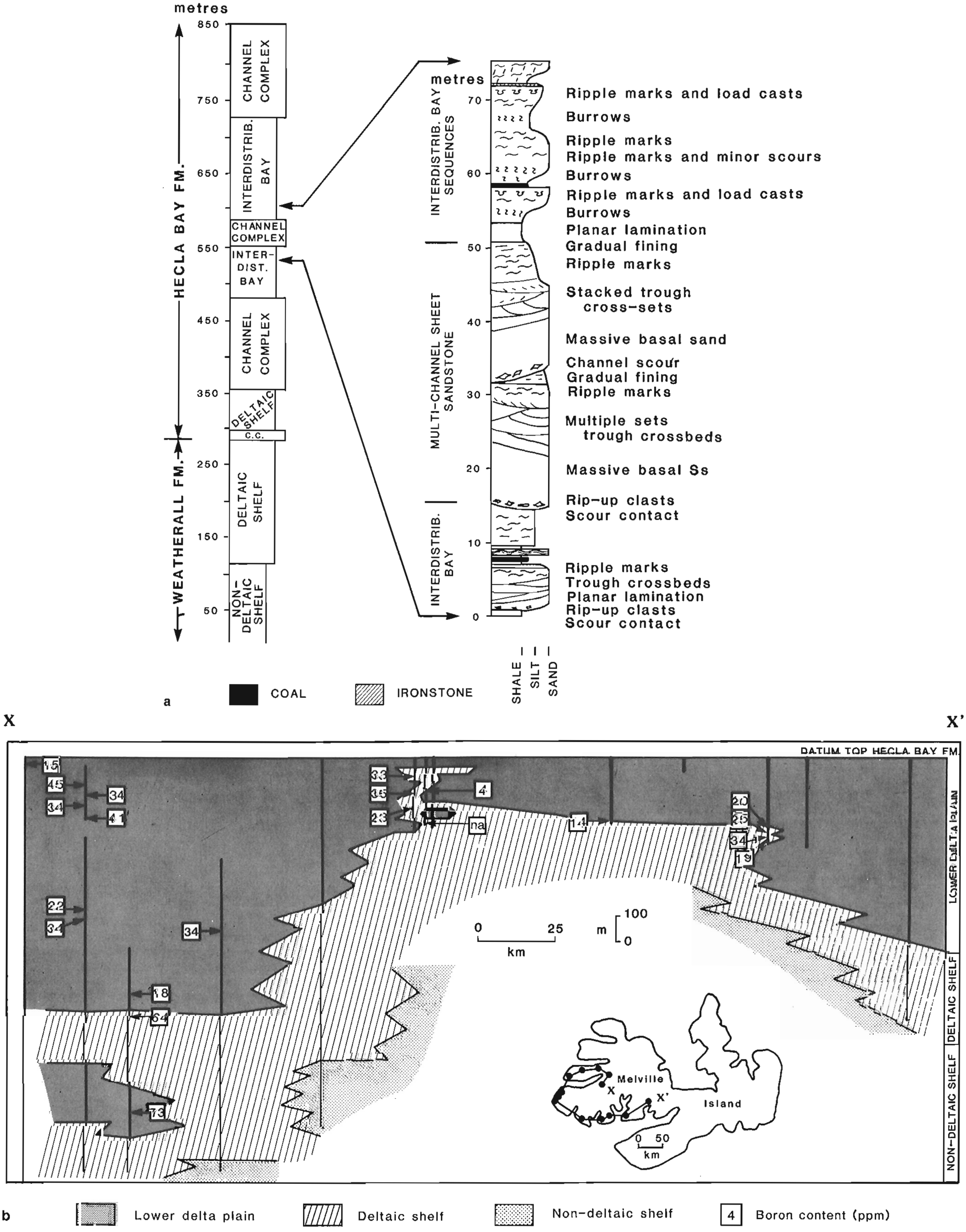


Figure 34. Depositional settings (a), facies relationships, and location of samples (b) for coals of the Hecla Bay subwedge, southwestern Melville Island. (After Goodarzi and Goodbody, 1990.)

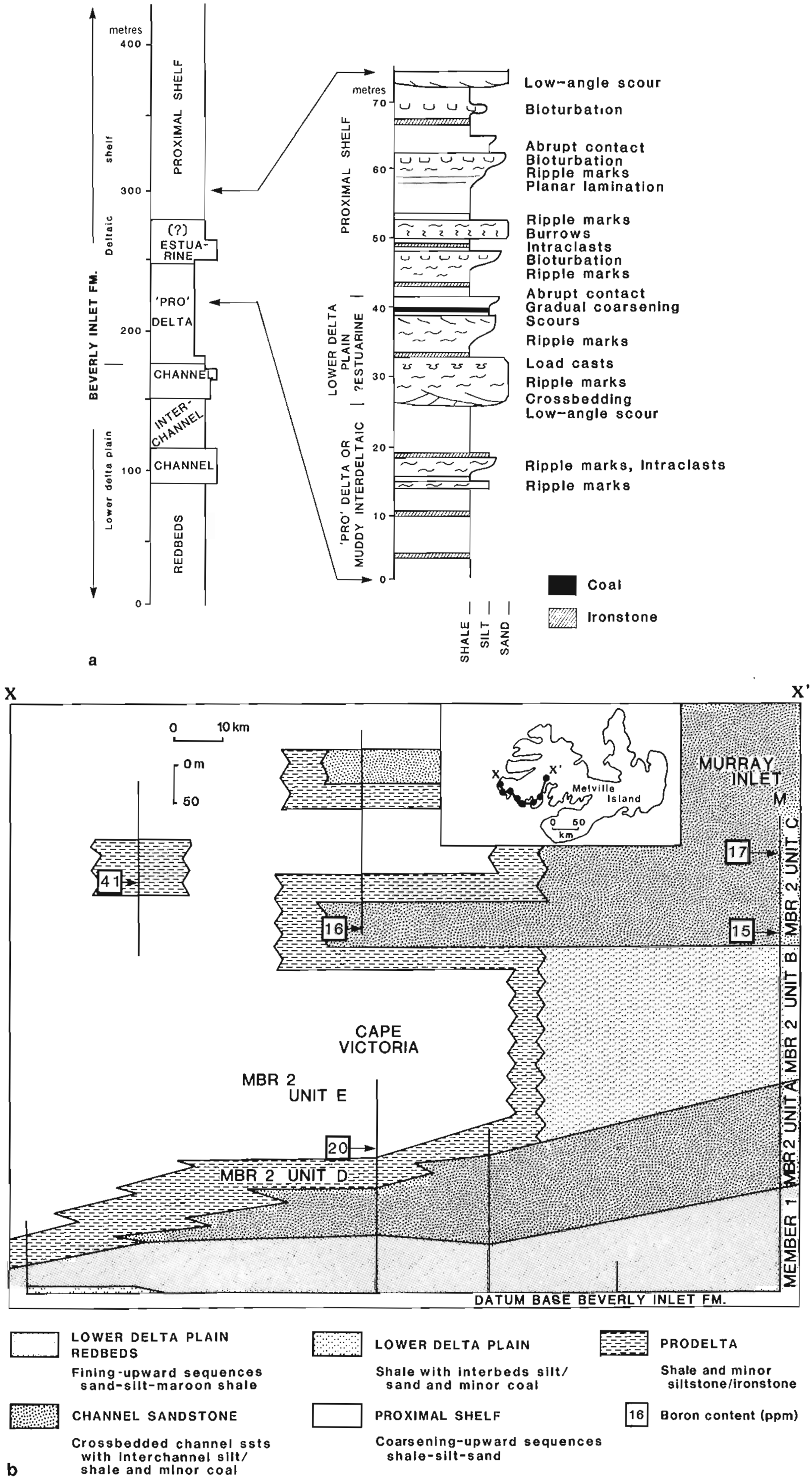


Figure 35. *Depositional settings (**a**), facies relationships, and location of samples (**b**) for coal of the Beverley Inlet subwedge, western Melville Island. (After Goodarzi and Goodbody, 1990.)*

Coal deposits of various ages are found throughout the Yukon Territory. Coals of the Tantalus Formation are of Upper Jurassic/Lower Cretaceous age and were deposited in a coastal-plain environment (Richards et al., in press). A detailed geochemical study of these coals is still in progress (Beaton, pers. comm., 1991). However, the preliminary data indicate that the boron content of 24 coal samples (ash 12–24%) from Division Mountain near the settlement of Brae burn is 29 to 59 ppm, with an average of 44.5 ppm (ash 19%), which is within the range of freshwater coals (Table 14). Only one sample has a boron content of 63 ppm. Samples analysed from Mount Granger, south of the town of Whitehorse, have a high ash content of 47 to 91% and a boron content of 11 to 63 ppm. Only two of the samples are coal (ash 26–30%) and these have boron contents of 27 and 29 ppm (Table 14).

Atlantic Provinces (Nova Scotia)

Interpretations of the depositional environment of the Upper Carboniferous coals from Nova Scotia (Fig. 36) are summarized by Calder and Naylor (in press). These coals were formed in both localized intermontane and extensive regional basins. The intermontane coals of Springhill Coalfield occur in multiseam sequences and were developed in a rapidly subsiding, elongate basin (Calder, 1986). The coals in the regional basins are laterally extensive and cover a large area.

The boron data for Nova Scotia coals are summarized in Table 15. The boron content of intermontane coals from Nova Scotia (<50 ppm) is consistent with the freshwater depositional environment of other intermontane coals in Canada; for example, the Hat Creek deposit, British Columbia (Goodarzi, 1988). The coal seams in the St. Rose–Chimney Corner Coalfield of western Cape Breton Island (Fig. 36) have boron contents of <50 ppm, in agreement with their freshwater environment of deposition, as indicated by the abundance of ostracode and pelecypod (*Anthracosiidae*) faunas in the roof strata of Seam 5 from this coalfield (Calder and Naylor, in press). The ostracodes are of freshwater origin (Hacquebard et al., 1967). The Pictou Coalfield lies in north-central Nova Scotia (Fig. 36) and is restricted to the Stellarton Graben (Yeo et al., 1988; Naylor et al., 1989). The coal seams in this coalfield were deposited in a lacustrine environment. Three coal seams (Acadia, Foord, and Mackay), representing the lower, middle, and upper coal-bearing members of the Stellarton Formation, were examined by Yeo et al. (1988). Coal in the Acadia Seam has a boron content of 38 ppm.

The Foord Seam "was deposited in a lake margin setting on an abandoned lower delta plain in a subsiding basin" (Yeo, 1989). Boron content of the Foord Seam is 40 ppm, in agreement with the proposed freshwater environment and similar to the contents of other intermontane coals (Goodarzi, 1987a; Goodarzi and Van der Flier-Keller, 1989). The MacKay Seam has a boron content of 16 ppm (Yeo, 1989), indicating that it also was deposited in a freshwater environment.

The boron content of coal is either primary, resulting from the influence of the environment of deposition and in agreement with other geological evidence, or is due to secondary enrichment (Beaton, 1990). The higher boron content in some Nova Scotia coals deposited in the intermontane setting (Table 15) is usually due to a secondary enrichment of this element, and is related to the occurrence of Lower Carboniferous evaporite deposits and diapirs, extensive fault systems associated with the coalfields, and the activity of groundwater. This type of boron enrichment is similar to that in coal seams from Saskatchewan (Beaton and Goodarzi, 1989). Seam 3 in the Springhill Coalfield, Cumberland Basin, is an example of secondary enrichment of boron in Nova Scotia coals (Goodarzi and Calder, 1992).

The depositional setting of the Springhill Coalfield is intermontane and the coal seams formed in a "flood-plain/braid-plain environment" (Potter 1967). Calder and Naylor (in press) state that "coals are accumulated in an inland river valley setting bordering a piedmont of mature, coalesced alluvial fans, derived from Cobequid Highlands to the south" (Fig. 37). The shales associated with these coal seams are of freshwater origin. According to Calder (in press), "during deposition of this major coal-bearing assemblage, peat-forming ecosystems 4 to 7 km in width flourished along a margin of retreating coalesced alluvial fans." Furthermore, Calder and Naylor (in press) state that, "successive peatlands become increasingly dependent on the piedmont as a source of groundwater recharge as the basin infills and groundwater supply becomes more restricted."

Hacquebard et al. (1967) stated that "both gypsum and salt are present in the Springhill coalfield and formation of the Springhill anticline is probably related to the displacement of these evaporites." The boron content of coal seams in the Springhill Coalfield is related to the location of the seam, which in turn, might be influenced by groundwater circulation (Fig. 38). The boron content of the coal in the piedmont zone near the Cobequid Highlands massif is 36 ppm, within the range of freshwater coals elsewhere (Goodarzi, 1987a), which indicates that the boron

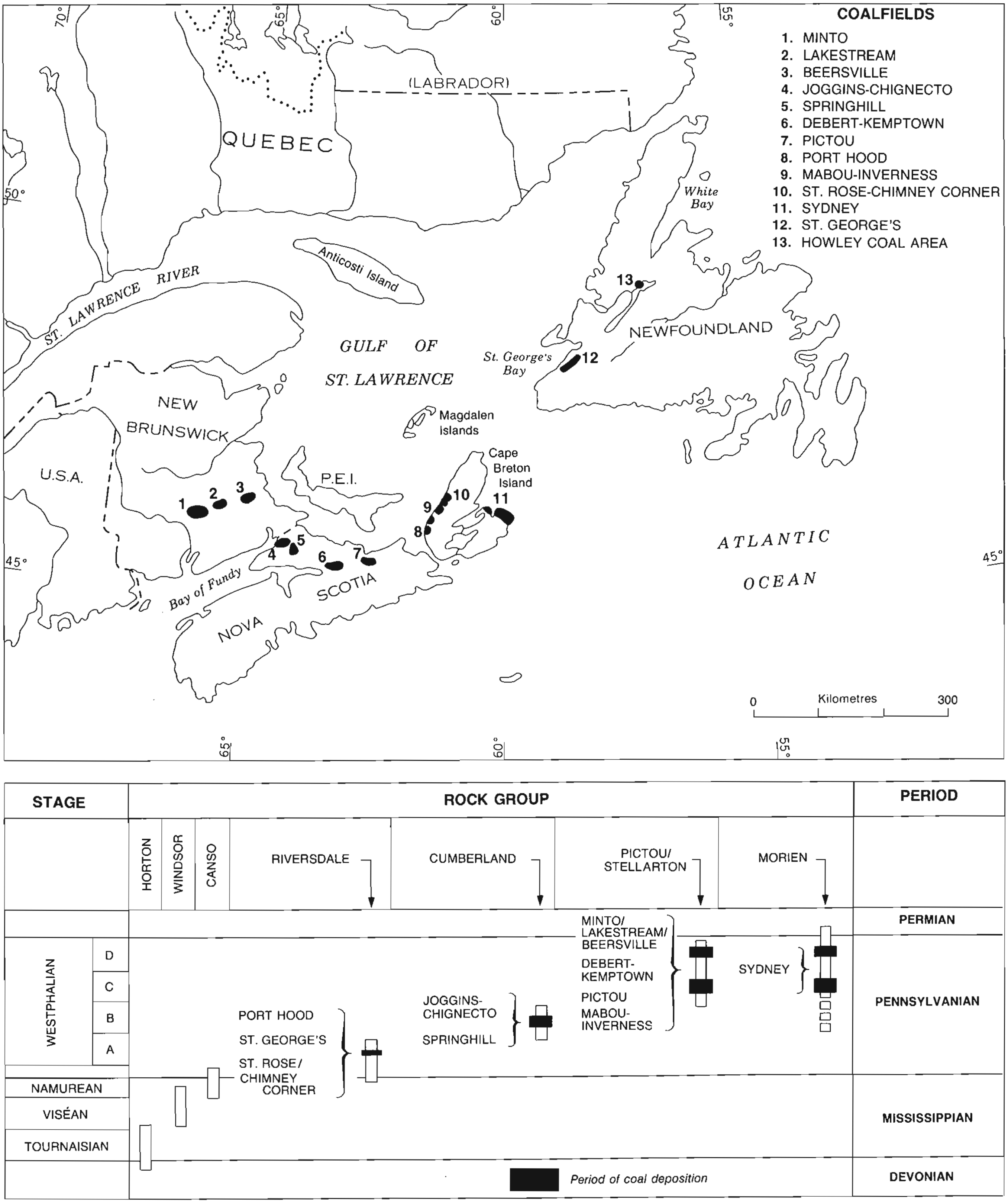


Figure 36. *Coalfields and chronostratigraphy of the Atlantic Provinces. (Map, after Smith, 1989; chronostratigraphy, after Roland, 1982.)*

content of these coals is true primary boron. The direction of groundwater circulation is controlled by surface topography and both local and regional recharge and discharge zones. The coal seam in the piedmont area was formed in proximity to the Cobequid Highlands massif (Fig. 37) (Calder, in press). Therefore, the coal seam with a low content of boron (36 ppm) was probably located in the recharge zone, so that the seam did not encounter upwelling waters from the basin. In contrast, the high concentration of boron in the inner mire (190 ppm) and riverine (210 ppm) zones is secondary in nature and probably is due to the addition of boron (dissolved from evaporites) from groundwater discharged into the mire and riverine zones in which the ancestral peat was deposited. The coal seam in the riverine zone is split into two parts, which are separated by a sandstone (Fig. 38). The upper part of the seam has a lower boron content (150 ppm) than the lower part (330 ppm) (Fig. 38). The higher concentration of boron in the lower part of the seam is probably due to the inclusion of material from detrital Carboniferous evaporites, as this part of the coal seam commonly contains detrital sporinite of Lower Carboniferous age (J.H. Calder, pers. comm., 1991).

