COAL UTILIZATION POTENTIAL OF GETHING FORMATION COALS, NORTHEAST BRITISH COLUMBIA

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ABSTRACT

Existing and some new coal quality data from Gething Formation coals are organized to help document changes in rank and coal quality. The formation outcrops in a number of fold trends extending along the length of the Peace River Coalfield. Trends are separated by thrusts or reverse faults. Within the formation the maceral composition of seams is very variable also along strike within each trend rank ranges from high-volatile bituminous to semi anthracite. The coal quality, oxide and trace metal data are interpreted in ways not often applied to data to help differentiate thermal coking and coal used for injection into blast furnaces (PCI coal).

INTRODUCTION

There are two major coal-bearing formations in northeast British Columbia, both of which outcrop extensively the length of the Peace River Coalfield (Figure 1). Coal seams of economic interest are generally contained in the younger Gates Formation (Table 1) in the southern part of the coalfield and in the older Gething Formation in the northern part of the coalfield. The area where exploration interest tends to switch formations is in the vicinity of Mount Spieker (Figure 2).

The Gething Formation, which is Early Cretaceous, overlies the Cadomin Formation (Table 1) and is therefore younger than the Mist Mountain Formation, which outcrops in southeast British Columbia and underlies the Cadomin Formation. The type section for the Gething Formation is in the Peace River Canyon where it is 550 metres thick (Gibson, 1992). It generally thins to the south and at the Saxon Property (Figure 2) at the southern end of the coalfield, is only 7 metres thick but still contains coal seams.

Recently coal prices have risen substantially sparking a renewed interest in the economic potential of coal in the Gething Formation. In fact at present there are two mines extracting coal from the formation and at least four advanced exploration programs. In the north, Pine Valley Mining Corporation is mining coal from its Willow Creek mine at an average rate of about 60 000 tonnes/month and intends to increase annual production to 2.2 million tonnes in the near future. To the south, Western Canadian Coal Corporation is extracting coal from the small Dillon pit on its Burnt River property and hopes to commence operations on the adjacent, and much larger, Brule pit shortly. The mine is presently operating at a maximum of 80 000 tonnes/month. Several companies are also exploring along the Gething coal trend from Pine Pass to Five Cabin Creek (Figure 2) and coal tenures cover most of the land underlain by coal.

Coal seams in the Gething and Gates formations have different coal quality characteristics. The quality and rank of coal in the Gates Formation do not vary greatly along the coal trend. In contrast, the rank of coal in the Gething Formation ranges from high-volatile bituminous to semi-anthracite and there are also significant changes in other coal quality characteristics. The quality of Gething coals was studied by a number of authors and is summarized most recently by Ryan (1997). The wide range of coal rank in the formation means that, depending on location, Gething coals may be thermal coals, coking coals or low-volatile PCI coals (coal used for pulverized coal injection in blast furnaces). In addition the variable organic inerts content of seams has a major influence on the quality of coke made from coals in the coking-coal rank window (approximately 1.0% to 1.6% Mean maximum vitrinite reflectance Rm%) and can extend or contract the rank range over which the coal has coking potential.

As a warning to the occasional reader; rank indicated by measurements of vitrinite reflectance is reported as mean maximum reflectance of vitrinite in polarized light in oil (Rm) or mean random reflectance of vitrinite in oil in non polarized light (Ro) and occasionally as true maximum reflectance of vitrinite in oil in polarized light (Rmax). Mean maximum reflectance is about 10% greater than mean random reflectance based on various empirical relationships. In this paper an attempt is made to report all data as Rm.
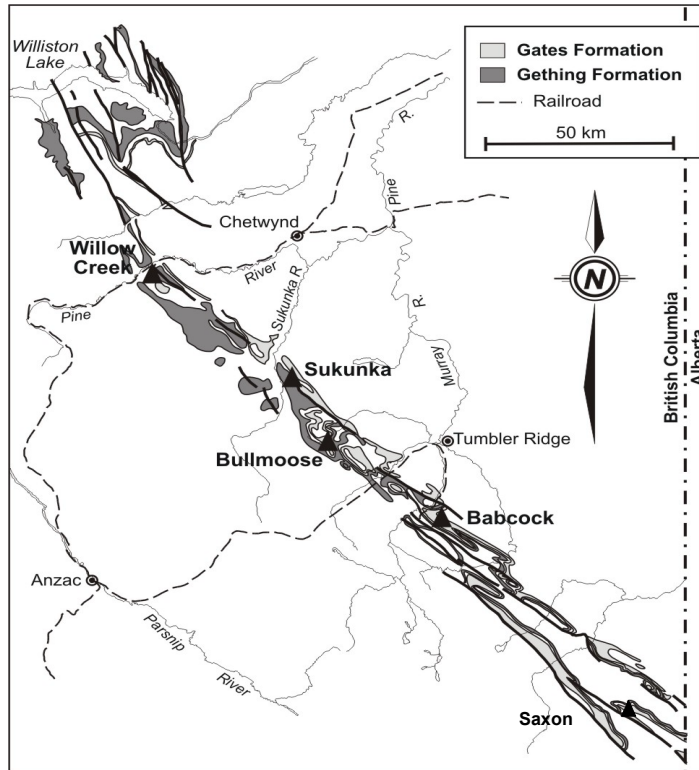
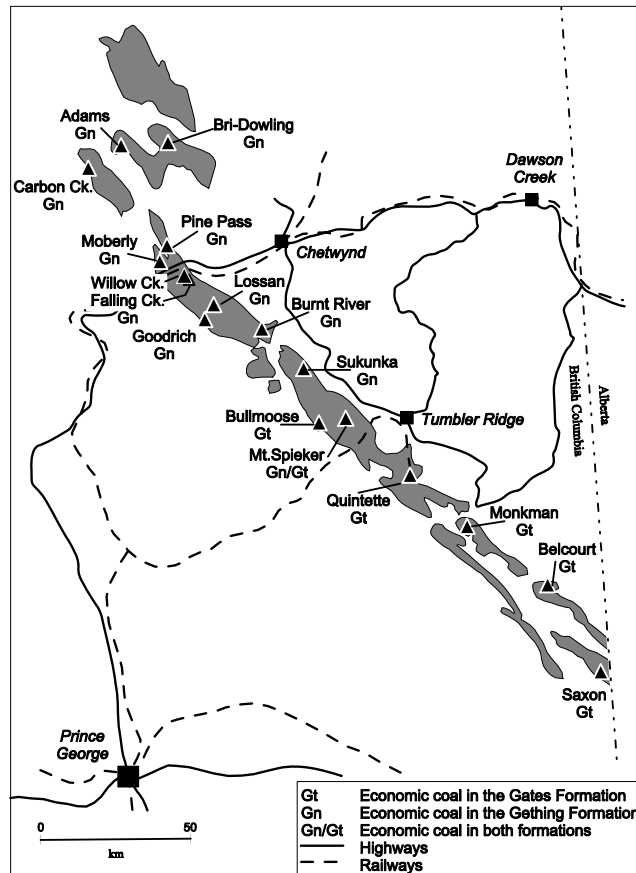Figure 1. Regional geology of the Peace River Coalfield; outcrop of Gething and Gates formations.

Figure 2. Property locations Peace River Coalfield: Mt Spieker, Saxon, Sukunka and Lossan.

TABLE 1. STRATIGRAPHIC TABLE NEBC

	NORTHEAST			SOUTHEAST	
Age	Group	Formation	Description	Formation	Group
Lower Cretaceous	Fort St. John	Hasler	Marine shale		
		Gates	Non marine sandstone, siltstone and **coal.**		
		Moosebar	Marine shale.		
	Bullhead	Gething	Siltstone, mudstone and **coal.**		Blairmore
		Cadomin	Conglomerate.	Cadomin	
Lower Cretaceous and Jurassic	Minnes		Non marine sandstone, siltstone and minor **coal.**	Elk	Kootenay
			Sltstone, mudstone and **coal.**	Mist Mountain	
	Fernie		Sandstone, siltstone and shale.	Morrisey	Fernie

There is a long history of coal exploration in the Peace River Coalfield, and numerous informal property names have resulted. With the up-swing in exploration some of these names are retained, often applied to slightly different areas and in other instances new names are used. Some of the long standing names often connect to Coal Assessment Reports submitted to the government during the period of intensive exploration from 1975 to 1985 and stored in the Ministry of Energy, Mines and Petroleum Resources building Victoria or on the Ministry web page as pdf files. They often provide a treasure trove of coal quality information that is still useful today.

COAL QUALITY OUTLINE

Coals from the Gething Formation have the potential to be sold into three markets; thermal coals (low to moderate rank and low price); coking or metallurgical coals (medium rank and high price) and high rank low-volatile PCI coals (moderate price). Each of these categories has some-what different coal quality requirements. In simplistic terms, there are three important and fundamental coal quality parameters that interact to determine the quality of a coal especially its coke-making potential. These are rank, coal petrography (inerts/vitrinite ratio) and ash chemistry. The Gething Formation, probably more than any other coal bearing formation in British Columbia, exhibits a wide range in these three important quality parameters.

There are numerous quality parameters measured on coke that are predicted with more or less reliability using coal quality parameters. ASTM Coke stability is predicted (sometimes not very well) using coal petrography and rank, whereas prediction of coke strength after reaction (CSR) requires the introduction of at least the third variable, ash chemistry and often a

fourth, coal rheology. Obviously these approaches ignore the effect of process variables and size-consist, both of which can substantially influence CSR and ASTM Coke Stability. In fact it is often forgotten that both stability and CSR decrease as the size of inert particles increases. It is important to consider the size of ash particles that remain in the wash coal but it is also important to consider the size of inert coal fragments (intertodetrinite fragments) in the coal especially in coals with high proportions of inert macerals. Small inertinite fragments may actually enhance Stability whereas large semifusinite particles may act to decrease Stability (Lui and Price, 1991).

This report documents rank, which varies from high-volatile bituminous to semi-anthracite, using conventional reflectance analyses and rank calculated from volatile matter (dry ash free) values (VM daf). Variation in petrography is documented by microscope maceral analyses but is also indicated by variation in VM daf values *versus* depth and ultimate analyses plotted onto Van Krevelen Diagrams. There is evidence in a lot of coal quality data from the formation that seams are characterized by large variations in inertinite content and petrographic analyses indicate inert variations from 10% to over 70%. Many reports mention variable FSI values for apparently low ash un-oxidized samples and this probably indicates varying inertinite content. Plots of VM daf *versus* depth do not provide consistent trends of decreasing VM daf with depth and the saw tooth pattern probably also reflects major changes in the inertinite content of seams.

Coal Assessment Reports provide a lot of coal quality information on Gething coals, though not always of a type that is relevant for the present study. As an example, there are many proximate analyses but very few rank or petrographic analyses, which are more useful for an over-view study. Often rank is estimated from values of volatile matter corrected to a mineral matter free basis (VM dmmf) or dry ash free basis (VM daf). The relationship between VM daf and rank is illustrated by a number of authors (Figure 3 adapted from Taylor *et al.,* 1998). It should be noted that the diagram uses mean maximum reflectance (Rm) and presumably samples that are close to 100% vitrinite. As the amount of inertinite in a sample increases a lower VM daf value corresponds to the same rank. Consequently any estimation of rank from volatile matter measurements must also take account of the petrography of the sample. Estimating VM daf from high-ash samples does not provide accurate values of VM daf. In this case it is better to plot a set of ash *versus* VM daf data and project back to derive the value VM daf value at zero ash.

An equation was derived to predict rank using VM daf and percent reactives in a previous paper (Ryan, 2002) and is adapted here based on data from the Lossan Property (Figure 2), which includes proximate and petrographic analyses. The Equation predicts rank based on VM daf and percent reactives or predicts variation in petrography if rank and VM daf values are known:

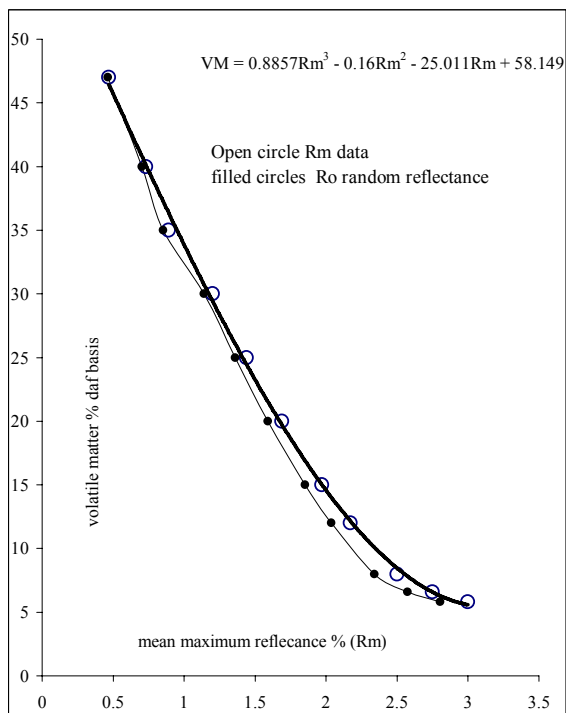**Rm=-0.7431*ln(VM daf)+0.004486*(reactives%)+2.967 Equation 1**

Figure 3. Relationship of VM daf to random reflectance; diagram simplified from Taylor *et al*., (1998).

