STRUCTURAL CONDITIONS AND VIOLENT STRESS RELIEF IN COAL MINES OF THE SOUTHERN CANADIAN CORDILLERA

Thesis by

Donald Kring Norris

In Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

1953

ACKNOWLEDGMENTS

Eleven mines in five coal fields were visited during the course of the investigation. The writer wishes to express his sincerest appreciation for the facilities and very kind assistance rendered him in the progress of the survey.

Special thanks is given H. Wilton-Clark, General Superintendent, Coleman Collieries, Limited, Coleman, Alberta, for his sincere interest in the progress of research on the stress problem, and his offering assistance in every possible way. Moreover the writer is very much indebted to W. Fraser, Mine Manager, International mine; W. Goodwin, Mine Manager, McGillivray mine; J. Marconi and T. Marconi, Pitbosses, International mine; and E. Allen, Pitboss, McGillivray mine.

Of the Crow's Nest Pass Coal Company Limited, Fernie, British Columbia, many thanks are rendered J. Littler, Mine Manager; D. Chester, Overman, Number 9 mine; J. Anderson, Overman, Number 3 mine; and C. McNay, Overman, Number 1 East mine, for their kind cooperation in arranging for the writer to travel through the respective mines.

The writer also wishes to extend a hearty thanks to W. A. Wilson, Executive Vice President of the Canmore Mines Limited, Canmore, Alberta, for invaluable assistance in acquiring data on the stress relief problem in the Number 3 and 4 mines. Moreover he is grateful to W. J. Riva,

Mining Engineer; V. Mrokvia, Mine Manager and J. Brown, Pitboss, Number 4 mine, for the many courtesies extended.

During the writer's brief visit to the Brazeau Collieries Limited, Nordegg, Alberta, he was very much indebted to A. D. Sturrock, General Manager, and Z. D'Amico, Mine Manager, for facilitating an inspection of the Number 2 and 3 mines.

In extending his studies to the undisturbed seams of the Alberta Syncline, the writer wishes to thank A. Wilson, Mine Manager, Red Deer Valley Coal Company for his showing the writer through the underground workings and for his very kind hospitality.

Moreover the writer is deeply grateful to R. Spillers, Coleman, Alberta, for his able assistance, cheerfully rendered during the course of investigation of regional structure of the various coal fields.

The author is also very much indebted to the engineering staffs of the coal companies cited above for their generosity of time and effort in supplying technical data on the workings of the respective mines. Furthermore sincere thanks are extended to the many firebosses and other underground personnel who offered assistance so very many times during the course of the investigation.

Very special thanks are rendered the writer's associates of the Canadian Department of Mines and Technical Surveys for generously providing technical data on other aspects of the stress problem with which to temper his own

observations. Special mention is made of A. Brown, S. K. Bhattacharjee, L. Casey, T. S. Cochrane, and H. Zorychta, Mining Engineers of the Fuels Division, and R. J. W. Douglas of the Geological Survey of Canada.

Above all the writer is extremely grateful to A. Ignatieff, Mining Engineer of the Canadian Department of Mines and Technical Surveys, and Professor J. P. Buwalda and Professor J. A. Noble of the California Institute of Technology, for their invaluable guidance and critical analysis of both the mining and geological aspects of the thesis.

ABSTRACT

The problem was investigated under the auspices of the Geological Survey of Canada in an attempt to evaluate the relation of geologic structure to the mining practices which gives rise to occurrences of violent relief of stress. An understanding of this problem is imperative to the winning of coal at depth.

The faulted and drag-folded condition of the seams in the Crowsnest and Cascade coal areas may be interpreted by the mechanics of shear-thrusting. Gentle flexing of the overthrust masses was effected through similar folding for the combined series of competent and incompetent units.

Alternate stretching and compression of the Kootenay formation at Coleman and Canmore resulted in the development of an abundance of extension and contraction faults transecting the seams, and a sheared condition within the coal. Frictional resistance tended to retard those beds in the overriding masses closest to the thrust planes so that in every instance the upper beds moved slightly further to the east relative to those below them. Consistent drag-fold patterns within the coal seams were the result.

The fractured and sheared condition of the coal is all important in governing the stress relief characteristics of the seams. Bump phenomena occur only in structurally strong coals, whereas blowouts have been experienced where the seams are both sheared and unsheared.

In contrast to violent bumps which show a definite increase in frequency with depth, beginning at a cover interval of about 500 feet, blowouts first occur at about the same depth, but after reaching a maximum frequency between 700 and 1100 feet, show a marked decrease at progressively greater cover intervals to the point where no blowouts are recorded in the 1 East mine, Coal Creek, at 2000 feet.

Whereas a bump condition is created by faulty mining practices which result in the failure of overstressed coal in abutment zones, a blowout condition is believed to be due in part to redistribution of stresses associated with the advance of the working face, and in part to the physical-chemical relation of the coal to the associated gases. Secular strain is not believed to be a primary factor in the genesis of violent stress relief phenomena.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

List of illustrations (continued)

STRUCTURAL CONDITIONS AND VIOLENT STRESS RELIEF IN COAL MINES OF THE SOUTHERN CANADIAN CORDILLERA

I. INTRODUCTION

Coal mining in structurally complex belts is presented with innumerable problems not encountered in the exploitation of flat, undisturbed seams. It is the purpose of this thesis to interpret the relation of structure to the mining practices which give rise to the problem of violent stress relief.

Upturning and overriding of beds during an orogeny, followed by erosional dissection, results in the frequent occurrence of seams dipping into mountain sides. The combination of a dipping seam and a rugged topography is ideal for rapid increase in cover interval, so that in tectonically disturbed ground a considerable portion of coal mining activities is carried on under depths of cover of several hundred feet.

Deformation of the seams has resulted in many instances in radical changes in the nature of the coal and the associated rocks. Intense shearing of the coal frequently has completely destroyed any remnants of original bedding or cleat. Thrust, reverse and normal faulting have so completely fractured the coal-bearing strata that rocks overlying the seams are unable to support themselves over large spans. Pre-fracturing of the strata is therefore favorable to extensive caving of extracted areas and to minimizing transfer of load to the unmined coal. This 'conditioning' of the seams and the associated rocks is all important in governing the violent stress relief characteristics of the coal.

The challenge for an adequate solution to the stress problem in coal mines has been stimulated by the fact that it is a difficulty encountered the world over in orogenic belts. In spite of more than a century of active exploitation of seams subject to occurrences of violent stress relief, there is tremendous diversity of opinion as to safe and economical methods of extracting such coal.

Thus far the tendency has been to exploit those seams and segments thereof which are most accessible and least disturbed tectonically. In orogenic belts, however, such coal is quite limited, and inevitably operations must be pushed into more difficult ground. An intimate knowledge of geologic structure both regionally and within the mines is needed for successful operations in orogenic belts.

It was because of these considerations that the Government of Canada undertook a systematic investigation of the complex relation of coal mining practices and structure with particular emphasis on the problem of violent stress relief. As the purely theoretical aspects of stress distribution about mine openings have been extensively investigated, the approach adopted was a practical and empirical one in which the mine was the laboratory.

The strain characteristics of coal and associated rocks were investigated by physicists of the Physical Metallurgy Research Laboratories. Precise leveling and convergence surveys were conducted by mining engineers of the Fuels Division in order to study the influence of mining on absolute movement of strata in the immediate vicinity of seams. The writer undertook a detailed study of regional structure in relation to the character of the seams being investigated by the aforementioned physicists and mining engineers. Close cooperation of all concerned facilitated a better understanding of the influence of geology on the profitable exploitation of coal at depth.

As should be expected the final answers to problems which have confronted the coal mining industry for more than a century were not forthcoming in the course of the first eighteen months of investigation. Considerable light has been shed on the subject however, and it is the geological aspects of the progress which form the body of this thesis.

II. STRATIGRAPHY

The Table of Formations (tab. 1, app.) will familiarize the reader with the sequence of rocks encountered in the various coal fields of the Canadian Cordillera and will aid in the correlation of the coal-bearing strata at the different mines. Thicknesses are taken from the designated authorities. The writer supplemented stratigraphic data in the Coleman area, where by far the most detailed studies of stratigraphy and structure were conducted.

A gradual thinning of the formations from west to east has been discussed by MacKay (1933), Beach (1943), Crockford (1949), Douglas (1950a), and others. Thus in the Coleman area where more than one fault slice is considered a corresponding number of thicknesses is given, as successive slices expose different segments of the stratigraphic sequence.

Of the total stratigraphic column the only commercially exploitable coal seams are contained in the Belly River and Kootenay formations in the southern portion of the Canadian Cordillera, and the Paskapoo and the Luscar formations in the Central Foothills (Nordegg, Alberta). On the south-west side of the Fernie Basin (Coal Creek Collieries) the four thousand feet of Kootenay includes about twenty-three coal seams (medium volatile bituminous) having a total thickness of 170 feet (MacKay, 1932); of these a half dozen have been mined at intervals in the past fifty years. Farther to the east, and beyond the main range of the Rockies, two seams have been worked extensively in the Coleman area. Here approximately 15 feet of coal (medium volatile bituminous) is included in the 565 feet of Kootenay which have been brought to the surface on the Coleman fault. At Canmore on the other hand some 3400 feet of Kootenay contain in the neighborhood of 20 seams amounting to a little over 60 feet of coal (low volatile bituminous and semianthracite). Mining operations have been carried on in about five of these seams. The Luscar formation at Nordegg contains at least five seams (low volatile bituminous) of which two are commercially exploitable, the upper averaging 13 feet in thickness, the lower about 6 feet. From MacKay's cross-section (MacKay, 1941) the estimated thickness of the Luscar is about 1700 feet.

Late Cretaceous and Paleocene coals are not being worked in the Canadian Cordillera. Limited coal deposits of the Belly River formation outcrop along the east flank of the main range of the Rockies in the Crowsnest Pass; one five foot seam (high volatile A bituminous) was worked some years ago by the Canadian-American Coal Company. Moreover a few miles east of Nordegg, Alberta, Paskapoo coals (five principal seams, high volatile C bituminous, ranging in thickness from one to six feet) were mined spasmodically until 1950.

As might be expected those deposits closest to the source of sediments are the thickest and contain the greatest proportion of coarse detritus. In the Fernie Basin for example, interbedded coarse- to fine-grained sandstones and chert pebble conglomerates toward the top of the coal-bearing sequence are the forerunner of the massive sandstone and conglomerates of the overlying Blairmore formation. Conformably underlying the Kootenay are the dark gray, silty, marine shales of the Fernie formation.

Farther east at Coleman however, the top of the Kootenay is characterized by dark gray to black shales and in places a massive, hard, coarse-grained sandstone. The contact with the Blairmore is unconformable as indicated by the variation in stratigraphic interval between the Number 2 seam and the basal conglomerate of the Blairmore. Figure 2 was compiled from a series of sections measured along the strike at the outcrop. It will be noted that this interval ranges from 78 feet at Prospect 5, to 12 feet at Number 1 Fan, McGillivray mine, to 33 feet at Prospect 24 at the extreme northern end of the seam. Within the McGillivray mine the basal Blairmore conglomerate is in contact with the Number 2 seam at a few points. This massive chert and quartzite pebble conglomerate is found to vary in thickness from 10 to 35 feet.

