Cleat Development in Some British Columbia Coals

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INTRODUCTION

Many coal seams contain coalbed methane (CBM) yet most of the world's production comes from the San Juan Basin in the United States. In fact CBM production from this basin of about 0.9 tcf/yr accounts for about 80% of the CBM production in the US (1.2 tcf/yr) and about 60% of world production. Success in the San Juan Basin is not because of increased gas content in the coals compared to coals in other basins, rather it is because of permeability. Permeability of CBM through coal seams is generally the most important coal seam property affecting the viability of a CBM field and it is controlled mainly by the degree of cleat development. Cleats are orthogonal closely spaced tension fractures characteristic of coal seams and their importance in controlling permeability in coal seams is documented and discussed in numerous papers.

This paper discusses cleats and describes cleating and other structural features seen in a number of coal outcrops in British Columbia. A version of the paper containing numerous photos of cleats in British Columbia coals is available on CD from the Ministry of Energy and Mines.

All coalmines in operation in British Columbia in the last few years were visited, as well as a number of properties where good coal exposures exist. Also notes are provided on some other properties that the author has visited over the years. The mines and properties discussed are located in Figure 1.

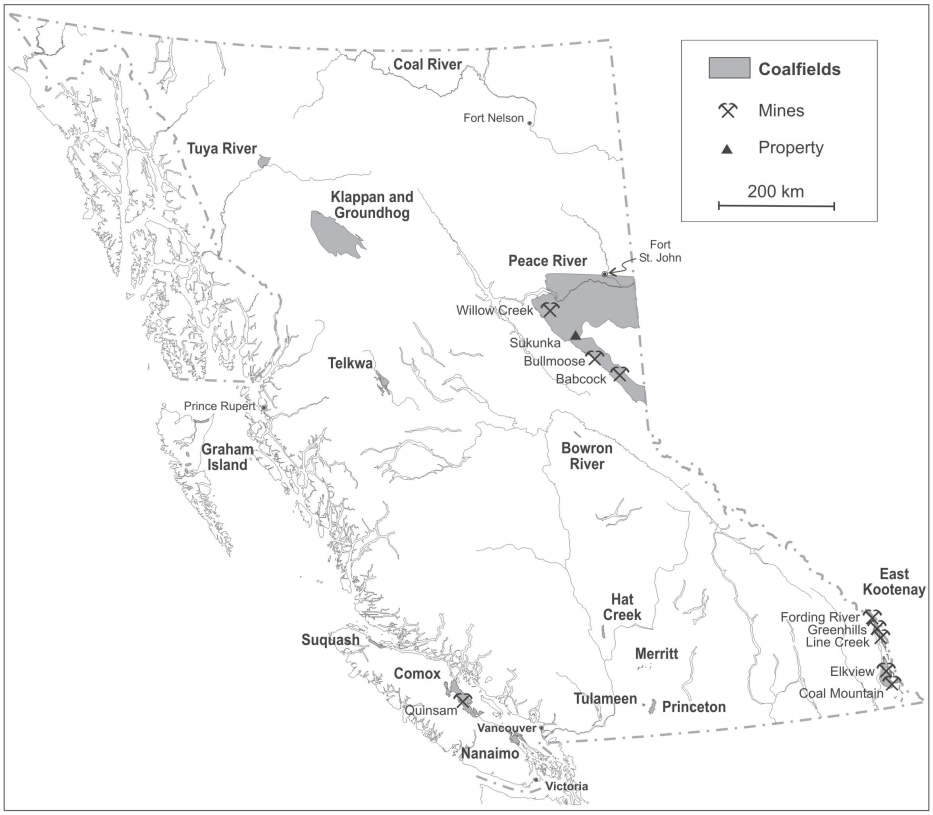


Figure 1. Regional map locating areas visited during this study.

In general there are three tectonic settings useful for describing cleat development and preservation in coals in British Columbia.

- Coals in the northeast and southeast coalfields and the Bowser Basin (Klappan and Groundhog coalfields) have experienced varying degrees of folding and thrusting. Coals are variously cleated, shear jointed or fragmented.
- Cretaceous coals at Telkwa and on Vancouver Island in general experienced only mild folding and steep angle faulting. Coals are well cleated when not close to faults.
- Coals in a number of Tertiary basins are generally of low rank and have experienced simple tectonic histories. Coals are generally well cleated.

SOME GENERAL COMMENTS ON CLEATS

A number of authors have described cleats in coal and Laubach *et. al.* (1998) provide a comprehensive summary. The approach taken in papers may be purely descriptive, describing the geometry of cleats and degree of development; or may attempt a genetic classification by outlining possible origins of cleats.

A descriptive or geometric classification is used by a number of authors (Faraj, 2002) and to some extent in this paper. The simplest descriptive classification refers to cleats as face or butt cleats depending on degree of development and then records their spacing and planar extent. This can usually only be estimated by measuring height of cleats as it is generally not possible to measure cleat development into the outcrop. Surface coating of cleats indicates that at one time they were open, though they may now be cemented. Otherwise it is difficult in outcrop to estimate the relative openness of cleats, especially in mines where most outcrops are the result of blasting and excavation in the immediate area, both of which tend to open cleats.

The degree of cleat development varies through seams depending on lithotypes. Dull lithotypes (inertinite rich layers) tend to be massive and poorly cleated whereas bright lithotypes (vitrain rich layers) are often finely banded and well cleated. The best descriptive approach involves measuring and describing cleat sets, where developed, but also attempts to provide a description of the seam as a whole in terms of degree of fragmentation. This approach is used by Frodsham and Gayer (1999) in their description of deformed coals in South Wales, UK. Using their approach, it is possible to recognize a progression in the degree of fragmentation and shearing of the whole coal seam as indicated below.

1. Parts of the seam are massive and preserve original compositional banding, if present, and maybe some widely spaced cleats. Other parts that are vitrain rich contain closely spaced cleats.
2. The seam is cleated though out with cleats that are perpendicular to bedding but it also contains sets of shear joints that are not perpendicular to bedding. These inclined joints break the seam into random sized and shaped fragments.
3. The seam is highly fractured into fragments less than 3 centimeters cubed by folding or shearing. Any early cleating is destroyed and late forming cleats do not form because the seam is already fragmented. Fragments may reveal minor (drag ?) folds in the seam.
4. The degree of shearing increases and vitrain rich zones are reduced to a grit or powder consistency. Some bands of powdered coal form at acute angles to hanging wall and footwall.
5. The original layering in the seam is largely destroyed. Finely crushed coal is compacted and cut by closely spaced shear surfaces of variable orientation. The surfaces are fluted or striated with lineations having a variable orientation. The surfaces are curved rather than planar and have a greasy luster. They are similar to surfaces described by Bustin (1982a, 1982b) who compared some of them to cone in cone structure or shatter cones (Bustin (1982a).

This type of descriptive approach is useful because it emphasizes the overall appearance of the seam rather than concentrating on those areas where well-preserved cleats are visible and only recording their orientation and appearance.

Ammosov and Eremin (1963) used a genetic classification. A detailed study by these authors classified fractures in coal as endogenetic (related to coal maturation) or exogenetic (related to tectonism). Endogenetic fractures in coal are the classic "cleats" that form under tension probably in response to dewatering and shrinkage of the coal matrix as coal rank increases. Exogenetic fractures are formed by regional stress fields and their orientations are controlled by these fields. There is therefore no reason why they should be restricted to coal seams.

ENDOGENETIC CLEATS AND COAL MATURATION

Law (1993) describes a relationship between cleat spacing and coal rank, with cleat spacing decreasing as rank increases, in the same fashion as the moisture content of coal decreases with increasing rank. The implication is that cleat spacing is related to the loss of water as rank increases. Alternatively cleat spacing at a particular rank could be related to the strength or compressibility of coal at that rank. The first explanation for endogenetic cleats leads to an early origin related to progressive maturation. The second leads to a late origin associated with uplift and decompression.

Formation of early-formed endogenetic cleats is probably related to shrinkage of the bulk coal caused by loss of water and volatile matter during progressive coal maturation. It is possible to estimate the loss of mass of coal, as rank increases, by using average inherent water and as-received volatile matter contents for different ranks starting with lignite. The required coal quality data are available in coal petrology textbooks such as Taylor *et al.* (1998). It is assumed as a first approximation that the amount of fixed carbon in a sample does not decrease as rank increases. It is then possible, using matching values of volatile matter (daf) and rank (mean maximum reflectance Rm values), to track the decrease in coal mass and mass or volume of water and volatile matter expelled as rank increases. The volume occupied by the expelled volatile matter is estimated by converting rank into temperature using relationships in Taylor *et al.* (1998) and then using a geothermal gradient to derive depth and hydrostatic pressure. This method of estimating coal mass loss with rank probably provides a minimum estimate because some fixed carbon is converted to volatile matter as rank increases.

It is possible once weight loss is calculated to use standard estimates of coal density for different ranks, to calculate the volume decrease of the coal mass generated by the loss of volatile matter and water. Insitu coal density is difficult to measure (Ryan, 1991) but values do not change much as rank increases and are in the range of 1 to 1.4 (corrected to an ash-free basis). This volume is the volume available for the water and volatile matter to occupy.

Obviously there are a lot of assumptions and approximations made in the calculations, however by the time lignite is converted to a rank of Rm=0.7%, it is estimated that its volume has decreased by over 50% (Figure 2). In the calculations the starting coal is lignite to sub bituminous coal from Hat Creek (British Columbia), which has a rank of Rm = 0.38% to 0.5% over a depth of range 600 metres (Goodarzi and Gentzis, 1987). It is possible plot the incremental coal mass loss as rank increases (Figure 3). The curve has 2 maxima at temperatures of about 50°C and 160°C and these temperatures correspond approximately with the production of CO_2 and water at low temperature and CH_4at higher temperature (Rightmire, 1984). The effect of adsorption onto the coal of gases distilled out of the coal as rank increases, does not have much effect because, at the temperatures in effect, adsorption capacity is low compared to the amount of gas generated.

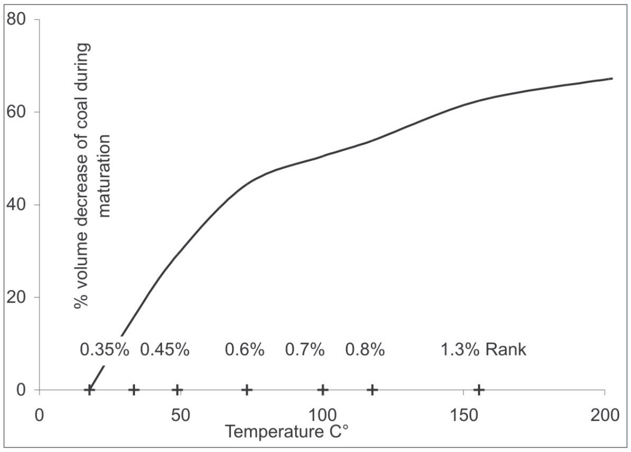


Figure 2. Estimates of percent volume decrease *versus* rank.

