Research

Rank variation, coalification pattern and coal quality in the Crowsnest coalfield, British Columbia

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ABSTRACT

A rank-map of Crowsnest coalfield, showing the distribution of the bituminous coal measures and the locations of major structures, has been produced from vitrinite reflectance measurements on over 560 coalsamples. The timing of coalification in relation to these major structures has also been determined.

In the west-central portion of the coalfield a complete stratigraphic succession of coal measures which rides on major thrust surfaces is all of high-volatile bituminous rank, but despite the structural discordance no break in rank is discernible across these structures. The thrust faults therefore predate much of the coalification.

Three major valleys expose cross sections of the folded coal measures and in each an increase in vitrinite reflectance is demonstrable as individual seams are tracedfrom ridge crest to valley floor. Thus, in these sections, a significant amount of coalification post-dates folding. The proportion of this post-folding coalification is found to increase toward the south of the coalfield.

A late gravity-fault, exposed along the east crop of the coalfield, places high-volatile coal-bearing successions in contact with low-volatile coal and demonstrably is a reactivated thrust fault. Coalification at this locality occurred between these two different ages of faulting.

The variations in rank and the subtleties of the coalification pattern have, together with systematic changes in the maceral composition of coal seams, had a profound effect on coal quality in the coalfield. Coking coals with a variety of properties occur together with some coals that have no caking capacity.

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Keywords: Coal preparation, Coalification, Rank gradients, Stratigraphy, Coal quality, Structural setting, Crowsnest coalfield.

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Paper reviewed and approved for publication by the Coal Division of CIM. CIM Bulletin, September 1985

Introduction

The East Kootenay coalfields of southeastern British Columbia comprise three structurally separated remnants of the Jurassic-Cretaceous Kootenay Group (Fig. 1). Crowsnest coalfield, which is pear-shaped, is about 50 km long, 20 km wide and occupies a structural depression referred to as the Fernie Basin. The Sparwood operations of Westar Mining Limited are located at the north end of the coalfield.

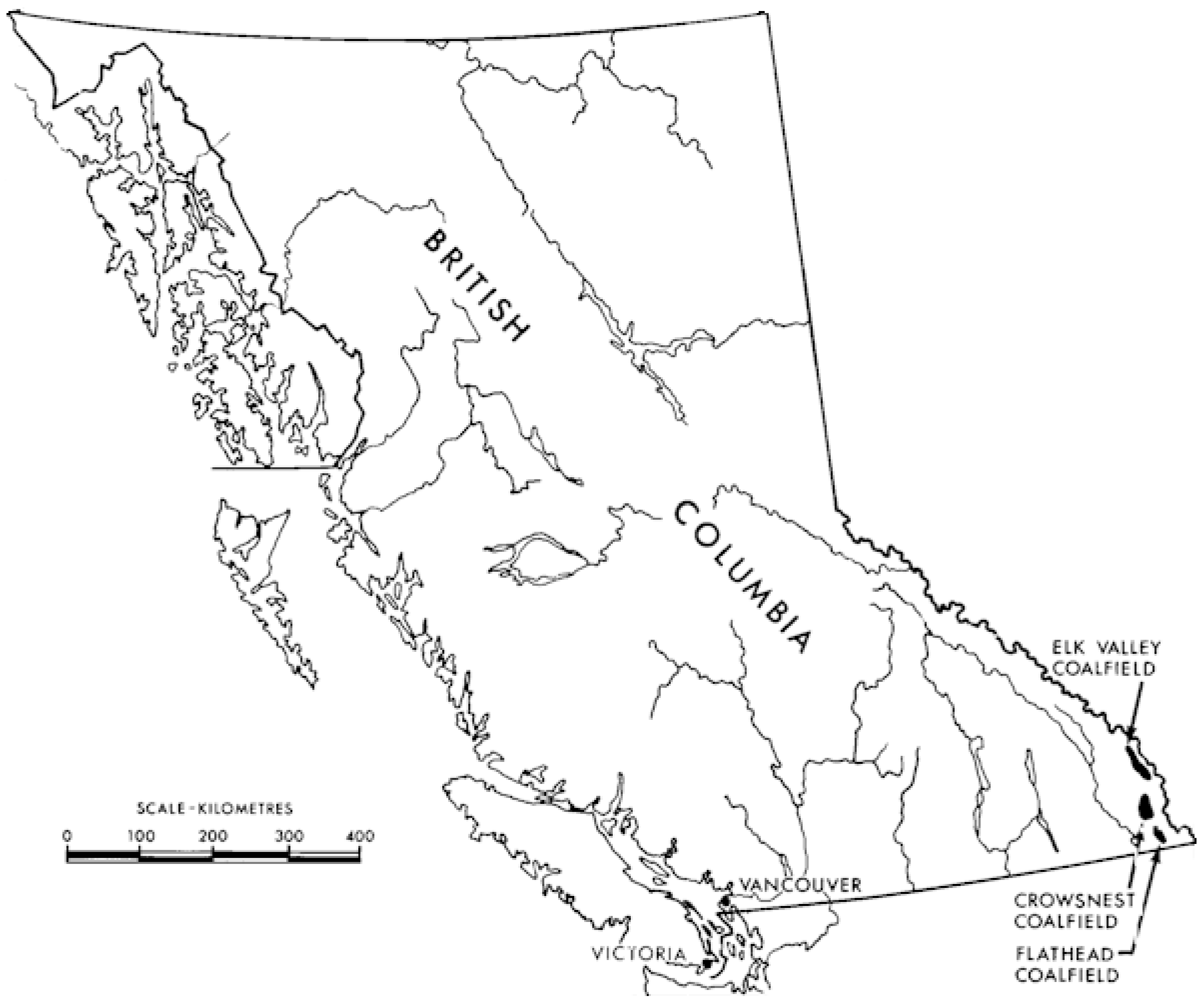

Figure 1: Locations of the Crowsnest coalfield, British Columbia.

The general geology of the coalfield has been described by Newmarch (1953) and Price (1962, 1965). The sedimentology and stratigraphy of the Kootenay Group has most recently been described by Jansa (1972) and Gibson (1977 and 1979). The only published coal petrographic work is that by Cameron (1972).