Irregular conditions of deposition within the Kootenay are exemplified by the progressive northerly thinning and final disappearance of the Number 2 seam, with a gradual predominance of hard, blocky, cross-bedded, coarse-grained sandstone. Moreover the 90 foot interval of black, carbonaceous, and silty, gray, thinly bedded shale between the Number 2 and 4 seams toward the northern end of the McGillivray workings reduces to the point where the two seams merge in International Pit 3. This convergence of the seams is portrayed in figure 6, a geologic map of that part of the

Kootenay formation in the vicinity of Coleman, Alberta.

In the Coleman area the Kootenay formation is composed of massive-bedded, cross-bedded coarse-grained, gray, rusty brown weathering sandstone; interbedded flaggy to thinly bedded, gritty, dark gray, rusty brown weathering shale and flaggy, to blocky, fine-to medium-grained, cross-bedded, gray sandstone; gray, silty, thinly bedded shales; and three coal seams of commercial significance. As the various sandstone and shale beds grade erratically into one another, the Number 2 and 4 seams are the only beds within the Kootenay that are of any use as markers throughout the extent of the underground workings. Some reserve should be used when referring to figure 3, a presentation of the only complete section of the Kootenay, as exposed on York Creek, three miles south of Coleman.

Unlike the depositional contact at the base of the Kootenay at Fernie, the coal-bearing sequence at Coleman is underlain by a major thrust fault (the Coleman fault) along which the Kootenay has overriden the Belly River formation some 7500 feet higher in the section.

At Canmore in the Cascade Coal Basin, outcrops of the Kootenay are few and fragmentary so that familiarity with the stratigraphy here is dependent largely on the Mount Allan section about six miles to the south-east, described by Crockford (1949, pp. 32-34). The interbedded dark gray to black, fissile, silty shales; black carbonaceous shales;

dark gray to black siltstones; fine-to coarse-grained, cross-bedded, rusty brown weathering sandstone; chert and quartzite pebble conglomerates; and abundant coal seams are lithologically analogous to the coal-bearing sequence exposed in the Fernie Basin. At Canmore also the Kootenay is underlain by the silty, dark gray shales of the Fernie formation.

The coal-bearing sequences at Fernie, Coleman, and Canmore are all below the basal conglomerate of the Blairmore formation. At Nordegg however, the coal-bearing Luscar formation lies above what is considered to be the time and lithologic equivalent of the Blairmore conglomerate (the Cadomin conglomerate). Although generally poorly exposed, the Luscar is known from exploratory drilling to consist largely of interbedded platy, cross-bedded, medium-grained sandstone, silty shales and black, carbonaceous shales, much as in the Kootenay formation.

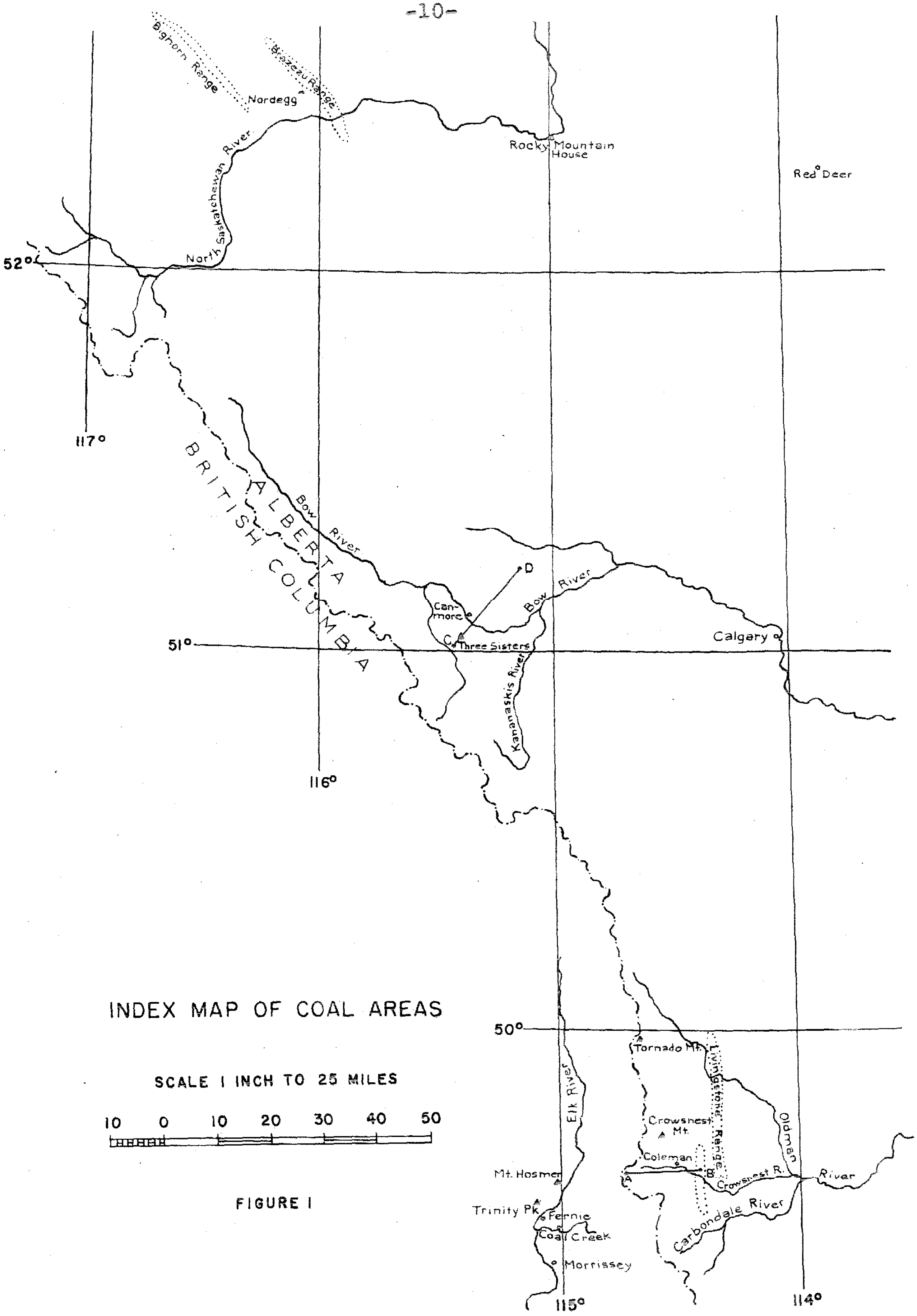
III. STRUCTURAL GEOLOGY

General Statement

In the limited time available to the writer detailed studies of regional structure were restricted to the Coleman and Canmore areas (Alberta), while underground studies were limited to four mines of Elk River Collieries, British Columbia; two mines of Coleman Collieries, Coleman, Alberta; two mines of Canmore Mines Limited, Canmore, Alberta, and two mines of Brazeau Collieries, Nordegg, Alberta. Figure 1 shows the geographic distribution of these localities. Not all of these mines have been subject to occurrences of violent stress relief. However, in order to evaluate the influence of structure on such occurrences it was necessary to compare and contrast structural differences within mines in the same as well as in different tectonic units. Significant variations in structure and physical makeup of the seams were helpful in explaining why all collieries within a given unit were not subject to violent stress relief occurrences.

The problem of establishing the general structural pattern within the mines examined was difficult because of the inaccessibility of large portions of some workings. After the coal has been mined out, the area is immediately abandoned, and the consequent caving of the superjacent strata renders it inaccesible. Hence the only parts of a given mine within reach are the active workings, which include main haulageways, airways, and freshly driven openings in areas being prepared for complete extraction. Even in haulageways considerable difficulty is encountered because of incessant convergence of roof and floor. This convergence necessitates a continual blasting away of strata in the hanging-wall and foot-wall in order to maintain adequate height for movement of mine cars, locomotives and mining machinery. Hence in many instances structural features in strata contiguous to a seam are made exceedingly difficult to discern.

In thick seams or swelled areas of thin seams it is common practice in the course of cutting the coal bed into



INDEX MAP OF COAL AREAS

SCALE 1 INCH TO 25 MILES

FIGURE I

pillars to drive openings in the upper portions of the seams. Thus structural studies are confined to the roof strata and the top few feet of coal. It is only at the extraction line of thick coal that one is able to study the deformation of roof and floor simultaneously. This is a decided disadvantage, as will be seen later, in establishing whether faults observed in the roof actually transect the seam, and in the eventuality that they can be positively identified in the floor, whether or not there has been any displacement of the counterparts in the plane of the seam.

Moreover it has not been the practice of the 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 portions of the mines.

The Fernie Coal Area

This region may be divided physiographically into two parts, the Lizard Range to the west, and that part of the Fernie Basin which abuts against it. Structurally the reason for these subdivisions is the existence of a major, folded, generally west-dipping thrust fault, the surface trace of which extends for miles along the west side of the Elk River Valley. Upper Devonian and Mississippian limestones, thrust eastward over the Fernie shales for considerable distances, present two contrasting lithologies.

The Elk River through incising deeply the relatively incompetent units beneath the thrust has accentuated the physiography and added to the grandeur of such peaks as Hosmer and Trinity Peak in the Lizard Range. In addition the more resistant sandstones and conglomerates of the eastwardly dipping Kootenay and Blairmore formations stand out in bold relief along the east side of the valley. These massive units of the Lower Cretaceous have been disconnected from their westward extensions. It is the cutting down by the Elk River and its tributaries which is responsible for the extensive exposures of coal seams along the west side of the Fernie Basin.

The present gentle eastward tilt of the Kootenay and Blairmore strata of the west side of the Fernie Basin is believed to be due in large part to folding beneath this major thrust plane. Immediately to the west of Mount Hosmer the thrust is observed to cut rapidly up section in the underlying strata through the massive, late Paleozoic limestones and quartzites prior to its flattening out in the Fernie-Kootenay zone of bedding-plane slippage under Hosmer. The compressive force transmitted by the overthrust mass against this steeper segment of the fault plane is believed to have been responsible for the folding underneath the fault.

Mining operations at the Elk River Collieries, three miles from Fernie, are presently conducted in the five uppermost, economically exploitable 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 the Elk River Valley to a gently undulating condition within a few miles to the east. The basin-like form is excellently revealed by the more weather-resistant sandstones and conglomerates on both sides of the valley of Coal Creek.

Underground studies included a detailed mapping (scale: 100 feet to the inch) of the Number 1 East, 9, 4, and 3 mines. As only limited sections of the seams are accessible, the acquired data are merely a sample from the overall picture. However a consistent pattern of deformation was encountered throughout all the seams investigated, and it is believed that this sampling must be fairly representative of actual structural conditions within the various seams.