The first maxima accounts for most of the volume decrease of the solid coal and is probably accompanied by the formation of face cleats. There will be a lot of water movement along these cleats and there may be precipitation of low temperature minerals such as kaolinite on the cleat surfaces (Spears and Caswell, 1986). The higher temperature maxima corresponds with the volume decrease associated with the production of methane and only a little water by the coal. It is possible that this dry volume decrease is associated with the formation of butt cleats**.** Butt cleats are cleats that form at 90° to and terminate against face cleats. In this model butt cleats may not be present in low rank coals that had not reached sufficient rank to generate large volumes of methane. Because the butt cleats form after most of the water has been driven off the coal they are less likely to be mineral coated. Minerals likely to form on butt cleats at high temperature include calcite (Spears and Caswell, 1986).

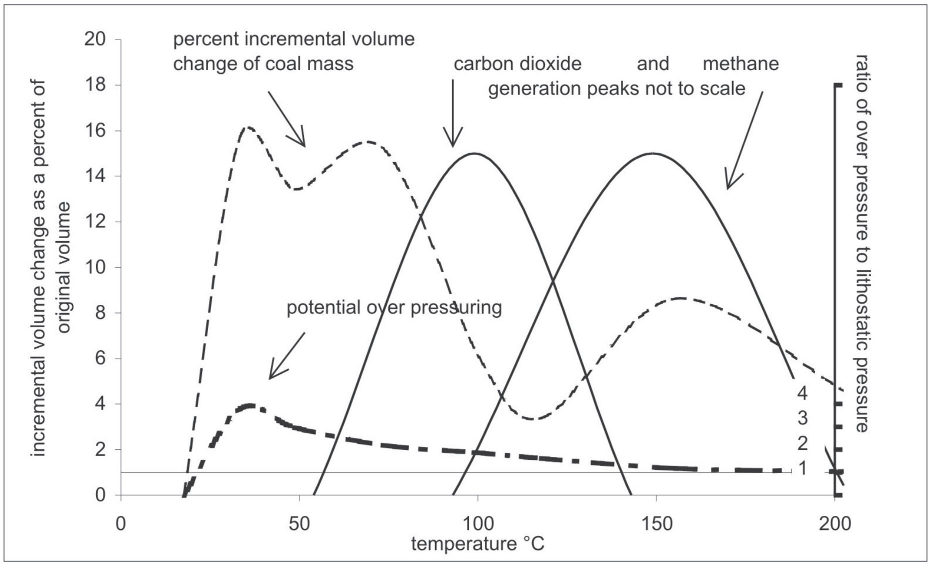


Figure 3. Incremental volume decrease during coalification, potential over pressuring and approximate temperatures for generation of carbon dioxide and thermogenic methane.

Of the various processes that influence cleat development relative to time (Figure 4), probably volume decrease and the relationship between deformation history and changes in hydrostatic pressure are the most important. **V**olume decrease is generally controlled by the various lithotypes in seams. The inherent moisture content of macerals at a rank of 0.7% Rm varies from over 15% in vitrinite to under 8% in inertinites, but by the time rank reaches 1.2% Rm, the difference in moisture contents is only about 4% (Sanders, 1984). There is a similar difference in volatile matter contents and the result is that vitrain bands may shrink by over 50% when rank increases from lignite to high-volatile bituminous, whereas inertinite rich bands may shrink by less than 25% over the same rank increase. It is not surprising that cleating is closer spaced and more developed in vitrain than inertinite rich bands.

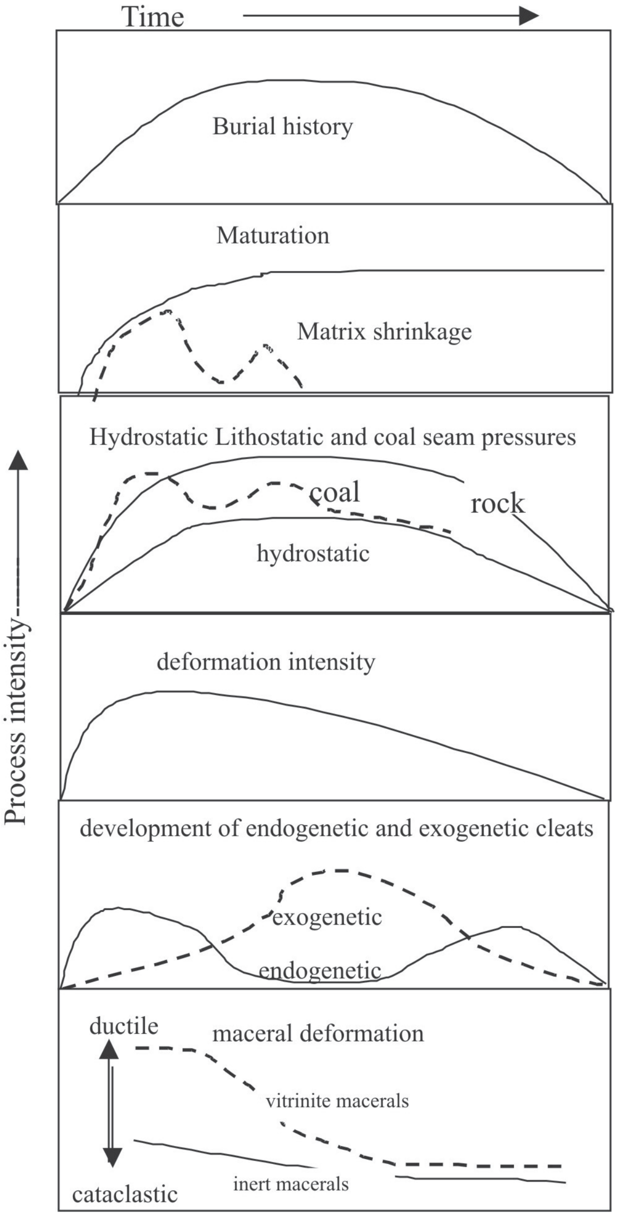


Figure 4. Schematic of various processes that influence cleat development.

Cretaceous coals in British Columbia are characterized by variable and increased contents of inertinite compared to carboniferous coals. Inertinite rich seams may not develop endogenetic cleats, if tectonic stresses produce strain that counters the effects of shrinkage. They may only develop normal shear and tension joints with orientations reflecting the regional stress field. These joints are likely to traverse into the hanging wall and footwall and therefore may not confine fluid flow along the seam.

The volume vacated by the shrinking coal mass, as rank increases, is occupied by the expelled water and volatile matter (now a gas). The part of the coal that becomes volatile matter after heating is probably either part of the coal structure or adsorbed onto the coal with a density of liquid. Consequently once it is converted into a gas it occupies a greater volume. The increase in volume depends on temperature and pressure conditions. If the volatile matter and water cannot escape into the surrounding rocks, then there is therefore the potential for over pressuring within the seam. Over pressuring occurs when the hydrostatic pressure within the seam exceeds that which would be generated by a water column extending to the surface. The amount of potential over pressuring is high and reaches a maximum at a temperature of about 50°C (Figure 3) and is decreasing during the generation of thermogenetic methane. The plot is only an estimate of the ratio of potential over pressure to lithostatic pressure because a more accurate calculation requires an assumption of the porosity of the seam unrelated to maturation.

If fractures interconnect upwards through the stratigraphy, then fluid pressure in the seam is that of a water column extending to surface, and fluids generated by coalification are dispersed into the surrounding lithology. Lithostatic pressure is effective through the seams and seams may compact vertically and shrink horizontally to form vertical cleats normal to the horizontal minimum stress direction within the seam (Figure 5). These face cleats will generally be normal to the regional fold axis at any depth. However in the surrounding rocks the minimum stress axis may be vertical at shallow depth (with the intermediate stress axis horizontal) and horizontal at greater depth (with the intermediate stress axis vertical). Associated tension fractures will be vertical at shallow depth. Shear fractures that form at shallow depth will intersect the seam at shallow angles and those that form att depth will be vertical intersecting the seam at high angles (Figure 5). This may influence permeability across the coal rock interface. It should also be appreciated that the early stages of coal maturation may occur under conditions in which surrounding rocks may not be indurated and coherent enough to fracture. Depending on composition they may act as permeability barriers.

If fluids cannot escape from the seam, then fluid pressure may approach or exceed normal hydrostatic or even lithostatic pressure leading to the development of over pressure conditions. If this happens at shallow depth, then bedding plane cleats as well as or instead of bedding-normal cleats may form (Figure 5). At greater depths over pres-

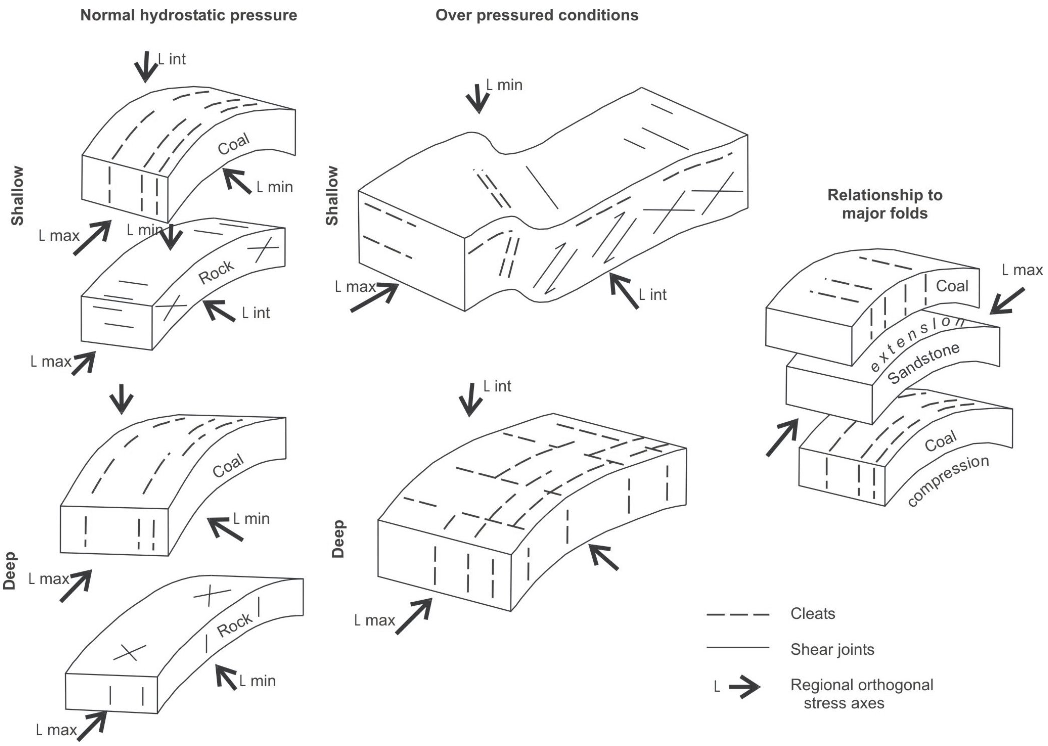


Figure 5. Schematic of cleat formation in thrust and fold tectonics.

suring caused by coalification is less likely because at higher ranks the progressive expulsion of water is less. However if it does occur at depth, because of rapid burial and low geothermal gradient, then cleats or tension fractures may form normal to bedding and probably normal to the fold axis. In an over pressure environment and absence of any directional stress field, cleat sets may not form and the coal may simply fragment or powder as it shrinks. Low angle shear fractures that form in coal seams probably form when hydrostatic pressure returns to normal.

