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CANADA

DEPARTMENT OF MINES AND TECHNICAL SURVEYS

GEOLOGICAL SURVEY OF CANADA

BULLETIN 44

STRUCTURAL CONDITIONS IN CANADIAN COAL MINES

By

D. K. Norris

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
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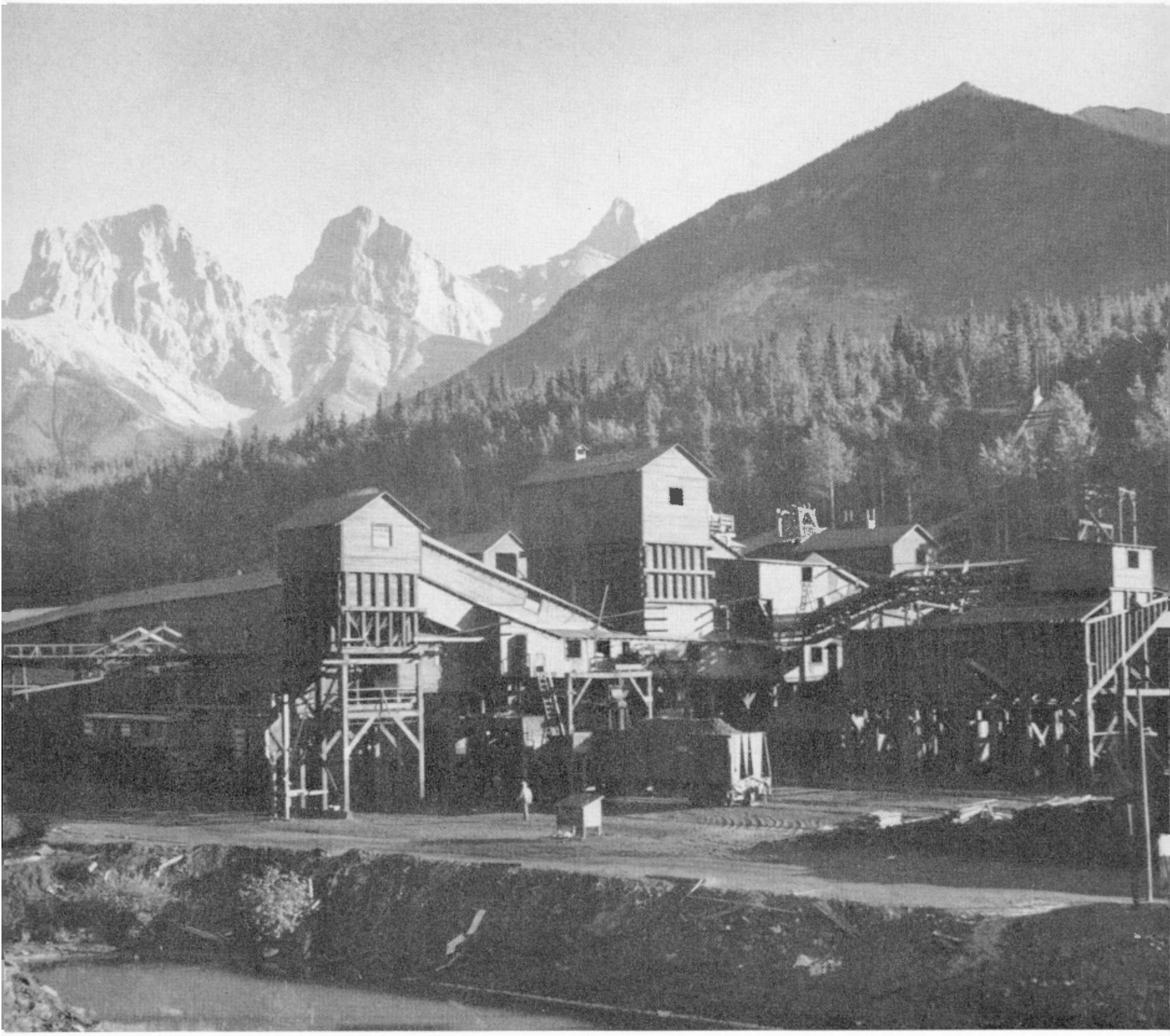

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A coal tipple in the lee of The Three Sisters, Canmore, Alberta. The coal measures underlie treed slopes in middle background.

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PREFACE

In order to develop criteria that may assist the coal mining industry to establish safe and economical deep mining practices, the author, in cooperation with officers of the Mines Branch, made a detailed examination of structural conditions in some of the coal mines in the eastern part of the Cordillera and in Nova Scotia. Thus far coal mining has been restricted mainly to those parts of seams that are most accessible and that are least disturbed structurally. Supplies of such coal are, of course, limited and operations must be continually extended to greater depths and to highly deformed ground.

This report presents the author's interpretation of the relationship between geological structure and mining practice in the extraction of coal at depth and in areas of structural complexity.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, May 27, 1957

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STRUCTURAL CONDITIONS IN CANADIAN COAL MINES

CHAPTER I

INTRODUCTION

Coal mining in structurally complex belts is faced with problems not encountered in the exploitation of flat, undisturbed seams. Faulting, folding, and shearing of the seams have in many instances radically deformed the coal and associated rocks. Thrust, high-angle reverse, and normal faults have so completely fractured the coal measures that rocks overlying the seams cannot support themselves for any length of time over haulageways and airways, let alone over large spans in extracted areas. Consequently maintenance costs in vital arteries of the mines may become prohibitive. Moreover, faults may offset the seams so that brushing and driving of rock tunnels are necessary. Gentle folding of the measures is not serious but tight folding may render economic coal extraction impossible. Where the measures are deformed the seams are commonly highly sheared, with the primary sedimentary features and cleat being completely destroyed. Shale partings are sheared, resulting in a finely divided coal with abnormally high ash content. In extreme cases the seams pinch and swell, and many barren areas develop. The correspondingly thickened parts can rarely be completely extracted, because the coal cannot support the roof strata.

An intimate knowledge of geological structure, both regionally and within the mines, is needed for successful coal extraction in orogenic belts. Thus far the tendency has been to exploit those seams or parts of seams that are most accessible and least disturbed structurally. In orogenic belts, however, such coal is limited and inevitably mining must be carried out in complex areas. In many instances the workings have been extended so far along strike that haulage costs are prohibitive and the workings can only be extended downward. Additional problems then arise such as the continuous convergence of roof and floor, which necessitates continual brushing in order to maintain adequate height for movement of mine cars, etc., and the violent failure of coal pillars in the vicinity of the extraction line.

It was difficult to establish the general structural pattern within the mines examined because large parts of some workings were inaccessible. An area is usually abandoned when the coal has been mined out, and it is soon rendered inaccessible by caving of the superjacent strata. Consequently, the only parts of a mine within reach are the active workings, which include main haulageways, airways, and recently driven openings in areas being prepared for complete extraction. Even in haulageways the structures are commonly masked through brushing of the hanging-wall and foot-wall and tight spacing of the timber supports.

In thick seams or swelled parts of thin seams it is common practice, in the course of cutting coal beds into pillars, to drive openings in the upper parts of the seams. Structural studies are then confined to the roof strata and the top few feet of coal. It is only at the extraction line of thick seams that deformation of both roof and floor may be examined. It is, therefore, difficult to tell if faults in the floor actually cut the seam and continue uninterrupted into the roof. The roof and floor counterparts of some faults are indeed offset with respect to one another in the plane of the seam.

It is not the practice of coal operators to maintain a systematic record of structural features encountered in the course of mining operations. The progressive invasion of new parts of seams with abandonment of worked-out areas has resulted in considerable loss of structural data for large parts of the mines.

The pillar-and-stall method of coal extraction is practised in the Drumheller mine, but in all other mines listed from Western Canada the room-and-pillar method is used. Longwall mining is practised in all workings visited in Nova Scotia.

Areas Examined

To evaluate the interplay of geological structure and mining practice on problems of coal extraction it was necessary to compare and contrast structural differences within the same, as well as in different, tectonic units. Both regional and underground studies were made. The mines considered are in two widely separated coal belts, one in the southeastern Cordillera and the Alberta syncline, and the other in Nova Scotia, in the northern extension of the Appalachian Mountain system (*see* Figures 1 and 7).

In Alberta and British Columbia, the principal areas discussed are the Fernie area on the west side of the Crowsnest coalfield[1] of British Columbia, and from south to north, the Crowsnest, Cascade, Drumheller, and Nordegg coal areas[2] of Alberta. In Nova Scotia the Springhill, Joggins, and Sydney coalfields were studied.

Regional structures were examined in the Crowsnest coalfield, and the Crowsnest and Cascade coal areas. Underground studies were carried out

[1]The Crowsnest coalfield is distinct from the Crowsnest coal area of Alberta, and is herein defined as that area in southeastern British Columbia delineated by the Kootenay formation on the flanks of the doubly plunging syncline lying between the Elk River thrust on the west and the Lewis thrust on the east (*see* Figure 1).

[2]The coal areas referred to in Alberta are as defined by the Research Council of Alberta (Allan, J. A., 1943).

in the Fernie area, in Number 1 East, 9, 4, and 3 mines of Elk River Collieries, British Columbia; in the Crowsnest coal area, in McGillivray and International mines of Coleman Collieries, Coleman, Alberta; and, in the Cascade coal area, in Number 4 and Upper Marsh seams of Canmore Mines Limited, Canmore, Alberta. Structures underground were also studied, in the Nordegg coal area, in Number 2 and 3 seams at Brazeau Collieries, Nordegg, Alberta; and, in the Plains region, in the workings of Red Deer Valley Coal Company, Drumheller, Alberta. In Nova Scotia, deep-mining problems were studied, in the Springhill coalfield, in Number 2 and 4 mines of the Dominion Steel and Coal Corporation, and, in the Sydney coalfield, in Dominion Number 18 Colliery, New Waterford, N.S.

Acknowledgments

The writer is indebted to the administrative and engineering staffs of Coleman Collieries Limited, Crowsnest Pass Coal Company, Canmore Mines Limited, Brazeau Collieries Limited, Red Deer Valley Coal Company Limited, and Dominion Steel and Coal Company Limited for time and effort generously given in supplying technical data on the workings of the respective mines. Sincere thanks are also extended to the many firebosses and other underground personnel who offered assistance so many times throughout the investigation.

Special thanks are rendered the writer's associates of the Department of Mines and Technical Surveys for providing data on other aspects of the problems with which to temper his own conclusions. The writer is most grateful to A. Ignatieff, Mining Engineer of the Mines Branch, Department of Mines and Technical Surveys, and to Professor J. A. Noble and the late Professor J. P. Buwalda of the California Institute of Technology, for their invaluable guidance and critical analysis of both the mining and geological aspects of the investigation.

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CHAPTER II

GEOLOGY OF SOUTHEASTERN CORDILLERAN COAL AREAS

The coal areas considered lie in three different structural environments. The Crowsnest coalfield (*see* Figure 1) lies entirely within the Rocky Mountains, the Crowsnest, Cascade, and Nordegg coal areas lie within the Disturbed belt, and the Drumheller coal area is within the Alberta syncline.

Commercially exploitable coal seams in the southeastern Cordillera and Alberta syncline are all of Cretaceous age (*see* Table I, Correlation Table). They occur in the Belly River, Luscar, and Kootenay formations in the Cordillera, and in the Belly River and Edmonton formations in the Alberta syncline.

Both Upper and Lower Cretaceous coals have been mined in the southeastern Cordillera. Small coal deposits in the Upper Cretaceous Belly River formation occur along the east flank of the main range of the Rocky Mountains in the Crowsnest coal area, but are not being mined at present. Lower Cretaceous coal, however, is being actively mined throughout the Disturbed belt. The Luscar formation, about 900 feet thick, in the Nordegg coal area contains at least five seams (low volatile bituminous), of which two are commercially exploitable. The upper seam averages 13 feet in thickness and the lower about 6 feet. In the Cascade coal area, 3,300 feet of Kootenay strata contain in the neighbourhood of twenty coal seams amounting to a little over 60 feet of coal (low volatile bituminous and semianthracite). Mining has been carried out in about five of these seams. In the Crowsnest coal area two seams (medium volatile bituminous) have been extensively worked at Coleman. There, about 15 feet of mineable coal are included in 355 feet of Kootenay strata underlain by the Coleman fault. In the Fernie area of the Crowsnest coalfield, 2,000 feet of Kootenay strata include about twenty-three coal seams (medium volatile bituminous) having a total thickness of roughly 170 feet. Of these, a half dozen have been mined at intervals in the past 50 years. In the Drumheller coal area the Edmonton formation is about 880 feet thick and five seams have been mined. The coal is subbituminous B and is primarily for domestic use.

In the Nordegg coal area, coal is mined in the homoclinal sequence on the west flank of the Brazeau Range, in the Brazeau thrust sheet (Douglas, 1956)[1]. The Cascade coal area is structurally analogous to the Nordegg coal area, the coal being mined beneath the Rundle fault on the east flank of the Mount Allan syncline, in the Lac des Arcs thrust sheet (Clark, 1949). In contrast to the Nordegg and Cascade coal areas, where Palæozoic strata occur

[1]Names and dates in parentheses are those of references cited at the end of Chapter I.

ERA	PERIOD OR EPOCH	CROWSNEST COALFIELD OF BRITISH COLUMBIA	CROWSNEST COAL AREA	CASCADE COAL AREA	NORDEGG COAL AREA	DRUMHELLER COAL AREA
MESOZOIC	UPPER CRETACEOUS					Edmonton
						Bearpaw
			Belly River		Brazeau	Belly River
			Alberta: Wapiabi		Alberta: Wapiabi	Lea Park
			Alberta: Cardium		Alberta: Cardium	
			Alberta: Blackstone		Alberta: Blackstone	Colorado
			Disconformity		Disconformity ?	Viking
	LOWER CRETACEOUS		Crowsnest		Mountain Park	
					?—	
		Blairmore	Blairmore	Blairmore	Luscar	Blairmore
					Cadomin	
			Unconformity			
		Elk		Pocaterra Creek	Nikanassin	
G. S. C.		Kootenay	Kootenay	Kootenay		

Table I. Correlation table of Cretaceous formations in coal areas of the southeastern Cordillera and Alberta syncline.

within the thrust sheet in which the mines are located, the Lower Cretaceous coal measures at Coleman are faulted at their base (Norris, 1955), and the mines investigated occur within a few hundred feet of the Coleman fault plane. The measures in the Drumheller coal area are essentially flat lying and occur about 65 miles east of the axis of the Alberta syncline.