The Number 1 East mine is operated in the 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 relief of stress. Unfortunately very little data are available on structural conditions in the inner workings of this mine beyond a survey of elevations of the roof of the seam at various points. Roof contours however reveal a relatively horizontal, undulating condition throughout the seam. In the outer workings only one fault, a normal fault with maximum stratigraphic throw of six feet, was encountered. It was traceable for about 800 feet along the strike of the seam. As will be seen in part VII the 1 East mine is of great importance in the problem of violent relief of stress.

Insofar as the Number 9, 4, and 3 mines are concerned, the deformation of the seams is so very much alike that a detailed discussion of the last named mine will suffice for all three.

Reference to figure 4, a structure map of this seam, will reveal the generally uniform dip of around 20 degrees, and in certain sections, particularly the Number 4 Incline, the workings southward from the top of this incline, and the Number 8 Incline, the profusion of faults. In the first two instances faults within the respective clusters have common trends while in the 8 Incline section the pattern of traces is not so definite. A very high percentage of faults are extensional features. Note that the orientation of a fault on the map is a projection into the horizontal of the trace of the fault on the roof of the seam.

As there is good reason to believe that the coal-bearing sequence was subjected to some rotation during the period of development of many of these faults, the writer prefers to avoid the use of the normal and reverse concept as applied to faulting within the mines, and to use the bedding across which the faults transect as the datum plane. Thus those faults permitting an extension in the plane of the bedding will be referred to as extension faults, whereas the reverse type of phenomenon will be referred to as contraction faults. With this designation, no implication is made as to the genesis of these features.

Although ranging in stratigraphic throw from negligible displacement to twelve feet, the extension faults which have been mapped have an average throw of from two to three feet. Contraction faults on the other hand are characterized by much larger throws, commonly from ten to twenty feet. Many of these faults are not traceable from the roof into the floor of the seam. The faults indicated on the structure map (fig. 4) are only those found in the roof. As the Number 3 seam ranges in thickness from ten to twenty feet, unless the total height of the seam is mined out, the structures in the floor are of course, not visible. Moreover in many instances where the total thickness of the seam is mined out, the corresponding segment of a fault in the floor is conspicuously absent. In addition, the roof of the seam (and presumably the floor) is cut by innumerable extension faults of very small displacement (less than one inch) and exceedingly irregular trace. So abundant are these minor features and so irregular is their pattern that no attempt has been made to map them.

Aside from these offsets in the roof and floor, the seam itself has been subjected to intensive shearing which has resulted in most places in a complete disappearance of any original cleat. Moreover this shearing motion has produced abundant polish and slickensides on the roof of the seam. Note from figure 4 that slickensiding on the roof and drag-folds within the coal indicate a motion of the hanging-wall up the dip relative to the seam during the period of deformation. In those areas where caving has taken place abundant evidence of bedding-plane slippage was found within the superjacent strata, the slickensiding in all cases paralleling that on the roof of the seam. This testimony in combination with axial thickening of the coal in folds suggests that during the period of flexing, the coal-bearing sequence tended to produce similar folds.

As the reader is already aware, a number of interesting problems relating to the mechanics of seam deformation have been brought to mind. After a discussion of the other areas examined an attempt will be made to interpret these features in terms of the regional structure of the respective areas (see pt. III).

The Crowsnest Coal Area

The area under consideration is located along the western margin of the Disturbed Belt, that major tectonic subdivision lying between the main range 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. Whereas massive, late Paleozoic limestones, dolomites and quartzites form the core of the outer ranges, the inner area consists largely of sandstones, shales and coal seams of Mesozoic age.

To familiarize the reader with the structure in the vicinity of Coleman, reference is made to figure 5, a cross-section from Crowsnest Lake on the west to Bluff Mountain on the east, a distance of eleven miles (see fig. 1 for geographic location of the section).

Movement on the Lewis thrust during the Laramide orogeny is responsible for the present disposition of Upper Devonian limestones over moderately disturbed sandstones of the Upper Cretaceous age. Note that the thrust plane parallels the bedding of the Devonian sediments above, but cuts through the underlying Belly River sandstones at a moderate angle; the inference is that the latter are cut off a few thousand feet down the dip of the fault plane. That the thrust may pass fairly rapidly through the Belly River is substantiated by the fact that ten miles to the south Crockford (1951) found pre-Belly River sediments and volcanics faulted in between the Belly River, and the Beltian and Paleozoic rocks of the Flathead Range.

Crowsnest Mountain, a klippe, has been projected five miles in a direction S 10° E, the general trend of the structures in this area, into the line of section. As there is no radical change in the structure over this distance, it is felt that such a projection is justified.

Between Crowsnest Lake and the klippe, the Lewis thrust plane has cut up section considerably in the overlying mass so that whereas some 2600 feet of Devonian sediments are observed above the fault at the lake, only 400 feet are to be found on Crowsnest Mountain. Moreover within the first half mile along the trace of the Lewis thrust to the north of Crowsnest Lake approximately 300 feet of the lowest Devonian beds are cut out. This cutting up section of the thrust plane to the east and north is consistent with the findings of Douglas (1950a, pp. 86-87) on Tornado Mountain, 20 miles north of Crowsnest Lake. Here the Lewis thrust is within the upper 1000 feet of Devonian strata along the east flank of the High Rock Range. In passing across the valley of Dutch Creek into Tornado Mountain the fault plane cuts up section in the overthrust mass into the base of the Banff formation.

Where the Lewis thrust passes from the Devonian into the basal Banff on Tornado Mountain, an anticline was formed with a gentle syncline immediately to the east of it. The axes of these folds coincide with the axes of folds in the beds underlying the fault. The analogy with the structure involving Crowsnest Mountain is immediately apparent. In order to cut out such a large section of Devonian strata between the present front of the main range and the klippe, as well as to produce a bedding-plane fault on the klippe, it is necessary to fold the beds above the fault into an anticline with an equally gentle syncline to the east of it. Over and above this initial flexing required of the beds in the overthrust mass, the fault plane is folded to roughly the same degree as the beds above and below it. It is apparent then that this accentuation of the folds above the fault plane in association with the flexing of the underlying mass must have taken place simultaneously, and that the flexing must have been initiated by folding of the Upper Cretaceous strata below the thrust plane.

Between Crowsnest Lake and Coleman is a relatively undisturbed sequence of westward dipping Cretaceous sediments and volcanics. This sequence from the Belly River formation to the Kootenay has been thrust on to the Belly River by the Coleman fault. Again note that the thrust plane is about parallel to the beds in the overthrust mass and cuts down section through the strata in the underlying block. That the fault must cut down section at depth through the Belly River is borne out by the occurrence of thin slices of the Crowsnest, Wapiabi, and Blairmore formations between the Kootenay and the Belly River at several points along the trace of the thrust plane (see fig. 6).

For considerable distances in the vicinity of Coleman the thrust is localized as a zone of bedding-plane slippage in the Number 5 coal seam. An airway in the

International mine follows this zone for 2000 feet up the dip. Reference to figure 6, a geologic map of the coal-bearing sequence in which the McGillivray and International mines are respectively located, will illustrate this point.

The Coleman fault is particularly interesting in that its behavior is known in detail throughout its length. The break begins within the Kootenay formation in the extreme north-west corner of the Mount Head Map Area (Douglas, 1950b), at a point about 60 miles north of Coleman. Whereas it remains a bedding-plane feature *relative to the overthrust mass* almost throughout the entire length of the break, below the fault plane it cuts up section toward the south. Thus in the vicinity of Coleman the Kootenay and formations above it in the sequence have been thrust over the Belly River. About five miles south of Coleman however, the fault plane cuts down section in *the underlying mass* through Belly River strata into Wapiabi so that in this region Kootenay lies over Wapiabi. Moreover in the Carbondale River area (Crockford, 1951), thirteen miles south of Coleman, the fault passes rapidly upwards in *the overthrust mass* through the Blairmore and Crowsnest formations into the Wapiabi so that within three miles along the trace of the fault the stratigraphic throw is reduced to zero and the fault dies out in the Wapiabi. Briefly then, throughout the seventy-five miles over which the Coleman fault may be traced, the thrust plane has Kootenay above it for all but the last five miles or so where the fault cuts upwards through the overthrust mass into the Wapiabi. Below the fault however occurs a regular succession of formations beginning at its northern extremity with the Kootenay, passing upward into the Belly River and then down section into the Wapiabi where the stratigraphic throw diminishes to zero a few miles south of the Carbondale River.

The next fault slice to the east of Coleman is contained between the Coleman fault on the west and the Mutz fault on the east, and consists of a regular succession of westward dipping Cretaceous strata from the Belly River through to the Blairmore. Associated with this passage through successively older formations is a regular increase in dip from 22° in the Belly River formation close to the Coleman fault to 55° to 60° within the Blairmore.

The behavior of the Mutz fault along its surface trace in a southerly direction is an excellent illustration of the concept proposed by Rich (1934, pp. 1589-90) of the control by competency of units in a stratigraphic sequence on the path of a low-angle thrust plane through it. The initial break begins about six miles north of the line of section in figure 5 in the sandy shales of the Blackstone formation, where because of poor outcrops the attitude of the thrust cannot be ascertained. However within five miles the fault has cut down section both above and below the slip plane into the massive sandstones and conglomerates of the Blairmore formation. Within the latter unit the fault is almost vertical. Moreover, when the fault reaches Crowsnest River it has cut down section in the overthrust mass so that for the next eleven miles to a little beyond the Carbondale River the coal seams of the upper Kootenay are thrust over Blairmore strata. The fact that the fault plane parallels the bedding in the Kootenay, but transects the Blairmore strata at an angle of about 20 degrees is fairly definite evidence that it must flatten into a zone of bedding-plane slippage within the Kootenay. For this reason, in the cross-section (fig. 5), the Mutz fault has been interpreted to flatten at depth in the incompetent carbonaceous shales and coal of the Kootenay formation. Competency then is apparently playing a significant role in the mechanics of faulting in this region.

The reader will note in the cross-section that a second fault is postulated within the Blairmore. Although there was no positive surface indication of this feature, the fact that an abnormal thickness of Blairmore is encountered above the Mutz fault necessitates such a consideration. From the cross-section it is seen that approximately 4000 feet of Blairmore lie between the Mutz fault and the Crowsnest formation. Recall from table 1 that 2500 feet of Blairmore was measured in what was believed to be an unfaulted sequence at Coleman. Moreover MacKay (1933, p. 7), found the Blairmore formation to be 2300 feet thick on Byron Creek, on the east flank of the Blairmore Range a few miles south of the line of section. Even though almost the total thickness of Blairmore strata is faulted in (recall that immediately south of the Crowsnest River, Kootenay overlies the Blairmore), the thickness still falls short by around 1500 feet. The only other possibility is that a plastic condition in the strata allowed an abnormal thickening. However such a notion is difficult to conceive in view of the massiveness of the sandstone and conglomerate beds within the Blairmore, and the entirely normal aspects of bedding and jointing in the outcrops in this fault slice.