Obviously the equation provides only an approximation of any one of the three variables if the other two are known. The estimation of the percent reactives in a sample depends on the assumption of the amount of semifusinite that is reactive. It is very important to document seam petrography through an area in order to blend a consistent coking coal product.

Vitrinite reflectance is generally considered to be a measure of coal maturity, but it can also be influenced by environment. There are a number of papers that document vitrinite suppression related to hydrogen infusion into vitrinite. There is also the possibility of vitrinite enhancement. Diessel and Gammidge (1998) indicate that early coal forming environments can influence vitrinite reflectance. Partial oxidation in an environment that gives rise to seams rich in inertinite will also produce vitrinite with a higher reflectance than vitrinite in seams that do not form in this type of environment and have higher concentrations of reactive macerals. The difference in reflectance is maintained as rank increases, so that vitrinite in seams that have the same maturity may have different reflectance values; vitrinite in inertinite rich seams having higher reflectance than seams rich in reactive macerals. There are indications that this might be the case for data from the Gething Formation. Rank and petrographic data from Seam 1 Lossan property correlate (Figure 4) and this may be a coincidence or indicate that vitrinite reflectance may be inversely correlated to the reactives content of a seam. The reactives range from 42% to 82%. A range of this magnitude will have major effects on rheology and coking properties and will make it difficult to estimate rank from VM daf data.
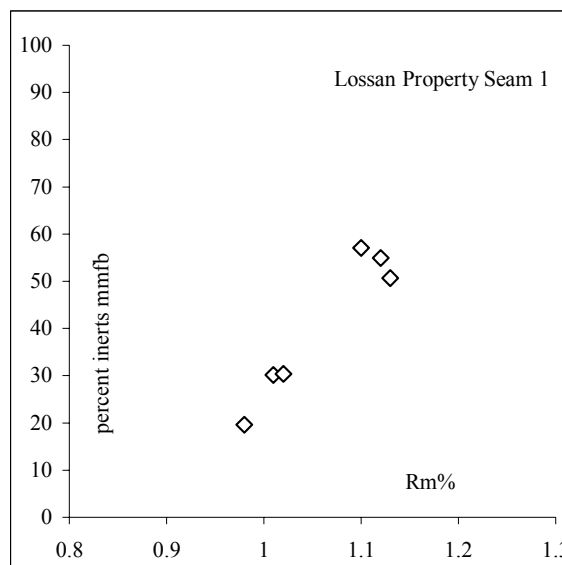

Figure 4. Percent reactives *versus* Rm for seam 1, Lossan Property.

The Van Krevelen Diagram illustrates the change in O/C and H/C as rank increases for various kerogen types. It tends to be used in more academic studies of coal, but is also useful for outlining coking potential of coals. Both atomic ratios (O/C and H/C) are sensitive to rank and to maceral composition of coal and consequently tend to bypass some of the confusions in determining the actual content of reactive macerals in coal samples. A previous study (Ryan *et al*., 1999) provides rheology and ultimate analyses for medium-volatile production coals (ash contents all close to 10%) and the data indicate the change in FSI within a Van Krevelen Diagram (Figure 5).

Ash chemistry influences the quality of coal in terms of it's use as thermal coals or for coke making. It has a major influence on CSR and is therefore important here because most Gething coals are planned for coke making or PCI use in blast furnaces. Ash chemistry is presented as base/acid ratios (oxides of Fe, Ca, Mg, Na and K divided by oxides of Si, Al and Ti). The mineral form of the base oxides also affects CSR (Price *et al.,* 1992).

Generally sulphur contents in Gething coals are less than 1% and not a concern, except for the seam underlying the marine Moosebar and Bluesky conglomerate, which often has higher sulphur contents. This is important because it means that most of the Fe in an ash oxide analysis is probably in iron carbonates. The relative concentrations of Ca, Mg and Fe may be represented on triangular plots, which illustrate changing trends in relative carbonate concentrations with increasing rank. The oxides have different impact on CSR and studies indicate that Ca from carbonates is probably more damaging to CSR than Fe in carbonates (Ryan *et al*., 1999). The paper also documents the negative correlation of SO_3 to CSR. Probably breakdown of carbonates is forming sulphates in the ash, which results in the appearance of SO_3 in the ash analysis. Oxides of K and Na, which also negatively affect CSR, probably occur in clays dispersed in coal.
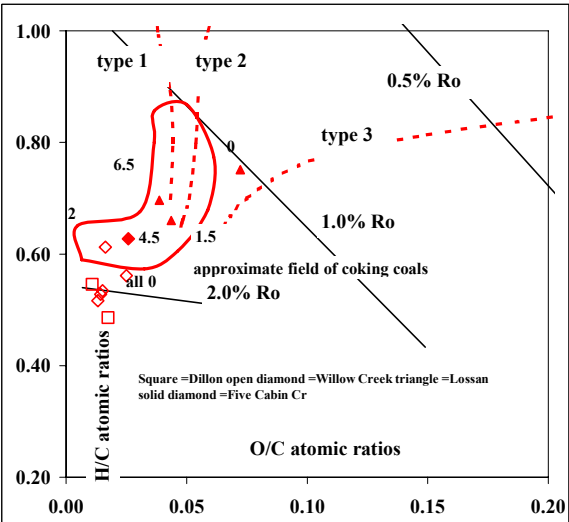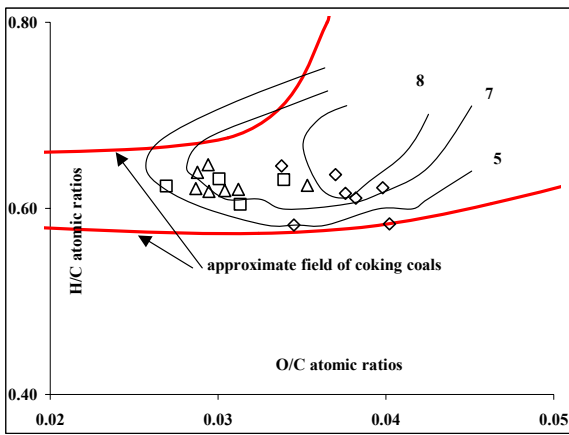
Figure 5. FSI contours for medium-volatile BC production coals in a Van Krevelen Diagram. Data from Ryan *et al*. (1999).

Variations in contents of Ca, Mg and Fe tend to track changes in the composition and amount of carbonate in coal. The mix of carbonates present (siderite, ankerite, dolomite and calcite) may be temperature dependent and can therefore give an indication of when fluids infiltrated coal and caused precipitation of carbonates. Spears and Caswell (1986) outline a sequence of cleat mineralization that from low to high temperature is sulphide, silicate and then carbonates. Carbonate mineralization starts with diagenetic deposition of siderite (becoming more Ca and Mg rich with increase in temperature). At higher temperatures, carbonates precipitate in the sequence ankerite, dolomite, Fe rich calcite and finally calcite (indicating a general decrease in Fe content). This sequence covers the temperature range 50°C to 150°C and therefore coal ranks up to medium-volatile bituminous, which covers the temperature range when most of the thermogenic methane is generated.

The mix of carbonates in coal gives information on when fluids infiltrated the coal; they may also indicate the composition of the fluid associated with the coal. Van Voast (2003) reveals some interesting correlations of water chemistry with coal in productive coalbed gas (also referred to as coalbed methane, CBM) basins. He

found that coal waters rich in bicarbonate and Na and impoverished in Ca, Mg and SO_4 (mainly because of biogenic reduction of sulphate and precipitation of calcite and dolomite) are often associated with productive CBM basins. Obviously in coals with low sulphide content the relative concentrations of Fe, Mg and Ca may provide information about when carbonates were deposited and may also provide hints about the CBM potential. Coals with ash chemistries enriched in carbonates and impoverished in Na may have been in association with water with a CBM favourable fingerprint.

Phosphorous is an important contaminant in steel and customers generally look to purchase coal with less than 0.1% P (sometimes down to 0.03%) concentration in coal. Phosphorous concentrations are measured as P_2O_5 oxide concentrations in ash. A more useful value is the concentration of P in the total sample and it is these values that are presented here. Phosphorus has a complex association with coal as discussed by Ryan and Grieve (1996) and Ryan and Khan (1997). It sometimes concentrates in the inert coal macerals and not ash and is therefore difficult to wash out.

COMMENTS ON THE REGIONAL STRUCTURE IN THE GETHING FORMATION

Within the Peace River Coalfield, the Gething Formation outcrops as synclinal cores in a number of fold or thrust blocks that follow the trend of the fold belt and in large part define the coalfield (Legun, 2003). East of the fold belt a number of thrusts depress the Gething Formation below depths of interest for surface or underground coal mining and interest switches to CBM, oil or natural gas potential. However, in the north, east of the fold belt, the Gething is at shallower depths and there are a number of open synclines and anticlines in the outer foothills where there is underground coal mining and CBM potential.

Rank and possibly other coal characteristics change as one traverses from southwest to northeast across the trend of the fold belt into different thrust blocks. Often rank is lower on the west-southwestern edge of the fold belt, higher in the middle before decreasing again to the east-northeast along the eastern edge of the belt and into the Western Canadian Sedimentary Basin (Karst and White, 1980; Marchioni and Kalkreuth, 1982; Ryan *et al*., 2005).

In the north, coal is contained in the upper and middle part of a thick Gething section. To the southeast along the trend of the fold belt in the Sukunka area (Figure 2) the Gething Formation contains a marine tongue (Bullmoose Member, Gibson, 1992; Duff and Gilchrist, 1983; Legun, 1987) with coal in the Upper Gething Chamberlain Member and in the underlying Gayland Member. The tongue does not extend to the south and as the formation thins, coal is probably equivalent to the Lower Gething (Gayland Member) in the south. Broatch (1987) suggested that there may be other marine tongues in the Gething that wedge out to the south. This means that on the regional scale one can

expect major coal quality variations across and along the trend of the fold belt within the formation.

Fold axes along the fold belt maintain a northwest/southeast trend but plunge amount and direction both vary and in some cases there are major changes over short distances. There is no obvious pattern of cross folding in the fold belt, however north of the Pine River the synclines cored by the formation tend to be doubly plunging forming basin structures. A line following the Peace River east of Hudson Hope and projected southwest into the fold belt outlines a possible structural high with structures plunging to the north on the north side and to the south on the south side. This line approximately follows the trend of the Peace River Arch, which therefore may influence structures in the deformed belt. It also intersects the deformation front at a location where the trend deflects to a more northerly trend north of the line. This interaction may have implications for regional fracture patterns and local present day extension important for CBM exploitation.

The orientation of the present day horizontal maximum stress direction is northeast-southwest (Bell, 2002). Cross folding may tend to open (anticline) or close (syncline) fold-axis normal cleats and therefore have a fundamental influence on permeability, which is required for successful CBM production. Reversal of fold plunge even in individual thrust blocks may be key to understanding permeability. There is some evidence that in the northern part of the fold belt cleats are axial planar whereas in the south they tend to be fold-axis normal (Ryan, 2003). Based on the present orientation of the maximum horizontal stress direction the axial planar cleats may indicate a local re orientation of the stress direction from a north-northeast trend to a south-southeast trend. This may signal areas of improved permeability.

Hughes (1967) discussed the structural style in the fold belt. Synclines are underlain by shallow dipping thrusts and appear to have ridden on the underlying thrusts somewhat passively. Where thrusts cut up section tight anticlines form in the thrust plate and thrusts sometimes break through the hinges. In this geometry the western limbs of anticlines above thrusts are more likely to be in extension than eastern limbs below thrusts. In areas of intense folding, coal seams often contain axial planar fractures that may or may not predominate over early-formed fold-axis normal cleats.

Timing of coal maturation, with respect to the onset of deformation, can influence coal quality parameters. If coal achieves moderate to high rank prior to onset of deformation it will withstand deformation better and shearing may be limited to areas of folds (hinges) that experience most strain. If coal has only achieved low or moderate rank when deformation starts it is more likely to be pervasively sheared. The most obvious result of the latter situation will be fines generation and a high Hardgrove Index. This impacts coal washability, fine circuit capacity in a wash plant and plant yield as well as causing handling problems for the producer and customer. In the southern part of the coalfield deformation of Gates Formation coals post dated coal maturation (Kalkreuth et al., 1989). Further north they considered results of reflectance studies across thrusts to be inconclusive. However, the form of the iso-rank contours mirror the folded outcrop pattern of the Gething indicating imposition of rank prior to folding (Figure 6).

In the foothills coal exploration companies have not traced the coal-bearing section of the Gething Formation much north of Williston Lake. However, coal exists in the formation at depth to the east in the Western Canadian Sedimentary Basin (Ryan et al., 2005) and to the north, for example Pink Mountain (Kalkreuth et al., 1989). To the southeast the fold belt trends into Alberta and in this area the Gething Formation is thin.