As only limited parts of the seams are accessible, the data acquired in the course of detailed underground mapping merely sample the whole picture. The pattern of deformation observed throughout all the seams investigated was, however, consistent, and it is believed that this sampling truly represents the actual structural conditions within the various seams.

The writer prefers to avoid the use of the terms "normal" and "reverse" in referring to the faults in the mine workings as the coal measures were rotated after the development of many of the faults. The bedding plane, instead of the horizontal, will, therefore, be used as the plane of reference. Consequently those faults permitting an extension of the strata in the plane of the bedding will be referred to as *extension faults,* and the opposite type as *contraction faults.* With this designation no implication is made as to the spatial orientation of the major principal axes of stress in their development.

Although the stratigraphic throw was observed to range from nearly zero to something in excess of 25 feet, only those extension faults with stratigraphic throws in excess of 6 inches were mapped. In view of their scarcity, contraction faults were mapped wherever observed.

Fernie Area

STRATIGRAPHY

As is characteristic of most of the formations in the southeastern Cordillera, the Kootenay formation thickens westward and contains progressively greater proportions of coarse sediments. Thus, where Coal Creek has incised the western margin of the Crowsnest coalfield, Newmarch (1953) measured 2,060 feet of interbedded, dark grey to black, fine- to coarse-grained, crossbedded, thick- to very thick-bedded (Gray, 1955) chert and quartz sandstones; dark grey to black, silty, carbonaceous shales; and twelve coal seams of commercial thickness. Occasional chert and quartzite pebble-conglomerates occur as lenticular interbeds, thicker towards the top of the formation.

The Elk formation (Newmarch, 1953) rests conformably between the Blairmore group above and the Kootenay formation below (*see* Table I, Correlation Table). It thins eastward and consists of 1,700 feet of strata lithologically similar to the Kootenay beds, but with thick-bedded, pebble- and cobble-conglomerates. In the Crowsnest coal area Blairmore beds rest unconformably on the Kootenay formation. If the Blairmore strata are equivalent in the two areas then the Elk formation, if deposited, was removed by pre-Blairmore erosion. Conformably overlying Elk strata is a thick-bedded, chert and quartzite pebble-conglomerate, followed by typical maroon and green shales of the Blairmore group.

In the Fernie and Crowsnest coal areas, the contact between the Cretaceous Kootenay and Jurassic Fernie formations is gradational and is drawn at a colour break (especially on the weathered surface) between dark grey weathering, thick-bedded Kootenay sandstone and rusty brown weathering, thick-bedded Fernie sandstone.

GENERAL STRUCTURE

The Crowsnest coalfield is a doubly plunging syncline (*see* Figure 1); the Fernie area is on its west flank. Immediately to the west is the Lizard Range, underlain by the folded but generally west-dipping Elk River thrust. The surface trace of the fault extends throughout the length of the western margin of the Crowsnest coalfield. Along it Upper Devonian and Mississippian strata are thrust eastward over Jurassic rocks.

Elk River has incised deeply into the relatively incompetent units beneath the thrust and the more resistant sandstones and conglomerates of east-dipping Kootenay and Blairmore strata stand out in bold relief along the east side of the valley. It is the cutting down by Elk River and its tributaries that is responsible for extensive exposures of coal seams along the west side of the Crowsnest coalfield.

DETAILED STRUCTURE

Mining operations at Elk River Collieries, 3 miles east of Fernie, are presently conducted in the four uppermost, mineable seams on the south side of the valley of Coal Creek. The gentle easterly dip of Kootenay and Blairmore strata ranges from about 30 degrees at the outcrop on the east side of Elk River valley, to a gently undulating condition within a few miles to the east.

Underground studies included the mapping of the Number 1 East, 9, 4, and 3 mines. In so far as the last-named three mines are concerned, the deformation of the seams is so alike that a detailed discussion of Number 3 mine will suffice for all three.

Number 1 East mine is operated in Number 10 seam, the highest workable seam in the Kootenay formation on the valley slopes of Coal Creek. Only the outer fringe of this mine was accessible because of the hazard of violent stress relief in the deeper workings. Few data are available on structural conditions in the inner workings except for surveyed elevations of the seam at various points. Roof contours based on these points reveal a relatively horizontal, undulating condition throughout the seam. In the outer

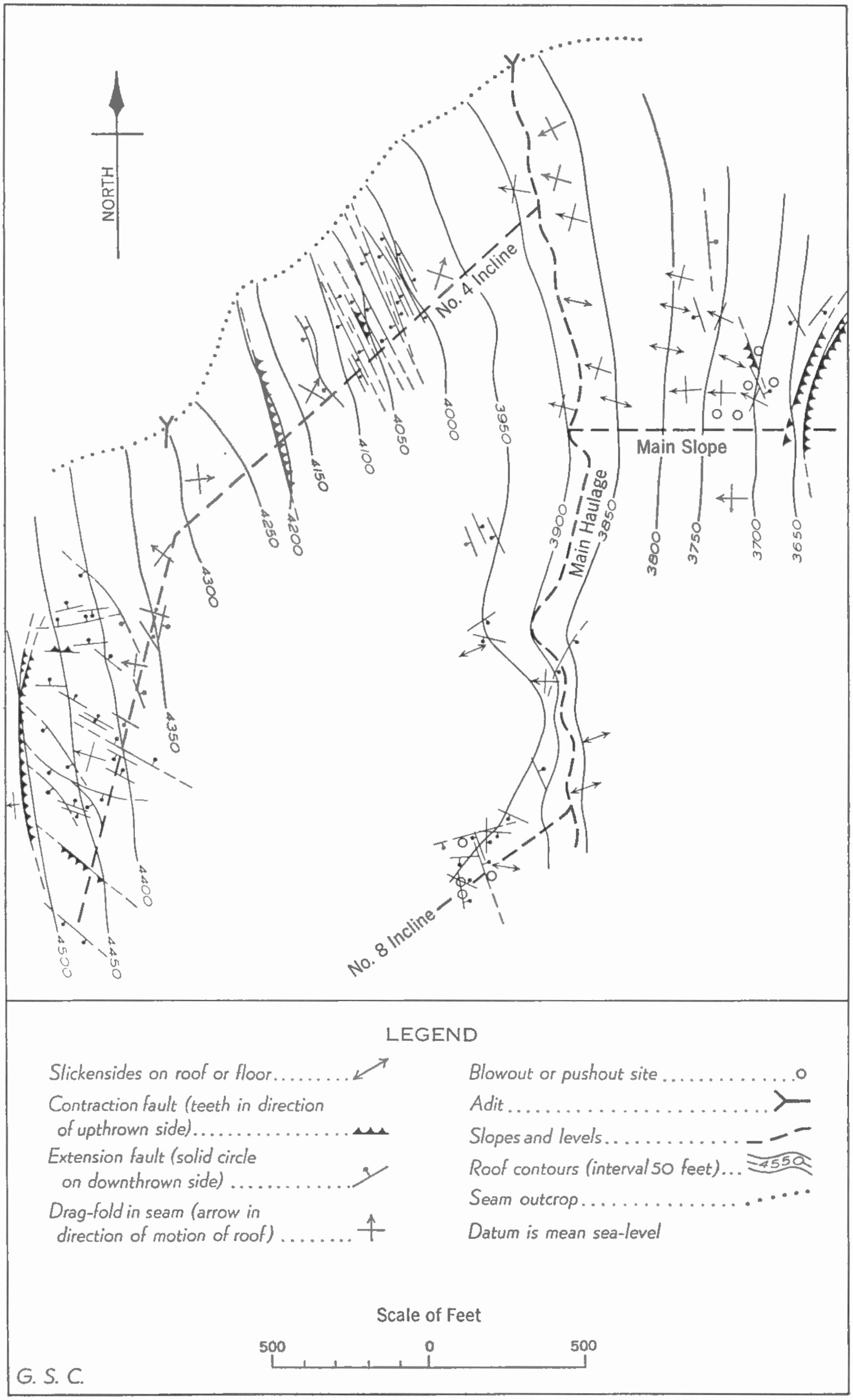

Figure 2. Structural map of Number 3 mine, Elk River Collieries, B. C.

workings only one fault, an extension fault with maximum stratigraphic throw of 6 feet, was observed. It was traceable for about 800 feet along the strike of the seam.

The coal seam in Number 3 mine (*see* Figure 2) has a generally uniform dip of 20 degrees and, in certain sections especially those up slope from the main haulageway, a profusion of faults. (The faults on the map are projections into the horizontal of the trace of the faults on the roof of the seam.) In the vicinity of Number 4 incline, and in the workings south from the top of this incline, the faults within individual clusters have the same trend, whereas near Number 8 incline the fault trends vary considerably. A high percentage of the faults are extensional and most of them have throws of less than 1 foot. In addition to those mapped, innumerable extension faults of very small displacement and exceedingly irregular trace cut roof and floor of the seam. Contraction faults rarely have throws less than 1 foot, and throws from 10 to 20 feet are common.

Many of the faults are not traceable from roof to floor of the seam, mainly because the bottom coal has not been mined out and the structures in the floor are not visible. However, in most cases where the coal is highly sheared and all extracted, the continuation in the floor of a fault in the roof is conspicuously absent, and vice versa.

Aside from those offsets involving roof and floor, the seam itself has been subjected to intense shear which has resulted in most places in a complete disappearance of any original cleat or primary bedding features. This shearing has produced abundant polish and slickensides on the roof of the seam. Slickensides on the roof and drag-folds within the coal (*see* Figure 2) indicate that the hanging-wall moved up the dip relative to the seam during the period of deformation. In those areas where caving has taken place or the measures are cut by rock tunnels, evidence of bedding-plane slippage was found within the adjacent strata, the slickensides in all cases paralleling that on the roof of the seam. This observation in combination with axial thickening of the coal in folds suggests that similar folds were produced in the coal measures.

Crowsnest Coal Area

STRATIGRAPHY

The Kootenay formation in the Crowsnest coal area is composed of interbedded, medium- to thin-bedded, gritty, dark grey, rusty brown weathering siltstones and medium-bedded, fine- to medium-grained, crossbedded, grey sandstones; dark grey to black, silty shales; thick-bedded, crossbedded, coarse-grained, grey, rusty brown weathering sandstone; and three coal seams of commercial value. Whereas the sandstone and siltstone beds are lenticular Number 2 and 4 seams persist for many miles along strike.

Irregular conditions of deposition within the Kootenay formation are indicated by the progressive northward thinning and final disappearance of Number 2 seam, its place gradually being taken by hard, thick-bedded, coarse-grained sandstones. The 90-foot interval of black, carbonaceous, silty mudstones and thin-bedded siltstones between Number 2 and 4 seams at the north end of the McGillivray mine thins southward to the point where the two seams merge, in International Pit 3, 3,000 feet south of York Creek.

The contact between the Kootenay and the overlying Blairmore strata is unconformable, as indicated by variation in stratigraphic interval between Number 2 seam and the basal conglomerate of the Blairmore group. In surface sections the interval ranges from as little as 12 feet in the vicinity of Coleman to as much as 78 feet, 4 miles south of the town. Within McGillivray mine, the basal conglomerate is in contact with Number 2 seam at a few points.

Unlike the depositional contact at the base of the Kootenay formation at Fernie, the coal-bearing sequence at Coleman is underlain by the Coleman fault of about 7,500 feet stratigraphic throw. Upper Cretaceous, Belly River strata predominate in the immediate foot-wall of the fault.

GENERAL STRUCTURE

The Crowsnest coal area lies within the western part of the Disturbed belt, that major structural subdivision lying between the main ranges of the Rockies and the Alberta syncline. It is roughly divisible into two parts, an inner or western area of low relief containing the headwaters of the Crowsnest River, and an outer or eastern system of mountains containing the Blairmore and Livingstone Ranges. Five major west-dipping thrust faults underlie the area (Norris, 1955). From east to west respectively they are Mill Creek fault, Livingstone thrust, Turtle Mountain fault, Coleman fault, and Lewis thrust.

East of the Livingstone Range, strata of the Belly River formation and the Alberta and Blairmore groups overlying the Mill Creek fault are closely folded and broken by several splays from this fault, some of which are warped. Above the Livingstone thrust late Palæozoic rocks appear along the Livingstone Range in close folds which plunge south beneath intricately folded and faulted Mesozoic strata immediately north of Crowsnest River.

Within the Blairmore Range late Palæozoic strata overlying the Turtle Mountain fault are folded into a large doubly plunging anticline. In the south, on Hastings ridge, this anticline plunges gently south whereas in the north, on Bluff Mountain, it plunges steeply north and is truncated by the Turtle Mountain fault, where it swings abruptly west before continuing north along the crest of Grassy Mountain. Incompetent Jurassic and Lower Cretaceous rocks on Grassy Mountain are intricately faulted and folded, with thickening of the coal seams in the cores of some flexures.

In the hanging-wall of the Coleman fault is a relatively undisturbed sequence of west-dipping Cretaceous sedimentary and volcanic rocks. In the immediate foot-wall are Upper Cretaceous Belly River strata. For some miles along strike in the vicinity of Coleman the fault is localized as a zone of bedding-plane slippage in Number 5 coal seam completely spoiling the economic possibilities for that seam. An airway in International mine follows this zone for 2,000 feet up the dip.

The Lewis thrust underlies the High Rock and Flathead Ranges in the Crowsnest area. Upper Devonian, Cambrian, and late Beltian rocks rest on moderately disturbed Belly River strata. Between Crowsnest Lake and the Crowsnest Mountain klippe the thrust plane cuts up section in the overlying mass, as some 2,600 feet of Upper Devonian sediments were observed above the fault at the lake but only 400 feet on Crowsnest Mountain. Moreover, within the first half mile along the trace of the Lewis thrust to the north of Crowsnest Lake, roughly 300 feet of the lowest Devonian beds are cut out. Twenty miles to the north the Lewis thrust is within the upper 1,000 feet of Devonian strata along the east flank of the High Rock Range. In passing eastward across the valley of Dutch Creek and beneath Tornado Mountain the fault cuts up section in the overthrust mass and parallels the bedding about 250 feet below the top of the Devonian Palliser formation.

DETAILED STRUCTURE

During the last 50 years extensive mining has been carried on in Number 2 and 4 seams at Coleman. Both seams are worked from two mines; McGillivray mine, north of Crowsnest River, and International mine south of the river. In each mine rock tunnels facilitate easy access to both seams. Number 2 seam is emphasized here because of the extent of operations within it and the accessibility of the workings. Number 4 seam is mostly mined out and only the haulageways within it are being maintained to facilitate complete extraction of the overlying Number 2 seam.

