STRUCTURAL FEATURES OF COAL MEASURES OF THE KOOTENAY FORMATION,
SOUTHEASTERN CANADIAN ROCKY MOUNTAINS

BY

R.M. BUSTIN

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We accept this thesis as conforming
to the required standards

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Department of Geological Science

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date Dec 5 79
Frontispiece: Number 4 pit, Tent Mountain, Alberta. Coal measures of the Kootenay Formation are folded into a broad but complex syncline. The west limb of the syncline has been faulted out in part by a west dipping thrust.
ABSTRACT

Coal measures of the Late Jurassic-Early Cretaceous Kootenay Formation are complexly deformed in the southeastern Canadian Rocky Mountains. The structural style and associated features of the coal measures are in part characteristic of the 'Foothills Family' of structures. In addition, by virtue of the major contrast in competency between the coal seams and adjacent strata, the structural features of the coal measures display considerable variation which, to some extent, can be correlated with the regional and local structural setting. The variation in the structural features of the coal measures have a marked influence on the mineability of the coal and both directly and indirectly on coal quality.

During deformation the coal seams were the loci of interstratal slip, thrust faulting and detachment during folding. The coal seams vary markedly in thickness; in some areas coal seams have been thickened as much as an order of magnitude in response to thrust faulting, normal faulting and folding, whereas in other adjacent areas, the seams may be completely pinched-off or faulted out. Structural thickening of the coal seams has been facilitated by cataclastic flow of the finely sheared coal along a myriad of discrete shear surfaces. The mesoscopic and microscopic fabric of the coal is cataclastic with the exception of local areas of apparently high strain where the vitrain and clarain components have behaved plastically. Shearing of the coal and adjacent strata has resulted in the introduction and dissemination of formerly discrete rock partings which in turn have produced abnormally
high ash contents and poor washability characteristics and has made the coal more susceptible to oxidation. Measurement of vitrinite reflectance of coal in some major shear zones suggests, by comparison with samples heated in the laboratory for short durations, that frictional heating during shearing may have resulted in temperatures of up to 450°C. Adjacent to and within other shear zones there is no evidence for frictional heating. The presence or absence of frictional heating may be the result respectively of stick-slip and stable sliding conditions during shear, which in turn may be a product of variable pore pressures.

In underground mines the structural features of the roof rock and the coal seams have a pronounced effect on roof stability. In the Vicary Creek mine, located in the hanging wall of the Coleman Fault, the Number 2 seam and some of the roof rock were pervasively sheared as a result of interstratal slip during flexure of the coal measures and possibly as a result of drag from overriding thrust faults. In such areas the coal pillars have low bearing strength and the cohesion between successive beds in the immediate roof rock has been destroyed, resulting in poor roof conditions. Slickenside striae on bedding surfaces, joints in the roof strata and some extension faults which cut the seam, define a kinematic and dynamic pattern which is consistent with the regional structure.

In the Balmer North, Five Panel and Six Panel mines, located in the northern part of the Fernie synclinorium, the coal measures are only mildly deformed. A cleat system is present at all sample localities but no consistent pattern
exists which can be related to the overall structure or to joints in the roof and floor. In the Balmer North mine, young, gently west dipping, shear surfaces are present throughout which, in conjunction with slickensided bedding surfaces, have promoted roof and coal rib failure along north to northwesterly trends. In the Five Panel mine roof and coal rib failure have been facilitated by steep easterly dipping fractures. The absence of a consistent joint or cleat pattern in the Balmer North, Five Panel or Six Panel mines may be the result of mechanical anisotropy of the strata or of multiple episodes of deformation.

Striated structures, many of which are conical in form, are common mesoscopic elements on fracture surfaces in the deformed coal. Such structures, although rarely reported previously in the literature, occur at many localities in the study area. The structures are planar, conical and pyramidal in form, and are characterized by striae which radiate from a common apex and 'horsetail' to form subsidiary structures on the master surface. All three types of striated structures are considered the products of dynamic, brittle shear fracture which was possibly facilitated at failure by high inter- and/or intra-particle pore pressure.
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INTRODUCTION

Introductory Statement

Structurally complex coal deposits in the eastern Canadian Cordillera represent a major proportion of Canada's coal resources. Exploration and exploitation of such coal deposits has, however, been seriously hampered by seemingly unpredictable variation in coal seam thickness, coal quality and roof and floor rock characteristics. Many of the unforeseen difficulties which have been encountered can be attributed to the lack of understanding of the origin, distribution and significance or structural features of the coal measures. Much of our present knowledge of the structural characteristics of coal measures has been based on research and mining experience with flat, undisturbed or only mildly deformed coal deposits. As coal reserves in readily accessible areas diminish, however, there is becoming an increasing incentive to expand coal mining operations to more structurally complex areas and to greater depths. Mining in such areas, as pointed out by Norris (1958) over twenty years ago, will require a more intimate knowledge of both the local and regional geological structure. With the notable exception of the earlier studies by Norris (1958, 1964, 1966) in the Canadian Cordillera, there have been few studies of the structural features of complexly deformed coal measures and their consequences on mining operations.

In the southeastern Canadian Rocky Mountains exceptional exposures of the Late Jurassic-Early Cretaceous Kootenay Formation in and around mine sites provided an excellent
opportunity to observe and document the structural features of the coal measures in a variety of structural settings. The objectives of this thesis are to describe and interpret the structural features of the coal measures, the behavior of coal during deformation, and to assess those structural features which affect the mineability and quality of coal. The observations of this thesis have bearing on a number of interrelated problems in structurally deformed coal measures. These are: 1) What are the mechanisms leading to the formation of structurally thickened coal deposits and what are their characteristics? 2) What 'flow' mechanisms are involved in deformation of the coal? 3) What interrelationships exist between local structural style of the coal measures and the regional structure? 4) What geological factors have a bearing on roof conditions in underground mines and what is the interrelationship between the kinematics and dynamics of deformation of the coal measures and the roof conditions of mines in different geological settings? 5) What is the effect of shearing and resulting comminution of the coal on coal quality and rank? 6) Does frictional heating occur along major or minor thrust faults in the Rocky Mountains and to what extent? and 7) What is the morphology, genesis and significance of striated conical structures and related fractures which occur in structurally deformed coal seams.

**Geological Setting and General Geology of the Study Area**

The study area lies in the southeastern Canadian Rocky Mountains of Alberta and British Columbia, in the vicinity of
the Crowsnest Pass (Fig. 1-1). Within the study area the Kootenay Formation ranges in thickness from 90 m in the east, south of Blairmore Alberta, to more than 1100 m in the west, in the Fernie synclinorium (Fig. 1-2; Gibson, 1977). The Kootenay Formation conformably overlies interbedded sandstones, shales and siltstones of the Passage Beds of the Fernie Formation and is unconformably overlain by conglomerates and sandstones of the Blairmore Group (Fig. 1-3). It is composed of interbedded dark-grey to black shales, siltstones and mudstones and up to 11 seams of mineable thickness of low- to medium-volatile bituminous coal. Locally, north of the study area, semi-anthracite coal is present. Jansa (1972) and Gibson (1977) have interpreted the Kootenay Formation as deltaic, interdeltaic and alluvial sediments deposited as part of a clastic wedge which prograded to the east and northeast into a Late Jurassic epicontinental sea. The stratigraphic nomenclature applied to the Kootenay Formation has recently been summarized and revised by Gibson (1977) who has adopted a three-fold division consisting of a Basal Sandstone member, a middle Coal Bearing member and an upper Elk member. Gibson's nomenclature is followed throughout this study.

The structural setting of the study area is characterized by the 'Foothills Family' of structures, which consists of concentric folds, decollements, low angle thrust faults and tear faults of latest Cretaceous and early Tertiary age and later normal faults (Dahlström, 1969, 1970). The thrust faults and associated splays are parallel to sub-parallel to one another and impart a distinctive northwest structural grain to the
Figure 1-1. Index map to the study area showing the major tectonic elements of the Canadian Cordillera (modified from Wheeler and Gabrielse, 1972).
Figure 1-2. Generalized geological map of part of the southeastern Canadian Cordillera showing the location of areas discussed in the text (modified from Price, 1972). Abbreviations are the same as those in Figure 1-3 and in addition: P=Pennsylvanian and Permian, M=Mississippian, D=Devonian and C=Cambrian. Contours on all figures are in feet.
Figure 1-3. Summary of Mesozoic-Cenozoic stratigraphy, southeastern Canadian Cordillera (modified from Price, 1972).
southern Canadian Rocky Mountains (Fig. 1-2). The folds are concordant with the thrusts and have vertical to west-dipping axial surfaces (Price, 1962). Tear faults locally occur in sets transverse to the structural grain and usually have large displacements. Total shortening from folding and faulting does not vary appreciably along strike, but rather the displacement is apparently transferred to adjacent structures such that the cumulative displacement across the whole fault system changes gradually as compared to displacement along individual faults (Price, 1962; Dahlstrom, 1969). The coal measures of the Kootenay Formation and the underlying incompetent shales of the Fernie Formation have played a fundamental role in determining the structural character of the study area (Price, 1962; Norris, 1966; Dahlstrom, 1969). Coal seams of the Kootenay Formation were the loci of interstratal slip, thrust faulting and detachment during concentric folding and decollement formation. The structural style of the coal measures is thus in part incongruent with that of the regional structure.

**Thesis Format**

The format of this thesis is a series of papers, Parts 1 through 4, each of which addresses a particular aspect or aspects of the study as a whole. Each part, although a separate entity, shares a common study area and the common theme of the thesis as outlined in the 'Introductory Statement'. In order to avoid repetition the 'Geological Setting and General Geology of the Study Area' and associated figures appear only once, in the introduction to the thesis.
In Part 1, the characteristics of, and mechanisms leading to the formation of, structurally thickened coal deposits are described. The rapid variation in coal seam thickness in the southern Canadian Rocky Mountains has seriously hampered mining in some areas, whereas in other areas, structural thickening has facilitated mining of otherwise uneconomic deposits. In this paper examples of structurally thickened and thinned coal seams are described from three different areas; Grassy Mountain, north of Blairmore, Alberta; Vicary Creek, north of Coleman, Alberta; and at Tent Mountain, north of Corbin, British Columbia.

Part 2 considers those geological factors affecting roof conditions in some underground mines in the study area. This study examines the origin and significance of structural features in coal and roof strata in two areas of contrasting structural style: 1) the Vicary Creek mine, located north of Coleman, Alberta, in the immediate hanging wall of a major thrust, the Coleman Fault; and 2) the Balmer North, Five Panel and Six Panel mines, located near Michel, British Columbia, near the northern end of the Fernie synclinorium. In the Vicary Creek mine, the coal and roof rock are sheared pervasively, whereas in the Balmer North, Six Panel and Five Panel mines the coal measures are only mildly disturbed.

Part 3 considers the effects of shear and associated comminution of the coal on coal quality and rank and discusses possible temperatures associated with shearing and their implications with regards to fault mechanics. Extensively sheared coal comprises a large proportion of the coal reserves in the study area. In this study the mesoscopic and microscopic
fabrics of the sheared coal are described and defined and the effect of shearing on coal quality is discussed. In addition, this paper addresses the problem of whether or not frictional heating occurs along major faults.

Part 4 describes the morphology, origin and significance of striated conical structures and related fractures which occur in structurally deformed coal seams. Such structures have only rarely been reported previously in the literature and their occurrence apparently is restricted to coal. In structurally deformed coal seams of the Kootenay Formation, these structures are apparently more abundant and morphologically more diverse than previously described.
REFERENCES


PART 1

CHARACTERISTICS AND MECHANISMS FOR THE FORMATION OF STRUCTURALLY THICKENED COAL DEPOSITS IN THE SOUTHEASTERN CANADIAN CORDILLERA
ABSTRACT

Structural thickening of coal seams of the Late Jurassic-Early Cretaceous Kootenay Formation in the southeastern Canadian Cordillera enables open pit mining of otherwise marginally economic deposits. In some areas coal seams are structurally thickened by as much as an order of magnitude in response to thrust faulting, normal faulting and folding.

Structural thickening of the coal seams has been facilitated by cataclastic flow along a myriad of discrete shear surfaces. In sites of high strain the vitrain and clarain components of the coal show minor plastic flow. The fusain- and durain-rich coal behaved as a brittle material throughout deformation. Along some major shear zones the rank of the coal, as measured by vitrinite reflectance, has been increased locally by frictional heating. Other seemingly major faults evidently had no effect on coal rank.

Shearing of the coal and adjacent strata has locally resulted in the introduction and dissemination of formally discrete rock partings and has markedly increased the ash content of the coal and its susceptibility to oxidation.

Predicting the distribution of structurally thickened coal requires a closely spaced drilling program, a well planned trenching program and an understanding of the structural style of the coal measures.
INTRODUCTION

In the southern Rocky Mountains of Alberta and British Columbia structurally thickened coal seams of the Late Jurassic-Early Cretaceous Kootenay Formation occur in a variety of settings. Structural thickening and associated thinning of coal seams has occurred through a variety of mechanisms and has imparted distinctive characteristics to the coal deposits. In several areas structurally thickened coal deposits have facilitated open pit mining of otherwise marginally economic or uneconomic coal seams. Because of the complex structures associated with these deposits an understanding of their characteristics and mechanism of formation is important in both exploration and evaluation.

In the southern Rocky Mountains of Alberta and British Columbia open-pit mines and, to a lesser extent, underground mines provide an exceptional opportunity to study the mechanisms of formation of structurally thickened deposits in a variety of structural settings. In this study deposits at three localities are discussed (Fig. 1-2): (1) Vicary Creek north of Coleman, Alberta, in the hanging wall of the Coleman Fault; (2) Grassy Mountain, north of Blairmore, Alberta, in the footwall of the Turtle Mountain Fault; and (3) Tent Mountain on the British Columbia-Alberta border north of Corbin, British Columbia, on the Lewis Thrust plate.

The only previously published accounts of the structurally thickened coal deposits in the southern Canadian Rocky Mountains are the studies of Norris (1955, 1956, 1958,
1959, 1964, 1966 and 1971) and Johnson (1977). From regional mapping and detailed studies of mine sites Norris documented many of the structural attributes of the coal and coal measures and was able to correlate many of the observed features with the regional structure. Subsequent mining operations in the southern Rocky Mountains have exposed additional features which re-confirm many of Norris' earlier findings and reveal additional structures not previously apparent. Studies in other coal fields, including the excellent early compilations by Sax (1946) and Deenen (1942) in the South Limburg coal basin, the studies of Darton (1940) in the Northern Anthracite coal basin of Pennsylvania, and the studies by Teichmuller and Teichmuller (1954) and others in the Ruhr Basin have also done much to further our understanding of the deformation of coal measures.

MECHANISMS OF STRUCTURAL THICKENING

Excellent exposures of structurally thickened coal seams of the Kootenay Formation occur at several localities in the study area. The scale of the thickened deposits ranges from that of a hand specimen to 130 m and even thicker deposits have been reported from the subsurface by Johnson (1977). In the following discussion examples of structurally thickened deposits are described from a variety of structural settings to demonstrate some of the different mechanisms leading to the formation of structurally thickened coal deposits and to illustrate the behavior of coal during deformation. In a later section of the paper the general concept of 'flow' of coal during deformation is discussed and the microfabric and quality
of the coal are described.

In order to establish the kinematic picture leading to the formation of the structurally thickened deposits, slickenside striae (slip linears) were measured on bedding surfaces and fault planes. Although the coal is commonly extensively polished, slip linears are rarely present and those which display a random fabric as a result of successive stages of deformation and rotation of the coal and were thus found of little use for kinematic analysis. In this study the slickenside striae are represented in stereographic projection as the pole to the plane which is perpendicular to the shear surface and includes the slickenside striae on the shear surface. The poles so plotted represent the kinematic-\( b \) axis during slip (Hoeppener, 1955). Some slickenside striae are also represented by the portion of the plane which is perpendicular to the shear surface and includes the slickenside striae and an arrow denotes the direction of relative displacement of the hanging wall.

The local fabric axes of the coal seam are defined such that \( a \) and \( b \) are in the plane of the interface between the coal and roof rock and the \( b \) axis parallels the strike of the seam; \( c \) is perpendicular to \( a \) and \( b \).

The terminology used here with respect to small scale faults which have been rotated follows Norris (1958), who refers to contraction faults as those faults along which displacement has resulted in shortening in the plane of layering, and extension faults which result in elongation in the plane of layering.
Vicary Creek

At Vicary Creek the Kootenay Formation occurs in the immediate hanging wall of the Coleman Fault, a west dipping thrust fault with a stratigraphic separation of about 2200 m (Fig. 2-1). A seam of medium-volatile bituminous coal, locally referred to as the Number 2 Seam, occurs about 100 m stratigraphically above the fault and has been extensively mined at Vicary Creek and adjoining areas. The seam strikes 175 degrees, parallel to the trace of the Coleman Fault and dips between 35 and 45 degrees to the west. It is nearly planar but pinches and swells, ranging in thickness from 0.5 m to 10 m, with an average stratigraphic thickness of about 5 m. Although some of the variation in thickness of the seam may be depositional, the associated structures and character of the coal indicate that it is primarily structural.

The principal structural features associated with the seam are slickenside striae on the hanging wall and footwall strata, contraction and extension faults which offset the seam, and small folds and flexures within the hanging wall. Contraction faults lie in h0l, rise out of surfaces of interstratal slip along the hanging wall or within the seam, cut up section at angles of 10 to 35 degrees and pass into other surfaces of interstratal slip. The extension faults lie in hkl,  

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1 The symbols hkl, 0k0, h0l, and hk0 refer to the orientation of the defined fabric axes where hkl are respectively the a, b, and c fabric axis; '0' indicates parallelism with a fabric axis.
Figure 2-1. Vicary Creek. (A) Geological map of part of the Vicary Creek area. In this and other figures: JKk=Kootenay Formation undivided, JKkb=Basal Sandstone member, and JKkc=Coal Bearing member. (B) Axes of slip on slickensided bedding surfaces (☉) and extension faults (▼), 'b' is the b fabric direction of the seam.
have displacements between several centimetres and two metres and cut bedding at preferred angles of 40 to 60 degrees.

Number 2 Seam is highly fractured and locally pervasively sheared and polished. Systematic cleat, if it was ever present, has been destroyed by subsequent deformation. Along major shear planes the coal is finely granulated. At some locations drag folds indicative of up-dip motion of the hanging wall are present in the coal seam.

The axis of rotation of slickenside striae on bedding surfaces and contraction faults (Fig. 2-1B) defines a mean kinematic-\(b\) axis during slip which is nearly horizontal and close to parallel to the \(J_b\) fabric direction of the seam. The direction of motion during slip inferred from the slickenside striae, dip of contraction faults and drag folds in the coal seam implies movement of successively high strata towards the east. The axis of rotation of slickenside striae of the extension faults does not define a preferred axis of slip. In outcrop, as well as in underground workings south of the study area (Norris, 1958), extension faults cutting the hanging wall strata are commonly offset in an up-dip direction, which indicates that some extension faults pre-date interstratal slip. A late stage of normal faulting is recognized on a regional scale but is not considered here.

The mechanisms leading to structural thickening and thinning of the Number 2 Seam are closely related to the overall kinematic pattern of the coal measures. Contraction faults, which arise out of surfaces of interstratal slip within the coal seam, result in local duplication and thickening of the seam up
to several metres. Because such faults arise out of surfaces of interstratal slip, thinning of the seam which must accompany thickening need not be, and rarely is, localized adjacent the region of thickening (Fig. 2-2A). In several areas, the seam shows marked pinching and swelling which is not reflected in faulting. In these areas interstratal slip surfaces, contraction faults and drag folds within the seam attest to differential transport of coal up-dip, thinning some areas of the seam and thickening others. Such a mechanism of structural thickening is augmented in some areas by early extension faults and heterogeneities in the hanging wall of the seam.

Interstratal slip has occurred preferentially along the hanging wall-coal interface in almost all areas. Early extension faults which cut the seam form discontinuities in the plane of slip. During differential displacement of the hanging wall relative to the footwall of the seam, the extension faults and discontinuities in the hanging wall strata are either peeled off and dislodged from the hanging wall, facilitating slip along the hanging wall-coal seam interface, or the fault block moves as part of the hanging wall. In the latter case the fault serves as a 'coal plow' resulting in thinning of the seam in the area of offset and thickening in advance of the fault (Figs. 2-2B, and 2-3). Isolated blocks of sandstone and shale which occur in some highly deformed seams are probably portions of roof strata that formed discontinuities in the hanging wall and were subsequently dislodged from the hanging wall during interstratal slip.

The significance of interstratal slip as a mechanism of
Figure 2-2A. Contraction fault with 2 m of stratigraphic separation in the roof rock of the Number 2 seam. There is no off-set in the footwall strata in the vicinity of the outcrop.