To the east of the Mutz fault is a regular sequence of west-dipping formations from the Lower Cretaceous to the late Paleozoic in the Blairmore range. On the east side of Bluff Mountain however is a thrust fault responsible for the uplift of the Rundle formation and the overturning of Kootenay and Blairmore strata of the syncline immediately to the east. The interpretation of the behavior of this thrust at depth is conjectural because of limited control to the north and south of the line of section. However the fact that a complete thickness of Rundle is exposed above the fault indicates that the zone of slippage must be localized at least in part within the Banff. Moreover the sinuous trace of the fault in the gap between Bluff and Turtle Mountains is indicative of its proximity to a bedding-plane feature relative to the overthrust mass.

During the last fifty years mining operations have been carried on extensively in the Number 2 and 4 seams at Coleman. Both seams are worked from two mines, the McGillivray mine to the north of the Crowsnest River, and the International mine to the south. In each instance rock tunnels between the seams facilitate easy access to both horizons. Emphasis will be laid here on the Number 2 seam because of the extent of operations within it and the accessibility of the workings. The Number 4 seam is mostly mined out, and operations within it are now at a minimum.

The proximity of the Number 2 seam to the Coleman thrust (approximately 550 feet stratigraphically above the fault plane) is doubtless responsible for the multitude of small faults cutting the seam and the intense degree of shearing of the coal.

Figures 7 and 8 are structure maps of the accessible workings in the Number 2 seam in the McGillivray and the International mines respectively. The profusion of faults over the six miles of strike-distance investigated shows no regional pattern, although in some sections of the McGillivray mine particularly, the faults tend to have a preferable azimuth.

As in the case of the mines at Elk River Collieries, the greater proportion of faults in the Number 2 seam are extensional features. Their mean stratigraphic throw of from two to three feet is somewhat in contrast to the much larger throws of the contraction faults (commonly ten to twenty feet).

The most outstanding feature within this seam is the low-angle contraction fault cutting the Number 5 Level of the McGillivray mine (fig. 8) at latitude 28000 feet, and resulting in a 160 foot horizontal offset of this level. The fault cuts upward through the section at an angle of about 20 degrees to the bedding. From latitude 34000 feet north however, it changes to an overturned fold. Further up the dip at these latitudes the seam is flexed into a gentle anticline and syncline, much in contrast to the remarkably planar condition of the rest of the seam from latitude 27000 feet south to the southern end of the International workings.

As a result of extensive bedding-plane slippage, localized particularly within the seams, the Number 2 coal is in large part reduced from a blocky to a soft, platy, drag-folded condition. By means of columnar sections, a comparative study was made of the influence of tectonics at different geographic locations in the seam. In order to portray the trend from extremely sheared coals at the southern end of the International workings to coals of a more blocky nature further north, a plot (fig. 9) was made of the ratio of the percentages of solid to sheared coals in any given columnar section, against distance to the north of the zero latitude of the International property. At the extreme south the coal is intensely sheared from roof to floor and of course, the ratio of solid to sheared coal is zero.

Farther north, although there are radically varying proportions of solid coal, the latter is consistently the more abundant. In view of the large scatter, the ratios at the northern end particularly are not representative of east-west cross-sections at their respective latitudes, but they indicate there are sections of the seam carrying very high proportions of solid coal.

Associated with the intense shearing in the southernmost workings of the International mine, the Number 2 seam exhibits irregular variations in thickness. Both of these factors, the shearing and the pinching and swelling are indicative of the exceedingly great degree of deformation to which the seam has been subjected in this area. Farther to the north however the proportion of sheared coal progressively diminishes and the amount of bedding-plane slippage within the seam was correspondingly less. It is believed that whereas the deforming stresses found some relief through folding and low-angle contraction faulting to the north, differential motion between the beds continued to shear that section of the seam to the south.

That there was a minimum of differential movement involving the seams in the McGillivray mine is substantiated by the structural relation of two volcanic dikes to the seams. One transects the Number 2 seam at latitude 25000 feet and the other at 35000 feet. These dikes are genetically related to the Crowsnest formation and hence are post-Kootenay and

THE VARIATION IN DEGREE OF SHEARING ALONG THE STRIKE OF THE NUMBER 2 SEAM COLEMAN, ALBERTA

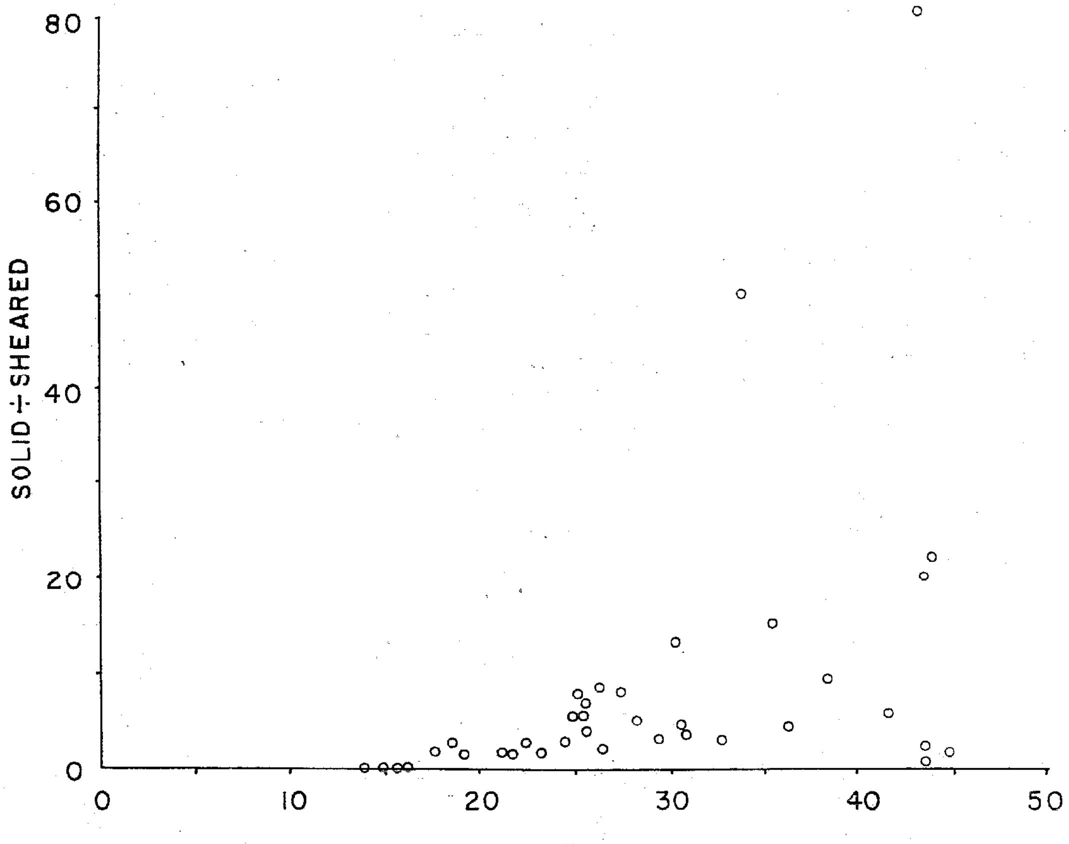


Figure 9.

pre-Laramide in age. Whereas the former dike is not offset within the Number 2 seam, that segment of the latter within the hanging-wall is offset 32 feet up the dip in the plane of the seam relative to its continuation in the foot-wall.

A knowledge of the behavior of extension faults throughout the length of their trace on the roof of the seam as well as in the vertical is particularly important in the control of caving in extracted areas. It is immediately apparent that large overhangs must lead to abnormal loading in abutment zones. Hence if advantage is taken of natural lines of weakness within the superjacent strata, overstressing in close proximity to the extracted areas may be lessened. Moreover it is frequently necessary to leave barrier pillars of coal to support the strata under a river or some public property. The vertical extent of faults is all important since if they extend only short distances above and below the seam their presence may be neglected and much smaller barriers may be used. However should they be found to cut through the strata for great distances, caving at depth may be instantaneous at considerable heights above the seam; in this case, a wide barrier is essential.

There is no uniform variation in stratigraphic throw of an extension fault along its trace. Such a fault may gradually increase in throw to one or two feet, then seemingly without reason increase in amplitude by a factor of several times only to diminish equally as quickly to zero within a few tens of feet. As a generalization however, it may be said that the faults of largest throws persist for the greatest distance in the plane of the seam.

The problem of tracing the behavior of these faults in the vertical direction is difficult for two reasons. In the first place it is necessary that mining operations be carried on in more than one seam in the stratigraphic sequence; and in the second place, because of the aforementioned bedding-plane slippage, localized particularly in the coal seams and their immediate vicinity, different segments of a fault plane may be offset from one another so that should such a fault cut through to another seam it may not be recognized. Simple geometrical projection is frequently impossible not only because of these offsets, but also because of variations in attitude of the fault planes as they transect different strata.

In spite of these difficulties however, an opportunity of making this study was afforded in the McGillivray mine in the immediate vicinity of the aforementioned dike at latitude 25000 feet. As was pointed out, there was no perceptible offset of the dike in the plane of the seam so that bedding-plane slippage must have been at a minimum. Moreover this was one of few points where workings in the Number 2 and 4 seams were simultaneously safe for travel. Hence a detailed structural study could be made of the accessible segments of the two seams overlying one another.

The Number 4 seam at this point is 81 feet stratigraphically below the Number 2 seam.

The identification of a particular set of faults common to the two seams was very simple in this instance, as will be seen from figures 10 and 11, structural maps of overlying segments of the Number 2 and 4 seams respectively. The most prominent features common to both seams are the two intersecting, extensional faults AB and CD. That these are quite probably the same pair of faults is borne out not only by the common trends and angle of intersection, but also by the common direction and degree of dip. Moreover there is a similar variation in throw of corresponding faults along the trace, and fault CD is observed to splay in both seams a short distance south of the point of intersection of AB and CD. Neither fault is offset between the roof and floor of the two seams. Finally, a projection of the line of intersection of the two fault planes (which projection is feasible in this instance), from one seam to the other further confirms the correlation.

Since each of the faults has about the same stratigraphic throw at corresponding points in the two seams, it is believed that they must continue for considerable distances vertically. It will be noted that a correlation of those faults of small throw (less than three feet) which have been mapped in the two seams is not so definite and that many of them must die out within a few tens of feet above and below their respective seams.

From the multitude of extension faults of small stratigraphic throw that have been mapped within the seams at Coleman and elsewhere it is apparent that if such faults have only limited vertical extent, there must be a profusion of faults within the coal-bearing sequence which never actually transect the seams. That these faults are not localized about the coal beds is borne out by detailed studies in the many rock tunnels above and below the seams. Faults are equally as frequent in the immediate vicinity of the seams as away from them.