The profusion of faults throughout the workings in Number 2 seam of McGillivray mine shows no regional pattern. The proximity of the seam to the Coleman fault (about 340 feet, stratigraphically below it) is doubtless responsible for the multitude of small faults cutting the seam and the intense shearing of the coal. As at Elk River Collieries, most faults in the seams are extensional.

The outstanding feature within Number 2 seam is the low-angle, west-dipping contraction fault cutting Number 5 level and resulting in a 160-foot horizontal offset of the seam at this level. The fault cuts upward through the section at about 20 degrees to the bedding. About 6,000 feet to the north of this point it changes to a fold overturned to the east. The foot-wall of the fault is flexed into a gentle anticline and syncline. This deformation is in marked contrast to the planar condition of the seam in the International workings.

As a result of extensive bedding-plane slippage, localized particularly within the seams, Number 2 coal is highly sheared, especially in the southernmost workings of International mine. There, shearing and pinching and swelling of the seam indicate the intensive deformation of the coal. In McGillivray mine the proportion of sheared coal progressively diminishes to the north and the amount of bedding-plane slippage within the seam is correspondingly less. Deformation in that mine was primarily in folds and low-angle contraction faults, whereas in the south of International mine it was in bedding-plane slip.

Two dykes, 2 miles apart and cutting the seams in McGillivray mine, provide evidence of minor bedding-plane slip. The more southerly one is not offset within Number 2 seam, whereas that part of the other in the hanging-wall is offset 32 feet up the dip in the plane of the seam relative to its continuation in the foot-wall.

The amount of stratigraphic throw of the extension faults varies. The throw of such a fault may gradually increase to 1 foot or 2 feet, then abruptly increase by a factor of several times only to diminish equally as quickly to zero within a few tens of feet. As a generalization it may be said that faults of largest throws extend for the greatest distance in the plane of the seam.

The identification of a particular fault in two different seams is impossible unless mining is being carried on simultaneously in the critical areas of both seams, and there has been a minimum of bedding-plane slippage. A fault may be offset at one or more horizons in the plane of the bedding, so that even though it cuts through to another seam it may not be recognized. However, conditions were favourable in McGillivray mine in the immediate vicinity of the dyke which was not offset. There, faults with stratigraphic throws greater than 3 feet were traceable from Number 2 seam to Number 4 seam, 81 feet stratigraphically below it. Common trends, angles of intersection in the plane of the seams, displacement, strike, and dip all facilitated recognition. Faults of small throw (less than 3 feet) could not be correlated and many must peter out within a few tens of feet above and below the seams in which they were observed.

Studies in cross-measure tunnels reveal that faults are equally as prevalent in the immediate vicinity of the seams as away from them.

Cascade Coal Area

STRATIGRAPHY

The section of Kootenay strata on the northeast slope of Mount Allan is practically continuous and affords detailed information on the stratigraphy of the coal measures in the Cascade area. In order of decreasing abundance the rock types are: dark grey to black, silty shales; dark grey to black, thin-bedded, calcareous siltstones; fine- to coarse-grained, crossbedded, limonitic sandstones; black carbonaceous mudstones; chert and quartzite pebble-conglomerates; and coal.

The formation is divisible into four members (Crockford, 1949). The base of the formation is marked by a persistent, cliff-forming member (the lower sandstone member), about 300 feet thick. This is overlain by 800 feet of strata (the shale member), dominantly shales which weather back and grade upwards into 1,700 feet of a cliff-forming sandstone with several thin coal seams (the upper sandstone member). The top of the formation is marked by 500 feet of interbedded sandstone and conglomerate, termed the conglomerate member. This uppermost member is believed by Crockford to be the equivalent of the Pocaterra Creek member (Allan and Carr, 1947), 50 miles to the southeast. The conglomerate member and the upper sandstone member appear to lie in a stratigraphic position equivalent to the Elk formation in the Crowsnest coalfield.

On Mount Allan the contact with the Blairmore group is drawn at the base of the first thick-bedded to massive, chert and quartzite pebble-conglomerate, with interbedded light grey-brown, calcareous, medium- to coarse-grained sandstone. The contact with the Jurassic Fernie formation is drawn at the base of the lowest massive sandstone bed.

GENERAL STRUCTURE

The Cascade coal area is included in the Lac des Arcs thrust sheet (Clark, 1949). It is limited on the west by the Rundle fault, which underlies the massive limestone peaks of the Rundle Range, and on the east by the Fairholme Mountains and Fisher Range. Formations from Middle Cambrian to Lower Cretaceous are included in this sheet.

The major thrust in the Cascade coal area is the Rundle fault along which sub-Devonian, Devonian, and Mississippian formations have been thrust over Kootenay strata. Repetitions through folding with minor faulting within Devonian and Mississippian strata are evident in the majestic peaks of the Three Sisters of Canmore.

In conjunction with the thrusting, the Kootenay formation was folded into a prominent, asymmetrical syncline, the Mount Allan syncline (Crockford, 1949) which extends throughout the length of the Ribbon Creek area immediately to the southeast. Its vertical to overturned west flank is overridden northwards from the vicinity of the Three Sisters by the Rundle fault sheet. Upper Kootenay beds exposed on the east flank of the syncline dip gently west from 10 to 20 degrees. The incompetence of Kootenay strata is evidenced by considerable small-scale faulting and folding of the coal-bearing sequence.

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Under the glaciated and drift-covered Bow River valley is a homoclinal sequence of Mesozoic strata through to the west flank of the Fairholme mountains. There Palæozoic rocks are deformed into open folds in the immediate hanging-wall of the Lac des Arcs thrust.

DETAILED STRUCTURE

Of the seams studied at Canmore, Number 4 is the only one in which there is some semblance of a fault pattern. There, the general trend of the faulting is a few degrees west of north and cuts across the levels at an acute angle. Moreover, the faulting is concentrated in the northwest workings; to the southeast, where the seam is somewhat flattened, faults are few.

At several points in the seam (especially at the bottom of the main slope) it was possible to study the time relationships of faults that offset one another. There, as elsewhere, nothing systematic was found, and it is concluded that faults with a common trend were not necessarily all formed simultaneously. This is further borne out by the fact that some faults cutting roof strata have offset counterparts in the floor (and vice versa), whereas others may be traced directly from roof to floor through the coal seam.

As in the case of all seams investigated, about 90 per cent of the faults are extensional, and stratigraphic throws less than 2 feet predominate.

In contrast to all other seams investigated in Western Canada, Number 4 seam exhibits a remarkable cleat and fracture system. Throughout the seam the cleat system consists of two sets, the one paralleling the strike of the seam (north 30 degrees west) but dipping at 70 degrees northeast, and the other paralleling the direction of dip (north 60 degrees east) but dipping at 90 degrees. Their surfaces are characteristically bright, especially where they cross vitrain bands. The set paralleling the dip is by far the most prominent and as a result the coal breaks into smooth, tabular sheets as thin as ⅛ inch, and up to ¼ inch. The counterpart of this cleat set is generally poorly developed. The fracture system also consists of two sets, the one striking north 10 degrees east and dipping 70 degrees northwest, the other striking north 85 degrees west, and dipping 70 degrees southwest. They were in general, equally well developed throughout the seam, although at some points one or the other may be absent. Characteristically the fracture planes are spaced from 1 foot to 2 feet apart and extend from roof to floor of the seam so that the coal may break into distinct rhombohedrons. Their dull and minutely slickensided surfaces indicate shear and suggest a different origin from those sets paralleling the dip and the strike of the seam.

If the seam were rotated into the horizontal, the bisectrix of the acute angle between these two sets of fracture planes would strike north 50 degrees east and plunge 50 degrees northeast. The direction of maximum shortening of the strain ellipsoid (of which these two fracture sets correspond to the planes of maximum shear) strikes within 10 degrees of the perpendicular to the regional structural trend and hence close to the direction of maximum shortening in this part of the Cordillera. It is suggested, then, that this system of fractures was developed in the coal early in the Laramide orogeny and rotated into its present position.

The blocky coal of Number 4 seam has been little sheared. In most instances faults may be traced from roof to floor, occasionally with minor offsets. Polish and slickensides, where evident, conform rigorously with the general pattern of an up-dip motion of the roof with respect to the coal seam.

In contrast to Number 4 seam, Upper Marsh seam has been intensely sheared and fractured. Drag-folds within the coal and polish and slickensides on the roof and floor indicate extensive riding of the strata up the dip over one another away from the axial region of the Mount Allan syncline. Because of this movement there are rarely counterparts in the floor of faults in the roof and vice versa.

Two possible explanations of why some seams in the Mount Allan syncline are more sheared than others are, first, radical differences in ability of seams to resist shear; and second, some seams more than others, may be protected from shear. Petrographic and elastic modulus data on Number 4 and Upper Marsh seams are lacking. The presence of thick, incompetent shales adjacent to coal seams should, however, minimize shearing of the coal, for there bedding-plane slippage is distributed throughout the incompetent mass and is not localized in the coal bed. Thick, competent units, on the other hand, tend to maintain larger radii of curvature and to override beds on the flanks of the fold. Coal seams in close proximity to such units would be highly sheared. It would be expected then, that hard, blocky coals are characteristic of the shale member, and such is found to be the case.

Nordegg Coal Area

STRATIGRAPHY

The coal-bearing Luscar formation at Nordegg conformably overlies the Cadomin conglomerate, the lithological equivalent of the basal conglomerate of the Blairmore group (*see* Correlation Table). Although generally poorly exposed in the area of the mines, Luscar strata are known from exploratory drilling to consist largely of interbedded, thin-bedded, crossbedded, fine- to medium-grained, quartz sandstone; dark grey to black, shaly siltstones; black, carbonaceous, shaly mudstones; and coal seams rarely exceeding 15 feet in normal thickness. The contact with the dark grey, silty shales of the overlying Mountain Park formation is sharp and commonly marked by a thin, chert pebble-conglomerate.

GENERAL STRUCTURE

The Nordegg coal area is in the central foothills of Alberta. It is limited on the northeast by the Brazeau Range, and includes part of the Bighorn Range in the southwest. Coal was, until recently, mined at Nordegg in the gently west-dipping homocline on the west flank of the Brazeau Range. The Luscar formation also outcrops on the flanks of the Bighorn syncline to the southwest of the Bighorn Range.

DETAILED STRUCTURE

The Lower Cretaceous Luscar formation at Nordegg is horizontal or dips as much as 14 degrees west. The average dip within the mine workings is about 8 degrees. Number 3 seam and Number 2 seam about 100 feet stratigraphically below it, both in the Luscar formation, have been extensively worked at Nordegg. Number 3 seam averages 13 feet in thickness, and Number 2 averages 6 feet. Both seams have been so intensely sheared through bedding-plane slip that only in the central part of the seams is there any blocky coal, and that only locally. As in all other seams investigated, drag-folds and slickensides on the roof and floor, confirm an up-dip displacement of upper beds over lower. Irregular pinching and swelling of the seams is additional evidence of large-scale movement between roof and floor at the time of overriding.

In contrast to all other seams studied in which the counterpart of a fault in the roof was frequently found in the floor, no such occurrences were observed at Nordegg. Corresponding offsets on the roof and floor have been widely displaced from one another because of interbed movement.

Slickensides on extension faults paralleling the dip indicate that the predominent movement was strike-slip. Moreover, whether such faults were left-handed or right-handed, the down-dropped block is offset to the east relative to its counterpart. Thus the movement of one block relative to another must have taken place when there was an easterly directed component of force.

Drumheller Coal Area

In contrast to the coal measures of the Canadian Cordillera, those of the Alberta syncline have been little disturbed. The coal-bearing Edmonton formation of the Drumheller area (*see* Figure 1) is about 65 miles east of the axis of the Alberta syncline, and is flat lying or dips very gently west. There has been no appreciable interstratal slipping and consequently the coal has retained its original cleat. Moreover, extension faults cutting the seams are scarce. Those observed are dip-slip, with stratigraphic throws rarely exceeding 2 feet. No contraction faults were observed.

Analysis of Small-Scale Faults in the Southeastern Cordillera

In all, 828 faults were mapped underground in the southeastern Cordillera. Of these 747 (90 per cent) were extension and 81 (10 per cent) were contraction faults. A similar study of faults at the Willem Sophia mine in the coal measures of The Netherlands, revealed that of 2,102 faults 21 per cent were "upthrusts" and 79 per cent were "normal" faults (Sax, 1946). The samples in the Cordillera may be inadequate for statistical purposes but there are sufficient data to indicate significant relations between the faults, their respective dips and stratigraphic throws, and the angle between the faults and the bedding planes they cut. It was not possible to measure both dip and throw of all faults examined so that the number of faults used in the analyses is a few per cent less than the totals given.

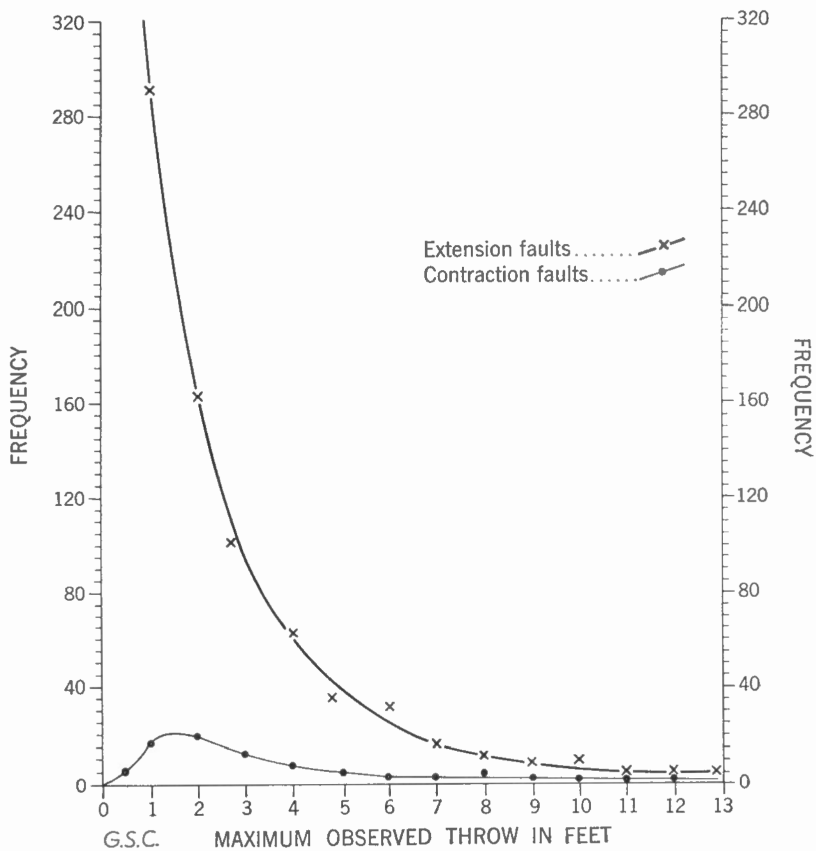

Figure 3. *Frequency of faults with respect to throw, Kootenay formation, southeastern Cordillera.*

Approximately ½ per cent of the faults observed are perpendicular to the bedding and have not been considered. Their stratigraphic throws rarely exceed 1 foot. The relative insignificance of these faults indicates that joint systems perpendicular to the bedding do not act as incipient fault planes.