Figure 2-2B. 'Coal plow' in hanging-wall of the Number 2 seam. Drag folds indicative of up-dip motion (to the right) of the hanging-wall relative to the foot-wall are evident in the coal seam on the lee side of the plow.
Model showing how extension faulting followed by interstratal slip results in thinning in the region of off-set and thickening in advance of the plow.
structural thickening in the Vicary Creek and other areas is a function of the total amount of interstratal slip, the character of the roof rock and, likely the ambient stress field. The amount of interstratal slip is among other factors, a function of the amount of flexure of the strata and the thickness of the beds (Ramsay, 1967). Also, a component of interstratal slip may be related to drag from overriding thrusts, as documented by Norris (1958) in other areas. In the Vicary Creek area, the footwall of the seam is rarely exposed and the total amount of interstratal slip is unknown. At one locality, however, extension faults on the footwall of the seam have been dislodged from the footwall and transported with the coal in an up-dip direction as much as 0.5 m, indicating the whole seam has locally moved up-dip by at least this amount. In the now abandoned McGillivray mine south of the study area, Norris (1958) observed a dike in the hanging wall which was offset about 10 m in an up-dip direction from its continuation in the footwall. The influence of the character of the hanging wall strata on interstratal slip is particularly evident in the Vicary Creek underground mine. Here there is a good correlation between thinly bedded carbonaceous hanging wall strata and less extensively sheared coal, and between thickly bedded sandstone hanging wall strata and pervasively sheared coal. Apparently the thinly bedded strata facilitated interstratal slip along the coal-hanging wall interface whereas the thick bedded sandstones did not, and interstratal slip occurred within the seam. The affect of the ambient stress field cannot be evaluated; however, by analogy with simple shear, high normal stress during
interstratal slip would facilitate drag of underlying strata and thus promote structural thickening and associated thinning and shearing of the coal.

**Grassy Mountain**

At Grassy Mountain, coal measures of the Kootenay Formation occur in the immediate footwall of the Turtle Mountain Fault, a west dipping thrust fault with about 150 m of stratigraphic separation in the area of study (Norris, 1955; 1971). One exceptional exposure of a structurally thickened coal seam occurs in an abandoned open-pit mine (Figs. 2-4, 2-5A and 2-5B). The seam is medium-volatile bituminous coal and occurs in the upper part of the Coal Bearing member which is thin at this locality and is disconformably overlain by the Cadomin Formation of the Blairmore Group. The structure, which had been described by Norris (1971), consists of an anticline and two synclines above the coal and two synclines and an anticline below the coal (Fig. 2-4, 2-5A and 2-5B). The average stratigraphic thickness of the seam is about 10 m, whereas it is about 27 m thick in the most easterly syncline and about 1.5 m thick in the hinge of the collapsed anticline (Norris, 1971).

The structural fabric of the coal measures at the Grassy Mountain locality has been described by Price (1967). The folds are concentric and cylindrical, although disharmonic in total aspect. The overall kinematic pattern is one of shortening of hanging wall and footwall strata about a north-trending axis as a result of folding and, to a lesser extent, contraction faulting. Extension faults with displacements of 10 cm to 30 cm
Figure 2-4. Cross-section of the Grassy Mountain structure showing thickening of the coal and the principal structures. Modified from Norris (1971).
Figure 2-5A. Axial region of the anticlinal thickening to the west in Fig. 2-4.

Figure 2-5B. Axial region of the synclinal thickening to the east in Fig. 2-4.
occur locally in the hanging wall strata.

The major anticlinal structure to the west in Fig. 2-4 is developed over a decollement within the coal seam. The basal portion of the seam is nearly flat lying and primary stratification is still evident. Overlying the detachment surface and within the seam are numerous distinct east and west dipping shear surfaces symmetrically arranged about the axial surface. Most of the coal within the anticline is, however, highly brecciated and distinct shear surfaces are not evident. The synclinal thickening of coal to the east is no longer well exposed. The coal appears to be largely pervasively sheared and granulated and distinct mappable shear surfaces are not evident.

Although transport of the coal into the hinge of the anticline by contraction faults is evident in outcrop, calculations by Norris (1971), made when the exposures were fresh, showed that the total amount of shortening in the ac deformational plane of the structure could not account for the area of coal exposed. Norris showed that the cross-sectional area of the seam was too large by 48% and concluded that coal must have been transported obliquely into the ac deformational plane.

The exceptional local thickening of coal in the Grass Mountain structure was probably largely facilitated by decollement in the coal seam or at the level of the coal seam during folding. Burns et al. (1977), using a theoretical model of Ramberg (1964), have demonstrated that during folding of interbedded competent and incompetent strata constrained above by the overlying fold and below by basement (detachment
surface), plastic layers may be squeezed from the synclinal areas towards the dome. The competent stata which are constrained can accommodate folding only by bending and stretching and in the late stages of folding the central region of the dome is a region of extension rather than compression (Burns et al., 1977; Ramberg, 1964).

The overall structure associated with the thickened coal seam at Grassy Mountain is in close agreement with that predicted by Burns et al., (1977). The coal, however, has flowed at least in part cataclastically, rather than plastically, towards the hinge of the anticline above the decollement and towards the hinge of the syncline below the decollement. In addition, late extension faults on the hanging wall of the seam provide evidence for a late stage of extension, as predicted by Ramburg (1964), which probably facilitated transport of coal oblique to the ac deformation plane of the structure towards the culmination.

**Tent Mountain**

At Tent Mountain in the Lewis Thrust sheet (Fig. 1-2), complexly folded and faulted coal measures of the Kootenay Formation have been exposed by mining operations. Coal seams of anomalous thickness occur at three localities where they have been actively mined. Although the overall structure of Tent Mountain is interwoven, each of the deposits has unique features and they are, therefore, considered separately in the following discussion.
Southern Deposit:

On the southern side of Tent Mountain a seam of medium-volatile bituminous coal, locally referred to as Number 4 Seam, occurs in the immediate footwall of a westerly dipping thrust fault (Figs. 2-6 and 2-7). The fault has a stratigraphic separation of about 100 m and a displacement which is approximately 1 km. The fault dips about 45 degrees to the west at the present level of mining, flattens rapidly with depth and cuts down-section to the north and south. In the footwall of Number 4 Seam occur contraction faults which are cozenal with the overlying thrust and which have stratigraphic separations up to 2.5 m. In addition, there are several south dipping contraction faults with stratigraphic separations up to 2.5 m and low amplitude, west plunging folds and flexures which attest to shortening more or less perpendicular to the strike of the overlying thrust.

Number 4 Seam has a normal stratigraphic thickness of about 4 m immediately to the south of the mine, whereas at the present level of mining it is thickened to 33 m. Down dip the seam flattens and thins; it also apparently thins to the north and south before being cut off by the overlying fault. In the region of thickening, the seam is pervasively sheared and brecciated; primary stratification of the coal has largely been destroyed and it is extensively polished. The coal consists of relatively large blocks (up to 20 cm) of more coherent fusain- and durain-rich 'dull' coal and rock partings and more finely brecciated and granulated clarain- and vitrain-rich coal. Many large competent blocks of 'dull' coal have clearly been rotated
Figure 2-6. Southern deposit, Tent Mountain. (A) Generalized geological map. (B) Schematic cross-section through A-B. (C) Axes of slip on slickensided bedding surfaces and contraction faults (•), 'b' is the fabric direction of the coal seam. Legend is on Fig. 2-12.
Figure 2-7. Mosaic of Number 4 seam at present level of mining. The overlying thrust cuts up-section to the east. In the footwall of the coal seam a southeast dipping contraction fault (C) is visible.
during deformation. Few discrete shear surfaces are evident in the coal; those which do occur are marked by finely granulated coal and can be traced only for a few metres.

Measurements of slickenside striae on bedding surfaces and contraction faults and flexures in the footwall of the seam were made at a locality near the present level of mining. The axes of rotation during slip, when considered in aggregate, show a fairly well defined kinematic-b axis which was horizontal, northerly trending and closely paralleled the strike of the overlying thrust fault (Fig. 2-6). Additional axes of slip show considerable scatter, but many are indicative of slip about axes of rotation which are more or less perpendicular to the overlying fault. The direction of motion inferred from the slickenside striae and dip of contraction faults attests to motion of the hanging wall (of the shear planes) both in an easterly up-dip direction and in a northerly direction. The relative timing of the two movements is not apparent.

Structural thickening of Number 4 Seam was the result of transport of coal both in an easterly up-dip direction as well as in a northerly direction about both axes of rotation during slip. Shortening and thickening of the seam about a horizontal, northerly trending kinematic-b axis of slip probably was the result of drag of the coal up-dip along the base of the overlying thrust fault as it cut progressively up section. Much of the structurally thickened coal is likely fault breccia formed during cataclasis and flow of the coal as a result of simple shear of the overlying fault. Such an interpretation is suggested by the paucity of discrete shear surfaces in the coal.
and the presence of pervasively sheared and polished coal throughout much of the seam.

Southerly dipping contraction faults, which occur locally in the footwall of the seam, result in shortening and thickening of the seam in a northerly direction. Because the contraction faults do not cut the hanging wall strata, displacement of the faults must be compensated for by thickening and thinning within the coal seam. Similarly, flexures and folds in the footwall of the seam, not evident in the hanging wall, must result in variation in thickness of the seam. Even if the folds or faults preceded the overlying reverse fault they would still result in a variation in thickness since the overlying thrust is essentially planar. Transport of coal in front of advancing contraction faults or away from anticlinal flexures and folds was probably also along diffuse shear surfaces, notwithstanding that later movements may have destroyed the earlier structural fabric of the seam.

Northern Deposit:

On north-central Tent Mountain, four seams of medium-volatile bituminous coal are exposed in a broad, south-trending syncline (Fig. 2-8). The syncline is the immediate footwall of a west dipping thrust fault with a stratigraphic separation of about 600 m and a displacement probably in the order of several kilometres. The fault cuts abruptly down section to the south where only the eastern limb of the syncline is present. The syncline has been faulted out in part and flattened by the overriding thrust. The structure of the syncline is complex and
Figure 2-8. Northern deposit, Tent Mountain. The overlying west dipping thrust has faulted out much of the eastern limb of the syncline.

Figure 2-9. Axial region of the syncline in Fig. 8. The much thickened seam in the hinge at the top of the photograph is Number 7 seam whereas the underlying seam is Number 6.
only those features which relate to the variation in thickness of the coal seams are discussed here. Contraction faults and extension faults are common on both limbs of the syncline. The faults arise out of surfaces of interstratal slip, cut across several beds, either up or down section, and then pass into other surfaces of interstratal slip. North-trending, east-dipping extension faults with displacements of 0.5 m to 5 m cut obliquely across the syncline. An additional set of faults strike obliquely to perpendicularly to the fold axis and are arranged more or less symmetrically about the axial surface. These faults result in contraction or extension in the plane of bedding.

Of the four major seams exposed in the syncline, the three stratigraphically highest seams in the succession show notable variation in thickness around the syncline (Fig. 2-9), whereas the lowest seam is exposed only on the eastern limb. The uppermost seam, referred to as Number 7, ranges in thickness around the syncline from about 6 m on the eastern limb to 17 m in the hinge area and 12 m in a flexure on the western limb where it is largely faulted out. Below Number 7 Seam the hinge of the syncline is partially collapsed, whereas above the seam the hinge is offset to the east and the beds are more gently folded. Number 6 Seam ranges in thickness from about 6 m on the eastern limb to 9 m in the hinge area and is faulted out on the western limb. Number 5 Seam ranges in thickness from 8 m at a point high on the eastern limb to about 30 m at the hinge of the syncline, 2 m at the inflection point on the western limb and about 25 m in the tight anticlinal hinge to the far west.
Number 4 Seam shows no consistent variation in thickness. In addition to the variations described above, all the seams locally vary in thickness as a result of extension and contraction faulting.

The coal seams are pervasively sheared and polished in areas of structural thickening or thinning, whereas they are only mildly brecciated in areas of normal stratigraphic thickness. In all areas, however, systematic cleat, if it was ever present, has been destroyed by subsequent deformation. Distinct shear surfaces similar to those evident at Grassy Mountain are present in most areas; however, Number 7 Seam is finely granulated and polished in the hinge area of the syncline.

The axis of rotation of slickenside striae during slip on bedding surfaces (Fig. 2-10B) shows a strongly preferred orientation which is essentially horizontal and parallel to the fold axis. Many of the contraction faults are cozonal with, and rise out of, surfaces of interstratal slip. The direction of preferred motion inferred from slickenside striae and dip direction of contraction faults (Fig. 2-10A) indicates movement of the hanging wall strata out of the hinge zone of the syncline, consistent with flexural slip folding. In addition to a well defined kinematic-b axis of slip there is a large scatter of slip axes on both bedding planes and contraction faults which have no readily apparent geometric significance. Included in this latter group are faults which are oriented obliquely and perpendicular to the fold axis. The direction of motion inferred from the slickenside striae on these faults indicates
Figure 2-10. Northern deposit, Tent Mountain. (A) Axes of slip on contraction faults (●), poles to contraction faults (↑) and slip linears (←). (B) Axes of slip on slickensided bedding surfaces.

Figure 2-11. Idealized right-section of a flexural-slip (flow) fold in which the incompetent beds (shaded) are thinned on the limbs and thickened in the hinge areas. The competent beds show little or no variation in thickness. Modified from Whitten (1966).
most of the movement of the hanging wall was toward the north or northeast (Fig. 2-10A). These faults collectively offset, and in turn are offset by, planes of interstratal slip, which indicates that slip about the fold axis (flexural slip) was coeval with slip oblique to the fold axis.

Variation in thickness of the coal seams from the limbs to the hinge of the syncline is not accompanied by a similar variation in thickness of competent sandstone units. The overall synclinal form is thus analogous to the flexural flow folds of Donath and Parker (1964) which are common in rocks of moderate ductility and in sequences with beds of moderate to high ductility contrast. In flexural flow folds, as described by Donath and Parker (1964), flow occurs within less competent layers, resulting in layer boundaries that are no longer parallel; redistribution of material in the layers is most commonly reflected by thickening in the hinges and thinning in the limbs. In the Tent Mountain syncline the flow of coal into the hinge area, particularly in the case of Number 7 Seam, was probably in part the result of the squeezing together of the competent rock units on the limbs during folding and flattening resulting in cataclastic flow of the less competent coal towards the hinge, such as described by Ramsay (1974) during chevron folding. During formation of chevron folds, and apparently some flexural slip folds (Whitten, 1966), dilatation spaces are created in the hinge areas between successive competent layers, which in conjunction with squeezing in the limbs would facilitate flow of the coal to the hinge area (Figs 2-11). In addition to transport of coal in the ag fabric (deformational)
plane of the syncline, extension and contraction faults may have transported coal to the north obliquely into the hinge area.

Local variation in thickness of the seams is related to both contraction and extension faults. Faults which rise out of surfaces of interstratal slip cut both up and down section, respectively resulting in thickening and thinning of the coal seams. Faults which transect the coal seams or which lie within them commonly change markedly in orientation over short distances, resulting in a rapid variations in coal thickness.

Western Deposit:

On west-central Tent Mountain a seam of medium-volatile bituminous coal occurs in the core of a syncline which trends 165 degrees (Fig. 2-12). The western limb of the syncline is nearly vertical or overturned to the west, whereas the eastern limb dips 50 to 60 degrees to the west. On both the east and west limbs numerous northerly trending flexures and folds with amplitudes up to 5 m and wavelengths of 20 m are present. The syncline occurs in the immediate footwall of a west dipping thrust fault with a stratigraphic separation of about 300 m and a displacement which is on the order of several hundred metres. The syncline has been accentuated and overturned in part by the overriding thrust fault. To the north, the syncline has been faulted out, whereas it opens to the south. Open-pit mining has largely removed the coal from the core of the syncline, but it appears that prior to mining the coal deposit was about 130 m wide and 80 m thick in the hinge area. The normal stratigraphic thickness of the seam in areas to the east is about 7 m. The
Figure 2-12. Western deposit, Tent Mountain. (A) Generalized geological map. (B) Schematic reconstructed cross-section. (C) Axes of slip of slickenside striae on bedding surfaces (●). 'B' is the fold axis.
coal is presently exposed in isolated areas on the footwall, where it is extensively fractured and, in part, finely granulated. In general, the coal is not as extensively polished as it is in the northern deposit.

The axes of slip determined from slickenside striae on strata in the footwall of the seam at accessible areas (Fig. 2-12C) show a well defined kinematic-\(b\) axis which is subhorizontal and closely parallels the synclinal axis. The kinematic-\(b\) axis for slip on bedding and the direction of slip inferred from the slip linears are consistent with flexural slip folding about the fold axis of the syncline.

Because almost all the coal has been mined from the core of the syncline the mechanisms leading to the formation of the much thickened deposit can only be inferred. The total aggregate shortening of the seam within the syncline is not adequate to account for the volume of coal in the core of the syncline; coal must therefore have been transported into the hinge area from the limbs of the syncline. The overall mechanisms of thickening of the coal were probably analogous to those previously described for the Northern Deposit. The total thickening of the seam is, however, much greater, likely as a result of the tighter folding and possibly greater degree of flattening of the syncline.

"FLOW" OF COAL DURING DEFORMATION

In addition to considering the mechanisms of structural thickening in terms of the kinematics of the coal measures, thickening can be envisaged simply as a result of flow (mass
transport) of coal from areas of high stress to areas of low stress. The flow of coal at all the examined localities has been cataclastic. There is no evidence on a mesoscopic scale for truly ductile behavior of the coal in the usual sense. Cataclasis and plastic flow represent completely different material behavior, respectively brittle and ductile, and the laws of plastic flow cannot be applied to brittle materials (Sture, 1976).

Flow is generally considered a "...process whereby a rock is deformed continuously in space without loss of cohesion..." (Turner and Weiss, 1963, p. 37). Loss of cohesion, however, must be considered relative to the scale of the structure and, if the loss of cohesion is smaller than the scale of the structure, it is a mechanism of flow (Stearns, 1968; Price, 1974). Cataclasis as a mechanism of flow in rocks has been studied experimentally (Handin and Hager, 1957; Borg et al., 1960; Donath and Fruth, 1971; Kerrich and Allison, 1978). When a rock loses cohesion as a result of brittle fracture it may flow by displacement of its constituent parts relative to one another, accompanied by dilatation, mechanical abrasion and granulation. The fragments of the rock thus may behave and flow in a macroscopically ductile-like manner (Stearns, 1968). As indicated by Stearns (1968), the extent of fracturing can be considered a measure of the relative ductility of the rocks and the degree of dependence on cataclasis as a mechanism of flow. Furthermore, the total strain, strain rate, temperature, and geometry and thickness of the beds will influence the mode of deformation and extent of fracturing (Stearns, 1968; Donath and
Fruth, 1971).

Because of extensive fracturing, much of the coal in this study can be considered to have relatively high ductility as compared to adjacent lithologies. The fracturing of the coal probably included an initial cleat system; however, the extensive fracturing which facilitated cataclastic flow is probably related to the strain softening characteristics of the coal. Strain softening can be considered as the progressive loss of shear resistance with strain after peak shear strength. A common feature of strain softening of materials in progressive failure of rock structures is that excess stress, when relieved in one area, is redistributed to adjacent areas which may thus be brought to failure (Sture, 1976). Sture has experimentally studied the strain softening behavior of Pittsburg coal and has detailed the sequence of progressive failure and cataclasis. He found that, at peak strength, shear zones progressed throughout the sample and the 'weakest link' was the shear zone where the cohesion was smaller than that of the unfractured rock, but where the intrinsic friction angle may still be high. Dilatation occurs as a result of fracture as intact coal pieces undergo rigid body rotation and translation along the shear zone. Movement further results in a large dilatation, tearing loose of more fractured pieces and abrasion which changes the angularity and grain-size distribution of the fractured mass (Sture, 1976). During sliding, the shear zone may 'lock up' and fracture may initiate in another fracture zone, the end result being a multitude of diffuse shear surfaces and a cataclastic fabric.
The high relative ductility of the fractured coal, and its ability to flow, is particularly apparent in small scale structures where the geometry of the enclosing rocks is completely exposed. Fig. 2-13 shows boudinage in interbedded sandstone and coal; the sandstone beds have failed brittlely in extension, forming boudins, whereas the more highly fractured coal flowed cataclastically into the neck regions, indicating that the more highly fractured coal has a very low apparent viscosity as compared to that of the sandstone interbeds. Fig. 2-14 shows the occurrence of coal within the plane of an extension fault with about 4 m of offset; dilatation in the fault plane has accommodated flow of coal into the fault plane, where the coal is about the same thickness as in the 'feeder' coal seam. Based on volumetric considerations, the coal must have been 'injected' rather than simply dragged along the fault plane. Also of interest in this example is the development of a crude foliation in the coal seam parallel to the fault plane, probably as a result of slip parallel to the fault and rotation of the larger coal clasts, perhaps similar to the development of bedding foliation in incompetent strata during flexural slip (Whitten, 1966).