TABLE 15

Assessment of the degree of marine influence on coals in Nova Scotia

Location	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Pictou Coalfield				
Stellarton Formation				
Upper McKay Seam	6	30	F	This study, new data
Lower McKay Seam	4	58	MB	This study, new data
Ford Seam	15	46	F	This study, new data
Acadia Seam	4	38	F	This study, new data
Pictou Group (coal seam)				
Caribou Island	2	30	F	This study, new data
Coal Point	3	30	F	This study, new data
Toney River	1	16	F	Yeo et al. (1987)
Munro	1	49	F	This study, new data
	8	40	F	
Sydney Coalfield				
(?)Harbour Seam	1	149	B	Landheer et al. (1982)
Phalen	1	22	F	Landheer et al. (1982)
Backpit	1	21	F	Landheer et al. (1982)
Stony	1	8	F	Landheer et al. (1982)
Emery	1	10	F	Landheer et al. (1982)
Gardiner	1	12	F	Landheer et al. (1982)
Mullins	1	20	F	Hawley (1955b)
Tracy	1	8	F	Landheer et al. (1982)
Port Hood Coalfield	1	8	F	Landheer et al. (1982)
St. Rose Coalfield				
Seam 2	1	107	MB	Hawley (1955b)
Seam 5	7	26	F	Birk et al. (1990)
Seam 5	10	42	F	This study, new data
Springfield Coalfield				
Seam 3	3	40	F	J.H. Calder (pers. comm., 1991)
	4	*205	F	
	2	*280	F	

*The high boron content is due to secondary enrichment
F = Freshwater environment; MB = Mildly brackish water environment; B = Brackish water environment

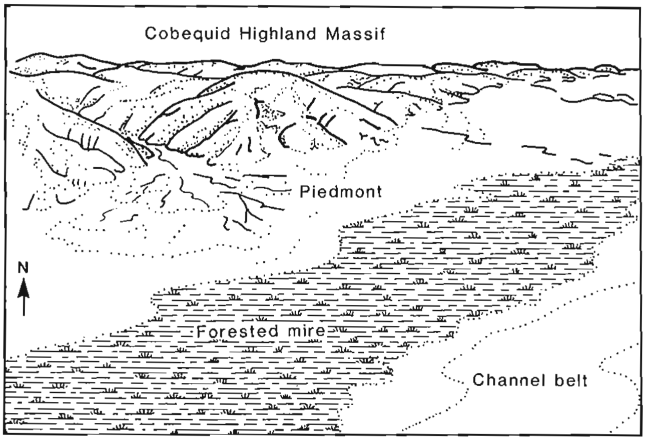


Figure 37. Paleoenvironment of deposition for the Springhill Coalfield, Cumberland Basin, Nova Scotia, showing basin infill sequences. (From Calder, in press.)

The regional basins in Nova Scotia include the Gulf of St. Lawrence and Sydney basins. The Sydney Coalfield is located in the northeastern part of Cape Breton Island. Hacquebard et al. (1967) classified the Sydney Coalfield coals as paralic. Paralic coalfields contain marine sediments. The coals of this coalfield were formed in proximity to the sea, as indicated by the presence of agglutinated Foraminifera (Thibaudeau and Medioli, 1986), and coal-bearing cyclothems that are related to the eustatic sea-level changes (Bird, 1987). The Harbour coal seam from this coalfield has a boron content of 90 to 170 ppm with an average of 123 ppm, indicating a brackish water origin for the seam (Table 15).

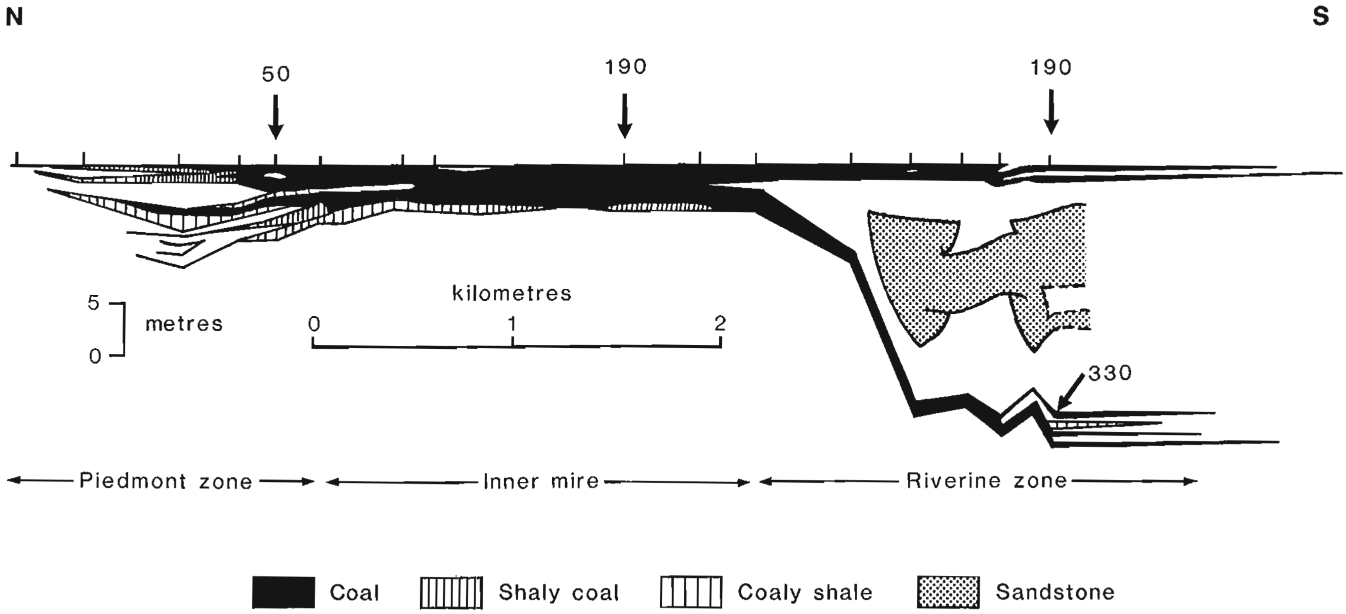


Figure 38. North-south cross-section of the Springhill Coalfield, Nova Scotia, showing generalized stratigraphy and depositional zones. 50, 190 etc. indicate the boron content (ppm) of the coal. (Redrawn from Calder, in press.)

DEGREE OF MARINE INFLUENCE ON AUSTRALIAN COALS

Sydney Basin, New South Wales

The following assessments are based on results from samples of subsections within seams and for clean-coal composites (representative samples of seams). All coal samples had ash yields of less than 35 per cent. Some of the results shown in Table 16 have been published (Clark and Swaine, 1962) or referred to (e.g., by Swaine 1962a, 1967). The boron concentrations indicate predominantly freshwater conditions for seams in the Illawarra Coal Measures (Southern Coalfield) and most of the Newcastle Coal Measures, the main exceptions being the two lower seams which have boron contents of 52 to 79 ppm (mildly brackish water). On the basis of boron contents, the three seams in the Tomago Coal Measures (Fig. 39) were deposited under mildly brackish to brackish water conditions (Swaine, 1962a). This suggestion is supported by the occurrence of marine fossils associated with *Glossopteris* in the lowest beds of the Tomago Coal Measures (Booker, 1960). Furthermore, Diessel (1980) proposed that "throughout the Tomago Coal Measures marine, or at least a brackish influence remained."

Results for coals from the Singleton-Muswellbrook district indicate that most of the coals are freshwater-influenced, although some may have been affected by mildly brackish water conditions. Detailed studies of the Lithgow Seam in the Western Coalfield, over a distance of 100 km, showed boron contents of <50 ppm, indicating a freshwater influence (Swaine et al., 1984b).

In the Ashford Coalfield to the northeast of the Sydney Basin the coals have a boron content of 150 ppm, suggesting exposure to brackish water conditions. However, the source of the boron could have been a glacial marine sequence that overlies the coal seam (Britten, 1975). Chou (1984) has postulated that coal overlain by marine rocks contains more boron than coal overlain by lacustrine rocks.

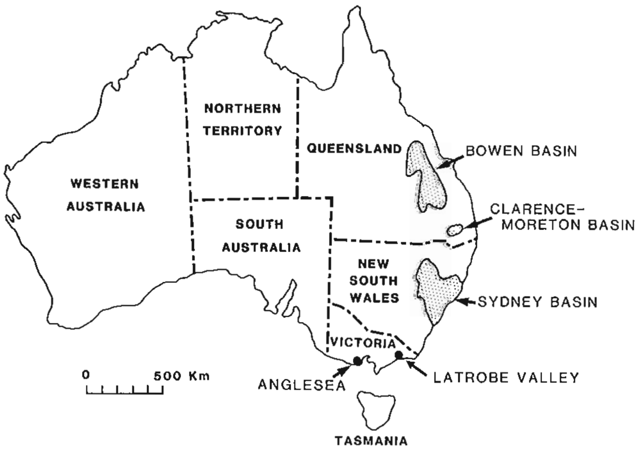


Figure 39. Map of Australia, showing the location of coal deposits discussed in the text.

Bowen Basin, Queensland

Several hundred coals from the Bowen Basin were analysed for boron content. Samples from the Big Seam at Blair Athol were collected from three drill cores, each representing about 30 m of seam thickness. The results (Table 17) show the predominance of freshwater influence. However, at the southern end of the basin, the lower levels of the Nipan Seam are an interesting exception (Fig. 40) with boron concentrations denoting mildly brackish and brackish water effects (Swaine, 1971). Perhaps changes in topography, caused by tectonic activity that originated in the southern part of the basin (Hawthorne, 1971), limited the incursion of seawater to the south.

TABLE 16

Assessment of the degree of marine influence on coals in the Sydney Basin, New South Wales, Australia

Location	No. of samples	Boron (ppm)	Environment of deposition
Illawarra Coal Measures			
Bulli Seam	75	1–34	F
Balgownie, Tongarra,	28	4–39	F
and Woonona seams	19	4–50	F
Wongawilli Seam	5	58–72	MB
Newcastle Coal Measures			
Upper 7 seams	48	7–50	F
Part of the Great Northern Seam	6	55–85	MB
Lower 2 seams	39	13–50	F
	11	52–79	MB
Tomago Coal Measures			
Donaldson Seam	2	40, 44	F
Big Ben Seam	20	63–114	MB
Rathluba Seam	5	118–126	B
Greta Coal Measures			
Greta Seam	27	59–110	MB
Pelton Seam	68	112–352	B
Homeville Seam	2	80, 86	MB
	6	120–198	B
Singleton–Musewellbrook District			
13 seams	23	7–48	F
	9	55–94	MB
Western Coalfield			
Lithgow Seam	141	10–49	F

The above assessment is based on results from Clark and Swaine (1962), CSIRO (unpublished), and Swaine et al. (1984b).
F = Freshwater environment; MB = Mildly brackish water environment; B = Brackish water environment

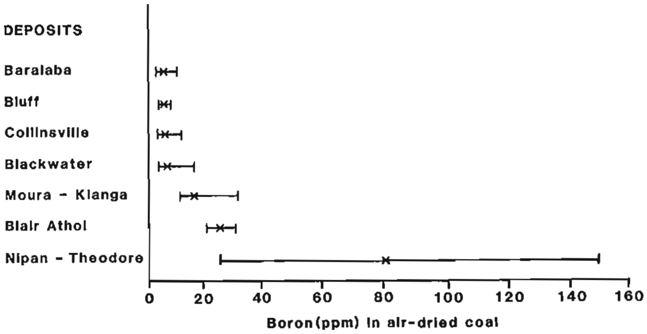


Figure 40. *Boron contents of bituminous coals from Queensland, Australia (based on 905 samples). (From Swaine, 1983.)*

Other Queensland areas

On the basis of boron contents (Table 17), coals from the Ipswich–Callide area and the Clarence-Moreton Basin are considered to have been mainly the product of freshwater depositional environments.

Latrobe Valley, Victoria

The boron contents of brown coals from this area (Table 18) indicate only freshwater influences.

Anglesea Coalfield, Victoria

The results of boron content analysis (Table 18) indicate fresh, mildly brackish, and brackish water influences on these brown coals, depending on seam locations. In some parts seams are overlain by marine formations (Douglas and Ferguson, 1976).

TABLE 17

Assessment of the degree of marine influence on coals in the Bowen Basin and other areas, Queensland, Australia

Location	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Blair Athol				
Big Seam	96	5–48	F	CSIRO (1960)
Bowen and Blake seams	32	<1–13	F	CSIRO (unpublished)
21 other seams	118	<1–50	F	CSIRO (unpublished)
Theordore District				
Nipan seams	6	16–36	F	Swaine (1971)
Levels 1–3	9	51–103	MB	
Levels 4–10	9	122–156	B	
Ipswich–Callide area	54	1–37	F	CSIRO (unpublished)
Clarence-Moreton Basin	6	849	F	CSIRO (unpublished)
	2	64, 68	MB	CSIRO (unpublished)

F = Freshwater environment; MB = Mildly brackish water environment; B = Brackish water environment

TABLE 18

Assessment of the degree of marine influence on brown coals from Victoria, Australia

Location	No. of samples	Boron (ppm)	Environment of deposition	Source of data
Latrobe Valley	9	3–50	F	CSIRO (unpublished)
Anglesa Coalfield	4	7–47	F	CSIRO (unpublished)
	6	60–99	MB	
	5	119–130	B	

F = Freshwater environment; MB = Mildly brackish water environment; B = Brackish water environment

LATERAL VARIATIONS OF BORON CONTENTS IN COAL SEAMS

It appears that the only detailed study of long distance (approximately 100 km) variations in the boron content of coal from one seam is a study of the Lithgow Seam in the Western Coalfield, NSW, Australia (Swaine et al., 1984b). One hundred and thirty samples were collected from 9 locations. The Variance Ratio (i.e., the ratio of the maximum to the minimum value) is used as a measure of variability. As shown in Table 19, the variance ratios for all samples are from 2 to 3. However, the ratio is 2 for 125 samples; that is, for 96 per cent of samples. This low variance over such a long distance is perhaps unexpected. However, it is in keeping with the geological conditions that are suggested for the Western Coalfield "where stable basement conditions have prevailed since Middle Permian times. Hence the degree of folding and faulting is minimal" (Morris, 1975). According to Bembrick (1983) the "Western Coalfield presents a sequence of shoaling lower deltaic sedimentation with relatively minor fluvial channel conglomerates developed near the base." The relatively small changes in boron contents of coal from this seam would make it "likely that stable conditions prevailed during most of the coalification period" (Swaine, 1990). These results may not be typical of other seams, "indeed they may well indicate the least variability that can be expected in any one seam" (Swaine, 1990) over a long distance. However, low variance ratios may well be common in any seam over a short distance.

Eight seams (Table 20) were studied to ascertain the lateral variation of boron contents in Canadian coals. The eight seams examined are: Seam 7 in the

TABLE 19

Variance ratios for boron contents in samples of coal from the Lithgow Seam at nine separate locations in NSW, Australia (Variance Ratio = maximum value divided by minimum value.)