The frequency distribution of stratigraphic throws of extension and contraction faults is decidedly different. For the 747 extension faults, the distribution is J-shaped (*see* Figure 3, upper curve). It is apparent that extension faults with little throw are very common, but with increasing throw they are less frequent and above a certain size do not occur. The moderately asymmetrical distribution for the 81 contraction faults suggests that the most frequent value for the stratigraphic throw is from 1 foot to 2 feet, with the frequency falling off more rapidly for smaller values than for larger (*see* Figure 3, lower curve). If the sample is representative, these relations are not nullified by the inclusion of major faults. For every thrust fault with its associated splays there exists a multitude of extension and contraction faults with stratigraphic throws distributed according to the above relations.

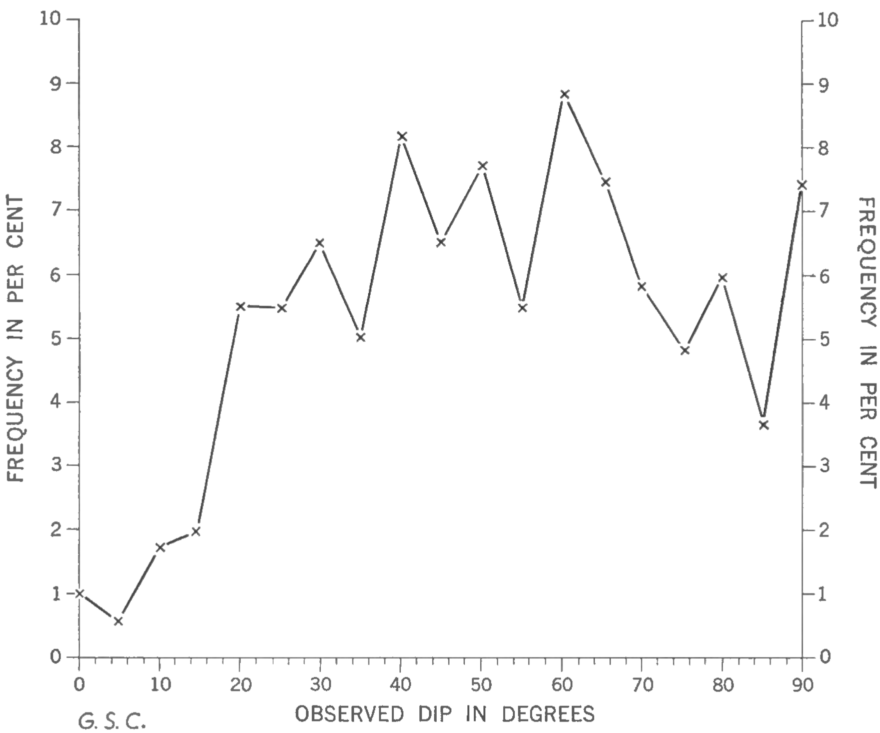

Figure 4. **Frequency (per cent) of extension faults with respect to dip, Kootenay formation, southeastern Cordillera.**

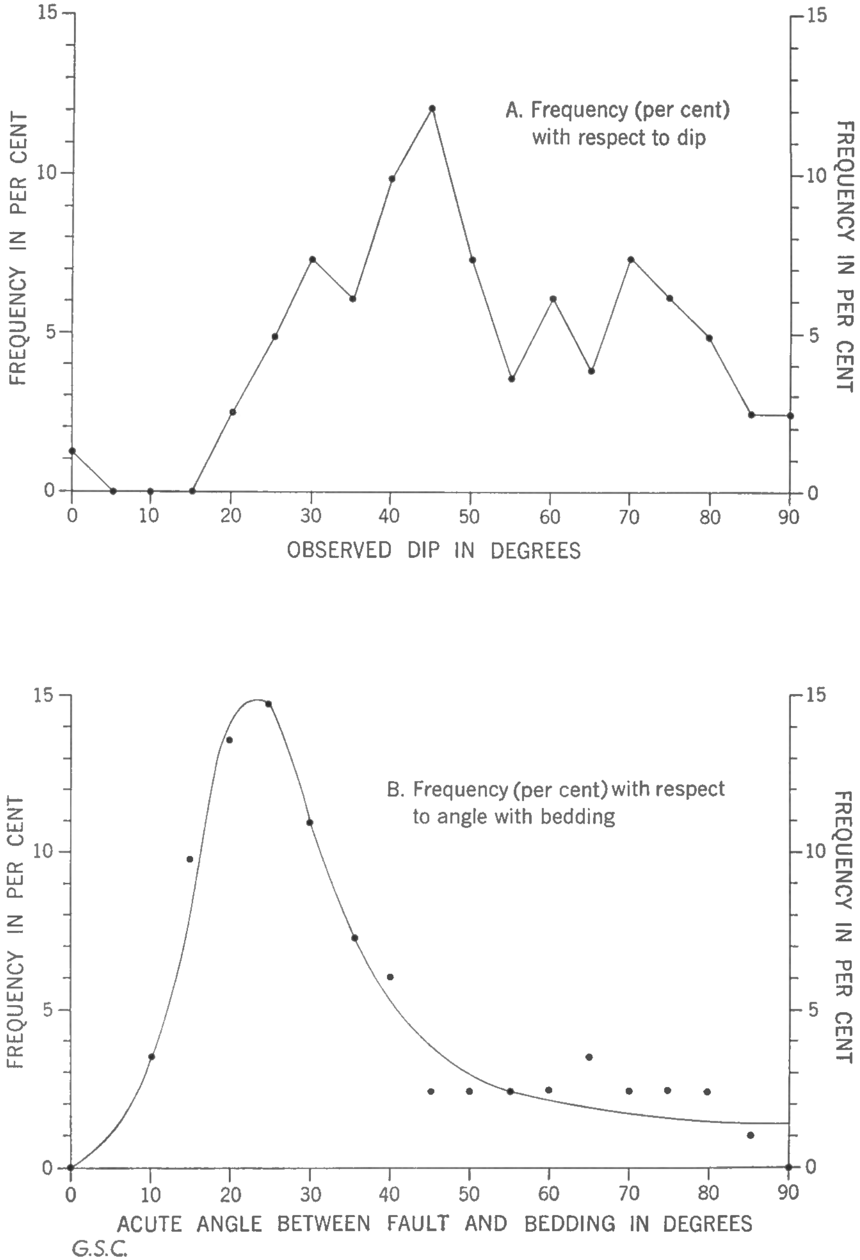

Figure 5. **Study of contraction faults in the Kootenay formation, southeastern Cordillera.**

The frequency distribution of stratigraphic throws of faults indicates the weakness of the rocks in relaxation and the strength in compression. The data suggest that adjustment in relaxation took place on a profusion of extension faults of negligible throw and few with a throw of over 13 feet. Moreover, the strength of strata in compression is indicated by the small proportion of contraction faults. The ability of the strata to transmit compressive forces favoured the development of few contraction faults with small throw and still fewer with either negligible or very large throw.

Frequency polygons of observed dips of extension and contraction faults show no obvious trend (*see* Figures 4 and 5). The distributions although irregular are not completely random as few faults dip at less than 20 degrees. This is to be expected because most of the seams investigated dip within the relatively small range of from 20 to 40 degrees, and a tendency exists for contraction and extension faults to cut the bedding at about 20 and 60 degrees, respectively. Raasveldt's data (Sax, 1946) for the frequency distribution of the dip of faults in the Willem Sophia mine revealed a peak value of 63 degrees for "normal" faults and 22 degrees for "up- or overthrusts". The fact that no similar relation is apparent in Figures 4 and 5 emphasizes the difference in tectonic setting and topographic relief between the Netherlands coalfields and the coal measures of the southeastern Cordillera. Dispersion of the data is believed due to rotation of these contraction and extension faults after their development and the influence of topography, bottom shear stresses, and stratification within the measures on the disposition of the principal stress axes.

To determine the existence of a preferred angle at which contraction faults cut bedding planes, the strata in the immediate vicinity of the 81 faults examined were, in imagination, returned to the horizontal and the dips of the fault planes then computed. Small though the sample is, the frequency distribution curve of the dips after rotation of the beds is moderately asymmetrical (*see* Figure 5) with a peak value at approximately 23 degrees. That the distribution does not reach zero for angles greater than 50 degrees is due to the presence of contraction faults with a strike-slip component. If strike-slip were dominant the major and minor principal stress axes would be in the plane of the bedding and high-angle or vertical shears would form.

A similar analysis was made of the angle at which extension faults cut the bedding planes, using the combined data from Number 3 mine, Elk River Collieries and Number 4 seam, Canmore Mines Limited. The frequency polygon of observed dips of the faults (*see* Figure 6), shows a trend for higher values of dip between 35 and 70 degrees. The frequency distribution of the angles at which the extension faults cut the bedding shows a smooth curve with a peak value at about 58 degrees (*see* Figure 6).

The peak values for contraction and extension faults are roughly complementary and are within 5 degrees of values determined from sandbox experiments by Hubbert (1951). There are, then, preferred angles at which

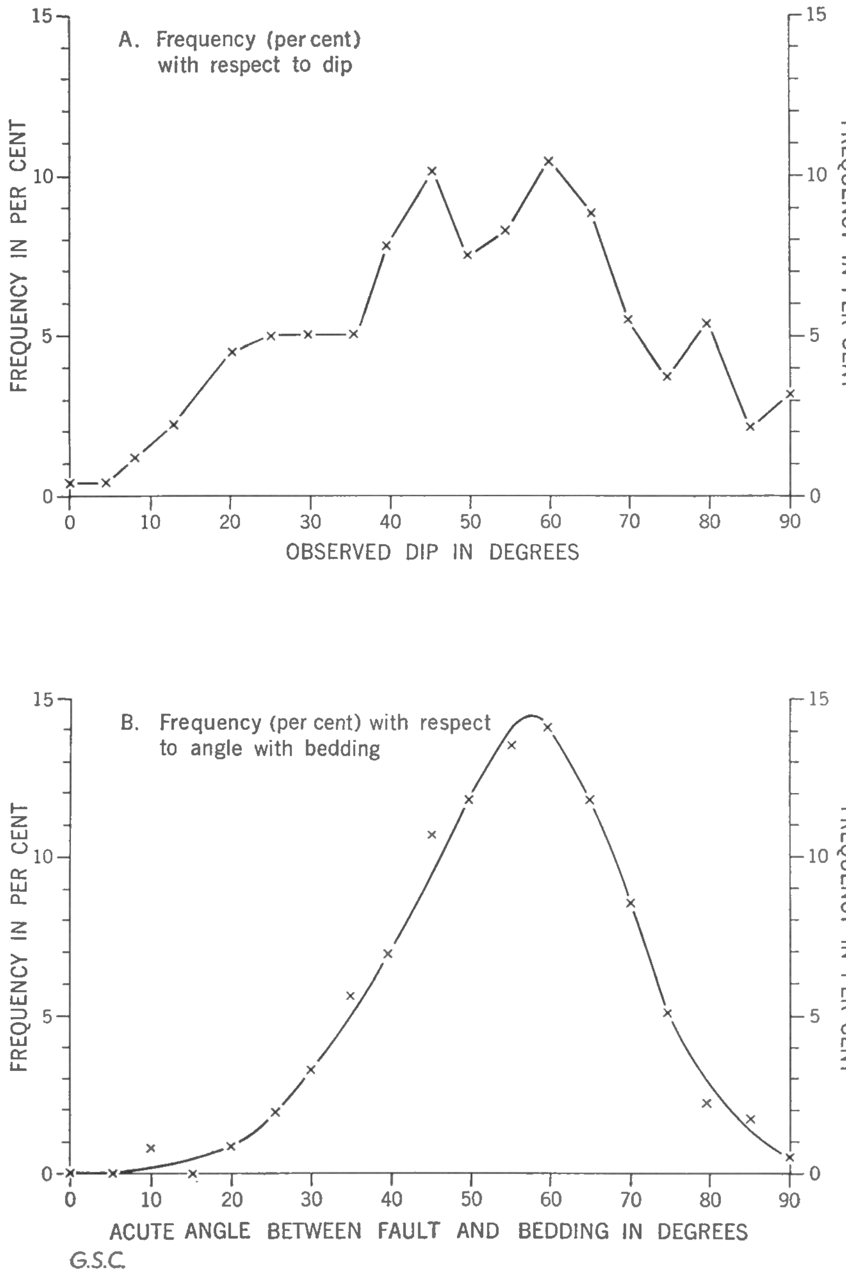

Figure 6. ***Study of extension faults in Number 3 mine, Elk River Collieries, B. C. and in Number 4 seam, Canmore Mines Ltd., Alberta.***

both types of faults cut the bedding. It is suggested that in extension faulting the major principal stress axis is about perpendicular to the bedding, and in contraction faulting, about parallel to the bedding. The skewness of the curves may be due to inadequate sampling and/or tilting of the principal stress axes with respect to the bedding during overriding of thrust sheets.

The peak values for contraction and extension faults, and hence the preferred angles between the shear planes and the major principal axis of compressions are related to the angle of internal friction of the rock (Hubbert, 1951). A peak frequency of 58 degrees for extension faults would yield 26 degrees for the angle of internal friction. This value is in agreement with the results of uniaxial compression tests (Hardy, 1957) on 52 cylindrical specimens of medium- to coarse-grained, quartz and chert sandstones from the Kootenay formation in the Crowsnest coal area. Hardy's tests gave a mean value of the angle of internal friction of 26 degrees, with a standard deviation of 12 degrees. Only those wedge angles were measured in which the failure was dominantly by shear. Similar results were obtained by Nijboer (1942) from triaxial tests on road building aggregates. Under a wide range of values of the principal stresses, more than 95 per cent of his measurements lay within the range of 28 degrees ± 4 degrees. This would correspond in rocks to extension faults with dips of 59 degrees ± 2 degrees. The abnormally high value of the angle of internal friction (44 degrees) determined from the data on contraction faults is believed to be due to the existence of bottom shear stresses acting on the thrust sheets (Hubbert, 1951). Such stresses would warp the stress trajectories downward, thereby making the dip of contraction faults less, and the angle of internal friction correspondingly higher.