Although structural thickening and thinning is more apparent in small scale examples which are well exposed, the larger scale examples, previously discussed, also attest to the ability of coal to flow to areas of low stress. In other coal fields similar structural variations in thicknesses are probably also a result of cataclastic flow of coal. Nickelsen (1963) has described thickening in the hinge areas of some folds resulting
Figure 2-13. Boudinage in interbedded sandstone and coal. The sandstone beds (light toned) are about 0.3 m thick.

Figure 2-14. Extension fault with about 4 m of displacement and coal injected into the fault plane. Notice the foliation in the coal which is more or less parallel to the fault plane.
in a similar fold style in central Pennsylvania. Petrascheck (1937) described thickening of coal in the hinge areas of some folds and both Petrascheck (1937) and Bessiar (1948) have documented the complex structures and thickening of coal associated with faults.

MICROFABRIC OF THE COAL

Coal from some of the structurally thickened deposits was examined with a reflected light microscope, with a photometer for vitrinite reflectance measurements, and with a scanning electron microscope. The results of this study will be reported elsewhere and are only summarized here.

The microfabric of the coal from structurally thickened areas is similar to that of the coal from areas of normal stratigraphic thickness with the exception of adjacent to major shear zones and in areas of intense deformation. The finely granulated coal along shear zones generally consists simply of fragments of the larger coal clasts with no evidence of internal deformation. Locally, however, aggregates consisting of angular fragments of inertite-rich coal in a groundmass of vitrite or clarite occur. In these aggregates the inertite components have undergone brittle fracture whereas the clarite or vitrite groundmass apparently behaved ductilely. Ductile behavior of the clarite and vitrite is also apparent from the occurrence of microfolds of similar style and 'wild' folds. Somewhat similar structures have also been described from tectonically deformed parts of the Ruhr Basin by Teichmüller and Teichmüller (1954). The occurrence of coal in the study area showing evidence of
ductile behavior even on a microscopic scale is restricted and may represent areas of 'locking' during cataclastic flow.

Measurements of vitrinite reflectances were made on the highly polished and sheared coal to ascertain the effect of deformation on coal rank. The results of the analysis indicate that adjacent to some shear zones the rank of the coal has been raised to semi-anthracite. The increase in rank is not predictable, however; adjacent to some major faults there is no evident change whereas in adjacent, seemingly minor, shear zones there may be a notable increase in rank.

EFFECT OF STRUCTURAL THICKENING ON MINING AND COAL QUALITY

Structural thickening of some coal seams in the study area has enabled open-pit mining of seams which are otherwise too thin. However, in underground mines such as in the Vicary Creek area the rapid variation in thickness of the coal seam and accompanying irregularities in the hanging wall and footwall strata result in unpredictable and unfavourable mining conditions. Moreover, the pervasively sheared coal forms pillars of low bearing strength and it is not possible to hold the sheared coal in the roof. Additional problems are also encountered in predicting coal reserves and distribution of the coal deposits. Even with a densely spaced drilling program it is difficult to predict the variation in seam thickness or to unravel the structure.

The quality of the coal is also commonly poor. The coal has a disproportionately large amount of ash, poor washability characteristics and is commonly partly oxidized. The high ash
content and the poor washability of the coal are related at least in part to shearing and to the dissemination throughout the coal of formerly discrete rock partings. The high ash content of some deposits as mined may be artificial, resulting from difficulties in mechanical mining and the incorporation of protrusions of roof and floor strata. Oxidation of the coal is largely related to the fine grain-size of the sheared coal which markedly increases the susceptibility of coal to oxidation. In addition, the highly fractured and faulted coal and associated strata facilitates exposure even at depth to atmospheric oxygen or circulation of oxygenated waters.

CONCLUSIONS

The mechanisms leading to the formation of structurally thickened coal deposits in the southern Rocky Mountains of British Columbia and Alberta are closely correlatable with the kinematic pattern of the coal measures. At Vicary Creek, the variation in thickness of Number 2 Seam is a result of contraction faulting, interstratal slip and extension faulting. At Grassy Mountain thickening is related to folding of the coal measures and decollement at the level of the coal seam which facilitated transport of the coal both obliquely to and in the ac fabric plane of the folds. At the Southern Deposit at Tent Mountain Number 4 Seam has been thickened as a result of drag of portions of the seam up-dip along the base of a thrust fault and, to a lesser extent, as a result of contraction faulting in the footwall of the seam. In the Western and Northern Deposits at Tent Mountain thickening of the coal seams is primarily the
result of squeezing of coal from the limb regions of the synclines to the hinge areas, similar in gross aspect to that of flexural flow and chevron folding.

In all of the examples, structural thickening of the coal resulted at least in part from cataclastic flow of coal from areas of high stress to areas of lower stress. The apparent ductility of the coal and its ability to flow is a result of intense fracturing and granulation of the coal which results in a low apparent viscosity as compared to that of adjacent lithologies. There is no evidence on a macroscopic scale for truly ductile behavior and microscopic studies indicate that ductile behavior of the vitrite and clarite components of the coal is restricted to areas of intense deformation. Vitrinite reflectance studies show that only rarely is there any increase in rank associated with polishing and shearing of the coal.

Structural thickening of coal seams in some areas facilitated open-pit mining of otherwise too thin seams. However, in areas of underground mining the rapid variation in thickness of the seams and the highly sheared character of the coal result in unfavourable mining conditions. It is furthermore difficult to predict the coal reserves or extent of the coal deposits and the quality of the coal is generally poor, with disproportionately high amounts of ash, poor washability characteristics and common oxidation.
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PART 2

GEOLOGICAL FACTORS AFFECTING ROOF CONDITIONS IN SOME UNDERGROUND COAL MINES IN THE SOUTHEASTERN CANADIAN ROCKY MOUNTAINS
ABSTRACT

Variability in roof conditions in some underground coal mines in the southeastern Canadian Cordillera is in part attributed to sedimentary and structural features of the roof strata and the coal. Examination and measurements of mesoscopic fabric elements in accessible parts of the mines at Vicary Creek, located in the hanging wall of the Coleman Fault, and the Balmer North, Six Panel and and Five Panel mines, located in the northern part of the Fernie synclinorium, indicate that a correlation exists between the structural conditions in the mines and the regional structural setting.

In the Vicary Creek mine, the roof rock ranges from thin-bedded, very fine-grained, carbonaceous sandstones and siltstones to thick-bedded sandstones which are respectively interpreted as distal and proximal crevasse splay deposits. The thin-bedded strata include carbonaceous laminae that were preferred horizons for interstratal slip and which form major structural discontinuities along which separation of the roof strata may occur. The thick-bedded sandstones are well jointed resulting in a blocky roof rock which did not facilitate interstratal slip. Rather, interstratal slip was accommodated by slip within the coal seam itself resulting in extensive shearing and comminution of the coal, which has reduced the bearing capacity of coal pillars. Slickenside striae on bedding surfaces and some extension faults define a kinematic pattern which is consistent with that of the Coleman Fault, the major structural element in the area of the mine. Joints lie in hkl and hk0 and appear to be dynamically related to interstratal
slip. Some extension faults lie in hkl and h0k and cannot be related to the overall structure. At least some extension faults pre-date interstratal slip. They have displacements up to 2 m and, in conjunction with low amplitude folds and flexures in the roof strata, locally result in poor roof conditions.

In the Balmer North, Six Panel and Five Panel mines, the immediate roof rock is composed of carbonaceous siltstones and very-fine grained sandstones. There is no marked variation in roof rock lithology throughout the mines. The lack of lithologic variations, in conjunction with the transitional contact between the roof strata and the coal seam, suggests that the coal and roof rock were deposited on a broad, low energy delta plain, and that abandonment of swamp conditions was gradual. As a result of flexural slip during folding, bedding surfaces are slickensided which has in part destroyed the cohesion between successive beds in the roof rock. Although a cleat system is evident at almost all sampling localities, no consistent pattern is evident that conforms to the regional structure. Locally in the Five Panel and Six Panel mines, the cleat appears to be dynamically related to local flexing of the seam. Joint sets in the roof and floor strata lie in hkl and hk0 and only at a few localities do they conform to the cleat system. Few major extension faults are present in the mines. Those which do occur lie in h0l. In the Balmer North mine, young, gently west dipping shear fractures (cleat) which lie in h0l are present throughout the mine. This cleat system, in conjunction with cczonal extension faults and slickensided bedding surfaces, results in failure of both roof strata and
coal ribs along northerly to northwesterly trends. Slip linears on extension faults and shear surfaces in the coal are antithetic to those expected during flexural slip and probably post-date folding. In the Five Panel mine both roof and coal rib failure occur along steep, easterly dipping shear surfaces in conjunction with slickensided bedding surfaces.
INTRODUCTION

Considerable resources of high quality coking coal occur at depth within the stratigraphically and structurally complex southern Rocky Mountains of British Columbia and Alberta. Underground coal mining in this area has been seriously hampered by seemingly unpredictable variation in structural conditions and roof rock characteristics which are not evident from either the sparse outcrops or exploratory drill holes.

The purpose of this study was to identify and assess those geological factors that are associated with and promote roof problems in underground coal mines in the Crowsnest Pass area of the southern Canadian Cordillera. An objective of the study was to relate the observed roof conditions to the sedimentology and the kinematics and dynamics of deformation of the coal measures in order to develop geological criteria for predicting roof conditions.

Presently, underground coal mines in the southeastern Canadian Cordillera are operating in a variety of structural settings and stratigraphic levels, thereby providing an opportunity to assess and compare roof conditions and the structural fabric of the mines in different geologic settings. In this study, the Vicary Creek mine located in the immediate hanging wall of the Coleman Fault, north of Coleman Alberta, and the Balmer North, Five Panel and Six Panel mines at the northern end of the Fernie Synclinorium, near Michel, British Columbia were studied (Figs. 1-1 and 1-2). Examination of the mines entailed mapping of roof strata and mesoscopic fabric elements of both the roof strata and the coal in accessible parts of the
mines. Although some areas with poor roof conditions were not accessible, a special effort was made to examine and sample the roof strata around and in areas presently experiencing roof support problems.

Roof conditions in underground mines are not only a product of the inherent geological factors, but also reflect the mining methods which are determined not only by the geology, but by economics, engineering and other considerations. In this study only the inherent geological factors are considered; it is not the purpose of the study to assess or pass judgement on mining methods. It is hoped, however, that this study might prove useful, if not in presently operating mines, in mines which may be developed in the future in similar geological settings.

Previous studies of the structural conditions of coal mines in the southeastern Cordillera have been made by Norris (1958, 1963, 1965, 1966). The present study is in part an extension of the earlier work of Norris to some presently operating coal mines. Other pertinent studies of geological factors affecting roof and structural fabric in coal mines include those of Diessel and Moelle (1965) and Shepherd and Fisher (1978) in Australian coal fields, the studies of Benedict and Thompson (1973) and Moëbs (1977) in Pennsylvania, Krauss et al., (1979) in Illinois, and Deenen (1942) and Sax (1946) in the Dutch coal fields.

In this study, mesoscopic fabric elements are plotted on the lower hemisphere of Schmidt equal area stereonets. The terminology of Sanders (1942) is followed with respect to the
fabric directions. Three mutually perpendicular fabric axes are referred to as \( a \), \( b \) and \( c \) where \( a \) and \( b \) are in the plane of bedding and \( c \) is perpendicular to \( a \) and \( b \). The \( b \) axis is parallel or subparallel to the fold axis (\( B \)) or, in the case of homoclinal sequences, it is defined as parallel to the strike of the seam. In order to deduce the kinematic picture and dynamic history, slickenside striae are represented in stereographic projection by a portion of the great circle which passes through the pole to the shear surface and the slickenside striae. The plotted segments are thus centered about the axis of rotation during slip on their respective surfaces (Hoeppener, 1955). The sense of relative motion on the slickensided surface has been inferred from either the roughness or accretion methods (Norris and Barron, 1968) and where the direction of motion is deduced an arrowhead is used to show the relative motion of the hanging wall.

The orientation of the intermediate principal stress at failure \( (\sigma_2) \) is uniquely defined by the axis of rotation of the slip linears. The orientation of the maximum principal stress \( (\sigma_1) \) and least principal stress \( (\sigma_3) \), however, can be inferred only from the character and symmetry of the joint and cleat systems. According to theories of brittle fracture and laboratory tests, tension (extension) fractures occur between complementary sets of shear fractures and the acute angle between the shear fractures is bisected by \( \sigma_1 \) (Stearns, 1968, Friedman, 1975). Without representatives from all three sets it may not be possible to resolve the stress geometry during deformation (Norris, 1967). Also, it is not always possible to
differentiate regional fractures from those associated with a particular structure (Currie and Reik, 1977). In this study the geometry of fractures and their interpretation are discussed in terms of the sub-patterns recognized and described by Stearns (1964, 1968).

VICARY CREEK MINE

At the Vicary Creek mine the Kootenay Formation consists of 150 m of interbedded dark-grey to black shales, siltstones, dark-grey sandstones and three seams of medium-volatile bituminous coal. The formation occurs in the immediate hanging wall of the Coleman Fault, a major west dipping thrust fault with an estimated 2200 m of stratigraphic separation (Fig. 1-2). A steep west-dipping splay of the Coleman Fault repeats the upper part of the Kootenay Formation in the region of the mine site. The Vicary Creek mine is developed in the uppermost coal seam which locally is named the Number 2 seam. The mine workings at the portal are located 50 m stratigraphically above the Coleman Fault and 40 m below the overlying splay-fault.

Within the mine workings, the Number 2 Seam strikes 170° and dips between 35° and 45° to the west (Fig. 3-1). The seam is being mined by following the roof; nowhere in the mine are floor strata exposed.

Roof Rock Characteristics

Lithology and Sedimentology:

The immediate roof rock of the Number 2 Seam was mapped
Figure 3-1. Vicary Creek mine. (A) Structural contour map on top of the Number 2 seam and principal structural elements in the roof rock. (B) Joint fabric, contours are at 2, 5, 10, 15, and 20% per 1% area. (C) Extension fault fabric, poles (●), axes of slip (■), and slip linears (→), 'b' is the b fabric direction of the seam.
throughout the accessible part of the mine. Two lithofacies are recognized (Fig. 3-1); a thick-bedded sandstone lithofacies which occurs in the southern portion of the mine workings and a thin-bedded sandstone and siltstone lithofacies present in the northern part of the mine. The transition between the two lithofacies is gradational and is not well exposed. The thick-bedded sandstone lithofacies consists predominantly of fine-grained, parallel to irregular bedded, quartzose sandstone. The thin-bedded sandstone and siltstone lithofacies is composed of fine-grained, wavy to irregular bedded, carbonaceous sandstones and siltstones, discrete coaly laminae, very thin seams of coal and carbonaceous shale. Strata overlying the immediate roof rock are visible only in areas of caving. In caved areas the immediate roof rock appears to persist stratigraphically for at least 0.5 m. Locally, thin seams of coal or thin beds of carbonaceous shale are present 1 m to 3 m above the immediate roof.

Very little sedimentological evidence is provided by the immediate roof rock. Generally, however, the facies change from the thick-bedded sandstone lithofacies in the south, to the thin-bedded sandstone and siltstone lithofacies to the north is similar to facies change from proximal to distal crevasse splay deposits documented from recent and extensively studied ancient deltaic environments (Reineck and Singh, 1973; Horne et al., 1978). The transition from swamp conditions responsible for formation and accumulation of the coal (peat) is abrupt in the southern part of the mine, attesting to rapid influx of clastic detritus during flooding and inundation of the swamp. In the
northern part of the mine, however, contemporaneous lower energy conditions prevailed, resulting in the deposition of finer grained sediment and possibly periodic re-establishment of the swamp prior to complete destruction of the peat forming environment.

Structural Fabric of the Coal and Roof Rock:

In the Vicary Creek mine the main mesoscopic structural fabric elements are extension faults, small folds, joints and slickenside striae on bedding planes. Figure 3-1 summarizes the distribution and orientation of some of the structural elements. The distribution of folds and faults shown on the accompanying structural contour map (Fig. 3-1) reflects in part the accessibility to various parts of the mine, but also is representative of the clustering of the structures. From the modal attitude of the coal seam the ac fabric plane and the b direction are defined and are plotted together, with poles to joints and faults on the stereonets shown in Figs. 3-1B and 3-1C.

Extension faults occur throughout the mine (Figs. 3-1A and 3-2) and have stratigraphic separations varying from a few millimetres to two metres. They cut bedding at angles close to 60°, in agreement with the mean dip of extension faults reported in other coal mines in the southeastern Cordillera by Norris (1958). Although the orientation of the faults shows considerable scatter there is a fairly distinct maximum which lies in Okl (Fig. 3-1A). Only one contraction fault was observed in the underground workings; it lies in Okl and has a
Figure 3-2. Northwest dipping extension fault with about 0.5 m of stratigraphic separation in the roof rock in the Vicary Creek mine. Stereo-pair.
stratigraphic separation of 1 m. The paucity of contraction faults in underground coal mines in the southeastern Canadian Cordillera was previously noted by Norris (1958), who has reported that extension faults outnumber contraction faults by 10:1. In open pit mines adjacent to the underground workings at Vicary Creek, several contraction faults were mapped which lie in h0l and cut the roof strata at angles between 10° and 35°. Such contraction faults, if present, would be difficult to recognize in the underground mine.

Concentric, north to northwest plunging folds with amplitudes ranging from 1 m to 2 m and with wavelengths up to 6 m occur at several localities (Fig. 3-1). Although the folds are not numerous they result in exceedingly poor roof conditions and are described in a later section.

Jointing in the roof rock is restricted to the thick-bedded sandstone lithofacies. The joint system is summarized in Fig. 3-1B and is divisible into three distinct sets. One set lies in the ac fabric plane (0k0), whereas the other two sets lie in hkl. The acute angle between them is about 30° and is bisected by the ac fabric plane of the roof rock. No characteristic surface markings were noted on any of the joints.

Slickenside striae on bedding elements are present throughout the mine and are particularly prevalent in the thinly bedded sandstone and siltstone lithofacies. In these strata, interstratal slip was facilitated by carbonaceous laminae and it now imparts a slabby to platy split to the roof rock and destroyed the interbed cohesion.
Kinematic Analysis

Slip linears are rarely present on polished surfaces in the coal even though shear surfaces pervade the coal seam itself, and those present define a random fabric attesting to subsequent deformation and rotation. Consequently, the following discussion is based largely on the kinematic pattern determined from the roof and floor rock and adjacent strata rather than the coal seam.

Slip linears and the axis of rotation during slip measured on bedding surfaces of the immediate roof rock are presented in Fig. 3-3. In aggregate the axis of rotation defines a modal kinematic-\( b \) axis for slip which is nearly horizontal, trends 170°, and is almost parallel to the defined \( b \) fabric axis of the seam. In addition to this well defined axis of slip, there is a second population of slip axes which is also sub-horizontal, but trends 195°. Cross-cutting relationships between the two populations of slip linears observed at two localities indicate that motion about the \( b \)-fabric axis of the seam preceded the oblique motion.

Measurement of well-defined slickenside striae on extension faults was rarely possible in the underground workings. The few measurements made (Fig. 3-1C) show a broad scatter of axes of slip that are more or less parallel to the \( a \) fabric direction of the seam.

The relative timing of extension faulting and interstratal slip is not evident in the underground workings. Consequently, measurements were made of slickenside striae on bedding surfaces and extension faults in the roof and floor
Figure 3-3. Vicary Creek mine. Poles (●), axes of slip (■), and slip linears (→) of slickensided bedding surfaces and trend and plunge of folds in the roof rock (▲). Figure 3-4. Poles (○), axes of slip (●) and slip linears (△) of slickensided bedding surfaces, and poles (●), axes of slip (■) and slip linears (△) of extension faults and poles (▲) to contraction faults in the now abandoned Race Horse strip mine north of the Vicary Creek mine.
strata of an abandoned open pit mine developed in the Number 2 seam to the north of the underground mine. The axes of slip of extension faults and on bedding surfaces are cozonal, horizontal to sub-horizontal, and closely approximate the defined b fabric direction of the seam (Fig. 3-4). At this locality many extension faults in the floor of the seam are offset up to 50 cm in an up dip direction indicating that faulting, at least in part, has preceded interstratal slip. Other extension faults that are not offset may post-date interstratal slip. Unlike the extension faults in the underground mine that lie in Okl or hkl, the faults in the open pit mine lie in hOl. Hence, extension faults in the underground mine may not be related to the same deformational event, or may not have the same deformational history as those in outcrop. The reason why the orientations of the faults are so different is not evident.

In order to relate the local kinematic pattern evident in both the mine and adjacent outcrops to the regional structural pattern slickenside striae on shear surfaces within the Coleman Fault plane were measured. The measurements were made directly below the mine portal, in a wedge of highly sheared green mudstone and siltstone of the Crowsnest Volcanics Formation which lies within the Coleman Fault. Figure 3-5 summarizes the orientation of the slip linears and associated axes of slip. Although the shear planes are curved, a distinct preferred orientation of the slip axes is evident which defines a modal kinematic b-axis that is nearly horizontal, and closely parallels the defined b-fabric direction of the coal seam and the modal kinematic-b axis during slip. In addition to this
Figure 3-5. Poles (●), axes of slip (■) and slip linears (→) of shear surfaces within the Coleman Fault plane, about 50 m below the portal of the Vicary Creek mine.