Briefly then, the coal-bearing sequence at least, has been intensely fractured and broken by extension and contraction faults as a result of Laramide stresses. The bearing of such a highly fractured condition of the strata on the ability of the rock units to behave as elastic beams will be discussed in part VIII.

The Cascade Coal Area

Throughout its length the Cascade coal area is limited on the west by the abrupt rise of the massive limestone peaks of the Rundle Range and on the east by the Fairholme Mountains. The low relief of the area is due in large part to the softness of the Triassic, Jurassic and Cretaceous sediments underlying it.

Structurally the coal area is included in Clark's Lac des Arcs fault block (Clark, 1949, p. 633), and is limited on the east and west respectively by two major west-dipping thrusts, the Lac des Arcs fault and the Mt. Rundle fault. As may be seen in figure 12, this block includes all mappable units from the Cambrian to the Lower Cretaceous. The cross-section (C-D) begins at the Spray Lakes to the south-west of the Rundle Range, cuts through the latter in a north-easterly direction at The Three Sisters, and continues across the valley of the Bow River into the Fairholme Mountains (Grotto Mountain) to the vicinity of the Lac des Arcs fault.

The major thrust in the Canmore area is the Mt. Rundle fault along which the Cambrian, Ghost River, Fairholme and Palliser formations have been thrust over the coal-bearing Kootenay strata. A number of subsidiary faults occur within the Rundle Range, and are responsible for repetitions within the Paleozoic which give rise to the majestic peaks of The Three Sisters.

In conjunction with the overthrusting the Kootenay formation has been flexed into a prominent, asymmetrical basin, the Mount Allan syncline (Crockford, 1949, p. 44) which extends throughout the length of the Ribbon creek area immediately to the south-east and an unknown distance along the front of the Rundle Range to the north-west. In the vicinity of The Three Sisters the upper Kootenay beds exposed on the west flank of the syncline are vertical or overturned, whereas those on the east flank dip gently westward from 10 to 20 degrees. Faulting within the syncline has resulted in considerable thickening of the coal-bearing sequence. Two of the major thrusts responsible for this thickening were observed in the valley of Three Sisters Creek immediately to the north of the line of section. The incompetency of the Kootenay as a whole is borne out by the intense degree of faulting and folding of the coal seams worked within the formation.

Under the strongly glaciated and alluviated valley of the Bow River is a gently west-dipping sequence from the Kootenay through to the Spray River formation. The reddish brown weathering siltstones of these latter beds outcrop low on the west flank of the Fairholme Mountains, and dip 30 to 35 degrees to the south-west. From the Spray River through to the Banff formations the sequence is relatively undisturbed. However on the eastern flank of Grotto Mountain is a minor fault along which Banff strata are thrust over Rundle and the sequence is again repeated from the Rundle formation to the Cambrian. At this point the latter formation has been thrust over Rundle strata on the Lac des Arcs fault.

Of the many seams studied in the course of the investigation the Number 4 seam, Canmore, is outstanding in many respects. In the first place it is the only seam in which some semblance to a fault pattern exists. As will be noted from figure 13, a structure map of the accessible portions of this seam, the general structural trend of the faulting is a few degrees west of north and cuts diagonally across the levels at an acute angle. Moreover this faulting is concentrated in the workings of the north-west section where the seam is relatively planar; to the south-east, where the seam is flattened somewhat, faults are few in number.

At several points in the seam opportunity was afforded to study the time relationships of faults which offset one another. Here, as elsewhere, nothing systematic was found, and it must be concluded that all faults with a common trend were not necessarily formed simultaneously. This is borne out moreover by the fact that some faults transecting the roof strata have offset counterparts in the floor (and vice versa), while others may be directly traced from roof to floor through the coal seam. The mechanics of these peculiarities of seam deformation will be discussed in the next part.

As is the case of all the seams investigated, over 90 per cent of the faults are extensional and have a mean stratigraphic throw of from two to three feet. The Upper Marsh on the other hand is cut by very few faults, all of which are extensional.

In contrast to the Upper Marsh, and in fact all the seams investigated, the Number 4 seam exhibits a remarkable development of cleat. A detailed study of the spatial orientation of these fracture planes throughout the seam revealed a consistent pattern: two systems of cleat, one at N.10° E., 70° W., and N.85° W., 70° S.; the other at N.60° E.90°, and N.30° W., 70° NE. These data are relative to a mean orientation of the coal seam at N 30° W, 21° SW. For consideration of average values, only those measurements taken where the seam is quite planar are included.

In terms of relative strengths of the different cleats, the one parallel to the dip of the seam (N.60° E.) was by far the most prominent, and resulted in the breaking of the coal into smooth, tabular sheets as thin as one eighth inch, and up to one quarter inch. The complement of these planes of fracture was in general rather weak, but it was quite evidently parallel to the strike of the seam and essentially perpendicular to the bedding.

The fracture planes at N.10° E. and N.85° W. were in general of equal strength throughout, although at some points one or the other may have been absent and its place taken by a system of fracture planes which in a regional sense had random orientation. Characteristically the fracture planes of this set of cleats had a separation of one to two feet, and by running prominently from roof to floor of the seam they resulted in a breaking of the coal into distinct rhombohedrons. As both systems of cleat are superposed, a fragmentation of one of these rhombohedrons produces a large number of parallel laminae because of the prominent cleat in the direction of dip of the seam (N.60° E.).

Note that the spatial orientation of the bisectrix of the set of cleats at N.10° E., and N.85° W. is N.45° E., with a plunge of 30° to the north-east. Upon rotation of the seam into the horizontal, the bisectrix assumes a new plunge of 41° in the direction N.15° E.

The cleat system paralleling the dip and strike of the coal bed conforms well with the general pattern of fracture cleavages in tilted seams. Moore (1950, p. 10) suggests that this set is due to desiccation of the carbonaceous matter, with shrinkage and cracking. Moreover if one may apply the strain ellipsoid (in spite of its insurmountable restrictions in practical work) to the interpretation of the second cleat, the azimuth of the direction of maximum shortening of the ellipsoid (the bisectrix) is at 45° to the regional trend of the structures in this area when the seam is rotated into the horizontal. It plunges in the direction of the Laramide forces at an angle of 41°. It might be suggested that this tilt in the bisectrix is the resultant of gravity and deforming forces directed toward the north-east. Hence this cleat may possibly be tectonic in origin.

The blocky coal of the Number 4 seam has been subjected to a minimum of shear. In most instances faults may be traced from roof to floor, occasionally with minor offsets. However some polish and slickensides are distinguishable and conform rigorously with the general pattern of an up-dip motion of the roof over the seam. This would be produced by a tendency for the beds in the axial region of the Mount Allan syncline to retain a large radius of curvature and hence to slip over one another along bedding-planes.

In contrast to the Number 4 seam, the Upper Marsh has been intensely sheared and fractured from roof to floor. Drag-folding within the coal as well as polish and slickensiding on the roof (and for that matter on the floor also when it is visible) indicate extensive bedding-plane slippage and riding of the strata up the dip over one another away from the axial region of the syncline. Because of this motion there is no counterpart in the floor of faults found in the roof and vice versa.

The problem of why some seams more than others are sheared as a result of this differential riding out of beds is difficult. There are two possible explanations. Either there are radical differences in ability of seams to resist shear or some seams more than others are protected from shearing. As for the first possibility, petrographic data on the Number 4 and Upper Marsh seams are lacking so that little can be said of the intrinsic strengths of the two coals. In the second instance, it is reasonable that the more massive and competent units should exert a greater tendency toward this overriding, and the presence of such units in close proximity to a seam might lead to its being sheared. With thinly bedded units in the immediate vicinity of a seam, on the other hand, the bending of the sequence would be taken up by small scale slippage on innumerable bedding-planes, and the effect on the seam would be lessened. Thus the original blocky nature if the coal would be preserved. However stratigraphic data between the seams at Canmore are nil, since logging of drill-core (beyond recording the presence of absence of coal) is not practised.

The Nordegg Coal Area

The Nordegg coal area lies in the Central Foothills of Alberta, in a broad structural basin between the Brazeau Range on the east and the Bighorn Range on the west. These are two of a number of northwest-trending anticlinal ranges of the Central Foothills (Erdman, 1950). Displacement of large masses of Upper Devonian and late Paleozoic rocks on southwest-dipping thrust planes is responsible for these anticlinal structures.

From the dip-slope of the west flank of the Brazeau Range to the rugged scarps of the northeast face of the Bighorns, the gently west-dipping Cretaceous strata are moderately faulted and folded. In contrast to the massive limestones and quartzites of these ranges, soft Cretaceous sediments underlie the intervening basins.

The lower Cretaceous Luscar formation, in which occur the coal seams under consideration, outcrops low on the west flank of the Brazeau Range. The gentle, southwesterly dip of these beds averages about 8 degrees, although it ranges from horizontal to as much as 14 degrees.

Coal seams in the Luscar, the Number 3 seam and the Number 2 seam approximately 100 feet stratigraphically below it, have been extensively worked at Nordegg. The former seam averages 13 feet in thickness, the latter 6 feet. Both seams have been so intensively sheared through differential movement of the beds that only in the central part of the seams is there occasionally any blocky coal. As in all the other seams investigated, drag-folds within the coal, as well as slickensides on the roof and floor, indicate an up-dip motion of the upper beds over the lower. Irregular pinching and swelling of the seams emphasize the large scale movement of the coal within the seams which took place during the 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. Either the faults did not cut through the seam, or the corresponding offsets in the roof and floor have been widely displaced from one another because of this differential motion. Unfortunately only a limited area of the workings was accessible in both coal horizons so that if counterparts exist they could not be positively identified.

A study of slickensiding on extension faults whose traces cut diagonally across the dip of the seam revealed that whether a fault was left-handed* or right-handed, the down-dropped block moved in an easterly direction 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. This could have been during the period of differential slippage of the beds.

Summary

Abundant polish and slickensiding on the roofs and floors of the seams as well as drag-folds within the coal indicate almost without exception that the upper strata have moved differentially up the dip relative to those below them in the sequence. The only exceptions were found where the seams were intensely fractured and broken, as for example in the 4 Incline section of the Number 3 mine, Elk River Collieries (fig. 4).

Depending on the extent of this differential motion between the beds, the seams have been sheared to varying degrees. In those seams over and under which there has been a minimum of slippage, sheared coal is confined to within a few inches of the top and bottom of the seams. With more

---

*Footnote: A left-hand fault is designated as one in which the major component of slip is to the left for an observer standing on one block (which is considered fixed) and facing the active block.

extensive motion, in addition to an exaggeration of these initial shear zones, drag-folding is localized at various points within the seam. In those instances where there is a complete destruction of primary bedding-features and cleat, drag-folds extend without interruption from top to bottom of the seam (for example in the southernmost workings of the International mine, Coleman), or the seam is broken into a number of subsidiary drag-folds (as for example in some sections of the Number 2 and 3 mines, Brazeau Collieries, Nordegg). Intimately associated with this intense shearing is an irregular pinching and swelling of the seams.

