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Influences of structural setting on coal rank and thickness in the Grande Cache area, Alberta, Canada

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Abstract

In addition to mapping areas of deformed coal-bearing strata, structural geological studies are used to explain coal rank variations, to predict the location of the thickened coal and to explain certain optical properties of coal.

In the coalfields of the Canadian Rocky Mountains and Foothills, north of Grande Cache, Alberta, the level of coalification decreases progressively from the undeformed part of the Alberta basin towards the western edge of the Foothills. This decrease is due to a westward decrease in duration and depth of burial as a consequence of the timing of Laramide deformation across the area, indicating synorogenic coalification. Within the smaller Grande Cache area it can be shown that coalification ended after deformation and resulting uplift and erosion. The presence of optically biaxial vitrinite anisotropy may indicate the presence of a tectonic stress field during the later stages of burial and subsequent deformation. The maximum vitrinite reflectance axis is generally oriented parallel to fold axes in the area.

Structurally thickened coal can be attributed to at least two structural positions: fold hinges and fold limbs. Dilation occurs at chevron fold hinges and incompetent material, such as coal, flows into these dilation zones. The resulting structure is similar in geometry to a saddle reef. Duplexes are present in fold limbs, where the roof thrust is the top and the floor thrust the bottom of the coal seam, resulting in tectonic thickening of the coal. These structurally thickened coals are important exploration targets. Prediction of structurally thickened coal by computer constructed down-plunge cross sections has proved useful in coal exploration in the Canadian Rocky Mountain Foothills.

Introduction

The structural setting of coal basins influences coal properties, such as rank and thickness. Consequently, structural geological studies may be used to explain coal rank variations and to predict the location of thickened coal seams.

The degree of coalification (rank) is governed primarily by rise of temperature during burial and the time during which this occurs. In the Ruhr basin of West Germany it has been demonstrated that coalification was largely completed before folding (Teichmüller & Teichmüller, 1966). Similarly, in the Anthracite region of Pennsylvania coalification occurred prior to and during (Alleghanian) folding. In addition, data from Pennsylvania indicate that much of the former overburden may have been emplaced tectonically (Levine, 1983 and 1986). In

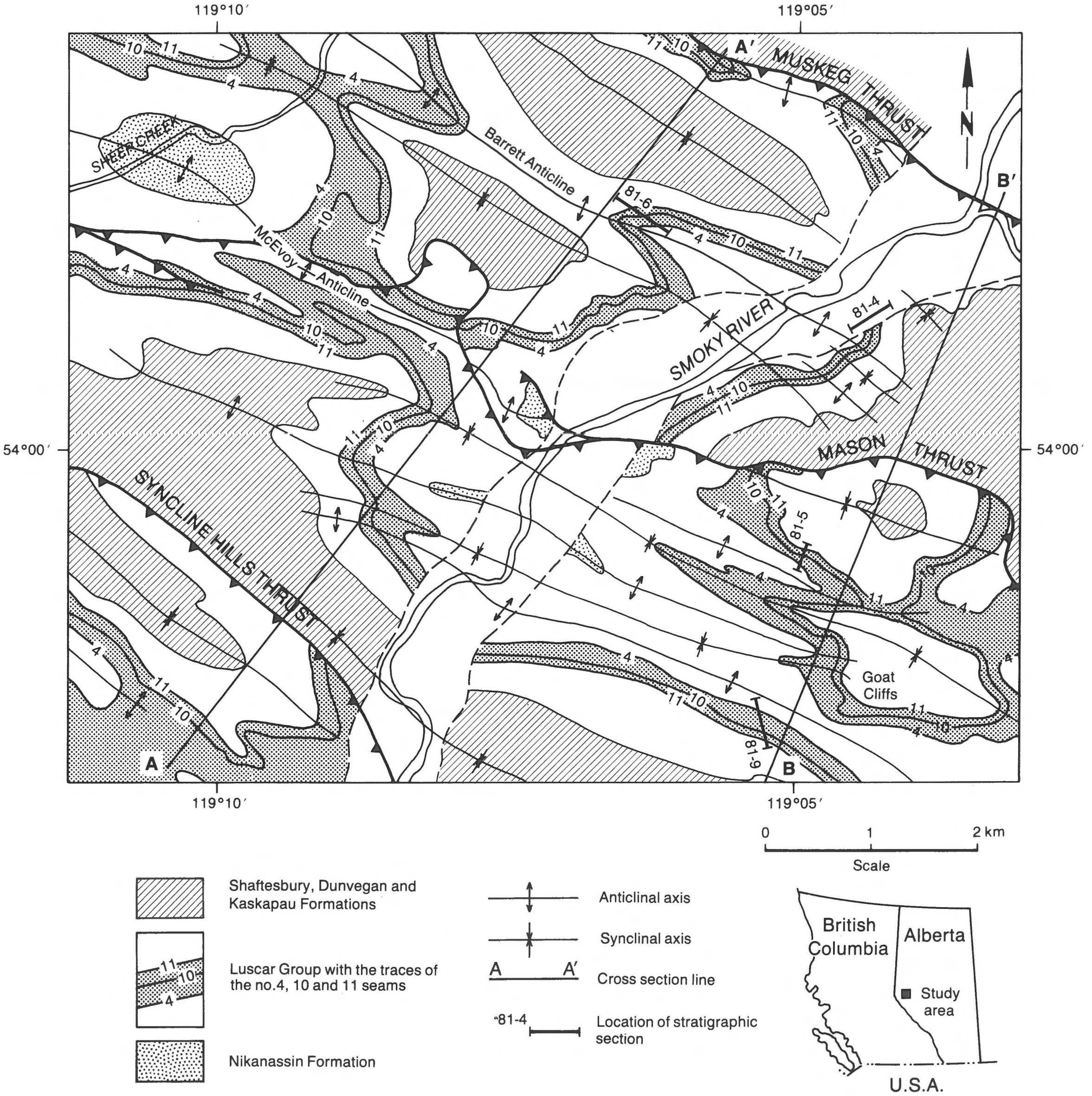

Fig. 1. Geological map of parts of the Grande Cache area, simplified from Langenberg et al. (1987). Cross sections AA′ and BB′ are shown in Fig. 5.

