UNIQUE ASPECTS OF BRITISH COLUMBIA CBM GEOLOGY: INFLUENCES ON PRODUCEABILITY

By Barry Ryan[1]

KEYWORDS: Elk Valley, Crowsnest and Peace River coalfields; gas composition; Lewis Thrust; deformation history.

INTRODUCTION

The title refers to coalbed methane. The predominance of literature refers to the extraction of coalbed methane (CBM) from coal. This is not scientifically correct as the gas extracted from coal is a mixture of methane carbon dioxide and other gases. The British Columbia government is adopting the term coalbed gas (CBG). The abbreviations CBM and CBG both refer to the commercial gas extracted from coal at depth. To avoid confusion with existing scientific literature this paper uses the term CBM.

Based on the amount of public data available British Columbia is still in the grassroots stage of coalbed methane (CBM) exploration. In the last few years companies have drilled a number of holes in southeast, northeast and central British Columbia. Most of the drilling was done as part of experimental schemes, which provide a three-year confidentiality period and consequently most of the information is still confidential. This paper therefore relies in part on coal rather than CBM data and speculation as input for a discussion of influences of CBM geology on produceability. Under this general topic a number of observations or ideas are developed. They are related only in that they may all help in delineating prospective CBM areas.

Most of the coalfields in British Columbia have experienced some level of deformation. It is very important to understand the timing of coal maturation relative to deformation. In the simplest context one should know whether structural traps were formed before or after generation of thermogenic methane. In the southeast of the province the Elk Valley and Crowsnest coalfields (Figure 1) form part of the Lewis thrust sheet and this somewhat unique macro tectonic environment should be considered when assessing the CBM characteristics of the coalfields. This leads to a provisional comparison of the structural setting between the Peace River in the northeast and southeastern coalfields. Finally one of the most important aspects of CBM produceability is the recent tectonic history of coalfields and how it may improve permeability and interrelate with coal properties.

COMMENTS ON THE TIMING OF DEFORMATION AND COAL MATURATION

Coal more than any other rock changes during maturation. The main change is shrinkage, at first associated with loss of water, then carbon dioxide and finally methane. There are a number of experimental ways of determining mass loss during maturation but it can also be estimated from standard analyses of coals of different ranks. In the later case it is assumed that the fixed carbon component of a proximate analysis remains constant and coal shrinkage is caused by loss of water and volatile matter. This is obviously only an approximation of what happens as coal rank increases. However it enables a useful plot to be developed (Figure 2), which indicates that most of the water loss and coal shrinkage occur in the rank range defined by mean maximum vitrinite reflectance (Rmax) values of 0.4% to 0.7% also represented by the transition between sub-bituminous to high-volatile bituminous. A second period of rapid shrinkage corresponds to the expulsion of thermogenic methane at a rank of about Rmax=0.9%.

During the two periods of rapid shrinkage (Figure 2), seams are expelling water and volatile matter and may become over pressured. Under these conditions, especially during the first period, seams are most susceptible to bedding parallel slip and thrusting. If deformation starts when seams are in the rank window Rmax=0.4% to 0.7%, then pervasive deformation may well be localized in seams, in part because of over pressuring. Seams will be extensively sheared and may not develop cleats or pre existing cleats may be destroyed. Methane generated as rank continues to increase may have structural traps available but permeability in seams may be low. On the other hand, if deformation occurs when the coal has reached higher ranks, then it is less likely to be as pervasive within seams and pre existing cleats may survive. Methane generated prior to development of structural traps may be lost as it is expelled with increasing rank.

The two periods of matrix shrinkage indicated in Figure 2 may correspond with cleat development. The earlier one is caused in part by compaction and loss of surface water with some loss of CO_2 from the coal matrix.

[1] *Resource Development and Geosciences Branch, B.C. Ministry of Energy and Mines, barry.ryan@gems4.gov.bc.ca*

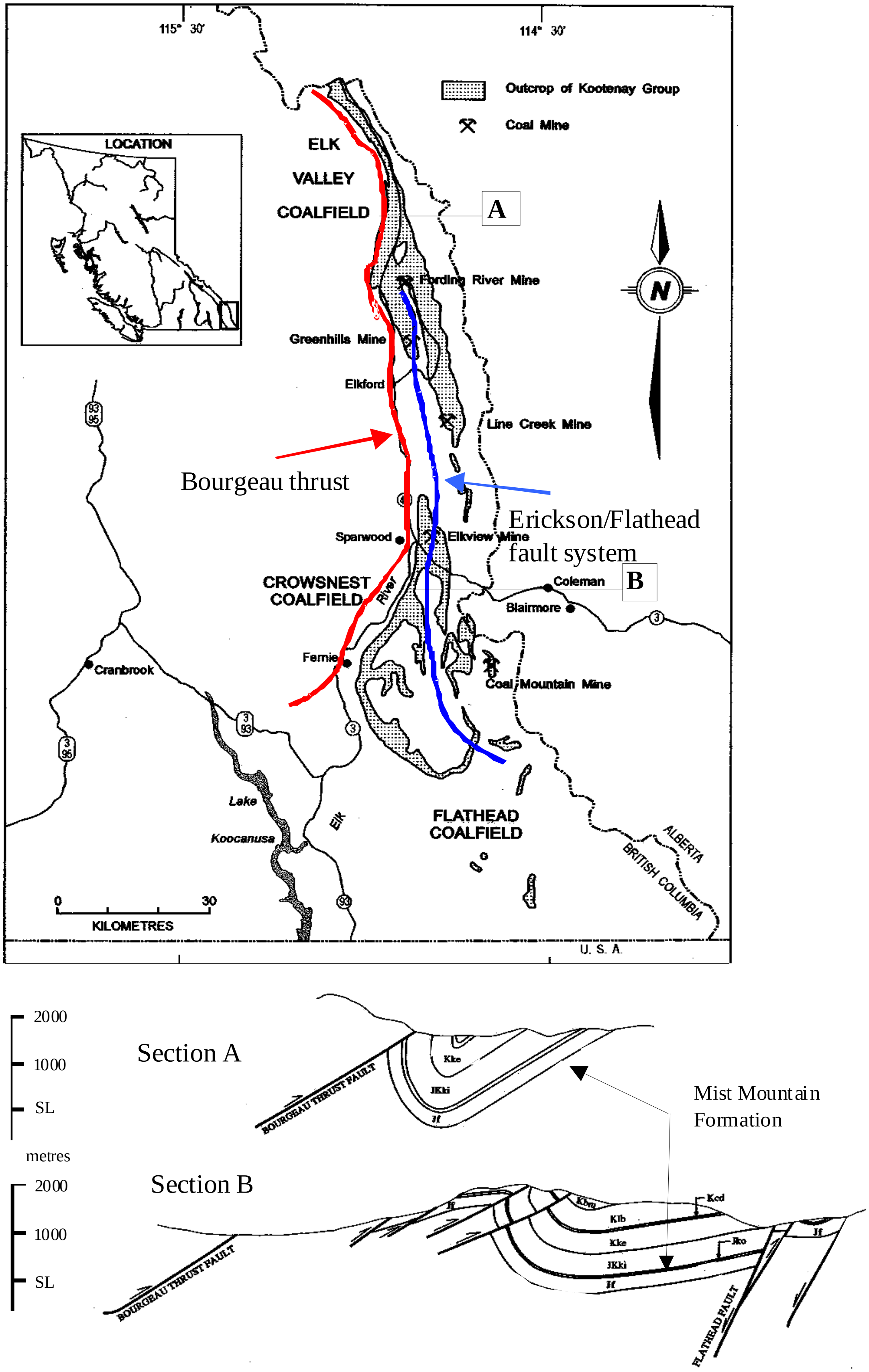

Figure 1: Structural setting of the Elk Valley and Crowsnest coalfields.

This shrinkage probably forms widely spaced cleats because coal at this rank still contains in part a vegetation structure that will hinder the formation of closely spaced cleats. At increased rank (about Rmax=0.9%) the coal goes through another period of rapid contraction that is caused by loss of methane from vitrinite. At this time closely spaced cleats may form in vitrain rich bands.

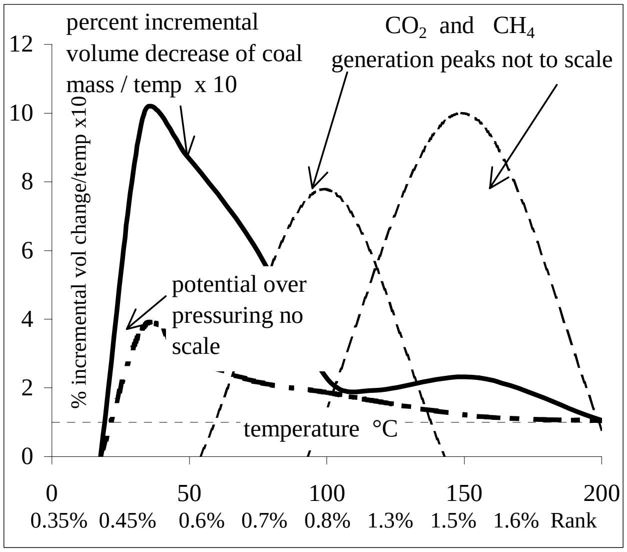

Figure 2: Matrix shrinkage and potential over pressure as estimated from proximate analyses.

Face cleats exist in Powder River Basin coals, which have ranks in the range of Rmax=0.4%. Generally face cleats form parallel to the direction of regional compression and perpendicular to the basin axis. In that they are probably forming at fairly shallow depth (represented by a rank of about 0.4% to 0.7%), it is easy for the fold axis normal direction to become extensional especially because of coal shrinkage. The regional nature of these fractures is probably accentuated because they offer pathways for water expelled from coal to escape upwards within seams to basin margins. Butt cleats that may form latter during methane generation will generally be constrained to form at 90° to bedding and face cleats. These are surfaces of no or low cohesion and therefore principle compressive stress directions must be perpendicular to them.