Figure 3-6. Back-limb reverse fault in a fold in the Number 2 seam above the portal at the Vicary Creek mine. Offset across the fault is about 3 m.
well defined axis of slip, there is a scatter of slip axes which are generally subhorizontal and trend east-northeast. This group is generally of similar orientation to the second, younger set of kinematic-\(b\) axes observed in roof strata of the mine (Fig. 3-3); hence they may be products of the same period of movement.

**Dynamics of Deformation**

The mesoscopic fabric of the roof rock and associated outcrops provides evidence for at least three periods of deformation each of which may represent a different deformational phase in which the orientation of \(1\) was different. These are: 1) extension faulting, in which the kinematic-\(b\) axis paralleled the \(b\) fabric direction (open pit mine); 2) interstratal slip, in which the kinematic-\(b\) axis closely paralleled the \(b\) fabric direction; and 3) a later stage of interstratal slip, in which the kinematic-\(b\) axis was sub-horizontal and trended to the southwest-northeast. Based on the symmetry of the joint system in the roof rock, jointing is considered contemporaneous with the first phase of interstratal slip as discussed later. There is no evidence for the chronology of the extension faults in the underground mine. On a regional scale a late stage of normal faulting is evident but it does not appear to be geometrically or genetically related to the measured faults in the mine, and is therefore not considered here.

The kinematic-\(b\) axis of mesoscopic fabric elements uniquely defines the local orientation of \(\theta_2\) at failure. The near parallelism of the modal kinematic-\(b\) axis of some extension
faults, interstratal slip surfaces, and shear surfaces in the Coleman Fault plane indicates that \( \sigma_2 \) maintained a nearly horizontal, northerly trend throughout deformation. It further suggests that a genetic relationship exists between the structures. Extension faults cozoal with interstratal slip surfaces, although they in part clearly precede some interstratal slip, also probably followed at least some rotation of the coal measures. Otherwise, it would be completely fortuitous that the structures are cozoal. Independent indicators of the orientation of \( \sigma_1 \) during extension faulting are absent. However, \( \sigma_1 \) can be considered to have been oriented approximately normal to bedding at failure, in keeping with experimental observations (Griggs and Handin, 1960), and as documented in other coal mines by Norris (1967).

The close agreement between the kinematic-\( b \)-axis during interstratal slip of the roof rock and the defined \( b \)-fabric direction of the coal seam is similar to that expected during flexural slip folding of sequences in which a planar anisotropy exists (Donath and Parker, 1964). Interstratal slip probably occurred, at least in part, during buckling of the coal measures in response to rotation on the Coleman Fault, as suggested by the congruence of their respective kinematic-\( b \)-axis. A component of interstratal slip may also be related to shortening within the Coleman Fault plane as a result of overriding thrust sheets as has been suggested in some other areas by Norris (1958) and evident from the local structure adjacent the mine (Fig. 3-6). The orientation of \( \sigma_1 \) during interstratal slip can show considerable angular variation with respect to bedding.
(Donath and Parker, 1964). The symmetry of the joint system in the roof rock, however, provides an independent estimate of the stress geometry at failure. By analogy with the symmetry of extension and shear fractures produced in laboratory studies and documented in the field (Donath, 1963; Stearns, 1968; and others), the conjugate joint sets in the roof rock are considered to be shear fractures whereas the set parallel to the ac fabric direction are extension fractures. The stress geometry at failure thus indicates that the maximum principal stress was parallel with the a fabric direction of the seam and in close agreement with that predicted from the regional direction of tectonic shortening. The later stage of interstratal slip evident from slip linears in the roof strata suggests that some re-orientation of the stress field occurred during the later stages of deformation.

**Relationship Between Roof Conditions and Geology**

In the Vicary Creek mine, a close correlation exists between the two recognized lithofacies in the roof rock and the roof conditions. The thin-bedded carbonaceous sandstone and siltstone lithofacies forms a roof rock with a platy split. The split is parallel to bedding and occurs along carbonaceous laminae where interstratal slip has destroyed the cohesion between beds (Fig. 3-7). The thick-bedded sandstone lithofacies, on the other hand, is commonly well jointed, resulting in a blocky roof rock in which roof failure is facilitated along joint planes (Fig. 3-8). In addition to the above association, a good correlation exists between the type of
Figure 3-7. Thin-bedded carbonaceous roof rock which has parted and caved along slickensided carbonaceous laminae. Roof bolt in uppermost left of the photograph for scale.

Figure 3-8. Thick-bedded, well jointed and partially caved roof rock. The cavity is controlled by jointing and bedding. Beds are about 20 cm thick.
roof rock and the extent of fracturing of the coal seam. The thin-bedded sandstone and siltstone lithofacies is associated with less extensively sheared coal than either the thick-bedded sandstone lithofacies or areas in which the upper portion of the seam is composed of dull coal. Such an association suggests that the thin-bedded sandstone and siltstone lithofacies facilitated interstratal slip along the roof of the seam during deformation, or within the immediate roof rock. On the other hand, where the upper portion of the seam contains either dull coal, which is more competent, or thick-bedded sandstone, interstratal slip apparently occurred to a greater extent within the seam. Shearing and comminution of the coal as a result of interstratal slip has markedly reduced the bearing capacity of the coal pillars. Failure of the coal ribs results from 'flow' of the coal out of the ribs rather than by failure along discrete surfaces. Calculations of the bearing capacity of pillars developed in such highly sheared coal would require considering the coal as a pre-failed aggregate already past peak strength, and within the region of strain softening.

Local variations in the roof-rock characteristics are associated with faults and folds. Extension faults disrupt the adjacent roof rock, and facilitate failure along sheared bedding planes. None of the observed extension faults completely offset the seam. It is impossible, however, to predict the orientation or location of the minor faults even to adjacent roadways. Small folds in the roof rock are associated with particularly bad roof conditions. The bedding surfaces of the folds are extensively slickensided as a result of flexural slip, which has
destroyed the cohesion between successive bedding planes. An associated problem is the local structural thickening and thinning of the seam associated with folding. Because of the highly sheared character of the coal it is not possible to hold coal in the roof. Consequently, in areas of structural thickening, the coal must be either completely removed or special supports emplaced. As in the case of faults, the occurrence of folds is unpredictable. Once located, however, the folds can be projected to adjacent roadways with confidence.

In several areas roof failure is associated with the occurrence of coal in the strata overlying the immediate roof rock. The coal seams provide poor anchorage for roof bolts and form major discontinuities. The coal is not evident in outcrop adjacent the mine site and may either represent a fault repeat of part of the Number 2 Seam or a separate seam of restricted lateral continuity.

BALMER NORTH, SIX PANEL AND FIVE PANEL MINES

The Balmer North, Six Panel and Five Panel mines are located at the north end of the Fernie synclinorium, a major structural element on the Lewis thrust plate (Fig. 1-2). The Fernie synclinorium is structurally discordant with the underlying Paleozoic strata (Dahlstrom, 1969) and is characterized by northerly trending, broad, open, doubly plunging folds with curved axial surfaces. The Balmer North mine is located on the west dipping flank of the gently south-plunging Natal syncline, whereas the Six Panel and Five Panel mines are located on the east dipping flank of the Michel
syncline (Fig. 3-9). Between the Michel and Natal synclines is a relatively low amplitude, faulted anticline. The eastern flank of the anticline is upthrown, with a stratigraphic separation on the order of 100 m, along two parallel high angle reverse faults which have been referred to as the Mackay fault(s) by Crabb (1962).

The Kootenay Formation in the region of the mine site is about 600 m thick and contains 11 coal seams ranging from 1 m to more than 12 m thick. The Balmer North, Six Panel and Five Panel mines are developed in the thickest and lowest seam of mineable thickness, referred to as the Balmer seam. Within the Balmer North mine the Balmer seam strikes 170° and dips between 15° and 40° to the west. In the northeastern part of the mine the seam dips gently to the east. In the Six Panel and Five Panel mines, the Balmer seam strikes approximately 178° and dips between 35° and 47° to the east. In all of the mines, henceforth referred to collectively as the Michel mines, the seam is being mined following the roof. The Balmer North mine and Six Panel mines are presently being mined using continuous miners, whereas in the Five Panel mine, hydraulic methods are used. Because of the mining method in the Five Panel mine and because the Six Panel mine is still in the development stage, observations were limited primarily to ventilation raises. The data collected in these mines are thus largely restricted to cleat measurements in the coal and joint measurements in the rock tunnels. In the Balmer North mine access to different areas was excellent and it was possible to obtain data from a number of partially caved areas. In the following discussion
the Balmer North, Six Panel and Five Panel mines are considered collectively because of their similar structural style and roof rock characteristics. More emphasis is placed, however, on observations in the Balmer North mine because of its greater accessibility.

**Roof Rock Characteristics**

**Lithology and Sedimentology:**

The immediate roof rock of the Balmer seam consists of highly carbonaceous shales, siltstones and mudstones. The contact between the Balmer seam and the roof rock is gradational over 0.5 m to 1.0 m in the Balmer North mine, whereas in the Six Panel and Five Panel mines the contact is more abrupt. Generally, however, there is no notable lateral variation in lithology of the roof rock at the scale of the mine.

In the Balmer North mine, the immediate roof rock consists of carbonaceous siltstones, shales and mudstones which pass upwards to thin- to thick-bedded, fine- to medium-grained sandstones with rare carbonaceous laminae. The sandstones are parallel to wavy bedded, whereas the mudstones and siltstones are primarily homogeneous. Locally, well preserved plant remains are present on the bedding planes of the mudstones.

In the Five Panel and Six Panel mines the roof rock consists of carbonaceous siltstones and shales that grade upward into thin- to medium-bedded, fine- to medium-grained sandstone. The shales, siltstones and sandstone are parallel to wavy bedded.

Similar to the Vicary Creek mine, little diagnostic
sedimentological evidence is provided by the roof rock in the Michel mines. The gradational contact between the Balmer seam and roof rock does, however, indicate gradual abandonment of the swamp areas and slower rates of clastic sediment influx compared to the more abrupt transitions in the Vicary Creek mine area.

Structural Fabric of the Coal and Roof Rock:

In the Michel mines the major mesoscopic structural fabric elements are extension faults, joints and cleat. Slickenside striae on bedding elements in the roof rock could be measured only at a few localities because of the height of the roof and the presence of thick rock dust.

Extension faults, although present throughout the mines, rarely have displacements exceeding 20 cm. The only major extension fault observed occurs in the northern part of the Balmer North mine. This fault dips steeply to the west and has a displacement of 1.5 m to 3 m. Figure 3-10 summarizes the slip linears, axes of slip and poles to extension faults with displacements greater than 5 cm. Although the orientation of faults show considerable scatter, the majority are parallel or sub-parallel to the fold axis (lie in h01). Most extension faults cut bedding at angles between 10° and 35° and have an angular rotation component of between 5° and 30°.

Jointing is pervasive in medium- to thick-bedded sandstones above the immediate roof rock and in the footwall strata of the Balmer seam throughout the Michel mines. The orientation of the joints measured at localities within the access rock tunnels to the mines are summarized in Fig. 3-9.
Figure 3-10. Balmer north mine. Summary diagram of poles (●), axes of slip (■) and slip linears (→) of extension faults following rotation of bedding to the horizontal.

Figure 3-11. Balmer North mine. Young, west dipping shear surface in coal rib.
The joints are planar, have no surface markings and impart a flaggy to blocky split to the rocks. In the Five Panel rock tunnel a well developed steep westerly dipping joint set which is parallel to the fold axis (h0l) is present at all three sample localities. In addition, at sample stations N and O, there is a prominent, nearly vertical joint set which lies in 0k0. At stations M and O joint sets lie in hko. In the Balmer North mine (station A), only one prominent joint set which lies in hko, is present. In the Six Panel mine (station T) the joint system is poorly developed.

Cleat:

Cleat, the naturally occurring fractures (joints) in coal, was measured at sample localities throughout the underground mines in order to determine if a consistent or predictable orientation exists and to interpret their origin. The importance of cleat orientation in mining practice is well documented. Coal has been mined parallel to the direction of the major cleat to take advantage of the preferred parting since the advent of coal mining. The orientation of the cleat system also results in a strong permeability anisotropy which is important in degassing the coal seam prior to mining (McCullock, et al., 1974; McCullock et al., 1976) and both the orientation and spacing of the cleat influence the bearing strength of coal pillars and the size-consist of run-of-the-mine coal (Touseull, 1977). In most coal seams two major cleat sets are recognized, which are referred to as face and butt cleat. The face cleat is the major fracture set within the coal seam whereas the butt
cleat is short, generally poorly defined, and commonly truncated at angles of about 90° by the face cleat. Invariably, the face and butt cleat have been reported to be perpendicular to bedding. Many of the previous studies on the origin and orientation of cleat have been summarized by McCulloch et al., (1974). The origin of cleat has been considered either endogenetic, related to compaction and coalification, or exogenetic, related to tectonic forces.

In the Michel mines the distinction and classification of cleat as face or butt is not possible. Cleat measurements, summarized in Fig. 3-9, show that at some localities up to five distinct sets of cleat is present, none of which are necessarily perpendicular to bedding, whereas at other localities, no distinct cleat sets are present.

In the Balmer North mine, both systematic and nonsystematic cleat sets occur at most sample localities (Fig. 3-9). The most prominent systematic cleat set (following rotation of bedding to the horizontal) dips between 5° and 15° to the west and lies in h0l. This cleat set is parallel to the major set of extension faults, has polished and commonly slickensided surfaces and truncates, and in some areas offsets, other cleat sets (Fig. 3-11). Other systematic cleat sets present at some localities include northeasterly and northwesterly trending sets which lie in hk0. The surface of these cleat sets are commonly polished, and locally there are radiating, striated structures somewhat resembling chevron marks occurring. Other well defined cleat sets occur at particular stations but are not represented at adjacent sites.
In the Five and Six Panel mines, a systematic cleat set is present at all sample localities. This cleat strikes north to northwesterly, and is perpendicular to sub-perpendicular to bedding (hk0 to hkl). It is planar, commonly polished and spaced at between 10 cm and 40 cm, imparting a blocky split to the coal. At least one additional systematic cleat set is present at most localities which strikes in a north to northeasterly direction, and is sub-perpendicular to bedding (hkl to hk0). The cleat sets are planar, but not always well developed, and their surfaces are commonly dull. Collectively, the cleat sets in the Five and Six Panel mines show little or no preferred orientation with respect to the fabric axis of the syncline. At many individual sample localities, however, the north and northeasterly striking cleat sets are symmetrically disposed such that the acute angle between them is bisected by the local ac fabric plane of the seam. The north to northwest striking cleat sets at most localities are close to parallel with the local b fabric direction of the seam as determined by the orientation of the roof rock.

**Kinematic Analysis**

Slip linears and axes of slip on cleat surfaces, together with the modal poles to systematic cleat sets following rotation of bedding to the horizontal, measured in the Balmer North mine, are shown in Fig. 3-12B through 3-12L; a composite of all slip axes on cleat surfaces and extension faults are shown in Fig. 3-13. Throughout the Balmer North mine slip linears on bedding and cleat surfaces define one major preferred orientation, more
Figure 3-12. Summary of axes of slip (■), slip linears (→), and modal poles to cleat sets (○) following rotation of bedding to the horizontal. Balmer North mine (stations B through L), Five Panel mine (station P) and Six Panel mine (stations Q, R, S, U, V, W, and X).
Figure 3-13. Balmer North mine. Summary of axes of slip on bedding surfaces and extension faults (•).
or less within the $ac$ fabric plane (deformational plane) of the fold; thus, the modal kinematic-$b$ axis during slip closely approximates the fold axis. Other slip linears show considerable scatter and do not define a preferred orientation. Also, they do not appear to be geometrically related either to the local or regional fabric axis of the seam. Slip linears and associated axes of slip of extension faults (Fig 3-10) in the Balmer North mine, considered in aggregate, indicate the presence of two poorly defined kinematic patterns. The first is defined by slip linears which are sub-parallel to the $ac$ plane of the fold, with axes of slip which diverge from the fold axis by up to $15^\circ$. The second pattern is also poorly defined and is characterized by slip linears which lie in $hkl$, trend in a more or less northerly direction and have axes of slip which plunge gently to the east. In the Five Panel and Six Panel mines, the slip linears and axes of slip (Fig. 3-12P through 3-12X) show one major preferred orientation of slip that closely parallels the $ac$ fabric plane, and has a modal kinematic-$b$ axis of slip which approximates the fold axis. Additional slip linears which lie in $hkl$ show a wide dispersion and are not readily related to either the geometry of the fold nor the local fabric axis of the seam.

The preferred orientation of slip linears and axes of slip in the Balmer North mine and in the Five and Six Panel mines are congruent with the geometry of the synclines, which suggests that a genetic relationship exists. All slip linears which are co-axial with the $ac$ deformation plane of the fold in the Balmer North mine, lie on the pervasive and best developed
cleat set, which dips gently to the southwest and cuts bedding at angles between 10° and 15°. The direction of motion can rarely be inferred from the slip linears but, where possible, they invariably suggest southwest transport of the hanging wall, parallel to that of some extension faults. Although the congruence of the axis of slip with the fold axis suggests a genetic relationship, the direction of motion and the parallelism with some extension faults in the roof strata suggests that they are incipient extension faults. Furthermore, the direction of motion is antithetic to that which would be predicted during flexural slip. In the Five and Six Panel mines slip linears sub-parallel to the \( ac \) deformation plane of the seam lie mainly on cleat surfaces which dip steeply to the east following rotation of bedding to the horizontal. If the cleat set formed late, however, the slip linears could have formed as westerly dipping shear surfaces. The direction of the motion of the hanging wall on these surfaces is unknown.

**Dynamics of Deformation**

The orientation of the major folds, including the Michel and Natal synclines and adjacent reverse and thrust faults in the region of the Michel mines indicates a consistent direction of shortening in a northeasterly direction. The geometric relationship between joint and cleat sets at the sample localities does not, however, suggest a consistent stress geometry during deformation. In Fig. 3-14A and 3-14B the acute bisectrices between all cleat sets showing some evidence of shear at localities in all the mines are plotted. If the shear
Figure 3-14A. Balmer North mine. Acute bisectrices of cleat sets which show some evidence of forming as a result of shear fracture.

Figure 3-14B. Five and Six Panel mines. Acute bisectrices of cleat sets which show some evidence of forming as a result of shear fracture.
surfaces are conjugate sets and related to the same stress geometry then their acute bisectrices should approximate $61^\circ$ (Stearns, 1968) and have a more or less consistent orientation, which is not the case. Furthermore, no simple rotation about any axis will decrease the observed dispersion.

The observed dispersion of the acute bisectrices at the different sample localities may reflect inhomogeneities of the strata and their anisotropy (Price, 1967; Curry and Reik, 1977), superimposed stress geometries resulting in a chaotic fabric or highly divergent stress fields. At most localities in the Five Panel and Six Panel mines conjugate cleat and joint sets are bisected by the locally defined $ac$ fabric plane of the seam determined from the local orientation of the roof rock. The cleat sets have polished surfaces which, in conjunction with their symmetry, suggests that they are conjugate shear fractures formed during brittle fracture with $61^\circ$ parallel to the local $a$ fabric direction similar to the type 1 fractures of Stearns (1968). The coincidence of the acute bisectrix of the conjugate cleat and joint sets further suggests that the fracture patterns are related to the local stress field of varying geometry rather than one overall stress field related to the general fold pattern. The north trending, nearly vertical cleat set present at most sample localities show considerable variation in orientation. These fracture surfaces rarely show evidence of displacement, suggesting an extensional origin. However, they are not singularly diagnostic of any particular stress geometry.

In the Balmer North mine, with the exception of the well-defined west dipping cleat set that parallels extension faults,
there is no consistent cleat or joint system among the sample localities. Furthermore, only at sample station L (Fig. 3-9L) is there any apparent geometric relationship between conjugate cleat sets and local fabric directions of the seam. At this locality the acute bisectrix between conjugate cleat sets is close to parallel to the local a fabric direction, which suggests that these sets are probably conjugate shear fractures. The orientation of $\theta_1$ for formation of the fractures is thus coincident with, and thus probably related to the stress geometry during local flexure of the seam. At other sample stations in the Balmer North mine there are no apparent geometric relationships between cleat and local fabric direction of the seam. Because of the diversity of cleat orientations at different localities, it is not possible to resolve the stress geometry at failure. Moreover, it cannot be established whether the present cleat pattern reflects multiple stress geometries and failure, or the effect of anisotropy of the coal resulting from more than one episode of fracture.