contrast, data from the Sydney coalfield of Nova Scotia, Canada, indicate that coalification was post-folding (Haquebard & Donaldson, 1970).

Previous work on coal rank in the Canadian Rocky Mountains and Foothills north of Grande Cache suggests that the degree of coalification was achieved prior to deformation (Haquebard & Donaldson, 1974; Kalkreuth & McMechan, 1984; Kalkreuth & Langenberg, 1986). However, in the Crowsnest coalfield of southeastern British Columbia a substantial amount of coalification was found to be post-folding (Pearson & Grieve, 1985). In addition, England & Bustin (1986) documented components of post-thrusting coalification in deep wells from the southern Alberta Foothills. Components of post-deformational coalification were also suggested by Hughes & Cameron (1985) in the Canmore coalfield of Alberta, resulting from loading by the Rundle Thrust Sheet.

This article will discuss the synorogenic context of the pre-deformational coalification in the Grande Cache area. In addition, two models of structural thickening of coal will be introduced, related to the position of coal in fold hinges or fold limbs. Techniques to predict the location of these thickened coals will also be described.

Geologic setting

The Grande Cache area is situated 350 km west of Edmonton in the Inner Foothills of the Province of Alberta, Canada (Fig. 1). This area forms part of the Smoky River coalfield. Some 1000 m of Cretaceous marine and non-marine clastic sediments are present in the study area. A simplified columnar stratigraphic section representing this succession (Fig. 2) includes the position of major coal seams. The stratigraphic units are described in detail in Irish (1965), Langenberg et al. (1987) and McLean (1982).

The lowermost unit is the Nikanassin Formation consisting of Early Cretaceous non-marine sandstones and shales. The Cadomin Formation consists of 45 m of alluvial conglomerates and forms one of the best marker horizons in the area. It is Neocomian-Albian (?) in age. The Gladstone Formation is 115 m thick and consists of alluvial sequences of sandstone, shale and minor coal and is largely of Early Albian age. The Moosebar Formation consists of 60 m of marine shale and minor sandstone and is also of Early Albian age. The non-marine Gates Formation is 345 m thick. It consists of sandstones, shales and coal and can be divided into three members, i.e., the Torrens, Grande Cache and Mountain Park Members. The age of the Gates Formation ranges from Early to Middle Albian. The Torrens Member (30 m thick) consists of sandstones deposited in a shoreline environment. The Grande Cache Member (155 m thick) shows coastal plain sandstones, shales and major economic coal seams. It grades into the Mountain Park Member (160 m), which consists of

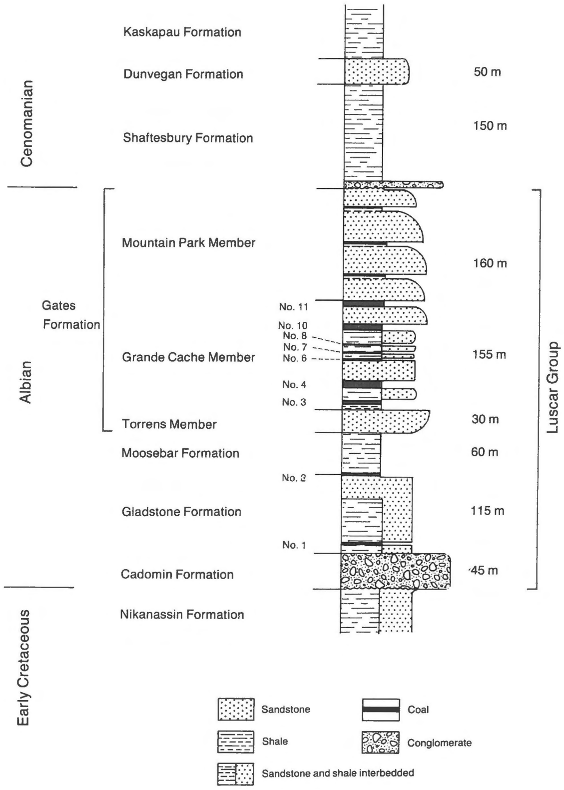

Fig. 2. Simplified columnar stratigraphic section of study area with positions of seams Nos. 1–11.

fluvial, fining-upward sandstones, shales, and minor coal seams. The Cadomin, Gladstone, Moosebar and Gates Formations together form the Luscar Group (Langenberg & McMechan, 1985).

The Mountain Park Member is abruptly overlain by 150 m of marine shales of the Shaftesbury Formation, which is Albian to Cenomanian in age. The overlying Dunvegan Formation is 50 m thick, consists of deltaic sandstones and is of Cenomanian age. It is overlain by marine shales of the Kaskapau Formation. Only the lower part of this formation is present in the study area and is Cenomanian in age.