It appears that endogenetic face cleats are most likely to form when the coal is at shallow depth and not over pressured. Identification of over-pressuring in seams, if not accompanied by extensive deformation, may indicate an environment in which gas generated during maturation may be trapped in adjacent sediments. The gas will therefore be available for adsorption by coal during uplift. If butt cleats form during generation of the thermogenic methane peak then their presence may indicate over pressuring at this time. In the absence of over pressuring, deformation of the seam may counter the effects of coal volume decrease and negate the necessity to form butt cleats.

Endogenetic cleats are nearly always perpendicular to bedding. Part of the reason is probably that with the disparity in volume shrinkage between various coal litho types and between coal and hanging wall and foot wall rock, these contact surfaces are initially slip surfaces that develop into surfaces of low cohesion. Principle stress axes must therefore be parallel or perpendicular to these surfaces.

Butt may form during maturation as discussed or in a response to elastic expansion during uplift and unloading of the coal. Their frequency will therefore in part be related to strength of coal litho types and to the amount of stored elastic energy. Expansion in one direction (vertical) produces shrinkage in another and the easiest direction for expansion is normal to the hanging wall and consequently shrinkage is parallel to the hanging wall and results in the formation of cleats normal to both face cleats and bedding. Expansion is normal to the hanging wall because if the seam is horizontal this is the direction of unloading but even if the seam is not, the hanging wall surface represents a low cohesion surface so that principle stress axes are normal to the surface. Butt cleats therefore form in response to coal properties and not regional tectonics and are best classified as endogenetic despite the fact that they may form late and after coal maturation. In fact butt cleats may form during the final stages of uplift and may not be present in coals intersected in deep CBM holes.

Price (1966) suggests that the frequency of cleats (butt cleats ?) in coal may be related to the amount of strain energy stored in coal, which for all coal ranks is greater than that stored in other lithologies. He and many others have also noted the inverse relationship between unit thickness and tension joint spacing.

Ammosov and Eremin (1963) further classified endogenetic fractures and indicated that endogenetic "cleats" restricted to vitrain bands attain a maximum frequency at mid rank and have lower frequencies at high and low ranks. The implication may be that endogenetic cleats are annealed at higher ranks. Xianbo *et. al.* (2001) also describe annealed cleats in higher rank coals.

Face cleats or the better-developed endogenetic cleats are often perpendicular to the regional fold basinal axis, for example the San Juan Basin (Close and Mavor, 1991), the Mississippian and Pennsylvanian anthracite fields (Levine and Edmunds, 1993) and the Greater Green River basin (Laubach *et al.*, 1993). They are considered to form parallel to the direction of regional compression (Tyler, 2001). Butt cleats, which terminate against the face cleats, are therefore generally oriented parallel the basin axis and often intersect bedding to form a line parallel the strike of the bedding.

EXOGENETIC CLEATS AND COAL MATURATION

Exogenetic fractures (fractures of tectonic origin) in coal are obviously of prime concern in the northeast and southeast coalfields of British Columbia. They are not necessarily perpendicular to bedding and their geometries are controlled by regional stress fields. In contrast to endogenetic cleats, they may form under compression and therefore tend to generate powdered coal, which can migrate and damage permeability. Experience in Russia (Ammosov and Eremin, 1963) indicated that increased development of exogenetic fractures in coal progressively decreased permeability to the point that it was difficult to drain methane (CH_4) from underground mining blocks. Development of exogenetic fractures in coal is in part dependent on the strength of the litho types that make up the seam. Ammosov and Eremin (1963) indicate that coal strength is a minimum for medium rank coals and consequently coals of this rank will tend to develop a greater frequency of exogenetic fractures as well as endogenetic cleats. Hardgrove Index is a measure of the friability of coal (high numbers equal friable coal) and is a measurement used to appraise coals for mining and handling characteristics. It varies with rank indicating a minimum hardness at medium rank (Figure 6 from Yancy and Geer, 1945). The variation is not as extreme as the variation in cleat spacing with rank (Law, 1993) and this might be interpreted as evidence for an early endogenetic origin for many cleats.

Hardgrove Index values often exist in the literature separate of CBM studies. If they indicate that a coal is more friable than expected for its rank then the coal is probably fragmented and not cleated. If numbers are lower than expected, then the coal is hard considering its rank and may contain a predominance of inertinite. It is likely to be less fragmented and well cleated compared to coals of similar rank with higher Hardgrove Index values.

It is important to remember that exogenetic cleats owe their origin to regional or local stress fields and not coal maturation. They are therefore more likely to extend across hanging wall and footwall boundaries. This may make it difficult to dewater and de-pressure a coal seam without also accessing the surrounding lithologies. As mentioned, coal maturation may occur before the surrounding rocks are coherent enough to fracture. Therefore exogenetic fractures in coal and surrounding rocks may form after endogenetic cleats in seams.

CLEATS AND MATRIX SHRINKAGE CAUSED BY DEGASSING

Matrix shrinkage, initiated by gas desorption, has been discussed by a number of authors (Harpalani and Chen, 1997). Coal that over its life desorbs 500 scf/t (15.6 cc/g) actually looses about 11 kg of mass per tonne (1.1 wt%). If the gas was held in the coal with the density of a liquid then this accounts for about 3% of the volume of the coal. The coal may or may not shrink to accommodate this volume loss. Obviously if the 500 scf/t of gas is concentrated in only part of the coal (vitrain rich bands), then the shrinkage in some layers will be much greater. Matrix shrinkage increases permeability as long as the rate of shrinkage is greater than the strain rate induced in the coal as a consequence of the decrease of hydrostatic pressure resulting from pumping the water out of the seam. Reducing hydrostatic pressure increases deviatoric stress and initiates a strain response in the coal.

Some coals are substantially under saturated. This may be the result of degassing at their present location or indicate that the coal was unable to adsorb gas, as temperature decreased and adsorption capacity increased, during uplift. If under saturation is the result of degassing, then it must be accompanied by matrix shrinkage that might leave evidence in the form of cleats or micro fractures. There is sometimes a correlation between vitrinite content and micro permeability (Clarkson and Bustin, 1997) and between permeability and degree of under saturation (Bustin, 1997). In situations where ground water movement starts to strip gas from coal, the accompanying matrix shrinkage may form micro cleats and accelerate the process. It might be possible to recognize micro fractures associated with matrix shrinkage under an optical microscope or scanning electron microscope.

In the more deformed seams in northeast and southeast British Columbia, coal has flowed into fold hinges, along thrusts or along duplex surfaces within seams. Movement of coal into lower pressure areas may trigger desorption and

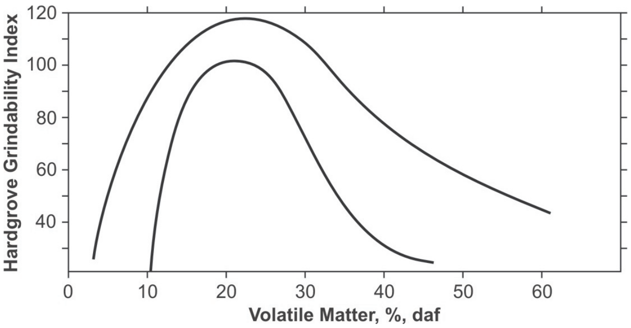


Figure 6. Variation of Hardgrove Index with rank from Levine (1993).

matrix shrinkage and generally aid the flow process. Unfortunately this will produce sheared and degassed coal. As the structural regime changes and pressure increases, coal will be under saturated and may adsorb methane or carbon dioxide. It is important, that once desorption and matrix shrinkage start, that the desorbed gas can migrate. If this is the case, then there may be rapid desorption with a half life for desorption approaching that of coals in a canister where half lives are often less than 1 day. Half life is obviously related to pressure drop and gas content and together both provide information on the stain rate produced by matrix shrinkage. Matrix shrinkage associated with pressure drop and degassing, may, to some extent, be countered by elastic expansion. The strain rate induced by a rapid decrease in pressure can be estimated from the relationship of (delta Volume) / Volume to pressure and pressure to gas content (isotherm). For example if pressure decreases by 4 MPa (equivalent to about 400 metres) and coal looses half its gas in 1 day for a 1% shrinkage then this could indicate a strain rate of 1.16×10^{-6} Sec^{-1}. This rate is much faster than geological strain rates. There may be situations where deformation and changes in hydrostatic pressure can initiate degassing and matrix shrinkage in coals, with the accompanying strain rate greater than normal geological strain rates.

SOME COMMENTS ON THRUST AND FOLD GEOMETRIES

Thrust thickening of coal, seams is more prevalent in seams low in the Mist Mountain Formation in southeast British Columbia than in the Gething and Gates formation coals in northeast British Columbia. Seams are thickened by combinations of thrusting, duplexing and cataclastic flow. It is important to consider the mechanisms of these processes and to understand the implications on coal quality and permeability. In simple terms the three processes re arrange the internal layering or coal quality variations in different ways. Thrusting produces a repetition of any quality variations within the seam (*i.e.* higher ash or inertinite in the upper part of a seam). Duplexing increases the seam thickness but does not totally destroy the original quality layering within the seam. Cataclastic flow, in the extreme, homogenizes any quality variations in the seam. All three processes probably destroy or damage any regional flow paths along seams in terms of through going cleat systems.