The agreement among the values of the angle of internal friction for cohesive materials as determined from extension faults, test specimens of sandstones from the coal measures, and road building aggregates would indicate that the type of strata failure is constant over a wide range of conditions of triaxial stress corresponding to various depths within the sedimentary cover. This fact is borne out by consistent patterns of deformation observed in thrust sheets exposing rocks from widely varying initial depths of cover.

Mechanics of Seam Deformation

It is evident from the constancy of each type of deformation in the coal seams of the southeastern Cordillera that the behaviour of seams in all areas is nearly identical despite differences in regional geological setting. Shearing and faulting in the coal measures appear to be the direct result of overriding compression with localized compression and relaxation on shoulders and flexures. Extension faults, resulting in elongation of the strata in the plane of the bedding, may be due to local relaxation either on shoulders or on the outside of the neutral axes of folds. Contraction faults, on the other hand, are due to compression, either from lateral forces involved in movement of thrust sheets or from forces arising inside the neutral axes of folds.

FOLDING OF OVERRIDING MASSES

In the eastern Canadian Cordillera it has been suggested that the major thrust faults originated from primary fracture planes within the stratigraphic sequence and that there was no appreciable initial folding (Douglas, 1950). Moreover, the paths of these fracture planes, as they cut through the section, were controlled by the competency of successive units.

In cutting up section these primary fracture planes generally pass through the more massive limestone, sandstone, and conglomerate members at steeper angles than in the incompetent shales and coal, so that regionally the thrust planes are made up of a series of shoulders and flats, the latter approximating zones of bedding-plane slippage, and the former, zones of rapid cutting up section through the sequence. With variations in stratigraphic throw along strike, the fracture planes cut through progressively higher or lower units in the sequence.

Movement over shoulders in major thrust planes necessitates moderate flexing of overriding masses. A small displacement on such a fault plane results in folding of an overthrust mass into an anticline where the fault cuts rapidly up section in the more competent units. A gentle syncline develops between successive anticlines because of the bedding-plane characteristics there of the underlying fault. With progressive movement, the part of the overriding mass that is initially flexed into a syncline is then flexed into an anticline as it moves over the top of a shoulder. The strata are then straightened along a stratigraphically higher zone of bedding-plane slippage. In this manner the overthrust mass is flexed first one way then the other, so that a given bed in the sequence is alternately relaxed and compressed. The greater the displacement, the more shoulders and other irregularities the strata pass over and consequently the greater is the amount of flexing to which the displaced mass is subjected.

There may be shearing and faulting of the strata in association with folding within a thrust sheet, as for example in the development of the Mount Allan syncline beneath the Rundle fault. This deformation is, therefore, not directly associated with displacement on an underlying thrust.

It is believed that during the relaxation of a particular segment of the compressed mass, extension faulting is effected. The fact that all extension faults do not parallel the strikes of the major tectonic units may be due to irregularities in the fault surface over which the mass is riding. Aside from shoulders parallel to the strike of the thrust as well as across it, lateral changes in competency of the different units must result in numerous irregularities in the fault surface.

As extension faults have been traced through as much as 80 feet of strata with no apparent offset of the fault plane, it would appear that large intervals, in some instances involving diverse rock types, may relax as single structural units. Evidence from interstratal slippage suggests that adjustments to compression on the inside of folds, on the other hand, take place as successive lithological discontinuities. The data suggest, then, that the Kootenay formation behaved like a laminated beam, with each lamina free to slip at its interfaces, and with a neutral axis corresponding to each structural unit in the formation. The thickness and character of these units vary according to whether the strata are in a state of relaxation or compression.

If a segment of a seam is subjected to overriding compression or to lateral compression inside the neutral axes of folds, contraction faults may be developed. That they are characteristically rare suggests the great strength of the displaced mass in compression. Intense crumpling of the soft, incompetent, carbonaceous shales which characterize the immediate foot-wall of many seams is a natural sequel to compression.

Thus an abundance of minor faults may be developed by means of a gentle flexing in an overriding mass. It has been shown that each is, in general, of limited vertical extent and that they are equally as common everywhere in the stratigraphic sequence as in the immediate vicinity of coal seams.

A natural consequence of bedding-plane slippage within a coal seam is the frequent displacement of faults in the roof and floor. Those faults whose counterparts are readily traceable across a seam were developed either during the waning phase of bedding-plane slippage or in segments of a seam in which there has been little slippage. The absence of a time relationship among extension faults, as in Number 4 mine, Canmore, suggests that different faults were developed at different stages of interstratal slippage.

Despite the aforementioned flexing back and forth of the overthrust masses, drag-phenomena within the seams almost always indicate an up-dip motion of a given bed over those lower in the sequence. With progressive forward movement of an overriding mass, resistance along the thrust plane must retard those beds lower in the thrust sheet. Thus there is an overall differential movement within the mass, resulting in the upper beds moving slightly farther in the direction of the applied force.

All evidence indicates that creeping ahead of the upper beds in overthrust masses is of limited extent. At the northern end of the McGillivray mine, for example, the continuation of a pre-Laramide dyke into the superjacent strata of the Number 2 seam is offset 32 feet up the dip in the plane of the seam. As drag-folds in the coal indicate a differential slip of the beds perpendicular to the strike, 32 feet must be a fair approximation of the absolute displacement of the roof over the floor of the seam in this sector. It would be expected moreover, that bedding-plane slippage is in large part localized within coal seams and other thin, incompetent units. The data suggest that a forward creep of the beds over one another of a few tens of feet would produce the observed pattern of drag-folds within the seams.

Briefly then, overriding compression and folding are responsible for the intensely fractured and faulted condition of the coal measures. Abundant extension faults of small stratigraphic throw are the direct result of relaxation of coal beds, whereas contraction faults, few in number but commonly of larger throws, developed by compression. Similar folding is a natural sequel to an interspersing of competent and incompetent strata. The seams vary in their reaction to flexing, in some instances being intensely sheared, in others retaining for the most part their original blocky nature. Resistance to forward movement of the overthrust mass permitted an overall creep of the upper strata over those lower in the sequence so that a consistent pattern of drag-folds is observed.

CHAPTER III

GEOLOGY OF APPALACHIAN COAL AREAS

Springhill, Joggins and Sydney Coalfields

STRATIGRAPHY

The seams of the Springhill and Joggins coalfields occur in the Cumberland group of the Pennsylvanian system. They are high volatile A bituminous. At Springhill six seams, ranging in thickness from 4 to 10 feet, have been mined. They occur as interbeds in fine- to medium-grained sandstones and silty, carbonaceous shales. The seams in the Springhill area are considered to be stratigraphically higher in the group than those on the opposite side of the Cumberland coal basin at Joggins (Bell, 1944). There, five seams, only one of which has a maximum thickness of more than 3 feet, have been mined. The productive seams of the Sydney coalfield occur in the Pictou group disconformably overlying Cumberland rocks, and hence are slightly younger than those at Springhill and Joggins. They also are high volatile A bituminous. Pictou strata consist primarily of silty and carbonaceous shales, and lenticular conglomerates.

GENERAL STRUCTURE

The coal-bearing strata of the Joggins and Springhill coalfields outcrop on the flanks of the Cumberland basin, a depositional basin (Bell, 1944) whose long axis trends east-northeast and plunges about 10 degrees southwest (*see* Figure 7). Joggins and Springhill, on opposite flanks of the basin, are about 18 miles apart. In contrast, the measures of the Sydney coalfield have been deformed into a series of gentle, open, northeast-plunging folds 6 to 8 miles apart. The seam examined in the Sydney coalfield (New Victoria mine, New Waterford, N.S.) occurs on the north flank of the Bridgeport anticline. Open folds, which predominate in all three fields, are in marked contrast to the intense deformation of the coal measures of the Cordillera.

DETAILED STRUCTURE

At Joggins, Springhill, and New Waterford the coals have retained a strong cleat and the few faults observed are extensional features with slickensides perpendicular to the bedding, and stratigraphic throws rarely exceeding 1 foot. Only one was observed with an offset as great as the thickness of the seam (11,800 level, Number 2 mine, Springhill). Faults are traceable from roof to floor with no apparent offset in the plane of the seams. The absence of bedding-plane slip has favoured remarkable preservation of plant remains.

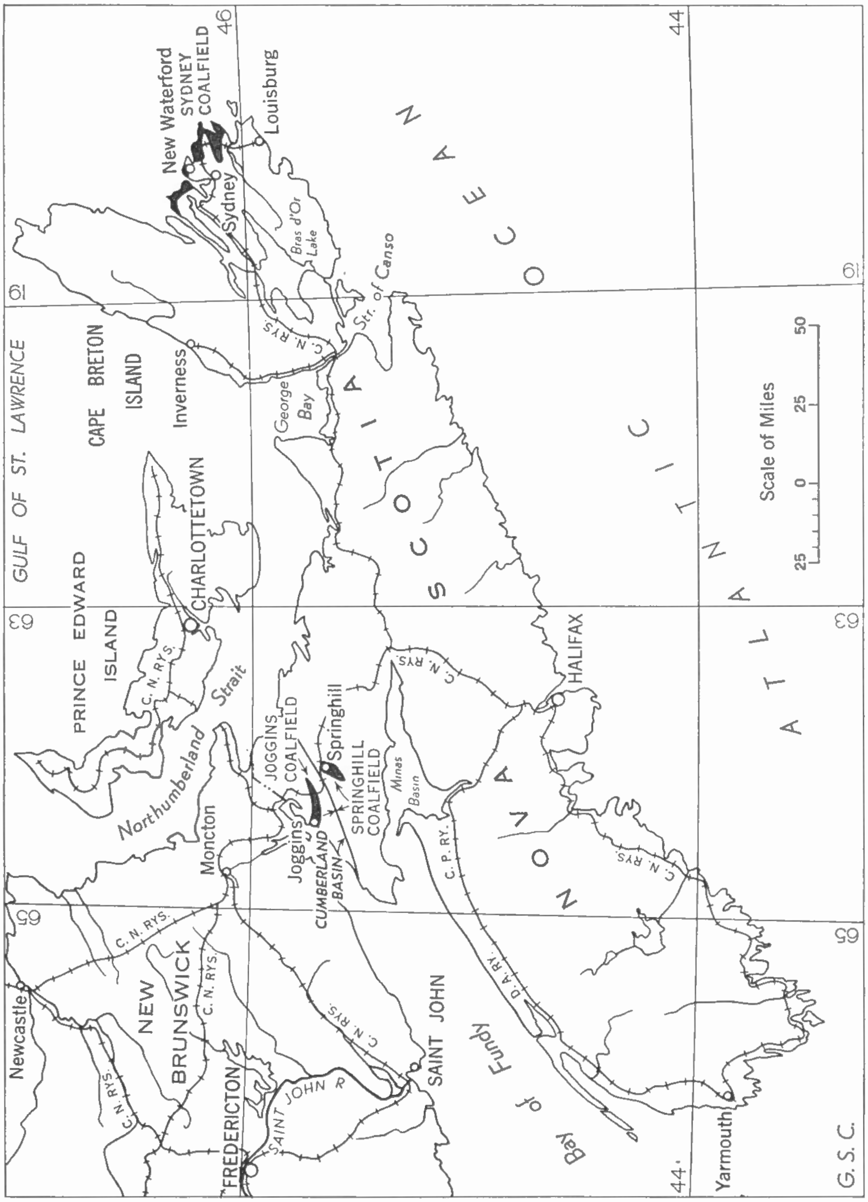

Figure 7. *Coal areas studied in Nova Scotia.*

Jointing in Carboniferous Strata, Joggins, Nova Scotia

Where coal extraction has been carried to depth, joint systems play a significant role in the failure and subsidence of roof rock. The closing of mine cavities behind longwall faces is directly affected by the direction and spacing of joints, and these must be considered in its control.

Extensive outcrops of the coal measures on the shores of Chignecto Bay at Joggins were particularly favourable for joint studies. There, on the northwest flank of the Cumberland Basin, about 6,000 feet of alternating fine- to medium-grained sandstone and rubbly, silty mudstone are continuously exposed along 4 miles of coast-line.

The joint planes occur in two principal sets, the one with an average strike of north 24 degrees east, the other with an average strike of north 80 degrees west. They are dominantly perpendicular to the bedding. Only a few were traceable from one bed to the next through intervening mudstones.

The attitude and spacing of all joint planes at seven places are plotted on the upper hemisphere of equal area Schmidt nets (*see* Figure 8). At some places the joint sets are compound as indicated by the double maxima. From place to place the components of each set vary in relative prominence but the variations do not appear to be related to distance from the axis of the Cumberland Basin. They may simply be due to local adjustments to the regional force that caused them.

The predominant cleat in the Forty Brine seam, both underground and on the surface at Joggins, is about parallel to the joint set with a strike of north 24 degrees east. The second cleat strikes north 70 degrees west.

It appears that the joints were caused by the same stresses or ones similar to those that tilted the flanks of the Basin. The axial plane of the Cumberland Basin strikes approximately north 60 degrees east and hence the direction of maximum shortening is about north 30 degrees west and roughly bisects the obtuse angle formed by the two joint sets. Joint measurements on the Wills Mountain anticline, West Virginia, reveal a similar relation to structure (Gilkey, 1953), although joints dominantly parallel with and perpendicular to fold axes are common (de Waard, 1955).

To show quantitatively that joints are more closely spaced in thin sandstones, the sets were measured in individual beds occurring as isolated interbeds in thick mudstones. The average spacing for each bed is plotted in Figure 9. Although the relation may not be linear, the graph indicates that joint spacings are related to thickness of beds in the manner outlined.

The persistence and preferred orientation of two compound sets in over 6,000 feet of sediments emphasize the importance of these natural planes of weakness in the collapse of the hanging-wall of mine cavities. Joint spacing in sandstones of the immediate roof should be a fair index of the thickness of these beds (*see* Figure 9) and hence their ability to withstand fracture when unsupported.