Stratigraphic and Structural Setting

Economic coal seams in the East Kootenay coalfields are restricted to the non-marine Mist Mountain Formation of the Kootenay Group (Gibson, 1979). The coal measures, which are about

560 metres thick, contain 5 - 10% coal in seams that range in thickness from centimetres to in excess of 15 metres.

Mist Mountain Formation is underlain by the basal sandstone of the Kootenay Group (Morrissey Formation, [Gibson, 1979]) and is overlain by the Elk Formation (Gibson, 1979). A resistant, coarse-clastic facies, here referred to as "Elk conglomerate", generally marks the base of the Elk Formation in Crowsnest coalfield.

The East Kootenay coalfields lie on the Lewis Thrust plate, within the Front Ranges of the Rocky Mountains. They are characterized by early compressional structures (folds and thrust faults) and late extensional structures (normal faults) (Bally et al., 1966). Some of the early thrust faults were later reactivated and formed the locus of normal fault movement.

Significance of Rank Distributions

The areal distribution of coal rank, the relative timing of coalification and tectonic events, and comparison of rank gradients within the study area are the fundamental tools in determining coalification patterns.

Timing of Coalification. The principles involved in determining the relative age of coalification with respect to deformational events have been outlined by Teichmuller and Teichmuller (1966). Figure 2 summarizes these principles in cross section, displaying two extreme cases (coalification all pre-folding and coalification all post-folding) and an intermediate case.

A. Coalification all pre-folding. In this case, lines of equal rank lie parallel to bedding and both are subsequently folded together. The vitrinite reflectance ($R_o$max) of an individual seam remains the same regardless of elevation, whereas the rank of successively deeper seams increases in any vertical drillcore section.

B. Coalification all post-folding. In this example, isorank lines cross the previously folded bedding. The vitrinite reflectance of individual seams therefore, increases down-dip at the same rate as successively deeper seams increase rank in a vertical drillcore section.

C. Syntectonic coalification (or some pre- and some post-folding). In this instance, the coalification lines are seen to dip in the same direction as the bedding but at a shallower angle. The vitrinite reflectance of individual seams increases down-dip but the rate of reflectance change is greater between successively deeper seams in a vertical drillcore section.

D. Faulting. Determination of timing of coalification with respect to faulting follows similar reasoning. In the case of coalification which is pre-faulting a jump in reflectance values will occur across a normal fault and a repetition of values will occur at a thrust fault. If coalification post-dated faulting, no disruption of isorank lines takes place across the fault plane despite the obvious stratigraphic break that marks the fault trace.

Hacquebard and Donaldson (1970) defined **rank gradients** in folded rocks in terms of reflectance change per 100 metres elevation ($_o$ R_o/lOOm). They derived two distinct gradients, one representing rank change in a stratigraphic (ideally, vertical) section and the other representing down-dip reflectance change within individual seams. The former was termed **Total Rank Gradient** and the latter, the **Down-Dip Rank Gradient**, was shown to represent coalification which occurred after folding. The %R_o-vs-Depth graphs in Figure 2 demonstrate these principles.

In the case where coalification pre-dates folding there is no variation in reflectance of individual seams with increasing depth and seam gradients parallel the ordinate in R_o/Depth diagrams (Fig. 2A). Such is the case in the Ruhr coalfield of West Germany where, because of this fact, correlation of individual seams can be made confidently on the basis of Rmax (Teichmuller and Teichmuller, 1966). Where coalification post-dates folding, however, the changes in reflectance of both individual seams and stratigraphic sections are the same, depending wholly on the depth, and rank gradients parallel each other in R_o/Depth diagrams (Fig. 2B). Such a situation exists in the Sydney coalfield of Nova Scotia, where rank of coal increases with depth, and surface exposures of coal, in an area of only gentle relief, are essentially the same regardless of stratigraphic position (Hacquebard and Donaldson, 1970). Thus, only in those cases where some, or all, of the coalification post-dated tectonic activity is it possible for an individual seam to have a varying rank.

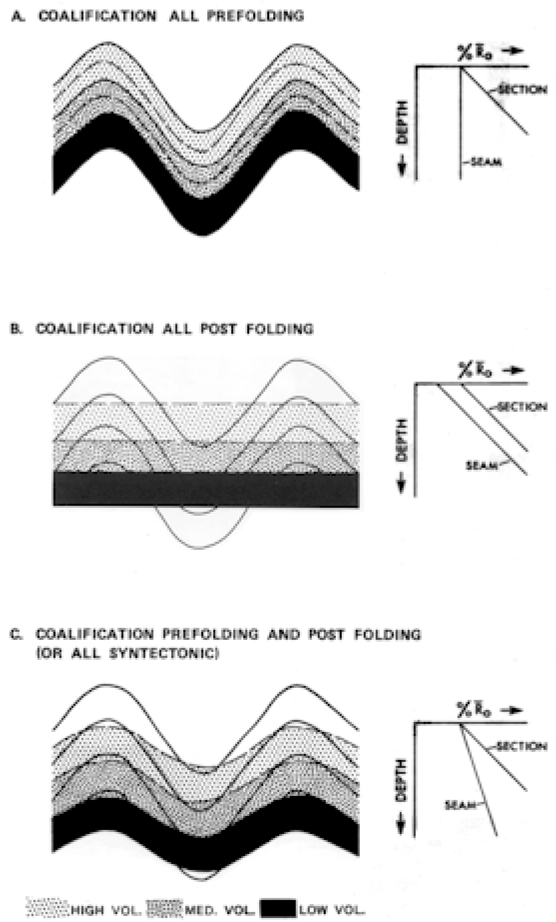

Figure 2: Cross sections through coal seams amd coalification planes with corresponding R_o/Depth diagrams, where timing of coalification is (a) pre-folding, (b) post-folding and, (c) some pre-folding and some post-folding, or all syntectonic. (modified after Techmuller and Techmuller, 1966).