The degree of deformation at a given point in a seam is naturally dependent in part on the intrinsic strength of the coal at that point. Thus some reserve must be exercised in interpreting drag phenomena in relation to the extent of slippage of roof over floor.

A second feature common throughout the mines is the predominance of extension faults (roughly 75 to 90 per cent of faults mapped), the mean stratigraphic throw of which is from two to three feet. In terms of the regional tectonics it might be said that these features are of little significance, but the fact that there is such a predominance of them is indicative of some fundamental feature in the mechanics of seam deformation. Within any given mine the trend of these faults reveals no consistent pattern although in local areas a common structural trend is evident. For those extension faults whose traces on the seam cut diagonally across the strike, the slickensides indicate motion of the down-dropped block from a simple dip-slip to an oblique-slip motion. No instances are found where the down-dropped block has moved against the direction of the applied force.

Although contraction faults are very much in the minority they consistently have throws from 10 to 20 feet, commonly exceeding those of extension faults by a factor of at least five. Contraction faults characteristically trend parallel to the strike of the seam, or cut across the strike at a very acute angle.

The problem of determining whether many of these faults with no observable counterparts actually transect a seam or stop at it, is particularly difficult because of limitations imposed through inaccessibility of mine workings. However in most instances it is believed that such faults actually do continue across a seam. When the slickensiding on an extension fault is indicative of a dip-slip motion, the counterpart of an offset in the roof is commonly found in the floor along the projection of the fault plane. Moreover in coal seams exhibiting little or no shearing, faults observed in the roof are easily traced into the floor rock. They are either not displaced in the plane of the seam, or are displaced but a few feet and are readily identified. However where a seam is intensely sheared from top to bottom (suggesting large scale movement) no counterpart of faults observed in the roof can be found in the floor and vice versa. The possibility of faults ending abruptly at a coal seam (or any incompetent unit of comparable thickness for that matter) cannot be overlooked, but it is believed that in the majority of cases such faults with no apparent counterparts actually do transect the seams. Their continuations in the roof and floor have been offset relative to one another.

No systematic time relationship was found to exist among extension faults. Moreover no positive conclusions could be reached as to the relative timing of extension and contraction faults beyond the fact that both types have offset counterparts. Thus both must have developed either before or during the period of bedding-plane slippage.

Generally speaking the strata immediately underlying the seams are incompetent carbonaceous shales. During the deformation of the coal-bearing sequence the strata in the immediate foot-wall have been subjected to a greater degree of buckling and crenulation than has the immediate roof. It would appear that in some instances during the period of deformation the strata underlying a seam flexed rather than fractured.

IV. MECHANICS OF SEAM DEFORMATION

The reader will note that throughout the mines studied certain deformational features were consistently found. It is apparent that some common peculiarity in the mechanism of seam deformation is responsible for this consistency. In the Coleman and Canmore areas the diastrophic histories of the seams are similar in the sense that the coal-bearing sequences have been carried considerable distances on low-angle, west-dipping thrusts. It is the writer's contention that in these areas at least, the deformation within and about the seams is the direct result of movement of these overthrust masses.

In the southern Canadian Rockies it has been well established that the major thrusts originated from primary fracture planes within the stratigraphic sequence (Douglas, 1950a, p. 96). There was no appreciable initial folding. Moreover the paths of these fracture planes as they cut through the section were controlled by the competency of the successive units which they transected. In this manner they tended to follow three horizons in particular: the soft, carbonaceous shales and coals of the upper Belly River formation; the shales and coal seams of the Fernie and Kootenay; and the soft shales of the Exshaw and basal Banff. Furthermore in cutting up section these primary fracture planes pass through the more massive limestone, sandstone, and conglomerate members at rather steep angles so that in a regional sense the thrust planes are made up of a series of shoulders and flats, the latter representing zones of bedding-plane slippage and the former zones of rapid cutting up section through the sequence. It should be borne in mind that with variations in stratigraphic throw along the strike, the fracture plane must cut through progressively higher or lower units in the sequence. Thus the aforementioned shoulders exist not only across the trend of the thrust plane, but also along its strike. It will be recalled from the discussion of the structures of the Coleman and Canmore areas that although data to substantiate these views are limited, there is every indication that this type of low-angle thrusting has taken place.

The existence of shoulders in major thrust planes necessitates moderate flexing of the overriding masses. As may be seen in the idealized example in figures 14, a small displacement on such a fault plane results in the folding of the overthrust mass into anticlines where the fault cuts rapidly up section in the more competent units (B'C' and D'E', fig. 14b). A flat-bottomed syncline must develop in between because of the bedding-plane characteristics of the fault in this sector (C'D, fig. 14b). Moreover with progressive movement, a section of the overriding mass which is initially flexed into a concavity (B^oC^oB', fig. 14b), passes through the neutral form and is then flexed in the opposite direction (fig. 14c) as it moves over the top of a shoulder. It then levels out along another zone of bedding-plane slippage (fig. 14d). In this manner the overthrust mass is flexed first one way then the other, so that a given bed in the sequence is subject to alternate periods of stretching and compression. The greater the horizontal displacement, the more shoulders are encountered and consequently the greater is the amount of flexing to which the displaced mass is subjected.

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

The multitude of extension faults of such small throw may indicate the overall weakness of the displaced mass when it is being stretched. The inability to transmit tensile stresses any distance prevents the development of few extension faults of large stratigraphic throw. An oblique-slip motion so characteristic of extension faults whose traces trend across the strike of the seams substantiates the view that many of these faults must have been developed during the period of active compression. In all cases the down-dropped block moved in an easterly direction relative to its counterpart.

When a portion of a seam is on the inside of a

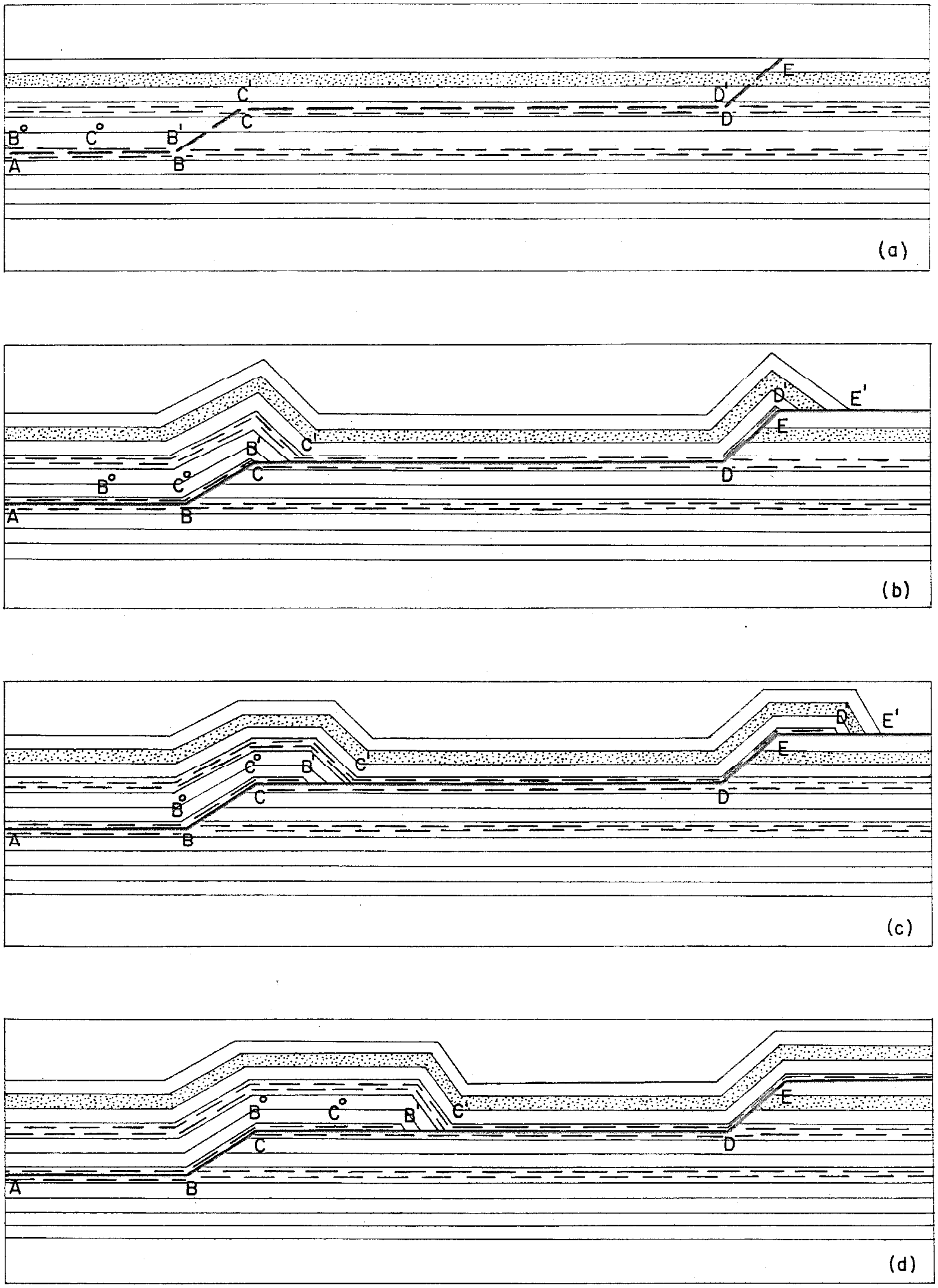


Figure 14. Diagrams illustrating successive stages in the flexing of an overthrust mass. After Rich, Douglas.

flexure, contraction faults are developed. They are characteristically fewer in number but of stratigraphic throw several times that of extension faults. This would suggest the overall strength of the displaced mass in compression. The ability to transmit compressive forces through the mass favors the development of few contraction faults of large stratigraphic throw. It is believed that the intense crumpling of the soft, carbonaceous shales of the subjacent strata is a natural sequel to the compressive action.

Thus it is concluded that an abundance of minor faults may be developed by means of a gentle flexing of an overriding mass. A natural consequence of bedding-plane slippage is the frequent disharmony between faults in the roof and floor. Those faults whose counterparts are readily traceable across a seam were developed either during the waning phase of the compressive period or in segments of a seam in which there has been a minimum of slippage. Moreover the fact that no time relationship could be established between extension faults, as in the Number 4 mine, Canmore, intimates that diverse faults were developed during different periods of stretching of an overriding mass.

It is interesting to note that in spite of 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. It is suggested that with progressive forward motion of an overriding mass, frictional resistance along the thrust plane must tend to retard those beds lower in the section. 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 this creeping ahead of the upper beds in the overthrust mass is of limited extent. At the northern extremity of the McGillivray mine, the continuation of a pre-Laramide dike into the superjacent strata of the Number 2 seam is offset 32 feet up the dip in the plane of that seam. Since drag phenomena within the coal indicate a differential motion of the beds perpendicular to the strike, this 32 foot offset must be a fair approximation of the absolute motion of the roof over the floor in this sector. Moreover in the southern sector of this same mine where a second dike of the same age transects the seam, there is no apparent offset of the dike in the plane of the seam. As pointed out earlier, this must indicate a minimum of slippage in the plane of the seam in this area. The data would suggest that in a regional sense, 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 seam.