Thrusts may traverse footwalls or hanging walls of seams, but on close inspection it is obvious in many seams that there is also a lot of internal deformation, which in some cases appears to have developed into duplexing within seams. Geometries of this type of deformation are described by (Boyer and Elliott, 1982), Gayer (1993) and Frodsham and Gayer (1999). Gayer (1993) described polished, closely spaced, sigmoidal surfaces oriented at 30° to 45° to bedding that result from internal deformation in seams experiencing progressive easy slip thrusting (PEST). Surfaces of this type are prevalent in seams in southeast British Columbia. The intersection of these shear fractures with the hanging walls usually defines the regional fold axis trend. If they are not pervasively developed then regional permeability will be anisotropic and best along fold axis directions. Bedding plane slip and duplexing have been described in seams in China (Li, 2001) and are responsible for increased risk of mine outbursts. The sheared and powdered coal has low permeability and tends to seal in gas until mining reduces most of the confining pressure. It is not clear if the shearing increases the ability of coal to adsorb gas. Studies in southeast British Columbia appear to indicate that shearing does not affect coal adsorption capacity **(**Vessey, 1999)

The combination of thrusting and duplexing may destroy permeability in seams but it can generate tension fractures in the hanging wall rocks. The process of developing horses within seams and differential movement between footwall and hanging wall forms an anticline and syncline pair in roof rocks that migrates forward as thrusting and duplexing develop (Boyer and Elliott, 1982). The forward propagation of these folds produces extensional features in the hanging wall rocks and dilation of the coal as they pass. As they migrate forward fluid pressure in the local area may be reduced and coals partially degassed. This is not important in terms of CBM resource because the process probably occurs during the early stages of coal maturation and before generation of thermogenic methane. If the coal is not already fragmented, folding and decrease in hydrostatic pressure may allow fold axis normal cleats to form, however the predominant orientation of cleats will probably be axial planar. Because of fold migration in the hanging wall rocks in the thrust direction, these rocks may be extensively fractured out of keeping with the present fold style and intensity.

Folds in adjacent lithologies can cause extension or compression in coal seams. Competent units fold by flexural slip or buckling, in which case regions of extension and compression are controlled by the neutral surface (surface of zero strain). A seam folded into an anticline may experience extension (above neutral surface) or compression (below neutral surface), depending on its relative position with respect to the neutral surface in an adjacent competent sandstone. Identifying these regions may outline fold axis oriented areas of improved permeability. In a tectonic regime where seams are developing folds and are not over pressured, regional cleats will form normal to the fold axis direction (Figure 6) though local cleats may form parallel the fold axis in local regions of extension.

RELATIONSHIP BETWEEN COAL MATURATION AND DEFORMATION

Coalfields in the northeast and southeast of British Columbia have experienced varying degrees of thrusting and folding. This needs to be considered when exploring in the coalfields for CBM. It is important to match coal maturation and the accompanying shrinkage of the coal mass, with the deformation history in order to understand the interplay between the formation of endogenetic and exogenetic fractures in seams. Coal shrinkage during maturation influences the formation of face cleats (and maybe butt cleats) and the formation of larger structures in seams.

There is probably a strong linkage between thrusting and early coal maturation (ranks from lignite to high-volatile bituminous) in coal sequences, where thrusting forms part of the deformation history. Gayer (1993) suggests that fluid over pressuring in seams causes thrusting. He has built on the descriptions of thrust geometries by Boyer and Elliott (1982) to explain thrust geometries seen in seams and describes progressive easy slip thrusting (PEST) imitated in coals because of fluid over pressuring. Over pressuring is a direct result of dewatering and de-volatilization associated with increasing coal rank. There is therefore a close relationship between the environment in which coal progresses through the ranks of lignite to high-volatile bituminous and the initiation of thrusts associated with thick seams.

Over pressuring within a seam provides the ideal conditions for thrust development. Even with the escape of some fluid, if hydrostatic pressure is equal to lithostatic pressure, then after a coal mass volume decrease of 50%, the coal will be effectively floating and experiencing no deviatoric stress. In these conditions over pressuring probably causes extension in the vertical direction, rather than the horizontal, and horizontal tension fractures form. It may also be responsible for the generation of coal fines rather than a coherent set of cleats.

Thrusts initiated in coal seams by over pressuring form at moderately shallow depths and at these depths over pressuring will produce bedding parallel fractures that will participate in thrusting and not aid in the development of cleats. This may explain in part why some seams can be a mixture of highly sheared zones and fairly massive coal. The development of the duplexing and or thrusts may produce, in bands of coal that escape shearing, cleats that are parallel to the axial plane of thrust ramps (Figure 6). In this tectonic regime the orientation of face cleats will vary somewhat between thrust blocks and they will owe their origin to the temporary generation of extension as folds migrate forward during thrusting.

Once the geometries of cleats and fractures in seams are documented, it is important to relate their orientations to that of the present stress field. There are some obvious and important considerations. The contact between coal seams and hanging wall and footwall lithology is probably a surface with low cohesion and therefore principle stress axes will tend to be parallel and perpendicular to these surfaces whatever the dip of the seam. If the present minimum stress direction is perpendicular to the main cleat direction, then there will be a tendency for the cleats to remain or be opened. The magnitude and orientation of the present day stress field described in terms of effective stresses and stress gradients combined with the orientation of cleats and fractures in seams together are by far the most important factors controlling permeability. In fact studies in the Black Warrior Basin indicate that ultimate gas recovery correlates better with the magnitude of the minimum stress within the bedding surface (Shmin) than gas in place (Sparks *et al.*, 1995).

Water disposal is usually one of the costs associated with CBM production. It may be possible to use water disposal from one seam to aid in CBM production from another by enhancing its permeability. If water is injected into one horizon isolated in terms of permeability from a second, then the increase volume in the second zone may open cleats and improve permeability in it. This may help production in shallow buried seams. In more deeply buried seams dewatering a lower seam may produce enough subsidence in an overlying seam to increase permeability. Staged dewatering of a stack of seams may increase produceability in upper seams. In coal sections where seams are isolated by impermeable layers such as bentonites it may be possible to re inject water into depleted seams to stimulate production in other seams and thus gain the double advantage of cheep water disposal and improved permeability.

MICRO DEFORMATION AND COAL MATURATION

The style of deformation of macerals, as seen under the microscope, should reveal something about the timing of deformation relative to coal maturation. To some extent coal is made up of two structural components, one of which is brittle, hard and of unchanging characteristics during maturation (inert macerals) and one that is initially ductile but becomes progressively more brittle as coal rank increases (vitrinite macerals). Evidence for deformation that occurs early during coal maturation will include compaction and rotation effects in vitrinite (collodetrinite) around inert fragments and the general impression of flow structures in collodetrinite. Deformation that occurs later in coal maturation will take the form of micro fracturing, strain shadows and cataclastic flow.

There may also be tendencies towards different microstructures in coal based on whether it was over pressured or not at the time of deformation. If the coal was over pressured at shallow depth in a thrusting environment, in which horizontal cleats were forming, then compaction effects may be perpendicular to cleats and therefore probably act along bedding. The effects would not be very conspicuous but would tend to be visible against the sides of inert fragments buried in collodetrinite. There may also be evidence of flow and rotation of inert fragments in collodetrinite. If the coal is not over pressured, then there may not be signs of rotation and compaction may operate across bedding.

COMMENTS ON COAL SEAM POROSITY

Some geophysical logs measure seam density. If the ash content of seams is determined later when core is recovered, then it is possible using a simple equation (Ryan, 1991 and Ryan and Takkanin, 1999) to calculate porosity. An even simpler way of estimating seam porosity in outcrop is to collect outcrop samples where the seam is water saturated. Seal the sample and send it to a laboratory for a determination of as-received and air-dried moistures. The difference the two moisture analyses will provide a weight of surface water, which if the fracture porosity was saturated can be converted into a volume percent porosity. In small diameter holes drilled to collect coals for desorption, careful use of density logs and coal analyses can provide useful and cheep information about coal porosity, which may correlate with permeability.

COMMENTS ON INDIVIDUAL LOCATIONS

All the mines and a number of coal properties were visited during the study. A lot of photos were taken at the various sites and these are available with the text in the form of a CD from the ministry.

PEACE RIVER COALFIELD

There are two coal-bearing formations in the coalfield (Figure 7). The lower Gething Formation contains coal over an extensive area, though the best development is in the area between the Sukunka and Pine rivers. The formation is enclosed by the underlying Cadomin conglomerate and the overlying Bluesky conglomerate, above which is the marine Moosebar Formation. This formation is overlain by the coal-bearing Gates Formation, which contains coal from the Sukunka River southeast to the Alberta border.

The deformed belt of the coalfield (inner foothills), which trends northwest, is defined by the outcrop of the Gething Formation on the west and a number of major thrusts on the east; the main one being the Gwillam Lake Thrust. East of the thrusts Cretaceous beds dip into the trough of the western Canadian Sedimentary Basin and are in places too deep to be of interest for CBM development. Fold style is generally chevron with well-developed flat limbs and shorter steep dipping limbs. Regional thrusts are west dipping, though at least at Willow Creek (Figure 7) reverse faults and axial planes dip steeply to the east. Locating fold hinges at depth may require knowledge of the dip of axial surfaces.

Bachu (2002) studied the present insitu stress regime in the coal-bearing strata of the northeastern plains area of British Columbia and data in his paper may be applicable to coals in the deformed belt to the west in the Peace River Coalfield. Shmin is oriented northwest southeast in the study area (Bachu, 2002) and is therefore following the trend of the regional structures. Permeability will be enhanced in a direction northeast southwest and fractures or cleats with this orientation will have more chance of being open. Langenberg (1990) found that face cleats in the Rocky Mountain Front Ranges are oriented northeast southwest and are therefore perpendicular to the fold axis trends and to the present day Shmin. As mentioned below face cleats in the Gething in the north in the deformed belt appear to be parallel the regional fold trend and face cleats in the Gates to the south tend to be fold axis normal. If these orientations are maintained regionally, then the Gates coals may have better permeability than the Gething coals. However the regional structural trend indicates that drainage areas around individual wells will be elongated in a northwest southeast direction. The ideal situation would be where permeability is also enhanced in this direction.

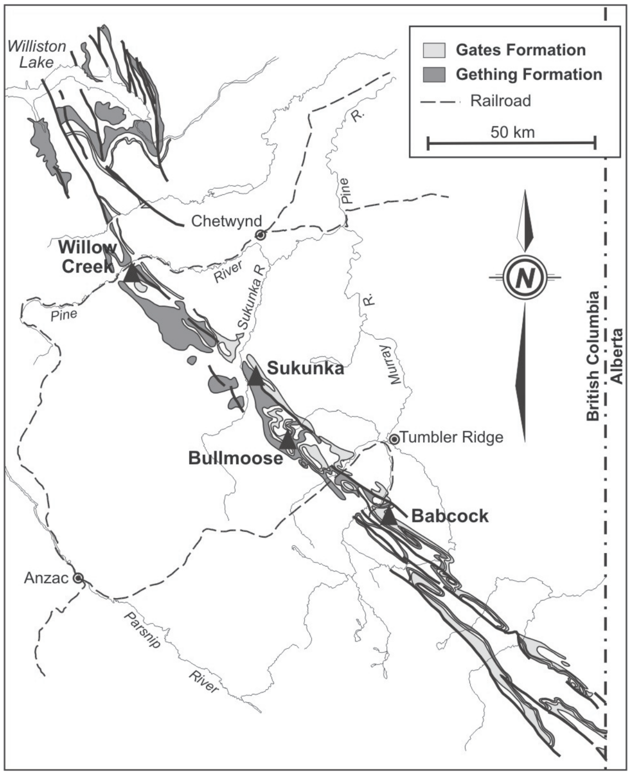


Figure 7. Distribution of Gething and Gates formations northeast British Columbia.