Maceral Distribution in Crowsnest Coalfield

Macerals, which are analogous to minerals in inorganic rocks, comprise three groups with contrasting properties, namely Liptinite, Vitrinite and Inertinite. The relative proportions of these groups define the petrographic composition of a coal and profoundly affects caking, coking and combustion properties (see, for example, Pearson, 1980). In detailed or reconnaissance coal mapping, vitrinite reflectance and maceral composition are the two independent petrographic variables that provide information on the quality of coals being examined regardless of their oxidation state.

In the East Kootenay coalfields, maceral composition of coals varies according to a persistent pattern. Coals near the base of the Mist Mountain Formation are relatively enriched in inertinite and deficient in vitrinite, whereas those near the top of the Formation are enriched in vitrinite and inertinite deficient. This trend was first recognized by Cameron (1972) and has been verified by results of this study.

Methods of Study

The results reported here are based on 1:10 000 scale geological field mapping (Pearson et al., 1977; Pearson and Grieve, 1978a; Pearson and Grieve, 1981; Gigliotti and Pearson, 1979). During the mapping program grab samples of coal were collected routinely for later measurement of vitrinite reflectance. Representative channel samples were also collected of all major seams in nineteen stratigraphic sections (A to S in Fig. 3). All samples were collected from surface exposures and are known to be oxidized (Pearson and Kwong, 1979; Pearson and Creaney, 1981).

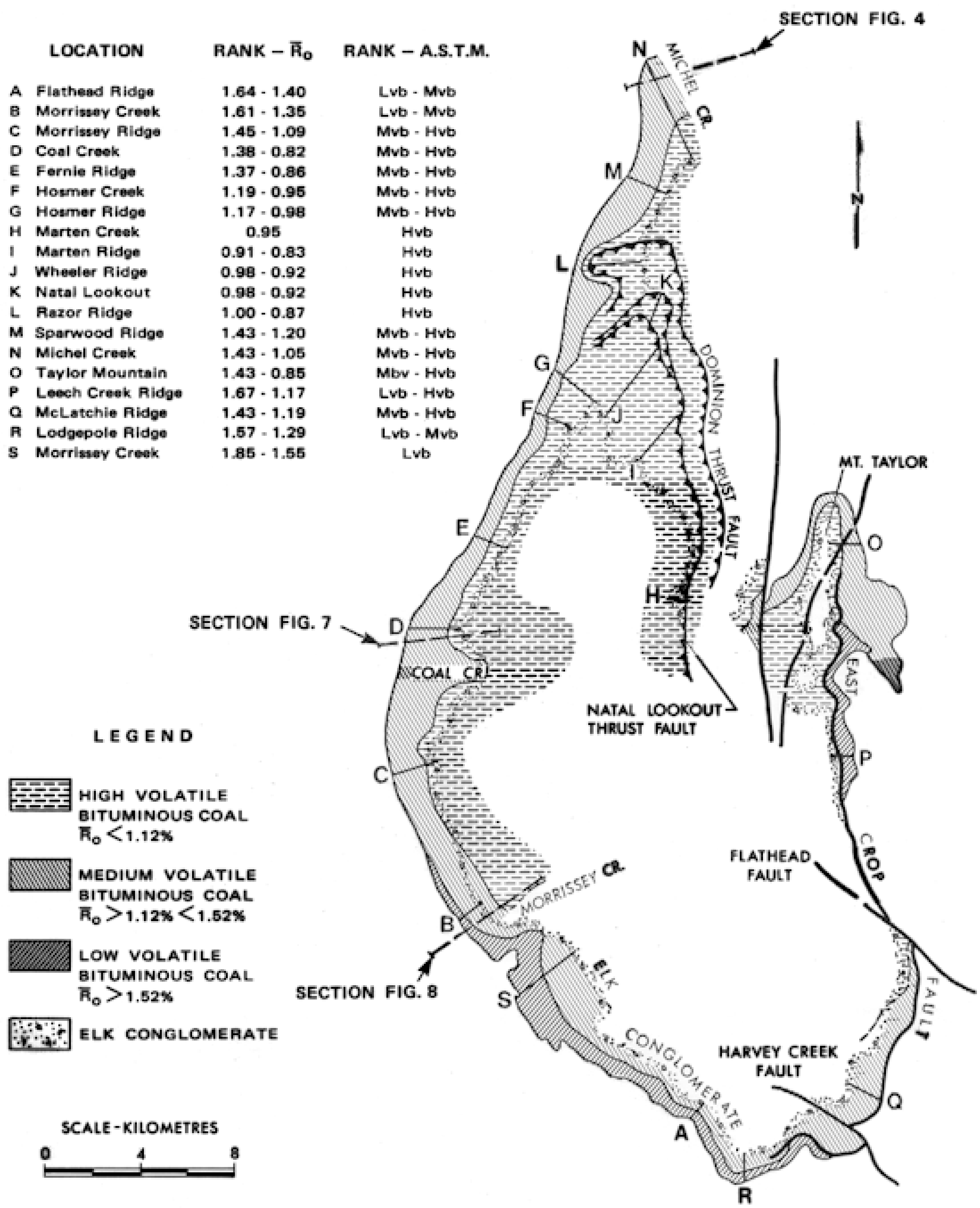

Figure 3: Rank map of Crowsnest coalfield.

Samples were crushed to pass through a 20-mesh sieve (850 µ and pelletized. On over 560 samples, rank was determined as the mean of the maximum reflectance, in oil, of 50 vitrinite type-A grains per sample ($R_o$max) measured at 546 μ. Samples were assigned to ASTM rank classes as follows (McCartney and Teichmü, 1972):

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Romax < 1.12% > 0.50% - High-volatile bituminous.
Romax > 1.12% < 1.51% - Medium-volatile bituminous.
Romax > 1.51% < 1.92% - Low-volatile bituminous.
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Maceral compositions were determined by point-counting 1000 random grains per sample. Semifusinite was assigned 1/3 to the reactive maceral category and 2/3 to the inerts, and a constant 9% ash and 0.5% sulphur was used to compute mineral matter content by the Parr formula.

Rank Distributions

Figure 3 shows the outline of the coalfield with rank distribution (based on vitrinite reflectance) superimposed. The area of current mining activity to the north of Michel Creek was not included in the study.