MAJOR SYNCLINAL TRENDS AND RANK IN THE GETHING

It is possible to outline structural and coal quality trends in the Gething Formation using a combination of regional maps (for example, Legun, 2003) and Coal Assessment Reports. Major synclinal fold trends within the deformed belt are outlined in simplified figures (Figures 7 and 8) to help illustrate the following discussion. Exploration properties are located with reference to these approximate fold trends as this provides the easiest way to compare the major coal quality trends. Table 2 provides a summary of rank, ash chemistry and phosphorous data for properties along each synclinal trend. Data are averaged and provide only a general idea of variations. The deformation front separating the foothills from the Western Canadian Sedimentary Basin is defined by a number of thrusts some of which are responsible for considerable change in depth of the Gething Formation. In the Tumbler Ridge area the Gething is down-dropped 100's of metres by the Gwillam Lake Thrust. To the north and south in the foothills the there is less increase in depth of the Gething as the subcrop is traced into the Western Canadian Sedimentary Basin.

There are a number of regional studies of rank in the Gething Formation (Karst and White, 1980; Kalkreuth and McMechan, 1988; Kalkreuth et al., 1989; Marchioni and Kalkreuth, 1992). Most of these studies concentrate on rank of the formation east of the deformed belt and therefore do not provide a regional overview of rank in areas presently considered for surface or shallow underground mining. However, regional rank data of Kalkreuth et al. (1989) represented as contours for the top and bottom of the Gething (Figure 6) covers some of the area covered by Figure 7. The data when overlain on the regional geology (Figure 7) indicate that in the area south of Williston Lake rank increases to the east. Rank in the East Mt Gething Property (number 6, Figure 7) and Cinnabar
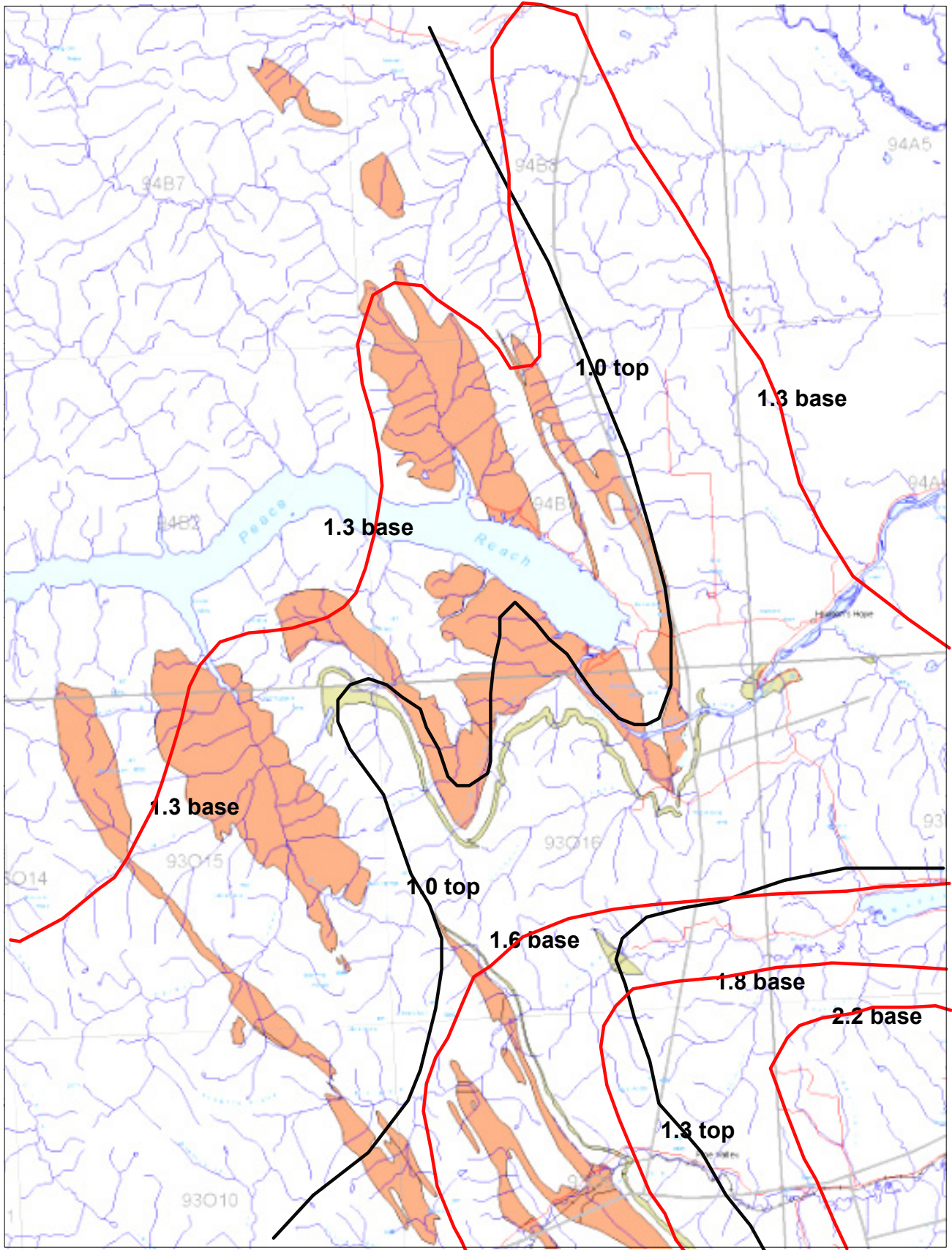
Figure 6. Reflectance values for top and bottom of the Gething (data from Kalkreuth *et al*., 1989) with regional geology.
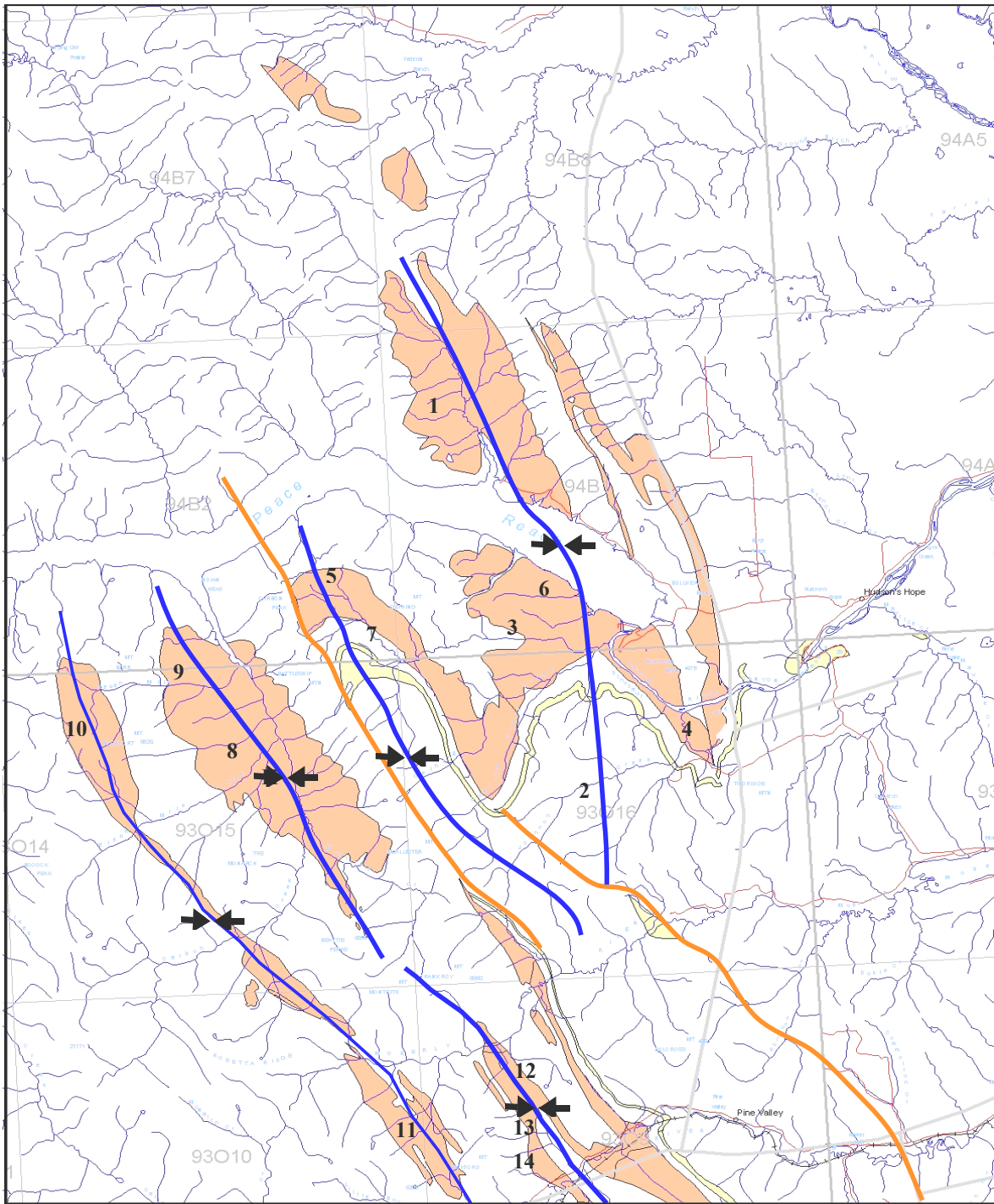
Dunlevey	1	South Mount Gething	7	Pine Pass	13
Bri Dowling	2	Carbon Creek	8	Norman Creek	14
Mount Gething	3	North Carbon Creek	9		
Cinnebar Peak	4	West Carbon Creek	10		
Adam Creek	5	Mt Bickford	11		
East Mount Gething	6	Fisher Creek	12		

Figure 7. Cartoon of regional structures in the Gething north of Pine River.
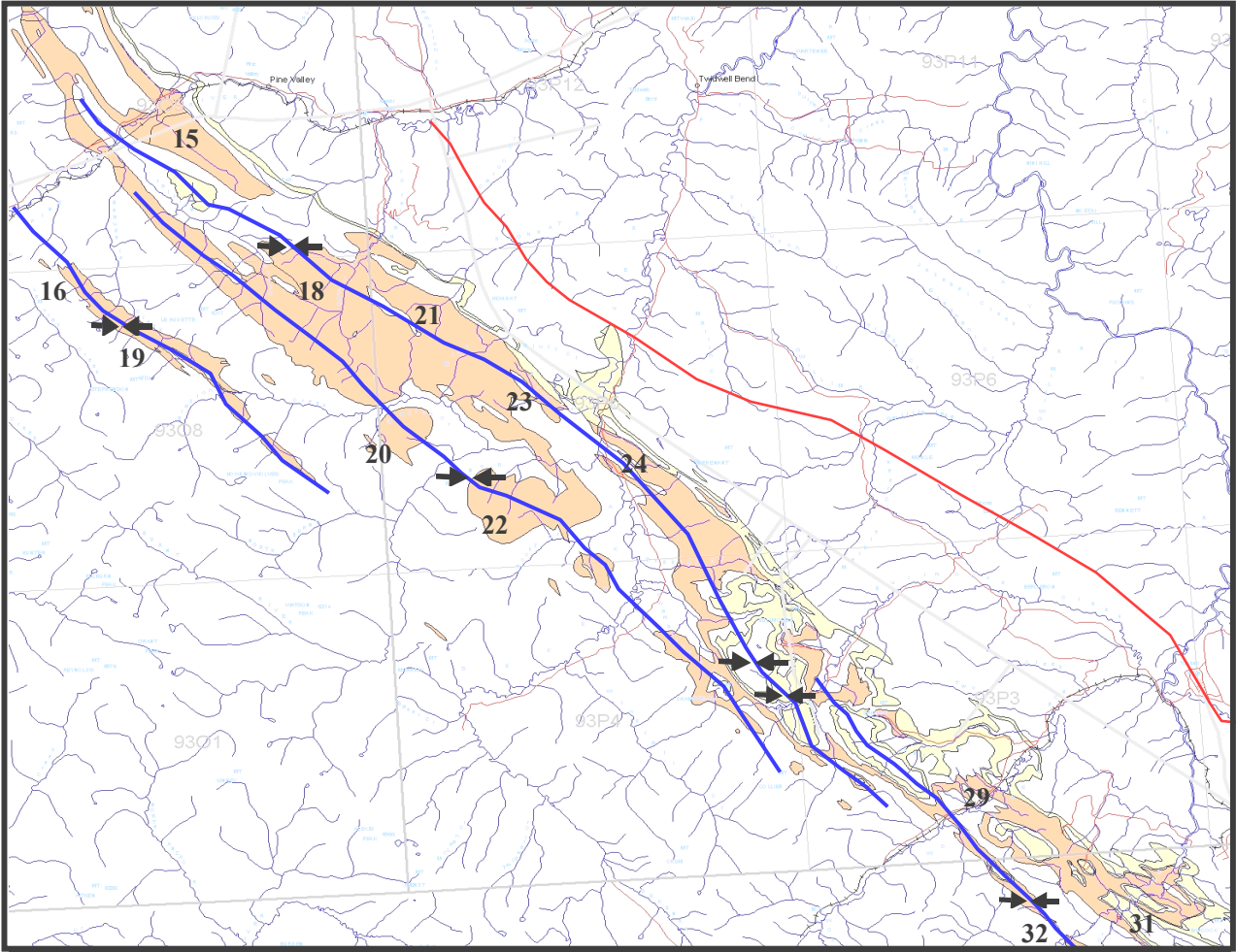
Willow Creek	15	Burnt River South	22
Goodridge central south	16	Dillon	23
Falling Creek	18	Sukunka	24
Lossan	19	Trend	31
West Brazion	20	Five Cabin	32
Hasler	21		

Figure 8. Cartoon of regional structures in the Gething south of Pine River.