The spacing of face cleats decreases as rank increases up to a rank of low-volatile bituminous or semi anthracite and then may increase (Law, 1993). If cleat development and spacing is related to the two periods of maximum shrinkage then there should be a relationship between the plot provided by Law (1993) (Figure 3 this paper) and Figure 2. The curve in Figure 3 can be represented by a number of model points (open diamonds) that allow for the calculation of the change of cleat frequency *versus* rank or temperature. It is apparent that the maximum rate of change in cleat frequency is at low rank or temperature and tends to conform to the maximum period of coal shrinkage.

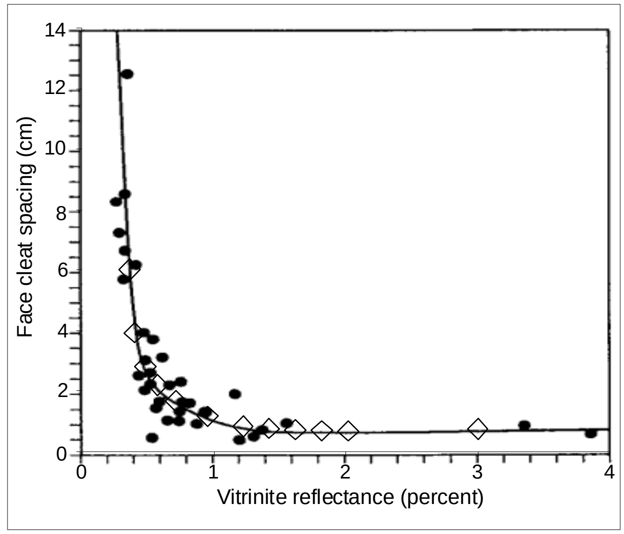

Figure 3: Spacing of face cleats versus rank from Law (1993); open diamonds are model points.

The generation of thermogenic methane can start at ranks as low as 0.5% in liptinite rich coals. The gas is rich in heavier hydrocarbons i.e. wet gas (Scott, 2001). The main stage of thermogenic methane generation starts at a rank of about 0.8% (Figure 4, from Scott, 2001) and the gas becomes progressively drier defined as C1/(C2+C3) as rank increases. However it will generally have lower ratios than biogenic gas, which has high C1/(C2+C3) ratios. Coals rich in inert macerals may generate fairly dry gas (high C1/(C2+C3) ratio).

In deformed seams in British Columbia, it is important to differentiate between the effects of regional deformation (thrust faults) and local (in seam) deformation. Regional deformation that precedes local folding probably occurs when coal rank is low and its intensity will not vary based on location in folds. Shear joints associated with the early thrusting may not intersect bedding along fold-axis directions of latter folding and they will not vary their relative orientation with respect to bedding depending on which limb they occur. The simplistic geometry of shear joints related to regional shearing and local flexural flow folding is illustrated in Figures 5 and 6

The data are plotted into lower hemisphere sterionets as poles to bedding and poles to shear joints. It is useful to note that in the sterionets, the pole to shear joint migrates away from the pole to bedding in the direction of shearing to form an acute angle between the two poles. The orientation of shear joints related to thrusting should be regionally consistent where as those related to folds will change orientation depending on which limb they are on. Limited data in southeast BC indicates that the shear joints at Greenhills on the west limb of the syncline are related to the flexural slip associated with the syncline. In other mines the relationship is less obvious. The shear joints are however rotated such that they appear to be related to folds trending more to the north west or thrusting from the south west. (Figure 7). Face cleats appear to strike normal to this early folding (or parallel

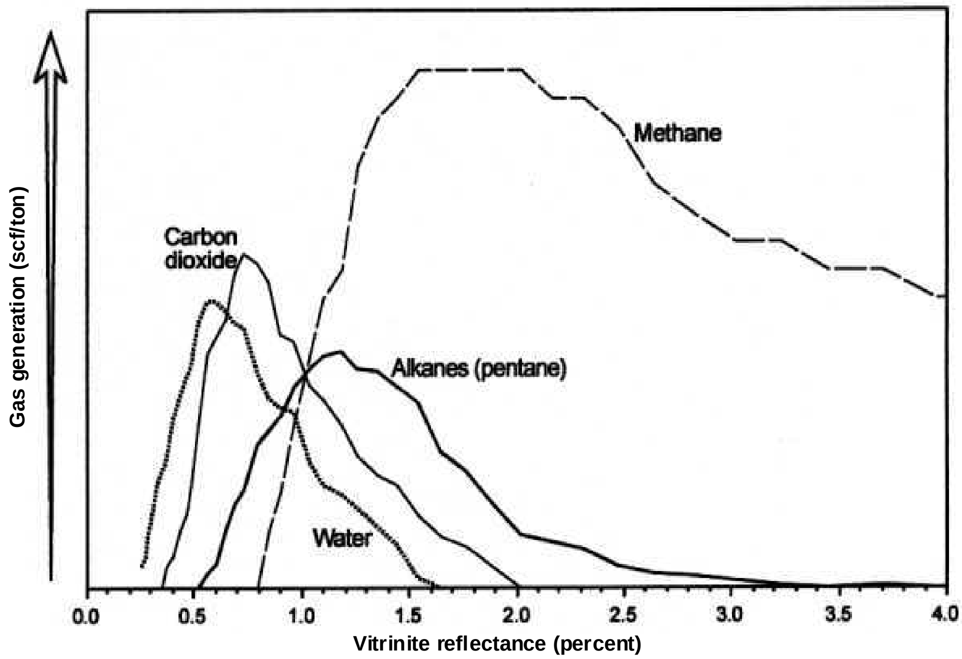

Figure 4: Generation of gases, diagram from Scott (2001).

the thrusting) rather than normal to the later fold-axis direction.

In the Peace River coalfield (Figure 8) shear joints indicate northeasterly directed thrusting or shear joints associated with the prevalent north-west trending folds. The properties indicated in Figure 8 are located in Figure 9. Face cleats are generally normal to the fold-axis direction except in the north in the Gething Formation where some trend parallel to the fold-axis direction. These cleats may in fact be axial planar features related to folding of the coal that occurred after it reached moderate rank. In the area, coal in the Gething Formation is inertinite rich and consequently would not have shrunk as much during early coalification. Inert rich coals that are characteristic of some Cretaceous British Columbia and Permian Australian coals may not form face cleats during early coalification and may contain fractures formed during later tectonic activity. These fractures may or may not be of extensional origin.

STRUCTURAL AND CBM HISTORY OF THE ELK VALLEY AND CROWSNEST COALFIELDS IN THE LEWIS THRUST SHEET

The Elk Valley and Crowsnest coalfields have had a complex tectonic history in part because they are contained in the Lewis Thrust sheet (Figure 1). This unique tectonic setting, in conjunction with the Cretaceous to Early Tertiary deformation history, may be significant in terms of the produceability of the CBM resource of the coalfields.

Coal in the coalfields is contained in the Mist Mountain Formation of the Kootenay Group (Table 1), which was deposited into the miogeosyncline developed of the eastern edge of the Purcell arch. Sediment was derived from the west as the Columbian Orogeny uplifted rocks. The Kootenay Group is separated from the overlying Blairmore Group by a disconformity that separates the Elk Formation from the overlying Cadomin conglomerate. To the north and east there was considerable erosion associated with this unconformity, though in the Elk Valley and Crowsnest coalfields it appears to be more of a disconformity.

The Mist Mountain Formation, which is Upper Jurassic to Lower Cretaceous (about 152-140 my. Mossop and Shetsen, 1994) is up to 625 metres thick in southeast British Columbia (Gibson, 1985). The overlying Elk Formation varies in thickness up to 488 metres (present thickness, Gibson, 1977). It is unlikely therefore that the coal seams in the Mist Mountain Formation were buried by much more than 1000 metres at the time of the pre Blairmore erosional event. Erosion and associated uplift probably did not have any lasting effect on gas contents of seams in the Formation.

The gas contents of coals in Carboniferous rocks in the Ruhr area of Germany reflect the effects of a post Carboniferous unconformity. Samples from just below the unconformity are close to saturated where as deeper coals are under saturated. This is the opposite of what might be expected based on degassing of the coal during erosion and uplift related to the unconformity. Freudenberg *et al.*, (1996) suggest that shallower coals were recharged with biogenic methane generated using CO_2 introduced during uplift and hydrogen from the coals. Seams deeper in the

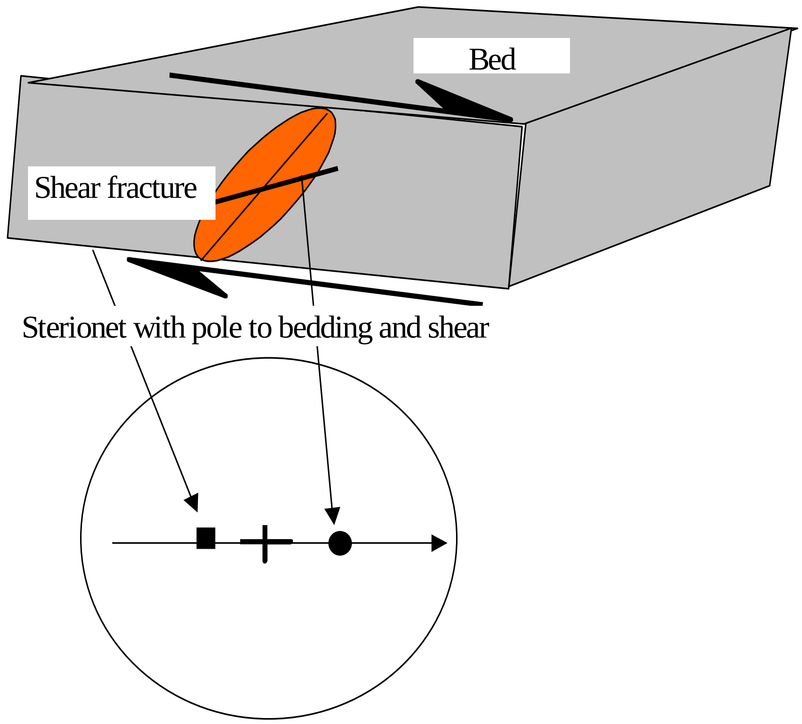

Figure 5: Orientation of shear joints in a thrust.