Analysis of the map reveals an asymmetric distribution of rank, with low-volatile bituminous coals occurring in the southwest portion of the coalfield (sections B,S,A, and R) and south of Mount Taylor (P). With only one exception, medium-volatile coals occur throughout the coalfield. On Wheeler and Marten Ridges (I and J), the virtually complete coal-bearing successions are of high-volatile bituminous rank only. The coal measures at these localities occur in two major thrust blocks situated on the Dominion and Natal Lookout Thrusts.

Changes in rank of individual seams along strike can be demonstrated on Fernie Ridge (E) and Morrissey Ridge (C). On Fernie Ridge, northward from Coal Creek (D), decreasing proportions of the coal measures are of medium-volatile rank so that on Hosmer Ridge (G) virtually the whole succession is of high-volatile rank. Similarly, on Morrissey Ridge (C), southward from Coal Creek, a decreasing proportion of the coal measures is of high-volatile rank, while an increasing proportion is of low-volatile rank.

On Mount Taylor (O), the upper portion of the coal measures is of high-volatile rank but within two kilometres high-volatile coal is juxtaposed with low-volatile coal across the East Crop Fault (P).

Coalification Patterns

As outlined above, rank data provide evidence concerning relative timing of coalification with respect to folding and faulting and allow estimation of the contribution of pre-folding and post-folding coalification to the total rank gradient. Examples from five locations in the coalfield are given below.

Michel Creek

A geological cross-section through the coal measures in the vicinity of Michel Creek, at the north end of the Crowsnest Coalfield, is shown in Figure 4. The section is drawn looking south in the direction of plunge of the Sparwood syncline. Only three of the twelve seams are shown. However, it can be seen that the 1.12% isoreflectance surface (separating medium- from high-volatile coals), in the Natal Ridge section, lies under the middle seam. This surface crosses the middle seam toward the west, so that on Sparwood Ridge it lies between the middle and uppermost seams. Similarly, there is considerable variation in vitrinite reflectance of the lowermost (Balmer) seam (R. Venzey, pers. comm.) and a small portion of it occupying the keel of the Sparwood syncline actually has reflectances greater than 1.51%. Thus, in the Michel Creek section, isorank surfaces dip in the same direction as coal seams but at shallower angles, a situation that coincides with the theoretical pattern shown as Figure 2C.

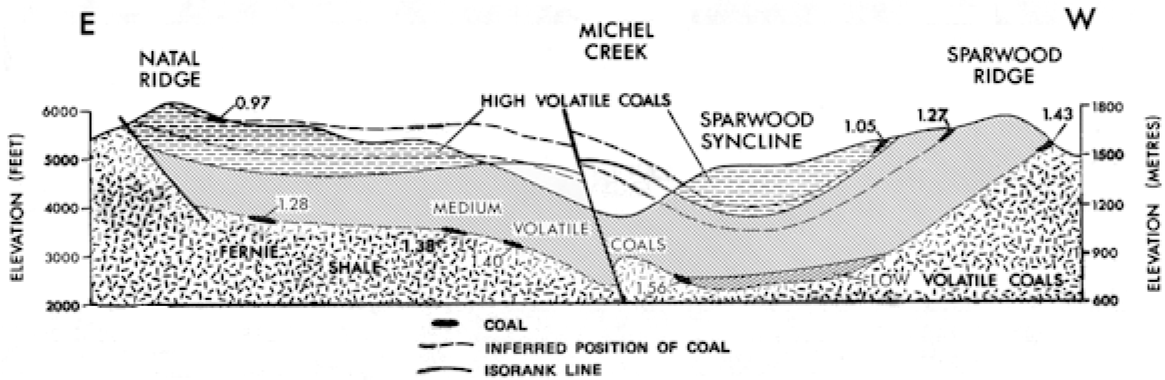

Figure 4: Vertical cross section through the Kootenay Formation in the vicinity of Michel Creek.

Calculations of total rank gradient for Michel Creek area, based on true thicknesses of measured sections and rank determinations of exposed coals, yield averages of about 0.08%R_o/100m (Fig. 5). (Although the thickness of measured sections is corrected for dip attitudes, the sampled coals are not taken in the plane perpendicular to bedding, and so calculated rank gradients values are probably low.)

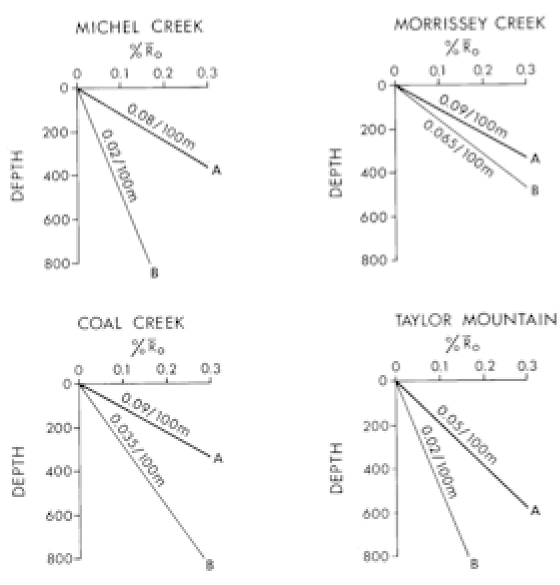

Figure 5: Rank-depth diagrams of Total Rank Gradient(A) and Seam Rank Gradient(B) in four principal localities of Crowsnest coalfield.

Seam rank gradients for individual seams in this area have also been calculated. West of Michel Creek, in the Sparwood syncline, the rank of the Balmer seam changes from 1.43% to 1.56% over an elevation of 1021 metres. Similar changes for other seams have been obtained giving seam rank gradients of about 0.02%R_o/100m (Fig. 5). Therefore, in this area of the coalfield, about 25% of the total coalification gradient can be attributed to post-folding coalification (Figs. 5 and 6).