The slickensided major west-dipping cleat set present in the Balmer North mine and the steep east-dipping set in the Five and Six Panel mines both locally offset other cleat sets and, therefore are probably younger. As previously discussed, the coincidence of the axes of slip of the fracture surfaces, the fold axis and some extension faults suggests a genetic relationship exists. If these late-formed fractures are genetically related to folding and developed as a result of extension due to bending or buckling, these fractures should parallel the strike of the beds around the fold and their
orientation should change with the dip of the beds (Stearns, 1968). If, however, they are related to a late stage of extension and normal faulting, the fractures may have a similar orientation regardless of bedding orientation and dip. The orientation of bedding within the mines does not vary appreciably and thus neither of the above possibilities can be dismissed solely on the basis of the geometry. Most extension faults observed in this study and in studies by Norris (1958) and Sax (1946) cut bedding at preferred angles of $60^\circ$. The shear fractures and many extension faults in the Balmer North mine, however, occur at angles of $10^\circ$ to $30^\circ$ to bedding. Either such fractures and faults formed with a orientation oblique to the vertical and the fabric direction of the seam or the mechanical anisotropy of the coal measures facilitated formation of shear at a highly acute angle to bedding. Similar west dipping shear surfaces in the coal and westerly dipping extension faults have also been described by Norris (1964) from the now abandoned A-North mine developed in the A seam and, like the Balmer North mine, located in the Natal syncline. The A seam is stratigraphically much higher in the Kootenay Formation than the Balmer seam but, significantly, both the axes of slip and direction of motion of the extension faults in the A-North mine are nearly identical to those reported here from the Balmer North mine. The A-North mine was located in the hinge of the Natal syncline and the seam and the strata strike about $100^\circ$. The similar orientation of extension faults and orientation of shear surfaces in the coal between the A-North and Balmer North mines, even though the strike of coal measures is markedly
different, strongly suggests that the extension faults and west dipping shear surfaces are not genetically related to folding but rather, that they are late formed structures related to regional extension.

**Geological Factors Affecting Roof Conditions**

The accessibility of partially caved areas in the Balmer North mine afforded an excellent opportunity to assess those geological factors affecting roof stability. In the Six Panel mine, which is under development, no observations of poor roof conditions were made and in the Five Panel mine observations of poor roof conditions could only be made at a distance.

In the Balmer North mine areas of poor roof conditions and partially caved areas characteristically occur as narrow, northeasterly trending zones. In the caved areas roof rock fractures which were kinematically active and control the geometry of roof failure, are summarized in Fig. 3-15. Roof failure is controlled by three distinct structural discontinuities in the roof rock: 1) an easterly dipping set of slickensided fractures which intersect bedding at angles between 5° and 30°; 2) a westerly dipping set of slickensided fractures which cut bedding at preferred angles of 10° to 40°; and 3) slickensided bedding surfaces. Most roof failures or partings of roof rock have occurred along the intersection of these structural discontinuities. Particularly important is the intersection of bedding and the westerly dipping fracture set. The caved areas are invariably parallel to the strike of the westerly dipping set (Fig. 3-16) and the dip of the fractures,
Figure 3-15. Balmer North mine. Summary of poles to fractures (●) which have facilitated roof failure and control the geometry of caves in the roof rock and failure of coal pillars. Pole to bedding (■).
Figure 3-16A. Balmer North mine. Partially caved roadway; low angle, westerly dipping shear surfaces in conjunction with steep, easterly dipping shear surfaces and slickensided bedding planes have promoted caving and control the geometry of caves.

Figure 3-16B Caved roof rock showing west and east dipping shear surfaces along which the roof rock has separated.
in conjunction with the width of the roadways and raises, control the size of many of the caved areas. Other areas of major roof problems in the Balmer North mine are solely related to the absence of cohesion between successive bedding planes resulting from interstratal slip and the presence of incompetent strata in the immediate roof rock of the seam. In these areas the lack of cohesion between successive beds has resulted in poor anchorage of roof bolts which, in conjunction with joint planes and steeply dipping fractures, has facilitated en masse failure of roof rock (Fig. 3-17). Failure of coal ribs is also closely related to cleat orientation in the Balmer North mine. In roadways parallel to the strike of the pervasive west dipping cleat set, the ribs have sloughed or failed along these fracture surfaces (Fig. 3-11). Failure of the coal ribs is less common along roadways or raises oblique to the major cleat sets; where failure has occurred it is generally along induced 'rupture' fractures which are rough, curviplanar surfaces similar to the ruptured fracture surfaces of Deenen (1942).

In the Five Panel mine observations made at a considerable distance from partially caved areas suggest that roof failure is largely controlled by steep east dipping shear surfaces and their intersection with slickensided bedding surfaces. Because the shear surfaces dip at high angles, the caves appear to be areally smaller and restricted more laterally than those examined in the Balmer North mine.

DISCUSSION AND CONCLUSIONS

Norris (1958, 1964, 1966) documented notable differences
Figure 3-17A. Balmer North mine. Partially caved entry; slickensided bedding surfaces have promoted separation of the roof rock along bedding planes. Packsack in the roadway for scale.

Figure 3-17B. Unsupporting roof bolt in caved entry. The steeply dipping shear surfaces have facilitated failure of the roof rock. Conventional roof bolts provide little support with such steeply dipping fractures.
in the structural conditions of Canadian coal mines. He was able to demonstrate that where the coal measures were only mildly deformed such as in the Drumheller coal area (central Alberta) and the Springhill, Joggins and Sydney coal areas (Nova Scotia), the cleat system and primary sedimentary structures were intact and there was no appreciable interstratal slip related to deformation. In mines of the southern Canadian Cordillera (now abandoned) Norris demonstrated that the coal seams were highly deformed as a result of differential movement between roof and floor strata and that extension faults were common, much more so than contraction faults. Norris further concluded that deformation of coal seams in different areas of the southeastern Cordillera are nearly identical despite differences in regional setting (Norris, 1958).

The results of this study generally concur with the findings of Norris (1958, 1964, 1966). The Vicary Creek mine and the Michel mines have different structural settings, yet they are all characterized by the prominence of extension faults and by major structural discontinuities in the roof rock in the form of slickensided bedding surfaces. Fundamental differences do exist however, between the mines. In the Vicary Creek mine the coal has been highly sheared and comminuted; a number of folds occur in the roof strata and the roof rock throughout most of the mine has been extensively sheared as a result of interstratal slip. In the Michel mines, on the other hand, the cleat system is intact, the roof rock is less extensively sheared and the roof conditions are a product largely of late formed shear fractures and extension faults. Such differences
are the result of not only the structural settings of the mines, but also more particularly, the extent of shortening and interstratal slip of the coal measures. In the Michel mines interstratal slip is probably completely the result of flexural slip folding of the broad, open Michel and Natal synclines, whereas in the Vicary Creek mine, in addition to flexural slip, a component of slip is probably related to drag (simple shear) from overriding thrust faults, as described earlier.

Furthermore, in the Vicary Creek area, the Kootenay Formation is thin and the Number 2 Seam is essentially the only major incompetent bed in the stratigraphic succession and may, therefore, represent the locus of slip as compared to the Kootenay Formation in the region of the Michel mines which is much thicker and contains 11 major seams of coal. The greater thickness of the Balmer seam in the Michel mines compared with the Number 2 Seam in the Vicary Creek mine cannot solely account for the observed contrast in conditions. The thicker seam should theoretically experience a greater degree of flexural slip between roof and floor strata during folding or buckling (Ramsay, 1967) which is the opposite of that observed.

Marked lithologic variations and sedimentary discontinuities such as documented in the roof strata of many mines (Diessel and Moelle, 1965; Donaldson, 1977; Horne et al., 1978; Krausse et al., 1979) are not evident in the Vicary Creek or Michel mines. The subtle variations in lithology that are present, however, strongly influence the response of the roof strata and the seam to deformation. The interrelationship between lithology and extent of deformation is particularly
evident in the Vicary Creek mine where contrasting roof conditions are related to the response of the different roof rock lithologies to the same stress system, viz. the development of platy roof rock in thin-bedded carbonaceous sediments which facilitated interstratal slip, and the formation of a jointed, blocky roof rock in thick-bedded, coarse-grained sediments which were more amenable to jointing. The absence of marked variations in roof rock lithologies in the Vicary Creek mine is probably largely a result of the scale of the mining operations. In outcrop and in abandoned strip mines, marked variations in lithology, attributable to channeling, are evident. In the roof rock of the Balmer seam the absence of major lithologic variations likely reflect deposition on a wide, sediment starved, delta plain which facilitated continuous deposition of peat for long periods of time. The gradational contact between seam and roof rock also attests to slow abandonment of the swamp as compared to rapid flooding and channeling conditions conducive to formation of heterogeneous roof rock (Horne et al., 1978). Such a depositional environment for the Balmer seam is supported by the great lateral continuity and homogeneity of the underlying sandstone unit, which is more than 384 km in length and at least 160 km in width (Gibson, 1977).

In the studied mines, many of the structural fabric elements of the roof rock can be readily related to the kinematics and dynamics of deformation of the coal measures. However, the geological factors affecting roof conditions and mineability of the coal seam can be predicted only in a general sense. In the Vicary Creek Mine, even though deformation of the
roof rock and coal seam is largely congruent with the regional structural environment it is not possible to predict the subtle variations in lithology of the roof rock or occurrences and location of folds and extension faults, all of which markedly affect roof conditions. It is, however, reasonable to predict both from the Vicary Creek Mine and other, now abandoned mines, (Norris, 1958) that mines developed in similar structural settings will be characterized by: 1) pervasively sheared coal of low bearing strength; 2) profusion of extension faults of varied orientations and displacements; 3) highly sheared and incoherent roof rock which will provide poor anchorage for normal roof bolts; and 4) variations in roof rock lithologies which, if present, will markedly influence roof conditions. Once major roadways are developed it should further be possible to map the location of folds and predict their trends, map lithologic variations in the roof rock and designate areas in which swarms of extension faults may occur.

In the Michel mines it is not possible to predict the orientation of cleat or joint systems in the adjacent sandstones from regional or local structure. The cleat pattern, particularly in the Balmer North mine, appears to reflect a much more complicated stress pattern than would be predicted from the broad, open folding of the area. Pervasive shear fractures in the coal and roof rock, which are apparently late structures, in conjunction with slickensided bedding surfaces, control the geometry of caves and roof instability in the mines. These structures show little variation in orientation throughout the mines. Orientation of roadways and ventilation raises oblique
rather than parallel to the strike of such structures would markedly increase the roof stability and bearing strength of coal pillars. Similar to the Vicary Creek mine, it is not possible to predict the location of extension faults. Comparable roof conditions in mines of similar structural setting as the Michel mines would be difficult to predict; the dynamics of the deformation resulting in formation of late shear fractures and extension faults which affect the roof conditions is unknown. Flexural slip accompanying folding and resulting in loss of cohesion between successive beds of roof strata can be predicted to occur in almost all coal mines in the eastern Canadian Cordillera. The intensity of interstratal slip is paramount in determining roof conditions and character of the coal in all of the mines studied.
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References


PART 3

EFFECT OF SHEAR ON COAL QUALITY AND RANK: TEMPERATURES ASSOCIATED WITH SHEAR ZONES AND SOME IMPLICATIONS REGARDING FAULT MECHANICS IN THE SOUTHERN ROCKY MOUNTAINS OF BRITISH COLUMBIA AND ALBERTA
ABSTRACT

Coal seams of the Late Jurassic-Early Cretaceous Kootenay Formation are extensively sheared in parts of the southern Rocky Mountains of British Columbia and Alberta. The coal seams were the loci of interstratal slip during flexural slip folding, and major-thrust faults, reverse and normal faults are localized in the coal seams or transect the seams at low angles. The mesoscopic fabric of the seams is cataclastic. Microscopically, there is evidence for local ductile behavior of the clarite component of the coal.

Measurements of vitrinite reflectance of coal in some shear zones suggest, by comparison with samples of coal heated in the laboratory for short durations, that frictional heating may have resulted locally in temperatures of up to 450°C. Adjacent to and within other shear zones, however, there is no evidence of frictional heating. The presence or absence of frictional heating is considered the result, respectively, of stick-slip and stable sliding conditions during faulting. The results imply that regions of significant and less significant effective stress may exist along some thrust and reverse faults. This supports the Hubbert and Rubey hypothesis of high pore fluid pressure facilitating overthrust faulting. In addition, however, to areas of low effective stress, areas of higher effective stress exist which may reflect loss of high fluid pressures. High temperatures calculated along the Coleman Fault occur in a region in which the fault is folded and a slice of Crowsnest Volcanics has been dragged up along the fault plane. Such areas where faults rapidly cut up section are probably
regions of stress concentration and adjacent fractured and faulted rocks may facilitate dissipation of high fluid pressure.

The thermal effects of shearing on coal quality are insignificant. Mechanical granulation as a result of shear of the coal and associated rock partings and interbeds of sandstone and shale result in disproportionately high ash contents, poor washability characteristics and rapid oxidation of the coal.
INTRODUCTION

Complex folding and faulting of the Late Jurassic-Early Cretaceous Kootenay Formation in the southern Canadian Rocky Mountains was facilitated by the presence of thick seams of incompetent coal. The coal seams were the loci for interstratal slip during flexural slip folding, and major thrust, reverse and normal faults are localized within the coal seams or transect the seams at low angles. To accommodate deformation, the coal, on a mesoscopic scale, either flowed cataclastically along a myriad of diffuse shear surfaces or was transported en mass along a few discrete shear planes. Tectonic transport of the coal in some areas has produced substantially thickened coal deposits, some of which are presently being mined.

Extensively sheared coal, particularly where tectonically thickened, comprises a large proportion of the coal reserves in the southern Canadian Rocky Mountains. The primary purposes of this study were to describe and define the mesoscopic and microscopic fabric of the highly sheared coal and to evaluate the effect of shear on coal quality. The multitude of shear zones within the coal seams and the occurrence of coal in the immediate footwall or hanging wall of, as well as within, major fault planes also provided an excellent opportunity to assess, by measurement of coal rank, whether or not any thermal affects are associated with faulting.

Previous studies by Teichmuller and Teichmuller (1966) demonstrated that a local rise in coal rank was associated with the Sutan overthrust fault in the Ruhr Basin. Ghosh (1970) described a significant increase in rank in tectonically
disturbed parts of coal seams in Lower Gondwana coal of the Darjeeling-Himalaya. Both of these studies attributed the local increase in rank to frictional heating during deformation and both documented an associated increase in the optical anisotropy of the vitrinite component of coal adjacent to shear zones. Frictional heating along fault zones has been considered theoretically by McKenzie and Brune (1972), Cardwell et al., (1978), Moore and Sibson (1978) and others. Cardwell et al., (1978) calculated temperature distributions during and after faulting for faults of finite width and McKenzie and Brune (1972) obtained solutions for planar faults. Frictional heating along subduction zones has been considered theoretically by Toksoz and Bird (1977), Bird (1978) and many others. On some fault planes in metamorphic terrains, the presence of pseudotachylite or hyalcmylonite, which show some evidence for flow indicate that, at least locally, melting has occurred (Scott and Drever, 1954; Philpots, 1964; Ermanovics et al., 1972; Masch, 1973; Wallace, 1976). In some frictional sliding experiments of sandstone on limestone (Friedman et al., 1974; Tuelfel and Logan, 1976), melting has apparently occurred and high temperatures have been documented (Bowden and Tabor, 1950). Most faults, however, show no evidence of melting or of high temperatures.

Because the sensitivity of coal to temperature change is much greater than that of common minerals it is an ideal rock with which to assess what thermal affects, if any, are associated with faulting. The use of coal rank measurements as an index to thermal metamorphism is well documented (Dutcher, et
Although some differences of opinion exist, it is generally accepted that the coalification process is governed primarily by rise in temperature and the time during which this occurs. The affect of time and temperature on coalification has been demonstrated experimentally (Karweil, 1956; Huck and Patteisky, 1964; Chandra, 1965a) by examination of deep bore-holes of known temperature (Castano and Sparks, 1974; Bostick et al., 1979) and metamorphic and intrusive aureoles (Bostick, 1973). Pressure, although responsible for compaction and reduction of moisture in low rank coals and anisotropy in higher rank coals, is not considered an important factor in coalification. Huck and Patteisky (1964) and others have suggested that pressure may actually retard coalification. Bostick (1973) found in hydrothermal experiments that there was no change in the degree of coalification when pressures were varied between $2.05 \times 10^4$ kPa and $1.105 \times 10^5$ kPa at constant temperatures. The effect of shear stress on coal rank has received little study. Teichmuller (1968) and Taylor (1971) have postulated that shear stress may facilitate formation of graphite at lower temperatures than generally considered necessary for its formation.

In this study samples of coal were collected specifically to evaluate the effects of shear on coal rank and quality and to evaluate the temperatures associated with shearing. Samples of pervasively sheared coal were collected within coal seams, from adjacent major thrust and reverse faults and from isoclinally folded seams in the Kootenay Formation at Tent Mountain and Vicary Creek (Fig. 1-2). Wherever possible, samples were
collected incrementally away from the fault planes.

Because part of the purpose of this study was to evaluate temperatures associated with shearing, it was also necessary to establish the sensitivity of changes in coal rank to different temperatures and durations of heating. Previous studies by Chandra and Bond (1956), Bostick (1973) and others established change in coal rank with temperature for periods of heating of a few hours to several months. Preliminary measurements and theoretical considerations suggest, however, that if heating was taking place, it was of very short duration. It was therefore necessary to heat coal samples experimentally for very short durations and for a variety of temperatures. It was also advantageous to obtain experimental data for coal within the study area since change in rank is not linear with temperature for coal of different ranks.

EXPERIMENTAL PROCEDURE AND ANALYTICAL TECHNIQUES

In order to assess the change in coal rank with temperature and duration of heating a large sample of vitrain-rich medium-volatile bituminous coal was collected from an adit within the study area. The sample was crushed to -20 mesh U.S. Standard sieve size and split into sub-samples. Each sub-sample was placed in a 25 ml ampoule which was then thoroughly flushed with nitrogen, partially evacuated and sealed. The sub-samples were then heated in a furnace for times ranging from 10 minutes to several days and at temperatures ranging from 100°C to 600°C.

Some field samples were also crushed to -20 mesh whereas other samples were impregnated with epoxy for examination of the
fabric. Inorganic material in some samples was removed prior to sample preparation by liquid separation techniques using a zinc-chloride solution or tetrachloroethylene with a density of 1.60 gm cm\(^{-3}\). The crushed and treated samples were then formed into pellets using Trans-optic powder as described by Bustin et al., (1977). All the samples were polished to a final grit size of 0.02 um.

Measurements of coal rank were made using the vitrinite reflectance method following the procedures outlined by Bustin et al., (1977). A Leitz MPV 1 microscope equipped with a photomultiplier, stable voltage supply and digital readout were used. The microscope was equipped with a polarized halogen light, a narrow band filter at 546 nm wavelength and a 50x oil immersion objective with an 8 um effective aperture. Standardization of the photomultiplier was with a glass standard of 1.01% Ro. Whenever possible, at least 50 measurements were made per sample and both the maximum and minimum reflectance were recorded in order to establish the degree of anisotropy of the vitrinite.

Measurement of vitrinite reflectance to establish the degree of coalification (rank) is well documented (see McCartney and Teichmuller, 1972). In this study the use of vitrinite reflectance to determine rank had a number of advantages over other methods: (1) because the method was performed microscopically it was possible to analyze samples with abundant inorganic material which otherwise would have had to be completely separated; (2) it was possible to make multiple measurements on blocks of sheared coal; and (3) it was possible
to analyze very small amounts of coal such as are present in some fault planes.

**Sensitivity of coal rank to heating for short duration**

The maximum reflectances of samples heated for 10 minutes, 1 hour, 4 hours, and 7 hours for different temperatures are summarized in Figs. 4-1, 4-2, 4-3 and 4-4. All the samples heated to temperatures of 200°C and greater show a statistically significant increase in mean reflectance regardless of heating duration. A sample heated at 160°C for 7 hours showed no statistically significant increase in mean reflectance. An excellent correlation exists between increasing temperature and mean reflectance for each of the heating durations. The only notable exception is the sample heated to 280°C for 7 hours (Fig. 4-4) which has the same reflectance as a sample heated to 200°C for the same duration. The lower vitrinite reflectance of the sample heated to the higher temperatures cannot be explained.