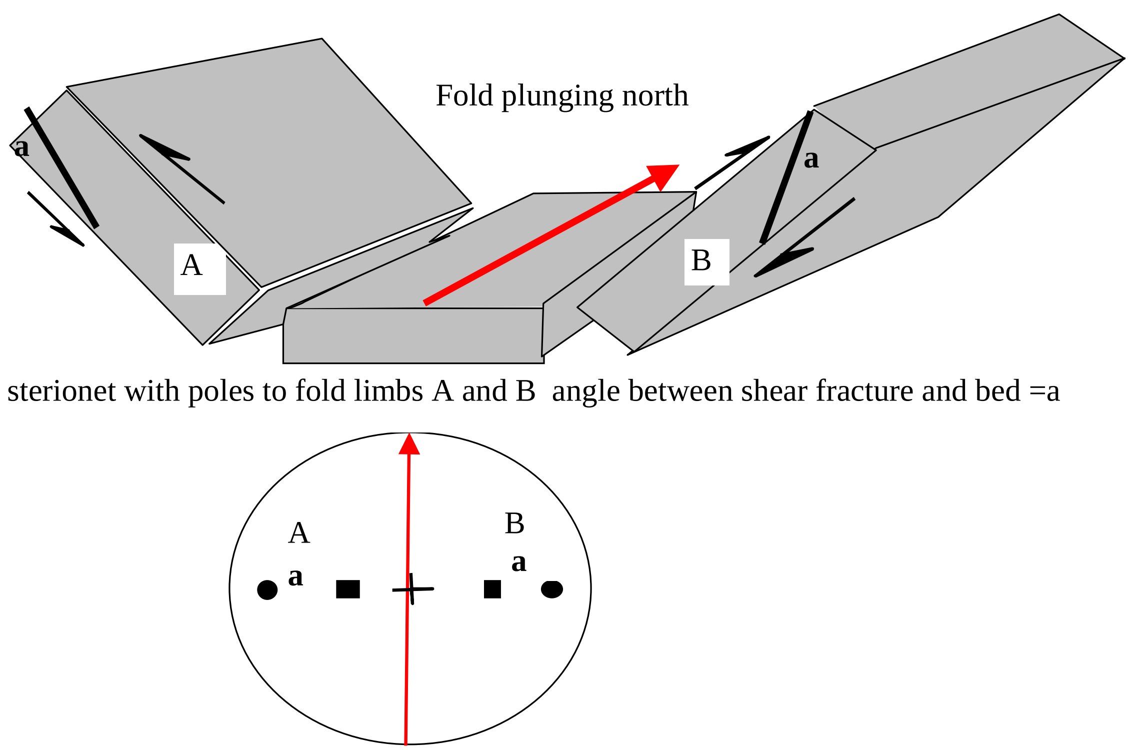

Figure 6: Orientation of shear joints in flexural flow fold.

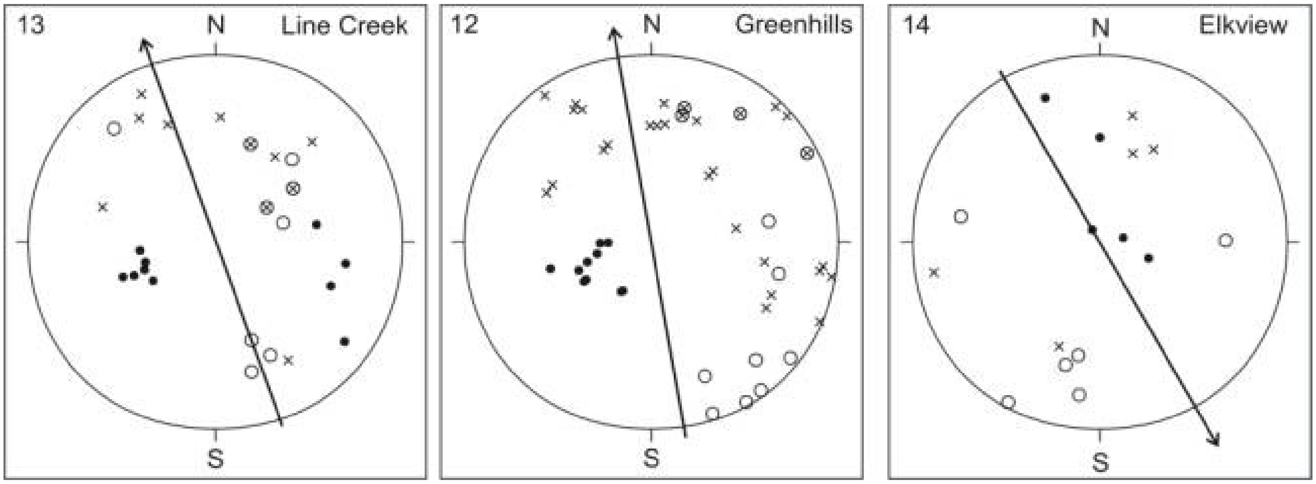

Figure 7: Sterionet of shear joints and cleats in southeast coalfields.
● = pole to bedding ○ = face cleat ⊗ = butt cleat × = shear fracture.

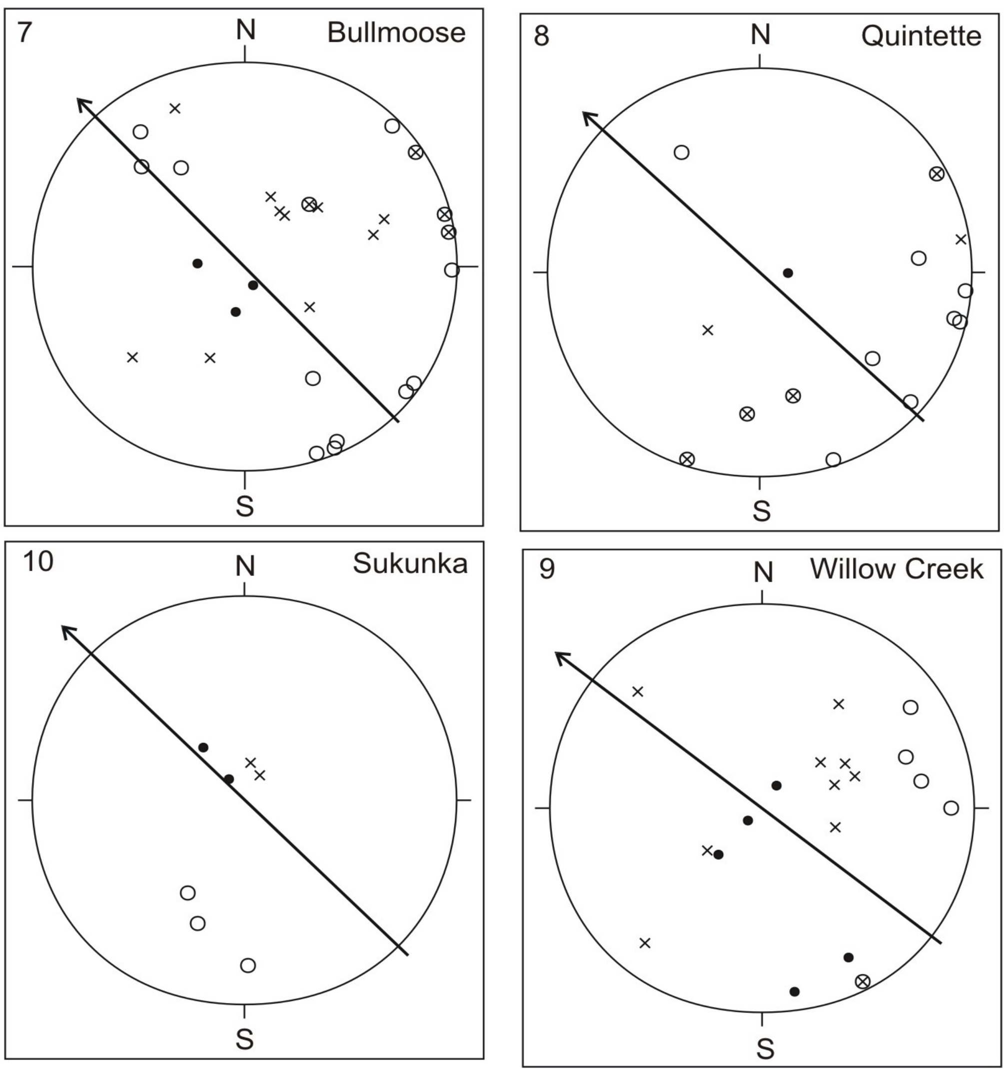

Figure 8: Sterionet of shear joints and cleats in northeast coalfields.