Briefly then, it is believed that, in the Coleman and Canmore areas at least, flexing during the period of overriding is responsible for the intensely fractured and faulted condition of the coal-bearing sequence. Abundant extension faults of small stratigraphic throw are the direct result of stretching in the immediate vicinity of the coal beds, while contraction faults, few in number but of larger throws, developed during periods of compression. Similar folding is a natural sequel to an interspersing of competent and incompetent strata. The seams are found to vary considerably in their reaction to this flexing, in some instances being intensely sheared, while in others retaining for the most part their original blocky nature. Frictional 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.

V. COAL-MINING TERMINOLOGY

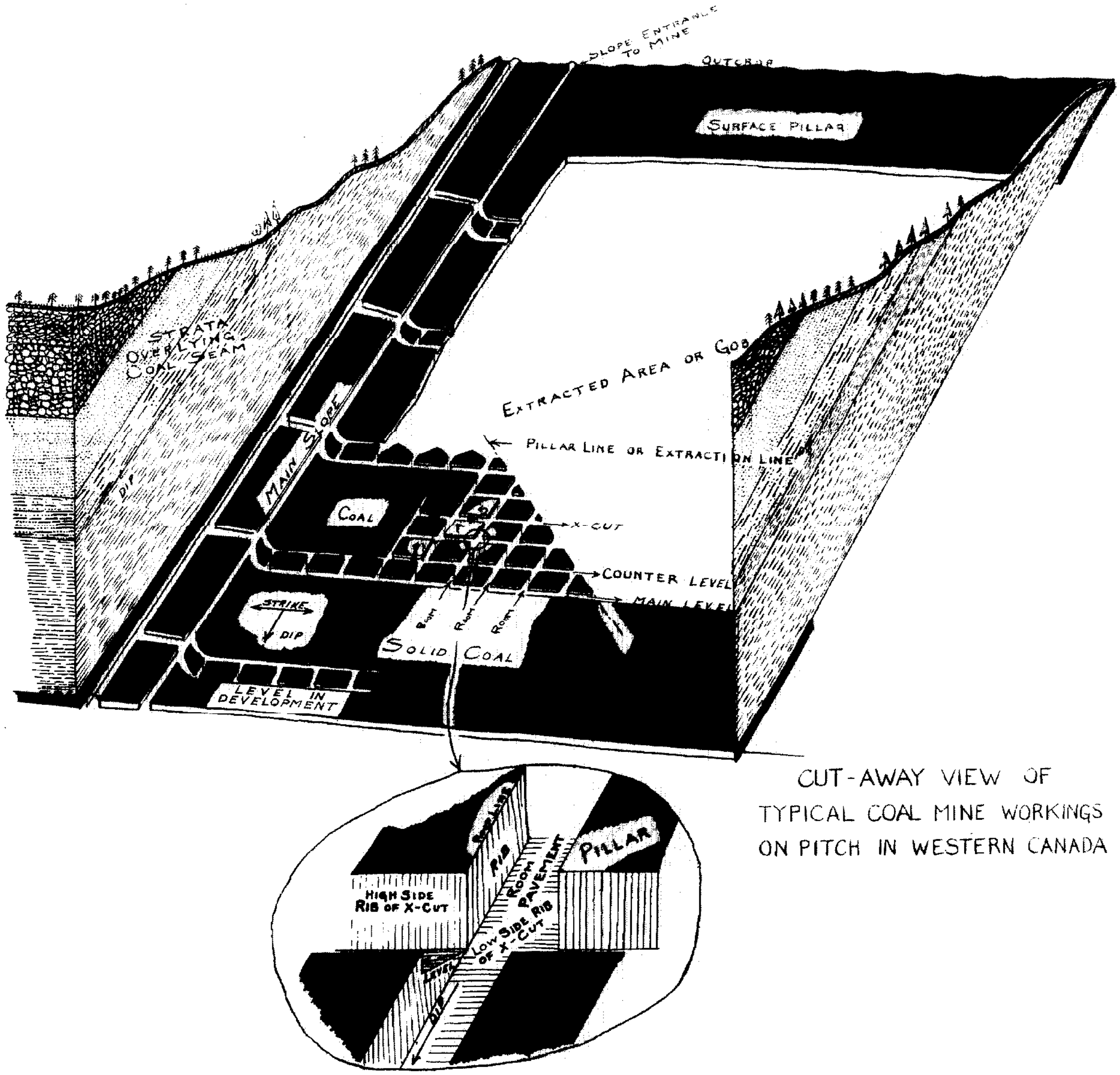
Figure 15, a tridimensional sketch of typical coal mine workings in a dipping seam, will illustrate the following points.

The principal haulage artery of the mine is the main slope. In both directions from this slope levels are driven at regular intervals along the strike of the seam to the proposed extremities of the workings. However in order to facilitate ventilation at the working face of a level, a counter level (or counter as it is frequently called), 80 to 100 feet up the dip is driven simultaneously, and the two are connected up by rooms driven at regular intervals (commonly 100 feet). Prior to the extraction of a given block of solid coal between two levels, the area must be developed, or cut up into pillars. This is done by extending the rooms from one level to the next and by driving cross-cuts parallel to the counter at regular intervals. Any of the four sides of a pillar is known as a rib. Directional terms commonly used in coal mining are outbye and inbye. At any point in the mine, those workings between the observer and the main slope are said to be outbye, whereas those in the opposite direction are inbye.

Referring to the inset in figure 15, the reader will note that the side of a level, counter or cross-cut which is in the up-dip direction is referred to as the high side. Moreover that particular rib of a pillar which is on this side is called the high side rib. Corresponding to these are the low side and the low side rib. The hanging-wall of a seam is commonly known as the roof and the foot-wall as the floor. Sets support the roof and consist of posts fitted against the ribs with a boom connecting the tops of the posts. Where the hanging-wall is unable to support its own weight it is said to be heavy. In these instances it is necessary to place the sets closer together and to insert timber slabs (lagging) between the booms and the roof strata.

In the process of mining out the pillars, a systematic pillar line or extraction line is maintained.

FIGURE 15



CUT-AWAY VIEW OF
TYPICAL COAL MINE WORKINGS
ON PITCH IN WESTERN CANADA

Successive slices taken off the pillars are known as *skips*. For control of subsidence of the roof strata into the *gob* or extracted area, *props* are placed tightly between the roof and the floor in close proximity to the working face. Moreover should it be necessary to prevent a wholesale collapse of the superjacent strata into the gob, *sacrifice pillars* or *stumps* are left behind to effect a more gentle convergence of roof and floor.

VI. STRESS PHENOMENA IN COAL MINES

General Statement

Prior to mining operations, the stress condition at any point in the earth's crust is that of full constraint. The lateral constraining forces are in the simplest case assumed to be of equal magnitude and to be acting in three mutually perpendicular directions. With increasing depth of cover, these constraining forces must increase in intensity. If the possibility of active tectonic stresses is neglected for the moment, a condition of equilibrium is believed to exist within the strata. With the creation of a mine opening this state of equilibrium is destroyed and the condition of full constraint in close proximity to the opening no longer exists. Readjustment of stresses occurs. The solid material about the void immediately begins to relax from its compressed condition. It first expands elastically, but with sufficient time it deforms plastically to the point of eventually filling the opening.

Associated with the tendency toward a restoration of equilibrium conditions about the mine opening is a redistribution of load. An arching effect results in concentration of load along two zones approximately parallel to the direction of the opening. Depending on the ability of the coal in the ribs to assume additional load, such zones will be of varying widths and will extend to varying distances behind the ribs. These zones of increased stress are referred to as abutment zones.

In the case of an advancing face the abutment zone moves forward at about the same rate as the face. When a face advance exceeds the distance over which the roof will span from solid coal ribs, the strata break. Wherever possible advantage is taken of natural lines of weakness in the roof rock in order to facilitate caving of gobs and hence to lessen the stressed condition in the abutment zones. However, should this stressed condition exceed the crushing strength of the coal the pillars may burst with violence. This form of stress relief is commonly referred to as a bump, and is quite analogous to certain types of rock burst phenomena in metal mines.

It frequently has been found that some forms of stress relief are intimately related to specific geologic structures. Because of this association the concept has been entertained by many writers that active vestigial, or regenerated tectonic stresses may be a significant factor in these instances. It is certainly true that in seismically active regions, as for example Southern California, where the deforming stresses are applied over very large areas, by far the largest amount of elastic strain energy is concentrated in the immediate vicinity of major faults. Hence if stress relief occurrences are truly tectonic in origin, they must be associated with specific geologic structures which act as reservoirs in the accumulation of strain energy. Such accumulations would be in existence prior to mining. However if these highly stressed zones are developed by load redistribution during mining operations, structural discontinuities such as faults, folds, pinches and swells may play a significant role in localizing, augmenting, and releasing stress, sometimes with violence.

Of the two categories of stress (gravity and tectonic), which is the more important in these phenomena? Is tectonic stress now negligible so that tectonic strain rather than tectonic stress is responsible for the frequent localization of violent stress relief in structurally disturbed ground? The writer, after a detailed discussion of the relation of mining practices to occurrences of such phenomena will attempt to shed some light on this problem.

Regional Aspects

The problem of violent stress relief has been confronted the world over in attempts to carry on the extraction of coal at progressively greater depths. Such phenomena are common in Canada, in the Crowsnest Pass coal field, Alberta and British Columbia; the Cascade Coal Basin, Alberta; the Nordegg area, Alberta; the Nanaimo coal field, Vancouver Island, British Columbia; and in the Springhill area, Nova Scotia. In the United States they have been known to occur in only a few coal-mining districts, as at the Sunnyside mine in the Book Cliff Mountains of Utah; at the Black Diamond and Carbonado mines in the Cascade Mountains of Washington; and in the Cumberland coal field of the Appalachian Mountains of Kentucky and Virginia. Since by far the greater proportion of coal mined in the United States is under a cover of less than one thousand feet, violent stress relief phenomena have not been a serious problem. It is only in the Rocky Mountains and the Cascades that sufficient depth of cover is attained to give rise to serious stress relief conditions. Outside of Canada and the United States the problem has gained serious proportions in the South Staffordshire field of England, in many collieries of the South Wales coal field, some fields of Belgium and France, the Lower Silesian coal fields of Germany, the Bihar coal field of India, and in many of the Russian coal fields, principally in the Don Basin.

Current Definitions of Violent Stress Relief Phenomena

Occurrences of violent stress relief have been classified into two major groupings on the basis of their observed characteristics; they are bumps or outbursts. In the case of bumps, two different approaches have been made to their subdivision, one on the basis of what was considered their genesis, the other on the areal extent over which they were experienced. Outbursts have not been subdivided.