Coal Creek

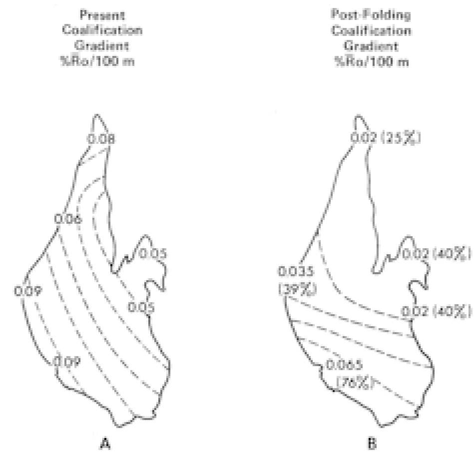

Figure 6: Contoured maps of rank gradients in Crowsnest coalfield. (A) Present coalification gradient or Total Rank Gradient (B) Post-Folding Coalification Gradient or Seam Rank Gradient.

A cross-section through the coal measures on the south-facing slope of Coal Creek mountain (D, Fig. 3) is shown in Figure 7. Only three of the ten exposed coal seams are shown. It can be seen that the 1.12% $R_o$max isoreflectance surface, which separates high-volatile from medium-volatile ranks of coal, cuts up-section to the east, so that at the eastern end of the section, all of the measures are of medium-volatile rank. The total rank gradient computed for Coal Creek mountain is about 0.09%R_o/1OOm. The highest rate of change on an individual seam is displayed by the middle seam shown in Figure 7 where a change in vitrinite reflectance of 0.34% over a 1000-metre change in elevation is recorded. This corresponds to a seam rank gradient for this seam of 0.35R_o/100m. In this section, it appears that about 39% of the total coalification gradient can be attributed to post-folding coalification (Fig. 6).

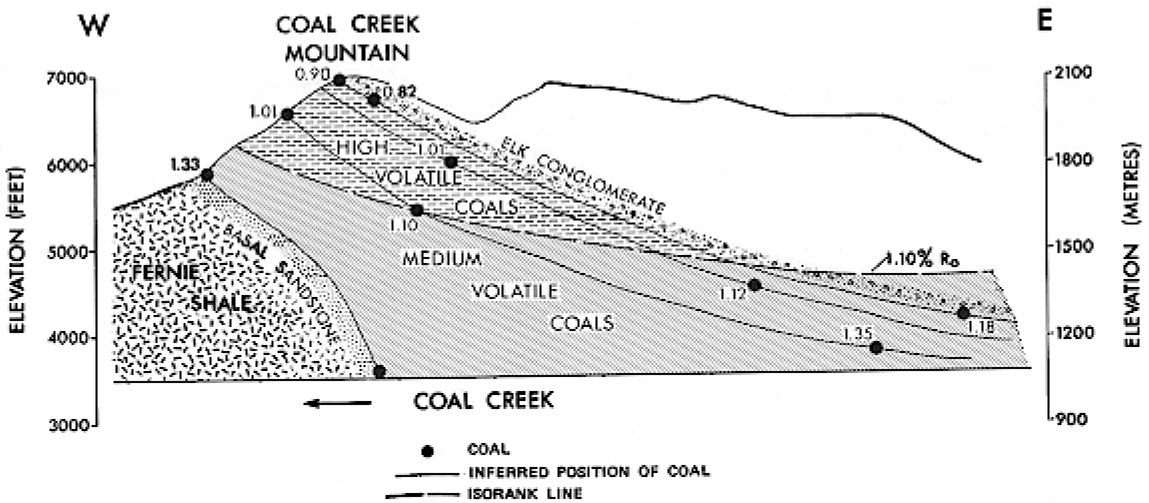

Figure 7: A section through the Kootenay Formation exposed on the south-facing slope of Coal Creek Mountain.

Morrissey Creek

A cross-section through the coal measures on the south-facing slope of Morrissey Ridge, overlooking Morrissey Creek, is shown in Figure 8. In the western part of this section, open-style folding which affects the lower portions of the succession is noticeably absent from the overlying Elk conglomerate. It is apparent, however, that the 1.51% isoreflectance surface that separates low-volatile from medium-volatile rank coals cuts across the fold limbs and fold axial surfaces. It can also be seen that whereas on the western ridge only half of the succession is of low-volatile rank, at the eastern end of the section all of the coal in the measures has this rank. The rank gradient computed for the section measured on the western ridge is 0.09%R_o/100m, corresponding to the observed rank change from 1.38% & to 1.69% R_o over 300 metres of elevation. Gradients of change computed for the upper and lower of the three seams shown in the section are both 0.065% R_o/100m (Fig. 5). These data demonstrate that about 76% of the total coalification gradient is attributable to post-folding coalification. (Fig. 6).

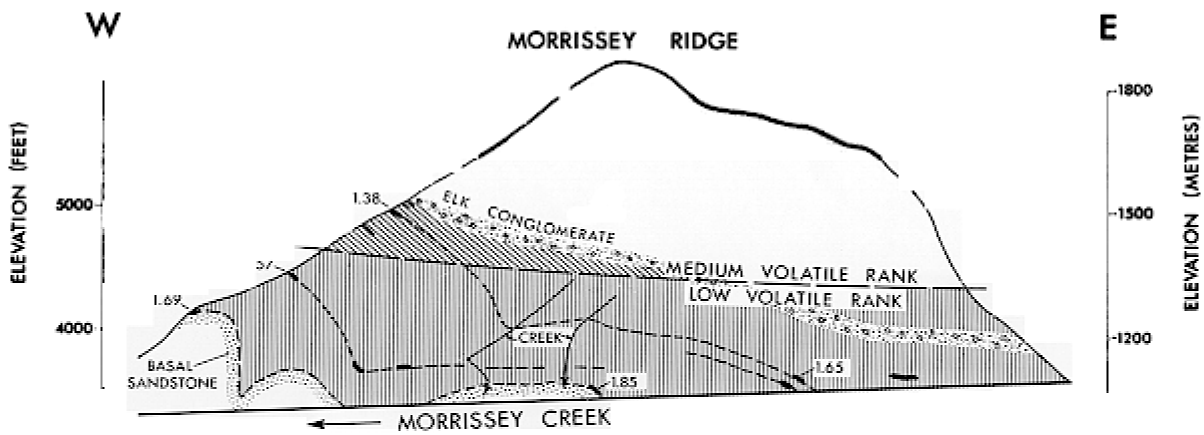

Figure 8: A section through the Kootenay Formation exposed on the south-facing slope of Morriessey Ridge, overlooking Morrissey Creek. Legend for the figure is the same as FIGURE 4.