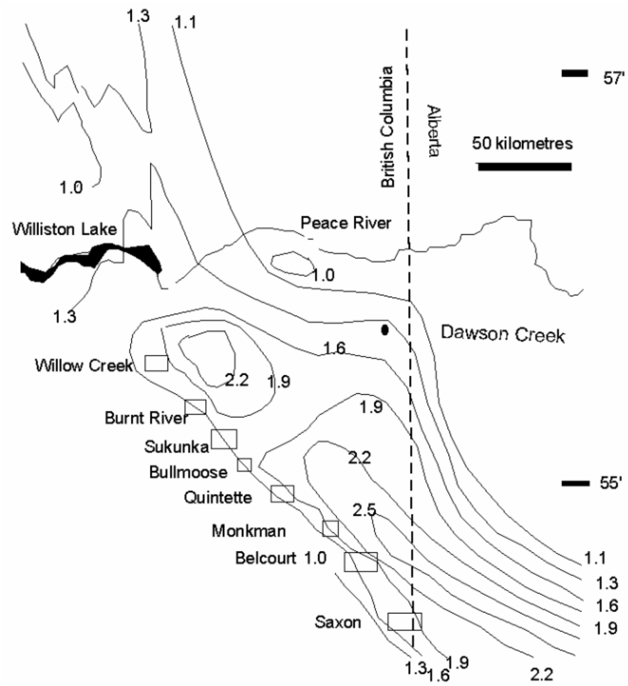

Figure 9: Reflectnace isograds for the top of the Gething Formation adapted from Machioni and Kalkreuth, (1992).

section are under saturated because they were hotter, did not have access to CO_2, and retained a thermogenic imprint. As discussed later it does appear that coals lower in the Mist Mountain section are under saturated but the above explanation cannot be used because the depth of burial of Mist Mountain coals at the time of the Cadomin unconformity was too shallow and subsequent increase in rank would have generated sufficient methane to remove any imprint of the unconformity.

The Cadomin Formation, which ranges up to 170 metres thick (White and Leckie, 2000), forms the base of the Lower Cretaceous Blairmore Group. It was probably deposited from about 140 to 125 my. Based on palynology data discussed by White and Leckie (2000). There is therefore not a major time difference between the deposition of the Elk and Cadomin formations. The Blairmore Group, which was deposited disconformably on top of the Kootenay Group spans the time 140 to 95 my. and therefore deposition predates formation of the Lewis Thrust, which was active from 74 to 59 my. (Sears, 2001). The thickness of the group ranges from 365 to 2000 metres (Price, 1961). It is overlain by the upper Cretaceous Crowsnest Formation (mainly alkaline volcanics), which is 40-100 metres thick below the Lewis Thrust, but does not occur within the thrust sheet. The Formation is dated at 95 my. using K-Ar (Follinsbee *et al.*, 1957) and its deposition therefore predates formation of the Lewis Thrust. Outcrops of the Upper Cretaceous Alberta Group survive in the Crowsnest Coalfield in the core of the McEvoy syncline where it is up to 750 feet thick.

Prior to thrust development in the period 74 to 59 my, seams in the Mist Mountain Formation were probably covered by over 3000 metes of rock composed of the cumulative thickness of the Elk Formation, Blairmore Group, Crowsnest Formation and Alberta Group. This is supposing that additional thrusts were not stacked on top of the Lewis Thrust sheet. At a depth of 3000 to 4000 metres and based on normal geothermal gradients, seams in the upper part of the Mist Mountain Formation would have achieved a rank of high-volatile bituminous represente‘d by Rmax values in the range of 0.6% to 0.8%. Seams lower in the section would have achieved higher rank. Thus at the time when Cordilleran orogenic forces to the west initiated development of the Lewis Thrust, some seams in the Mist Mountain were possibly over pressured with CO_2 laden water and in an ideal condition to participate in thrusting on all scales**.** Pearson and Grieves (1986) document evidence for post folding coal maturation in the southwestern corner of the Crowsnest Coalfield.

The Lewis Thrust carried a thick slab, which probably consisted of over 6000 metres (Price, 1962) of Paleozoic and Mesozoic rocks eastward over rocks as young as Mesozoic. Osadetz *et al*. (2003) estimate the thickness at over 7 km. Movement took place in the period from 74 to 59 my. at a rate of about 1.5 centimetres per year in the Crowsnest Pass area based on an estimated cumulative offset of between 140 and 200 km. Initiation of movement is indicated by profound cooling in the thrust block at about 75 my (Osadetz *et al*., 2003).

Thrust movement resulted in an increase in topography. It also fractured the cold and brittle thrust sheet increasing permeability and allowed cold fluids to reach greater depths (Price *et. al*. 2001). This refrigeration of the thrust sheet delayed increase in rank and reduced the risk of gas loss because the decrease in temperature increased the adsorption ability of seams. However at the time that this was occurring the Bourgeau Thrust (Figure 1) was emplacing Paleozoic carbonates over the Lewis Thrust and it was easy for fluids containing thermogenic CO_2 contained in the Paleozoic limestones to move downwards into the Lewis Thrust block. At the time of emplacement of the Bourgeau Thrust over the Lewis Thrust block, folds in the Lewis thrust block would probably be largely formed and to some extent depth below the overlying Paleozoic limestones would in part be controlled by stratigraphy and in part by position in folds. This may explain the high CO_2 concentrations seen in some of the upper seams in the Elk Valley (Figure10) (data from holes drilled by Norcen in 1990, Dawson *et al.*, 2000). There is therefore reason to suspect that the CO_2 is thermogenic though this cannot be confirmed with out isotope data.

There is very limited public data on CO_2 concentrations in coals in the Crowsnest coalfield. A report Rice (1918) provides some analyses. In 1916, 5 samples were collected from the working face in the underground Coal Creek Colliery and placed into sealed jars (Table 2). When the gas was analyzed it was apparent that all had leaked, however the CO_2 content is estimated

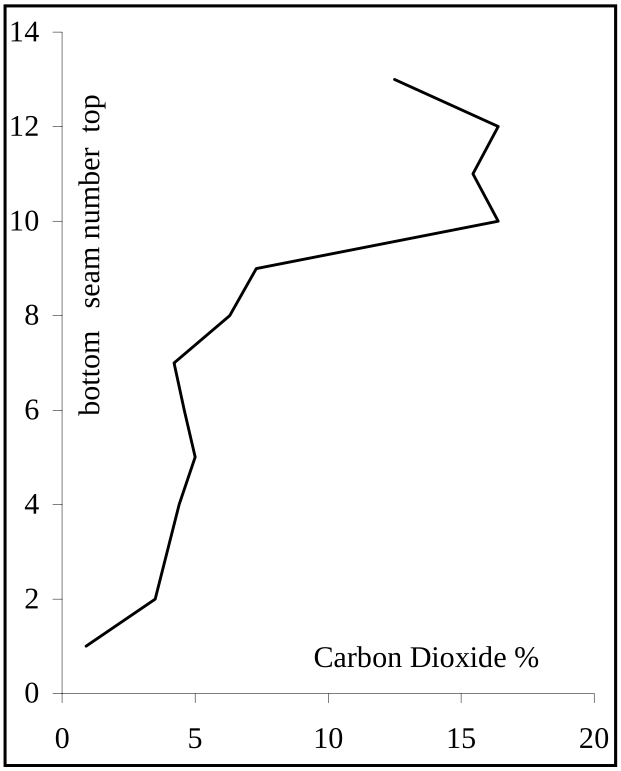

Figure 10: Elk Valley Coalfield, carbon dioxide contents by seam Norcen 1990 holes Elk Valley, (Dawson et al., 2000).

from the $CO_2/(CH_4+CO_2)$ ratio and it appears that except for one sample, CO_2 contents were probably less than 5% (data are reported as cc per 100 grammes equivalent to mole fractions). Based on the trace of the Bourgeau Thrust relative to the outcrop of the basin (Johnson and Smith, 1991 and Monahan, 2002), it appears that seams in the Mist Mountain Formation in the Crowsnest Coalfield may not have been as close to the limestones in the overlying Bourgeau thrust plate as seams in the Elk Valley Coalfield or close to the Crowsnest Volvanicsas and may therefore have lower CO_2 concentrations.

There is no public isotope data for the methane in the Elk Valley or Crowsnest coalfields however some compositional data provide hints as to the origin of the gas. The ratio C1/(C2+C3) is an indication of the thermogenic component of methane and ratios less than 100 tend to indicate thermogenic methane and ratios greater than 100 indicate biogenic methane (Wiese and Kvenvolden, 1993). This is complicated by the fact that biogenic activity can crack heavier hydrocarbons in thermogenic methane increasing the C1/(C2+C3) ratio and that at high ranks there may be secondary cracking of condensates to methane to increase the ratio. Also probably inert rich coals will generate gas with higher C1/(C1+C2) ratios. These processes are illustrated in Figure 11 from Warwick *et al.*, (2002).

In the Elk Valley, CO_2 increases as the ratio C1/(C2+C3) decreases in holes drilled by Norcen in 1990 (Figure 12) and increases for seams higher in the section (Figure 10). This tends to confirm a thermogenic origin

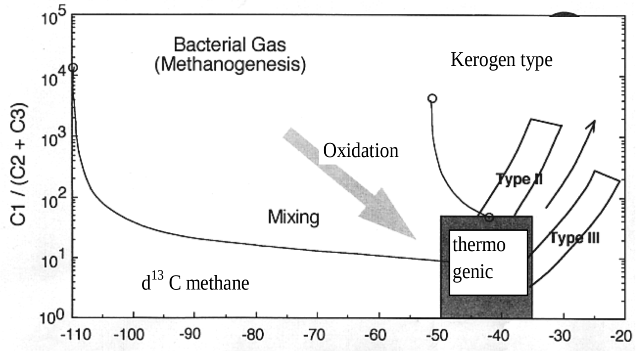

Figure 11: Isotope and gas comp diagram from Warwick et al., (2000).

for the CO_2. It also appears that seams lower in the section may have a biogenic imprint (high C1/(C2+C3) ratios) (Figure 13). The C1/(C2+C3) ratio varies during desorption and it is not clear at what stage of desorption into the canisters that the Norcen gas samples were collected. However gas composition data (Figure 14) collected from the hole drilled by Suncor into the Alexander syncline in the Elk Valley is for a single desorbing sample and indicates the extent that CO_2 concentrations and C1/(C2+C3) ratios can change during the desorption experiment. It is apparent that the range over which these values change within a single canister cannot explain the range in values seen in Figures 12 and 13.