Thus there is 765 m of overburden above the base of the Gates Formation preserved in the study area. In the outer Foothills an additional 4100 m of Cenomanian to Paleocene sediments is exposed (Irish, 1965; Kalkreuth & McMechan, 1984), bringing the total overburden above the base of the Gates to at least 4865 m. Because the inner Foothills were closer to the uprising hinterland during Cenomanian to Paleocene times, it is reasonable to assume that the sedimentation was slightly faster in this area. As a result the overburden above the base of the Gates Formation may have been as much as 5500 m. The rank of the coals from the Luscar Group ranges from medium-to low volatile bituminous.

Strata in the region are complexly folded and cut by numerous thrust faults. The Mason Thrust is the best exposed fault of the area. It forms ramps and flats. The displacement along this thrust increases from 150 m in the central part to about 1000 m in the southeastern part of the study area (Fig. 1). This increase in shortening by thrusting is compensated by a decrease in shortening by folding, as shown by the Barrett Anticline. It is an example of fold-to-fault displacement transfer (Langenberg, 1985). It is estimated that the main deformation occurred in the Grande Cache area during the Paleocene (Kalkreuth & McMechan, 1984).

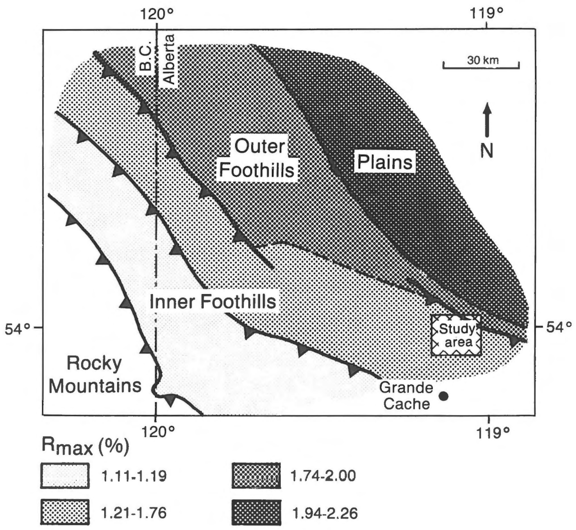

Fig. 3. Maximum vitrinite reflectance variations for coal samples from the Gates Formation in the area north of Grande Cache. Data for Plains and Outer Foothills are from subsurface samples (core and/or cuttings), while data for Inner Foothills come from outcrop samples. The location of the area shown in Fig. 1 is indicated. Modified from Kalkreuth & McMechan (1984).

Relationships of coal rank to deformation

The Grande Cache area forms part of the larger area studied by Kalkreuth & McMechan (1984). They show that the level of coalification decreases progressively from the undeformed part of the Alberta basin towards the western edge of the Foothills as illustrated by the variation in maximum vitrinite reflectance of Gates Formation coals (Fig. 3). This decrease is explained to be due to a westward decrease in duration and depth of burial as a result of the timing of Laramide deformation across the area. This explanation implies that coalification was taking place in the eastern part of the Foothills during deformation in the western part of this area, indicating synorogenic coalification (cf. England & Bustin, 1986, p. 610).

Within the smaller Grande Cache area, rank data from laterally continuous coal seams illustrate relationships between timing of coalification and deformation (Kalkreuth & Langenberg, 1986). These relationships are well illustrated by a map showing vitrinite reflectance variations (Fig. 4) and cross sections (Fig. 5). The levels of coalification, as expressed by reflectance ranges, run generally parallel to the bedding of the folded strata indicating pre-folding coalification. The rank of individual seams is a function of stratigraphic position, with No. 4 seam having the highest reflectances, No. 10 seam intermediate and No. 11 seam the lowest reflectances. Because the coalification pattern of No. 4, 10, and 11 seams show no significant change in rank across thrust faults, it can also be concluded that, in the Grande Cache area, coalification of the seams was established before thrusting started.

The relationship between stratigraphic depth and coal rank is further illustrated by several coalification profiles (Kalkreuth & Langenberg, 1986). In these profiles the reflectance values increase regularly with increasing stratigraphic depth. Coalification gradients range from 0.11 to 0.17% R_{max}/100 m. Rank in these coals is apparently largely a function of former depth of burial. The similarity of coalification gradients in the study area suggests that similar geothermal gradients occurred throughout the area. Kalkreuth & McMechan (1984) assumed on the basis of measured and