Location	No. of samples	Boron (ppm)[1]	Variance Ratio
A	33	20–40	2
B	21	15–30	2
C	23	10–25 (mostly 10–20)	2.5 (2)
D	19	10–25 (mostly 10–20)	2.5 (2)
E	16	15–40 (mostly 20–40)	2.7 (2)
F	10	15–30	2
G, H, I	8	10–30 (mostly 10–20)	3 (2)

[1] Data from Swaine et al. (1984b)

TABLE 20

Lateral variation of boron content in Canadian coals

Coalfield/region (Formation) Rank [Variance Ratio]	Station	Distance from Station 0 (m)	No. of samples	Mean boron (ppm)	Environment of deposition
Drumheller region/ Alberta					
(Horseshoe Canyon)					
Seam 7	A 1	0	7	120	B
Subbituminous	2	40	4	138	B
[1.9]	3	50	3	114	B
	4	50	4	122	B
	5	80	2	147	B
	6	30	4	115	B
	7	40	3	134	B
	8	40	3	115	B
	9	40	3	119	B
	10	60	4	115	B
	11	30	4	128	B
	12	200	4	126	B
	13	300	3	104	MB
	B 14	350	3	92	MB
	C 15	10.0 km	1	77	MB
	D 16	14.0 km	1	78	MB
	E 17	16.5 km	1	103	MB
Vesta Mine/ Alberta					
(Horseshoe Canyon)					
Seam 3	1	0	19	213	B
Subbituminous	2	100	17	201	B
[1.0]					
Flathead Coalfield/ British Columbia					
(Kootenay Group)					
Seam 2	1	0	7	32	F
High volatile	2	100	10	39	F
bituminous	3	200	6	29	F
[1.6]	4	250	5	25	F
Seam 4	1	0	4	22	F
High volatile	2	100	2	23	F
bituminous	3	200	2	46	F
[2.1]					
Northeastern British Columbia					
(Gates Formation)					
Seam 4	1	0	3	25	F
Medium to low	2	4.7 km	3	24	F
volatile bituminous	3	5.5 km	4	14	F
[2.8]	4	6.5 km	5	35	F
	5	7.5 km	2	40	F
Seam 10	1	0	2	17	F
Medium to low	2	1.2 km	3	10	F
volatile bituminous					
[1.7]					
Seam 11	1	0	3	10	F
Medium to low	2	1.7 km	2	10	F
volatile bituminous	3	2.5 km	4	10	F
[1.4]	4	3.0 km	4	10	F
	5	3.7 km	2	8	F
	6	5.0 km	3	7	F
	7	5.3 km	2	7	F
	8	5.9 km	2	8	F
	9	6.5 km	3	8	F
Springhill Coalfield/ Nova Scotia					
Seam 3	1	0	4	37	F
[5.7]	2	1.5 km	3	*210	–
[7.6]	3	3.0 km	4	*280	–

A, B, C, D and E are the sample locations for Seam 7 at Drumheller (see Figure 41).
F = Freshwater environment; MB = Mildly brackish water environment;
B = Brackish water environment; * = Secondary enrichment of boron

Drumheller region and Seam 3 at the Vesta Mine, Alberta; Seams 2 and 4 in the Flathead Coalfield, southeastern British Columbia; Seams 4, 10, and 11 in the Gates Formation in northeastern British Columbia; and Seam 3 at Springhill, Nova Scotia.

The boron content of Seam 7 is reported for 16 locations over a distance of 16.5 km, from the mouth of Kneehills Creek to Rosebud River in the vicinity of the town of Drumheller (Fig. 41). The rank of this coal seam is subbituminous and it was deposited in a mildly brackish to brackish water environment (Gibson, 1977). Samples were collected very closely wherever possible, in order to monitor the variations in boron content (Table 20). The boron content of this seam is between 77 and 147 ppm, indicating a mildly brackish to brackish water depositional environment. The Variance Ratio is 1.9 for all samples from the 16 locations. This is a low Variance Ratio over such a long distance and indicates the lateral stability of the environment over this distance (Table 20). However, the coals from a brackish water setting are mainly in the western areas, indicating a possible direction of brackish water intrusion into the area in which the coal formed.

Seam 3 at the Vesta Mine consists of subbituminous coal deposited in a brackish water setting (Gentzis et al., 1990). This seam was sampled from fresh surfaces in the mine, and the distance between the two stations sampled is 100 m. There is very little difference in the boron content of the two sets of samples (Table 20), and both indicate a brackish water environment. The Variance Ratio of boron within and between the seams is 1.1.

Coal seams 2 and 4 from the Flathead Coalfield are high volatile bituminous in rank (Ro_{max} 0.85%), and were formed in a freshwater setting (Gibson, 1985). They show little variation in their boron content over a short distance (Table 20), and their variance ratios are low (1.6 and 2.1).

Variations in the rank (medium to low volatile bituminous) and depositional environments of Seams 4, 10, and 11 were reported by Kalkreuth and Langenberg (1986). Boron shows little variation for these seams (Table 20). The variation of boron is as follows: Seam 4, from 14 to 40 ppm for five stations covering a distance of 7.5 km; Seam 10, from 10 to 17 ppm for two stations over a distance of 1.2 km; and

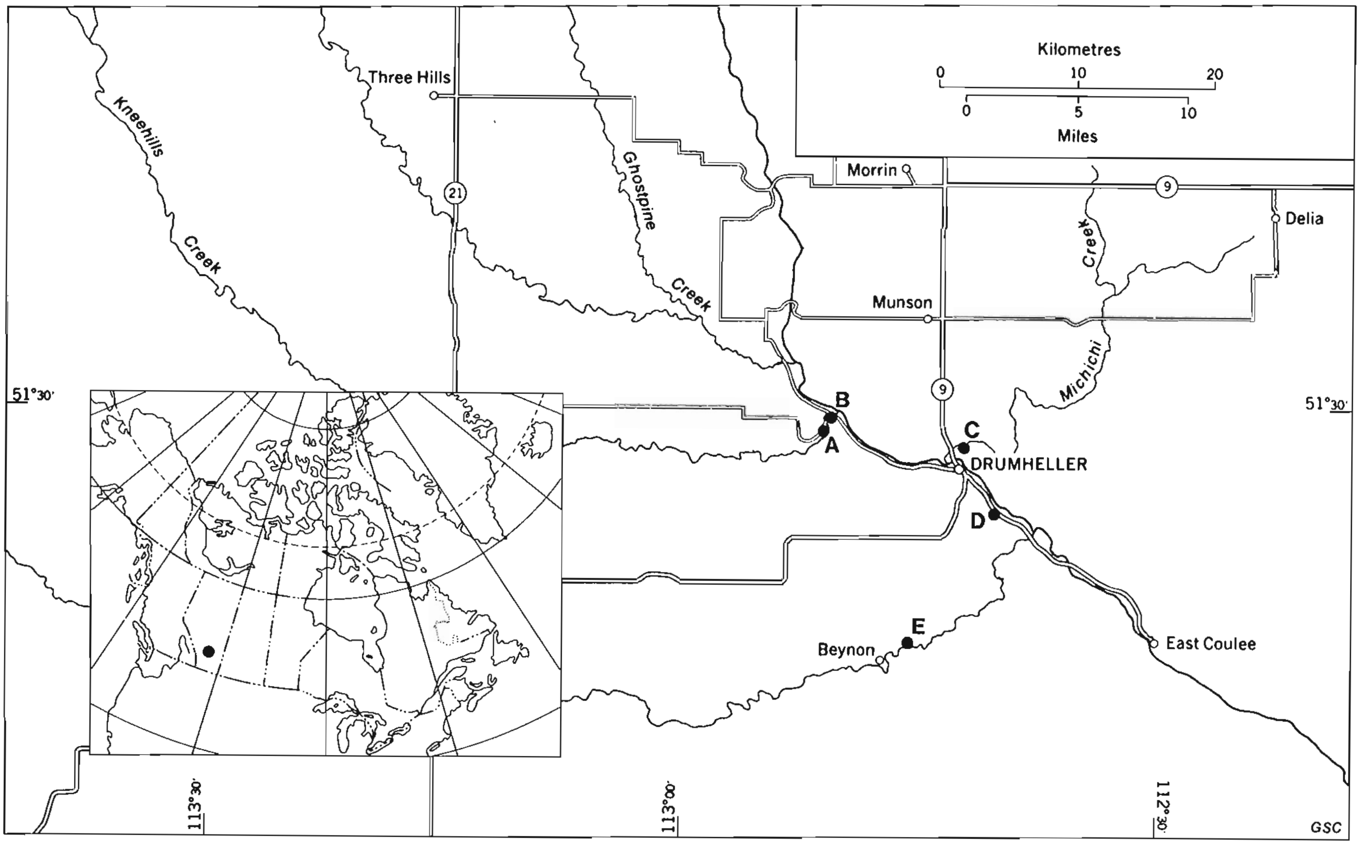


Figure 41. Map of the Drumheller area, Alberta, showing the location of samples taken from Seam 7. These samples were collected to indicate the lateral variation of boron (see Table 20 for boron contents).

for Seam 11, from 6 to 10 ppm for nine stations over a distance of 6.5 km. The low variance ratios for Seams 4 (2.5), 10 (1.7), and 11 (1.7), indicate the lateral consistency of boron content values for these three coal seams and a stable depositional environment during their deposition.

The lateral variation of boron concentrations in a coal seam does not necessarily indicate a variation in depositional setting (primary boron enrichment), but may indicate a secondary enrichment of boron as discussed above (see the section on Saskatchewan lignites). A good example is the variation of boron in Seam 3 at Springhill, Nova Scotia. Boron in this seam ranges from 37 ppm (primary enrichment) at location 0, to 210 pm and 280 pm at two other locations. The enrichment of boron at the last two locations is due to the influence of circulating brines. The variance ratios for coal at these two locations compared to coal at location 0 (boron: 37 ppm) are 5.7 and 7.6.

The boron content of coal seams is sensitive to the environment of deposition and usually remains relatively stable and within the range of values designated for each depositional setting laterally within a seam. However, boron values may show lateral variation within a seam as the result of changes in the environment of deposition and/or boron enrichment from a secondary source.

VERTICAL VARIATIONS IN THE BORON CONTENTS OF SEAMS

An investigation of 45 vertical sections of seams in the Sydney Basin, NSW, Australia, showed several trends, but it was "not possible to make general predictions on the distributions of trace elements between coal and dirt subsections" (Clark and Swaine, 1962). In places, increased concentrations of boron occur in the roof and floor subsections of a seam and in dirt bands compared to the amounts found in adjacent coal subsections, but the opposite effects also occur. In the Greta Coal Measures, where coal deposition was affected by brackish water conditions (Table 16), dirt bands usually have higher boron contents than adjacent coal subsections, or at least of the same order, but this is not always the case for roof and floor subsections.

Detailed analytical results for 96 coal samples and 22 dirt band samples from three drillhole cores taken from the Big Seam at Blair Athol in Queensland, Australia, are shown diagrammatically in Figure 42. Relatively high concentrations of boron occur in the roof and floor subsections (not shown) but high values for dirt bands are only seen in one drillhole core, in a seam approximately 30 m thick. Another thick seam (about 19 m thick) forms the coal-bearing section in the Blakeburn Mine (Fig. 19), near Tulameen, British

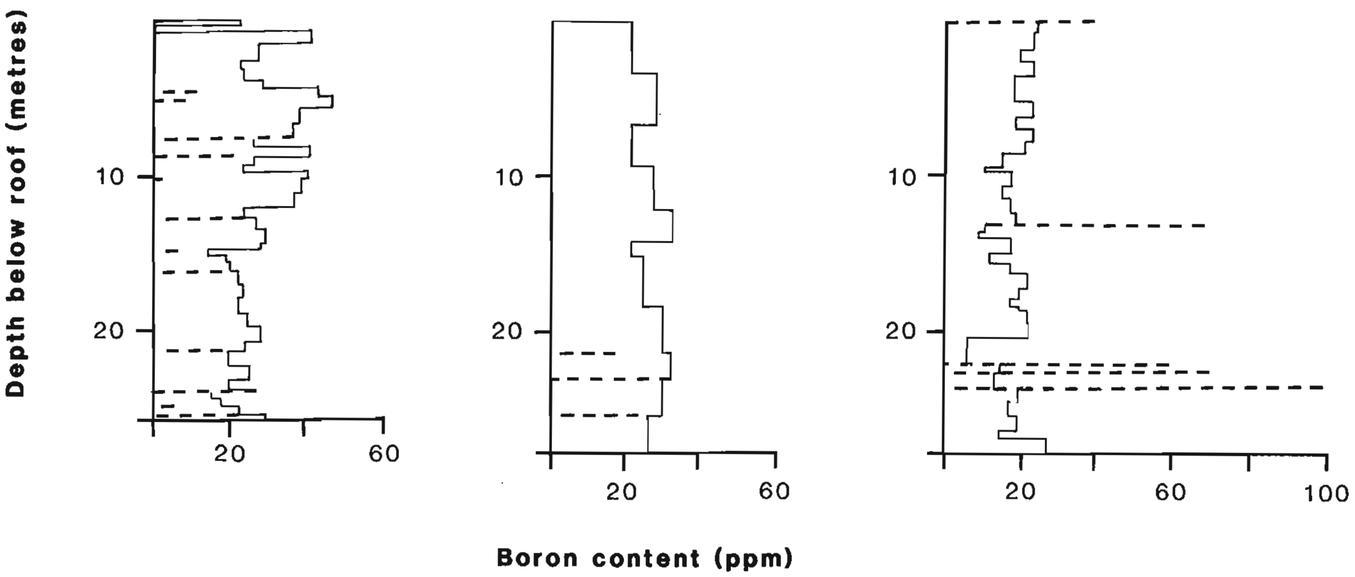


Figure 42. Variation of boron content with depth in three borehole cores from the Big Seam at Blair Athol, Queensland, Australia (CSIRO, 1960). Dirt bands are shown by dashed lines.

Columbia, Canada. The results of boron analysis of 27 coal samples and 34 dirt band samples (partings, mainly shale, tonstein, and clay) have been published by Goodarzi and Van der Flier-Keller (1989). In general, the boron contents of the dirt bands are less than those of adjacent coal subsections. Results showing the variations in boron contents of coals from four zones in Hat Creek Deposit No. 2 are shown in Figure 43 (Goodarzi and Van der Flier-Keller, 1988). The boron contents show very little variation (6–18 ppm).

Other detailed in-seam studies of Canadian coals have been made at Telkwa, British Columbia (Fig. 18); the Vesta and Highvale mines, Alberta (Fig. 14 and Table 11, respectively); the Obed Marsh Coalfield,

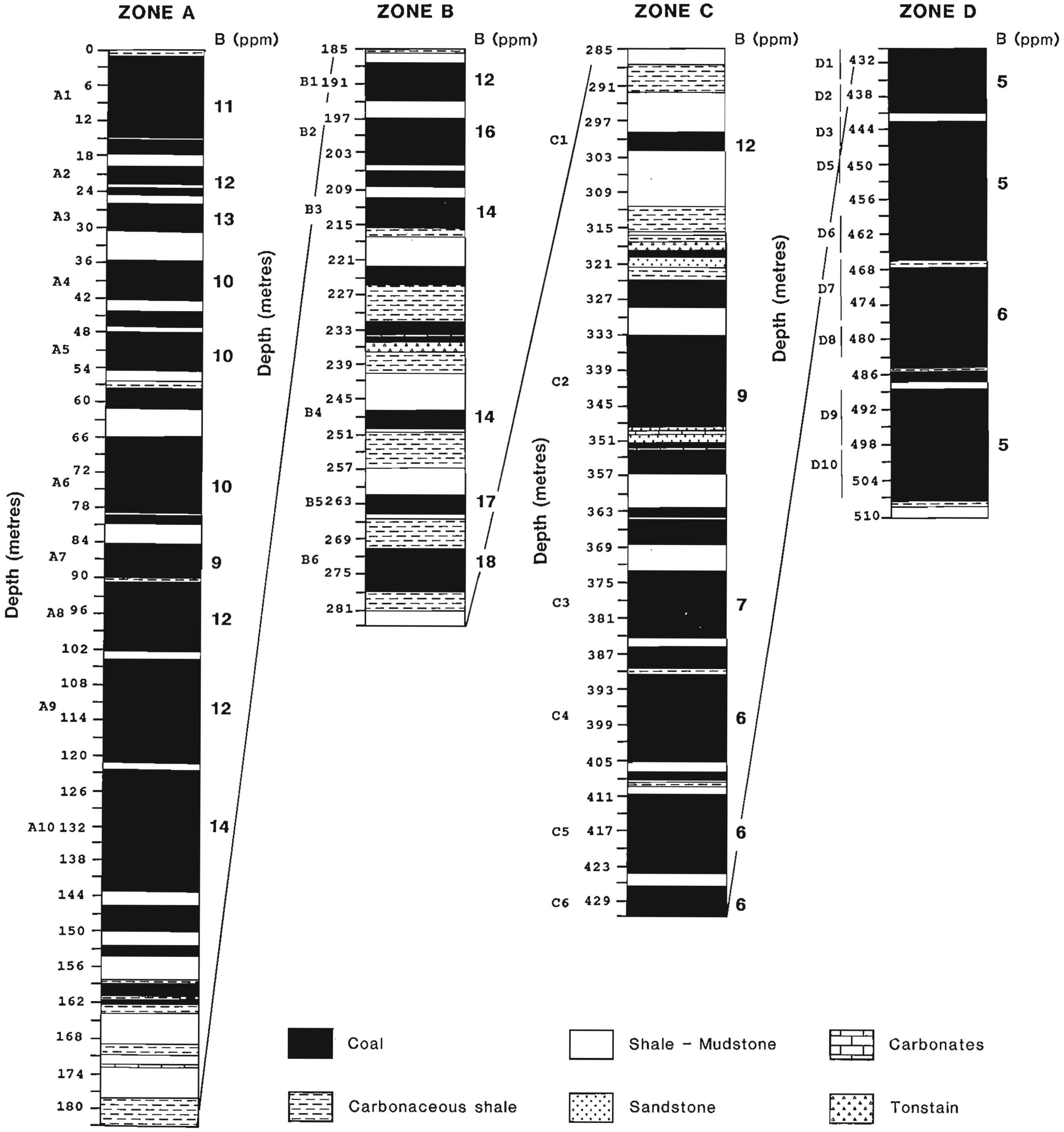


Figure 43. Variation of boron content for the coal zones in Hat Creek No. 2 deposit, British Columbia.