The rate of change of vitrinite reflectance with increasing temperature is nearly linear for all heating durations up to about 400°C. Between 400°C and 600°C there is an exponential increase in reflectance with increasing temperature. This jump in reflectance corresponds to the onset

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1 All reported statistics are at the 99% confidence level using Students 't' test.
Figure 4-1. Maximum vitrinite reflectance values for coal samples heated in the laboratory for 10 minutes at the indicated temperatures. The distribution, mean and standard deviation of measured values for each sample are shown.
Figure 4-2. Maximum vitrinite reflectance values for coal samples heated in the laboratory for 1 hour at the indicated temperatures. The distribution, mean and standard deviation of measured values for each sample are shown.
Figure 4-3. Maximum vitrinite reflectance values for coal samples heated in the laboratory for 4 hours at the indicated temperatures. The distribution, mean and standard deviation of measured values for each sample are shown.
Figure 4-4. Maximum vitrinite reflectance values for coal samples heated in the laboratory for 7 hours at the indicated temperatures. The distribution, mean and standard deviation of measured values for each sample are show,
of melting of the coal (420-450°C). Figure 4-5 which summarizes the data presented in Figs. 4-1, 2, 3 and 4, shows the effects of heating durations at constant temperature on vitrinite reflectance of the coal. Below 500°C the duration of heating has little effect on the mean maximum reflectance of the coal. At 500°C there is a marked increase in reflectance with heating duration; and the sample heated to 600°C for 10 minutes has lower mean reflectance than the sample heated at 500°C for 1 hour. In Fig. 4-6 some of the data from this study are compared with reflectance and temperature data from bore-hole samples and laboratory analysis compiled by Bostick (1973). This figure demonstrates the importance of heating duration on vitrinite reflectance for any given temperature. Other laboratory studies show similar results (Chandra and Bond, 1956; Taylor, 1961; Ghosh, 1967). In general it can be concluded that very short heating durations, such as those in this study, result in lower reflectances for a given heating temperature than longer heating durations. However, with different very short heating durations, as used in this study, the reflectances for a constant temperature are only notably different at high temperatures. It is also evident that with medium-volatile bituminous coal heating below 200°C for short durations has no detectable effect on coal rank as measured by vitrinite reflectance.

One of the most notable features of the experimentally heated coals of this study is the large increase in variance of the reflectance measurements with increased temperature and the associated increase in mean anisotropy of the vitrinite.
Figure 4-5. Summary diagram showing the variation in mean reflectance and standard deviation for samples heated at indicated temperatures and durations.
Figure 4-6. Mean maximum vitrinite reflectance of dispersed organic material and coal from bore holes and laboratory heated samples (modified from compilation of Bostick, 1973) compared with samples heated in the laboratory for 10 minutes and 7 hours in this study at the indicated temperatures. O=central eastern Oklahoma, Pennsylvanian, 900 to 3700 m; W=LaSalle County, southwestern Texas, Jurassic, 4000 to 6100 m; E=Angelina County, eastern Texas, Early Cretaceous, 1200 to 3400 m; S=Salton geothermal field, California, Late Pliocene and Pleistocene, 210 2500 m; L=Cameron Parish, Louisiana, Early Miocene, 2500 to 4600 m; M=Munsterland No. 1 well, northwestern Germany, Carboniferous, 1600 to 4520 m; V=Volga region, USSR, Middle Devonian to Middle Carboniferous, 108 to 4060 m; OR=Upper Rhine graben, Germany, Tertiary and Quaternary; T=Terresbonne Parish Florida, Middle Miocene. 5440 m; H=bomb samples, $1.36 \times 10^5$ kPa, 30 to 45 minutes.
The increase in variance and anisotropy are not independent, as suggested by the correlation between Figs. 4-7 and 4-8. Such a large variance and anisotropy is not characteristic of normal coal with the same mean maximum reflectance and probably is the result of different reaction rates of the vitrinite. Such large variances and anisotropies are not evident with longer heating durations. The large variance and anisotropy are not considered to be the result of non-uniform heating because the samples heated for 7 hours have similar variances as samples heated for 10 minutes.

MESOSCOPIC AND MICROSCOPIC FABRIC OF THE SHEARED COAL

Deformation and shearing of coal seams in the study area has been in response to folding, faulting, and interstratal slip. Almost all the examined coal seams show some evidence of shear and in some areas the primary stratification and systematic cleat, if ever present, have been largely destroyed. On a mesoscopic scale, the coal seams have a cataclastic-brecciated fabric consisting of highly fragmented and rotated blocks of coal. Adjacent to some major faults and in areas of intense deformation the coal is finely comminuted (Fig. 4-9). Both the larger blocks and the finely granulated coal are extensively polished. More competent beds of dull coal and interbeds and partings of sandstone and shale are commonly less fragmented (Fig. 4-10), although in highly deformed seams they too are finely granulated.

Shear planes cross-cutting or within the coal seams are most commonly represented by either polished surfaces on blocks
Figure 4-7. Standard deviation of mean maximum reflectance of laboratory heated samples.

Figure 4-8. Mean maximum minus mean minimum reflectance (as measured) of samples heated in the laboratory. Legend is the same as that in Fig. 4-7.
Figure 4-9A. Finely comminuted coal seam in a shear zone. Notice the more finely comminuted coal at the base, top and center of the seam. Pencil for scale.

Figure 4-9B. Pervasively sheared and polished coal. The coarser, folded clasts are more competent, dull, durain rich coal.
Figure 4-10A. Pervasively sheared and polished coal. The thick unsheared and rotated blocks are dull, durain rich coal.

Figure 4-10B. Pervasively sheared coal with a large sandstone inclusion. The inclusion has apparently been introduced into the seam as a result of shearing of the roof rock during interstratal slip.
of coal or by planar or curvi-planar bands of finely granulated coal in a coarser-grained groundmass (Fig. 4-9A). In many areas, such as shown in Fig. 4-9B, distinct shear surfaces are not evident, yet the coal is intensely polished and brecciated and markedly varies in thickness over short distances. In such areas the coal has apparently failed as a brittle material and flowed cataclastically along a multitude of diffuse shear planes. At some localities continued deformation or successive stages of deformation have further complicated the fabric of the coal.

Highly fragmented coal, adjacent to and within major shear planes, is commonly foliated parallel to the shear plane. In some areas such as shown in Figs. 4-11 and 12, the coal present within the fault plane (fault gouge) has been dragged up the fault for distances which locally must exceed tens of metres. The foliation of the coal is probably a result of granulation and rotation of the coarser coal clasts during slip.

The microfabric of the sheared coal is generally similar to the mesoscopic fabric, consisting of angular, brecciated fragments of coal without evidence of ductile behavior. Locally, in areas of apparently high shear strain, the clarite component of the coal has behaved ductily, flowing and engulfing adjacent fragments of inertite and ash which underwent brittle failure (Fig. 4-13). Ductile behavior of the clarite component of the coal is also evident in microfolds of similar style and 'wild' folds (Fig. 4-14). The optic axes of the brecciated fragments do not define a common orientation as was found by Smyth (1968) in brecciated coals of the Tomago coal measures,
Figure 4-11. Thrust contact between dark-brown-gray shales and siltstones of the Fernie Formation (above hammer head) and pervasively sheared and granulated coal of the Kootenay Formation (below). Stratigraphic separation across fault is about 600 m.

Figure 4-12. Foliated coal which has been injected into the plane of a normal fault. The 'dike' is orientated almost perpendicular to bedding.
Figure 4-13. S.E.M. photomicrograph of an aggregate of vitrite, clarite and fusite from a shear zone. x 400.

Figure 4-14. S.E.M. photomicrograph of a 'wild' fold developed in clarite, x 40.
which suggests that the maximum obtained degree of coalification was preceeded by at least some rotation of the clasts. Ribbon-like and vesicular structures, such as described by Ghosh (1970) from highly deformed coals from the Darjeeling-Himalaya, are not evident. However, if such structures had formed they would undoubtedly have been destroyed as a result of repeated shearing and comminution of the coal.

VITRINITE REFLECTANCE OF THE SHEARED COAL

The vitrinite reflectances of sheared coal and adjacent unsheared coal from 28 different localities are tabulated and briefly described in Fig. 4-15. Significant anomalously high vitrinite reflectance of the sheared coal as compared with unsheared coal occurs at localities 2, 5, 8, 24, 25, 27 and 28 (Fig. 4-15). At some locations (such as localities 6 and 10) the sheared coal has a slightly lower mean reflectance than the unsheared coal. Such coal has evidently not been exposed to high temperatures and the lower than normal reflectance may be a product of in-seam variability or, more likely, the result of oxidation, which tends to slightly lower the reflectance and has occurred preferentially in the finely comminuted sheared coal.

High mean maximum reflectance values were obtained from samples collected immediately adjacent to faults as well as samples collected at some distance from the actual hanging wall but within the coal fault gouge. At locality 24 anomalously high values are separated by intervening lower values.

The sheared coal samples with anomalously high vitrinite reflectances are not macroscopically distinguishable from those
<table>
<thead>
<tr>
<th>LOCALITY</th>
<th>LOCALITY DESCRIPTION</th>
<th>NORMAL REFLECTANCE</th>
<th>SHEARED COAL REFLECTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Adjacent thrust in upper part of Kootenay Fm. with a stratigraphic separation of about 1500 m. Tent Mtn.</td>
<td>0.86 ± 0.06</td>
<td>adjacent fault 0.85 ± 0.065</td>
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<td></td>
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<td></td>
<td>10 cm below 0.86 ± 0.066</td>
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<td></td>
<td>30 cm below 0.92 ± 0.07</td>
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<td></td>
<td>4 m below 0.89 ± 0.055</td>
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<td>2.</td>
<td>Adjacent thrust in lower Kootenay Fm. with stratigraphic separation of about 200 m. Tent Mtn.</td>
<td>1.09 ± 0.08</td>
<td>adjacent fault 1.35 ± 0.28</td>
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<td></td>
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<td>adjacent fault 1.32 ± 0.25</td>
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<td></td>
<td></td>
<td>1 m below 1.04 ± 0.06</td>
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<tr>
<td>3.</td>
<td>Hinge area tightly folded seam in upper Kootenay Fm. Tent Mtn.</td>
<td>unknown</td>
<td>hinge area 1.02 ± 0.60</td>
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<td></td>
<td></td>
<td></td>
<td>hinge area 0.93 ± 0.60</td>
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<td>limb 0.89 ± 0.04</td>
</tr>
<tr>
<td>4.</td>
<td>Hinge area tightly folded seam in upper Kootenay Fm. Tent Mtn.</td>
<td>unknown</td>
<td>hinge 0.92 ± 0.06</td>
</tr>
<tr>
<td>5.</td>
<td>Sheared coal seam, lower Kootenay Fm. Displacement unknown, Tent Mtn.</td>
<td>0.93 ± 0.03</td>
<td>from sheared 1.18 ± 0.30</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>portion of seam</td>
</tr>
<tr>
<td>6.</td>
<td>Sheared coal seam, middle portion of Kootenay Fm. Tent Mtn. Displacement unknown.</td>
<td>1.04 ± 0.07</td>
<td>from sheared 1.01 ± 0.10</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>portion of seam</td>
</tr>
<tr>
<td>7.</td>
<td>Sheared coal seam, lower Kootenay Fm., Tent Mtn. Displacement unknown.</td>
<td>1.08 ± 0.08</td>
<td>from sheared 1.02 ± 0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>portion of seam</td>
</tr>
<tr>
<td>8.</td>
<td>Sheared coal within fault plane with about 10s of meters of displacement, lower-middle Kootenay Fm. Tent Mtn.</td>
<td>0.97 ± 0.06</td>
<td>adjacent fault 1.10 ± 0.06</td>
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<td></td>
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<td></td>
<td>adjacent fault 1.10 ± 0.07</td>
</tr>
<tr>
<td>9.</td>
<td>Sheared coal within coal seam as a result of interstratal slip, upper Kootenay Fm. Tent Mtn.</td>
<td>0.97 ± 0.06</td>
<td>adjacent roof 1.03 ± 0.08</td>
</tr>
</tbody>
</table>

Figure 4-15. Summary table of mean maximum reflectance and standard deviation of sheared coal from fault planes and folds and unsheared coal (where available) from adjacent localities.
<table>
<thead>
<tr>
<th>LOCALITY</th>
<th>LOCALITY DESCRIPTION</th>
<th>NORMAL REFLECTANCE</th>
<th>SHEARED COAL REFLECTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.</td>
<td>Tightly folded coal seam largely sheared, upper Kootenay Fm. Tent Mtn.</td>
<td>0.97 ± 0.06</td>
<td>hinge area 0.94 ± 0.05</td>
</tr>
<tr>
<td>11.</td>
<td>Adjacent thrust in upper part Kootenay Fm. Tent Mtn. Stratigraphic separation is about 600 m. Refer to Fig. 4-11.</td>
<td>0.97 ± 0.06</td>
<td>adjacent fault 0.95 ± 0.06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 cm below 0.95 ± 0.09</td>
<td>25 cm below 1.00 ± 0.07</td>
</tr>
<tr>
<td>12.</td>
<td>Tightly folded and sheared coal, upper Kootenay Fm. Tent Mtn. Locality shown in Fig. 4-9B.</td>
<td>0.97 ± 0.06</td>
<td>synclinal 0.98 ± 0.05</td>
</tr>
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<td></td>
<td></td>
<td>hinge</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Adjacent thrust in lower Kootenay Fm. Tent Mtn. Stratigraphic separation is about 30 m.</td>
<td>unknown</td>
<td>adjacent fault 1.08 ± 0.06</td>
</tr>
<tr>
<td>14.</td>
<td>Sheared coal from within a coal seam, lower Kootenay Fm. Tent Mtn. Displacement (interstratal slip) unknown.</td>
<td>unknown</td>
<td>within seam 1.00 ± 0.05</td>
</tr>
<tr>
<td>15.</td>
<td>Sheared coal adjacent reverse fault with 2 m displacement, lower Kootenay Fm., Tent Mtn.</td>
<td>unknown</td>
<td>adjacent fault 1.03 ± 0.06</td>
</tr>
<tr>
<td>16.</td>
<td>Sheared coal within a coal seam lower Kootenay Fm., Tent Mtn. Displacement (interstratal slip) unknown.</td>
<td>unknown</td>
<td>within seam 1.01 ± 0.07</td>
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<td></td>
<td></td>
<td>within seam 0.92 ± 0.09</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Adjacent reverse fault upper Kootenay Fm., Tent Mtn. Displacement less than several metres.</td>
<td>unknown</td>
<td>adjacent fault 0.92 ± 0.11</td>
</tr>
</tbody>
</table>

Figure 4-15 continued
<table>
<thead>
<tr>
<th>LOCALITY</th>
<th>LOCALITY DESCRIPTION</th>
<th>NORMAL REFLECTANCE</th>
<th>SHEARED COAL REFLECTANCE</th>
</tr>
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<tbody>
<tr>
<td>18.</td>
<td>Adjacent reverse fault, lower Kootenay Fm., Tent Mtn. Displacement unknown</td>
<td>unknown</td>
<td>adjacent fault 1.10 ± 0.04</td>
</tr>
<tr>
<td>19.</td>
<td>Adjacent reverse fault, upper Kootenay Fm., Tent Mtn. Displacement 10s of metres.</td>
<td>unknown</td>
<td>adjacent fault 0.82 ± 0.05</td>
</tr>
<tr>
<td>20.</td>
<td>Adjacent thrust in upper Kootenay Fm., Tent Mtn. Stratigraphic separation 600 to 700 m.</td>
<td>unknown</td>
<td>adjacent fault 0.94 ± 0.04</td>
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<td></td>
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<td>adjacent fault 0.85 ± 0.10</td>
</tr>
<tr>
<td>21.</td>
<td>Adjacent reverse fault upper Kootenay Fm., Tent Mtn. Displacement unknown.</td>
<td>unknown</td>
<td>adjacent fault 1.04 ± 0.11</td>
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<td>adjacent fault 0.84 ± 0.11</td>
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<td>adjacent fault 0.88 ± 0.07</td>
</tr>
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<td>22.</td>
<td>Adjacent thrust in lower Kootenay Fm., Tent Mtn. stratigraphic separation about 20 m.</td>
<td>1.00 ± 0.06</td>
<td>adjacent fault 1.01 ± 0.06</td>
</tr>
<tr>
<td>23.</td>
<td>Adjacent thrust in lower Kootenay Fm., Vicary Creek. Displacement unknown. Stratigraphic separation 10s of metres.</td>
<td>1.09 ± 0.12</td>
<td>adjacent fault 1.25 ± 0.26</td>
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<tr>
<td></td>
<td></td>
<td>1.20 ± 0.10</td>
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</tr>
<tr>
<td>24.</td>
<td>Adjacent and within Coleman Fault plane, Wintering Creek north of Vicary Creek. Stratigraphic separation about 2500 m.</td>
<td>1.21 ± 0.12</td>
<td>adjacent fault 1.25 ± 0.26</td>
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<tr>
<td></td>
<td></td>
<td>1.08 ± 0.16</td>
<td>3 m above 1.42 ± 0.09</td>
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<td>1.5 m above 1.42 ± 0.09</td>
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<td>20 cm above 1.22 ± 0.09</td>
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<td>20 cm above 1.21 ± 0.09</td>
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<td>10 cm above 1.36 ± 0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>adjacent fault 1.78 ± 0.30</td>
</tr>
</tbody>
</table>

Figure 4-15 continued
<table>
<thead>
<tr>
<th>LOCALITY</th>
<th>LOCALITY DESCRIPTION</th>
<th>NORMAL REFLECTANCE</th>
<th>SHEARED COAL REFLECTANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.</td>
<td>Sheared coal within seam, lower Kootenay Fm. Vicary Creek, Displacement (interstratal slip) unknown.</td>
<td>1.05 ± 0.11</td>
<td>adjacent shear 1.24 ± 0.10</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>adjacent shear 1.13 ± 0.12</td>
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<tr>
<td>26.</td>
<td>Tightly folded coal seam, lower Kootenay Fm., Vicary Creek.</td>
<td>unknown</td>
<td>sheared coal 1.04 ± 0.10 in hinge</td>
</tr>
<tr>
<td>27.</td>
<td>Adjacent normal fault in lower Kootenay Fm. at Vicary Creek. Displacement less than 4 m.</td>
<td>1.21 ± 0.07</td>
<td>adjacent fault 1.27 ± 0.07</td>
</tr>
<tr>
<td>28.</td>
<td>Sheared coal within coal seam, upper Kootenay Fm. Tent Mtn. Displacement (interstratal slip) unknown</td>
<td>1.08 ± 0.08</td>
<td>adjacent fault 1.21 ± 0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>adjacent fault 1.09 ± 0.09</td>
</tr>
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with normal vitrinite reflectance values. Furthermore, the associated structure and fabric of the coal are not notably different between areas of high and normal values. The only exception is along the Coleman Fault (Fig. 4-15; Loc. 24), which has the largest stratigraphic separation of any fault studied as well as the highest mean reflectance (1.78%) and the thickest associated coal fault gouge.

The variance and anisotropy of reflectance measurements of sheared coal with anomalous vitrinite reflectance is comparable with that of laboratory heated coal of similar reflectance. All the samples have similar large variances and anisotropies. As found in this study, Marshall and Murchinson (1971) observed an increase in anisotropy with coal samples which were heated in the laboratory to progressively higher temperatures and they further documented an increase in anisotropy from low to higher rank coal. The variances of vitrinite reflectance measurements of coal heated in the laboratory in this study and those of field samples with high values are also similar to those reported from shear zones by Teichmuller (1975).

Prior to discussing the implications of the reflectance values it is necessary to consider the overall limitations of the data. The mean of the anomalously high vitrinite reflectance values of the samples, if considered separately, would correlate with an increase in rank from medium-volatile bituminous coal to low-volatile bituminous coal and semi-anthracite. Because of the large variance of the vitrinite reflectance values, it is unlikely that these samples would have
Figure 4-16. Coleman Fault plane at Wintering Creek, just north of Vicary Creek. At this locality a seam of medium-volatile bituminous coal occurs in and has been dragged up the fault plane. In addition a slice of Crowsnest Volcanics Formation (Kcr) intervenes between the hanging-wall strata of the Kootenay Formation (JKk) and footwall strata of the Belly River Formation.
the same chemical composition as normal coal with the same mean reflectance (also refer to Chandra, 1965a). Furthermore, because distinguishing the different macerals, particularly vitrinite from semi-fusinite and macrinite, is based in part on their reflectance, it is possible that highly reflecting vitrinite, in highly fragmented coal which has been successively sheared, may have been misidentified and thus not included in the analysis, which would result in values which are too low. Nevertheless with the large number of particles measured and samples examined, it is unlikely that the latter problem has seriously affected the results or the conclusions subsequently drawn.

**IMPLICATIONS OF THE ANOMALOUS VITRINITE REFLECTANCES**

The occurrence of natural samples with anomalously high vitrinite reflectance values in conjunction with their large variance suggests that these samples have locally been exposed to high temperatures. Furthermore, the high temperatures must have existed for short durations; otherwise, considering any reasonable thermal conductivity of coal or coal plus fluid, the zone of thermally affected coal would be much more extensive than the narrow zones observed. The high temperatures are therefore considered the result of frictional heating during stick-slip faulting. High temperatures could not have been generated by fault creep because of the very slow rates of slippage during creep (McKenzie and Brune, 1972). Moreover, had high temperatures been generated as a result of fault creep, the thermal halo in the region of the shear zone would have been
much wider. Even along the Coleman Fault plane (Fig. 16; loc. 24) no large scale thermal effects were observed that would provide evidence for sustained high heat flows as a result of fault creep or the emplacement of a 'hot' thrust sheet such as documented elsewhere by Beech and Fyfe (1972) and Bustin et al., (1977).