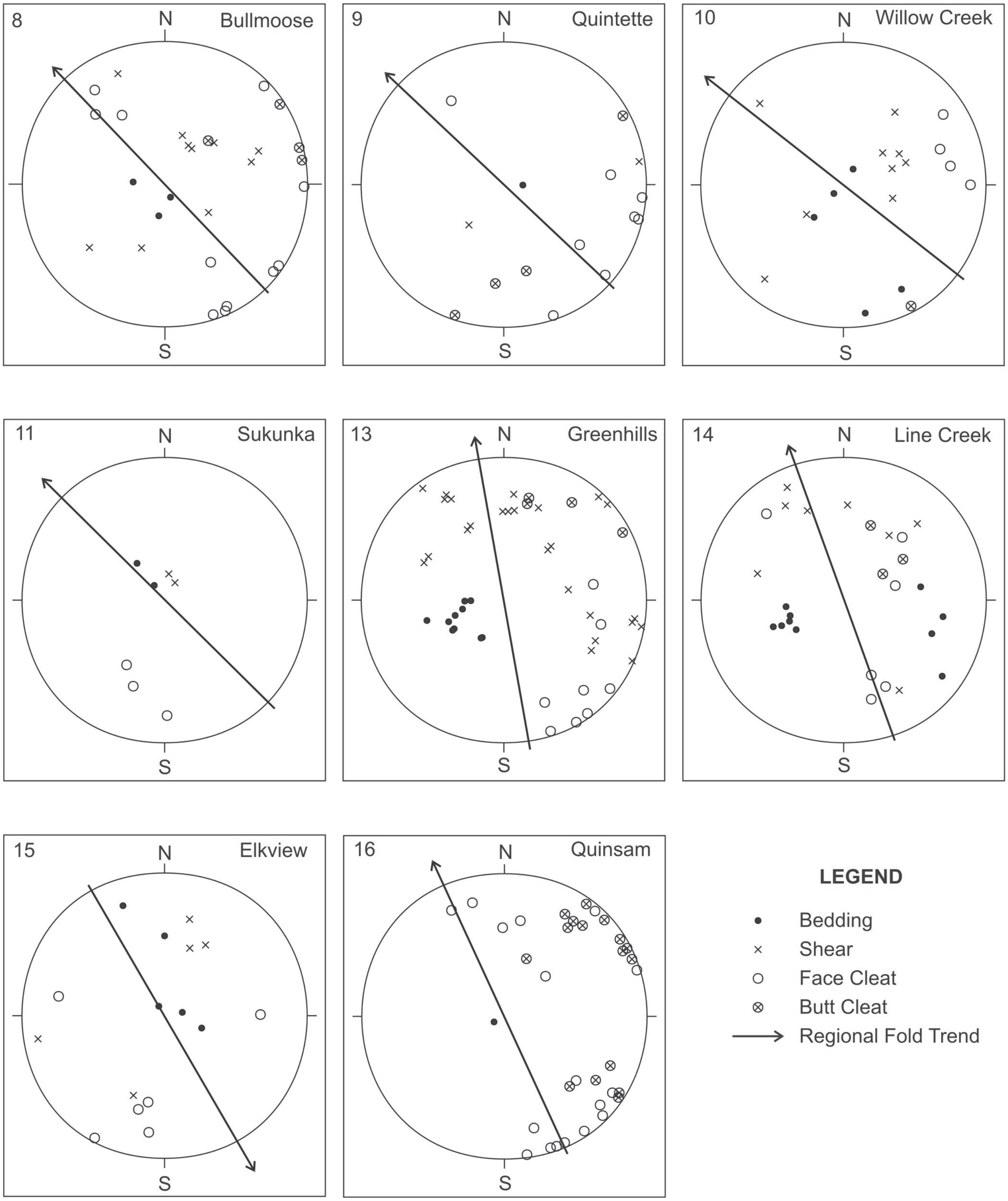
GATES FORMATION COALS

BULLMOOSE MINE

Coal at the Bullmoose Mine is contained in the lower Cretaceous Gates Formation. Seams at the mine are numbered from A seam at the base of the section, which is about 90 metres thick, upwards to E seam. The cumulative thickness of coal is about 12 metres with B seam being the thickest at about 4.8 metres. Seams A, B and C were observed. The mine will close in 2003 and is now only mining seams A and B.

Seam A is divided into an upper coal, A2 separated from A1 by a parting that can be up to 1.5 metres thick. The seam contains more vitrain than B seam. Face cleats are well developed in vitrain bands and are fold axis normal in the upper and lower zones (Figure 8). Some of the cleats are calcite coated. Low angle shear surfaces dip to the southwest and intersect bedding parallel to the regional fold trend.

Seam B, which is the thickest seam on the property, is generally high in inertinite but has a low ash content of 12%. Cleats strike northeast and southeast. Closely spaced cleats in vitrain bands strike southeast whereas more widely spaced cleats in inertinite rich bands strike northeast. The seam can be massive in places with occasional cleats appearing tight. There is no indication of cement on cleat surfaces.



Figures 8 to 11 and 13 to 16. Steriographic plots of poles to bedding, shear joints and cleats for data from the Bullmoose Mine, Quintette Mine, the Willow Creek Mine, the Sukunka property, the Greenhills Mine, the Line Creek Mine, the Elkview Mine and the Number 1 seam Comox Formation Quinsam Coal Mine.

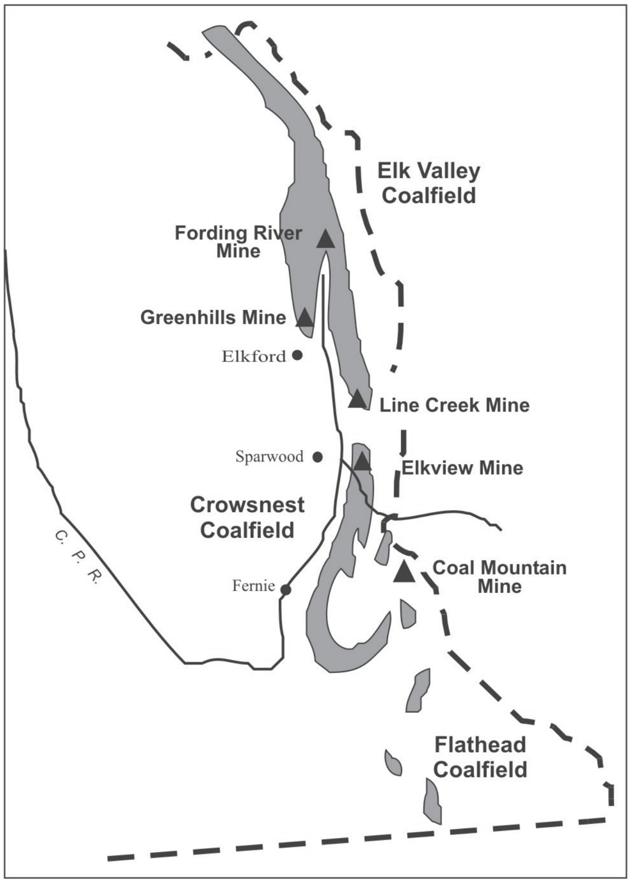


Figure 12. Coalmines and coalfields in southeast British Columbia.

Seam C, which is 1.8 metres thick, has a fairly high ash content (35%) and is inertinite rich. The seam is generally broken into blocks with intervening shear or fragmented zones. Face cleats strike 040° and dip 90° and therefore trend perpendicular to the regional fold trend. Butt cleats strike 135° and dip 47° to the southwest.

Based on limited measurements (Figure 8) the best-developed cleats tend to be fold axis normal as is common in other coalfields.

QUINTETTE MINE

The Quintette Mine extracted coal from the Gates Formation, but to ensure a level of confusion with reference to the Bullmoose Mine, seams are numbered from the base of the section starting at K and decreasing in letter to D at the top of the section, which varies in thickness up to 85 metres. Cumulative coal in the section varies from 14 to 23 metres. The mine is now closed and being reclaimed. During its life a number of deposits were mined in three areas each with different intensities of deformation. Coal on Mesa Mountain is extensively folded and faulted. In the Shikano pit, close to the wash plant, the coal measures are folded into a tight syncline with planar limbs. On Babcock Mountain, the Gates Formation is folded into a broad northwest trending anticline and this is probably the only perspective type of geology for CBM development in the area.

Cleats were measured in a number of seams on Babcock Mountain (Figure 9). K seam, which is the base of the section and thin, appears to be massive but is cut by numerous shear joints that intersect bedding parallel the regional fold direction (Figure 9). Cleats are poorly developed and restricted to small un-sheared blocks of coal between shear joints. J seam is about 4 metres thick and has about 20% raw ash. Cleats are normal or parallel the fold trend and it is not clear which trend formed first or is more persistent as the degree of development of the cleats changes along the outcrop. Seam F, which is 2.5 metres thick, is finely cleated with closely spaced cleats trending north and sub-parallel the fold axis trend. More widely spaced cleats trend east west. Seams E and D appear blocky with interspersed fracture zones.

GETHING FORMATION COALS

WILLOW CREEK PROPERTY

Pine Valley Coal Limited is developing a small open pit mine on the Willow Creek Property, which is 45 kilometres west of Chetwynd. The area is underlain by the Gething Formation, which in its upper 270 metes contains 8 seams numbered from 1 at the top of the section to 8 in the middle of the formation (personal communication, Kevin James, 1999). Cumulative coal in the section ranges from 21.2 metres at Willow Creek central to 16.1 metres at Willow Creek north. To date the company has excavated test pits in seams 6 and 7, which have exposed good outcrops of the seams.

Outcrops of 7 Seam form a monocline with an extensive flat limb and a short near vertical limb that breaks the surface. The steep limb appears to be duplexed with horses formed at an acute angle to bedding in the hanging wall. Cleating is not visible in the seam on the steep limb where slip surfaces intersect the hanging wall along a line parallel the regional fold axis (Figure 10). On the flat limb, 7 Seam contains cleats in occasional vitrain bands but is otherwise fairly massive. Cleats strike sub parallel to the regional fold axis trend. In places low angle southwest dipping shear joints are developed, which destroy cleats. These shears are evidence of the pervasive northeast thrusting and if they continue to develop probably lead to duplexing within seams. It is possible that the duplexing seen in the steep limb predated the folding and the zone of thickening it produced acted as a locus for the development of the fold hinge and steep limb.