Alberta (Figs. 44–46); the Byron Creek Collieries, British Columbia (Fig. 47); and three seams from seven locations in the Ravenscrag Formation, Saskatchewan (Fig. 48a–g).

Boron concentrations show very little variation within the coal seams and in the coal-bearing sections at Telkwa (18–40 ppm), British Columbia (Fig. 17) and the Highvale Mine (5–46 ppm), Alberta (Table 11). However, boron is slightly enriched (50–65 ppm) in the sediments associated with the coal seam at Telkwa (Fig. 17). In contrast, boron concentrations show a wide variation in Seams 1 and 2 from Obed Marsh, Alberta. Two sections of Seam 1 were examined (Figs. 44, 45). The amount of boron present in the coal strata at Section 1 (3.5 m thick), based on 13 samples, ranges from 27 to 87 ppm. The lower boron values are always associated with a parting (Fig. 44). Section 2 was sampled in more detail and a total of 24 samples, including three partings and sediments from the roof, were analysed. The boron content of the coal layers is in the range of 50 to 85 ppm. The partings within the

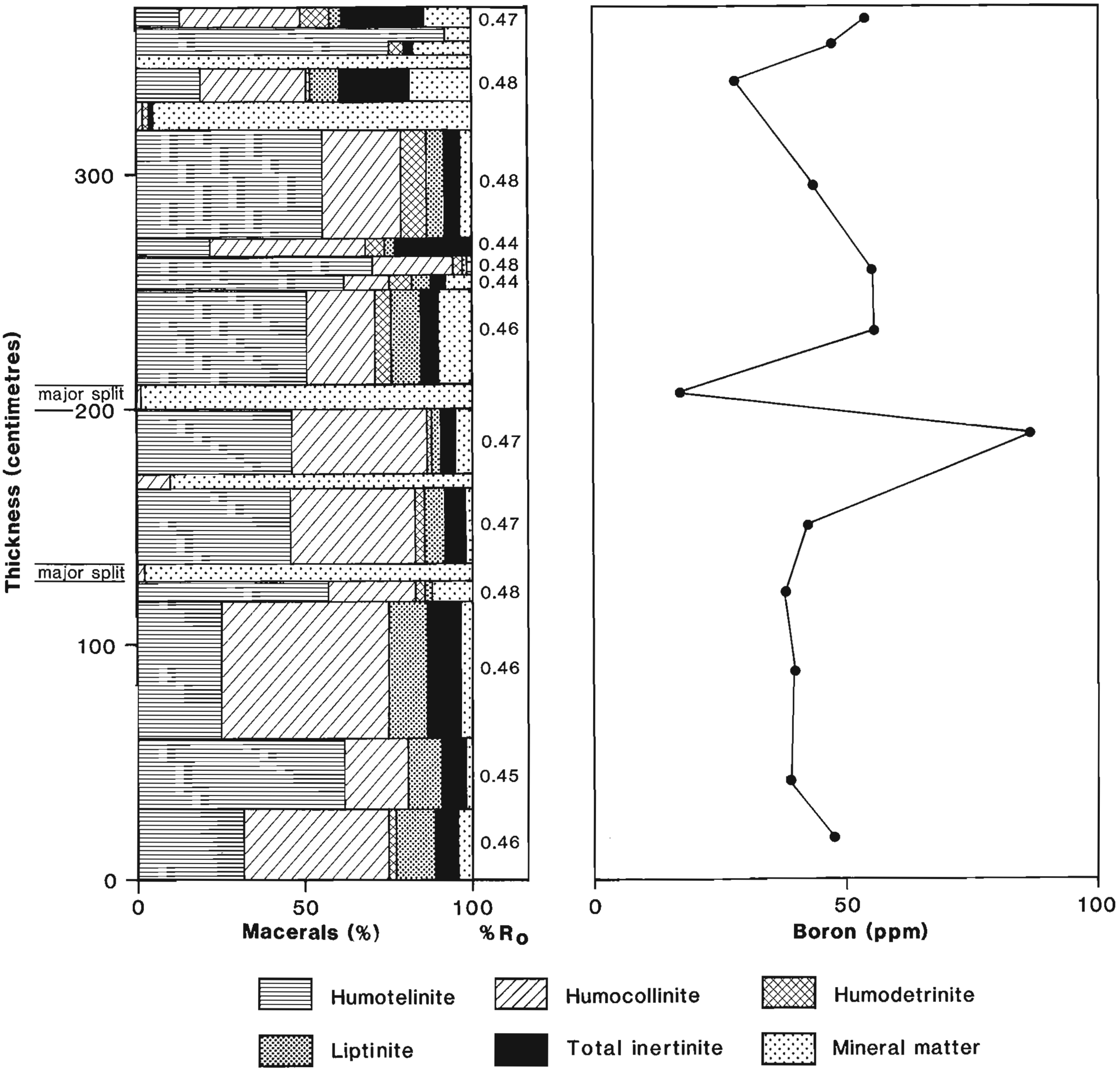


Figure 44. *In-seam variation of macerals, reflectance (% $R_{o random}$), and boron content for Seam 1, Section 1 of the Obed Marsh coal deposit, Alberta.*

coal seam have a lower boron content (12-27 ppm) than the coal layers. A sample from the roof also has a low boron content (30 ppm) (Fig. 45). There is a major split in Seam 1 at about 200 to 220 cm, which is evident in both sections (Figs. 44, 45). The boron content of this parting in the two sections is 17 and 27 ppm, respectively. However, the coal layers beneath this major split at the two sections show higher boron contents (87 and 89 ppm; Figs. 44, 45), which may indicate downward mobilization of boron from the parting into the coal during the early stages of coalification. The variation of boron in Seam 2 from Obed Marsh is shown in Figure 46. In general, there is little variation in boron content; however, samples from the roof and a coal layer under a major parting (250-300 cm) show an enrichment of boron (Fig. 46). The relative enrichment of boron in the roof sediment and the coal layer under the major parting is possibly

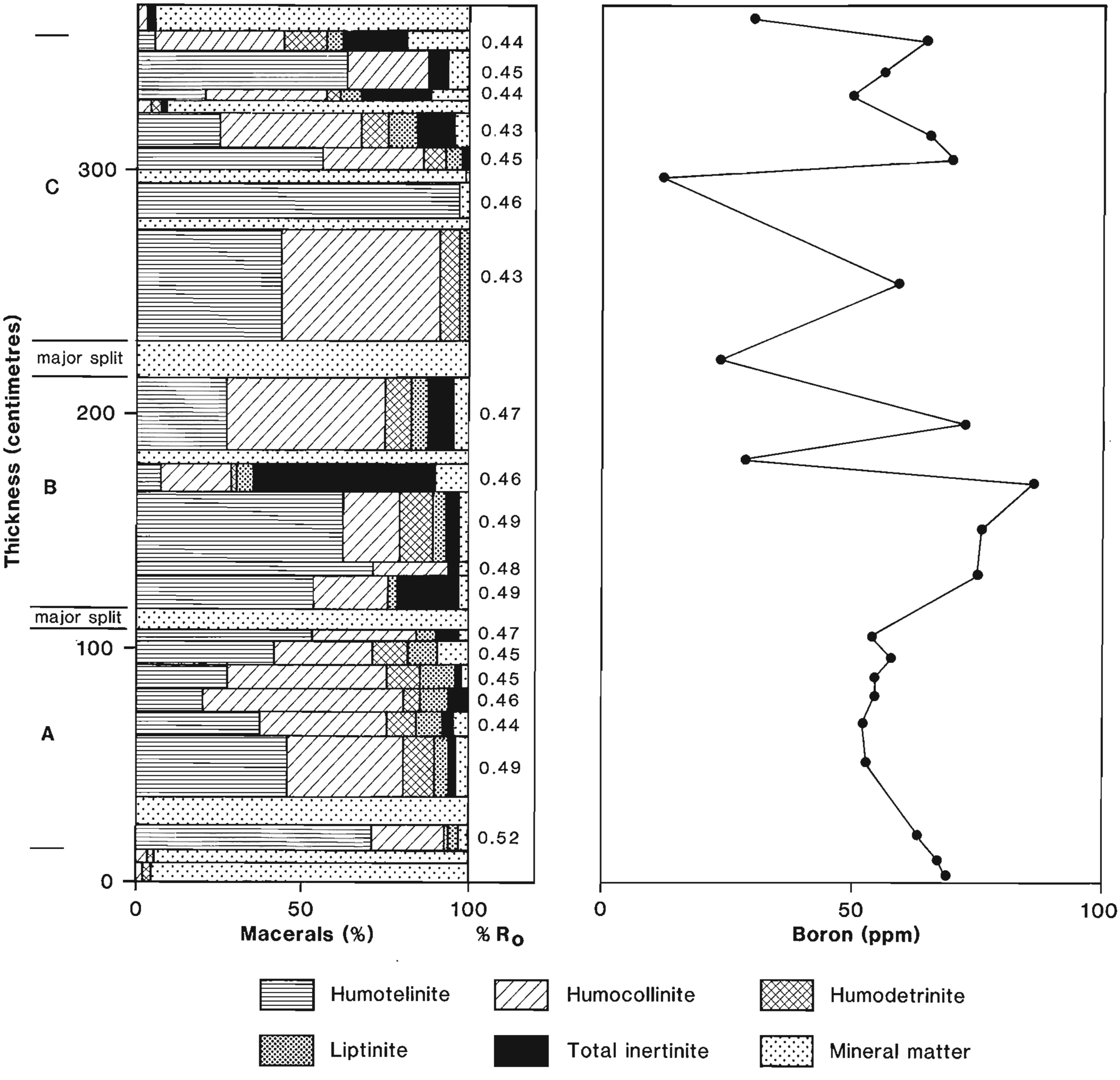


Figure 45. *In-seam variation of macerals, reflectance (% $R_{orandom}$), and boron content (ppm) for Seam 1, Section 2 of the Obed Marsh coal deposit, Alberta.*

due to the mobilization of boron after and/or during coalification.

The in-seam variation in the concentration of boron in brackish water coal from the Vesta Mine has been discussed above. The boron contents of almost all the coal layers are within a narrow range (171-262 ppm), with the exception of a significantly lower value (25 ppm) for the inertinite-rich layer (Fig. 14). The Variance Ratio for the coal layers, excluding the inertinite-rich layer, is low (1.4); however, this ratio increases to 10.6 when the inertinite-rich layer is included. This high Variance Ratio indicates a major fluctuation in the depositional conditions for the inertinite-rich layer compared to those under which the other coal layers were formed.

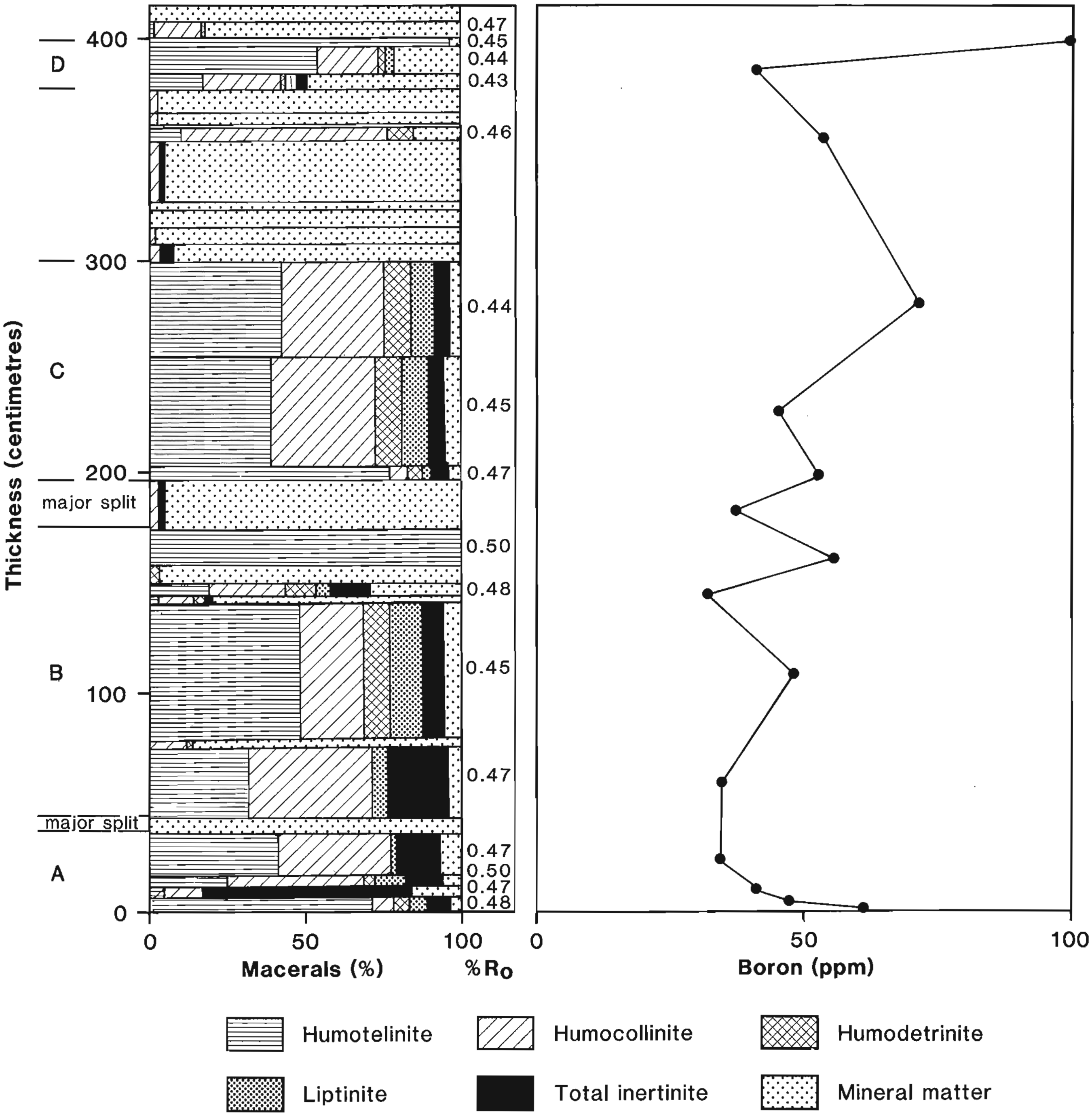


Figure 46. *In-seam variation of macerals, reflectance (% $R_{o random}$), and boron content (ppm) for Seam 2 of the Obed Marsh coal deposit, Alberta.*

The boron content of the coal layers in Seam 1 (Mammoth Seam) at Byron Creek Collieries is shown in Figure 47. This seam has been structurally thickened to 100 m, due to folding and faulting (Goodarzi, 1986a, b). The actual undisturbed thickness of the Mammoth Seam is a matter of some dispute. MacKay (1931) thought that it might vary from 4 to 60 m, whereas Norris and Price (1957) stated that it might vary from 4 to 8 m. Boron content of this seam, based on 20 samples, is 115 to 202 ppm, although two samples have boron contents of 87 and 91 ppm. The average boron content of all coal layers in this seam (22 samples) is 140 ppm (Fig. 47). This variation in boron content is probably due to the influence of faulting and folding, which produced a friable coal (Goodarzi, 1987b) and fracturing of the coal seam, and

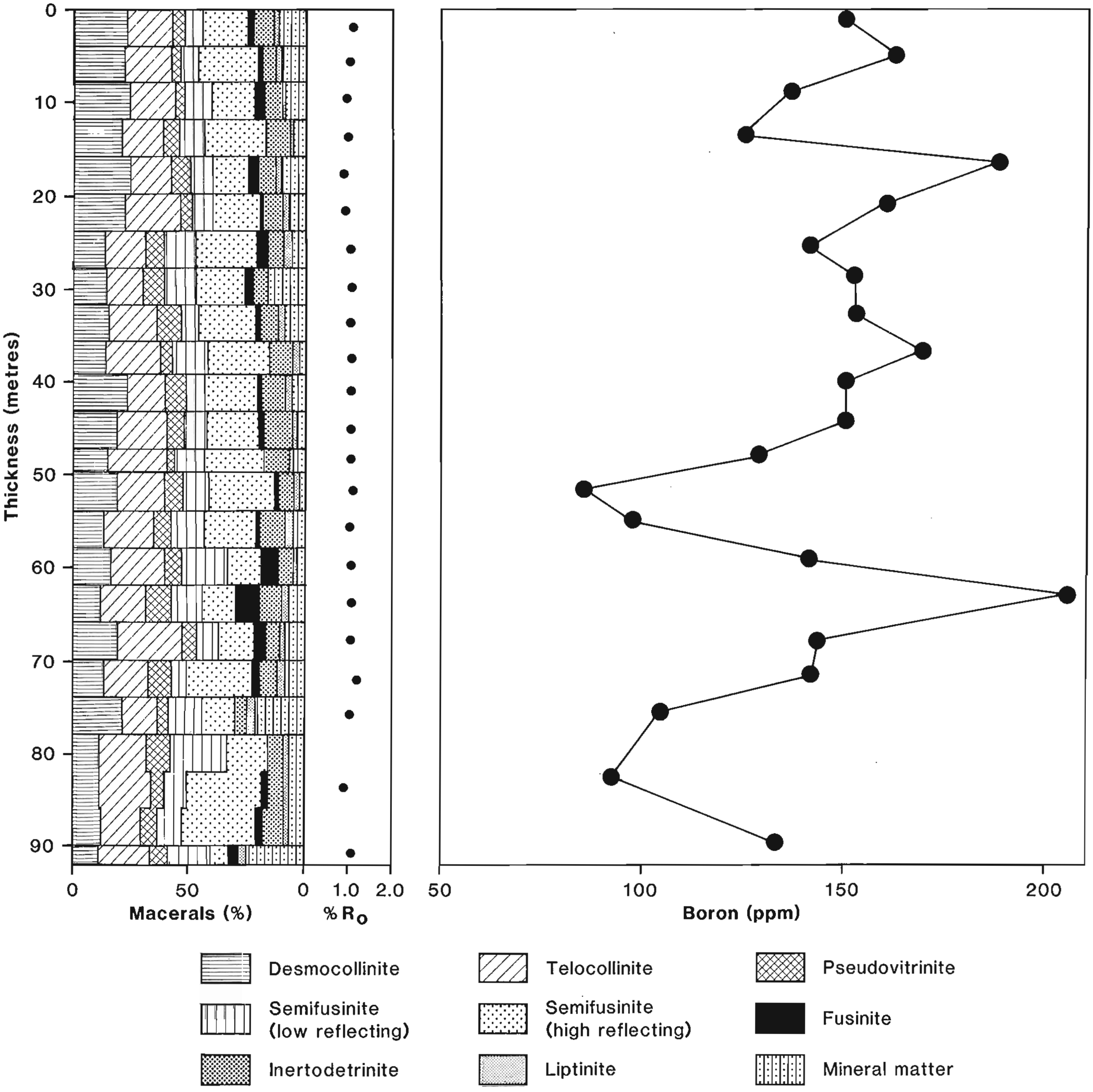


Figure 47. Variation of boron content, macerals, reflectance (% $R_{o random}$) in tectonically thickened coal of Seam 1 at Byron Creek Collieries, British Columbia.

facilitated the removal of boron from some coal layers by groundwater. The Variance Ratio for all samples from this seam is low (2.3), however, indicating a stable depositional environment.