TABLE 2. RANK, BASICITY AND PHOSPHOROUS DATA FOR PROPERTIES GROUPED BY FOLD TRENDS

West Carbon Creek				Carbon Creek				Fisher Creek				Dunlevey				Murray			
north	rank	basicity	P%/total sample	north	rank	basicity	P%/total sample	north	rank	basicity	P%/total sample	north	rank	basicity	P%/total sample	north	rank	basicity	P%/total sample
				North Carbon Cr	0.9-1.03*	0.29	0.036					Dunlevey	0.9-1.35*	X	X				
West Carbon Cr	1.02-1.18	0.51	0.059	Carbon Cr	0.9-1.03*	0.29	0.036					Bri Dowling	1.01-1.45	0.43	0.07				
Bickford	1.0-1.78			Fisher Cr	1.1							Mount Gething	0.95-1.45	0.55	0.11				
Goodridge Central South	1.24-1.54	0.26	0.072	Pine Pass	1.11-1.38	0.47	0.022	Willow Cr	1.61	0.43	0.02	Cinnebar Peak	X	X	X				
Lossan	0.98-1.33	0.11	0.19	Norman Cr	1.11-1.5*	X	X	Falling Cr		0.14	0.04	Adam Cr	1.11*	X	X				
				West Brazion	1.3-1.5*	X	X	Hasler	1.74			East Mount Gething	0.9-1.4	X	X				
				Burnt River South	X	X	X	Dillon	1.74	0.4	0.02	South Mount Gething	X	X	X				
								Sukunka	1.41	0.25	0.06								
																Five Cabin Cr	1.18-1.26	0.77	0.009
south				south				south				south				south			

Peaks (4) areas is higher than for Bri-Dowling (2) and South Mt Gething (7) properties to the west. In general, iso rank lines trace the outcrop pattern of the Gething and rank increases to the south as the depth of the Gething increases.

Southeast and east of the Gwillam Lake Thrust, the Gething Formation is generally at considerable depth; however to the northwest and east of the extension of the thrust, the formation is at shallower depths and defines a number of broad open folds. In the 1980s, the area north of Williston Lake (Figure 7) (Butler Ridge and Dunlevey Creek; area 1) was explored by Hudson Bay Oil and mapped by Legun (1984). The Gething Formation is about 500 metres thick in the Dunlevey area and contains numerous thin seams. A hole in 1973 drilled 246 metres of the formation and intersected 10 seams greater than 0.3 metres thick with a cumulative thickness of 4.24 metres. The hole was collared about 75 metres below the Moosebar Formation. Seams intersected in the hole were considered to be too thin for mining and no coal quality data was obtained. Rank in the area, at the top of the Gething is less than 1% Rm and at the base greater than 1.3% (Kalkreuth *et al.*, 1989). The Butler Ridge-Dunlevey area is underlain by a broad syncline in the outer foothills that on the regional scale plunges to the south-southeast intersecting the northern extension of the Gwillam Lake Thrust system west of Moberly Lake.

South of the Williston Lake and east of the projected trend of the Gwillam lake Thrust, the area, which is the southern extension of the Butler Ridge-Dunlevey Syncline, was explored by a number of companies. The area includes the properties, Bri Dowling (2), Mount Gething (3) and East Mt Gething (6). An anticline to the east is represented by Cinnabar Peak (4) Property and an anticline to the west by the Adam Creek (5) and South Mount Gething (7) properties (Figure 7). This area, which is underlain by multiple thin seams of high to medium-volatile rank at

favourable depths, has potential for CBM exploration and if individual seams are thick enough also for underground coal mining.

The East Mount Gething Property (6) explored by Utah Mines Limited (1978 to 1980) is the southern extension of the Dunlevey Creek Syncline and covers in general terms the western limb of the major syncline. A number of reflectance measurements were made on samples from the 1977 drill program (Figure 9, Creaney, ISPG, personnel communication). The Rm data do not vary consistently with depth, which may indicate the influence of variable petrography on vitrinite reflectance values. Samples from thick seams have higher Rm values than samples from thin seams at the same depth. This may be a sampling problem that introduced oxidation or relate to different petrography in thin seams (reactive rich) to thick seams (inertinite rich). The rank at the top of the Gething is estimated to be about Rm=1% in agreement with Kalkreuth *et al.* (1989). The predicted rank at the base of the formation depends on using thin or thick seam data and varies from medium to low-volatile bituminous in general agreement with Kalkreuth *et al.* (1989).

West of the Gwillam Lake Thrust extension, there are a number of complex synclinal trends that extend southeast along the trend of the fold belt. Each trend is described using information collected from coal exploration reports covering properties along the trend. In the north the Carbon Creek (8) and West Carbon Creek (10) properties identify two trends (Figure 7). The most westerly synclinal trend is defined in the north by the West Carbon Creek Property. Data from Kalkreuth *et al.* (1989) do not extend west of the northern projection of the Gwillam Lake Thrust except for some measurements in the vicinity of West Carbon Creek where Rm values of 0.95% and 0.98% are given for the top of the formation. Exploration data provide Rm data that ranges from 1.02% to 1.08% measured on samples from 1980 holes. There are numerous thin seams in the West Carbon Creek area and the formation

is estimated to be the same thickness as on the Carbon Creek Property. Tracing the trend to the southeast on the north side of the Pine River it covers the area variously referred to as the North Moberly, North-Central Goodridge or Mt Bickford Property (11). Rank is medium to low-volatile bituminous (Kalkreuth *et al.*, 1989) and cumulative coal in the section is less than in the Gething to the east in the Carbon Creek trend but details are sparse.

South of the Pine River (Figure 8) the West Carbon Creek trend continues as the South Central Goodridge (16), Lossan (19) and Cirque properties. Recent exploration has added to the data for the first two areas. However there is little information on the Cirque Property, which marks the end of this trend in terms of Gething outcrop. Rank on the Goodridge South Central Property ranges from 1.29% to 1.54% with no indication of the value at the top of the formation (Figure 10, data provided by First Coal). The data indicate a possible thrust in the section with upwards of 100 metres stratigraphic separation.

Most of the coal resource on the Lossan Property is in the upper Seam 1, which is 40 metres below the top of the Gething, and some in Seam 5, which is 160 metres below the top of the formation. Rank of Seam 1 ranges from 0.95% to 1.26%. An adit sample provided Rm values for the upper part of seam 1 of about 1.1% and the lower part 1.0% (Figure 4). The difference may relate to petrography in that higher inerts contents sometimes correlate with higher Rm values and high vitrinite contents with low Rm values. Alternatively the upper part of the coal intersection may have been thrust on top of the lower part of the intersection and originate stratigraphically at least 50 metres lower in the section. Rank of the lower Seam 5 is described as low-volatile bituminous, however if the seam has a high inerts content and rank was estimated from VM daf data then rank may be over estimated. As an example the inert rich upper part of seam 1 has a rank of 1.1%. If rank is estimated from VM daf data using the plot from Taylor *et al.* (1998), then a Rm value of over 1.3% is derived. The coking potential of a high-volatile seam with high inerts content is very different from a medium-volatile seam with high reactives content.

North of Pine River, the Carbon Creek (8) Property (Figure 7) defines a syncline trend that can be traced south. In the Carbon Creek area the Gething Formation is estimated to be 1067m thick (Legun, 1986) though Karst (1978) suggests that the formation may be thinner. It is possible that if the Cadomin is non-conglomeritic some of the underlying Minnes Group may have been included in the Gething Formation. To the south the formation is estimated to be about 500 metres thick. Karst (1978) also provides reflectance data for 2 holes and values range from 0.85% to 1.26% (Figure 11) and based on where they were collared in the section, rank at the top of the formation is less than 0.8%. There are over 100 thin seams with a cumulative thickness of 18.8 metres, though only 10 are of economic thickness.

The southern extension of the Carbon Creek Synclinal trend, north of the Pine River, is referred to as the Fisher Creek Syncline. The northeastern part was mapped as the East Moberly or Moberly Property, which covers the eastern edge of the Gething trend. The Norman Creek Property covers the west limb and center of the structure, the Pine Pass (13) Property the center and eastern part of the structure and the Fisher Creek (12) Property covers the eastern part of the structure (Figure 7). Along trend, folds get tighter and rank increases. On the Pine Pass (13) Property rank appears to be exclusively medium-volatile (Figure 12) and the cumulative coal thickness in the section is about 20 metres. Rank values do not increase systematically with depth and correlate with VM daf values (Figure 12). This may indicate multiple stratigraphic repeats or indicate that inerts content is influencing (increasing) Rm values of seams as discussed by Diessel and Gammidge (1998).

South of the Pine River the Fisher Creek synclinal trend, in very generalized terms, broadens and is defined by the two limbs of the syncline. The eastern limp is covered by the Willow Creek (Pine Valley Mine) Hasler and Dillon properties (locations 15, 21 and 23, Figure 8). Rank at Willow Creek is medium to low-volatile bituminous (Table 3). To the south, rank increases and at Hasler Creek is low-volatile bituminous with Rm values averaging 1.74% and ranging from 1.6% to 1.87% (Table 3). Rank at the Dillon Property further to the south is low-volatile bituminous averaging 1.76% for the lower seam (Table 3). East of the Dillon Mine, Burlington drilled a coalbed methane (CBM) hole that intersected the Gething Formation at a depth of 972 metres where it is 344 metres thick. Rank at the top of the Gething is 1.81% Rm and some seams are inertinite rich with total inerts contents (mmfb) varying from 43% to 60% (Petro-Logic Services, 2003 report).

The Fisher Creek Synclinal trend projects approximately through the Sukunka Property (location 24 Figure 8) and the Bullmoose Mine. Rank of Gething Formation coals at Sukunka is 1.32% Rm close to the top of the formation. The trend does not continue south. Rank in the trend is consistently higher than in the West Carbon Creek trend to the west and increases to the south reaching a maximum at the Dillon Property before decreasing somewhat at Sukunka.

The trend, which is the extension of the western limb of the Fisher Syncline south of Pine River, is defined by the West Brazion and Burnt River South properties (locations 20 and 22, Figure 8). Samples collected from the West Brazion Property (Gilchrist, 1979) were analysed by Kilby (unpublished data) and have ranks of 1.38% and 1.35% Rm. Samples are from Lower Gething or from coal below the Cadomin. To the south samples collected from Burnt River South Property provide ranks ranging from 0.97% to 1.16% Rm. The trend continues south to Mount Chamberlain before outcrop of the Gething Formation ends. Ranks in this trend increase to maximum in the vicinity of the Pine River and then decrease to the southeast. They are generally less than ranks in the trend to the east but similar to or higher than ranks in the West Carbon Creek trend to the west.

Further to the south (Figure 8) the Murray River Syncline has Gething coal potential between the Murray
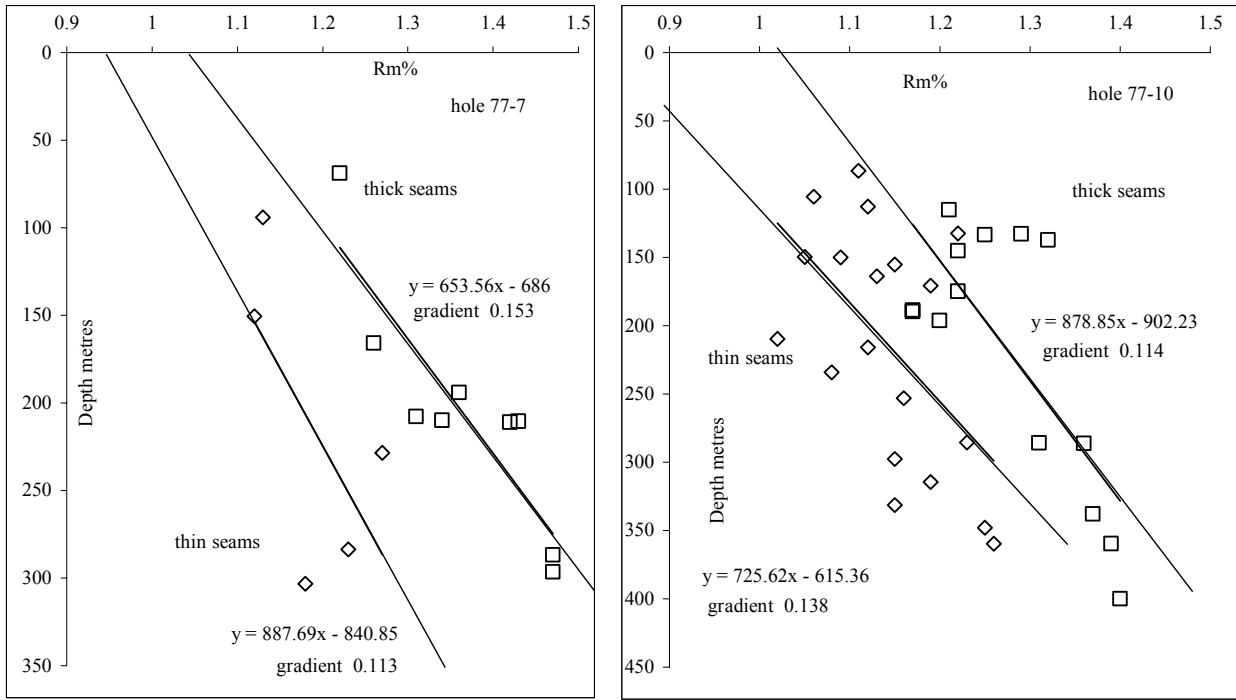
Figure 9 (hole 77-7)

Rm%

hole 77-7

thick seams

Depth metres

y = 653.56x - 686
gradient 0.153

thin seams

y = 887.69x - 840.85
gradient 0.113

Figure 9 (hole 77-10)

Rm%

hole 77-10

thick seams

thin seams

y = 878.85x - 902.23
gradient 0.114

Depth metres

y = 725.62x - 615.36
gradient 0.138

Figure 9. Reflectance values East Mount Gething Property (Creaney ISPG personnel communication).