Dominion Thrust Fault

When viewed from the Elk Valley, details of the Dominion Thrust on Sparwood Ridge appear as shown in the strike-section in Figure 9. At the north end of the section the coal seam resting directly on the basal sandstone has a vitrinite reflectance of 1.43%, and the uppermost seam exposed beneath the Elk conglomerate has a reflectance of 1.00%. South of this section, the coal measures lose elevation as they plunge beneath the Dominion Thrust Fault so that the Elk conglomerate is exposed in a creek south of Razor Ridge (L, Fig. 3) at an elevation 500 metres lower than on Sparwood Ridge (Fig. 9). In this creek, the coal seam located beneath the Elk conglomerate has a vitrinite reflectance of 1.22%.

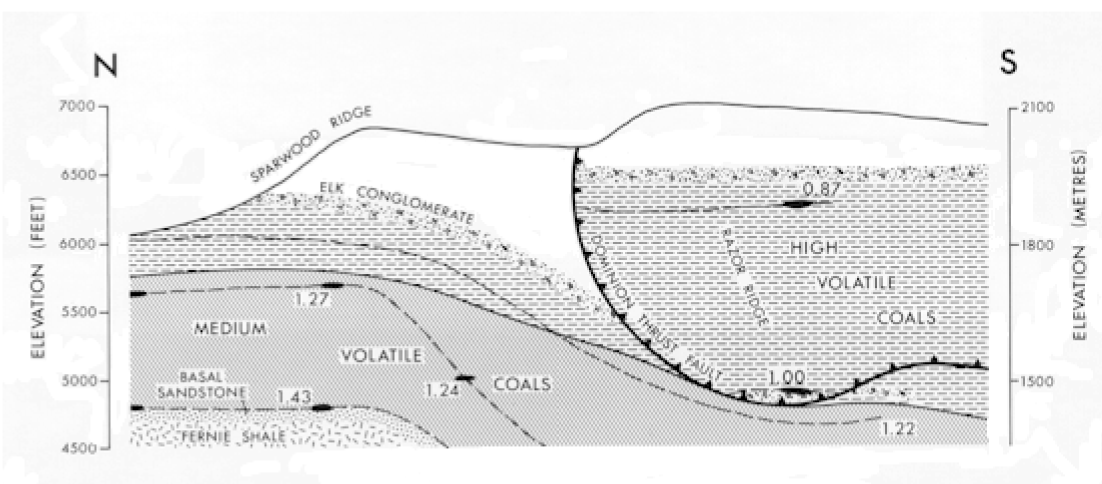

Figure 9: A strike-section of Sparwood Ridge, showing in cartoon-form details of the Dominion Thrust.

On Razor Ridge, the seam directly overlying the basal sandstone has a vitrinite reflectance of I.OOWO, whereas the highest stratigraphic seam in this section has a reflectance of 0.87%. Thus, a complete stratigraphic succession of coal measures, all of high-volatile rank, rides on the Dominion Thrust Fault and this overlies a complete stratigraphic succession, mostly of medium-volatile rank, two kilometres to the north (shown to the left of the section in Fig. 9). Despite the structural discordance, there is no discernible break or repetition of the 1.12% R_o isoreflectance surface in this section which suggests that coalification essentially post-dates formation of the Dominion Thrust.

East Crop Normal Fault

Some of the important features of the geology of the Mount Taylor area on the east margin of Crowsnest coalfield are shown in Figure 10 (from Gigliotti and Pearson, 1979). The distribution is shown of high-, medium- and low-volatile rank coals about two important structures, the Barnes antieline and the East Crop Fault. The location of a 400 m-thick section (A-B), on the north end of Mount Taylor is shown, together with vitrinite reflectance values of the five coal seams in the section. The computed total rank gradient in this section is 0.05%R_o/100m.

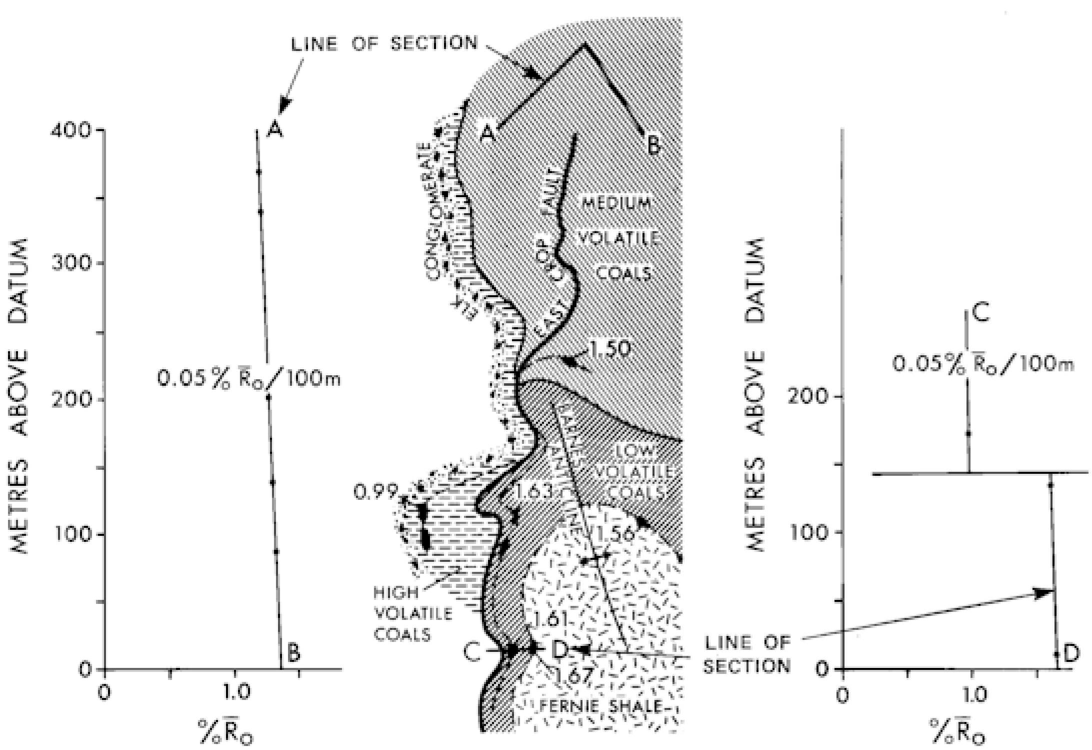

Figure 10: Geological map of the Mount Taylor area showing rank-depth diagrams for two sections A-B, C-D and the position of the East Crop Fault.