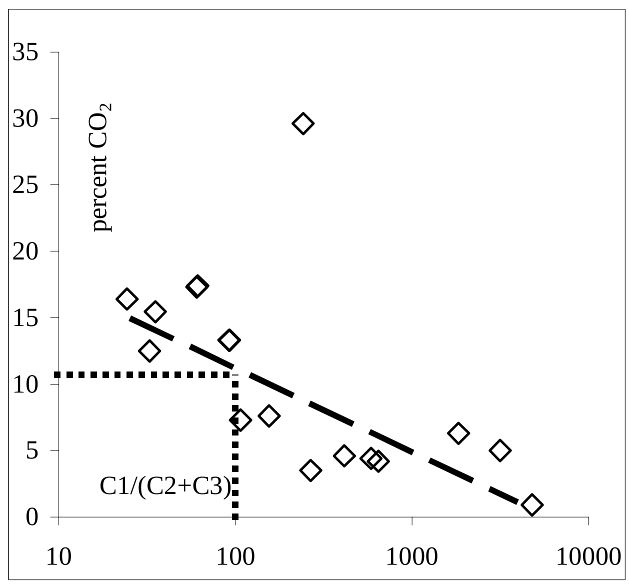

Figure 12: Elk Valley CO2 versus C1/(C2+C3) ratio for Norcen 1990 holes Elk Valley (Dawson et al., 2000).

The very high C1/(C2+C3) ratios seen in the lower seams may indicate the presence of biogenic methane but it is difficult to envisage a process that introduces biogenic methane into the lower seams but not into the upper seams. Alternatively the high ratios may indicate gas generated from liptinite poor and inertinite rich seams, in which case there should be a close correlation

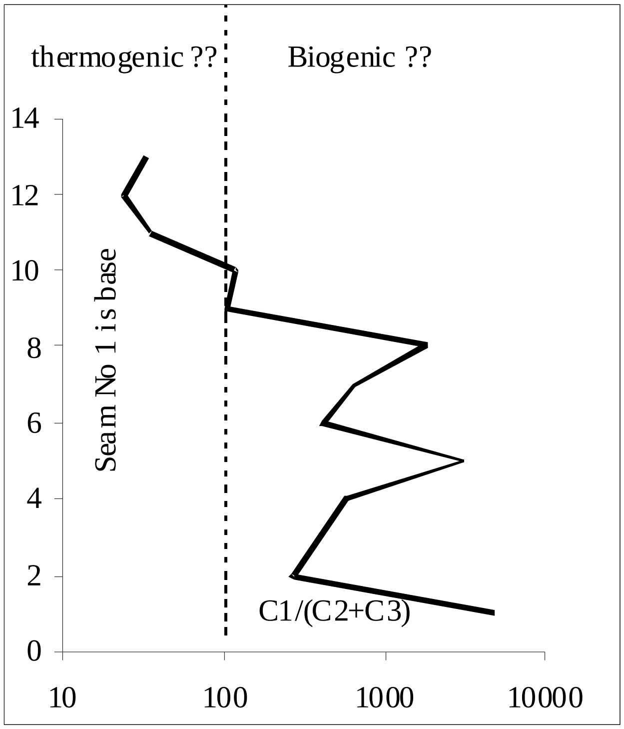

Figure 13: C1/(C2+C3) ratios versus seam number Norcen 1990 holes Elk Valley (Dawson et al., 2000).

between coal seam petrography and C1/(C2+C3) ratios. Grieve (1993) provides petrographic analyses of coals at Weary Ridge in the north end of the Elk Valley Coalfield close to the Norcen holes and similar data are available for the southern end of the coalfield (Figure 15). In both cases it is clear that there is considerable variation in vitrinite content in the lower seams and though usually the third seam above the base of the Mist Mountain Formation has a high inertinite content, other seams have variable and not necessarily low vitrinite contents. There is no clear correlation of high C1/(C2+C3) ratios with low vitrinite content. It is unlikely that petrography alone can explain the high C1/(C2+C3) ratios.

Often the degree of under saturation of a single seam increases with depth (Figure 16). In part the apparent near saturation of seams higher in the section may be because they contain a mixture of CH_4 and CO_2 and the total gas contents are being compared to CH_4 isotherms. In general partial degassing of a seam should decrease the C1/(C2+C3) ratio of the remaining gas. The high ratios are characteristic of seams irrespective of the depth at which they were sampled. The rank in the northern end of the Elk Valley Coalfield is higher than to the south and Rmax values range from 1.0% to over 1.6% (Grieve, 1993). It is possible that at the higher ranks thermal cracking of the heavier hydrocarbons has increased the C1/(C2+C3) ratio.

After emplacement of the Lewis Thrust, and before removal of the overlying Bourgeau thrust sheet, Laramide heating may have been responsible for increasing the rank of Mist Mountain coals. Symons *et al.*, (1999) discuss evidence for a Late Cetaceous to Tertiary Laramide heating and dolomatization event. This heating event must have ended prior to normal movement on the Flathead Fault at about 46 my. Evidence for post deformation maturation is recorded in the Crowsnest Coalfield by Pearson and Grieve (1985) and is evidenced in some deep drill holes (Bustin and England, 1989).

This second heating event may have effected seams low in the section more than seams higher in the section. Previously generated wet gas was expelled upwards and the increased rank was responsible for generating more gas with a much higher C1/(C2+C3) ratio. Because this event occurred after folding within the Lewis Thrust it was possible for gas to move upwards within a single seam until the decrease in temperature allowed it to be re adsorbed. It is important to remember that the heavier hydrocarbons have different adsorption characteristics than methane and will be preferentially adsorbed, where as some of the methane may escape the system. This could explain lower C1/ (C2+C3) ratios for seams higher in the section or at shallower depth.

The increase in rank of seams at depth or lower in the section was accompanied by matrix shrinkage that temporarily improved permeability allowing gas expelled because of increased temperature to move upwards either through the stratigraphy or along seams. The duration of the heating event was limited by the rapid unroofing of the Lewis Thrust sheet.

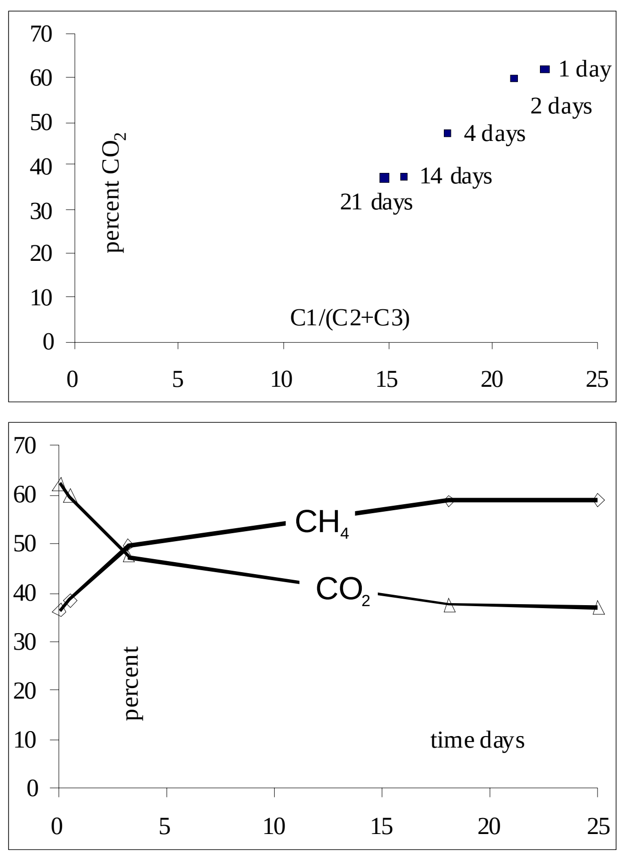

Figure 14: Data set of C1/(C2+C3) data from a single canister numbers are day after canister sealed. Suncor data, Elk Valley Coalfield (Dawson et al., 2000).