Variation in the concentration of boron in the coal seams of the Ravenscrag Formation is related to the ash content of the coal layers and the partings (Fig. 48a-g). The Ferris Seam at the South Fork and Shaunavon sections has boron contents consistent with the depositional environment (fresh water), while coals at the other five sections show secondary enrichment of boron (Beaton, 1990). However, although the boron content almost exactly follows the ash content (Fig. 48a, b) in the Ferris Seam, the reverse is the case for the other seams (Fig. 48c-g). There is a tendency for boron enrichment in the roof and floor sediments of the Ferris Seam (Fig. 48a, b). The boron content of the roof and floor sediments is between 90 and 120 ppm, whereas the boron content of the coal averages 27 ppm. Boron concentrations in the roofs and floors of the coal seams at the other five sections, which show secondary enrichment of boron, are similar to that in the Ferris Seam, in the range of 78 to 100 ppm, while the average boron contents of the coal seams are 154 to 233 ppm (Figs 48c-g). Comparison of the boron contents of roof and floor sediments for all sections, irrespective of secondary enrichment of boron, indicates that their boron contents are almost identical and have a narrower range (78-120 ppm) and lower Variance Ratio (1.5) than the boron contents of the coal in these sections, which show a wider variation (27-233 ppm) and higher Variance Ratio (8.6). This difference in the boron contents of coal seams and in the sediments that form their roofs and floors indicates that, unlike coal layers which are able to accommodate a secondary enrichment of boron, possibly due to their porosity, the sedimentary rocks associated with coal seams are not able to assimilate boron to the same extent.

Variance ratios for coal samples from vertical sections of various Canadian and Australian coals are given in Table 21. Detailed examination of the variance ratios for coals, at 6 Canadian and 42 Australian sections, indicates that most variance ratios range from 1.5 to 3.5. The high values for the Eagle Mountain seams and for the Byron Creek coals probably result from the fact that these sections were affected by different conditions, ranging from fresh water to brackish water. As can be seen from the diagram published by Goodarzi (1987b), the overall Variance Ratio for Byron Creek is 8.0, and yet the ratios, when seams are divided into the F, MB, and B categories, are only 2.0, 2.3 and 2.4. This indicates that within each subenvironment the geochemistry is consistent in that the variance ratios drop to values lower than those of the overall ratios. Similarly, in the Eagle Mountain section (Goodarzi, 1988), the variance ratios for the three groups are 2.6, 1.5, and 1.2. In general, it would seem that most Australian and Canadian coal sections should show variations in boron contents usually in the range of 1.5 to 3.5. However, the high variance ratios of 9.4 and 8.0 (Table 21) are in accordance with the varying conditions of salinity and/or secondary enrichment of boron.

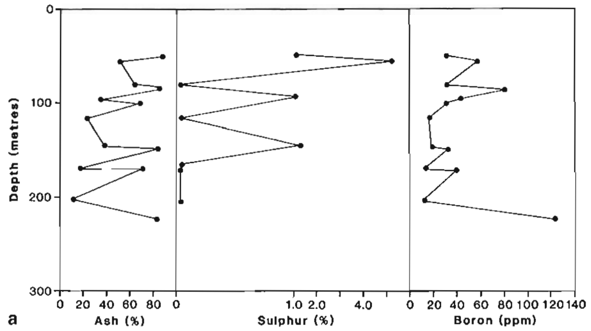
TABLE 21

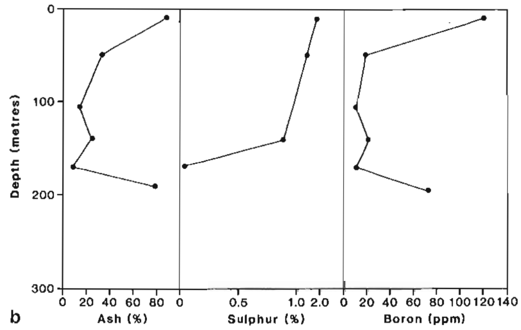
Variance ratios for boron contents in samples of coal from vertical sections of Canadian and Australian coals

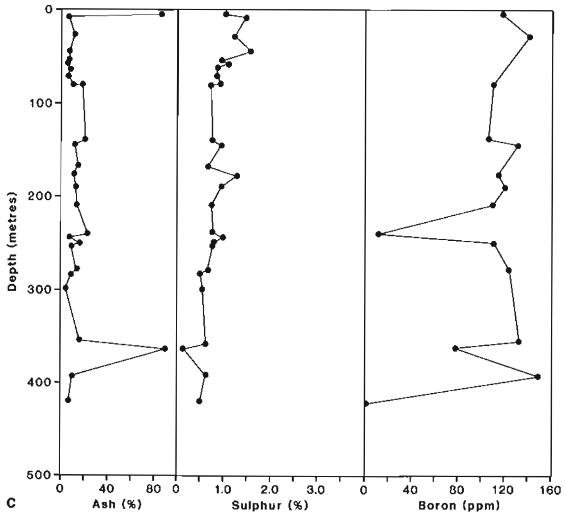
Location	Variance Ratio
Canada	
Hat Creek No. 1	2.6
Hat Creek No. 2	3.6
Fording Coal Mine	
Greenhills seams	2.7
Eagle Mountain seams	9.4
Blakeburn Mine	2.9
Byron Creek Collieries	8.0
Australia	
Illawarra Coal Measures (12 sections)	1.6–5.0
Newcastle Coal Measures (11 sections)	1.4–3.6
Tomago Coal Measures (4 sections)	1.5–3.6
Greta Coal Measures (9 sections)	1.8–3.8
Singleton–Muswellbrook District	1.9
Western Coalfield (2 sections)	1.8–2.5
Big Seam, Blair Athol (3 sections)	1.7–4.2

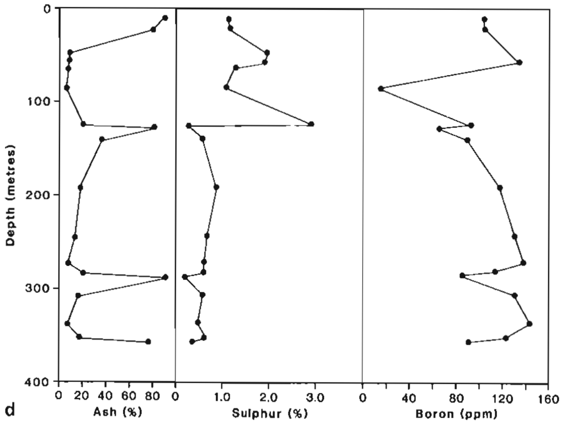
COMPARISON OF BORON AND SULPHUR AS INDICATORS OF THE ENVIRONMENT OF COAL DEPOSITION

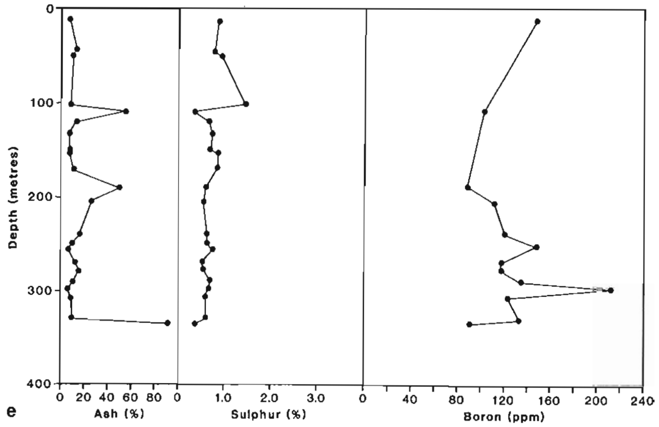
The sensitivity of boron as an indicator of the environment of deposition of coals is documented above. However, the significance of the sulphur content, which is often used as an indicator of depositional environment of coal, is more complex. Sulphur in peat and coal is present in the following forms: 1) as organic sulphur in the form of carbon- and oxygen-bonded sulphur (Altschuler et al., 1983; Casagrande, 1987), 2) in pyritic minerals, 3) as sulphates (Neavel, 1981; Cohen et al., 1984, 1987, 1989; Casagrande, 1985, 1987), and 4) as elemental sulphur (Altschuler et al., 1983; Casagrande, 1987).

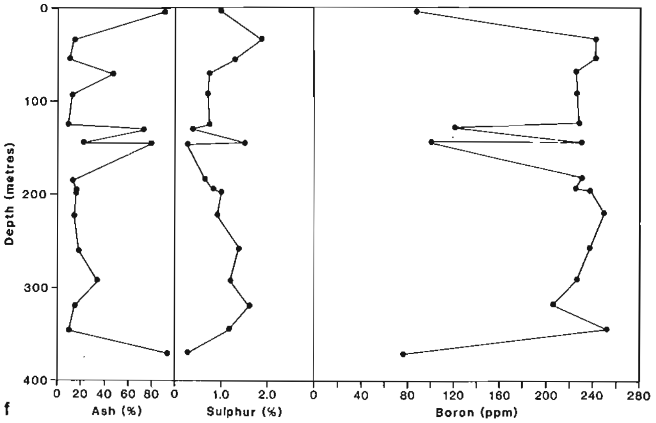












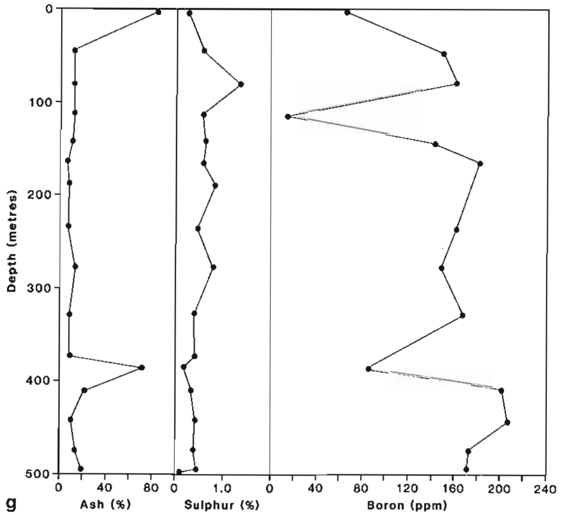


Figure 48. *In-seam variation of boron, sulphur, and ash contents for coal seams from Saskatchewan. (After Beaton, 1990.)* ***a.*** *Ferris Seam, South Fork;* ***b.*** *Ferris Seam, Shaunavan;* ***c.*** *Estevan Seam, Utility section;* ***d.*** *Estevan Seam, Boundary Dam section;* ***e.*** *Estevan Seam, Costello section;* ***f.*** *Hart Seam, Poplar River Mine section; and* ***g.*** *Estevan Seam, Bienfait section. See Figure 27 for the location of these seams.*

The total sulphur in coal is controlled by:

1. Sulphate availability (Casagrande et al., 1977; Cecil et al., 1982; Altschuler et al., 1983; Casagrande, 1985, 1987; Bustin and Lowe, 1987; Teichmüller, 1987). The majority of sulphur in brackish water coal originates from the activities of sulphate-reducing bacteria on seawater (Casagrande et al., 1977; Neavel, 1981; Altschuler et al., 1983; Styan and Bustin, 1983; Cohen et al., 1984; Casagrande, 1985; Given and Miller, 1985). Sulphate availability, therefore, is dependent on the presence of seawater.

2. pH of the peat/coal environment. Sulphate-reducing bacteria are most active and grow best in environments with a moderate pH (6.5–8) (Casagrande et al., 1977; Casagrande, 1987). The Eh and pH curves for the water column and peat in the Everglades Basin indicate a rapid depletion of oxygen downward and the formation of a slightly acidic environment in the upper part of the peat. In this regime Fe^{2+} and SO_4^{2-} are dominant and the formation of S^{2-} results in the generation of aqueous H_2S (Altschuler et al., 1983). Owing to limited oxidation near the surface of the peat, H_2S and polysulphides are formed. Sulphate-reducing bacteria flourish in this environment and pyrite is formed (Garrels and Naeser, 1958; Berner, 1970).

   The alkalinity of the seawater is critical, although water might also be alkaline in a carbonate terrain with little access to seawater.

3. Ferrous iron availability. This is controlled by transportation of clays containing adsorbed ferrous ions and other Fe-bearing minerals into the system.

4. Roof lithology. The total sulphur content of coal depends also on other factors such as roof lithology (Williams and Keith, 1963; Reidenouer et al., 1967; Gluskoter and Simon, 1968). In the Illinois Basin, roof shales deposited in fresh water are associated with <3.0% sulphur, and roof shales deposited in seawater are associated with >3.0% sulphur. Sulphur may also vary considerably within a coal seam. For example, the sulphur content of the Herrin No. 6 coal seam in the Illinois Basin is between 1.0 and 8.0%, depending on the location of sampling (Gluskoter and Simon, 1968). It is highest where marine shale (energy shale?) forms the roof of the seam (A.R. Cameron, pers. comm., 1992).

5. Epigenetic sulphur. The presence of epigenetic sulphur would also increase the total sulphur content of coal.

6. Peat bed geometry. Peat geometry, particularly the presence of domed peat (Cecil, 1988), may affect the sulphur content of coal.

Banerjee and Goodarzi (1990) have shown that the variation of total sulphur (as determined by ASTM procedures, 1978) versus ash content for the Mannville Group coals shows a wide scatter (Fig. 49). However, a closer examination of the data indicates that Suite 1 coals, which formed in a stacked shoreline sequence (Figs. 28, 49), have a much narrower range of total sulphur content (0.58–2.71%, daf) than Suite 2 coals (0.56–23.46%, daf), which formed in a lagoon/tidal flat environment (Figs. 29, 49). According to Casagrande (1987), the sulphur content of coal is related to the sulphur content of the ancestral peat. The total sulphur content of modern peat varies considerably; for example, peat in the Florida Everglades contains 0.1 to 10.0 per cent (Casagrande et al., 1977; Altschuler et al., 1983; Cohen et al., 1984; Casagrande, 1985; Given and Miller, 1985), while peat

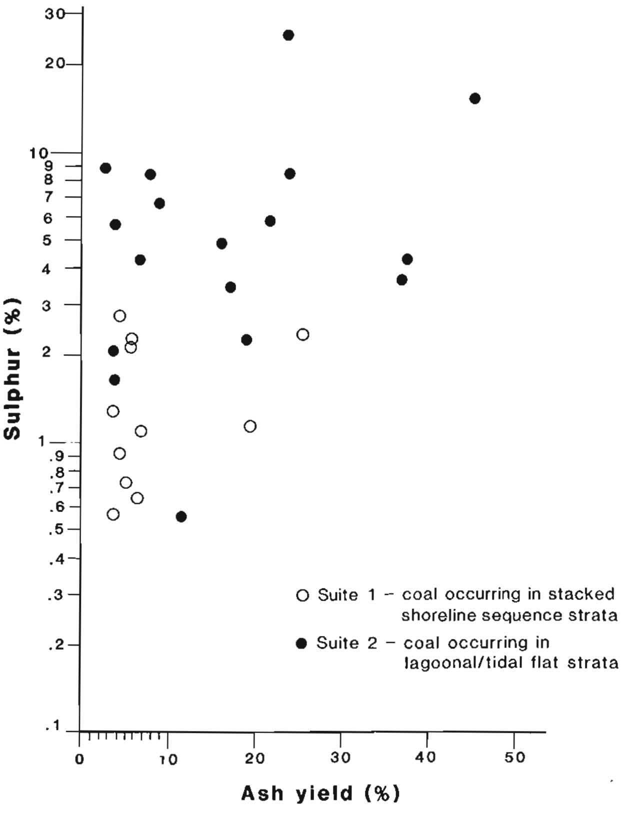


Figure 49. *Total sulphur content versus ash content of Mannville Group coals, plotted on semi-logarithmic paper.*

in the Fraser Delta, British Columbia, contains 0.48 to 3.03 per cent (Bustin and Lowe, 1987).