Figure 10

Rm%

Goodrige South Central
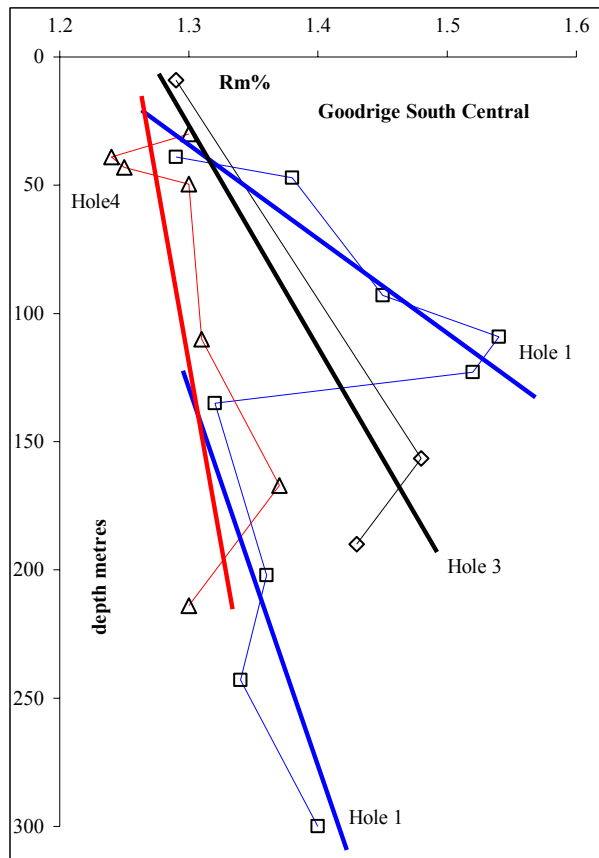
Hole4

depth metres

Hole 1

Hole 3

Hole 1

Figure 10. Rm% values from the South Central Goodrich Property data provided by Michael Hunter First Coal.

and Red Willow rivers (Five Cabin Creek Property, location 32, Figure 8) and extends north as the Wolverine Mine in the Wolverine Valley. In this location Koch drilled a hole for CBM into the Lower approximately 30 to 305 metres. Rank for the Lower Gething samples ranged from 1.59% to 1.7% Rm (Table 3). At Five Cabin Creek rank of Gething coal is medium-volatile (Table 3) with indications that the rank is lower on the west limb than the east limb. Southeast of the Five Cabin Creek Property the Gething Formation is thin but still contains coal. Based on rank in the overlying Gates Formation rank is lower along the Murray River Syncline trend and increases to the east-northeast in the Monkman-Belcourt trend before decreasing at depth to the east-northeast. The Monkman Property was explored mainly for the coal potential in the Gates Formation. The Gething Formation is 136 metres thick in the area and contains 3 seams thicker than 1.5 metres (Leckie *at al.,* 1988). The Rm value of the seams ranges from 1.3% to 1.32% with a fairly high rank gradient of 0.16 to 0.27%/100 metres. In the extreme south Mt Gorman property the Gething is 46 metres thick and contains a single 3 metres thick seam which appears to be high-volatile bituminous in rank.
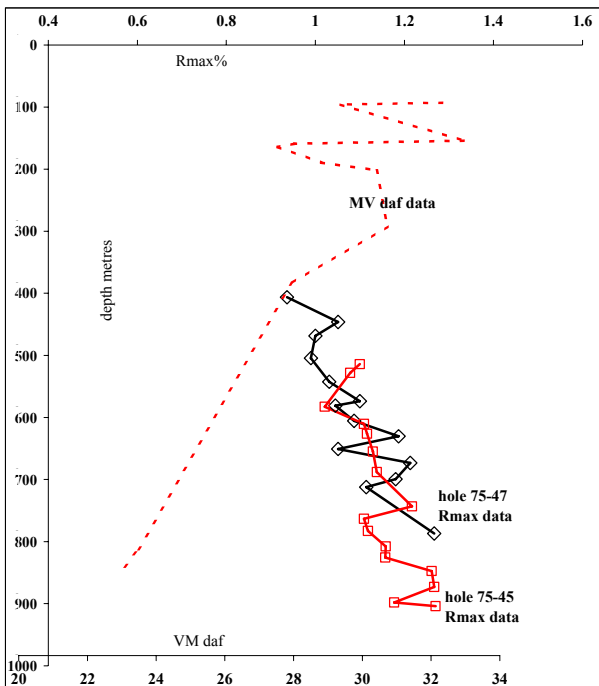

Figure 11. Reflectance values (Karst, 1978) and VM daf data for the Carbon Creek area.

TABLE 3. RANK AND PETROGRAPHY WILLOW CREEK AND DILLON PROPERTIES

| Mean maximum reflectance (Rm)		
Willow Creek (This study)		
6 seam	full seam	1.61
7 seam	top	1.66
	bottom	1.61
	dull	1.65
	bright	1.5
Dillon Mine (This study)		
Lower Seam	full seam	1.75
	top	1.79
	bottom	1.75
	Vitrain grab	
	Durain grab	1.67
Lossan Property (This study)		
Seam 1	Bottom	1.09
	Mid	1.10
	Top	1.02
	Grab	1.09
	Grab	1.08
	Grab	0.95
Five Cabin Creek (This study)		
seam B2	top	1.200
	grab	1.180
	core	1.260
Hasler Creek (Kilby)		
average Rm		1.74
range		1.60 to 1.87
High Hat (Burlington)	depth metres	
	1018	1.84
	1112	1.94
	1270	2.06
Wolverine (Koch)		
	depth metres	
Lower Gething	221.95	1.67
	222.98	1.67
	242.25	1.70
	242.95	1.68
	251.25	1.59
	255.5	1.64
	282.65	1.67
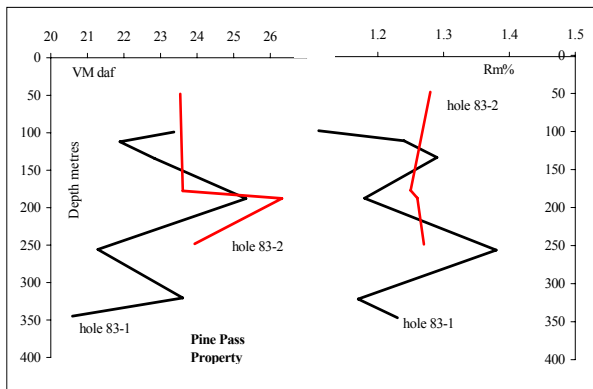
Figure 12. Vitrinite reflectance (Rm) values Pine Pass Property.

QUALITY TRENDS ALONG THE MAJOR SYNCLINAL TRACES

The Gething Formation is characterized by considerable variation in inerts content. Some of the early coal assessment reports confused oxidation with high inerts content when trying to explain low FSI values. In terms of coke making potential higher inerts content is favourable for medium rank coals but is detrimental in low and high rank coals. The optimum inert line for ASTM stability (Pearson, 1980) indicates that the maximum optimum inerts for stability occurs at a rank of 0.9% (other studies indicate a higher rank). The maximum optimum inerts for CSR occurs at ranks in the range 1.3% to 1.5 % Rm (Price *et al*., 2001) (Figure 13). Variation in inerts content (mainly fusinite and semifusinite macerals) is easy to document using petrography but the exact relationship of inerts content to coke quality is much more confused. There are many papers that discuss ways of partitioning semi fusinite between reactive and non-reactive components. It is possible in part to bi-pass this confusion by using ultimate analyses plotted onto a Van Krevelen Diagram, which allows separation of samples based on degree of reactivity and rank.
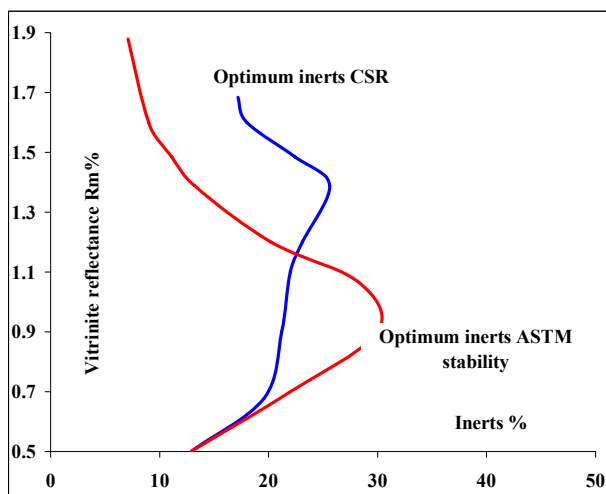

Figure 13. Optimum inerts line *versus* rank for ASTM stability or CSR; data from Pearson (1980) and Price *et al*. (2001).

South of Williston Lake (Figure 7), Van Krevelen diagrams of data from Butler Ridge-Dunlevey syncline East and South Gething properties (Figure 14) indicate that coal from the East Gething Property is more reactive and of slightly higher rank than that from South Gething. Based on the scatter of data in the Van Krevelen diagrams, there appears to be a wide range of inerts content in the samples. This is cohobated by Vm daf data from the properties, which do not have a consistent relationship to depth (Figure 15).

Ash chemistry in this area is indicted by data from Bri-Dowling and South Mt Gething properties as base/acid ratios and phosphorus content data (Figure 16). Both base/acid ratios and phosphorous contents are higher for the Bri-Dowling than Mt Gething property. In addition triangular plots of Ca, Mg and Fe (Figure 17) indicate that there may be, relative to Fe and Mg more Ca in samples from the Bri-Dowling Property.

Moving west into the northern part of the deformed belt, ultimate analytical data for the West Carbon and Carbon Creek trends (Figure 14) indicate in agreement with reflectance data (Figure 11) that rank is higher to the west and the coal is somewhat more reactive. Plots of VM daf *versus* depth data indicate wide variation in petrographic composition for seams from both the West Carbon Creek and Carbon Creek trends (Figure 15).

The southern extension of the Carbon Creek trend, north of the Pine River, is covered by the Pine River, East Moberly, and Fisher Creek properties. Rank increases in this direction but there is limited ash chemistry and ultimate analytical data to add to the discussion (Figures 14, 16 and 18). A triangular plot of Ca, Mg and Fe oxides for these properties and Willow Creek (Figure 19) indicate an increase in Ca content to the south. Though CSR correlates with base/acid ratio it is dis-proportionally sensitive to particular cations such as Ca (Ryan *et al*., 1999).

Three synclinal trends are traced south of the Pine River. The West Carbon Creek trend is represented by the South Central Goodridge and Lossan properties. Ash chemistry indicates that the Goodridge coal has more phosphorous and higher base/acid ratios than coal to the north (Figure 20). In addition ash is richer in Ca than ashes to the north (Figure 19). This may be because fluids were emplaced at higher temperatures. The Lossan Property is characterized by low base/acid ratios and phosphorous contents.

The trend roughly representing the east limb of the Fisher Creek Syncline is represented by the Hasler, Dillon and Sukunka properties. No data were located for the Hasler Property. Base/acid ratios for the Dillon Property are high but phosphorous contents low. The Sukunka Property was explored in the 1970s as a potential underground coking coal mine and there is a lot of coal quality information available. Unfortunately the exploration predated general introduction of some of the coke tests such as CSR that are considered to be important today. Ash chemistry for the Sukunka Property clearly indicates an increase in Ca carbonate (Figure 19, 20) and phosphorous contents are moderate with some higher values.

The Fisher Creek west trend is represented by the Brazion and Burnt River South properties but no quality data was located.

The northern end of the Murray Creek syncline trend is represented by data from the Koch Petroleum Wolverine CBM hole that intersected Gething coal. In this location base/acid ratios are low and the ash relatively richer in Mg (Figures 19,20), but this is probably not a carbonate association. The Fiver Cabin Creek property to the south is characterized by high base/acid ratios and low phosphorous contents (Figure 21).

COAL PETROGRAPHY

Petrography data for Gething coals exists in a number of papers for example Ryan and Lane (2002), but there is no systematic study, mainly because of the difficulty of getting representative samples from a full suite of Gething exploration properties. In this study a few samples collected from Pine Valley Coal, Dillon, Lossan and Five Cabin Creek were analyzed for petrography (Table 4). Standard preparation techniques were employed with 300-point counts per sample. No attempt was made to differentiate between vitrinite and pseudo vitrinite or to differentiate between reactive and non reactive semifusinite. Generally samples contain variable amounts of semifusinite + marcinite + inertodetrinite that range from 25 to 53%. Most samples contain some pseudo vitrinite and the inert macerals tend to contain less structured semifusinite than in other Cretaceous coals. In some areas of intense shearing the coal contains multiple curved surfaces that look a little

like cone in cone structure (Bustin, 1982). A sample of this material was examined and found to be composed almost entirely of vitrinite. A lot of the vitrinite is pseudo vitrinite but other than that there was no evidence of excessive micro fracturing or intra grain strain. The high inertinite content in some samples will decrease rheology and probably tend to contract the rank window over which Gething coals will make good coke.