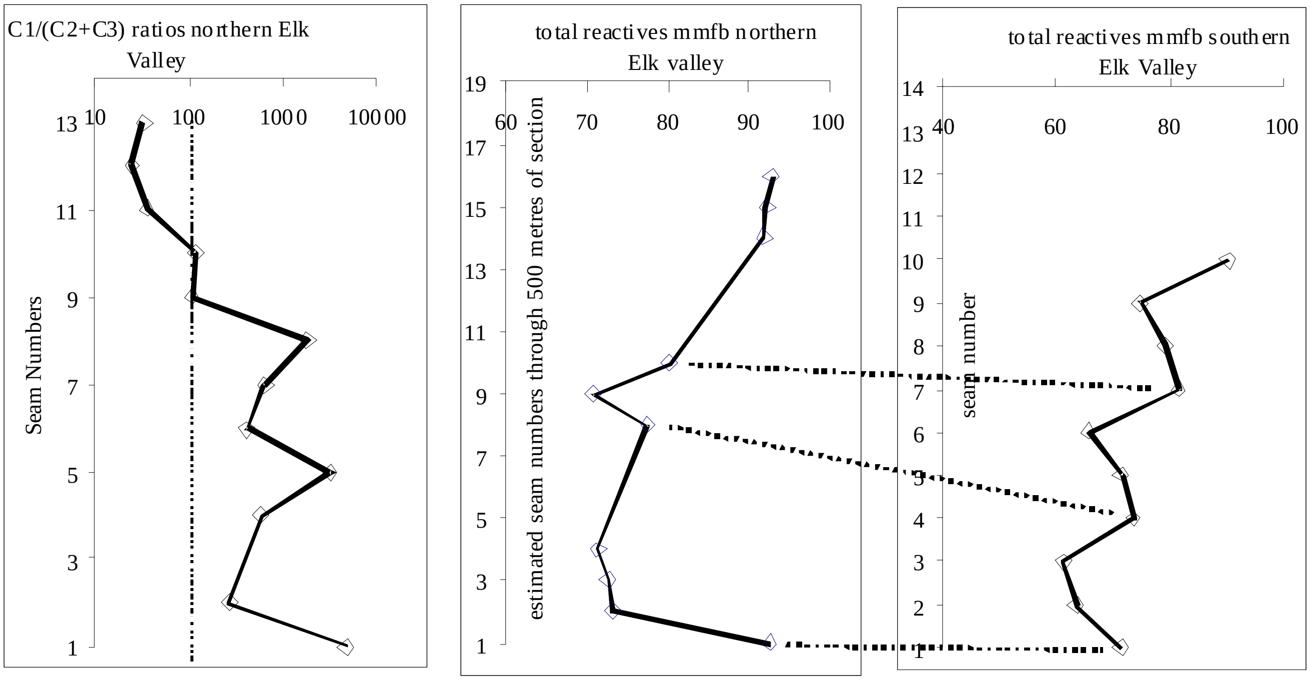

Figure 15: Petrographic variations in the Elk Valley and C1/(C2+C3) ratios. Petrographic data from Grieve (1993). High inert seams should correlate with higher C1/(C2+C3) ratios.

Any post thrusting and folding maturation of coals in the Elk and Crowsnest coalfields could mean that gas expelled from coals undergoing increased maturation would have the opportunity to move into existing structural traps. There should be a clear distinction between structures that act as traps for upward migrating thermogenic methane from those that might act as traps for biogenic gas moved in conjunction with ground water.

The onset of deformation when coal is at a rank range of 0.5% to 0.8% probably has detrimental effects on cleat development and seam permeability. The linkage results in the extensive shearing within seams and tends to destroy cleats or makes their development un- necessary in terms of the coals response to dehydration and de volatilization.

Present data indicate that permeability of seams in the Elk Valley and Crowsnest coalfields is low (Dawson *et al.*, 2000) and it therefore becomes very important to identify areas of recent stress relief. The Erickson and Flathead fault system may be part of the same failed thrust system in which the upper plates slipped back. If this is the case, then part of the plate may be in extension and this would improve permeability within seams. Movement on the Lewis Thrust increases to the north across the US border implying a clockwise rotation of the thrust sheet and this is consistent with the development of right lateral strike slip motion on a number of major faults. Stress environments around these faults may indicate areas of extension.

COMPARISONS BETWEEN NORTHEAST AND SOUTHEAST BRITISH COLUMBIA COALFIELDS

Coal bearing rocks of interest to CBM exploration in the Peace River Coalfield are contained in the Gething and Gates formations (Table 3). These formations cover the age span of about 110 to 100 my. (Mossop and Shetsen, 1994). They overly the Cadomin Formation and make up the second major Cordilleran-derived clastic wedge of the foreland basin. They record the first basin-wide sedimentation (Mossop and Shetsen, 1994, Chapter 17) and indicate the north-eastward movement of the center of deposition of the foreland basin. Initiation of thrusting at the craton edge caused it to subside, providing accommodation in the fore deep for the huge volume of sediments shed from the up-thrusted sheets. This thrusting predates the Lewis Thrust in the Elk Valley.

Deformation in the Peace River Coalfield started later than in the southeast coalfields. Coalification generally preceded thrusting and folding (Kalkreuth et al., 1989) and the Gething and Gates formations reached their maximum burial depth about 75 my. in the west and 50 my to the east. This timing of maturation relative to deformation is important because it means that, in the Peace River Coalfield, seams largely matured in the absence of thrusting and therefore may have escaped a lot of in seam shearing. In general, seams in the northeast have better cleat development than seams in the Mist Mountain Formation. However gas generated during

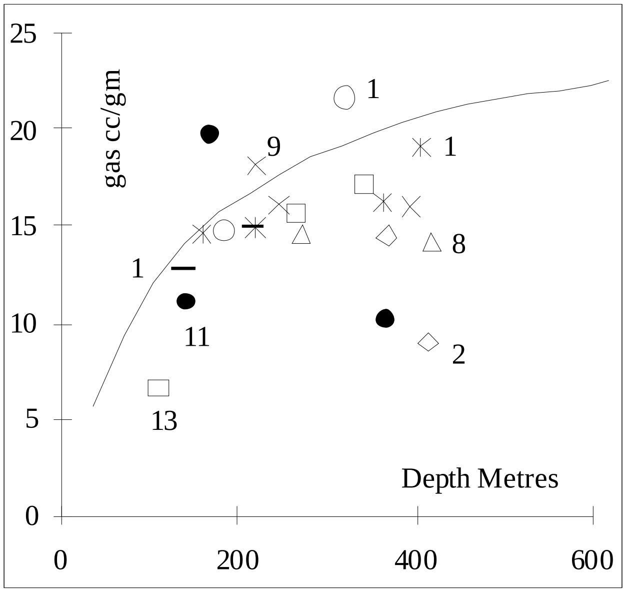

Figure 16: Desorption data from Norcen holes 1990 the Elk Valley (Dawson et al., 2000).

coalification did not have the opportunity to be contained in structural traps. At this stage only stratigraphic traps were effective for containing thermogenic methane expelled from seams. Later thrusting and folding caused extensive deformation in seams in some areas but not in others.

There is limited public desorption data available for seams in the Peace River Coalfield. Data from the Gates Formation (Phillips holes drilled in 1996, Dawson *et al.*, 2000) indicate that seams are nearly saturated. Also the gas has a clear thermogenic fingerprint based on C1/(C2+C3) ratios (Figure 17). The CO_2 concentrations are less than in the Norcen holes in the Elk Valley and increase as the C1/(C2+C3) ratio decreases and as depth increases. It appears that the CO_2 is of deep and thermogenic origin. Thrusting in the Peace River Coalfield has not emplaced Paleozoic limestones over Cretaceous coal bearing rocks and there are no extrusive or intrusive magmatic rocks in the sequence therefore access to thermogenic carbon dioxide is probably via deep faults.

There is probably semi quantative information that can be gleaned from the desorption curves. Airey (1968) modeled the shape of the desorption curve and indicated that his constant “to”, which is the time to 63.2% of total desorbed gas is strongly dependent on the degree of fracturing of the coal. This is confirmed by work of Harris *et al.*, (1996). Work by Gamson *et al.*, (1996) indicates that desorption time is also dependent on coal petrology with dull lithotypes desorbing faster. Data for Mist Mountain Formation coals indicate that they generally have desorption times (63.2% of total desorbed gas) less than 30 hours (Dawson, 1993, and Feng *et al.*, 1981). However desorption times for Gates Formation coals from the Phillips drill program in the Peace River Coalfield (Dawson *et al.*, 2000) average over 70 hours. On a regiona l scale desorption times may indicate the

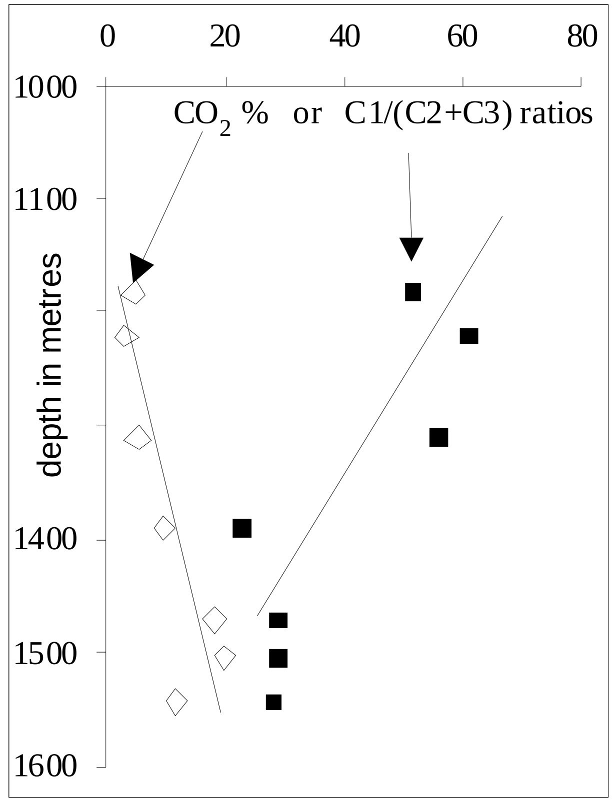

Figure 17: C1/(C2+C3) ratios for Gates Formation coals, Phillips exploration project 1996, (Dawson *et al*., 2000).

degree of micro fracturing of coals and pervasive deformation. On the local scale they may correlate with a combination of petrography and fracture size. As a caution desorption times can also be influenced by the way the desorption experiment is conducted.