The overlying 6 Seam, where exposed, is flat dipping and inertinite rich and consequently fairly massive. Closely spaced cleats are restricted to a single vitrain band and are oriented parallel the fold axis trend. Southwest dipping shear surfaces are also present but not pervasive. The seam is not well cleated where exposed but would probably fracture well under stimulation at the right depth. Inertinite tends to have higher diffusivity than vitrinite and this could compensate for the more widely spaced cleats in the inertinite rich parts of the seam.

In contrast to the Gates Formation in to the southeast the predominant cleats in the Gething in the Willow Creek area are fold axis parallel however the same southwest shear joints are present and in one area have developed to the extent of obliterating the original fabric of the seam.

SUKUNKA PROPERTY

The Sukunka Property is located about 60 kilometres south of Chetwynd and 35 kilometres west of Tumbler Ridge (Figure 1). The main seams are in the Upper Gething and are the Bird seam near the top of the formation and the underlying Chamberlain and Skeeter seams. The Chamberlain seam, which is split into an upper and lower member, is well exposed on the north side of Chamberlain Creek where a number of adits were constructed in the 1970's. The seam is blocky with widely spaced cleats that strike east southeast, approximately parallel the regional fold axis (Figure 11). In places southwest dipping shear surfaces break up the coal. They have similar geometries to those seen at Willow Creek and are evidence of incipient northeast directed thrusts. In general the seam does not contain extensive shear zones and the dip is flat. It is overlain by a prominent sandstone, which may limit the break out of thrusts from the coal seam but may also be permeable allowing for movement of gas and water across the seam boundary.

SOUTHEAST COALFIELDS

Coal is mined in five mines in the 2 major coalfields (Crowsnest and Elk Valley) in southeast British Columbia (Figure 12). Coal in the coalfields is contained in the Mist Mountain Formation, which in the mines varies in thickness from 150 metres at Coal Mountain Collieries to 550 metres at the Fording River Mine. The coalfields are in the upper plate of the Lewis Thrust. Folds in both coalfields trend north to northwest and in part postdate west-dipping thrusts with the same trend. Extension occurred in the Tertiary when the major north trending Erickson Fault formed. It down drops beds on the west and is responsible for the preservation of part of the Elk Valley Coalfield. The western boundary of both coalfields is partially defined by the Bourgeau Thrust.

There have been a number of studies of coal seam deformation in the Crowsnest Coalfield. Norris (1965) studied A seam in underground A-North Mine at the north end of the Crowsnest Coalfield. This seam is approximately 420 metres above the basal Balmer or 10 Seam in the Mist Mountain Formation. He describes the seam as being highly sheared with abundant shear surfaces and intrastratal folds. Joints tended to strike north or northwest with evidence of early minor extension faults cut off by renewed bedding plane slip. He does not directly discuss cleats or the degree of shearing in the seam but the impression is left that the seam is highly sheared and fragmented.

Bustin (1982b) studied the lowest seam in the Mist Mountain Formation in a number of underground coalmines (Balmer North, Five Panel and Six Panel) at the north end of the Crowsnest Coalfield. In the Balmer North Mine, the best-developed cleats formed acute angles to bedding, striking northwest and dipping shallowly to the southeast. Cleat surfaces were polished and striated. Other cleat sets were measured but did not have a consistent orientation through the mine. Cleats in the Five and Six Panel mines are more consistent with a set striking north to northwest with a steep dip to the west. These cleats are sub perpendicular to bedding and trend parallel to the regional fold axis. All fractures and most cleats in the seam appear to have a tectonic influence, with surfaces polished and often showing evidence of shearing. However their orientations are not easily related to a regional stress field. Thrusting probably started with differential movement between the roof and floor (Norris, 1965) that disrupted earlier extension faults. As seam thickening and thrusting progressed exogenetic fractures with fold axis parallel trends and variable dips to the west developed in the coal.

A number of authors have studied the relationship of coal maturation to thrusting and folding. Bustin and England (1989) studied a number of deep drill holes in southeast British Columbia and concluded that in 7 out of 11 holes a significant component of maturation postdated emplacement of over thrust sheets. In the Crowsnest Coalfield, Pearson and Grieve (1977, 1978) considered a large component of coalification to post-date folding. In that folding was probably synchronous or post dated thrusting, coal maturation must have continued after thrusting. This to be expected based on the correlation of possible over pressuring with low rank coals (Figure 3). In this case a seam could have different ranks in different thrust sheets, depending on depth of burial after thrusting and possibly folding. Obviously it would be very dangerous to generalize about the cleating or permeability in a seam across thrust blocks.

The number of seams in the Mist Mountain Formation ranges from 3 at Coal Mountain Collieries to over 30 at the Greenhills Mine. Unfortunately seam nomenclature varies between the 2 coalfields and between mines. Exploration in the Crowsnest coalfield has generally numbered the seams starting at seam 1at the base of the section. At the northern end on the coalfield mines in the Michel Valley referred to the thick basal seam as the Balmer Seam or at the Elk Valley Mine as the Number 10 Seam. Seam numbers decreased up section until the numbering system is forced to use letters. The same nomenclature is used in the southern end of the Elk Valley Coalfield at Line Creek Mine. In the northern part of the Elk Valley Coalfield seams are numbered 1 at the base of the section with numbers increasing up section. Seams are generally thicker lower in the Mist Mountain Formation and generally contain more inertinite than seams higher in the formation. Often the third seam up in the section has the highest inertinite content.

There has not been a regional study of present day stress fields in the Mist Mountain Formation. Local studies did not find a strong relationship between cleat orientation and regional stresses (Bustin, 1979, 1982).

GREENHILLS MINE

The Greenhills Mine occupies the core of the Greenhills Syncline, which plunges gently to the north. In the pit, seams on the west limb dip at 20° to 40° to the east and on the east limb beds dip 20° to 60° to the west. The east limb is cut off by the north-trending Erickson normal fault. On the regional scale the syncline is not broken by major thrusts but on the local scale there are a number of sub horizontal thrusts with minor offsets.

Up to 33 seams are exposed in the Mist Mountain section, which is about 560 metres thick. Seams are numbered as 1 at the base of the formation with numbers increasing up section. Seams 1 to 6 are not well exposed in the mine at the moment. Previously, where mined, 1 Seam was finely powdered and devoid of cleats. Polished sections of the seam indicate pervasive micro fracturing. A number of seams from 10 Seam up were examined for cleats and fracturing in the northern most footwall of one of the active pits.

Seam10, which is about 6 metres thick is moderately to highly fractured but does contain closely spaced face and butt cleats (Figure 13). Face cleats range in strike from 010° to 060° and are consistently perpendicular to bedding. They appear to be roughly fold axis normal but rotated anticlockwise. Butt cleats seem to have a more consistent orientation and strike parallel the fold axis.

Seam 1, which is about 1.5 metres thick, is generally moderately to highly sheared with only a few zones retaining closely spaced cleats that appear to be approximately fold axis normal. Sheared zones are welded and contain numerous grooved or lineated sigmoidal surfaces similar to the surfaces described by Bustin (1982a). The lineations have variable orientation. Seam 12 is 1.5 metres thick and is similar to seam 11 being highly sheared with remnant cleating that is approximately fold axis normal.

Seams 14 and 16 are fragmented and sheared and in some places coal is welded into a hard dull mass that breaks exposing sigmoidal surfaces with a greasy luster. Seam 17, which is 2 metres thick, is highly fragmented with occasional areas where closely spaced cleating survives.

Seam 18 is 1.5 metres thick. There is no cleating in the seam, which contains pervasive shear surfaces parallel bedding with no clear movement direction. Seam 19 is generally fragmented with a few surviving face cleats that are approximately fold axis normal. In contrast seam 20 seam, which is also fragmented and sheared, has cleats that are approximately parallel the fold axis trend in areas that have escaped shearing. Seam 21 is similar to seam 20.

In places seam 29-2 appears to contain original layering that has not developed cleats. In contrast. Seam 29-3 is sheared and welded with sigmoidal and grooved surfaces. Seam 30 contains original bedding in places but no cleats are present. Seam 31-0 is generally massive with no cleating though there are partings, which parallel bedding. There are areas within the seam, which are sheared to powder along zones parallel the footwall.

Despite the over all appearance of minimal deformation seams generally are fragmented or sheared with cleating surviving in only a few layers within seams. Seams observed occupy the mid to upper part of the section. Shear surfaces within them are either parallel the hanging wall or intersect bedding to define a direction that tends to be perpendicular to the fold axis trend. The shearing therefore has not increased the seam thicknesses and appears to have been directed along the fold axis direction rather than across it. The best-developed cleats form an oblique angle to the fold axis trend but appear to be rotated to the west off a fold axis normal trend. Butt cleats are also rotated westwards off a fold axis parallel trend. Possibly the initial stress field was directed more from the southwest and rotated to a westerly direction after formation of the face cleats.

LINE CREEK MINE

Coal in the Line Creek Mine is mined in a number of pits that occupy the west and east limbs of the north-trending Alexander Creek Syncline, which is truncated by the Ewin Creek Thrust. The syncline extends to the north to the Fording River Mine where it is referred to as the Eagle Mountain Syncline. Coal ranks appear to be lower in the lower thrust block. Seam numbering starts with 10 Seam at the base of the section with numbers decreasing upwards with the upper seams given letter designations. Seams on both limbs of the Alexander Creek Syncline were observed (Figure 14).

On the west limb of the Alexander Syncline, 9 Seam contains cleats in vitrain bands in the lower part. The mid part of the seam is fairly massive and the upper part is sheared and welded. Up section, 8 Seam is composed predominantly dull litho types and is generally massive with about one third of the seam sheared.

About one third of the 7 Seam is massive with no cleats, one third is sheared into small fragments and one third (the lower part of the seam) is massive with vitrain bands that contain some cleating. The top one third of 6 Seam is sheared and does not contain cleats, while the lower two thirds is blocky with shear joints that have shallow plunging lineations. Seam 6 is overlain by a coal-spar rich sandstone that could contain better permeability than normal bedded sandstones and mudstones.

A number of seams were examined on the east limb of the Alexander Creek Syncline below the Ewin Pass Thrust. Seam nomenclature is the same as on the west limb. Seams dip steeply to the west and are noticeably more sheared than on the west limb. Cleating is generally destroyed and where developed tends to be fold axis normal. Seam 8, which contains pyrite disseminated on fractures, is split into at least three members by rock splits. The lower part of the seam contains disseminated spherulites of pyrite or siderite.