COAL QUALITY DATA 2005 SAMPLES

A number of samples were analysed for proximate, ultimate, ash oxides and trace metals (Table 5). Trace metals data from the ICP-MS analyses are averaged by property and plotted into a correlation matrix (Table 6). Ash oxide analyses were made using XRF techniques on fused ash samples. Coal samples are ashed to provide the starting material and consequently the analysis provides an ash concentration as well as an analysis of major oxide concentrations in the ash. A comparison of the ash concentration analyses done by the conventional ASTM method with the XRF procedure (Figure 22) indicates that there is very little difference between the two methods and consequently an XRF analysis alone provides all the information necessary to calculate oxide concentrations on a total sample basis. The ashing of samples may volatilize some elements for example mercury but most elements will not be affected.
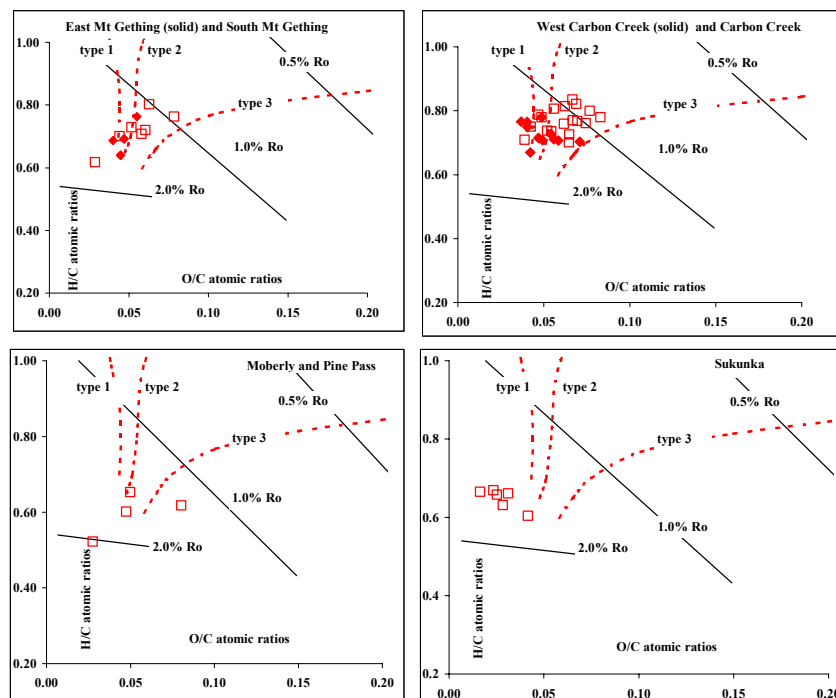

Figure 14. Kan Krevelen Diagrams for data from properties; East and South Gething, Carbon Creek, West Carbon Creek, Moberly, Pine Pass and Sukunka.
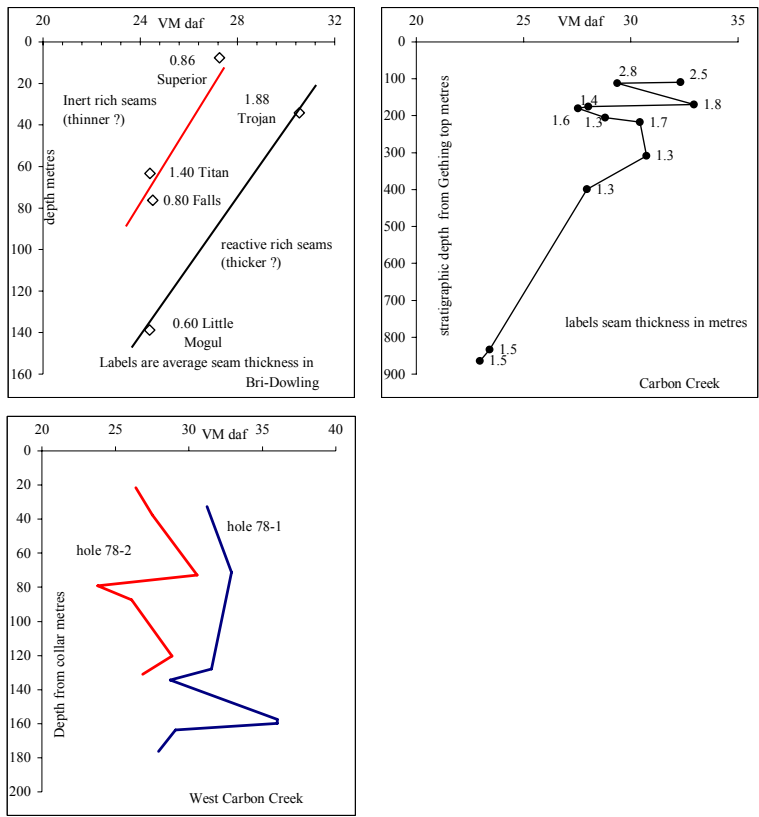
Figure 15. VM daf *versus* depth plots for Bri-Dowling, Carbon Creek and West Carbon Creek properties.
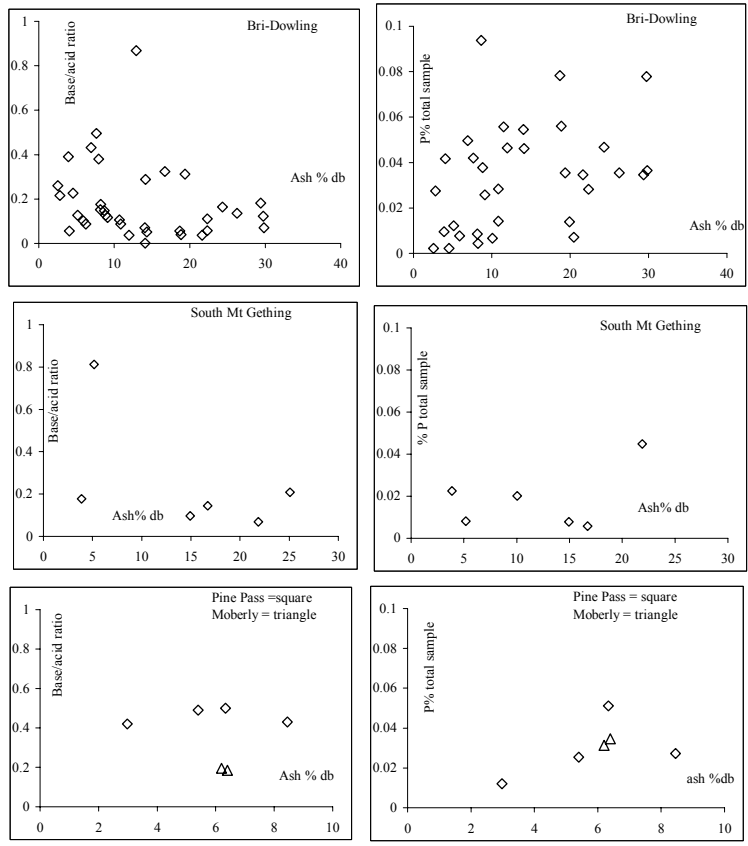

Figure 16. Base/acid and P% *versus* ash plots, Bri-Dowling and South Gething properties.
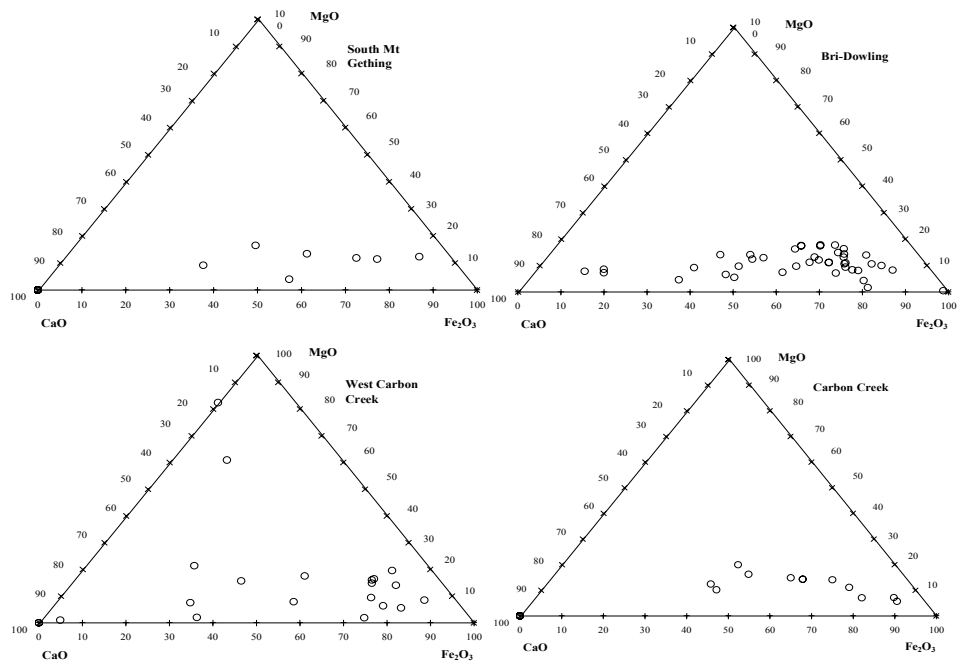
Figure 17. Triangular plots for Fe, Ca and Mg for Bri-Dowling, South Mt Gething, Carbon Creek and West Carbon Creek properties.
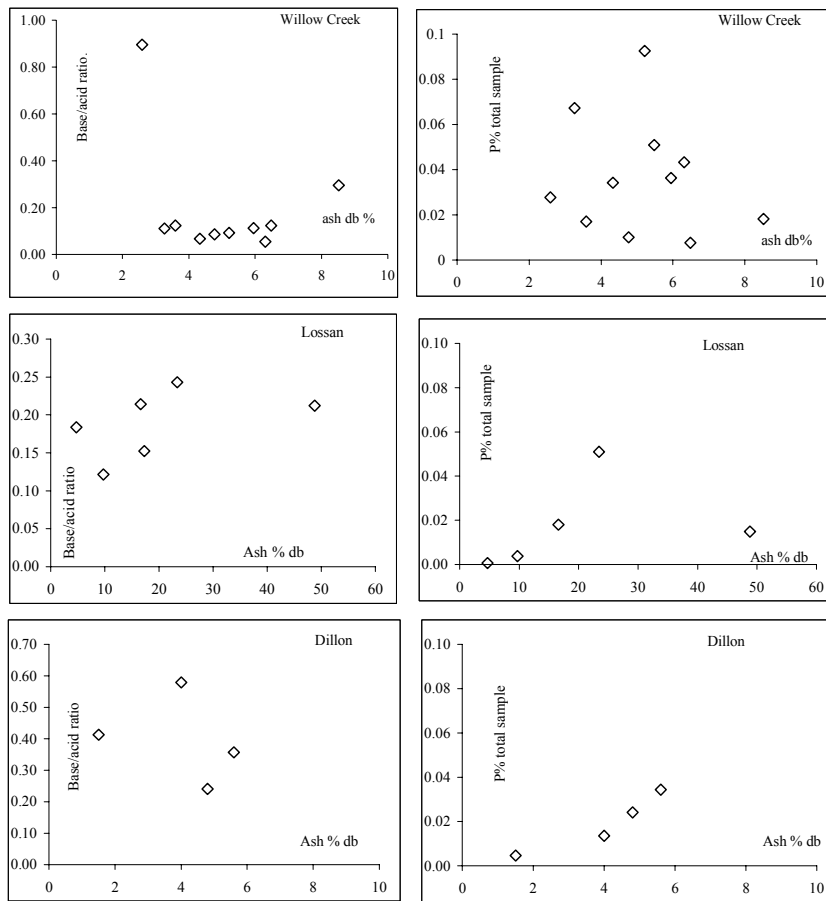
Figure 18. Base acid and P% *versus* ash plots, East Moberly, Pine Pass and Willow Creek properties.
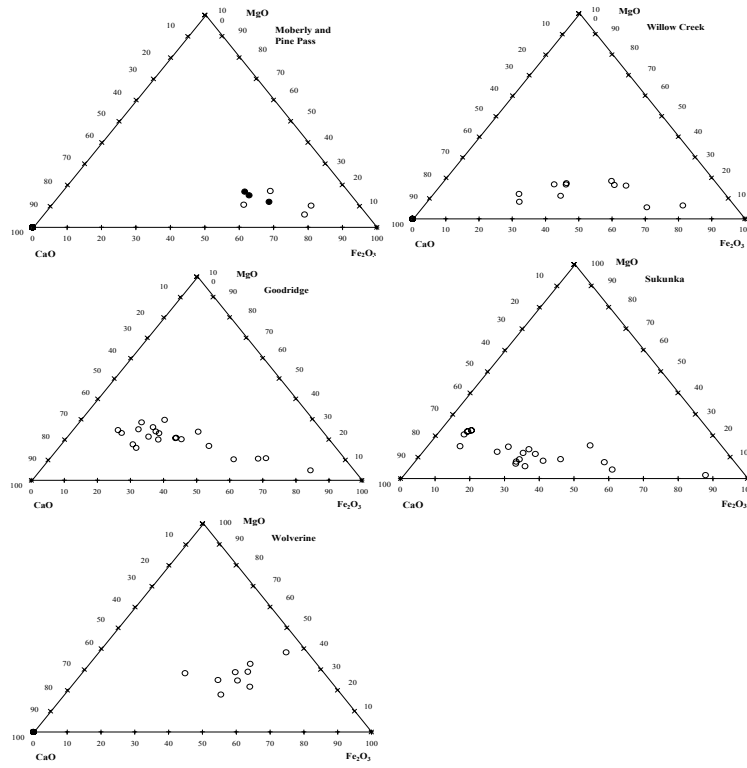
Figure 19. Triangular plots for Fe Ca and Mg for Pine Pass East Moberly, Willow Creek, Goodrich and Sukunka properties.
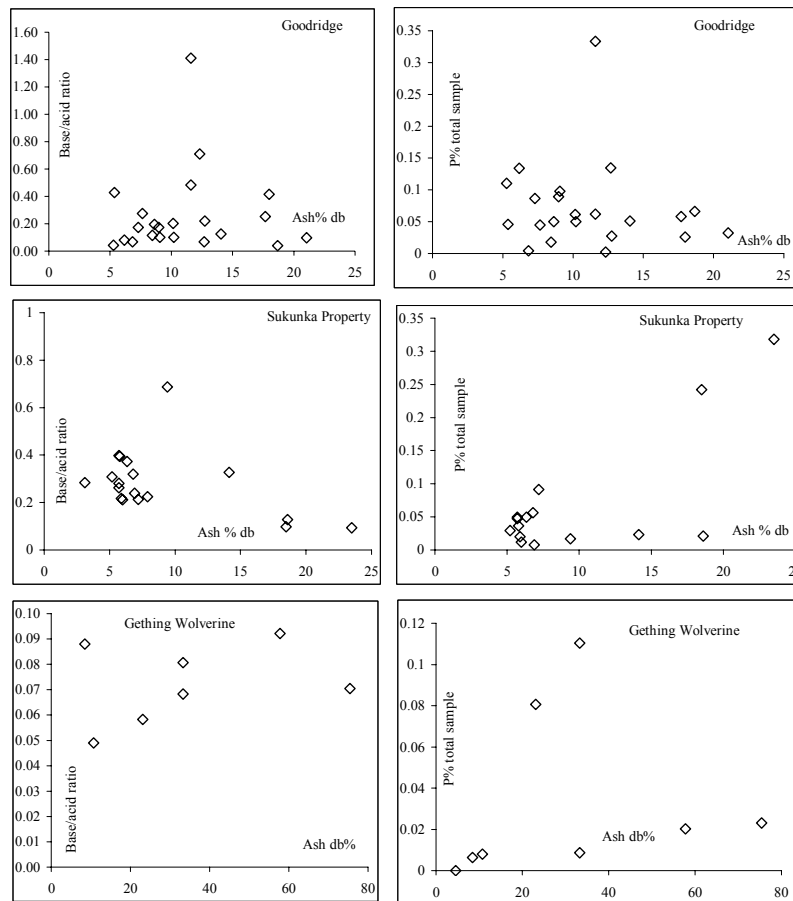