In the northeast variation in rank must be explained by variation in stratigraphic thickness or by variation in upward heat flow because coalification preceded deformation. There are a number of enclosed areas of high rank apparent in the Gething Formation (Marchioni and Kalkreuth, 1992) (Figure 9) and depending on their origin they could have implications for CBM exploration. One that is very conspicuous is located between the Willow Creek and Burnt River properties (Figure 9) and is responsible for locally increasing the rank of seams in the Gething Formation to semi anthracite. If convective movement of fluids causes rank increase, then methane could be swept out of seams and CO_2 introduced. On the other hand if it is caused by increased burial, then there is more chance that seams will retain methane and less chance of introduction of CO_2.

Convective movement of fluids should be evident by mineralization on cleat surfaces. Spears and Caswell (1986) provide estimates of the temperature of deposition for a number of diagenetic minerals found on cleats. Calcite and ankerite are deposited in the temperature range 100°C to 130°C, which corresponds to a rank of high-volatile bituminous. This represents the final expulsion of diagenetic water from seams. At this time cleats have already formed and may be mineralized. For higher rank coals preservation of calcite on cleats indicates that hotter fluids associated with the higher rank did not remove calcite. The rank of the Gething and Gates formation coals is generally higher than high-volatile bituminous and there is calcite on face cleats in Gates coals and indications of calcite on cleats in Gething coals.

Coal ash generally has CaO contents less than 4%; higher contents often indicate the presence of carbonates on cleats, especially if a plot of ash *versus* CaO% indicates that CaO concentrations increase as ash contents decrease. In fact in the absence of other data, ash chemistry data, available from existing coal studies, can provide information on the possible prevalence of carbonate on cleats. Calcite is present on cleats the lowest seam in the Comox Formation in the Quinsam area (Ryan, 1994), whereas calcite is absent on cleats in seams from the lower part of the Mist Mountain Formation but does occur on some seams in the upper part of the formation. These cleat facies are easily separable on a CaO *versus* ash plot (Figure 18).

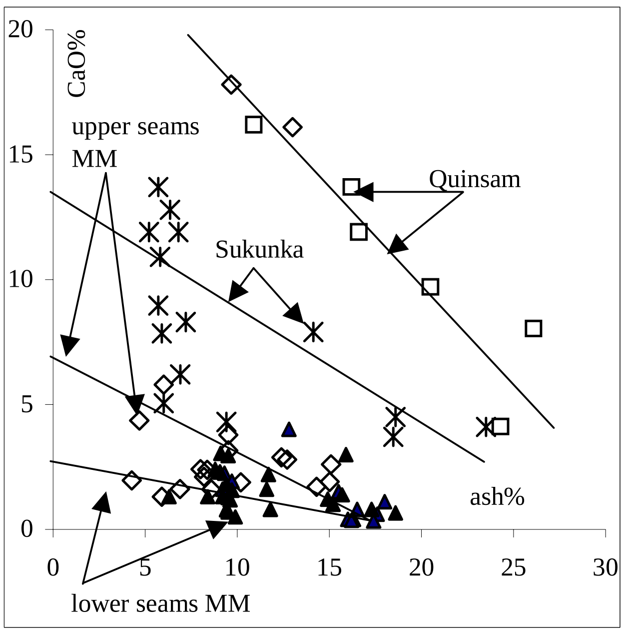

Figure 18: CaO% versus Ash% for seams from the Mist Mountain, Gething and Comox formations.

The limited amount of CaO analysis data available for Gates and Gething coals indicates that there is probably some calcite on cleats in Gething coals from south of Willow Creek to Sukunka River and in Gates coals from Bullmoose to Belcourt. The area of high rank in the Gething Formation centred on Highhat Mountain (Marchioni and Kalkreuth, 1992) does not appear to be an area where there is unusually high or low CaO in the ash. Two analyses from the Burnt River property, which is at the center of the area, are both under 3% CaO. A late thermal event would be expected to introduce CaO and CO_2 into the system on one hand leaving calcite on cleats and the other replace CO_2 with CH_4 in coal. A high temperature thermal event may introduce CO_2 and remove CH_4 from the coal and CaO from cleats. A more detailed study of ash chemistry may lead to a better indication as to whether to expect increased CO_2 in high rank areas of the Gething Formation

THE INTERPLAY OF COAL CHARACTERISTICS AND RECENT TECTONICS

Coal preparation involves the removal, of rock from the coal to reduce the ash concentration to acceptable levels for the customer. Luckily coal is less dense than rock and this property is used to advantage in wash plants, as also is the fact that coal is generally less wettable than rock. The hydrophopicity of coal *versus* rock is used for cleaning fine coal by froth floatation. The wettability of coal varies with rank, largely because as rank increases different oils and gases are expelled. This is referred to as the oil window (Dow, 1977) and is defined by Rmax values in the range of 0.5 % to 1.35%. The hydrophobicity of coal attains a maximum value in the middle of the rank spectrum at ranks ranging from Rmax =1% to 1.6% and is measured by contact angle of fluid on the coal surface (Osborne, 1988) (Figure 19).

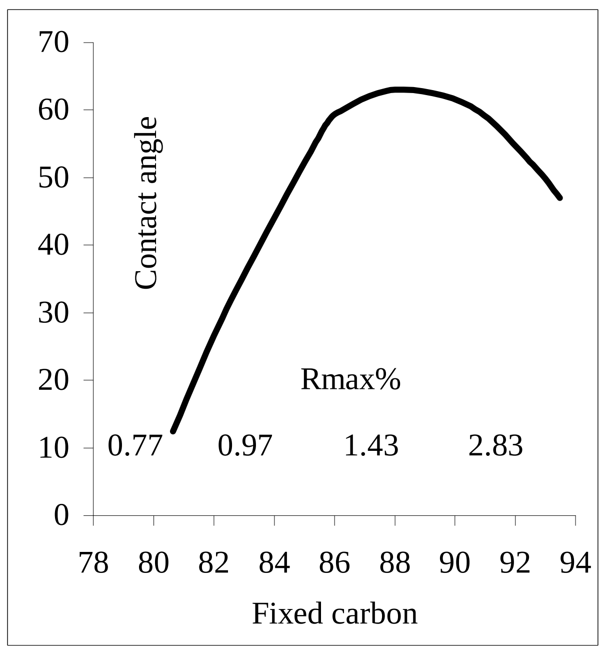

Figure 19: contact angles for coals of different rank (Osborne, 1988).

Obviously the exact placement of the oil window depends on the petrography of samples. Samples with high liptinites contents will generate oil at lower ranks. The generation of oil at medium rank probably affects the adsorption and surface properties of coal as discussed by Levine (1993). The most obvious effect on surface properties is that of capillary action or wetting as measured by contact angle. Another way of estimating the wettability of coal is to measure the difference between equilibrium moisture and air-dried moisture. This difference is probably a good measure of surface moisture and the value also is at a minimum for the range of ranks 0.9 to 1.5% (Figure 20). The shift to higher ranks of the surface effects from the oil window probably indicates that it is the heavier oils that have the most effect on surface wetting.

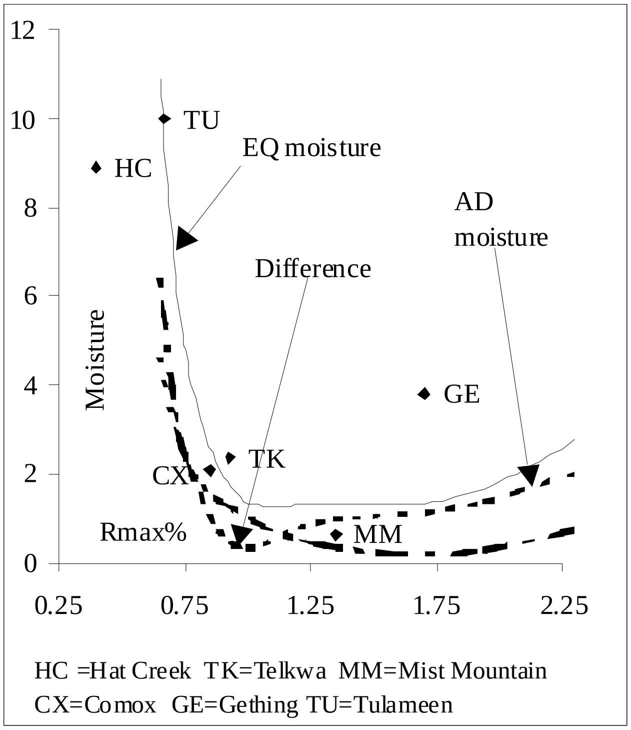

Figure 20: contact angles for coals of different rank (Osborne, 1988).

The minimum wettability identifies coals that will have longer diffusion times, but will have better relative permeability for gas because of lower water saturation on cleats than high or low rank coals. High or low rank coals with high wettability will have higher water saturation on cleat surfaces than mid rank coals and under set conditions will have lower relative permeability. This is because cleat surfaces of mid rank coals can be dewatered to lower saturation values and the relative permeability of gas approaches more closely the maximum permeability for a single fluid in the cleat system. Obviously coals in the mid rank window may have reduced adsorption ability (Levine 1993) but cleats may contain little water and they may produce gas with minimal extraction of water.

Even with low wettability on cleat surfaces, over time cleats will probably become water saturated. The ideal situation is one where cleats are opened up fairly recently. This would cause a decrease of pressure and desorption of gas into the cleats. Under these conditions a seam would be saturated because the adsorbed gas would be in contact with a free gas phase. The seam may be under pressured and gas contents may be low but gas will be produced quickly with little water production. Obviously this requires the combination of recent stress relief an opening of cleats (but not too much) and the correct rank window for the coal.

There are a number of areas where Tertiary stress fields are oriented such as to open cleats. However much of Canada has the advantage of another regional event that could help open cleats. The country is undergoing isostatic rebound as a result of the removal of the continental ice sheet. Uplift amounts are in the order of ten's of metres. The rapid removal of overburden pressure and resultant decompression of the more compressible units (coal) results in extension in a vertical direction and contraction in a horizontal direction. This will open cleats and for coals with low wettability, water may not have had time to penetrate all cleat surfaces because uplift is relatively recent.