Banerjee and Goodarzi (1990) discussed the role of various controls (1 to 6 above) on the sulphur contents of the Mannville Group coals (Fig. 49). Based on sedimentological evidence they concluded that: 1) seawater was close by to provide sulphur; 2) the pH of the environment was slightly acidic; 3) clays containing Fe^{2+} were transported into the system, as suggested by the high ash content of some coals; 4) roof lithology was variable (marine shale for Suite 1 coals and lagoonal shale and tidal flat sandstones for Suite 2 coals; Fig. 29); 5) the presence of epigenetic sulphur cannot be proved; and 6) no data for peat geometry are available because most coals are thin (<1 m) and areally restricted.

The variation of sulphur versus ash does not show a positive correlation with the depositional setting of coal seams from Western Canada (Fig. 50).

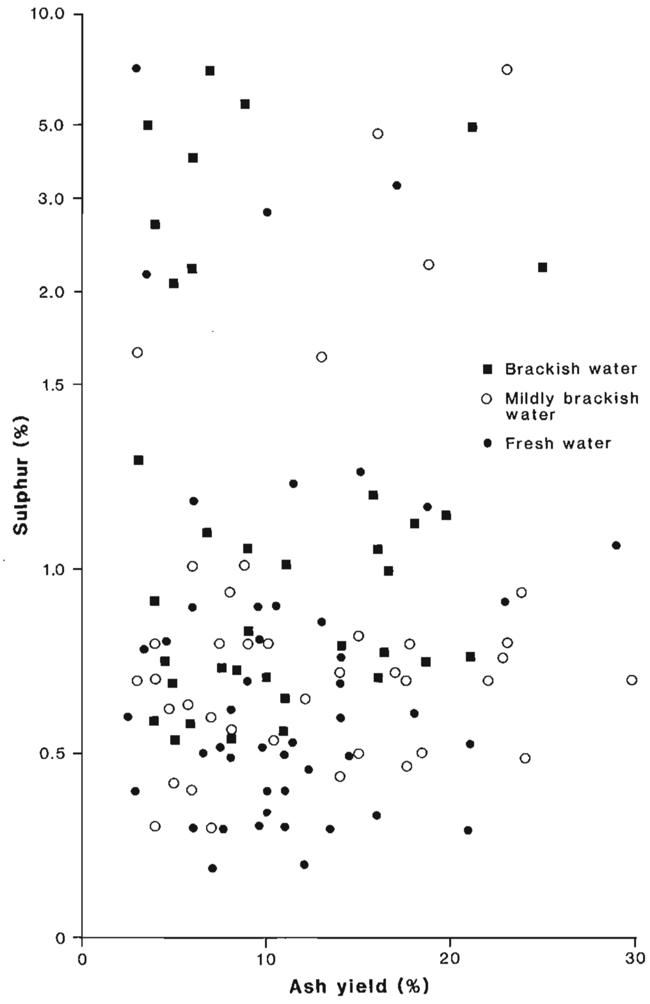


Figure 50. Total sulphur content versus ash content of western Canadian coals.

Boron/sulphur relationships

Studies of the geochemistry of coal indicate that both boron and sulphur contents of coals are indicators of paleosalinity, both elements increasing with increasing marine influence. A boron/sulphur plot for a group of coals, therefore, ideally should show a linear trend indicating a positive correlation.

The concentrations of boron versus sulphur for coals from Western Canada deposited in different depositional environments show an interesting relationship (Fig. 51). The coals are clearly divided into three groups. The separation of the coal samples into three groups is based on the varying content of boron related to different depositional environments (Goodarzi, 1987b, 1988). It is evident that sulphur does not show a systematic variation similar to that of boron with changes in the depositional setting from freshwater toward brackish water conditions.

A clear-cut trend for boron and sulphur content, versus each other and/or independently, has not been observed within coal seams. The variations in boron and sulphur contents are independent of each other for coal seams from Western Canada. [For example, in two sections of the same seam (no. 3) from the Vesta Mine in Alberta (Fig 52), and in Seam 2 from the

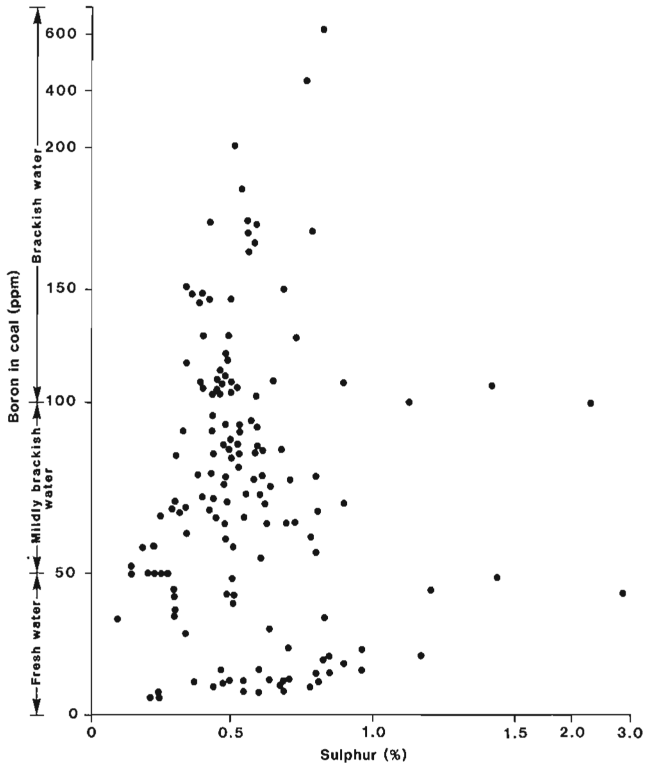


Figure 51. Variation in the boron versus sulphur contents of western Canadian coals.

Flathead Coalfield in British Columbia (Fig. 53)]. Sulphur shows a sudden increase in the middle of Seam 2 in the Flathead Coalfield (Fig. 53). This increase is not accompanied by an increase in either the ash and/or boron contents. A similar pattern is also evident in the variation of these two elements in Seam 7 at Drumheller (Fig. 54). In the brackish water coals from the Vesta Mine, Alberta (Fig. 52), the sulphur content stays within a narrow range, while the boron content fluctuates and has a wider range. A similar pattern is also evident in other coal-bearing strata, including those in the Drumheller area (Fig. 55) and the Mannville Group coals (Fig. 56) (Banerjee and Goodarzi, 1990). The variation of boron versus sulphur for coal seams in the Drumheller area is shown in Figure 55. Based on this relationship, it seems that the majority of these coal seams were influenced by brackish water, and are in mildly brackish (boron: >50–110 ppm) to brackish water (boron: 110–625 ppm) groups, and that only a few coal seams formed under freshwater conditions (Fig. 57). However, the sulphur contents in most of these coals

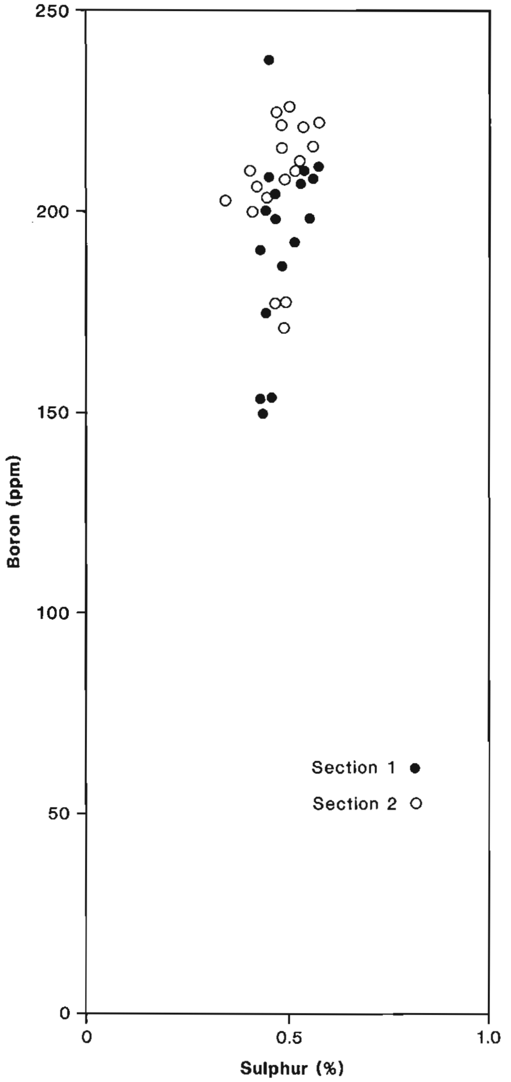


Figure 52. Variations in the boron versus sulphur contents of coals from two sections of Seam 3 at Vesta Mine, Alberta.

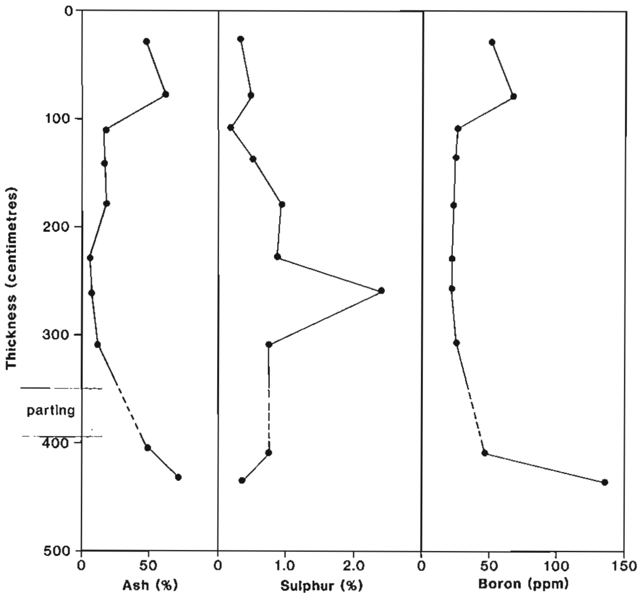


Figure 53. In-seam variation of ash, sulphur, and boron contents in Seam 2, Flathead Coalfield, British Columbia.

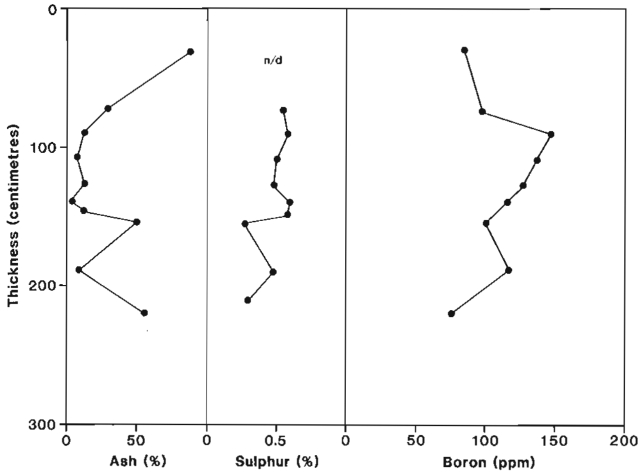


Figure 54. In-seam variation of ash, sulphur, and boron contents in Seam 7, Drumheller area, Alberta.

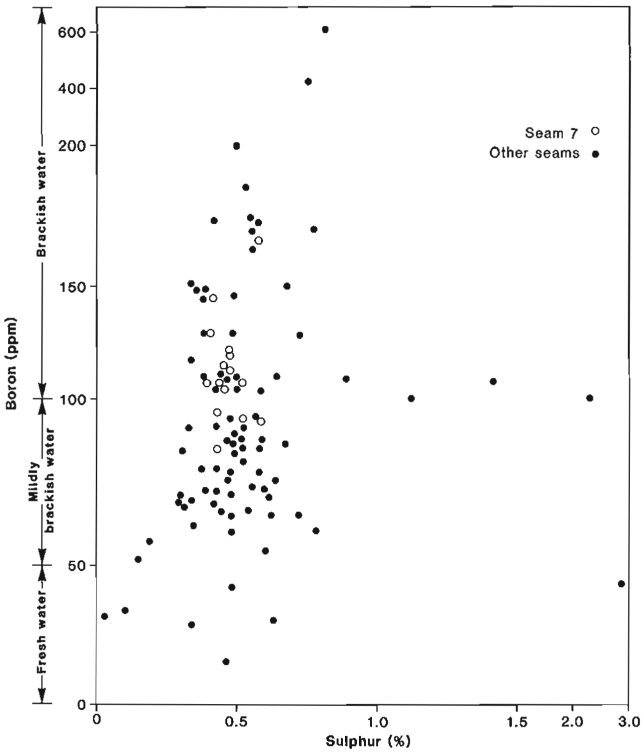


***Figure 55.** Variation of boron versus sulphur contents in coal seams of the Drumheller area, Alberta.*

are between 0.3 and 0.8 per cent, with some seams showing lower and/or higher values without any relationship to the depositional setting.

Cross-plots of the boron and sulphur contents of the coals from the Mannville Group do not show a positive correlation (Fig. 56). However, these cross-plots indicate that the coals belong to two distinct suites: 1) with a high boron content (256-1144 ppm) but low to moderate total sulphur (0.58-2.71%, daf), and 2) with a generally high but variable sulphur content (0.56-23.46%, daf) and low to moderate boron (18-247 ppm). The contents of boron and total sulphur in these two suites of coals appear to be related to the sedimentological setting of the coal; Suite 1 coals belong to "stacked shoreline" sequences, where each coal is directly overlain by transgressive marine sediments, which caused the anomalously high boron content in these coals. The reason for the low to moderate amount of sulphur in these coals is not clear. Suite 2 coals are encased within lagoon/tidal flat sediments and are not overlain by transgressive sediments. The fluctuating salinity in this type of environment produced the low to moderate boron contents of these coals. The stagnant, reducing conditions, and possibly the varying peat geometry, produced the generally high but variable total sulphur.

The boron/sulphur plot for Mannville Group coals shows two fields with a slight overlap, indicating two suites of coals, both showing a wide scatter (Fig. 56). The majority of samples, however, have total sulphur contents higher than one per cent and boron values higher than 50 ppm, which, along with the paleontological, sedimentological, and stratigraphic evidence, indicate that the coals were formed in paralic basins. The two fields shown in Figure 56 may also be explained by the probable presence of two separate linear trends, as shown by the dotted lines in this figure, each with a wide scatter, provided two off-the-trend samples are disregarded. Both trends then conform to the expected boron/sulphur relationship (concomitant increase with increasing paleosalinity) with two special conditions:

1. The relationship is not a simple linear correlation because the plot is on double logarithmic paper. The variables increase simultaneously but at vastly different rates. This could be explained in terms of degree to which paleosalinity affects these two elements.