Figure 20. Base/acid and P% *versus* ash plots; Goodrich, Sukunka and Wolverine properties.
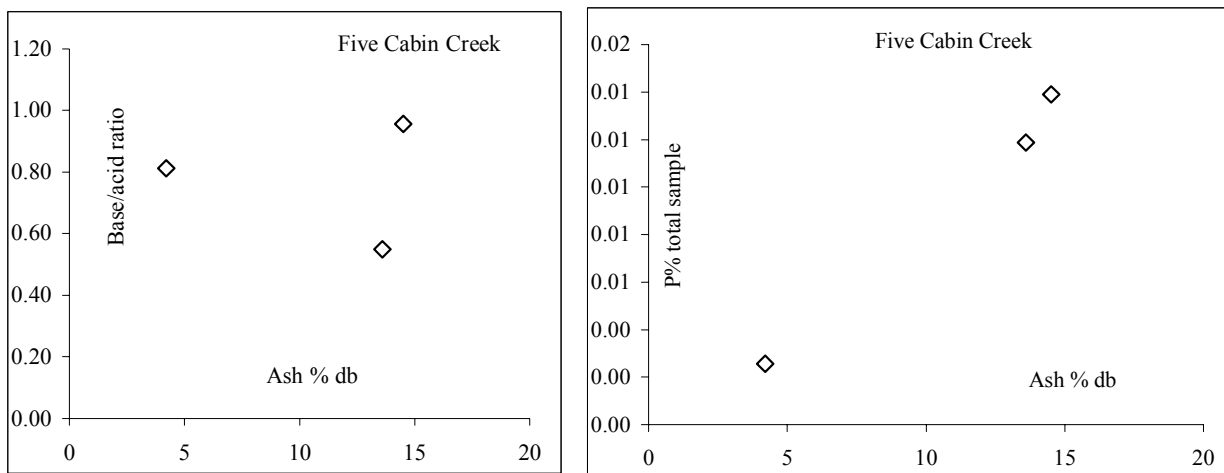
Figure 21. Base/acid and P% *versus* ash plots; Five Cabin Creek Property.

TABLE 4. PETROGRAPHY FOR SAMPLES FROM LOSSAN, DILLON, PINE VALLEY COAL AND FIVE CABIN CREEK

							Coal petrography 300 point count									
	telinite	collo telinite	collo detrinite	vitro detrinite	gelo vitrinite	liptinite	**total reactives**	micrinite	macrinite	semi fusinite	fusinite	inerto detrinite	**total inerts**	Volume mineral matter	wt mineral matter%	wt ash % (1.15)
Lossan Seam 1																
bottom 1/3	2	20	23	1	0	2	**48.3**	0	3	24	1	5	**33.6**	18	30.5	26.6
mid seam	0	9	29	1	0	7	**45.3**	0	2	21	0	7	**29.3**	25	40.5	35.2
top of seam	7	28	33	0	0	5	**72.4**	0	3	17	0	5	**25.3**	2	4.5	3.9
Grab	3	16	41	0	1	4	**65.4**	0	3	19	2	7	**30.3**	4	8.3	7.2
Grab	3	13	29	0	1	2	**48.0**	0	3	29	0	5	**37.3**	15	25.6	22.2
Grab	11	41	30	0	0	5	**87.5**	0	0	4	0	1	**4.9**	8	14.2	12.3
Dillon Lower Seam																
full seam	1	27	29	1	0	0	**58.4**	0	3	25	0	7	**36.0**	6	10.6	9.2
top 3 metres	0	7	35	0	0	0	**41.7**	0	5	39	0	9	**53.3**	5	9.5	8.3
bottom 1.7m	0	25	27	0	0	0	**51.7**	1	5	32	0	6	**43.0**	5	10.1	8.8
vitrain grab	1	41	53	0	0	0	**94.9**	1	0	2	0	1	**3.5**	2	3.2	2.7
cone in cone str	0	62	30	0	0	0	**92.3**	1	0	4	0	1	**5.7**	2	3.9	3.4
Willow Creek																
top of seam 7 1.55m	0	8	38	0	0	0	**46.3**	0	11	28	1	8	**48.0**	6	10.6	9.2
bottom of seam 7 1.0m	0	22	21	0	0	0	**43.0**	1	3	25	0	11	**39.7**	17	29.5	25.7
full seam 6	0	15	34	0	0	0	**48.7**	1	4	31	0	11	**46.7**	5	8.9	7.8
Five Cabin Creek																
seam B2 drill core	0	20	35	0	0	1	**56.0**	1	4	22	0	9	**35.7**	8	15.4	13.4

TABLE 5. SAMPLES ANALYZED BY ASHING ACID LEACH AND ICP-MS IN THIS STUDY; SOME VALUES COMPARED TO DATA FROM GRIEVE AND GOODARZI (1994). NA=NEUTRON ACTIVATION; AA=ATOMIC ADSORPTION. DATA CALCULATED TO CONCENTRATIONS IN TOTAL COAL SAMPLES

element		Lossan	Five Cabin	Goodridge Central	Pine Pass	Willow Creek	Dillon	Grieve and Goodarzi 1994	analysis
Analyses by ICP-MS on ash			Properties arranged in order of increasing rank						
		1	2	3	4	5	6		
Mo	ppm	1.14	0.81	2.83	1.29	1.65	1.55		
Cu	ppm	3.93	4.73	8.04	4.36	2.62	2.56	14	AA
Pb	ppm	6.54	2.29	3.92	4.31	0.89	0.77		
Zn	ppm	21.28	8.11	20.67	20.78	8.47	6.92		
Ag	ppb	36.71	23.15	65.78	50.08	18.48	11.69		
Au	ppb	0.66	5.04	1.18	0.17	0.12	0.12		
Ni	ppm	8.08	5.08	8.18	17.54	4.52	2.92		
Co	ppm	2.46	1.10	1.00	1.54	0.53	0.38	2.59	NA
Mn	ppm	10.31	49.97	1.79	24.74	2.29	0.92		
As	ppm	3.24	4.49	4.75	8.29	9.15	9.12	2.2	NA
U	ppm	1.48	0.61	1.39	0.99	0.55	0.53	2.28	NA
Th	ppm	3.38	1.10	2.66	2.20	0.98	0.71	4.21	NA
Cd	ppm	0.08	0.10	0.16	0.05	0.14	0.14		
Sb	ppm	0.15	0.10	0.32	0.24	0.12	0.09	0.77	NA
Bi	ppm	0.13	0.04	0.05	0.02	0.03	0.02		
Cr	ppm	9.94	6.87	15.08	14.96	4.54	3.89	20.7	NA
B	ppm	8.31	11.57	5.46	10.72	2.32	1.87		
S	%	0.04	0.23	0.33	0.41	0.03	0.03		
Hg	ppb	1.01	0.63	0.74	0.38	0.74	0.52	51	AA
Se	ppm	0.12	0.14	0.35	0.68	0.36	0.01		

TABLE 6. TRACE METAL DATA BY ICP-MS AVERAGED FOR THE PROPERTIES

| x	Mo	Cu	Pb	Zn	Ag	Au	Ni	Co	Mn	As	U	Th	Cd	Sb	Bi	Cr	B	S	Hg	Se
Mo	1.00																			
Cu	.63	1.00																		
Pb	-.04	.42	1.00																	
Zn	.30	.58	.90	1.00																
Ag	.58	**.86**	.65	**.87**	1.00															
Au	-.37	.28	-.06	-.29	-.10	1.00														
Ni	-.03	.28	.58	.74	.66	-.24	1.00													
Co	-.33	.17	**.95**	.75	.41	.03	.51	1.00												
Mn	-.66	.07	.08	-.13	-.07	**.84**	.20	.23	1.00											
As	.04	-.57	-.71	-.47	-.42	-.53	.00	-.69	-.33	1.00										
U	.36	.63	**.91**	**.93**	**.80**	-.18	.45	.76	-.21	-.69	1.00									
Th	.21	.52	**.96**	.94	.75	-.18	.52	.85	-.13	-.68	**.98**	1.00								
Cd	.71	.19	-.56	-.40	-.11	-.11	-.70	-.71	-.58	.18	-.19	-.35	1.00							
Sb	.71	**.83**	.48	.79	**.97**	-.23	.63	.21	-.21	-.21	.68	.61	.04	1.00						
Bi	-.16	.13	**.80**	.53	.20	.03	.00	**.84**	-.05	-.79	.73	.78	-.28	.01	1.00					
Cr	.40	.76	.70	**.90**	**.97**	-.10	**.82**	.50	.06	-.37	.76	.74	-.33	**.92**	.18	1.00				
B	-.51	.31	.57	.41	.36	.59	.59	.64	**.85**	-.55	.29	.38	-.79	.17	.27	.50	1.00			
S	.24	.69	.30	.53	.77	.20	.76	.14	.40	-.13	.30	.29	-.32	.76	-.28	**.84**	.60	1.00		
Hg	.08	.11	.45	.24	.05	.03	-.38	.48	-.26	-.66	.53	.53	.17	-.07	**.84**	-.09	-.11	-.51	1.00	
Se	.20	.26	.21	.51	.59	-.29	**.84**	.11	.06	.28	.19	.23	-.38	.66	-.33	.67	.30	.73	-.44	1.00
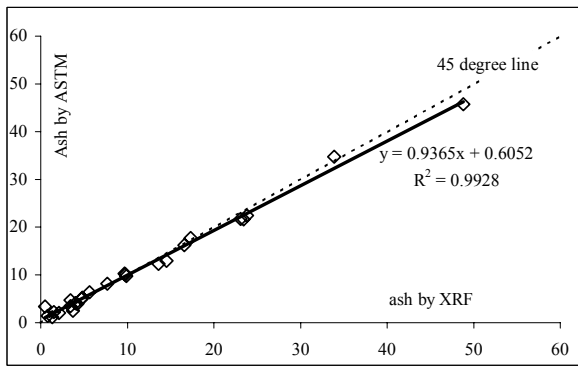
Figure 22. Comparison of phosphorous analyses by ICP-MS and XRF.