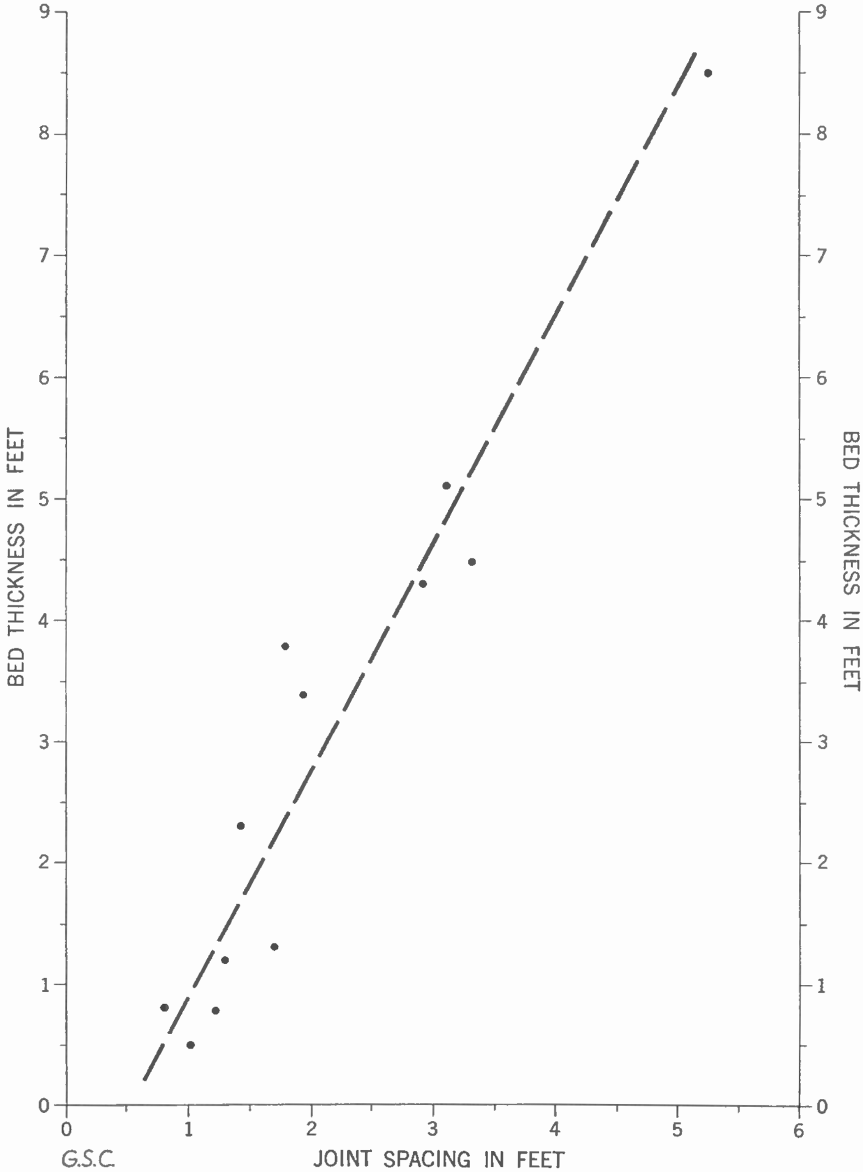

Figure 9. **Relationship between spacing of joints and thickness of beds, Joggins Beach, N. S.**

CHAPTER IV

THEORETICAL AND PRACTICAL CONSIDERATIONS

Summary of Deformational Features in Coal Seams

In areas where the measures have been mildly deformed, as for example the Drumheller coal area, and the Joggins, Springhill and Sydney coalfields, cleat systems and primary sedimentary structures in the coal are intact. There has been no appreciable interstratal slippage and the seams are little deformed by faulting.

In the southeastern Cordillera, on the other hand, coal seams are in many instances highly deformed through differential movement between beds, folding, and faulting. Abundant slickensides on roofs and floors of seams and drag-folds within them indicate almost without exception that the upper strata moved differentially up dip with respect to those below them.

The only exceptions are in areas of intense deformation, as for example the No. 4 incline section of Number 3 mine Elk River Collieries (*see* Figure 2). Depending on the extent of differential movement, the seams have been sheared more or less. In seams above and below which there has been little slipping, sheared coal is confined to within a few inches of the top and bottom of the seams. Where there is more extensive movement, these same shear zones are wider and stronger and, in addition, drag-folds occur at various points within the seam. In those instances where primary bedding features and cleat are completely destroyed, drag-folds extend without interruption from top to bottom of a seam (for example, in the southernmost workings of International mine, Coleman), or the seam is broken into several subsidiary drag-folds (as in some sections of Number 2 and 3 mines, Brazeau Collieries, Nordegg). It is evident from the condition of Number 2 seam, Coleman, that slippage of a few tens of feet may completely destroy bedding features and cleat systems in the coal. Intimately associated with intense shear is irregular pinching and swelling of the seams.

Ninety per cent of faults encountered underground are extensional features, with throws generally less than 6 feet. Within any particular mine there is no consistent fault pattern, although in local areas a common structural trend is evident. In terms of larger structures with which they are associated, these faults are minor features, but their occurrence in such profusion (in contrast to their rare occurrence in the relatively undisturbed seams of the Alberta syncline) shows that they are a fundamental feature in the mechanics of seam deformation.

For those extension faults whose traces on the roof or floor of the seam cut diagonally across the strike, slickensides indicate displacements from dip-slip to oblique-slip. The counterpart of an offset in the roof will not be found opposite it in the floor, if there has been bedding-plane slipping in the coal since the fault formed. It is believed that most faults without apparent counterparts in roof and floor actually cross the seams, but have been so dislocated along the seam that their components cannot be matched. No oblique-slip faults were found where the down-dropped block moved west with respect to its opposing block.

Contraction faults are rare. They commonly have throws from 1 foot to 6 feet and trend parallel to the strike of the seam or cut across the strike at a very acute angle.

Both extension and contraction faults appear to have developed before, during, and very late in the process of bedding-plane slippage. No positive conclusions could be reached on the relative age of the faults beyond the fact that both types have been offset.

Strata Failure in Deep Mining Operations, Springhill, Nova Scotia

A major problem in deep mining of coal is to control the rate and manner in which the roof sinks into the opening left by extracting the coal, as it is manfully impractical to hold it open indefinitely.

If the subsidence of the strata is to be effectively controlled the following factors must be considered: the depth, inclination and thickness of the seam; the nature of the adjacent strata, whether they are massive or shaly, or whether they are in thin, thick, or very thick beds; how the beds vary in lithology laterally; the pattern of cleat and joints; the folding and faulting of the coal measures; the direction of longwalls with regard to these initial planes of weakness; the distribution of fractures induced by mining; the rate of advance of the walls; the width of excavations; the nature and arrangement of supports; and the thickness and areal distribution of top coal left during extraction.

Fractures in the roof and floor are not always easy to observe because of the inaccessibility of caved areas. Moreover, the floor behind longwalls is invariably littered with debris and that along the entries is frequently brushed. Large areas of top coal left along many walls obscure the roof rock so that in many instances it is impossible to trace the extensions of fractures as walls advance (*see* Figure 10).

OBSERVATIONS

Along the 11,800 wall of Number 2 seam, under approximately 4,000 feet of cover, extraction is carried out on a series of retreating longwalls about 400 feet in length. The coal seam dips 12 degrees northeast and averages 7 feet thick. About 750 feet stratigraphically below this is Number 6 seam, and in it two longwalls roughly 300 feet long, advancing away from each other, were studied. Number 6 seam is 5 feet thick and varies in dip from 24 degrees at the top to 19 degrees at the bottom of the 5,700 walls. Above both seams the strata vary from thin- to thick-bedded, silty mudstones and sandstones. There is little variation in lithology in the immediate roof over the present workings.

The bituminous coals of the Cumberland Basin are prominently cleated by two sets of fractures that are essentially parallel to the major joint sets, but which may diverge by as much as 30 degrees in places. Both joint and cleat sets are within 10 degrees of being perpendicular to the bedding, and are nearly at right angles to each other. Commonly a minor complementary system of joints observable in the roof, cuts the quadrants of the primary system. In Number 2 seam, 11,800 wall parallels both the stronger cleat direction and one major joint set. On the 5,700 east wall of Number 6 seam the stronger cleat set and joint set paralleling it strike about 30 degrees from the direction of the wall and produce a notably different type of roof condition from 5,700 west wall of the same seam. There, the stronger cleat is at an angle of about 20 degrees to the direction of the wall and the stronger joint set parallels it and dips as little as 75 degrees into the wall.

Mining on all walls is carried on in a systematic cycle of operations. In Number 4 mine the daily cycle is loading, undercutting the face, and drawing off of certain face supports, each successive phase taking an eight-hour working shift. In Number 2 mine, the operation of undercutting has been eliminated and mining proceeds on two shifts each day. The face supports (chocks) in both mines are built, log-cabin style, of hardwood blocks (*see* Figure 10). Additional roof stability is obtained by building stone-filled chocks (midwalls) in the waste at regular intervals. These rows of supports are extended daily by an amount equal to the daily advance of the longwall face.

With advance of a longwall away from a heading a series of fractures, essentially parallel with the face, develops. At first the fractures are several feet apart, but as the wall advances and the void behind it widens, the fractures increase in number, anastomose, and develop a characteristic braided pattern (*see* Figure 11). These fractures cease within about 30 feet of the entries at the upper and lower ends of the walls. The patterns in both seams are similar although the spacing is narrower at 5,700 west wall Number 6 seam of Number 4 mine, than at 5,700 east wall and at 11,800 wall.

The roof fractures are of two main types, both of which strike in a direction roughly parallel with that of the wall. To one type belong shear fractures that characteristically dip in the direction of the advance of the wall. These will be referred to as "shear breaks". They most frequently cut the bedding at an angle of 55 degrees, and can be observed up to the working face and, in places, extend into it. Where two walls advance away from each other, shear breaks dip in opposite directions, as for example at the 5,700 east and west walls of Number 6 seam. A similar situation is evident in Number 2 east and west levels of the Harbour seam, Dominion Number 18 Colliery, New Waterford, N.S. To the other type of fractures belong linear, smooth breaks that apparently follow the joints of a major system.

Where joints are parallel with and dip into the wall associated shear breaks are more numerous and dip more steeply than elsewhere. Behind the west wall of Number 6 seam, for instance, shear breaks are spaced about half as far apart as those behind the east wall and collapse of the immediate roof is much more rapid. Within the first foot of the immediate roof, the shear breaks dip from 65 to 70 degrees. Above this point they merge with joints to present a surface concave towards the direction of advance of the wall.

As the longwall continues to advance new areas of roof are exposed and the zone of potential collapse under dead weight is enlarged. The strata in this zone are under tension as evidenced by the widening of, and movement along, shear breaks, opening of joint sets to produce serrated tension breaks roughly paralleling the direction of the wall, and frequent "drop outs" within the area of artificially supported roof. Prior to collapse, the roof steps down systematically at each break in the direction of the waste. Collapse of the roof strata behind the last row of packs is continuous.

The size and shape of the rock fragments from "drop outs" or from the waste match the spaces between planes of weakness in the roof and indicate the control of these planes on roof collapse. The fragments are characteristically bounded above and below by bedding planes, and "inbye" and "outbye" by shear breaks or joint surfaces. The size of the fragments also depends on the presence of prominent joints essentially perpendicular to the wall, on the distribution of midwalls, and on the failure characteristics of the packs. The rock fragment shown in Plate II was recovered from the waste and is typical of the shape of most blocks, although much smaller in size. It is bounded above and below by bedding planes, on the wall side by a joint surface dipping 70 degrees to the bedding, on the waste side by a shear plane dipping 50 degrees to the bedding, and has ragged ends. A joint set roughly perpendicular to the wall was present but had no effect on this fragment.

It is not uncommon for the superjacent strata in the waste behind the last row of chocks to remain intact for a few days. This puts an abnormal load on the forward abutments and violent stress relief may result. In many such instances it is found that the direction of the extraction face is at angles of 20 to 40 degrees to one or other of the joint or cleat sets. When the wall is swung parallel to one of these sets of natural planes of weakness there is noticeable increase in the rate of collapse of roof strata[1].

In contrast to the braided pattern of fractures developed in open workings behind longwalls, fractures in narrow workings such as entries and headings are few and simple. In Number 6 seam, for example, the immediate roof of 5,700 level is well supported in advance of the longwall and at the barrier pillars protecting the haulage slopes, and fractures are few. Only occasional, joint-controlled tension breaks appear. Where the immediate roof is supported only by the solid coal on the low side and a single row of packs on the high side it is more highly fractured and caved. Failure is by sag into the level, with concomitant opening of joints and scaling parallel to the bedding. The strata fail along natural lines of weakness in tension, rather than develop tension fractures independent of the joint sets as suggested by Dinsdale (1933).

SHEAR BREAKS AND MINING PRACTICE

At Springhill essentially the same pattern of shear breaks is developed in Number 2 and 6 seams, regardless of wide differences in cover interval, seam thickness, and extraction process. For example, Number 2 seam, where being mined, is 9 feet thick, under 4,000 feet of cover, the walls advance at 4 feet a day, and all coal is mined by hand; whereas Number 6 seam is 5 feet thick, under 2,500 feet of cover, the walls advance at 6 feet a day, and the coal is undercut and blasted down.

At Sydney coalfield the effect of the mining cycle on shear breaks is most apparent. There the breaks characteristically develop along the line of intersection of two successive swaths (4 feet) of the Dosco Miner and are evidently initiated at or immediately behind the face. The seam is not undercut. In contrast to the braided pattern so evident in the mines at Springhill, roof failure at Sydney is in a series of breaks, about 4 feet apart, parallel with the longwall face.

Facies changes in roof rock apparently exert little control in the spacing of shear breaks. The immediate roof throughout the areas studied is shaly to thin-bedded, silty mudstone, variably carbonaceous. Coaly stringers here and there appear to have little effect on inducing shears although they do favour scaling behind the working face. The closer spacing of the breaks along the 5,700 west wall, Number 6 seam, and the heavier roof condition there are more probably due to parallelism of the longwall face and a prominent joint set than to differences in the roof.