Accepting a very short heating duration, the calibration curves established in this study (Figs. 4-2, 4-3, 4-4, and 4-5) can be used to approximate the temperatures reached during slip. The highest mean vitrinite reflectance obtained along the Coleman Fault would correspond to temperatures of 450°C as long as the effective heating time was less than 7 hours. If the effective heating time was one month, Bostick's (1973) curve (Fig. 4-6) would suggest the temperature was in the order of 380°C. Other anomalously high values, in the range of 1.45% Ro., along the Coleman Fault correspond to temperatures of about 435°C. At location 2 a value of 1.35% Ro. equates with a temperature of 410°C whereas values of 1.20% at locations 5 and 25 correspond to temperatures of about 400°C. If the values at locations 8, 18, 27 and 28 are significant they could correspond to temperatures of 200°C to 380°C for short durations. The anomalous vitrinite reflectances thus represent temperatures which are probably between 100°C and 350°C greater than the ambient temperature, based on an estimated geothermal gradient of 25 °C km⁻¹ and a depth of burial of 4 km (100 °C).

The absence of measurable heating effects along some shear zones as compared to others may be the result of: 1) aseismic creep (stable sliding) rather than stick-slip during
shear; 2) low effective stress across the shear zone; or 3) slow rates of stick-slip sliding. Stable sliding and stick-slip sliding have been studied experimentally by Byerlee (1970), Steck et al., (1974), Summers and Byerlee (1977) and others who have shown that the frictional properties and fault stability are dependent on effective stress, temperature, surface roughness and thickness and composition of fault gouge. Summers and Byerlee (1977) found in experiments that, with fault gouge of uniform thickness, dry samples of widely different rock materials exhibited stick-slip behavior when the confining pressure was in the order of $1.5 \times 10^5$ kPa to $3.0 \times 10^5$ kPa. Such pressures were considered to be the point where sufficient force was applied to close cracks and lock grains together, forcing deformation to take place by fracturing through grains, as compared to lower pressures where grains apparently lift over each other. They further found that if water was present it had a stabilizing influence by reducing the effective stress when either trapped between rocks of low permeability or loosely bounded in a mineral structure, such as in hydrated clays.

The thickness of the fault gouge is probably important in determining whether or not stick-slip or stable sliding will occur, and there is a correlation between fault displacement and thickness of fault gouge (Otsuki, 1978); however, during stick-slip faulting the fault plane can be considered to be planar. Engelder et al., (1975) have shown that zones of slip are thin, even in the presence of fault gouge, in laboratory experiments but, as discussed by Cardwell et al., (1978), it is not clear whether this is actually the case with faults.
Heating as a result of frictional sliding has been investigated by Bowden and Tabor (1950) who have demonstrated that, when two bodies slide past each other, the friction between them is proportional to the normal force and not to the surface area because the bodies are only in contact at asperities and the normal force is transmitted through the asperities. The area of contact is thus determined by the yield pressure of the asperities. The law of friction

\[ F = \mu N \]  

(1)

where \( F \) is the frictional force, \( \mu \) is the coefficient of friction and \( N \) is the normal force, is thus related to the yield pressure of the asperities. McKenzie and Brune (1972), however, have argued that (1) will not apply when the normal force exceeds some function of the stress since the contact area will then be independent of the normal force. They further suggest that at depths at which most earthquakes occur (1) will not apply because at depths below 3 km both surfaces must be contact everywhere. McKenzie and Brune (1972) and Cardwell et al. (1978) have theoretically calculated temperatures resulting from faulting based on these assumptions. Although such calculations may be applicable to deep seated earthquakes, as they suggest, along faults in this study the effective normal stress was probably not of the magnitude envisaged by these authors. Low effective stress during thrust faulting has been argued on mechanical grounds by numerous authors (Hubbert and Rubey, 1959; Carlisle, 1963). Furthermore the presence of asperities, on
some scale, is probably largely responsible for the 'locking' of faults, the ensuing accumulation of elastic strain energy and the eventual failure which is required for stick-slip in the first place (Byerlee, 1970). Nor does it seem possible for high temperatures such as inferred from this study and assumed by McKenzie and Erune (1972) to occur during stable sliding.

Accepting that the usual law of friction (1) applies, the temperature change occurring during frictional sliding between two bodies of similar composition along the plane of sliding is given by (Bowden and Tabor, 1950):

\[ T - T_0 = \mu g v \left( \frac{W}{P_m} \right) \frac{h}{J K} \]

where \( T - T_0 \) is the change in temperature, \( \mu \) is the kinetic coefficient of friction, \( v \) is the sliding velocity, \( g \) is the gravitational constant, \( W \) is the load on the contact area, \( P_m \) is the yield point of the material, \( J \) is the mechanical equivalent of heat and \( K \) is the thermal conductivity. In Fig. 4-17, different potential temperatures are given as a function of load and sliding velocity using \( \mu = 0.2 \) (modified from Chapple, 1975), \( P_m = 1.789 \) dynes cm\(^{-2}\) (modified from Hobbs, 1964) and \( K = 5 \times 10^{-3} \) cal cm\(^{-1}\) sec\(^{-2}\) °C (modified from Hendrickson, 1972). A number of assumptions were necessary to construct Fig. 4-17, the most important of which is the assumption of dry conditions. Under lubricated conditions in laboratory experiments of Bowden and Tabor (1950), high temperatures were reached during sliding friction at moderate velocities and loads, but the temperatures were as much as several hundred degrees Celsius lower than under
Figure 4-17. Relationship between sliding velocity, effective stress and temperature calculated using Bowden and Tabor (1950) expression and assuming dry sliding conditions and parameters outlined in text.
dry conditions. During faulting some lubrication probably exists (Carlisle, 1963) but it cannot be quantitatively evaluated. Assuming that $F_m$, $K$ and $u$ remain constant with rising temperature and velocity also introduces error in the calculations but this error is considered insignificant as compared to the uncertainty in assuming dry friction.

Clearly only the broadest conclusions can be drawn from Fig. 4-17. Even if the assumptions outlined above are correct a temperature change of 350°C could correspond to pressures as low as $2.0 \times 10^3$ kPa with sliding velocities of 1 m s$^{-1}$ or pressures as high as $2.0 \times 10^5$ kPa if the sliding velocity was in the order of 1 cm s$^{-1}$ (Fig. 18). Calculations of McKenzie and Brune (1972) and Cardwell et al., (1978), although based on different assumptions, have similar limitations. High temperatures are theoretically predicted during frictional sliding over a wide range of effective stresses and slip velocities. Nevertheless, it is possible to draw some general implications and to speculate further about fault mechanics from the obtained values. First, along shear zones where high temperatures were measured there had to be a relatively high effective stress considering reasonable rates of stick-slip (10 to 100 cm s$^{-1}$) and based on the fact that stick-slip must have occurred; second, the effective stress and/or slip velocity were probably different during successive episodes of slip along the same fault zone, in as much as markedly different anomalous temperatures are calculated from the same fault zone (e.g., loc. 24). Because it is not known whether stick-slip faulting as compared to stable sliding occurred along shear zones where
no high temperatures were measured, it is not possible to evaluate the effective stress. However, that no detectable change in rank was observed in many fault zones indicates, by comparison with the experimentally heated coal samples, that shearing did not result in temperatures in excess of 200°C. The absence of such temperatures during faulting implies, by analogy with experimental studies (Logan, 1975; Summers and Byerlee, 1977), that the effective stress was lower in these areas.

The most important general implication of the results is that along reverse and thrust faults there are areas of significant and less significant effective stress. Such does not detract from but rather supports the contention of Hubbert and Rubey (1959) that high fluid pressure could relieve the effective normal stress to the degree that large thrust sheets could be pushed down slope under gravity without internal shear friction. As an alternative to low effective stress and high pore pressure, it would be necessary to invoke a fault mechanism involving viscous deformation, such as suggested by Smoluchowski (1909) and Kehle (1970). In terms of pore pressure areas of high effective stress may represent areas of drainage. For example, the high temperatures calculated along the Coleman Fault were obtained from samples collected at a locality where the fault steps rapidly up section and a slice of Crowsnest Volcanics Formation has been dragged into the fault plane along with the coal. Areas where faults rapidly step up section are undoubtedly areas of stress concentration; and furthermore, such areas are probably better drained because of associated extensive fracturing and faulting of the surrounding rocks.
EFFECT ON COAL QUALITY

The effect of shear on quality is principally mechanical rather than thermal. Only along the Coleman Fault can the thermal affects associated with shearing be considered significant and even at this locality a bulk sample analysis would probably reveal only a minor increase in rank. Even such pervasively sheared and polished coal as shown in Fig. 4-10 shows no notable increase in rank.

More important, however, are the mechanical effects of shearing which have greatly comminuted the coal and associated rock partings. Sheared coal in areas of tectonic thickening has been extensively mined in the study area; these coal deposits have disproportionately high amounts of ash, poor washability characteristics and are commonly partly oxidized. The degree of oxidation of the coal is directly proportional to the extent of comminution. The large surface area the comminuted coal has facilitated rapid and extensive oxidation of the coal. Moreover, the presence of numerous fault planes and fractures in adjacent rocks and the coal seams has enabled deep penetration of atmospheric oxygen and circulation of oxygenated waters. Such is the case on a large scale in the vicinity of Vicary Creek, where extensively granulated coal in areas of normal faulting is more highly oxidized and has a lower free-swelling index than coal either up- or down-dip from the region of faulting. An additional example is the highly faulted and tectonically thickened and comminuted coal deposits at Coal Mountain, British Columbia, which are also oxidized in part (British Columbia Task Force on Coal, 1976).
The disproportionately high ash content of deposits of highly sheared coal is largely the result of comminution during shearing of otherwise discrete rock partings and interbeds of sandstone and shale (Fig. 11b). The poor washability of the coal is probably similarly the result of comminution of the ash during shearing. In addition, plastic flowage of the clarite and associated engulfment of formerly discrete ash particles results in the formation of aggregates. Within the aggregates the ash is finely disseminated and thus not readily separated.

SUMMARY AND CONCLUSIONS

Pervasively sheared coal comprises a large proportion of some coal deposits in parts of the southern Rocky Mountains of British Columbia and Alberta. On a mesoscopic scale the coal has a brecciated fabric and adjacent to some faults the coal is finely granulated and extensively polished. The microfabric of the sheared coal is generally similar to the mesoscopic fabric consisting of angular fragments of coal with no evidence of ductile behavior. In areas of apparently high strain the clarite component of the coal flowed plastically, forming aggregates consisting of brecciated fragments of inertite and vitrite in a clarite groundmass. Microfolds of similar style and 'wild' folds are also present.

Samples of medium-volatile bituminous coal heated in the laboratory at temperatures up to 600°C and durations up to several days resulted in vitrinite reflectances lower than those previously reported for longer durations of heating. There is
very little difference however, between the reflectances of vitrinite in samples heated for 10 minutes or 7 hours. The lowest temperature of heating which resulted in a detectable change in vitrinite reflectance was 200°C. The change in reflectance with heating is almost linear up to the melting point of the coal where there is an exponential rise in reflectance. Samples heated for short durations have large anisotropies and a greater variance than normal coals, probably as a result of different reaction rates of the vitrinite rather than the effect of pressure or shear as previously suggested.

Measurement of vitrinite reflectance of samples collected from 28 different localities, adjacent to major and minor shear zones and isoclinal folds, revealed a significant change in rank adjacent to some shear zones and no detectable change in others. There is no macroscopic distinction, however, between areas of high and normal vitrinite reflectance. Using the correlation curves established from the experimentally heated samples, the highest measured mean reflectance (1.78% Ro.), measured in coal within the Coleman Fault plane, may correspond to a temperature of up to 450°C. Such a temperature is in the order of 350°C greater than that calculated considering a normal geothermal gradient and an estimated maximum depth of burial. Other anomalously high vitrinite reflectances correspond to temperatures between 200 and 430°C.

The anomalously high vitrinite reflectances are restricted to very narrow zones adjacent to and within the shear zones which, considering any reasonable thermal conductivity, required a very short heating duration. The high temperatures
are therefore considered to be the result of frictional heating during stick-slip faulting. The absence of measurable temperatures in some areas may be the result of stable sliding as compared to stick-slip faulting.

The obtained temperatures, when considered in conjunction with theoretical relationships, have major implications with regard to reverse and thrust fault mechanics. These are: (1) high temperatures are locally reached during faulting as a result of frictional heating; (2) stick-slip faulting occurs at least in part along such faults; and (3) areas of significant effective stress exist along the faults but also areas of lower and less significant effective stress exist. In general the implications of the results support Hubbert and Rubey's (1959) hypothesis that high pore fluid pressure may exist along major faults but the results also suggest that areas of lower pore pressure may exist. High temperatures measured along the Coleman Fault were obtained from an area where the fault is folded and a slice of Crowsnest Volcanics is present in the fault plane. In such areas stress concentration probably existed and drainage of high pore pressure may have been facilitated by the extensive fracturing of the footwall and hanging wall strata.

The effect of shear on coal quality is primarily related to mechanical comminution of the coal. Thermal effects due to frictional sliding are not significant on the scale of the coal deposits. The highly sheared coal has disproportionately high amounts of ash and poor washability characteristics and is oxidized in part. The high ash content and poor washability of
the coal are principally related to the comminution of former discrete rock partings and interbeds of sandstone and shale. The extent of oxidation of the coal is directly proportional to the fine grain size and greater surface area of the coal, which facilitated rapid rates of oxidation. In addition faulting and fracturing of the associated strata during shearing promoted deep penetration of atmospheric oxygen and circulating oxygenated waters.
ACKNOWLEDGEMENTS

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PART 4

MORPHOLOGY AND ORIGIN OF STRIATED CONICAL STRUCTURES AND RELATED FRACTURES IN BITUMINOUS COAL OF THE SOUTHERN CANADIAN ROCKY MOUNTAINS
ABSTRACT

Striated structures, many of which are conical in form, are common mesoscopic features in bituminous coal of the southern Canadian Rocky Mountains. The structures are planar, conical to pyramidal in outline and are characterized by striae which radiate from a common apex and bifurcate or 'horsetail' to form secondary structures on the master surface. They are up to 20 cm in length, 4 cm in width and have apical angles varying from 10° to 50°. The striated structures occur at numerous localities in both highly sheared coal and only gently folded seams.

The conical striated structures closely resemble some shatter cones developed in fine-grained rocks whereas the planar striated structures are somewhat similar to chevron-structured, hackle-marked joints. The pyramidal structures are apparently unique to coal. All three types of structures are considered to be the result of brittle shear fracture based on their occurrence, orientation, and morphology and on experimentally produced fractures. The apparently restricted occurrence of the structures to coal is likely a result of the low tensile and compressive strength of bituminous coal, possibly augmented by high inter- and/or intra-particle gas pressure resulting from devolatization of the coal during progressive coalification.
Conical structures which occur in rocks have generally been referred to as either shatter cones or cone-in-cone structures. Shatter cones are conical fracture surfaces which have been attributed to the passage of intense shock waves associated with a cryptoexplosion (Bucher, 1963; Manton, 1965; Dietz, 1968), whereas cone-in-cone structures are considered diagenetic, crystallization features (Woodland, 1964a; Pettijohn, 1975). In addition to shatter cones and diagenetic cone-in-cone structures, there are a few descriptions of conical structures which occur primarily in bituminous coal. This latter group of structures somewhat resembles shatter cones (cf. Dietz, 1968) but are neither associated with cryptoexplosion structures nor evidence for the passage of intense shock waves.

Conical structures in coal were documented by Garwood (1892) from the coal fields of Durham and South Wales and by Gresely (1892) who referred to 'cone-in-cone' structures in coal from Leicestershire, Belgium and western Pennsylvania. More recently, conical structures have been described in coal from Wales (Tarr, 1932), New Zealand (Fyfe and Wellman, 1937; Bartram, 1941), the Netherlands (Deenen, 1942), Poland (Kwiecinska, 1963; Gorezyea and Kwiecinska, 1963) and West Virginia and Idaho (Price and Shaub, 1963). Conical structures somewhat resembling shatter cones have also been described from Cambrian shales at localities in California and Newfoundland (Ray and Hansman, 1971) and from carbonaceous, Cretaceous shales in Colorado (Woodland, 1964b).
The origin of the conical structures has been attributed to a variety of processes. Gresely (1892) suggested that they originated 'as a kind of crystallization' and Tarr (1932) and Woodland (1964b) have proposed that they form by some diagenetic process. Price and Shaub (1963) and Kwiecinska (1963) considered a tectonic origin, whereas, Bucher (1963) suggested that shrinkage of the coal in conjunction with overburden pressure may have been important. All of the above interpretations have been hampered by the paucity of the structures and because the specimens described and interpreted by Bartram (1941), Bucher (1963), Price and Shaub (1963) and Woodland (1964b) were not collected in place by these authors.

In bituminous coal in the southern Canadian Rocky Mountains striated structures, many of which are conical in form, are a conspicuous mesoscopic fabric element. These structures are clearly of the same type as the conical structures previously described from coal; however, in western Canadian bituminous coal, the conical structures are apparently much more abundant and morphologically more diverse than previously described. The structures occur at numerous localities in both pervasively sheared coal and in gently folded seams, which provide an excellent opportunity to assess the origin of the structures. The purpose of this paper is to document the occurrence and characteristics of these interesting structures and to discuss their possible origin and significance.

Striated structures occur in coal of the Kootenay Formation at numerous localities within the Crowsnest Pass area.
A detailed examination of the structures was made at three localities: 1) north of Coleman, Alberta in the Coleman thrust sheet; 2) at Tent Mountain on the British Columbia-Alberta boundary in the Lewis thrust sheet; and 3) in the Balmer North coal mine near Michel, British Columbia near the north end of the Fernie synclinorium (Fig. 1-2). In the Balmer North mine the coal seams are gently folded, whereas at the Coleman and Tent Mountain localities they are, for the most part, pervasively sheared.

OCCURRENCE AND GENERAL DESCRIPTION OF THE STRUCTURES

The striated structures display a great variation in morphology, size and orientation. Their unifying characteristic is the presence of striations which radiate from a common apex and which commonly bifurcate or 'horsetail' to form subsidiary striated structures on the master surface (Fig. 5-1 and 5-2). The radiating pattern of the striae differentiates these structures from slickenside striae. Also, the absence of well developed transverse ribs, the absence of internal structure and gross morphology serve to distinguish them from diagenetic cone-in-cone structures or crystallization structures such as those described by Woodland (1964a), Pettijohn (1975) and others. The planar striated structures, as described later, are somewhat similar to chevron-structured, hackle-marks common on some joint surfaces in rocks.

At all localities, the conical structures are restricted to the coal seams and to lenses of coal within sandstones or shales. They occur in both clarain- and vitrain-rich coal and
Figure 5-1. Conical to oblate striated structures from Tent Mountain. Note the downward projection of the cone apices.

Figure 5-2. Conical to oblate structures showing the detail of the surfaces. Notice the radiating ridges and 'horsetails' on the structures to the lower right of the scale. Arrow points to the apex of one such structure.
commonly cross-cut stratification in the coal. The structures occur on, or define, distinct fracture sets in the coal. Their surface has a silky to dull lustre, in marked contrast to the glossy lustre of major shear surfaces which occur in the coal. The striae are intricately developed on the surface. The striae commonly terminate against adjacent striae or secondary striae (Fig. 5-2) and do not cross-cut or overprint each other. In cross-section the conical structures display no internal morphology with the exception of the outline of the regularly spaced striae along the edges. Vitrinite reflectance measurements made from the centre to the edge of the structures show no measurable variation in rank of the coal. Radial lines oriented perpendicular to the striae on the surface of the striated structures are commonly present particularly in the vitrain-rich samples. Observations of the striated structures at high magnification revealed a heterogenous, 'rough' surface (Fig. 5-3) similar to that shown on hackle-marked joint surfaces by Syme Gash (1971) and Dov (1979). Graphite plates, such as those found on surfaces of conical structures in coal by Gorezyea and Kwiecinska (1963) were not observed.

Based on variation in morphology three types of striated structures are recognized: 1) planar striated structures, which are essentially two dimensional; 2) conical striated structures, in which at least one side of the 'cone' is well-developed; and 3) pyramidal structures. Although gradations exist between the three type of striated structures, they are considered to represent natural end members and are discussed separately below.
Figure 5-3. S.E.M. photomicrograph showing the detail of a planar striated structure. x 400.

Figure 5-4. Planar striated structure on cleat surface from the Balmer North coal mine.
Planar Striated Structures

Planar striated structures, similar to their three-dimensional counter parts, have well-developed striae which radiate from a common apex and subsidiary radiating structures formed by 'horsetailing' of the striae (Fig. 5-4). The structures range from 5 cm in length and 1 cm in width to 15 cm in length and 3 cm in width and have length to width ratios in the order of 5:1 to 10:1. Apical angles vary between 10° and 35° and average 15°. These structures everywhere occur in parallel oriented sets on well developed fracture surfaces. On parallel fractures, the axes of the structures have a strongly preferred orientation, whereas on conjugate sets of fractures they are commonly oriented with their apices in opposite directions on opposed fractures such that the bases of the structures meet at an obtuse angle.