2. The suite (Suite 1) with a higher boron content (indicating a stronger marine influence) shows a reduction in the range of sulphur present and vice

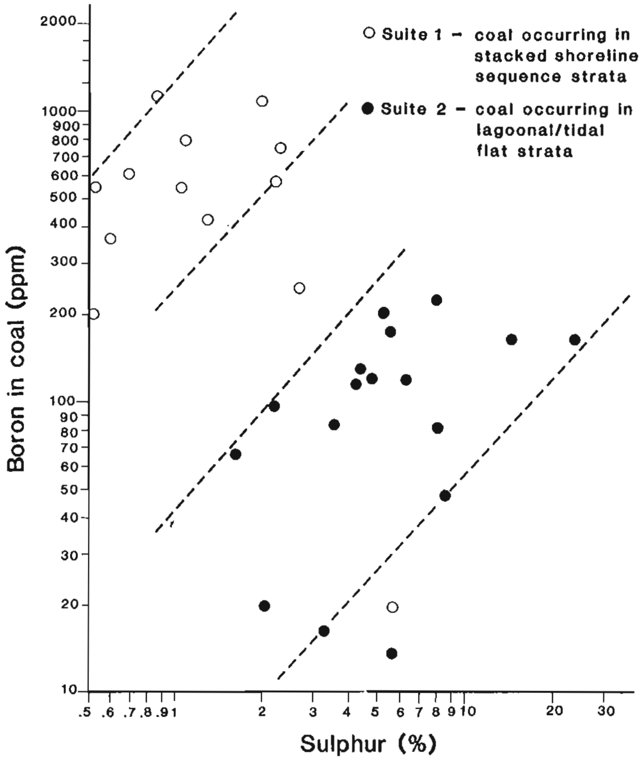


***Figure 56.** Variation of boron versus sulphur contents in coal seams in the Mannville Group, Alberta.*

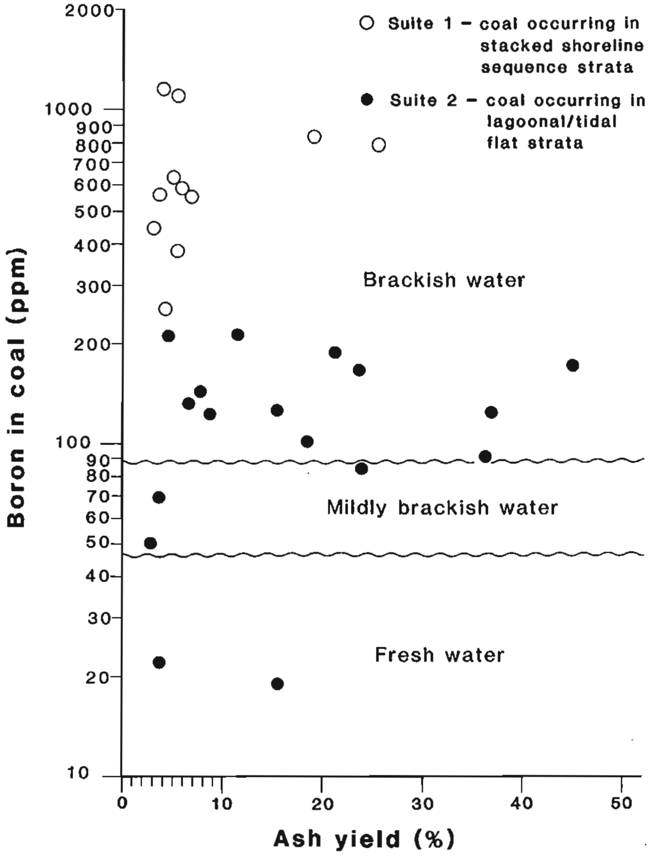


Figure 57. Depositional environments of Mannville Group coals, as determined from boron content.

versa. This is contrary to expectations and we have no clear explanation for this behaviour except to point out that some or all of the six factors that control the sulphur content of coals (mentioned above), may have influenced the two suites in contrasting manners.

The distinct behaviour of the two suites of coals shown in the diagram could be explained in terms of subtle differences in their sedimentological settings. The variable boron content in Suite 1 is perhaps partly due to the epigenetic input of boron from the transgressive sequences (Fig. 28) that directly overlie the coal. In contrast, the coals of Suite 2, which are encased in lagoon/tidal flat sediments, have variable but lower boron contents (Fig. 29). The variable sulphur content of Mannville Group coals, particularly those in Suite 2, is consistent with the total sulphur reported from single coal seams, such as Herrin No. 6 (Gluskoter and Simon, 1968). However, it is in contrast to the in-seam variation of boron and sulphur in Seam 3 at the Vesta Mine (Fig. 52), where sulphur content is low with a narrow range (0.34–0.68%), while boron content is high and has a wider range (150–295 ppm).

Sulphur contents vary considerably in modern, paralic, peat-forming environments (0.1–10.0%) (Casagrande, 1985, 1987) and even in freshwater peat (0.2–14%) (Cohen et al., 1989). Banerjee and Goodarzi (1990) attributed the wide variability of the sulphur content in Suite 2 coals from the Mannville Group (Fig. 49) to the back-barrier origin of these coals (Fig. 29), and compared the depositional environment of this suite of coals to those of modern coastal peats in Florida (Cohen et al., 1984) and Panama (Cohen et al., 1989). In the Panamanian example, the sulphur content of peat is generally very low in the central area but anomalously high in the vicinity of the edge that faces the sea or a brackish water bay. If the peat precursor to the Suite 2 coals was deposited in a similar environment, this may explain some of the very high sulphur concentrations in several samples of Suite 2 coals (Fig. 49) and the anomalously low boron (25 ppm) and relatively low sulphur (0.18%) contents in a coal layer from the Vesta Seam (Fig. 14).

Results from this study indicate that there is a strong relationship between boron content and the immediate superposition of marine strata, but the relationship between total sulphur content and marine influence is obscure. This study also suggests that suites of coals with known differences in their paleoenvironmental settings may give rise to distinct boron/sulphur trends. Such trends may, therefore, provide clues for the paleoenvironmental interpretation of coals whose origins are otherwise uncertain.

THE BORON CONTENTS OF HEAT-AFFECTED COALS

Natural burning of coal may start as a result of lightning strikes and bush or forest fires. Pearson and Creaney (1980) stated that the formation of meta-anthracite with a reflectance of 5.0% Ro_{max} at the Fording Coal Mine in British Columbia was due to lightning strikes, which started the burning of a weathered, low-volatile coal seam. Bustin and Matthews (1982) reported that the ignition of a high volatile bituminous (Ro_{max} 0.96%) coal seam, in the Lower Cretaceous Mist Mountain Formation in British Columbia, was due to a forest fire. This coal seam was 6 m thick; its upper 2 to 3 m were completely consumed by fire and the underlying 3 to 4 m were transformed into coke or remained unaltered.

A number of burning and/or heat-affected bituminous coal seams in Western Canada provide an opportunity to study the behaviour of boron during natural burning. Two burning coal seams, one at Coalspur, Alberta, and the other at Aldridge Creek, British Columbia, were examined. The properties ascertained for these seams are compared with those of a coal seam from the Fording Coal Mine, altered as the result of a lightning strike.

Burning coal seams

Coalspur, Alberta

The coal seam at Coalspur, Alberta (Fig. 58), has been burning since 1922 (Fryer, 1981). The rank of this coal seam is high volatile bituminous (Ro_{max} 0.70%).

Goodarzi (1988) divided this burning coal seam into two zones, an oxidation-combustion zone and a distillation zone, based on the petrological variation of coal and heat-affected residues (Fig. 59). Near the surface, the oxidation zone contains chars showing oxidation rims and fractures. The fractures are filled with fluorescing hydrocarbon material formed by the thermal cracking of coal macerals. Elemental sulphur and coal tar line the vent and loose fragments lie close to the vent on the surface. XRF analysis of these loose fragments indicates a high sulphur content (48 wt%) of

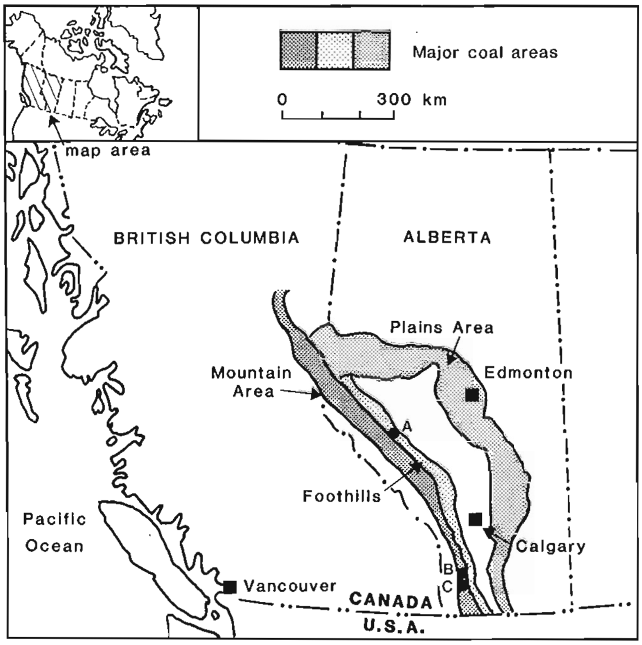


Figure 58. *Map of Western Canada, showing the locations of burning and heat-affected coal seams. A, Coalspur; B, Aldridge Creek; C, heat-affected coal seam at Eagle Mountain, Fording Coal Mine.*

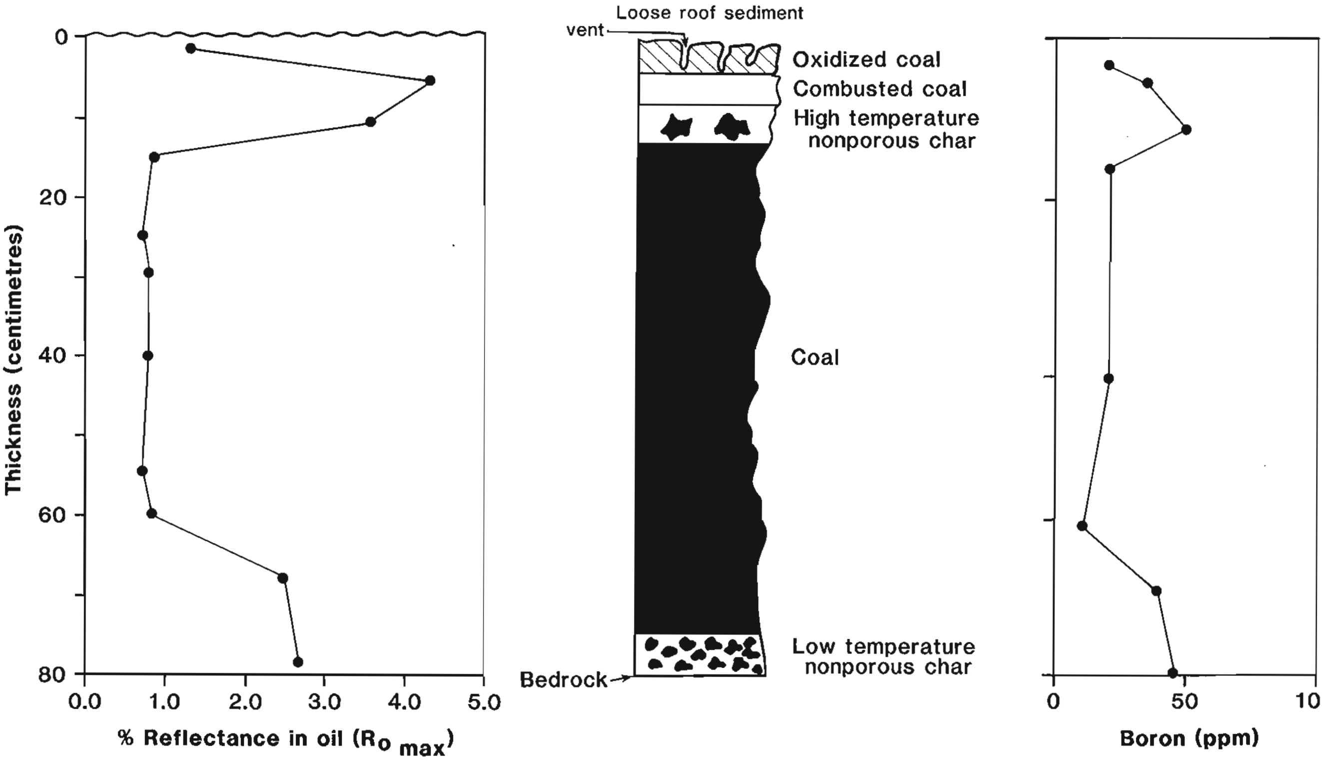


Figure 59. *Stratigraphic section of a burning coal seam at Coalspur, Alberta, with reflectance and boron content profiles.*

orthorhombic structure (Goodarzi, 1988). Boron content in the oxidation zone is 18 ppm. The char in the deeper part of the oxidation zone was combusted at 700°C, has a carbonized matrix and burnt rims, and a boron content of 32 ppm.

The distillation zone extends throughout most of the coal seam. Chars are mostly in the pre-carbonization stage, except those immediately below the combustion zone or near the base of the seam, which are carbonized (Goodarzi, 1988). The boron content of the carbonized samples is 43 ppm (Fig. 59).

It is evident that, despite the severe molecular structure changes in the coal, brought about by oxidation, combustion at a high temperature (700°C, Goodarzi, 1988), and carbonization, there is very little variation in the amount of boron in this coal seam (Goodarzi, 1990). The boron content increases from 19 ppm for the unaltered coal to 43 ppm for coal carbonized at 700°C (Fig. 59).

Aldridge Creek, British Columbia

Miard (1945) reported the ignition of a coal seam near the south bank of Aldridge Creek, British Columbia, believed to have been caused by a forest fire that swept through the area in 1936. Bustin and Matthews (1985) presented the history, a brief petrological study, and the mechanism of combustion for this burning coal seam. They noted a 10 cm thick area of coke underlying the burnt coal seam and estimated that temperatures during combustion were in the order of 1100°C or higher. The coal is a medium volatile bituminous coal (Ro_{max} vitrinite = 1.1%), belonging to the Jurassic to Lower Cretaceous Mist Mountain Formation of the Kootenay Group. The seam, originally up to 6 m thick, has been reduced to 1.2 m of heat-affected residues, and its outcrop forms a collapsed cliff of melted rock, mainly sandstone. At the time of field observations in June, 1983, active combustion was taking place near the mouth of a west-draining gully.

Three zones, namely combustion, distillation, and unaltered coal were detected in a partly combusted and coked coal seam at this locality (Goodarzi et al., 1988). Combustion had taken place in the uppermost part of the coal seam, immediately below the melted roof rock, at a temperature of about 1100°C (Bustin and Matthews, 1985). The only evidence of combustion was the presence of coke showing oxidation rims (Goodarzi et al., 1988). The distillation zone encompasses most of the coal seam; different stages of carbonization are evident in the samples from this zone, which has a coke subzone at the top and a pre-carbonization subzone at the base. An unaltered zone consisting of carbonaceous shale is present at the base of the coal seam. Figure 60 shows the boron contents of different zones within the altered coal seam. The boron content of the partly combusted char at the top of the seam is generally low (18 ppm). This unit is underlain by the three coke zones (34-37 ppm) and a semi-coke zone (18 ppm). However, the semi-coke subzone at the base of the seam has the highest concentration of boron (120 ppm) (Fig. 60) and contains chloroform-methanol (87/13 azeotrope) soluble hydrocarbon. The hydrocarbon is a pitch-like, viscous material, similar to coal tar pitch. This material was formed by the

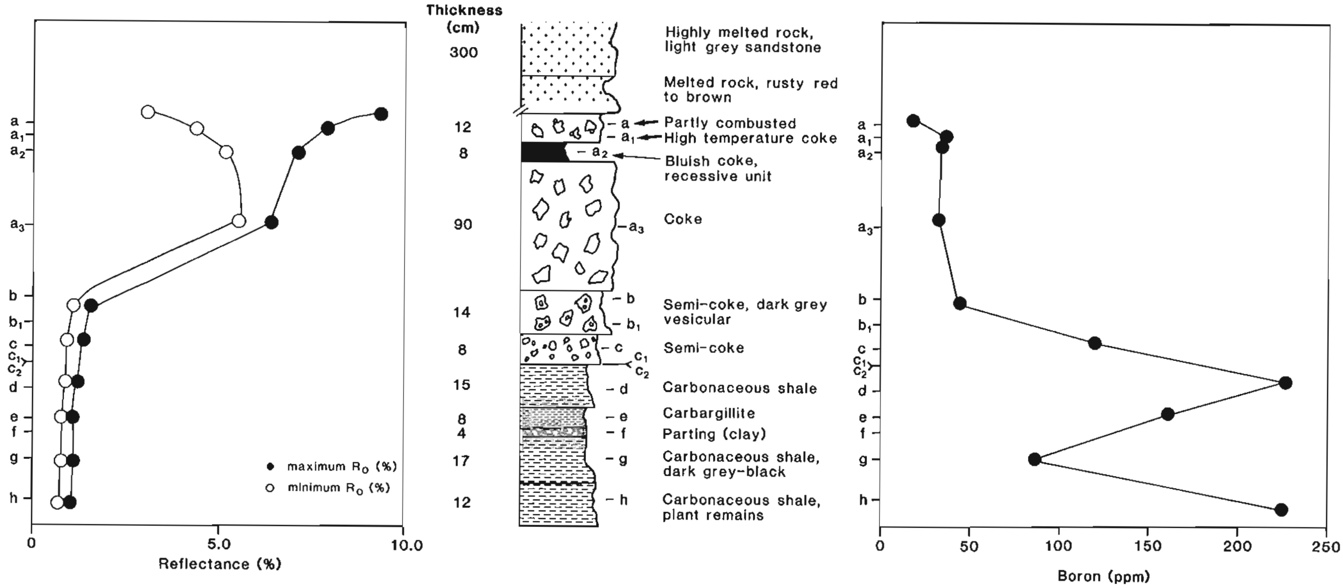


Figure 60. Stratigraphic section of a burning coal seam at Aldridge, British Columbia, with reflectance and boron content profiles.

carbonization of coal in the upper part of the coal seam and in the coke zone, and migrated downward, filling the devolatilization vacuoles of the semi-coke (Goodarzi et al., 1988).