CONCLUSIONS

British Columbia contains a very large coal resource available for CBM exploration. However much of this resource is in areas of fairly complex geology. Learning how to over come the challenges resulting from the geology by exploration can be expensive. Sometimes making better use of existing databases can reduce the cost.

The relative timing of deformation and the time at which the coal (based on rank) is the most susceptible to deformation is important. It affects the degree to which cleats form or are preserved in seams. Early deformation occurring when the rank is high-volatile bituminous may result in pervasive shearing of coal seams and limited development of cleats. Deformation that occurs later, after coal maturation has progressed, may cause more limited damage to cleat systems.

The orientation of cleats and fractures can help in understanding the sequence of deformation and coalification. The main problem for the geologist maybe remembering long passed structural geology courses.

Coalfields in southeast British Columbia occupy the Lewis Thrust Sheet and are partially over ridden by the Bourgeau Thrust Sheet. Coal may have attained maximum rank after thrusting and consequently may have experienced in seam deformation related to the Lewis Thrust. Thrusting also may be in part responsible for the introduction of thermogenic (?) CO_2.

In the Peace River Coalfield deformation post-dated most of the coalification and consequently the degree of in seam deformation is variable and in places seams retain good cleating. Rank in the Peace River Coalfield is more variable than in the southeast. This may indicate fluid movement that could be associated with lower gas contents and introduction of CO_2. However ash chemistry data collected from existing exploration projects does not indicate extensive fluid movement but does indicate that some cleat systems are mineralized with calcite.

After all this it may seem that there are more problems than challenges in British Columbia. However we may have at least one possible advantage that our neighbours to the south do not have. Isostatic rebound may be responsible for strain within seams that has opened cleats and improved permeability. This in conjunction with high-volatile coals that resist wetting may provide low-pressure gas saturated systems at moderate depth.

REFERENCES

Airey, E.M. (1968): Gas emission from broken coal: an experimental and theoretical investigation*; International Journal of Rock Mechanics and Mineral Science* Volume 5, pages 475-494.

Bustin, R.M. and England, T.D.J. (1989): Timing of orogenic maturation (coalification) relative to thrust faulting in the southeastern Canadian Cordillera; *International Journal of Coal Geology*, Volume 13, pages 327-339.

Dawson, F.M. (1993): Joint venture project Fording Coal Limited; *Geological Survey of Canada,* Summary Report.

Dawson, F.M. Marchioni, D.L. Anderson, T.C. and McDougall, W.J. (200): An assessment of coalbed methane exploration projects in Canada; *Geological Survey of Canada,* Bulletin 549.

Dow, W.G. (1977): Kerogen studies and geological interpretations; *Journal of Geochemical Exploration*, Volume 7, pages 79-99.

Feng, K.K., Cheng, K.C. and Augsten, R. (1981): Methane desorption of Fording coal from Greenhills multiple seams; CANMET, Energy Research Program, Mining Research Laboratories Division report ERP/MRL 81-67(J).

Freudenberg, U. Lou, S. Schlurer, R Schutz, K and Thomas, K. (1966):Mina factors controlling coalbed methane distribution in the Ruhr district, Germany; Coalbed Methane and Coal Geology, *Geological Society*, Special Publication Number 10, pages 67-88.

Follinsbee, R.E., Ritchie, W.D. and Stansberry, G.F. (1957): The Crowsnest volcanics and Cretaceous geochronology, in 7^{th} Annual Field Conference *Alberta Society of Petroleum Geologists,* pages 20-26.

Gamson, P., Beamish, B., and Johnson, D (1996): Coal microstructure and secondary mineralization: their effect on methane recovery; Coalbed Methane Geology, *Geological Societ,y* Special Publication Number 109, pages 165-179.

Gibson, D.W. (1985): Sedimentary facies in the Jura-Cretaceous Kootenay Formation, Crowsnest Pass area, southwestern Alberta and southeastern British Columbia; *Bulletin of Canadian Petroleum Geology*, Volume 25, pages 767-791.

Gibson, D.W. (1985): Stratigraphy, sedimentology and depositional environments of the coal-bearing Jurassic-Cretaceous Kootenay Group, Alberta and British Columbia; *Geological Survey of Canada*, Bulletin 357.

Grieve, D.A. (1993): Geology and rank distribution of the Elk Valley coalfield southeastern *British Columbia Ministry of Energy and Mines,* Bulletin 82.

Harris, I.H., Davies, A.G., Gayer, R.A. and Williams, K. (1996): Enhanced methane desorption characteristics from South Wales anthracites affected by tectonically induced fracture sets; Coalbed Methane Geology, *Geological Society*, Special Publication Number 109, pages 181-196.

Johnson, D.G.S. and Smith, L.A. (191):Coalbed Methane in southeastern British Columbia; *British Columbia Ministry of Energy and Mines, Petroleum Geology Branch*, Special Paper 1991-1.

Kalkreuth, W. Langenberg, W and McMechan, M. (1989): Regional coalification pattern of Lower Cretaceous coal-bearing strata, Rocky Mountain Foothills and foreland, Canada – implications for future exploration; *International Journal of Coal Geology*, Volume 123, pages 261-302.

Law, B.E. (1993): The Relationship Between Coal Rank and Cleat Spacing; Implications for the Prediction of Permeability in Coal; in Proceedings of the 1993 *International Coalbed Methane Symposium*, May 17-21 1993 Birmingham, Alabama, Volume 2, pages 435-442.

Levine, J.R. (1993): Coalification: The evolution of coal as source rock and reservoir rock for oil and gas; in Hydrocarbons from Coal; *American Association of Petroleum Geologists*, Series number 38, Chapter 3, pages 39-77.

Marchioni, D and Kalkreuth, W. (1992): Vitrinite reflectance and thermal maturation in Cretaceous strata of the Peace River Ach Region: West-central Alberta and adjacent British Columbia; *Geological Survey of Canada,* Open File 2576.

Monahan, P. (2002): The Geology and oil and gas potential of the Fernie-Elk Valley Area, southeastern *British Columbia Ministry of Energy and Mine,* Petroleum Geology Special Paper 2002-2.

Mossop, G.D. and Shetsen, I. (1994): Geological Atlas of the Western Canada Sedimentary Basin; Alberta Geological Survey.

Osadetz, K.G., Kohn, B.P. , Feinstein, S. and. Price, R. A. (2003): Aspects of foreland belt thermal and geological history in southern Canadian Cordillera from fission-track data.

Osborne, D.G. (1988): Coal Preparation technology; *Graham Trotman limited;* page 420.

Pearson, D.E., and Grieve, D.A. (1985): Rank variation coalification pattern and coal quality in the Crowsnest Coalfield, British Columbia; *Canadian Institute of Mining and Metallurgy,* Bulletin, Volume 78, pages 39-46.

Price, R.A. (1957): Flathead Map area, British Columbia and Alberta*; Geological Survey of Canada*, Memoir 336.

Price, R.A. (1961): Fernie map area east half, Alberta and British Columbia 82G E1/2; *Geological Survey of Canada*, Paper 61-24.

Price, R.A.,Kohn, B.P. and Feinstein, S. (2001): Deep refrigeration of a thrust and fold belt because of enhanced syntectonic penetration of meteoric water: the Lewis thrust sheet, southern Canadian Rocky Mountains; *Earth System Global Meeting* June 24-28 2001 Edinburgh International Conference Centre.

Rice, S.G. (1918): Bumps and gas outbursts of gas in mines of Crowsnest Pass Coalfield; *British Columbia Department of Mines*, Bulletin Number 2.

Ryan, B.D. (1994): Calcite in Coal from the Quinsam Coal Mine, British Columbia, Canada, Origin, Distribution and Effects on Coal Utilization; in Geological fieldwork 1994, Grant, B. and Newell, J.M., Editors, *B.C. Ministry of Energy, Mines and Petroleum Resources*, Paper 1995-1, pages 245-256.

Scott, A.R. (2001): A Coalbed methane producibility and exploration model: defining exploration fairways; 2001 *International Coalbed Methane Symposium*, Tuscaloosa, Short Course #1, chapter 5.

Sears, J.W. (2001): Emplacement and denudation history of the Lewis-Eldorado-Hoadley Thrust slab in the northern Montana Cordillera USA: Implications for steady-state orogenic processes; *American Journal of Science*, Volume 301, pages 359-373

Spears, D.A. and Caswell, S.A. (1986): Mineral matter in coals: cleat minerals and their origin in some coals from English Midlands; *International Journal of Coal Geology*, Volume 6, pages 107-125.

Symons, D.T.A., Enkin, R.J. and Cioppa, M.T. (1999): Paleomagnetism in the Western Canada Sedimentary Basin :Dating fluid flow and deformation events; *Bulletin of Canadian Petroleum Geology*, Volume 47, pages 534-547.

Warwick, P.D. Barker, C.E. and SanFilipo, J.R. (2002): Preliminary evaluation of coalbed methane potential of the Gulf Coastal Plain USA and Mexico; *Rocky Mountain Association of Geologists*, Coalbed Methane of North America II, pages 99-107.

White, J.M. and Leckie, D.A. (2000): The Cadomin and Dalhousie formations of SW Alberta and SE British Columbia; age sedimentology and tectonic implications; *Canadian Society of Exploration Geologists*, Conference 2000, abstract.

Wiese, K. and Kvenvolden, K.A. (1993): Introduction to Microbial and thermal methane*; US Geological Survey* Professional Paper 1570, pages 13-20.