Trace metals in ashed samples were analyzed using ICP-MS with a hot HCL+HNO3 acid leach. This leach will dissolve adsorbed metals, sulphides and carbonates and may also partially remove some elements from silicates. A comparison of the results of XRF and ICP-MS analyses for the major oxides Fe, S, Mg, Ca, Na, K and P provides information on amount of carbonate and sulphide in samples and amount of easily removed Na, K and phosphorous.

The comparison of phosphorous XRF and ICP-MS data indicate that about 1/3 of the phosphorous is removed by the acid leach (Figure 23). Phosphorous is usually contained in coal as apatite or alumino-phosphates (Gorceixite (Ba, Al, P) and Goyazite (Sr, Al, P)). There is a strong correlation of Sr with P in the ICP-MS data so it appears that the acid leach is removing goyazite. Based on the strength of the leach and the fact that only about 1/3 of the P is removed it is unlikely that acid washing of coal will be an economic way to reduce phosphorous contents.
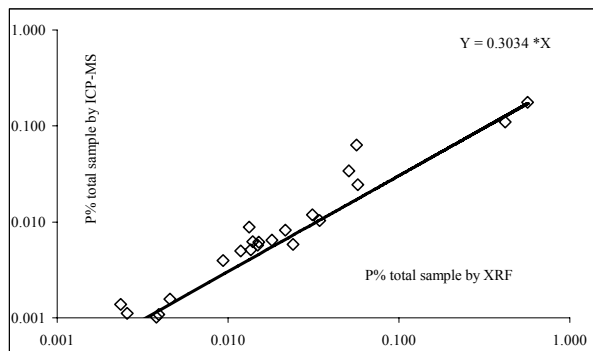

Figure 23. ICP-MS sulphur in ash acid leach *versus* total iron in ash by XRF.

A comparison of some average trace metal concentrations derived by ICP-MS on leach samples from this study (Table 5) and the study by Grieve and Goodarzi (1994) (analysis methods indicated in the table) indicates that concentration of Hg by ICP-MS is definitely low and concentrations of other metals appear to be somewhat lower. This may indicate that trace amounts of metals are probably held in silicates and not leached. It is unlikely that the metals are volatilized by the ashing process. ICP-MS data may not provide reliable total concentrations of some trace metals but more importantly it may give a much better idea of the

amount of trace metals that might be mobilized during mining and impact the environment.

The data (Table 5) are arranged in order of increasing rank to the right. Most of the metal concentrations appear to decrease slightly as rank increases except for arsenic concentrations, which appear to increase as rank increases. All concentrations are within normal limits for coal.

Comparison of concentrations derived from XRF analyses and from ICP-MS analyses on acid leach samples provides information on the amount of the element not held in insoluble silicates. Iron in samples may be bound in sulphides, carbonates or silicates. A plot of total Fe (XRF) *versus* leach Fe (ICP-MS) indicates a constant amount of 0.25% Fe probably in silicates (Figure 24). The leach Fe appears to be distributed between carbonates and sulphides based on how much the data plots right of the pyrite line in Figure 24. Some data plots to the left probably because of the presence of S leached from sulphate, which originates from weathered samples. It is apparent that a lot of the Fe in the samples is contained in carbonates.
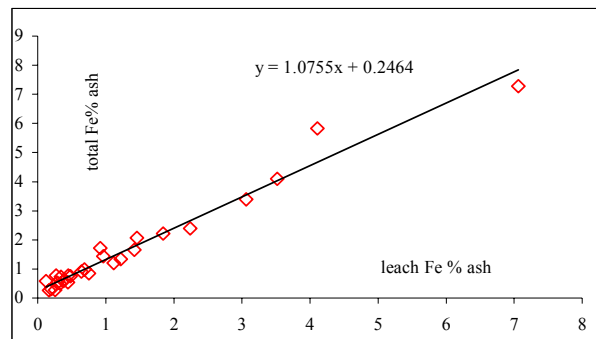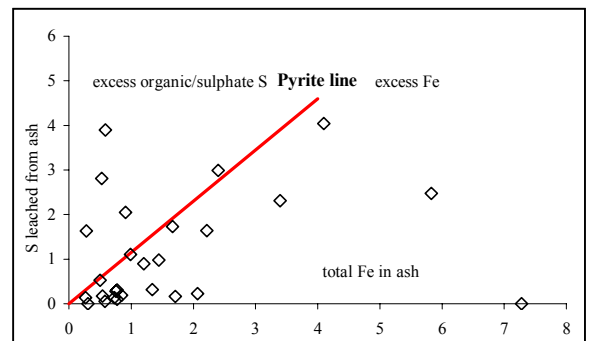

Figure 24. Triangular plot of Gething data ICP-MS leached Ca, Mg and Fe identified by rank.

Distribution of Fe, Ca and Mg in carbonates may provide information about the origin and temperature of cleat and micro fracture in filling. Plots of leach Ca *versus* total Ca and leach Mg *versus* total Mg indicate that nearly all Ca and Mg are removed by leaching. For Ca an amount of 0.06% is contained in silicates and for Mg the amount is about 0.1%. It appears that the leach amounts of Fe, Ca and Mg may provide a better picture of carbonate composition than the total concentrations derived from XRF. Concentrations plotted into a triangular plot (Figure 25) indicate a predominance of Fe, Ca carbonates (ankerite and siderite). There does not appear to be a change of carbonate composition as rank

increases, possibly indicating either an early or late emplacement of carbonates, rather than numerous emplacement events at different temperatures. The influence of Ca, Fe and Mg in carbonates on CSR has been mentioned and the ICP-MS data may provide an improved way of predicting the effect of ash chemistry on CSR.
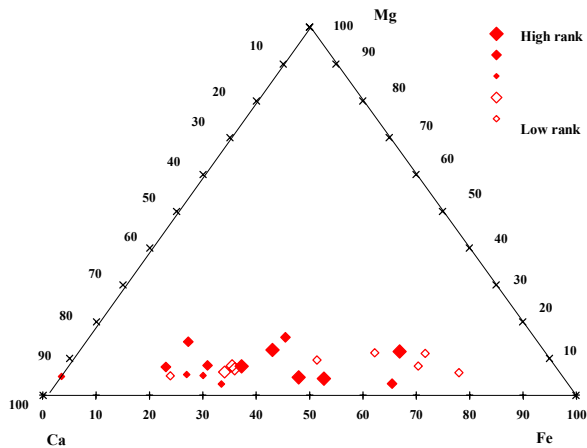

Figure 25. Total and leachable contents of Na and K in ash; solid symbols represent higher rank coals.

Increased concentrations of alkalies K and Na decrease CSR values of coals. Volatile K or Na can cause problems in a blast furnace but may be less damaging to CSR than non-volatile K (Price and Gransden, 1987). A comparison of leachable K *versus* total K and Na (Figure 26) indicates that about 40% of K and Na is leachable with amounts decreasing as total concentrations increase. Sodium concentrations appear to be higher in high rank coals and K concentrations a bit lower.

The use of total major element analysis and leachable concentrations can provide a fingerprint of ash chemistry that may help predict CSR values of cokes. Data may be cheap to obtain because both XRF and ICP-MS techniques are highly automated. Data from the Dillon Property (low-volatile bituminous rank) and the Lossan Property (high-volatile bituminous rank) (Figure 27) illustrate the different fingerprints possible; ignoring rank, ash chemistry for Lossan coals is worse than that for Dillon coals in terms of CSR. It has more leachable Fe, Ca and K than Dillon coal. This approach is in addition to using base/acid ratios or modified basicity indexes (MBI Price *et al.,* 1988). Mattila and Heiniemi (1996) and Price *et al.* (1992) discussed the effect of minerals on CSR and Mattila and Heiniemi provide a figure (Figure 28) that illustrates the relative damaging effect of free Fe, Ca, Na and K on CSR. Calcium and magnesium carbonates are worse than Fe and also Na and K effect coke reactivity index (CRI) more than CSR.
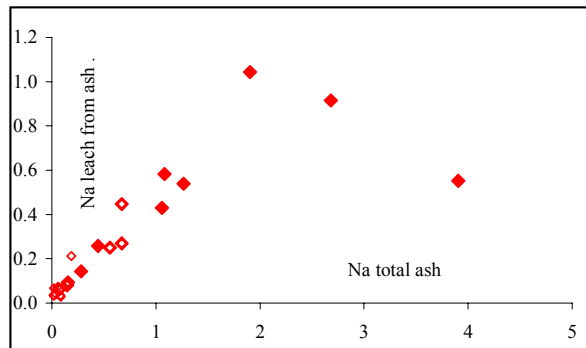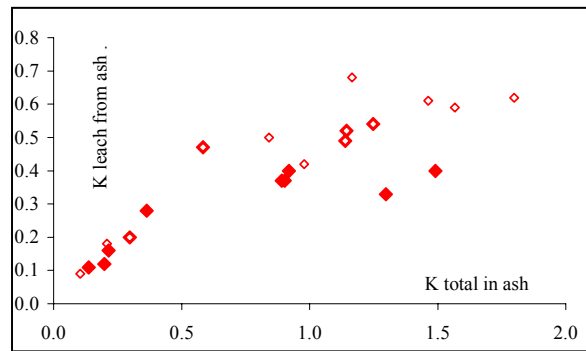

Figure 26. Fingerprints of leacheable and total major oxides in total samples for Dillon and Lossan properties.
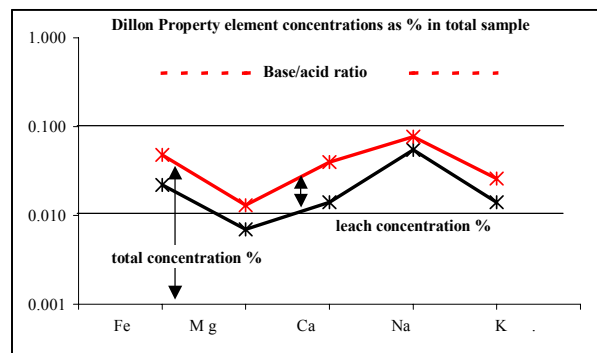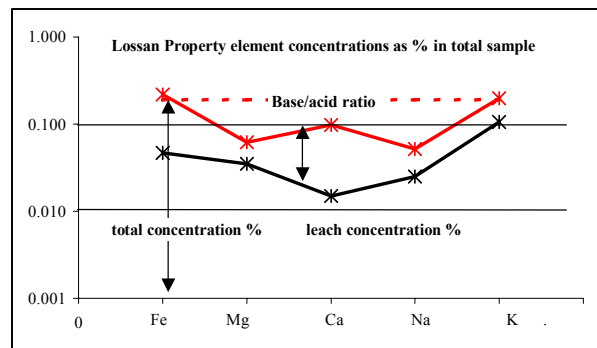

Figure 27. Finger-prints of leacheable and total major oxides in total samples for Dillon and Lossan properties.
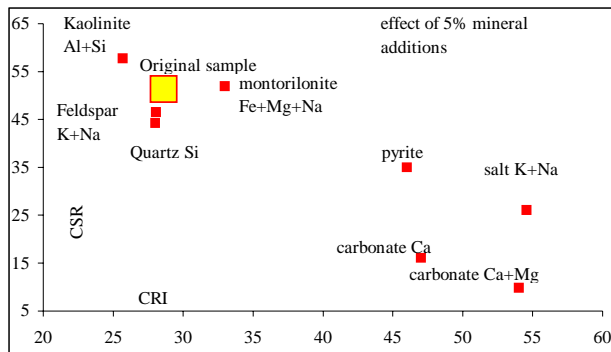
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Figure 28. Plot from Mattila and Heiniemi (1996) illustrating the effect on CSR and CRI of 5% mineral additions to a coal.

CONCLUSIONS

Coal quality in the Gething Formation is very variable and is best described using a number of synclinal trends that can be traced along the fold belt. It is possible to summarize the coal utilization potential of the Gething, using properties along these trends and concentrating on the three major coal quality variables of rank, petrography and ash chemistry.

Petrography data is not always available but ultimate analyses plotted into a Van Krevelen Diagram may provide a better summary of the influence of rank and petrography on coal utilization. The inerts content of Gething coals varies more than for Gates coals. Often it is difficult to estimate the percentage of reactive macerals in a petrographic analysis and the Van Krevelen diagram may provide a more consistent way of separating samples based on the relative maceral reactivity.

The variable inerts content in Gething coals sometimes makes it difficult to use FSI to identify oxidation and can provide miss-leading estimates of rank if it is estimated from VM daf data..

Plots of VM daf data by depth (even when calculated using low ash samples) provide a saw tooth pattern. This may indicate faulting in the section or wide variation in the inerts content of seams. If the inerts content of seams is widely variable this may make for difficult blending to maintain a consistent coking coal product especially if rank is on the edge of the rank window for optimum coking coals.

There are many empirical equations that attempt to predict CSR using properties of coal samples. Using a combination of XRF oxide analysis of ash and ICP-MS analysis of leachate from ash samples it is possible to fingerprint the ash chemistry in a way that might provide a better understanding of how ash chemistry affects CSR.. The process is simple and may be cheap.

It is important, especially for the Gething Formation, to understand the implications of coal quality during the early stages of exploration. The coal market remains volatile and there is a wide separation in price and market opportunities between thermal coals, PCI coals and coking coals of various qualities.

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