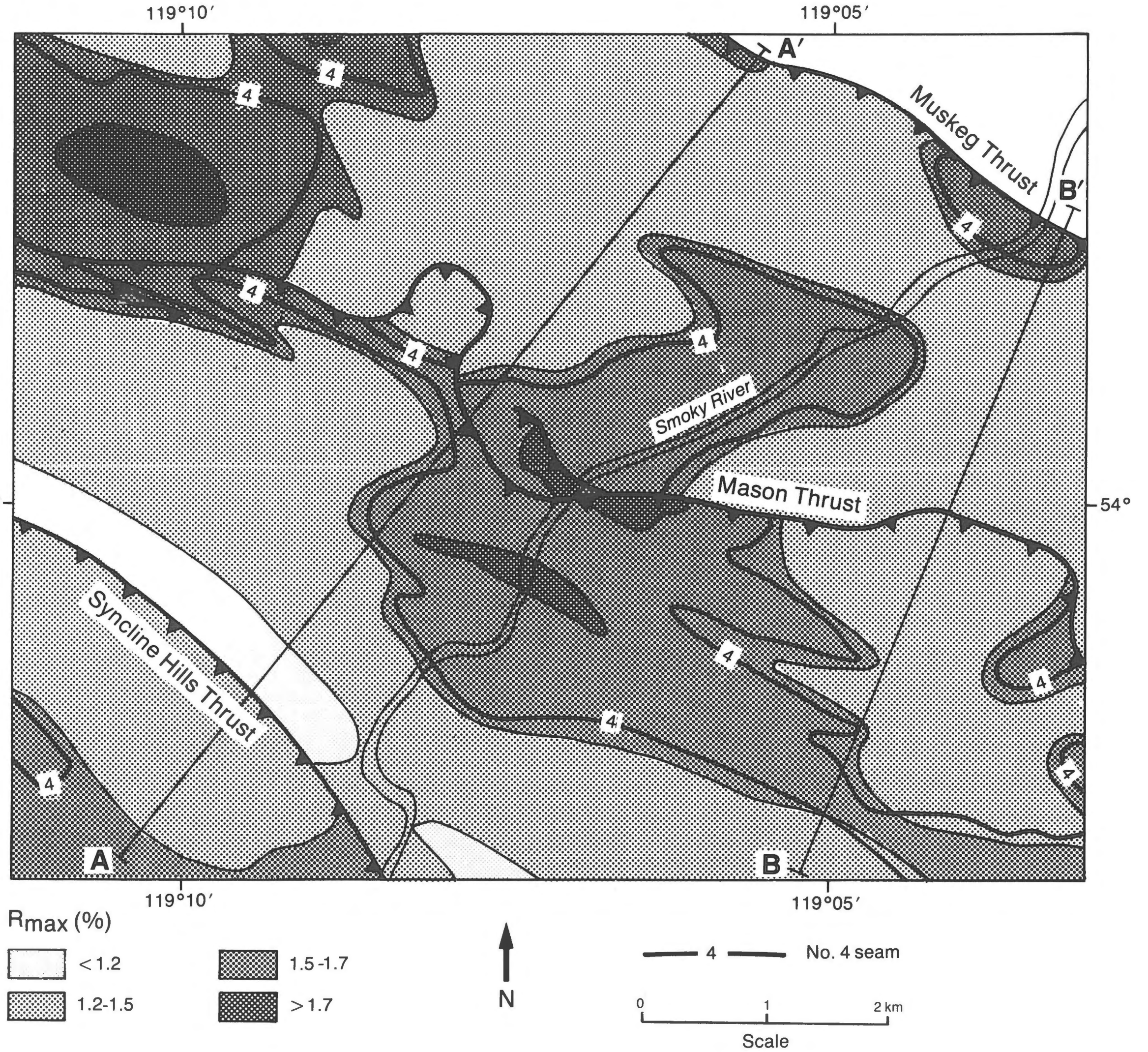

Fig. 4. Maximum vitrinite reflectance variations in the Grande Cache area, extrapolated from data from outcropping coal seams as reported by Kalkreuth & Langenberg (1986). The outcrop trace of the No. 4 coal seam is also shown.

calculated reflectances a paleogeothermal gradient of 2.7° C/100 m for the study area, which is similar to the present day geothermal gradient. Using this gradient the maximum temperatures for the base of the Gates Formation obtained at the time of maximum burial would be approximately 170° C based on an overburden of 5500 m and an average annual paleo-surface temperature of 20° C.

However, there is a trend to somewhat lower reflectance values (and hence lower rank) towards the southeast, as indicated by the intersection of the trace of No. 4 seam and the 1.5% iso-reflectance line on Fig. 4. This trend is also reflected in the slightly higher reflectances (around 1.69%) shown by the No. 4 seam in the Copton Creek area, 10 km westnorthwest of the study area (Kalkreuth & Langenberg, 1986). The range in reflectance from 1.49% in the southeast to 1.69% in the northwest can be explained by differences in former depth of burial. Using the average coalification gradient of 0.14% R_{max}/100 m, it would only require a difference of about 150 m in overburden to ex-