On the west limb of the Barnes anticline, a succession from the basal sandstone to the Elk conglomerate, measures only 200m (section C-D, Fig. 10). Moreover, low-volatile coals in the foot-wall of the west-dipping East Crop Fault are directly overlain by high-volatile coals in the hanging-wall. Thus, movement on the East Crop Fault was normal and all intermediate rank coals have been displaced. A rank/depth diagram for this section shows a similar rank gradient of 0.05%R_o/100m for the lower coals. Since displacement along the fault juxtaposes coals of 0.99Wo and 1.63clo reflectance, the normal movement component was in the order of:

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(1.63-0.99) / (0.05) = 1280 metres.
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The configuration of strata across the East Crop Fault prior to the 1280 metres of normal movement is shown in cross-section in Figure 11, Step 1. The current situation is shown as Step 2. It is apparent that the East Crop Fault was a thrust fault prior to normal movement. This fact was previously deduced on the basis of geological evidence observed in the field. Fold structures, indicative of constrictional tectonics, are associated with the East Crop Fault in three areas along its 25-kilometre length.

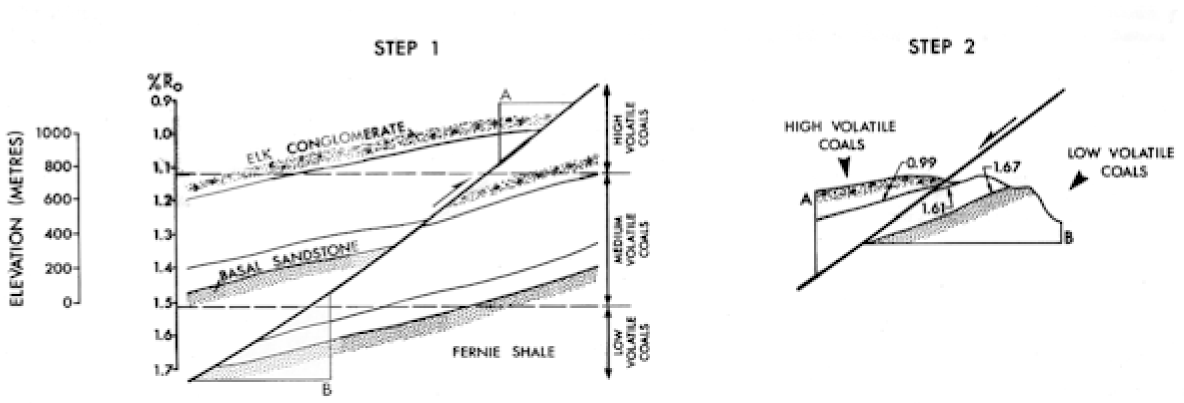

Figure 11: Palinspastic reconstruction of East Crop Fault prior to 1280 metres of normal movement. The diagram shows that the fault was originally a thrust fault subsequent to coalification and normal faulting.

Discussion

The rank distribution map (Fig. 3) and cross-sections (Figs. 4, 7, 8, 9 and 11) suggest that a significant proportion of total coal rank in Crowsnest coalfield was caused by coalification subsequent to formation of early compressional structures (folds and thrust faults). In the case of folded rocks, isorank lines dip in the same direction but at shallower angles than the coal measures (Fig. 2C). With thrust faulting, the fact that no repetition of rank values occurs across the fault surfaces is evidence for predominantly post-thrusting coalification. The rank distribution map (Fig. 3) and geological map of the Mount Taylor region (Fig. 10) both indicate that coalification was completed before normal movement took place on the East Crop Fault during the stage of extensional tectonics. Coal rank data have verified the conclusion that the East Crop Fault also had a thrusting stage in its history.

Another significant portion of total coalification occurred prior to formation of the compressional structures. Although the exact predeformational contribution is difficult to estimate, its contribution to total rank gradients varies from 75% at Michel Creek to 24% at Morrissey Creek (Figs. 5 and 6). These values are at least a rough indication of the proportions of total coalification.

The rank distribution map (Fig. 3) and the coalification pattern maps (Fig. 6) suggest that the south end of the coalfield achieved a higher temperature than other parts of the coalfield based on the higher rank and the larger proportion of post-folding coalification in this area. There are several possible explanations for this phenomenon, although a greater depth of burial is a likely cause. At 1100m elevation on Morrissey Creek, reflectance values of 1.85% R_o. have been recorded from the basal coal seam, whereas in the Michel Creek section the same seam at the 1100m level would have a reflectance of about 1.49% R_o. It is calculated that about 560 metres of extra cover existed at the south end of the coalfield subsequent to folding to explain these variations. This extra burial cover may have been in the form of either younger sediments, or an overthrust.

Coal Quality

Two independent variables are required to make petrographic predictions on the quality of coals. These are the rank, expressed as $R_o$max, and the petrographic composition of coals, expressed as the proportion of Inerts (Pearson, 1980). Figure 12 shows how these two parameters vary among six coal seams exposed at Hosmer Ridge (Section G, Fig. 3). The coals exposed in the lower portion of Section G, have higher vitrinite reflectances and higher Inert contents, whereas those in the upper portion have lower reflectance and lower Inert contents. Therefore, the coal seams, when displayed in stratigraphic sequence on the Ro/Inert diagram (Fig. 12), move from upper left to lower right. Figure 12 also outlines six groups of coal (G1 to G6), defined by Pearson (op cit.) in terms of their contrasting rheological properties. Coal seams in Section G belong to Groups 2, 4 and 5, based on their rank and petrographic composition.