ELKVIEW MINE

The mine is at the northern end of the Crowsnest Coalfield. The main pit occupies the Elk Syncline, which trends north on the west side of the Erickson normal fault. Seams are numbered as at Line Creek, though the basal 10 Seam at

Elkview is slightly higher in the stratigraphy than 10 Seam at Line Creek. Only two of the lower seams in the section were observed (Figure 15).

Seams 10 and 8 were examined at different locations in the mine. In general both seams are highly sheared with only a few areas where original banding or cleating survive. Shear surfaces have fragmented the seams into ellipsoidal chips often with striated curved surfaces with a greasy luster. The striations have variable orientations that are not consistently parallel or perpendicular to the fold axis trend. The few cleats measured tend to be fold axis normal.

Seam 10 in the Elk Pit has been thickened by thrusting or duplexing and is completely fragmented or sheared except for lower part where original banding is preserved. In places small-scale thrusts break out of the hanging wall and insert wedges of 10 seam in the overlying rocks. Striations in the sheared part of the seam trend roughly at 90° to the fold axis direction. Seam 8 is completely sheared, in places into ellipsoidal chips that are then folded into small drag folds. Often the slip surfaces have near horizontal striations with variable orientations though some trend 150° roughly parallel the fold axis trend.

FORDING RIVER MINE

Mining is taking place in the Eagle Mountain Syncline, which is the northern extension of the Alexander Syncline at Line Creek and east of the Erickson normal fault, which separates the active pits at Fording River from the Greenhills Mine. There are approximately 15 seams in the section numbered from 1 at the base to 15 near the top. No cleat measurements were made at the mine. The degree of shearing and seam fragmentation is similar to that at the Greenhills Mine.

COAL MOUNTAIN OPERATIONS

The Coal Mountain Mine occupies an outlier east of the Crowsnest Coalfield. Most of the coal is contained in the basal seam of the Mist Mountain Formation. The seam has been folded, thrusted and sheared and original bedding is often obliterated. Coal in some fold hinges has been mobilized to the extent of becoming diapers disconnected from the original fold hinges (personal communication, Pisony 2002). Cleats have not survived and outcrop structures were not documented.

Cretaceous Intermontane and Vancouver Island Coalfields

Coal on Vancouver Island is contained in the Upper Cretaceous Nanaimo Group, which survives in two coalfields. In the north, in the Comox Coalfield, coal is in the Comox Formation and in the south (Nanaimo Coalfield) in the Extension and Protection formations. Coal seams generally dip gently to moderately to the east and northeast. They are broken by north-trending steep-dipping faults and are un-folded to moderately folded. The Quinsam Mine in the northern part of the Comox Coalfield was visited. There are few references to cleats in the rest of the Comox coalfield. Cathyl Bickford (2002) describes cleats in the Comox Number 3 Mine (Number 2 seam) that strike 028° to 033° and dip 70° to 80° to the northwest. Butt cleats strike 115° to 125°.

QUINSAM MINE

There are 4 seams, in the Comox Formation numbered from 1at the base to 4 at the top of the coal section. Surface and underground mining has taken place in seams 1 and 3. Data were collected from the underground mine in 1 Seam and in small surface pits. Seam 1 is blocky and well cleated with cleats generally perpendicular to bedding. Face cleats are spaced between 0.5 and 10 cm apart and individual cleats having visible surface areas of over 1 metre square. Face cleats, which in 1 Seam tend to be calcite coated, strike northeast across the trend of the regional bedding and the basin. Butt cleats strike northwest parallel the strike of the regional bedding and generally are not calcite coated (Figure 16). Cleats are closer spaced and better developed in vitrain-rich coal. Cleats in the upper seams were not systematically observed but the calcite coating is restricted to the lower seam. The east west trending face cleats formed first and the tectonic history allowed them to remain open. Later east west compression tended to close the southeast trending butt cleats. Calcite could therefore have been introduced onto the east west trending face cleats at any time. Spears and Caswell (1986) suggest that calcite is deposited from diagenetic fluids at temperatures of about 100°C.

Early tensional faults, some times associated with calcite veining, trend east west (Kenyon *et al*., 1991 and Gardner and Lehtinen, 1992). These faults are responsible for graben structures and at surface are identified by low swampy ground. They also appear to act as channels for water into the underground mine. The calcite coated cleat set is either related to these faults or is related to early stresses that formed the north to northwest trending basin.

Gardner and Lehtinen (1992) identify a later period of pull-apart faulting that is largely restricted to 1 Seam zone. These faults are parallel the strike of the beds and are down dropped by a few metres on the down dip side with respect to the regional bed dip. The faults are shallow dipping and consequently produce a barren zone up to 20 metres wide where they cut seams. They probably represent ductile response of the incompetent 1 Seam to buckling and down warping of the sedimentary package. Kenyon *et al.* (1991) describe a later period of northeast to southwest compression. This deformation produced some folds and southwest verging thrusts. They also identify tear faults, trending northeast to east, that are probably post Late Eocene.

TELKWA PROPERTY

Ryan and Dawson (1994) summarized the CBM potential of the Telkwa coalfield (Figure 1) based on exploration data up to 1994 and the following is based on that paper. Since then Manalta Coal Limited conducted a number of exploration programs so that more data are available in coal assessment reports in the Ministry of Energy and Mines, Victoria.

Coal at Telkwa is broken by steep faults but has not experienced much folding and consequently seams are blocky and well cleated**.** They generally strike northwesterly and dip to the east. northwest-striking east-dipping reverse and thrust faults break the coal measures into numerous fault blocks. Folds are locally associated with these early faults. There are at least two episodes of later normal faulting. Older normal faults trend northerly. A few outcrops of andesite dikes, striking northwest, are apparently associated with these faults. Younger normal faults trend east-west. Folds trend north or northwest with shallow plunges to the northwest or southeast.

Outcrop is sparse but joints were measured in a test pit constructed in 1982. Joints tend to intersect bedding at large angles along a line of intersection trending northwest (fold axis trend) or intersect bedding at large angles along a line, which is perpendicular to the fold axis trend.

Subsurface bed orientations are available from dip meter logs and subsurface joint measurements were made in 1982 during a geotechnical program (Telkwa Stage Two report, 1982). Joint orientations were measured in core relative to bedding. Using dip meter logs to provide bed orientation, it is possible to rotate the joints into their “true orientation” using a sterionet. The technique is approximate because only a single average bed orientation is used to rotate all the joints in a hole. Joint data from 22 holes are summarized in Figure 18, which does not depict the true joint frequency because vertical holes tend not to intersect vertical fractures, despite this, it appears that the joints tend to form a great circle girdle about the northwest trending fold direction. Eigen vectors provide a pole to the great circle girdle trending 316° with a plunge of 1°. This means that the joints intersect the bedding surface along a line parallel to the northwest trending fold axis direction.

It is probable that the face cleats in the coal seams strike northwest and dip steeply east or west, based on the joint data from surface outcrops and drill holes. The surface joint pattern identifies a northeast trending joint set which is perpendicular to the fold trend. This may be the orientation of butt cleats in the coal.

Permeability will be improved in direction trending 315° to 360° (face cleats) and probably to a lesser extent in a direction trending 30° to 60° (butt cleats).

Faults observed in the test pit are generally tight and may block the flow of methane in an northeast direction along seams but probably will also not discharge a lot of water into seams as they are dewatered. The area in each coal seam available to be drained will be limited in a northeast to southwest direction but may extend further in a northwest southeast direction because of the improved permeability in this direction and the absence of cross cutting faults.

To ensure good permeability coal must have sufficient strength to resist overburden stresses and maintain some porosity along the joint surfaces. Data on the uniaxial compressive of rock types (Ryan and Dawson, 1994) indicates that the coal is as strong as the mudstone and weaker than other rock types. Compared to many coals from other areas in British Columbia, Telkwa coal is strong. This is substantiated by the Hardgrove Index values of Telkwa coal, which range from 45 to 65 compared to values of coal from southeast British Columbia that range from 80 to 110. At appropriate depths the coal will respond well to facing or cavitation.

Permeability measurements were made as part of the Telkwa Stage Two study (Ryan and Dawson, 1994). Permeabilities of seam numbers 2 to 8 in three drill holes in the east Goathorne area were measured at depths ranging from 29 to 158 metres. Permeabilities do not correlate with depth and values range from 0.5 to 50 millidarcies. This range is considered to be excellent for coal, considering the depth of the measurements. Data were reported as hydraulic conductivity (metres per second) and converted to millidarcies.

The permeability of sections of mudstone, siltstone and sandstone interburden varying in thickness from 14 to 27 metres were measured in drill holes north of the Telkwa River. Permeabilities range from 13 to 35 millidarcies. At the depths of less than 200 metres permeabilities of interburden rock and coal are moderate. The permeability of the interburden is on average greater than that of the coal. In order to be able to drain water from seams it will be important to have impermeable hanging wall and footwall material. This information is available in the core descriptions and geophysical logs included in the assessment reports submitted to the British Columbia government.