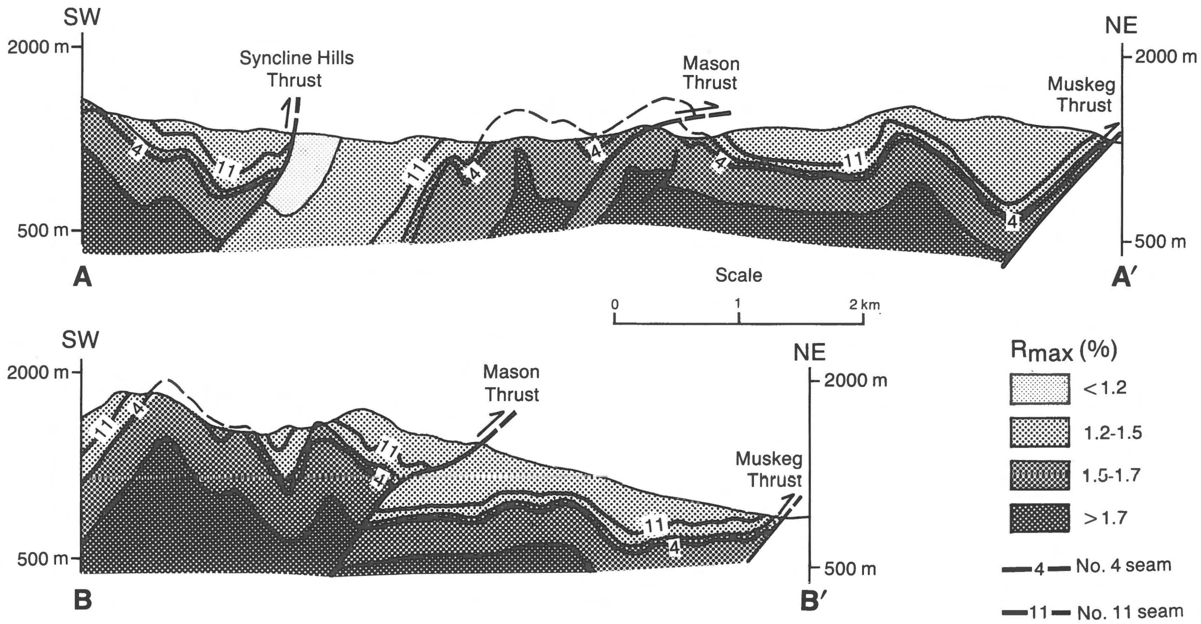

Fig. 5. Cross sections showing relationship of coal rank to deformed strata. The section lines AA′ and BB′ are indicated on Figs 1 and 4. Modified from Kalkreuth & Langenberg (1986).

plain the variation in rank. Still lower reflectances of 1.33% are obtained for No. 4 seam 9 km south of the study area (Kalkreuth & Langenberg, 1986). These lower ranks are probably a reflection of the regional trends shown by Fig. 3.

Based on this coalification pattern it can be concluded that the coal rank in the Grande Cache area was largely established during burial between Albian and late Paleocene times (from 100 Ma to 60 Ma ago), before folding and thrusting started. However, it should be realized that during coalification in the Grande Cache area overthrusting was taking place farther to the west (Kalkreuth & McMechan, 1984), resulting in the westward decrease of thermal maturation in Alberta's Foothills illustrated in Fig. 3. This implies, as mentioned earlier, that coalification in the Grande Cache area was synorogenic on a regional scale, while it was pre-deformational on a local scale. Some confusion was generated in this context by Teichmüller & Teichmüller (1966), who introduced the terms pre-orogenic and synorogenic coalification for pre-deformational and syn-deformational coalification. The term orogeny is generally used for regional scale mountain building processes and can not be used to describe local relationships between coalification and deformation as done by Teichmüller & Teichmüller (1966, their figure 16). Deformation in the Grande Cache area resulted in displacement and uplift of strata at the end of the Paleocene, after which rapid erosion started. These events essentially ended coalification in the Grande Cache area. Synorogenic coalification is further suggested by the biaxial optical nature of many coals in the Grande Cache area.

Biaxial vitrinite reflectance

Traditionally vitrinite is considered to have a uniaxial negative reflectance indicatrix. However, an increasing number of biaxial reflectance indicatrices have been reported from around the world, including the Canadian Rocky Mountain coalfields (Cook et al., 1972; Levine, 1983; Levine & Davis, 1984; Kilby, 1988). To investigate the relationships between the principal reflectance axes of vitrinite and the structural setting of the coals, a series of oriented coal blocks were collected from diverse structural positions in the study area. From these

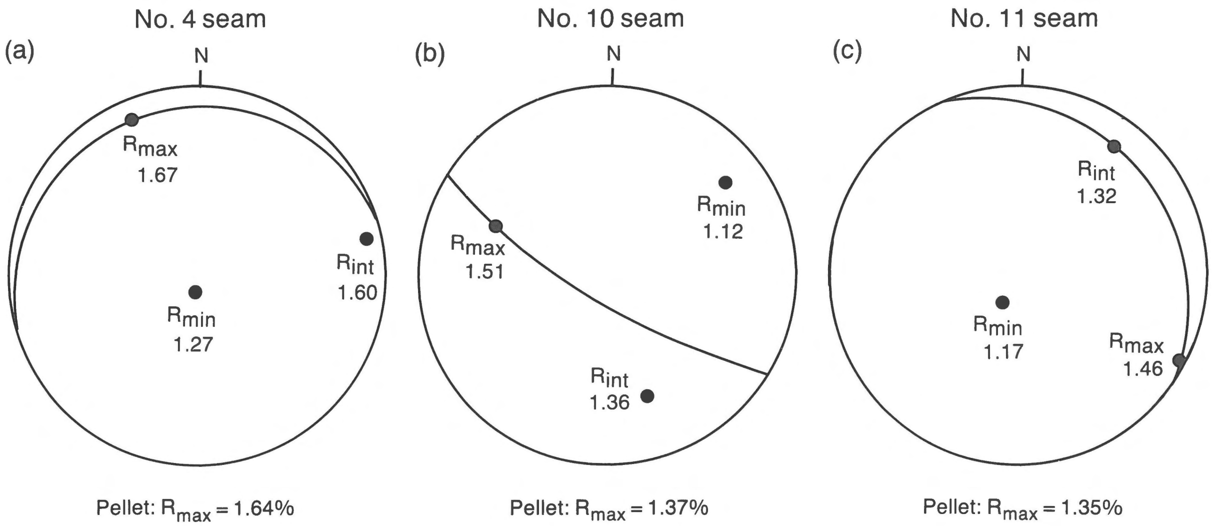

Fig. 6. Orientations and magnitudes (percent reflectance) of principal reflectance axes of vitrinite for samples from (a) No. 4 seam, (b) No. 10 seam and (c) No. 11 seam. The orientation of the bedding plane is indicated by the solid curve. The magnitudes of maximum reflectance of vitrinite as determined on pellets made of crushed coal particles of these samples are also shown.