Planar striated structures were observed at most localities and are particularly abundant in the Balmer North coal mine. Figure 5-5 summarizes the axial orientation of the structures and the b fabric direction of the seam which is sub-parallel with the regional fold axis (B). Although the structures show considerable variation in azimuth, two distinct maxima are present which are more or less symmetrically disposed about the ac fabric plane of the seam. The structures lie parallel to the plane of bedding and on conjugate fractures. The orientation of the striated structures in the Balmer North coal mine are parallel to bedding, irrespective of local structure, which suggests that the structures were formed early in the deformational history of the seam.
Figure 5-5. Axial orientation of planar striated structures from the Balmer North mine. Lower hemisphere Schmidt net. Contours are at 2, 5, and 10% per 1% area; 'b' is the b fabric direction of the seam and ac is the deformational plane.
Conical Striated Structures

This type of striated structure has at least one side which is conical in form (figs. 5-6 and 5-7). The cones rarely exceed 5 cm in length and have a basal width ranging from 5 mm to 5 cm. The length to width ratio varies between 2:1 and 5:1 and the apical angle between 5° and 35°. The apex is rounded to sharp and parasitic secondary cones are invariably developed on the master cone surface. Individual cones are rarely separable from adjacent ones. One conical surface is generally very well developed, and parting of the coal along the cone surface is facilitated, whereas the other side of the cone is poorly developed and displays little tendency to part from the surrounding coal.

The conical structures are known to occur in sheared coal only at the Coleman and Tent Mountain localities. A plot of the apical orientation of the cones at two adjacent localities on Tent Mountain (Fig. 5-8) depict two distinct maxima. Other plots, not shown, show distinct maxima at particular localities. However, there is no apparent relationship between the orientation maxima and the fabric directions of the seam at these localities. Extensive shearing of the seams and accompanying cataclastic flow of the coal (Bustin, 1979) has probably preceded, at least in part, the formation of the structures, resulting in the lack of consistent orientation.

Pyramidal Striated Structures

These structures are characterized by their sharp apex
Figure 5-6. S.E.M. photomicrograph of striated semi-conical structures. Stereo-pair. x 20.
Figure 5-7A. S.E.M. photomicrograph; semi-conical striated structures. x 20.

Figure 5-7B. S.E.M. photomicrograph; close up of 5-7A.
Figure 5-8. Summary of axial orientation of conical structures at Tent Mountain. Lower hemisphere Schmidt net. 'B' is the regional fold axis and ac is the deformation plane of the fold.
and pyramidal form. They are up to 3 cm in length and 3 cm in width and have length to width ratio varying from 3:1 to 1:1. The apical angle of most structures are close to 45°. The base of the pyramids is rectangular to square. The structures nearly everywhere occur in alternating sets such that every other cone apex points in the opposite direction to its adjacent neighbor (Fig. 5-9).

The pyramidal structures are most commonly oriented perpendicular to and abut slickensided surfaces. In some cases, such as shown in Fig. 5-9A, a slickensided surface in a sandstone or shale disappears upon passing into a coal lens and pyramidal structures are developed with apices oriented approximately 90° to the projected trace of the slickensided surface. In the observed samples, there appears to be no consistent relationship between the rectangular form of the base of the pyramids and the direction of motion inferred from the orientation of the slickenside striae.

The pyramidal structures were observed only at the Tent Mountain locality. With the exception of observed relationships between slickensided surfaces and the pyramids discussed above there is no apparent correlation between the structural fabric direction of the coal measures and the pyramids.

Comparison with Other Structures

The striated structures of this study resemble some previously described 'cone-in-cone' structures in coal and also have some features in common with shatter cones and chevron-structured hackle-marked joints.
Figure 5-9A. Pyramidal striated structures. Interlocking pyramids in a coal lens within a fine-grained sandstone. The slickensided surface (S) terminates at the coal lens.

Figure 5-9B. Close up of Fig. 5-9A. A nearly vertical view of the pyramids showing their recilinear outline.
Previously described conical structures in coal are similar to the conical striated structures of this study in the following respects: 1) they consist of striae which radiate from a common apex and which commonly 'horsetail' to form subsidiary cones; 2) they have apical angles which vary between 15° and 50°; 3) they are of similar dimensions; and 4) one side of the cone is invariably better developed than the other side. The only previous description of pyramidal structures in coal is that of Kwiecinska (1963), who has described 'pyramidal cones' from coal of the Lower Silesian coal basin. As with the pyramidal structures of this study the cones described by Kwiecinska occur in inverted sets and are bounded by a planar surface. 'Cockscomb coal' and 'double cone-in-cone' coal, referred to by Gresley (1892), also may be similar to the pyramidal structures of this study. Planar striated structures have not previously been described from coal, with the exception of the study of Deenen (1942); however, it is possible that these structures would not have been grouped with the conical forms.

Bucher (1963) and Dietz (1968) have alluded to the similarities between the conical structures in coal and shatter cones. Bucher (1963) has argued that because of the similarity of the structures, the shatter coning mechanism may not require the impact speed of meteorites, whereas Dietz (1968) has stated that the conical structures in coal, although superficially resembling shatter cones, are not shatter cones. The conical structures in coal closely resemble shatter cones developed in fine-grained rocks such as dolomites, limestones and shales.
shown by Dietz (1968) and Manton (1965), which have small apical angles (compare Fig. 5-1 with Plate V of Dietz, 1968 and with Fig. 5-3 of Manton, 1965). The apical angle of most shatter cones is in the order of 90°, which is the most notable morphological difference from the conical structures in coal. Shatter cones are also invariably considered to be associated with cryptoexplosion features and require intense shock pressures for their formation. Theoretical considerations by Johnson and Talbot (1964) led them to suggest that shatter cones are shock features formed as a result of the interaction of an elastic precursor in the shock front with an inhomogeneity in the rock. For shatter cones to form they have, therefore, argued that the strength of the shock wave must exceed the Hugoniot elastic limit of the material. This theoretical argument cannot be readily applied to conical structures in coal. There is no evidence for the passage of intense shock waves in associated lithologies and the experimentally determined Hugoniot for coal shows "practically no evidence for an elastic yield point" (Butcher and Stevens, 1975, p. 151).

The planar striated structures of this study closely resemble chevron-structured hackle-marked joints such as those described by Syme Gash (1971) and Dov (1979). The only significant difference is that the chevron structures are always bounded by two sub-parallel interfacies (Syme Gash, 1971), whereas the striated structures in coal commonly occur in parallel sets on the same fracture surface.
ORIGIN OF THE STRUCTURES

Early theories concerned with the origin of the conical structures in coal alluded to their similarities with 'cone-in-cone' structures of diagenetic origin. The morphology of 'cone-in-cone' structures is, however, markedly different from that of the conical structures in coal. As to their formation in coal, a diagenetic crystallization or pressure-solution origin of the structures is not feasible because of the insolubility of coal in most natural solutions (Price and Shaub, 1963). An organic origin can also be dismissed because of the absence of internal structure and because stratification passes through the structures.

All of the features of the structures described in this study suggest that they are brittle fracture surfaces. In an attempt to produce the structures experimentally, a number of macroscopically unfractured blocks of bituminous and subbituminous coal were impacted at velocities ranging from 1 m s\(^{-1}\) to 1250 ms\(^{-1}\). In all of the high velocity experiments the coal failed along a multitude of surfaces at various orientations. No conical structures were formed in any of the experiments. However, planar striated structures, similar to those previously described here, were visibly developed in blocks of bituminous coal impacted at speeds of about 350 m s\(^{-1}\) (Fig. 5-10). Low velocities did not result in formation of the structures whereas in experiments at higher velocities the coal was so intensively fractured that it was impossible to reconstruct the individual surfaces.

The planar striated structures artificially created in
Figure 5-10. Planar striated structures in coal artificially fractured by high velocity impact.
the bituminous coal formed on fractures oriented between 0° and 50° from the direction of impact. Such results clearly support neither a shear nor an extension origin of the structures. Shear fractures can form at various orientations with respect to the maximum principal stress (\(\sigma_1\)), depending on the difference between \(\sigma_1\) and the minimum principal stress (\(\sigma_3\)) and the magnitude of \(\sigma_1\). There is a range of shear fractures that can, therefore, develop at orientations close to those of tensile fractures (Syme Gash 1971). Shear fractures are generally expected to show some shear displacement (Conrad and Friedman, 1976), however there is little agreement on whether other striated hackle-marked structures such as found in rocks, metals, glass (Murgatroyd, 1942; Syme Gash, 1971, Dov, 1979; and others) and plexiglas (Correscio and Soperstein, 1977), which show no evidence of shear displacement, are tensile or shear fractures. Based on theoretical considerations, Syme Gash (1971) has suggested that hackle-marked surfaces are diagnostic of shear joints on dynamic fracture surfaces (see also Dov, 1979) and result from the interaction of compressional and tensile stress waves.

The planar striated structures of this study are considered shear fracture surfaces. The orientation of the structures on conjugate fracture sets bisected by the local ac fabric direction of the seam in the Balmer North mine suggests, by analogy with the geometry of shear fractures described by Stearns (1964, 1968) and others, that the striated structures develop on shear fractures in which no finite displacement has occurred. Furthermore, it is unlikely that such closely spaced
parallel, or conjugate sets of fractures could form in extension because formation of one fracture surface would disrupt the local tensile field such as described by Adams and Sines (1978). Formation of the striae however, probably does require tensile and compressional wave interactions such as argued by Syme Gash (1971). The low angle many of the experimentally produced fractures made with direction of impact as was found in this study is not easily explained. It is possible that the fractures are a product of stress wave interactions at the free surface of the coal samples, perhaps similar to some of the complex stress wave interactions predicted on theoretical grounds by Syme Gash (1971). Alternatively, the experimental results may reflect the presence of oriented flaws which would markedly affect fracture orientations (Adams and Sines, 1978), but which were not present during natural fracturing of the coal.

The conical and pyramidal striated structures are also considered to be shear fractures. For formation of perfectly conical structures, a radially disposed stress system would be necessary such that 61 is parallel to the cone axis (Price and Shaub, 1963; Bucher, 1963). Such conditions are probably no more common in coal than in other rocks, however, coal has a much lower strength than most other rocks (Hobbs, 1964) and a much finer grain size (Butcher and Stevens, 1975). In addition, simultaneous (dynamic) radial brittle shear fracture of the coal may have been augmented by high inter- and intra-particle gas pressure resulting from devolatization of the coal during coalification, which would further increase the brittleness of the coal. High gas pressure associated with coal is well
documented in underground mines where explosive release of carbon dioxide and methane result in outbursts or blowouts (Norris, 1958; Popp and McCulloch, 1976). Variation in gas pressure and in the orientation of the greatest principal stress plus heterogenities of the coal probably account for the observed variation in apical angle of the cones. As discussed by Price and Shaub (1963), perfectly symmetrical cones would require perfectly uniform lateral stresses which would be rarely encountered, and thus incomplete cones would be developed more commonly. However, it is unlikely that formation of the cones in coal is completely analogous to those produced in materials under uniaxial compression, as suggested by Price and Shaub (1963). Formation of conical structures in heterogeneous materials such as concrete is generally considered to be product of lateral confinement of the specimen in contact with the platens of the testing instrument (Neville, 1959).

The close association between the pyramidal striated structures and slickensided surfaces observed in this study suggests that a genetic relationship exists between the structures. Similar pyramidal structures bounded by planar structures in coal described by Kwiecinska (1963) furthermore indicate that this association is not unique to coal of this study. If the pyramidal structures are shear fractures analogus to the conical structures, as their general morphology suggests, the orientation of $\theta_1$ required for their formation would make an angle of between $45^\circ$ and $90^\circ$ with that required for the formation of adjacent slickensided surfaces. A similar stress re-orientation is also required if the pyramidal
structures are considered to form in a tensile stress field. Two equally probable (or improbable) mechanisms for the formation and association of these structures exist. First, it can be argued theoretically (Lajtai, 1968, 1969; Jaeger and Cook, 1971) that failure in one direction along the axis of the pyramids or the slickensided surface result in a local reorientation of the stress field. Second, it is possible that the structures formed simultaneously in response to the same stress system. Compressive or tensile stress waves (primary or secondary), propagating from a fracture in one medium, upon reaching an interface in a dissimilar medium (the coal) will be proportionally transmitted or reflected depending on the angle of incidence of the wave, the relative densities (and characteristic wave velocities) of the two media (Syme Gash, 1971). The energy of the original wave is proportioned and redistributed among a new set of waves. In the second medium, fracturing can occur at various geometries in response to tensile or compressive pulses, or a combination of the two, if the tensile or compressive strength of the material is exceeded (Syme Gash 1971). Of interest in this study is the reflection of transmitted waves. The pyramidal structures in coal invariably are in lenses bounded above and below by dissimilar lithologies (Fig. 5-9), which would result in reflection of the transmitted waves. Fracture by reflected stress waves has been discussed by Syme Gash (1971) however, it is unknown whether the reflected stress waves would be capable of fracturing the coal, nor is it possible to predict from present theory why the structures have a pyramidal outline. Both re-orientation of the
ambient stress field and the reflection of incident stress waves could account for the observed structures, yet there is no clear evidence or theoretical argument for accepting one or either of these possibilities over the other.

**DISCUSSION AND CONCLUSIONS**

The striated structures described in this study are more abundant and morphologically more diverse than previously described conical structures in coal. Nevertheless, the similarity in gross aspect, details of the striae and the ubiquitous occurrence of secondary structures indicate that the structures have a common origin. All previously described conical structures in coal similar to those of this study have been from bituminous coal. It is likely that such a restricted occurrence reflects the low strength of bituminous coal compared to either higher or lower rank coal (Brown and Hjorns, 1963), possibly augmented by inter- and/or intra-particle gas pressure resulting from progressive devolatization of the coal during the coalification process.

The apparently greater abundance of the striated structures in coal of the Kootenay Formation in this study area as compared to other coal deposits may be related to the chronology of deformation of the coal measures relative to the degree of coalification. The Kootenay Formation was rapidly deposited and buried to depths probably exceeding 3000 m during Late Jurassic and Early Cretaceous time and was probably uplifted from the Late Cretaceous through the Eocene. Compared to most Carboniferous coals, the rates of burial and uplift were
rapid, perhaps so rapid that the inter- or intra-particle pore pressure could not be dissipated to the extent possible with slower rates of burial and uplift. Alternatively, the paucity of striated structures in other coal deposits may simply reflect the lack of systematic investigation of fracture morphology of the coal. This latter suggestion is, in part, supported by the large percentage of descriptions of conical structures in coal by individuals who did not collect the samples in place, but who appreciated their significance.

The restricted occurrence of the conical structures to coal as compared to adjacent lithologies is probably a product of the relatively low compressive and tensile strength of coal, perhaps in conjunction with a further loss of strength and increased brittleness resulting from inter- and/or intra-particle pore pressure. The similarities between conical structures in coal and shatter cones, as discussed by Bucher (1963), does suggest that they are the same type of structure. Conical structures of this study are considered to be three-dimensional planar striated structures, but formed from a nearly radial stress system. Based on the similarity between the planar striated structures of this study and chevron-structured, hackle-marked joints, it is suggested that three-dimensional, conical structures should form in other rocks given a radially disposed stress system. Thus, the lack or rarity of such structures with the exception of those associated with, or considered to be associated with cryptoexplosion structures, indicates that intense stress waves are necessary for their formation in most rocks (Dietz, 1968). As pointed out by Bucher
(1963), however, high fluid pressure or gas pressure may augment the formation of conical structures in rocks by increasing their brittleness in much the same way as high inter- or intraparticle gas pressure may have facilitated the formation of the conical structures in coal of this study.
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SUMMARY AND CONCLUSIONS

The structural style and associated features of coal measures of the Kootenay Formation in the southeastern Canadian Rocky Mountains is in part typified by the "Foothills Family" of structures. In addition, by virtue of the major contrast in competency between the coal seams and adjacent sandstone units, the structural style of the coal measures displays considerable variation which, to some extent, can be correlated with the regional and local structural settings and lithologic variations of the strata. During deformation the coal seams were the loci of interstratal slip, and high angle reverse faults, normal faults and thrust faults commonly offset the seams. In many areas the coal is pervasively sheared and the original depositional fabric has been destroyed.

The mechanisms leading to the formation of structurally thickened coal deposits varies considerably in the study area. In all areas, however, structural thickening has been facilitated by cataclastic 'flow' of the coal from areas of high stress to areas of lower stress. At Vicary Creek the variation in thickness of the Number 2 Seam is a result of contraction faulting, extension faulting and interstratal slip. At Grassy Mountain, thickening is related to folding of the coal measures and decollement at the level of the coal seam, which facilitated transport of the coal both parallel and obliquely to the ac fabric plane of the fold. At the Southern deposit of Tent Mountain, Number 4 Seam has been thickened as a result of drag and plowing of portions of the seam up-dip along the base of a major thrust fault and, to a lesser extent, as a result of
contraction faulting in the footwall of the seam. In the Western and Northern deposits on Tent Mountain thickening of the coal seams is principally the result of squeezing of coal from the limbs of folds into the hinges, similar in gross aspect to that documented for flexural flow and chevron folding.

In underground mines the structural features of the coal measures have a pronounced affect on roof conditions. In the Vicary Creek mine the Number 2 Seam has been pervasively sheared by interstratal slip resulting from flexural slip and possibly from drag from overriding thrust faults. The coal pillars, which largely consist of highly sheared coal, have a correspondingly low bearing strength and fail by flowage of coal out of the rib areas rather than along discrete shear planes. Minor variations in roof rock lithology have notably influenced the response of the strata to deformation. Thin-bedded strata, interpreted as distal crevasse splay deposits, contain discrete laminae of carbonaceous material which were preferred horizons for interstratal slip and which now comprise major structural discontinuities along which roof failure may occur. Thick-bedded strata, interpreted as proximal crevasse splay deposits, did not facilitate interstratal slip, but rather are well jointed, resulting in a blocky roof rock which requires completely different support devices than thinner-bedded strata. Slickenside striae on bedding surfaces and some extension faults define a kinematic pattern which is consistent with the regional structure. Joints in the roof rock lie in hkl and hk0 and are dynamically related to interstratal slip. Some extension faults pre-date interstratal slip. Faults, low amplitude folds and
slickensided bedding surfaces in the roof strata result locally in poor roof conditions.

In the Balmer North, Six Panel and Five Panel mines, located in the northern end of the Fernie synclinorium, the coal measures are only mildly deformed. A cleat system is evident at almost all sample localities, but no overall consistent pattern exists. Joint sets in roof and floor strata lie in hkl and hko and only at a few localities do they conform to adjacent cleat systems in the coal. Only a few major extension faults, which lie in h01, are present in the mines. In the Balmer North mine young, gently west dipping shear surfaces are present throughout which, in conjunction with cozonial extension faults and slickensided bedding surfaces, have promoted failure of both roof rock and coal pillars along north to northwesterly trends. In the Five Panel mine both coal pillars and roof rock failure have been facilitated by steep, easterly dipping shear surfaces in conjunction with slickensided bedding surfaces. The absence of a consistent cleat or joint system in the mines may be the result of the mechanical anisotropy of the coal measures or multiple episodes of deformation.

Intensely sheared and comminuted coal is common throughout much of the study area. On a mesoscopic scale the coal has a brecciated fabric. Adjacent to and within major shear zones the coal is very finely granulated and polished. The microfabric of the coal is generally similar to the mesoscopic fabric, consisting of angular fragments of coal with no evidence of truly ductile behavior with the exception of areas of apparently high strain where the clarite component of
the coal *locally* has flowed plastically.

Measurements of vitrinite reflectance of coal in some shear zones suggest, by comparison with samples heated in the laboratory for short durations, that frictional heating may have resulted in temperatures of up to 450°C along the shear planes. Adjacent to and within other shear zones, however, there is no evidence of frictional heating. The presence or absence of frictional heating may be the result respectively of stick-slip as compared to stable sliding conditions during faulting. The results also *imply* that regions of significant and insignificant stress may exist during thrust and reverse faulting, which may have been the result of variable pore pressures.

The thermal effects of shearing on coal quality are insignificant. However, mechanical comminution as a result of shearing of the coal and associated rock partings has resulted in a disproportionately high ash content and poor washability characteristics, and have promoted pervasive oxidation of the coal even at considerable depths below the weathering horizon.

Striated structures, many of which are conical in form, are a common mesoscopic feature on fracture surfaces in the coal. The structures are conical, planar and pyramidal in form and are characterized by striae which radiate from a common apex and 'horsetail' to form secondary structures on the master surface. Although such structures have been reported previously from coal, the structures are much more abundant and morphologically more diverse in deformed coal seams of the study area. The abundance of the structures in the study area may be related to the deformational history of the seam. All three
types of striated structures recognized are considered to have formed during brittle shear fracture. The apparently restricted occurrence of the structures to coal is likely the result of the low tensile and compressive strength of coal, possibly augmented by high inter- and/or intra-particle pore pressure resulting from devolatilization of the coal during coalification.