BOWSER BASIN KLAPPAN AND GROUNDHOG COALFIELDS

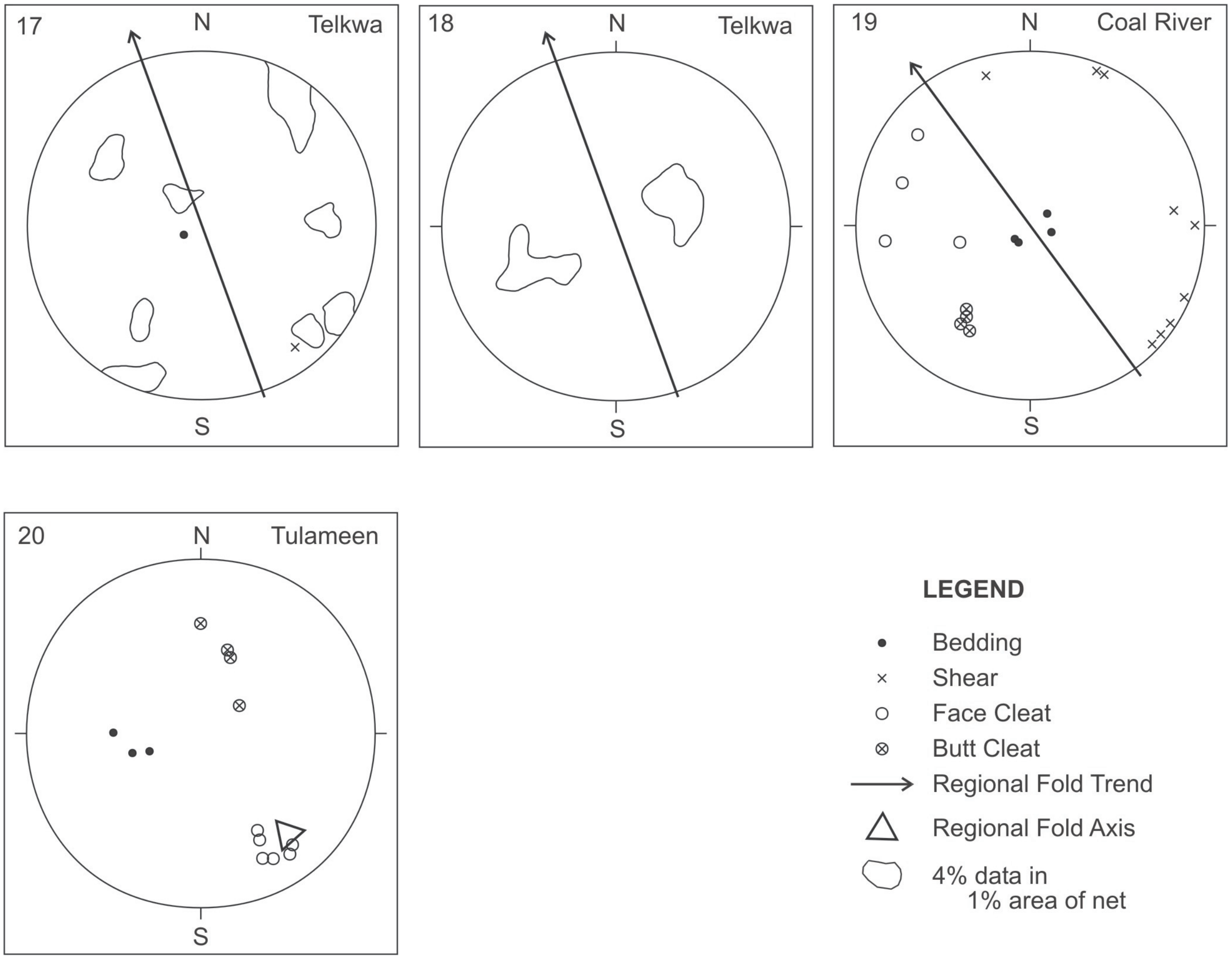
The rank of coals in the two coalfields, which are contained within the Skeena fold belt (Evenchick, 1991), is low-volatile bituminous to anthracite. These coalfields have been visited in the past but not in the context of a cleat study. Coal in the Klappan Coalfield has experienced a similar tectonic history to that of coals in northeast BC though the rank is higher. The coal has probably experienced some shearing and fragmentation. In 1982 Gulf Canada Limited excavated a test pit and some undocumented photos of the test pit and outcrops in the region survive (Jahak Koo, personnel communication, 1988). The coal at Klappan has fairly high CaO concentrations, which indicates the possible presence of calcite coating on fractures or cleats.

TERTIARY BASINS

Most of the Tertiary basins are relatively undeformed. Exceptions are parts of the Merritt Coalfield and the Hat Creek Basin. Three Tertiary basins were visited.

COAL RIVER PROPERTY

The Coal River property is in the north east of the province adjacent to the Alaska Highway and 40 kilometres south of the Yukon border. The property contains a resource of up to 200 million tonnes of lignite. A single seam in excess of 5 metres thick, with sub horizontal dip, is exposed either side of Coal River. The seam contains two sets of



Figures 17to 20. Steriographic plots of poles to joints from the test pit at the Telkwa Property, from drill core; Telkwa Property, from the Coal River Property and from the Tulameen Property.

cleats. The better-developed set has an average strike of 020° and an 80° dip to the east, the second set has a more consistent orientation and strikes 123° and dips 68° to the northeast (Figure 19). The bedding surfaces contain a strong lineation that appears to either derive from the original vegetation or water movement in the compacting vegetation. It varies in orientation but tends to be oriented between 120° and 180°. Cleats are widely spaced and have the appearance of tension fractures.

TUYA RIVER

The Tuya River property, which is northwest of the town of Dease Lake, was mapped in 1990 by the author (Ryan, 1991). The coal zone is folded into a broad syncline that is cut by normal faults. The coal is massive with well-developed cleats. No cleat measurements were taken.

TULAMEEN PROPERTY

The Tulameen Basin, which is about 20 kilometres northwest of Princeton, forms an elliptical sedimentary basin 5.4 by 3.6 kilometres that contains two well-developed thick coal seams of high-volatile B bituminous rank. The upper zone, which is 25 to 40 metres above the lower coal zone, is better developed and attains thicknesses ranging from 15 to 21 metres. The lower zone, which is generally less well developed, is 7 to 7.6 metres thick and averages 52% ash.

The basin is part of the Princeton group, which rests unconformably on volcanic and sedimentary rocks of the Upper Triassic Nicola group. Beds appear to be folded into a southeast trending syncline with beds on the southwest limb dipping shallowly to the northeast (20°-25°) and beds on the northeast limb dipping steeply southwest (40°-65°). The plunge of the syncline was estimated by Evans (1978) to be 15° in a direction 138°. Anderson (1978) describes the structure as an asymmetric northwest trending syncline and does not assign a plunge. The area is cut by a number of vertical faults that trend north to northeast (Anderson, 1978).

The upper seam was observed on the west limb in a test pit excavated ion 2000 (Figure 20). Bentonite rich partings make up from 10% to 60% of the seam, generally increasing in percentage to the northeast. Coal bands are vitrinite rich and well cleated with face and butt cleats. Ankerite sometimes coats cleats. Face cleats are well developed and are oriented perpendicular to the fold axis. Butt cleats appear to be approximately perpendicular to bedding and face cleats and therefore may form an axial plane fan around the fold axis. There are no shear joints in the coal though there is some shearing along the contacts of bentonite bands in the coal seam.

CONCLUSIONS

Coal proximate data gives some indication of the ability of coal to generate over pressure and the amount of volume decrease of the coal mass associated with rank increase. Over pressuring occurs at low rank and may play a part in initiating thrusting. The volume decrease *versus* rank (or temperature) plot indicates that there are maxima at low and intermediate ranks. The first may be associated with formation of face cleats and possibly thrusting and predates generation of thermogenic methane. The latter may be associated with formation of butt cleats and generation of thermogenic methane.

Possible useful insights into cleats can be derived if they are considered in the context of forming in over pressured or normal hydrostatic pressured environments. Other important parameters are depth, stress field and timing of coal maturation. Data on cleat development and orientation, as well as maceral textures observed under the microscope, may lead to an understanding of the interrelationships of hydrostatic pressure, depth, stress fields and coal maturation. The intent is to gain useful insights into development of permeability and anything that influences anisotropy of permeability in terms of direction. Permeability of the coal, more than the size of the CBM resource available to a hole, controls the economic potential of the hole.

Permeability decreases exponentially with depth. It increases with cleat development up to the point that the degree of fracturing decreases the ability of the skeletal structure of the seam to withstand lithostatic pressure once hydrostatic pressure is decreased. It also decreases as generation of fine coal increases, because migration of fines blocks flow pathways. It is improved if the present day stress regime is extensional and especially if the direction of extension is perpendicular to cleat surfaces.

The structural geology in northeast and southeast British Columbia is complicated and the conditions supporting improved permeability may be structurally controlled. Many of the fractures are exogenetic and therefore may not be restricted to coal seams. Development of thrusts at shallow depth and under conditions of over pressuring produce shears surfaces either parallel to bedding or at small angles to bedding. These surfaces and the over pressuring are responsible for generating fines in coal seams. Generally the best-developed cleats are normal to the regional fold trend. In areas where thrusting predominates, cleats if present may be parallel the regional fold trend and less consistent in orientation.

In coalfields where deformation has not been extensive such as Vancouver Island and Telkwa, it is important to identify areas where there is an expectation of a present day stress field that is extensional along the regional fold trend. This may take the form of culminations or depressions along the plunge of folds, doming over buried intrusions or development of sedimentary wedges. In areas where thrusting predominates one should look for areas where present day extension is normal to the regional fold trend. This may take the form of normal faults following the same trend as earlier thrust faults. Because cleats developed in this environment are less consistent in orientation the best permeability direction may be different in different thrust sheets.

In areas where fracturing and permeability are related to the deformation it is important to match CBM economics to classic structural geology domain analysis. If the rational for good permeability is cleating developed on a flat limb of

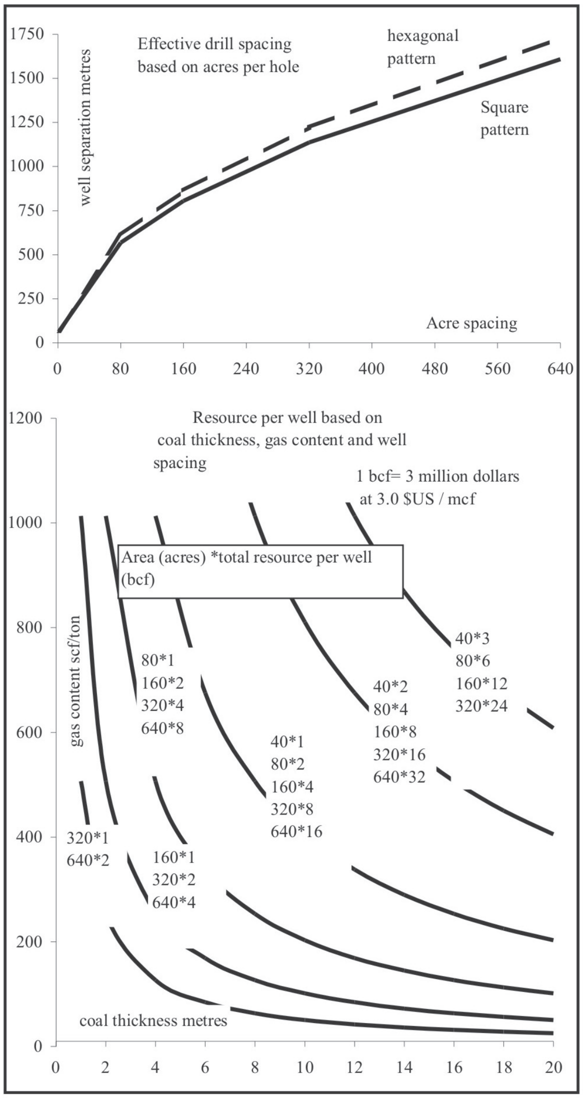


Figure 21. Relationship between cumulative coal thickness, gas content, total potential resource and well spacing.

a fold, then it is important that the extent of this structural domain match the requirements of basic CBM economics. In most areas it is possible to at least make educated guesses about cumulative coal thickness and gas content. With these data one can estimate the minimum economic well spacing. For example if a well spacing of 80 acres is required (Figure 21), then this implies a structural domain of about 600 metres square. One must be satisfied that this is possible based on an understanding of the local geology.

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