blocks the orientation and magnitudes of the principal reflectance axes (R_{max}, R_{int} and R_{min}) were determined using a method modified from Levine (1983) and Levine & Davis (1984). The results of three samples collected along the trend of the McEvoy Anticline (Fig. 1) are illustrated in Fig. 6. These samples (one each of the Nos. 4, 10 and 11 seams) are considered representative for the optical anisotropy encountered in the area. The maximum reflectances (R_{max}) of these samples are significantly higher than the intermediate reflectances (R_{int}), proving that optically biaxial coals are present in the Grande Cache area. Only about 20 percent of the 30 blocks analyzed so far has uniaxial anisotropy. The orientation of R_{max} is in all biaxial cases parallel or subparallel to the macroscopic fold axis (as shown by the stereoplots of Fig. 6 and the map of Fig. 1). Biaxial and uniaxial coals were generally found together with no clear relationship between structural position and anisotropy, except in the following example.

Oriented samples collected from the No. 11 seam within 1 m from the Mason Thrust along the Smoky River (see Fig. 1) show higher R_{max} magnitudes and higher bireflectances than samples from the same seam 100 m away from the thrust. These high bireflectances are the highest encountered in the Grande Cache area. Both sample locations have similar R_{min} magnitudes. All samples collected close to the thrust have biaxial vitrinite anisotropy, with the R_{max} axes parallel to the fold axes in the area. Coals sampled 100 m away from the thrust reveal both uniaxial and biaxial anisotropy. These data may indicate a slight increase in the degree of coalification during deformation, interpreted to result from increased preferred orientation of aromatic lamellae in coal. This increase in the degree of coalification does not necessarily imply frictional heating as suggested by Bustin (1983), although both processes could have acted together.

The biaxial nature of the vitrinite anisotropy with R_{max} parallel to fold axes is interpreted to result from preferential orientation of aromatic lamellae in coal in the direction of minimum compressive stress (see for example Levine & Davis, 1984). This stress field is different from that resulting from simple burial. Biaxial coals in the Grande Cache area can either be explained to result from a tectonic coalification overprint after burial, or from coalification during burial (before folding and thrusting started) with the presence of a tectonic stress field. Because there is no clear relationship between anisotropy and structural position, the latter possibility seems more plausible. In addition, isoreflectance lines indicate pre-deformational and not syn-deformational coalification. It might be reasonable to assume that this tectonic stress field was present during the later stages of burial, relatively shortly before deformation started in the Grande Cache area. Coalification with the presence of a stress field probably continued during deformation, but rapid erosion ended coalification soon thereafter. Minor coalification during deformation is further indicated by higher bireflectances close to thrust faults. However, it is clear that only a minor part of coalification took place during deformation. The majority of coalification happened during burial.

The biaxial nature of the vitrinite has implication on the determination of R_{max} in pellets made from crushed coal particles. R_{max} of the pellet will only be the 'true' R_{max} if vitrinite is optically uniaxial (Kilby, 1988). For biaxial coals, R_{max} of the pellet is expected to be between the 'true' R_{max} and 'true' R_{int}. To test this, pellets were made from crushed particles of the oriented blocks and R_{max} magnitudes of these pellets were measured. R_{max} values determined on these pellets of crushed coal and on oriented blocks from the same sample show that reflectances from the crushed coal are consistently lower. The pellets made from crushed coal from the samples shown in Fig. 6 obtain R_{max} magnitudes of 1.64% (No. 4 seam), 1.37% (No. 10 seam) and 1.35% (No. 11 seam) reflectance, respectivily. These results confirm the theory. Only in the case of the No. 4 seam (Fig. 6a) is the value of the pellet reasonably close to the 'true' R_{max} as determined from the oriented block. The reason is that this particular sample has a relatively low degree of biaxiallity. However from a practical point of view further investigations are needed to determine whether the observed differences in maximum vitrinite reflectances in biaxial coals imply any significant different technological characteristics. At present the higher R_{max} values of the oriented blocks can not be used to predict coke stability, because a new and different method of measuring maximum reflectance is used.

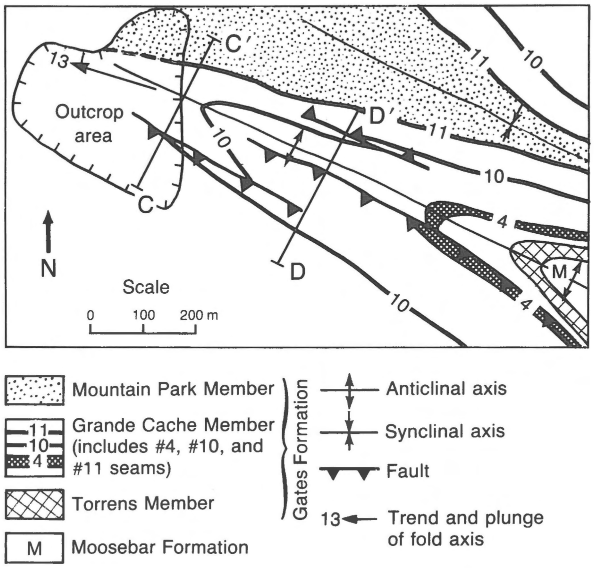

Fig. 7. Geological map of the South Pit area.

Structurally thickened coal

Structurally thickened coal pods can be found in several places in the study area, where it forms important exploration targets for the development of open pit mines. Presently there are two structural positions identified where thickening occurs, in fold hinges resulting from dilation and in fold limbs resulting from duplex faulting. These two positions will be discussed separately. Coal pods along fold hinges have been known and explored for many years (see for example Norris, 1971), while coal pods resulting from duplex thrusting have only been recognized recently.