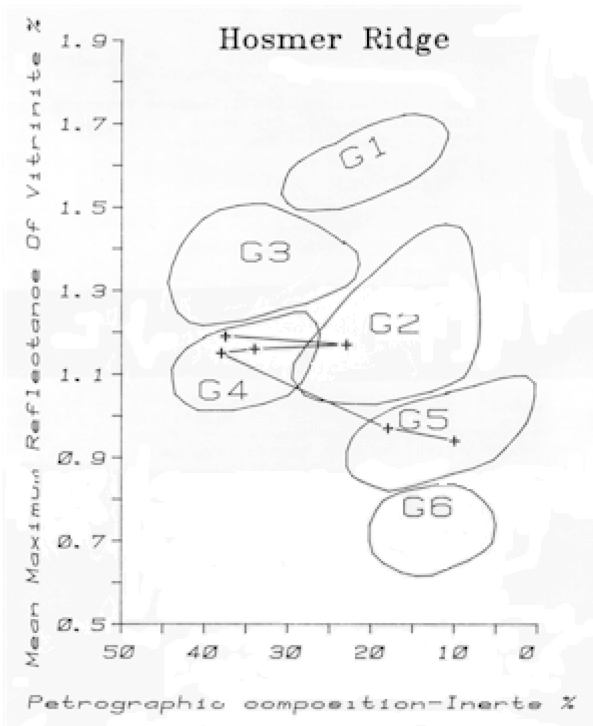

Figure 12: Rank and petrographic composition of the six seams exposed in the stratigraphic sequence of Hosmer Ridge (Section G, FIGURE 3), together with coal quality groups (G1 to G6).

A similar conclusion is reached by locating Section G on Figure 13, which shows the predicted areal distribution of coal quality groups in Crowsnest Coalfield, based on graphs like Figure 12 plotted for each of the nineteen sections in Figure 3. In general, sections in Crowsnest coalfield can pass, in going from base to top, from low-volatile G1-type coals to medium-volatile coals of G2-type (as, for example, south of Morrissey Creek on Flathead Ridge [Section S, Fig. 41), from low-volatile G3-type coals to medium-volatile G2-type coals to high-volatile GS-type coals (as for example, at Michel Creek [Section N, Fig. 31), or from medium-volatile G4-type coals to high-volatile G5-type coals (found on Marten Ridge and Wheeler Ridge [Sections I and J, Fig. 3]).

In other words, coal rank and composition variations combine to yield coals of contrasting qualities throughout the coalfield. All of the current production from Crowsnest coalfield is from the Balmer seam in the Sparwood area, a coal which falls into the G3 group. According to Pearson (op cit.), G3, or "Balmer-Type" coals, are characterized by the following properties:

Maximum Dilatation: - 10 to 100
Maximum Fluidity: 3 to 1500 ddpm
Free Swelling Index: 5-8
Volatile Matter: 19-26%
ASTM Coke Strength: 4(@-62

Substantial reserves of G5 coals were established in the upper seams on Hosmer and Wheeler Ridges (Sections G and J) during the 1970s. The combination of lower ranks in this area (Fig. 3) and the relatively low inert-maceral contents of the coals from the upper part of coal-bearing section, leads to higher values of maximum dilatation (100 to 300%), maximum fluidity (> 1500 ddm), free swelling index (7 to 9), and volatile matter (32 to 38%) than G3 coals (Pearson, op cit.).

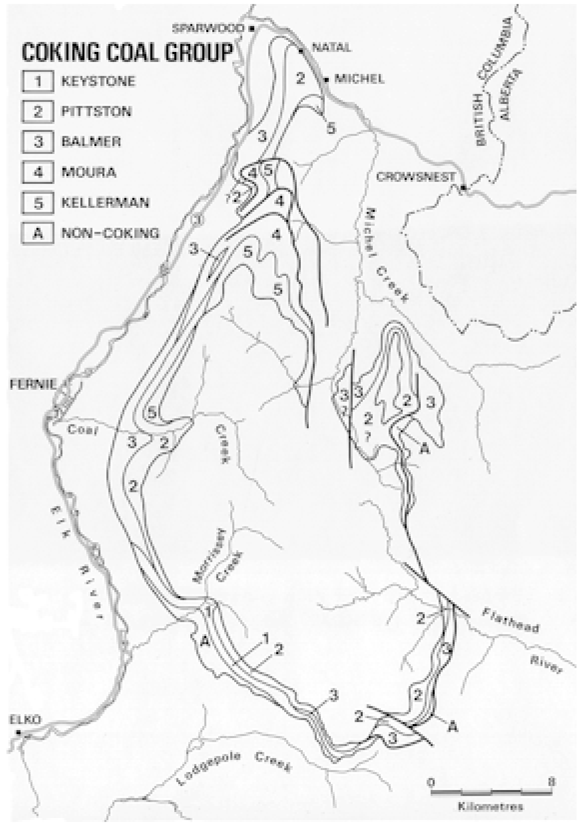

Figure 13: Predicted areal distribution of coking coal quality groups in Crowsnest coalfield.

The most recent exploration activity in Crowsnest coalfield (1983), was centred at Coal Creek in areas underlain by G2 coals. The earliest collieries in the coalfield, at Coal Creek and Michel, produced predominantly G2 coals. Such coals have slightly lower volatile matter (22 to 34%) than GS coals due mainly to their higher rank (Fig. 13), have excellent coke strengths (48-65), but are in other respects very similar to GS coals. (Pearson, op cit.).

A striking feature of Figure 13 is the predicted occurrence of coals unsuitable for coke-making. The lower seams in the Morrissey Creek area (B), for example, are too high in rank (Figs. 3 and 8) to be classed as coking coals. The early financial failure of the colliery and Beehive coke-ovens established at Morrissey at the turn of the century was in large measure due to this factor.

Acknowledgments

The fieldwork and sample collection for this paper was done between 1976 and 1980, when both authors worked for the British Columbia Ministry of Energy, Mines & Petroleum Resources. We thank our colleagues there for numerous kindnesses during that time. Ron Venzey, previously with Kaiser Resources Ltd. (now Westar Mining Limited), is thanked for discussions of the petrography of the Balmer seam near Michel Creek. Student assistants, including Mickey Welder, Peter Mustard and Frank Gigliotti contributed to the fieldwork.

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