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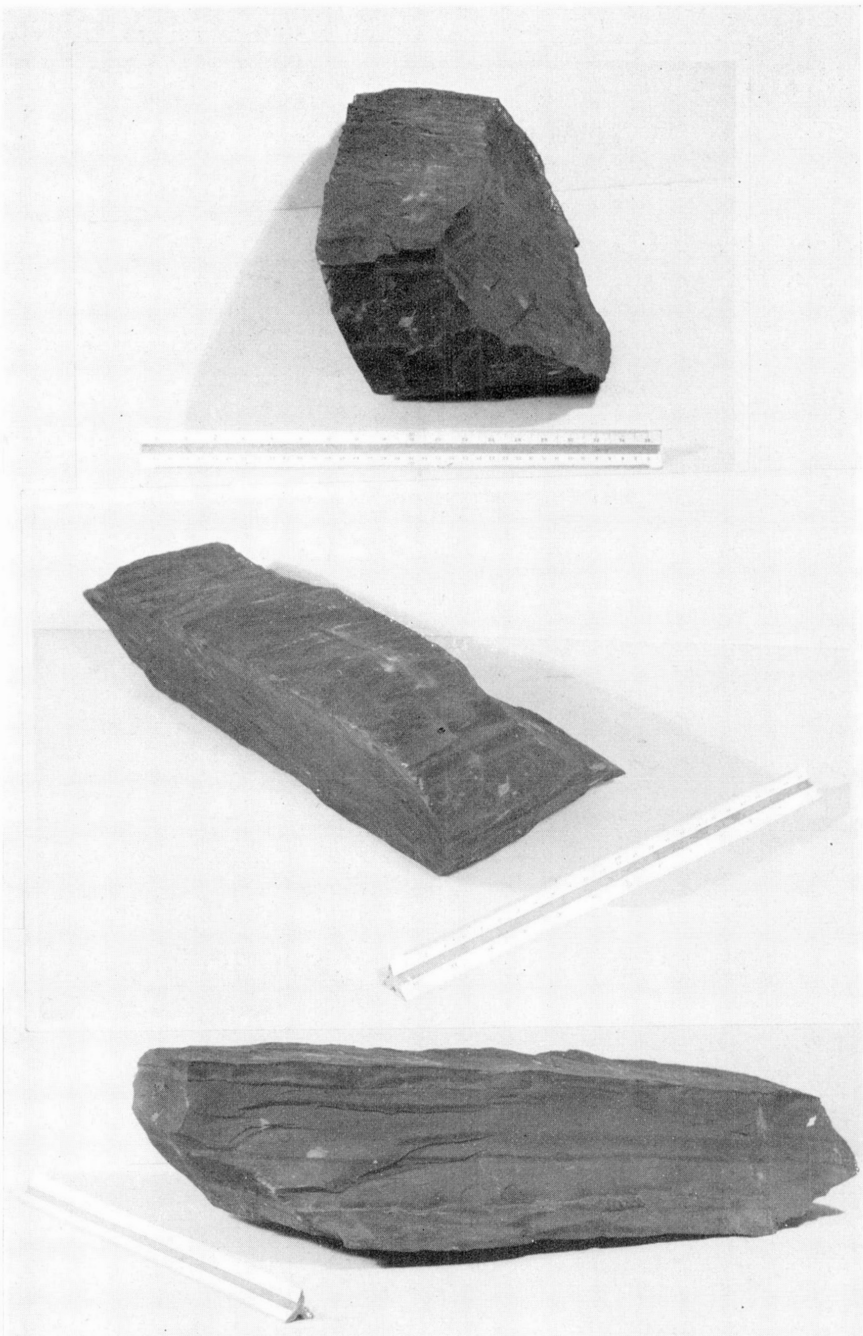
[1]T. B. Haites, oral communication concerning mining methods in the McBain seam, Sydney coalfield.



Fuels Div., M. & T.S.

Plate II. *Typical shape of rock fragments recovered from waste, Number 4 mine, Springhill, N. S.*

It may be that adequate support *immediately* behind an advancing face contributes to the uniform development of shear breaks. Where the Dosco Miner is employed the face is systematically advanced 4 feet, roof supports are installed promptly behind the advancing Miner and the breaks are simple and uniform. At Springhill, however, there is about a 12-hour delay between undercutting and chock building on the loading shift and the breaks are haphazard and braided. With the present mining method there is no alternative, as the coal must be undercut and the conveyor lines moved before chocks can be built. It seems apparent that immediate support delays relaxation and reduces the number of induced breaks.

In the mines of the Sydney coalfield, 80 to 90 per cent extraction is continued 3 to 4 miles offshore with no seepages from the sea. It is apparent that roof breaks associated with the mining do not extend any great distance upward and it is suggested that the interbedded, rubbly, silty shales permit considerable flexing of the superjacent rock without producing subsidence cracks. A surface search above the workings at Springhill revealed no subsidence cracks or ridges to a cover interval of 1,800 feet. At greater depths of cover the surface was thickly wooded and detection of cracks was impossible. At Coleman, Alberta, where the cover interval is about 1,300 feet, cracks 1 foot wide are visible at the surface, parallel with the general strike of Number 2 seam and average 50 feet apart.

Little is known of the stratigraphy above the workable seams at Springhill and in the Sydney coalfield. Mifflen (1941) generalized that 75 per cent of the productive measures in the Sydney coalfield are shales and fireclays, rocks more apt to bend than break with the closure of the wastes and, moreover, that are very impermeable.

Joint sets facilitate collapse of the immediate roof but their influence on high-level caving can only be inferred. The fact that joint systems persist and are similarly oriented through thousands of feet of strata, as at Joggins, should facilitate the filling up of the mine cavities as progressively higher beds collapse.

The few faults encountered in the Springhill and Sydney coalfields probably extend a long distance vertically and any with a throw of over a foot should be adequately supported by barrier pillars. Otherwise blocks outlined by such faults would doubtless collapse as a whole on complete extraction of the coal.

Thus it has been found that a consistent braided pattern of shear breaks is developed with the advance of a wide extraction face. Because such breaks are apparently the direct result of shearing forces in the abutment zone ahead of the wall nothing can be done to prevent their development.

They can, however, be minimized if the roof is adequately supported as soon as it is exposed. Uniform support is also essential to minimize additional breakage through differential settling, as the roof rock is lowered into the wastes. A longwall paralleling a joint set or fault favours heavy roof conditions at the face but should facilitate caving.

Violent Stress Relief in Canadian Coal Mines

With only the force of gravity acting, a condition of equilibrium exists within the earth's crust. It may be shown, however, that for homogeneous, elastic solids of infinite horizontal dimensions, in which the weight of the body is the only source of stress, the stress components in the horizontal plane may be substantially smaller than that in the vertical (Hafner, 1951); a hydrostatic state does not exist. This is presumed to be the condition in a sedimentary stratum under substantial cover. This relatively simple state is made far more complex by the presence of mine openings, different mining methods, various geological structures, and irregularities in the land surface above. Any or all of these may cause the orientation and magnitude of the principal stresses at depth to depart radically from that predicted by theory.

With the creation of a mine cavity the condition of equilibrium is destroyed and readjustment of stresses occurs. The solid material about the void relaxes, through elastic expansion and fracturing, and a skin of low stress termed the "fracture zone" (Roux, *et al.,* 1954) develops.

Concomitant with the development of a de-stressed skin about a mine opening is a concentration of stress within the solid on both sides of the opening and parallel with it. Depending on the ability of coal in the ribs to assume additional load, such zones will vary in width and hence will extend to different distances into the solid. These zones of increased stress will be referred to as "abutment zones".

The coal mining industry is at present concerned with safe extraction of coal at depths where the cover is so great that the abutment zones may be overstressed, with consequent failure of the coal support. It has been found, moreover, that violent pillar failure or other means of stress relief are frequently associated with geological anomalies, such as washouts, pinches and swells, and faults.

Because of this association of violent stress relief with geological anomalies, many writers have proposed that in these places active vestigial or regenerated tectonic stress may be in operation. In seismically active regions, as for example southern California, it is known that there is considerable concentration of elastic strain energy in the immediate vicinity of major faults. Hence, if stress relief is due to secular strain, then specific geological structures must act as reservoirs of secular strain energy. Such reservoirs would be in existence prior to mining.

Highly stressed zones are also developed by load redistribution during mining, and geological anomalies may there also play a significant role in localizing, augmenting, and releasing stress, sometimes with violence. Conditions vary not only from mine to mine but also within any one mine, so that a general theory should be applied cautiously to complex interrelated effects.

TYPES OF VIOLENT STRESS RELIEF

Violent stress relief may be classified as bumps and outbursts. They are defined as follows:

Bumps are those violent stress relief manifestations consequent upon failure of overloaded coal supports. Depending on the violence of this failure there may be widespread floor heave and shattering of artificial supports.

Outbursts, or blowouts as they are also commonly called, are defined as sudden outflows of large volumes of gas, with or without the projection of coal. In cases of extreme violence the ejected coal may be highly comminuted (Ignatieff, 1954).

CHARACTERISTICS OF BUMPS AND OUTBURSTS

Bumps. The violence of a bump depends on the extent of overloading and strain characteristics of coal supports. The principal factors in the accumulation and release of stress by bumping in the mine cavity are depth of cover, proximity and extent of extracted areas, and crushing strength of coal in the pillar. Faulty mining practices, such as irregularly shaped abutment zones and openings driven into highly stressed areas, frequently result in local failure of the coal support.

Stress relief by violent bumping has been experienced at depths as shallow as 500 feet. As the depth increases the number of bumps increases. For example, in Number 1 East mine, Coal Creek, between a depth of 500 and 1,500 feet an average of two bumps occurred for each hundred foot increase in depth. Below this the incident rate increased rapidly until from 2,300 to 2,400 feet, the deepest workings, eleven bumps were experienced. There is no simple relation between frequency and cover interval because of the effect of other factors, such as the nature of the roof and floor, the extent and distribution of extracted areas with respect to the active workings, and mining practice, on the stress condition in the abutment zones.

In contrast to violent bumping recorded from Number 1 East mine, stresses in Number 2 seam, Coleman, were released in general by frequent, less severe bumping. There, violent bumps did not occur until a depth of about 2,300 feet was reached. The reason is, in part at least, that the coal in Number 1 East mine is structurally strong and that in Number 2 seam much fractured and sheared. Extensive and gradual heaving of the soft, carbonaceous shale floor in the deeper workings of both mines is a means of relief of stresses pent up in the pillars. If the stress is not relieved by this means the pillars burst.

Some of the most serious bumps occur while pillars are being split near extensive gobs. The bump of 1950 in McGillivray mine will illustrate this point. Number 75 room was being driven up the dip from Five level in the abutment zone of large extracted areas, to the rise of Number 4 counter entry and to the north of the active workings. The coal below Five level was undeveloped. The pillars were overstressed to the point of failure.

Where the extraction line is advanced irregularly, parts of the pillars jut into extracted areas. As hanging-wall and foot-wall converge, these parts may become overloaded and burst. Two violent bumps in 1950 in Number 1 East mine occurred in such a pillar remnant.

Minor bumping in strong coals is commonly associated with driving headings and drawing pillars under a cover of 400 to 500 feet. It indicates a gentle release of accumulating stresses. Many bumps in Number 1 East mine took place while headings were being driven, when not more than 15 to 20 per cent of the coal was extracted. The more violent of these bumps are probably induced by blasting or vibration of an air pick (Herd, 1930).

The more rapid the advance of the extraction line the more frequent and acute is minor bumping. Reducing the rate of advance of a heading or extraction line in highly stressed coal, allows accumulating stresses to be released by degrees, and many bumps may, by this means, be avoided.

Violent heaving of the floor and settling of the roof over large areas of the workings commonly accompany sudden failure of pillars. When a pillar remnant in Number 1 East mine failed in 1950 the track was heaved 12 to 14 inches. Further evidence of violent movement of the floor is revealed from autopsies of bump victims. In many cases the leg bones were shattered at angles of about 45 degrees, suggesting a sharp blow from below.

A sequel to movements of roof and floor is extensive shattering of props and closing of haulageways, with flattening of mine cars. The main roof is, however, rarely broken under these circumstances, although cap rock may be shaken down in profusion and block exits from a bump area. The more violent and extensive bumps are frequently felt on the surface, causing moderate property damage. Pictures have been thrown from walls and dishes from shelves at Coal Creek, as a result of sudden pillar failure.

Bumps are, therefore, the instantaneous release of accumulated stresses through failure of overloaded coal supports. They do not necessarily occur at faults. At depths of 3,000 to 4,000 feet in the Springhill mine, there is occasional bursting of the floor into mine openings (Herd, 1930). These are of a different type, analogous to rockbursts in metal mines, and are restricted to the deepest coal mining. It would appear that the prerequisites of a bump condition are defective mining practices in strong coals at cover intervals in excess of 500 feet.

Blowouts. Blowouts were studied in Upper Marsh and Number 4 seams, Canmore, where many blowout sites could be seen.

Blowouts differ in the amount of gas and coal ejected and appear to result from the mining of coal in the solid, at depths of from 500 to 1,500 feet. They are most violent in structurally strong coals and most frequent in steep-dipping seams. Moreover, blowouts in inclined seams commonly arise in the top corner of the working face or on the top of the high side rib near it.

Statistics from the two mines at Canmore as well as those from Number 1 East mine, Coal Creek, (*see* Figure 12), show that there are upper and lower limits to the depth at which blowouts occur. In Number 4 seam, Canmore, for example, blowouts begin to occur at a depth of roughly 600 feet, and cease at between 1,400 and 1,500 feet, the present deepest working. The peak frequency is at about 1,100 feet. In Number 1 East mine no blowouts were recorded at depths less than about 400 feet or greater than 1,900 feet, although the deepest workings were at 2,300 feet. There, a peak frequency was found at a depth of about 700 feet.

It has been demonstrated that, for each set of conditions, there is a critical depth below which blowouts rarely if ever occur. This is not the case with bumps, indeed it was the increased frequency of bumps, not blowouts, in Number 1 East mine that was responsible for the curtailment of operations at depth.

Unlike bumps, blowouts characteristically occur during development work where, in general, not more than 15 to 20 per cent of the coal is removed. Of fifteen blowouts recorded in Number 4 seam, Canmore, twelve occurred while the seam was being cut into pillars and the remaining three while the pillars were being split prior to being extracted. Reports to the British Columbia Minister of Mines reveal that, without exception, all blowouts occurred during development work in Number 1 East mine.