The high boron content of this semi-coke indicates that boron becomes concentrated in the liquid as well as gaseous carbonization byproducts during the natural heating of coal. The coal tar migrated downward, away from the source of heat to the cooler area of the coal seam (Fig. 60). The aliphatic and alicyclic side chains in the coal structure are the main components of the volatile matter and tar (Berkowitz, 1967), and the concentration of boron in the tar may indicate an association of boron with organic components of this coal; for example, with aliphatic and alicyclic side chains (hydroxyl or ester groups) in the coal structure.

Thermally altered coal resulting from a lightning strike (Fording Coal Mine)

The high volatile bituminous coal of Seam 15 in the Eagle Mountain section on the east side of Eagle Mountain, at the Fording Coal Mine (Fig. 61), has been altered by a lightning strike (Pearson and Creaney, 1980). Rank changes have been measured laterally over a strike distance of 7.5 m, and range from Ro_{max} 1.24 to 7.1%, corresponding to a rank gradient of 0.78% Ro per metre (Pearson and Creaney, 1980; Goodarzi and Gentzis, 1990).

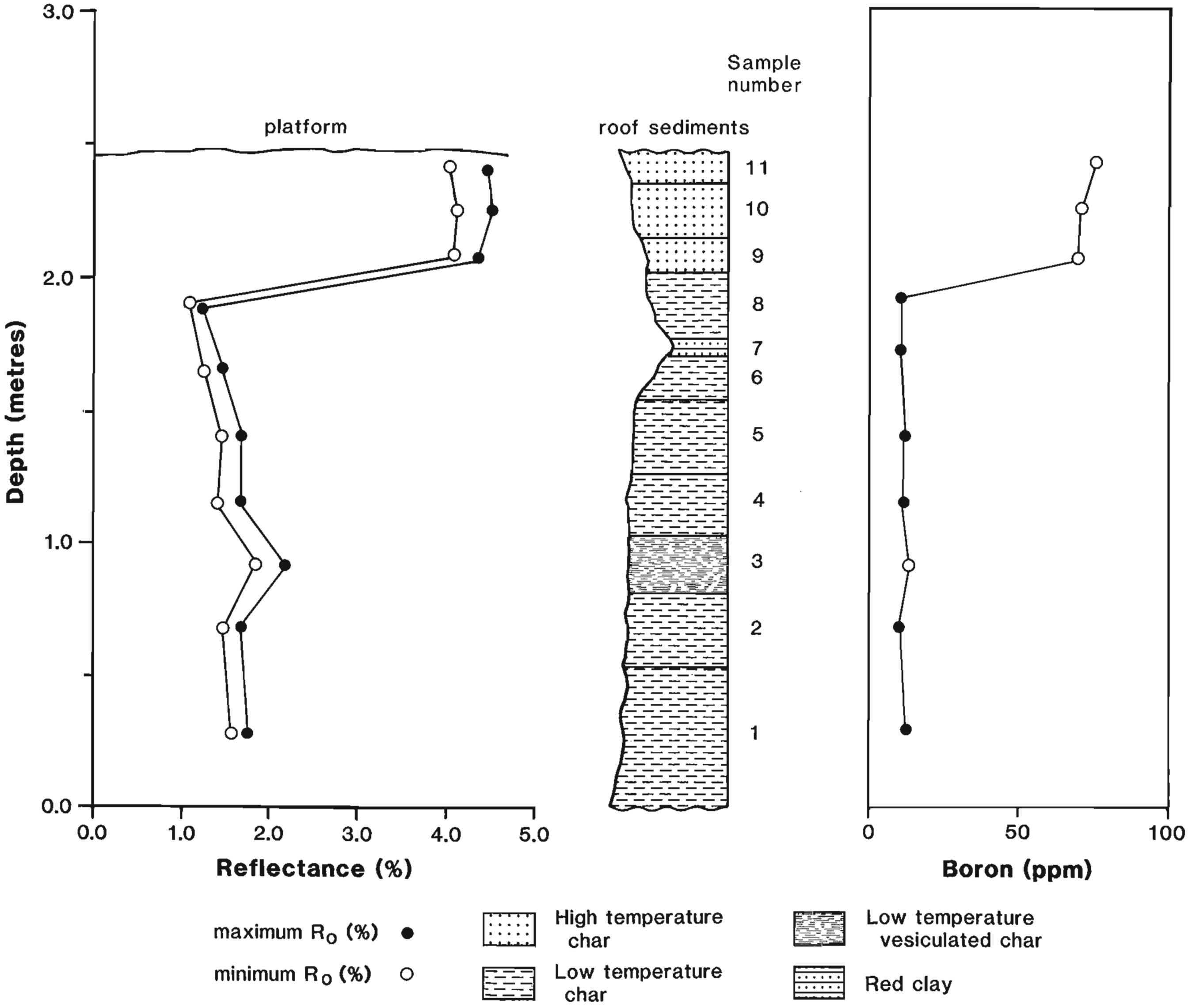


Figure 61. Stratigraphic section of a heat-affected coal seam at the Fording Coal Mine on Eagle Mountain, with reflectance and boron content profiles.

Petrologically, unaltered to extremely altered vitrinite [showing nongranular (basic) anisotropy], mosaic-textured liptinite, and pyrolytic carbon are the most abundant components. The limited presence of mosaic texture in the vitrinite is an indication that the coal seam may have been weathered prior to being heat-affected.

Evidence points to localized temperatures as high as 1000°C, which could have been caused by a lightning strike. Goodarzi and Gentzis (1990) determined the reflectance profile of this heat-affected coal seam (Section E). Samples from this section were analysed for their boron content.

Figure 61 shows the vertical vitrinite reflectance and boron variation for the samples from Channel E (Goodarzi and Gentzis, 1990). The variation of $\%R_o$ with depth indicates that the samples in the top part of the seam (samples 9–11) have undergone a high degree of thermal alteration and are coked. Samples 1 to 8 were less affected by the heat, because of the distance that separated them from the source of the heat, which, unlike the situation at Aldridge Creek and Coalspur (heating over a long period of time) was more of a shock heating phenomenon (high temperature, fast rate of heating, and a shorter duration of heating) in which heat was transmitted for a shorter distance (Fig. 61).

The vertical variation of boron concentrations in the samples indicates that a certain amount of boron enrichment took place near the source of the heat. This heat-affected coal seam is the lateral extension of Seam 15 in the Eagle Mountain section at the Fording Coal Mine. The boron content of Seam 15 is 10 ppm (Goodarzi, 1988), which is consistent with the boron content of the low-temperature chars (16 ppm) and the sedimentary partings (10 ppm) (Fig. 61).

Summary

A comparison of the results for the variation of boron in three heat-affected coal seams indicates that the behaviour of boron during the natural heating/burning of coal is partly dependent on the temperature of the system and the nature of the process. The boron content of chars and coke, compared to that of the coal, is lower in the oxidation/combustion zone, possibly due to volatilization of boron. There is some boron enrichment in the carbonization zone. The high boron content of semi-coke containing coal tar pitch indicates that boron became concentrated in the liquid fractions of the carbonization byproducts during the natural heating of the coal.

THE DISPERSION OF BORON FOLLOWING COMBUSTION

During the combustion of pulverized coal in a modern power station, boron is released and redistributed in the bottom ash, fly ash, and fine fly ash, some of which reaches the atmosphere with the stack gases. Australian bituminous coals have produced bottom ash with 40 to 80 ppm boron and fly ash with 20 to 400 ppm boron (Swaine, 1981). Since boron is a relatively non-volatile element, boron is not concentrated significantly on fine fly ash particles. The boron emitted into the atmosphere is mainly distributed by wind, and ultimately most of it is deposited either by dry or wet deposition. An in-depth investigation of the deposition of trace elements in an area around Wallerawang Power Station, about 120 km northwest of Sydney, NSW, was carried out over a period of three years (Swaine et al., 1984a). Initially there were 17 sampling locations, situated in different directions, 1.5 to 40 km from Wallerawang. The method of collecting material deposited from the atmosphere involved the use of *Sphagnum* moss, held in flat, fine-mesh envelopes, which were mounted two metres above ground on aluminum stakes. Sampling was carried out at three-month intervals. Results showed that the deposition of boron over a three-year period ranged from <0.01 to 13 mg m^{-2}, with a mean of 1.5 mg m^{-2}, per three months. The detailed results showed that most boron was deposited near the power station, within a radius of about 5 km, with boron concentrations decreasing with distance from the power station.

The major sources of boron deposited from the atmosphere were fly ash (30–100 ppm boron) and dust (soil- and rock-derived particles). A survey of the soils in the area around Wallerawang showed contents of 10 to 80 ppm boron, with a mean of 45 ppm. Examination of samples of deposited material, using scanning electron microscopy, showed the presence of spherical particles (fly ash) and angular particles (soil or rock). It is clear that the power station emissions are a major source of boron in the nearby area (2 km radius), while the areas farther away are dominated by soil and rock particles. Comparison of the amounts of boron from atmospheric deposition with those from rock weathering, litter decay, and fertilizers (Table 22) show that the dominant source is litter decay, but significant amounts are deposited within the 2 km zone around the power station. However, the amounts of boron deposited near Wallerawang are not regarded as detrimental, especially as most plants require boron for healthy growth. Another way of assessing the deposition of boron in the area around Wallerawang Power Station is to consider results for three-month periods over three years (Table 23). Even close to the power station these amounts of boron measured represent very small additions to surface soils.

The dispersion and deposition of boron from the stack gases depend on several factors, namely stack height, windspeed (low level and high level), wind direction, atmospheric stability (mixing conditions in a vertical plane in the atmosphere), rainfall, and the nature of the terrain. Wind conditions are probably the prime factor in the distribution of trace elements, including boron, emanating from stacks, but atmospheric stability is also important at certain times. In the Wallerawang area the results of deposition were in keeping with the prevalence of southwesterly, westerly, and northwesterly winds. A proper study of the deposition of boron in the environs of a power station is really a space–time study; that is, the patterns of deposition depend on the location of the sampling locations and on the time of year.

TABLE 22

Annual deposition of boron (as mg m^{-2}) near a coal-fired power station at Wallerawang, NSW, Australia, compared with annual inputs from rock weathering, litter decay, and fertilizers (Swaine et al., 1989).

Distance from Power Station (km)	Deposition	Rock weathering*	Litter decay*	Fertilizers**
1.8	23.0	0.27	55	1.5
6.6	5.6	–	–	–
27.4	1.5	–	–	–

*From Bowen (1979) **Based on data in Swaine (1962b)

TABLE 23

Deposition of boron (as mg m^{-2}) near a coal-fired power station at Wallerawang, NSW, Australia. Range of three-month results over a three-year period

Distance from Power Station (km)	Range of values	Mean values
1.8	1.7–12.5	5.8
6.6	0.25–24.0	1.4
15.3	0.4–1.6	0.92
27.4	0.15–0.55	0.33

SOME ENVIRONMENTAL ASPECTS OF BORON IN COAL

In this context, the word 'environmental' is used in its popular connotation, namely, possible effects, commonly thought to be only adverse, on soils, water, and air. It is essential to bear in mind that trace elements, including boron, may have both useful and deleterious effects, depending on several factors, including concentration, the form of the element (speciation), pH/Eh conditions, and the types of vegetation involved. Although boron has been rated as an element of "greatest concern" (PECH, 1980), a more appropriate assessment is that it is an element of "prime environmental interest" (Swaine, 1982), especially in terms of the growth of plants. The fate of boron during the combustion of coal in power stations has been referred to above. However, what happens to boron during mining, preparation, and storage of coal should not be overlooked. These matters have been discussed by Swaine (1980), who pointed out that "the consideration of weathering and the dispersal of trace elements should be seen in terms of the geochemical cycle, a dynamic system."

During underground mining there should not be adverse effects from boron in mine waters. However, surface mining, which involves stockpiling of overburden with consequent increased oxidation, may lead to leachates containing enough soluble boron to affect nearby waters. A similar situation could occur with washery rejects, and in bottom-ash/fly-ash disposal areas.

Consideration should be given to the possible effects of boron on vegetation used in reclamation projects following coal mining. Although plants need boron for healthy growth, different amounts are required by different species, and this also means that tolerance levels for boron are variable. The margin between essentiality and toxicity is small (Hem, 1970). In such cases, it is worthwhile doing some field trials with particular plants. The same approach should be used before adding fly ash to soils in order to ascertain whether the added boron would be useful or in excess of requirements, keeping in mind the relevance of rates of application of fly ash, soil conditions, and plant species (Elseewi et al., 1981). It may be possible to reduce the availability of boron by growing boron-tolerant species and harvesting them before growing plants with a low tolerance for boron (Swaine, 1980).

It cannot be assumed that an increase in the availability of boron to plants — by an increase in solubility for example — is necessarily harmful to all plants, and it may be beneficial. As Swaine (1989) pointed out, "Before making statements about adverse environmental effects, soil and plant experiments should be carried out. Then a proper assessment can be made." The idea of boron being toxic, *per se*, is not sound. Such a judgement is unjustified unless the toxicity has been established for a specific situation.

CONCLUDING REMARKS

The boron content of most coals is between 5 and 400 ppm, and it is usually predominantly organically-bound, although variable amounts are also associated with the mineral matter, mainly in clays and as tourmaline.

The detailed studies of boron in Canadian coals indicate that there is either no relationship or a very complex relationship between boron content and the rank of coals from the same age and geological setting; for example, high to medium volatile bituminous coal, Ro_{max} 0.85 to 1.35%, or medium volatile bituminous coal to semianthracite, Ro_{max} 1.30 to 2.50%. However, the lower rank coals (subbituminous to high volatile C/B) are more susceptible to secondary boron enrichment.

The variation of boron content with ash content for Canadian coals of different ages (Middle Devonian to Oligocene–Eocene) indicates that the boron content of coals is not governed by the age of coal. For example, coals from Hat Creek, British Columbia (Oligocene to Eocene); Mount Allan, Alberta (Upper Jurassic); Hoidahl Dome, Yukon Territory (Carboniferous); and Melville Island, arctic Canada (Devonian) all have boron contents of <50 ppm, indicating that boron is related to their freshwater setting and not to their age. There is some evidence, from Canadian coals, of a variation in boron content with maceral content, particularly as related to the lower boron content in inertinite.

An interesting use of boron contents in coals is the estimation of the degree of marine influence during deposition of the ancestral peat. Coal is preferred to clay partings for assessing varying degrees of marine influence; that is, degrees of salinity of swamp waters during the early stages of coalification.

After a reappraisal of earlier work (Swaine 1962a, 1971), and on the basis of later work on Australian coals and recent work on Canadian coals by Goodarzi and co-workers, it is proposed that the following ranges of values indicate the various degrees of marine influence on coals:

1. Up to 50 ppm boron: *freshwater-influenced coals*

2. 50 to 110 ppm boron: *mildly brackish-water-influenced coals*

3. >110 ppm boron: *brackish-water-influenced coals.*

The boron content of coal is either primary, and due to the influence of the environment of deposition, as supported by independently determined sedimentological evidence, or is due to secondary enrichment. Higher boron contents in coals deposited in freshwater environments are usually due to secondary enrichment of this element, related to the occurrence of evaporite deposits and diapirs, extensive fault systems associated with the coalfields, and the activity of groundwater. The boron content of coal seams is sensitive to the environment of deposition of the original peat and remains relatively stable and within the range of values designated for each depositional setting. However, it may also show variation within a given depositional setting, occasioned by changes (such as pH) within that depositional setting and also by boron enrichment from a secondary source.

On the basis of a detailed examination of lateral changes over 100 km in a coal seam from the Western Coalfield, NSW, Australia, the Variance Ratio for boron (the ratio of the maximum to the minimum value) was found to be 2 for 96 per cent of the 130 samples analysed. About 50 Australian and Canadian vertical sections show variance ratios for boron of between 1.5 and 3.5 for about 90 per cent of the sections.

Boron shows little lateral variation for Canadian freshwater to brackish water coals over a distance of up to 14 km. The low variance ratios for boron in Canadian coals indicate the lateral consistency of boron values for these coal seams, and the stability of their depositional environments. However, the lateral variation of boron in a coal seam may not necessarily indicate variation in the depositional setting (primary boron enrichment), but secondary enrichment due to the post-depositional influence of brines percolating through the bed. The Variance Ratio in this case is relatively higher than the lateral variation for the primary-enriched coal seams.

Comparison of the results for the variation of boron in heat-affected coal seams indicates that the behaviour of boron during the natural heating/burning of coal is dependent on the temperature of the system and the nature of the process. The boron content of chars and coke, as compared to that of the coal, is lower in the oxidation and combustion zone, possibly due to volatilization of boron.

There is some enrichment of boron in the carbonization zone. The high boron content of semi-coke containing coal tar pitch indicates that boron is concentrated in the liquid fractions of carbonization byproducts during the natural heating of coal.

During the combustion of coal, boron is redistributed into the bottom ash, fly ash retained by particle attenuation (usually electrostatic precipitation), and fine fly ash, and some of this boron reaches the atmosphere with the stack gases. Hence, coal burning is a source of boron in the atmosphere, although studies in Australia suggest that, in most cases, it may have little detrimental effect on vegetation, even in the close environs of power stations.

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