Dilation in fold hinges

The prominent deformation process of the Grande Cache area was flexural slip folding, which resulted in chevron folds (Langenberg, 1985). Dilation took place at the fold hinges. The dilation zone can be filled in two ways, either by flow of incompetent material (such as coal) into the void or by hinge collapse (Ramsay, 1974). In the Grande Cache area a combination of these two processes occurred.

Good examples of hinge dilations are exposed in open pits northwest of Sheep Creek. One of these

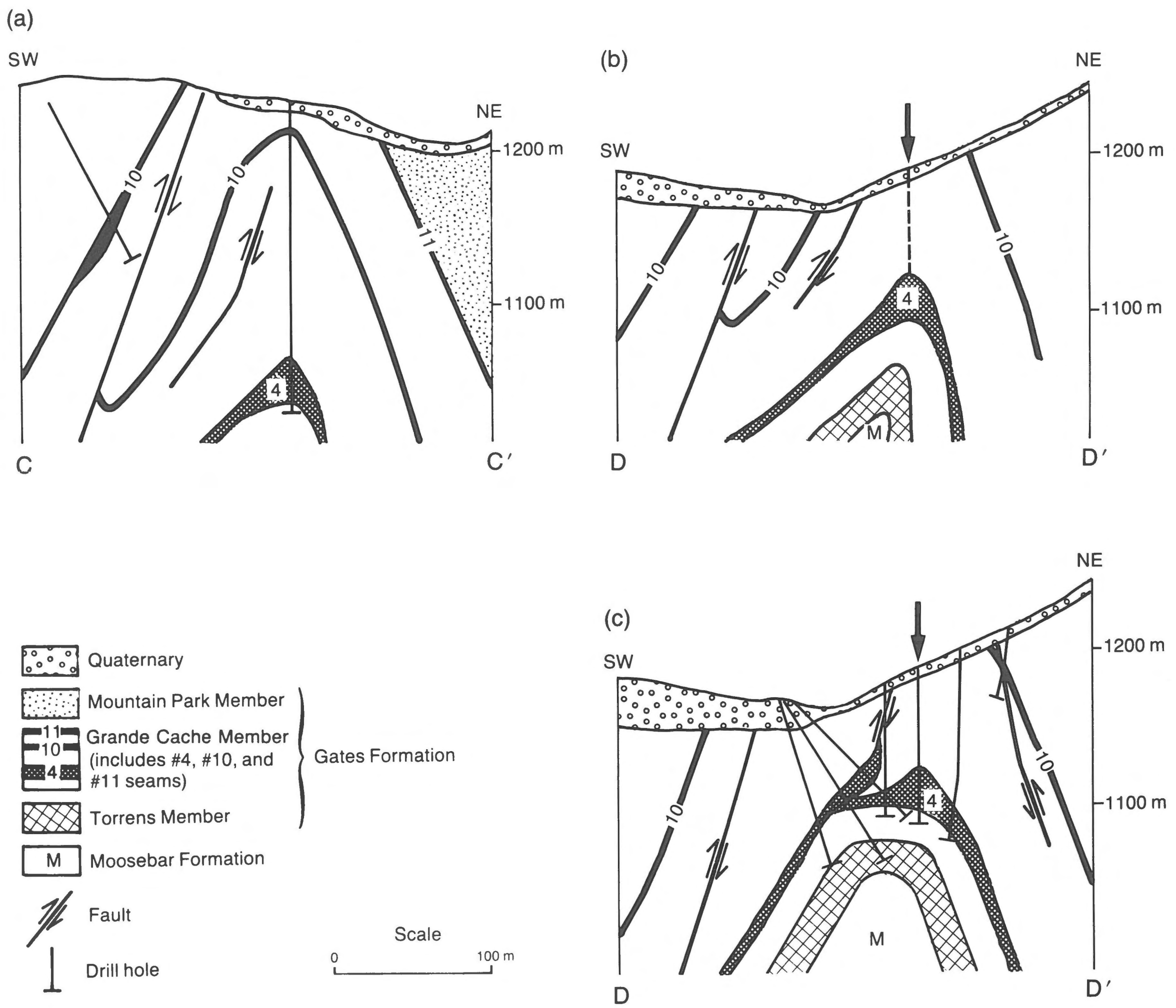

Fig. 8. Cross sections through the South Pit area. The lines of section are shown on Fig. 7. (a) Section CC′ based on outcrop mapping and two drill holes. (b) Section DD′ as predicted from Section CC′. The location of the first drill hole to test the structure is indicated with an arrow. (c) Section DD′ based on seven drill holes.

examples has been recently outlined in the South Pit area (Fig. 7), which is located about 1 km west of the study area. Here considerable reserves of metallurgical coal were found utilizing down-plunge projection techniques which are available in the TRIPOD mapping software (Charlesworth et al. 1976; Charlesworth et al. 1988). Mapping in the outcrop area of Fig. 7 determined that the fold axis plunges 14 degrees in direction N287° E. Information from the outcrop area, which included two drill holes, was projected parallel to the fold axis onto a vertical section along CC′. The interpreted cross section (Fig. 8a) showed a thickened No. 4 coal seam at about 150 m depth. The information west of section line CC′ was projected another 300 m onto a vertical section along DD′ (Fig. 8b). From this down-plunge cross section, No. 4 seam was estimated to be about 75 m deep in the hinge of the anticline and to be about 30 m thick as a result of structural thickening. This cross section predicted a potentially surface mineable area east of DD′ towards the estimated subcrop of coal below Quaternary sediments (Fig. 7).