When a blowout is imminent, the working face often shows signs of a highly stressed condition. In many instances the face becomes hard to mine, or as the miners say "becomes dead", sometimes at a considerable distance from the actual site of the blowout. The strained condition of the coal is

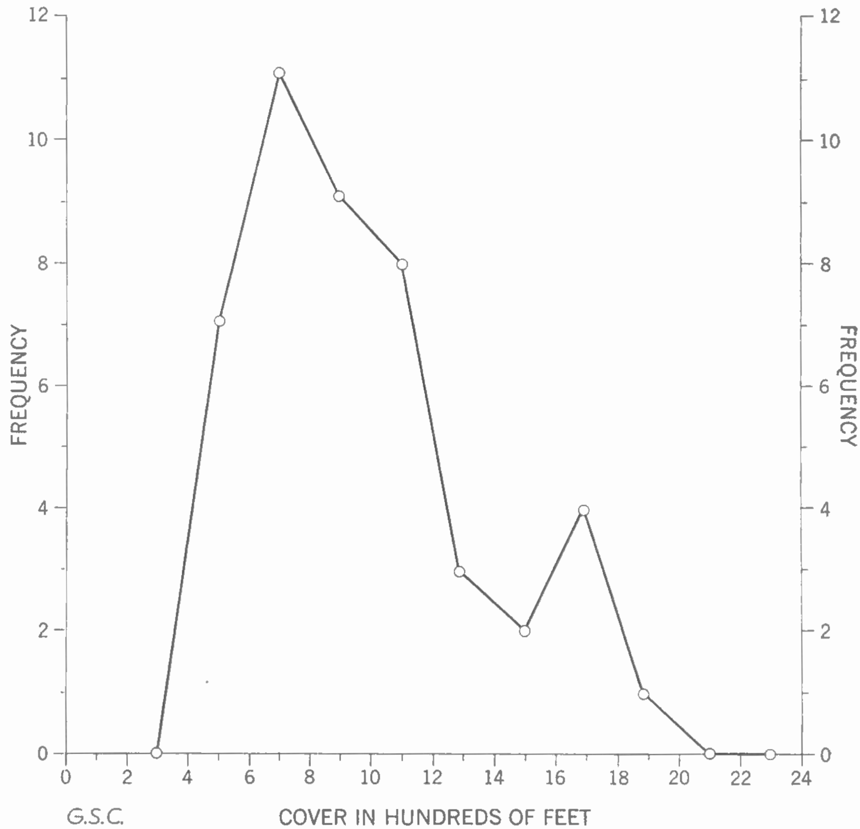


Figure 12. Frequency of blowouts with respect to depth, Number 1 East mine, Coal Creek, British Columbia.

relieved by spontaneous shattering of the face, indicated by continual cracking and minor bumping. An occasional more violent bump may temporarily relieve the stressed condition, and the cracking noises momentarily subside. Associated with this crushing and expansion of the coal, small amounts of gas are released. When the coal is in such a condition, a gentle touch of a miner's pick may trigger a blowout.

It has been observed again and again that when a working place shows signs of an imminent blowout, the time of its occurrence may be delayed, but not avoided, by progressing slowly or temporarily stopping work. Tests in the Pumpquart seam, Penthenry, Wales (Roblings, 1926), revealed the practicability of inducing outbursts by volley firing at points where their occurrence was imminent. "Shock blasting", as the procedure is now called, is common practice in coal mines of France and Belgium.

The cavities left after the ejection of the disintegrated coal are variously shaped. In one instance the cavity was bottle-shaped, the inside being wider than the aperture through which the coal was ejected (Ann. Rept., Minister of Mines, B.C., 1918, p. 336); in another the cavity was funnel-shaped for several tens of feet into the solid (Ann. Rept., Minister of Mines, B.C., 1928, pp. 411-414); in still others the cavities were cone-shaped with a flat side against the hanging-wall and the apex into the solid.

The energy released in the initial fragmentation of the coal is only partly responsible for the forceful ejection of the fragmented material, the bulk of the transportation being effected by the released gas. The coal fragments being transported in the rapidly moving gas are further disintegrated, at times to the consistency of flour, much like coal projected through an orifice at high velocities in the process of pulverized coal combustion.

In the hard blocky coal of Number 4 seam, Canmore, blowouts are frequently very severe and hundreds of tons of finely disintegrated coal are forcefully ejected. In the sheared, platy coal of Upper Marsh seam, on the other hand, rarely are more than 50 tons of loose coal displaced.

Most of the gas released in blowouts in the mines examined was methane. In certain collieries of the Lower Silesian coalfield, Germany, and the Gard Basin, France, however, outbursts releasing enormous volumes of carbon dioxide are frequent (Rice, 1931).

The amount of gas released per ton of coal is estimated to be about the same if it is released gradually as the coal is mined, or violently as the coal is dislodged in a blowout (Riffaud, 1946).

Experience shows that the occurrence of a blowout does not eliminate the possibility of further blowouts within a short distance. For example, in Number 1 East mine, five blowouts, two of a very serious nature, were experienced during a 600-foot advance of the face in unfaulted ground in 29 room off 10 East entry. This clustering of occurrences further emphasizes that blowouts, unlike bumps, are not entirely due to overloading.

Blowouts are not characteristically associated with faults in any of the accessible parts of those mines investigated. Although few or no geological data were recorded for the collieries at Coal Creek, the literature reaffirms the view that there, too, blowouts are not apparently localized along faults. In Number 4 seam, Canmore, however, it was observed that of fifteen blowouts, six occurred at faults and nine remote from them.

Because of the comparatively uniform dip of Upper Marsh and Number 4 seams, no data could be secured on the relative frequency of blowouts at different dips. A survey compiled by I. M. Yarovoi (Moscow Ougltehizdat, 1949), revealed that of 720 blowouts in the Don Basin, 92 per cent occurred in seams dipping more than 50 degrees. It is apparent that a steep dip favours the occurrence of blowouts.

Pushouts are mild forms of blowouts and there is no distinction between a severe pushout and a mild blowout. Although pushouts occur most frequently during mining operations at depths of over 500 feet in friable coals, they are occasionally experienced in hard blocky coal. During the advance of the face of the main gangway of Upper Marsh seam, pushouts were frequent and in Number 3 mine, Brazeau Collieries, at depths of 450 feet, they were a daily occurrence.

The coal in these seams has been completely disintegrated by differential movement between roof and floor and cannot support the increased load brought about by mining. The roof and floor in development work converge immediately, and a non-uniform stress condition is created in the coal at the face, a condition likely to produce pushouts.

That the working face, immediately prior to a pushout, is in an over-stressed condition, is indicated by the increased hardness of the coal. Sets tighten during and after a pushout, disclosing a redistribution of load.

During a pushout the coal is displaced, generally from the high side or corner of the working face, although occasionally the whole face or some segment thereof is eased forward a few feet. The coal is not ejected with violence or to great distance, but the angle of slope of the dislodged coal is unmistakable evidence that the ejection is forceable. For instance, the angle of slope of pushed out coal is often up to 15 degrees more acute than the normal angle of repose (about 40 degrees) of the same coal; the more violent the ejection, the greater the difference. Analogous to bumps, in contrast to blowouts, the fragments of dislodged coal are about the same size as those of coal mined in the normal way.

Pushouts in some mines more than others are localized at points where the workings are being advanced across a fault plane. The variation is well illustrated by the following examples. In Number 4 seam, Canmore, eight pushouts out of eleven took place next to faults; in Upper Marsh seam, all pushouts to the time of the investigation were in unfaulted ground; in Number 3 mine, Nordegg, pushouts have occurred at practically every fault and at innumerable places where the seam is not faulted.

With depths of over 1,000 feet in highly sheared coals, no pick work is required in driving rooms with moderate pitch; miners merely keep the sides of the excavation lagged tightly to the face in order to direct the course of the pushout. Where spontaneous pushing out of coal does not occur, blasting or minor bumping may trigger these gentle forms of blowouts.

Several instances of sloughing of large amounts of intensely sheared coal have been erroneously recorded as violent stress relief phenomena. The air blast produced by the fall of a large mass of coal is not unlike some of the effects of a bump or blowout and the erroneous conclusion is understandable.

In one or two cases on record for Upper Marsh seam, Canmore, up to 60 tons of coal have been displaced, and in one outstanding example, in the Drainage Level, Number 3 mine, Elk River, about 200 tons of coal were dislodged. The accompanying air blast was naturally great but no abnormal amount of gas was released.

Sloughs commonly occur where levels are driven with ribs either vertical or leaning over the mine opening. The highly sheared coal fragments of the de-stressed fringes of the pillars form an incoherent mass. This mass sloughs extensively, particularly on the high side where the coal can fall free, permitting further de-stressing.

In all instances sloughs are developed by continuous but gradual readjustment of the coal flanking mine openings. Unlike blowouts and pushouts which are associated with advance of the face, sloughs may occur at any point, at any depth, and at any time subsequent to development work. The ultimate dislodgement of the de-stressed material is frequently triggered by blasting or minor bumping at the face. There is neither readjustment of roof and floor immediately following a slough nor forceful ejection. There is, moreover, no difference in the size of the fragments of the sloughed coal from those of the coal mined, and no abnormal amount of gas is released.

CONCLUSIONS

From the preceding discussion it is apparent that violent relief of stress is inescapable in the mining of coal at depths in excess of 500 feet although the factors favouring bumps and blowouts are fairly well established.

A bump regimen is believed to result from a complex interplay of the following factors: cover interval and topography, extent and proximity of extracted areas, variation in physical properties of coal and associated rocks, and rate of advance of headings and extraction lines. An unfavourable combination of any of these factors may lead to abnormally high stress conditions and possibly a violent bump.

Although bumps generally occur at depths of over 500 feet, they may take place at lesser depths in alpine regions where the additional loading of mountain masses may augment the principal stresses about the mine openings. Similarly, bumps may occur at lesser depths in active workings in abutment zones of large extracted areas.

Variations in stress-strain characteristics along a seam may result in local, highly stressed areas, which if close to a free face, may fail with violence. Strong coals with a strong roof and floor favour the accumulation of strain energy as there is no means by which it may be gradually dissipated. This is especially true where headings and extraction lines advance rapidly.

The following factors favour the occurrence of blowouts: cover intervals between 500 and 1,500 feet in orogenic belts, mining of coal in the solid, and the shape of mine opening. An unfavourable combination of these factors leading to an overstressed condition of the coal may result in a blowout.

Structurally strong coals are characterized by more violent blowouts, that is, larger tonnages of coal more forcefully ejected and more highly disintegrated. Strong coals are better able to dam back strain energy until it is released with almost explosive violence.

It is uncertain whether the release of the gas is responsible for fragmentation of the ejected coal, or whether it is released as a result of the distintegration of highly strained coal. In either case it has been established that there is de-stressing and de-gassing of a large volume of coal around the cavity in a blowout, that is the tonnage of coal ejected is but a small part of the coal involved in the stress relief.

Whereas a bump is directly attributable to overstressing of coal in abutment zones, the reasons for the accumulation and release of stress in blowouts are not clear. The data suggest that a combination of the physical-chemical relations of the gas to the coal and a nonuniform stress condition in the coal are essential to a blowout condition.

Geology and Mining Practice

In contrast to Eastern Canada, where coal measures dip gently on the flanks of open Appalachian folds, the seams of the eastern Cordillera are tightly folded, repeated on low-angle thrusts, and mostly steep-dipping. Thus, in the east considerable coal is won at shallow depths and problems of deep mining become significant only in the late stages in the working of a seam. In the west not only is much less of the mineable coal at shallow depths, but many structural and stratigraphic complexities make recovery of coal difficult. Indeed, were it not that thrust faults have brought successive slices of the coal bearing strata up to the surface, most of the coal would be too deep to be mined.

Coal mining in the Cordillera is restricted to areas close to transportation and to depths of less than 2,500 feet because of prohibitive costs of maintaining haulageways over great distances and at depths where convergence and other forms of stress relief necessitate continual repair of timber supports.

Joints and faults hasten the subsidence of the roof into the mine cavity. It is particularly important in submarine workings, therefore, where disjointing of roof rock and block caving must be minimized, to keep extraction lines at an angle to the joints. Faults with throws in excess of 5 feet are known to cut hundreds of feet of strata which would lead to block caving in deep workings in Eastern Canada. In submarine mines these faults should be adequately supported by barrier pillars. On the other hand, fault planes generally have little effect on the collapse of roof strata in the Cordillera as many of them have been offset by deformation subsequent to faulting and movement along them is thus inhibited.

Many coal seams have been intensely sheared by interstratal slip with consequent loss of cleat and primary bedding features. In extreme cases the seams may pinch and swell, leading to wants on the one hand, and areas of very thick coal on the other. The friability of this coal and the increased ash content from highly comminuted stringers and partings seriously reduce its marketability. A sheared and rubbly condition of the immediate roof may seriously augment timbering costs and there is danger that this loose material will be shaken down by tremors arising from pillar failure and thus block escape exits.

Large quantities of coal are won cheaply by surface stripping methods in the cores of folds. There, the coal is abnormally thickened through similar folding. Great thicknesses of rock may be removed and mining still be profitable.

Underground mining, whether in strong or weak coals, should follow a systematic plan of development and extraction. This is difficult in practice, because of the unpredictable occurrence of splits, washouts, large faults, and impure coal, and because the demand for coal of different quality varies. This study has shown, however, that a modification of some mining practices should lead to increased coal recovery and margin of safety, and possibly decreased operating costs.

Two such methods of increasing extraction in multiple seam mining involve the proper placing of haulageways and an orderly mining out of successive seams. In the first instance, haulageways and airways should be driven stratigraphically below seams to be worked, if at all practicable. By means of cross-measure tunnels driven at regular intervals to the seams, the coal may be completely extracted and the maintenance costs greatly reduced as the main arteries of the mine are out of the zone of differential settling. In the second instance, the lowest seams should be extracted first. If this is done large coal pillars need not be left to support flooded workings in seams above.

Safe practices should include avoiding development work in highly stressed areas and the minimizing of roof falls. With either room and pillar or longwall method, it is imperative that all development in an area be completed well in advance of its being overtaken by the extraction line. Moreover, to keep the roof intact it should be supported as soon as it is exposed. Most accidents underground are due to rock falling from a loose and broken roof right at the face.

High maintenance costs in the mines are largely due to a sheared condition of the measures and it would appear that the only way such costs may be minimized is by driving main haulageways and airways out of the zone of differential settling, and extracting and abandoning areas prior to the onset of wholesale disintegration and collapse of the roof.

At depths of less than 1,000 feet, strong coals provide adequate support. In highly sheared coals roof and floor may converge to a serious degree at cover intervals as low as 200 feet. In extreme cases the coal may give so little support that it is economically impossible to maintain haulageways and airways and the only coal recovered is that from cutting the seam into pillars.

Additional difficulties in mining sheared coals are sloughing of ribs and squeezing of coal at the face. In the former instance the ribs should be trimmed to lean away from the entries, especially in steeply dipping seams, and in the latter it is recommended that narrow workings be driven down dip, to avoid sudden onrushes of coal from burying miners at the face.

In most Cordilleran mines the workings have been extended so far along strike that haulage costs are prohibitive. Of necessity, extraction is being carried to progressively greater depths where the crushing of abutment zones, sometimes with violence, is a serious problem. Although blowouts should not be serious at depths in excess of 1,500 feet, beyond a certain maximum depth the convergence of roof and floor cannot be properly controlled and mining is impractical. In Cordilleran mines this maximum depth will be about 2,500 feet and in Appalachian mines, about 4,500 feet.