A drill hole site (indicated by the arrow on section DD′) was selected and drilled to a depth of about 110 m. The No. 4 seam was encountered at 70 m depth with a thickness of 29 m, which is about four times normal stratigraphic thickness. Subsequently the structure was drilled out with a total of 7 drill holes along line DD′ (Fig. 8c). The predicted geometry of the thickened No. 4 seam was confirmed at the predicted depth, although the geometry was found to be more complicated as a result of hinge collapse faulting, with possible subsequent fault movements. Additional drilling confirmed the presence of about one million tonnes of mineable coal, showing that computerized down plunge projection techniques can be effectively utilized in finding coal reserves.

Duplexes

A duplex is an imbricate thrust system where each subsidiary thrust joins two common thrusts, an upper roof thrust and a lower floor thrust. A good discussion of duplexes has been provided by Boyer & Elliott (1982). Charlesworth & Gagnon (1985) give an example of duplexes in a coal seam of the outer Foothills at Coal Valley (Alberta) where the seam has been thickened 20 times the stratigraphic thickness. In the Grande Cache area duplexes are found in the limbs of macroscopic folds.

A good example of a duplex in coal is present in the No. 12 Mine area (Fig. 9), which is located 2 km southwest of the South Pit area (Fig. 7) and 3 km west of the western border of the study area. Eight drill holes and some outcrop information were used in the construction of a down-plunge cross section (Fig. 9b). No. 4 seam is 30 m thick in the thickest part of the structure, which is about four times normal thickness, and is faulted out at the surface. The overlying No. 7 seam and underlying Torrens Member do not show any significant folding, excluding thickening in a hinge dilation zone. The coal has been thickened by the stacking of thrust slices (also called horses) in a duplex.

The roof thrust is assumed at the top of the coal and the floor thrust at the bottom. Both thrusts dip northeast, indicating that they are backthrusts and that they are possibly related to the Syncline Hills Thrust, which outcrops to the north. The strike of bedding in the duplex is oblique to the regional

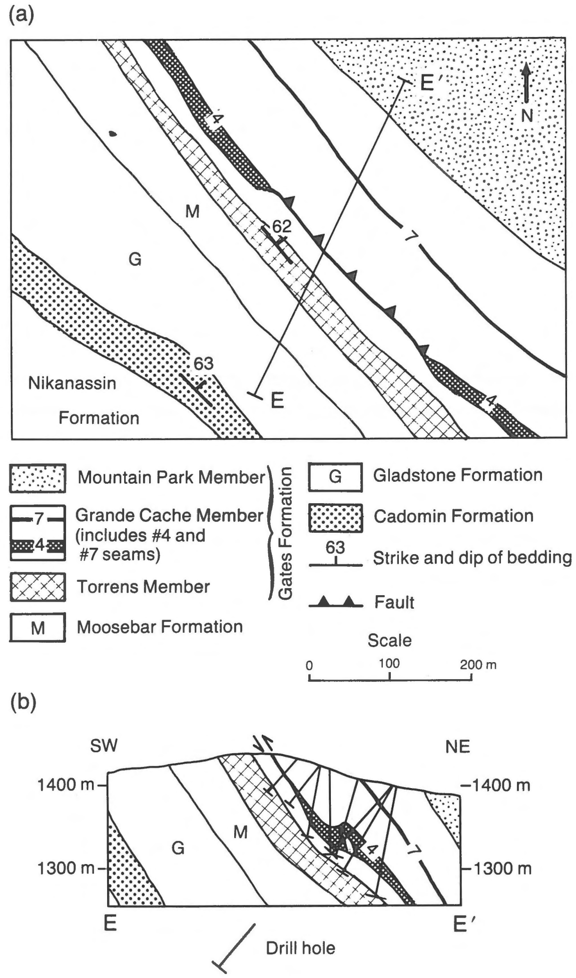

Fig. 9. Geological map (a) and cross section EE′ (b) of part of the No. 12 Mine area. The cross section, which is based on eight drill holes, illustrates the presence of a duplex in the No. 4 coal seam.

strike in the area and this may contribute to the presence of this duplex. The presence of a rock wedge indicates that the floor thrust of the duplex is locally below the base of the coal. At least four stacked thrust slices must be present to explain the observed thickness of the coal. However, the exact position of the subsidiary thrusts cannot be determined in the uniform coal pod. The coal reserves in the No. 12 mine area are significantly enhanced by the presence of the duplex.

Duplexes are generally located in limbs of folds. However, it is not yet understood why they form in some locations and not in others. Because duplexes have only been recognized recently in the Smoky River coalfield, they may become the major exploration target in the near future.

Concluding remarks

Pre-deformational coalification in the Grande Cache area was synorogenic on a regional scale. A tectonic stress field was probably present during the later stages of burial and subsequent deformation, resulting in biaxial anisotropy of vitrinite in many of the coals, in which R_{max} is developed parallel to fold axes. Deformation resulted in displacement, uplift and rapid erosion, which ended coalification.

Numerical mapping techniques such as employed by the TRIPOD software are strong tools for unravelling the geometry of deformed coal bearing rocks. This methodology has been successfully applied in the Grande Cache area, significantly adding to existing coal reserves. Consequently, these techniques provide a basis for the establishment of exploration targets. These targets include coal thickened in fold hinges and in duplexes. Further work is needed to understand why duplexes form in some locations and not in others.

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