G. S. Rice, formerly Chief Mining Engineer of the United States Bureau of Mines, recognized two types of bumps, each arising from a different cause (Rice, 1918). Pressure bumps, he believed were due to a lithostatic loading of coal pillars beyond their bearing strength, so that there was a violent release of stress through crushing of the pillars, the roof and floor of the coal seam remaining relatively intact. Pressure bumps would be analogous to rock bursts in metal mining as in the Lake Shore Mines of northern Ontario, the Kolar gold fields of India, and the gold mines of the Union of South Africa. Shock bumps were thought by Rice to be due to the breaking of thick, massive, strong strata some distance above the coal seam, causing a tremendous impact on the immediate roof and resulting in an instantaneous shattering of the coal pillars in the area.

Walter Herd, formerly Chief Mining Engineer for the Dominion Steel and Coal Company, subdivided bumps into three groups depending on the areal extent, or location over which they were experienced (Herd, 1930). Face bumps, as the name suggests were stress relief phenomena occurring at or near the working face, and occurred almost exclusively during tight work comparatively near extracted areas. The term district bump applied to those occurrences of violent stress relief affecting several acres of the mine workings. They are by far the most dangerous and destructive and result in violent heaving of the floor, crushing of pillars and settling of the roof over wide areas; they are practically always felt on the surface. Waste bumps was applied by Herd to those manifestations of stress relief in which a violent shock was felt on the surface although little or no damage was perceived underground. They were dismissed as having originated in the sealed off, worked out areas of the mine. In such cases this explanation could be neither proved nor disproved.

The term outburst is used synonomously with blow-out, and refers to a violent release of stress in the mine workings manifesting itself in an almost instantaneous disintegration and forceful ejection of large quantities of coal from the working face. There is a concomitant release of large volumes of methane, carbon dioxide, and other gases held within the coal.

The characteristics of violent stress relief phenomena in the coal mines of the Canadian Rockies confirm the view that bumps are quite distinct from blowouts. These latter stress relief occurrences however are observed to display a wide range of characteristics, and in some mines the term pushout is used for a very mild form of blowout. A further subdivision (sloughs) of stress relief occurrences has been created to include those instances of dislodgment of large tonnages of highly sheared coals in the relaxed zone about mine openings.

Hence stress relief occurrences may be subdivided into four groups: bumps, blowouts, pushouts, and sloughs. The classification is almost wholly on the basis of material effects, and no inference is made at present to the mechanics of causation.

<u>Bumps</u> refer to those manifestations of violent stress relief which result in widespread floor heave and shattering of sets. They characteristically occur in close proximity to extracted areas.

<u>Blowouts</u> are violent stress relief manifestations from small pockets of the seam and occur in intimate association with the working face. Attending the almost instantaneous ejection of highly disintegrated coal is the release of large volumes of gas.

<u>Pushouts</u> are in essence a very mild form of blowout in that the coal is literally pushed into the mine opening from pockets at the working face or in close proximity to it. The dislodged coal differs little in size characteristics from that of the coal as mined. A moderate amount of gas may be released.

<u>Sloughs</u> refer to those dislodgements of coal under

the influence of gravity from the destressed zones about mine openings. They are most frequent in highly sheared, thick seams, and characteristically do not occur in intimate association with working faces.

In the deeper workings of the Springhill mines (Nova Scotia), there is an occasional bursting of the floor rock into the openings (Herd, 1930). The writer has not had personal contact with this particular problem in the collieries of the Canadian Cordillera. From the descriptions in the literature however it appears they are quite analogous to rockbursts in metal mines. Mention is made of this here merely to point out that when workings in the coal mines in which the present studies have been conducted are pushed beyond their present maximum depth of cover (2500 feet), this further form of violent stress relief is likely to be experienced.

Historical Summary of Stress Relief Occurrences

Coal Creek, one of the mining camps at which the stress problem was investigated, gained world renown for its misfortune from these occurrences. From the very beginning of mining operations in 1897 the demand for coal was so great that emphasis was laid on production to the neglect of a systematic plan of operations. A combination of large cover intervals and the mode of mining, wide stalls and small pillars, led to dangerous overloading of the unmined coal.

In 1905, in the Number 1 mine, there occurred the first violent manifestation of stress relief. This incident had little effect, either materially or psychologically, in spite of the serious blowout of the previous year in which 14 men lost their lives at Morrissey, a coal mining camp six miles to the south. Not until 1906, when bumps of a very severe nature began to occur in the Number 2 mine did the people of Coal Creek sense the important role which stress relief phenomena were to play in the subsequent history of their mining community. In this mine the workings were quite unsystematic with irregular longwall panels in some places and the complete extraction of pillars in others. With 50 to 60 per cent of the coal in the area extracted, the remaining pillars must have been considerably overstressed by the superjacent 2000 feet of strata. Continuous heaving with an occasional bursting of the floor was a steady means of relief of the stresses transmitted to the subjacent strata by the pillars. Finally in 1908, a violent bump in one of the main entries of the Number 2 mine resulted in serious property damage and loss of life. The impact of this occurrence on mining activities was immediately apparent. At the suggestion of the British Columbia Department of Mines practically all the live workings of this mine were abandoned, with a resulting loss of large quantities of high quality coal and a decided drop in the colliery output.

These phenomena were not peculiar to Coal Creek, but were being encountered in ever increasing numbers in many of the French coal fields. In the blind search for an adequate solution to the problem, many suggestions offered the mining industry served only to impede production, create a false sense of security, and do nothing by way of minimizing the hazards to which the underground personnel was subjected. Considering the lack of appreciation of the state of stress of the coal at depth, it is not short of miraculous that the fatality rates were so low.

In 1911, the Number 1 East mine was opened in Number 10 seam, about 150 feet higher in the section than the seam worked by the Number 2 mine. Tempered by the serious bumps arising from small pillars in an irregular layout in the latter mine, the officials rigidly adhered to a systematic plan of operations in the 1 East workings. In the process of cutting the seam into pillars only 20 per cent of the coal was taken out. It was decided that no pillars would be pulled until the mine was in full retreat. As mining conditions were good advance work was rapid, so that in five years the headings were pushed beyond the limits of the underlying Number 2 mine. In the course of operations, the coal gave off large volumes of gas (estimated at from 1500 to 5500 cubic feet of methane per ton of coal mined (Rice, 1918) until November 1916. By that time the headings were 300 to 400 feet beyond the face line of the Number 2 mine.

Then a series of violent bumps resulting in loss of life and tremendous property damage brought about the closing of a large section of the 1 East mine, pending a detailed investigation of the stress problem. G. S. Rice was invited to examine the Coal Creek collieries and to offer suggestions on the nature of the phenomema and possible means of avoiding or at least mitigating their effects.

The first blowout of any consequence at Coal Creek occurred in the dip section of the 1 East mine in January, 1918. It was only the beginning of serious trouble to arise from another aspect of the stress problem. The instantaneous release of large volumes of gas in conjunction with the forceful ejection of hundreds of tons of intensely disintegrated coal led to many serious disasters both here and abroad.

Again as in the case of bumps, futile attempts were made to discover the cause of such phenomena. Holes were drilled ahead of the working face to tap the speculated pockets of gas which were believed to be responsible for blowouts. Neither were any such pockets encountered nor did such a procedure in any way alleviate the frequency of blowout occurrences.

In spite of earnest attempts to cope with the problem, bumps and blowouts continued to occur. After a very serious incident in the 1 East mine in May, 1943, culminating a rapid sequence of violent bumps, all of the inner workings were abandoned. Since then only two occurrences have been recorded from this mine, both of which instances, under a cover of less than 1000 feet, are directly attributable to mining practices.

With progressive abandonment of operations on the north side of Coal Creek, prospecting of the corresponding segments of the seams across the valley resulted in the opening up of a new set of mines, referred to as Elk River Collieries. As these mines have just begun to reach cover intervals where stress relief phenomena are encountered in increasing numbers, the problem has not as yet gained serious proportions.

On October 7, 1949, a blowout in the slope section of the Number 3 mine (cover approximately 600 feet), resulted in the forceful ejection of slightly under 500 tons of finely disintegrated coal, and large volumes of methane (Ann. Rept., Minister of Mines, B. C., pp. 288-289, 1949). Since then no serious occurrences of this nature have been recorded. However the pushout of November 27, 1951, in the highly faulted ground of the 8 Incline section of the Number 3 mine (cover approximately 1100 feet) marked the beginning of a series of incidents that resulted in the ultimate abandonment of this sector.

Unlike the notorious history of the mines at Coal Creek, Coleman collieries have been comparatively free of violent stress relief. In both the International and McGillivray mines, operations are being carried on under cover intervals as large as 2500 feet, which conditions led to an alarming number of occurrences in the Number 1 East mine.

Since the beginning of operations at Coleman around the turn of the last century, the extraction of coal by the conventional room and pillar method has been carried to progressively greater depths. Stress relief has manifested itself in almost all cases as either a gentle running of the coal at the face, or in continual bumping of a minor character. No blowouts have been experienced at Coleman.

However in December, 1950, a violent bump occurred in the Five Level North sector of the McGillivray mine, and resulted in two fatalities. A combination of the highly stressed pillars under a cover of 2300 feet and the heavy condition of the rubbly, carbonaceous shale of the nether roof resulted in adverse mining conditions. The dislodgment of the roof rock rather than the characteristic heaving of the floor and settling of the roof was the significant factor in the disaster, as escapeways were blocked for large distances.

Occurrences of violent relief of stress in the Canmore mines have been experienced only in comparatively recent years because of extensive exploitation near the outcrop and limited workings at depth. The pushout of June, 1944, in the Number 4 mine (see tab. 2, app.) ushered in a long series of incidents which became very much more frequent at cover intervals in excess of 700 feet.

Unlike Coal Creek, Coleman, and Canmore, the stress problem at Nordegg has been encountered at very low cover intervals. The first incident occurred during the early stages of development work in the Sixth Level of the Number 3 seam with a cover of approximately 450 feet. Since then (January, 1950) stress relief in the form of pushouts have been experienced in great numbers, notwithstanding that current operations are being extended along the strike rather than down the dip. Although only one instance is recorded from the underlying Number 2 seam, it should be borne in mind that operations in this seam are only now approaching cover intervals at which the stress problem became important in the Number 3 seam.

As the intensely sheared coal of both seams being mined is unable to support the superjacent strata for prolonged periods, considerable trouble is encountered in maintaining haulage ways. The gradual convergence of roof and floor results in stress accumulations in the more solid segments of the seams and extensive sloughing of the ribs (the high side particularly) through squeezing out of coal from the abnormally large destressed zones about the mine openings.

VII. CHARACTERISTICS OF STRESS RELIEF PHENOMENA

Bumps

In attempting to analyze the bump problem in any particular mine one is dependent to a large extent on the data kept by the company officials. Frequently only those instances are recorded which have resulted in extensive property damage or loss of life. For this reason there has been a tendency to segregate violent bumps from those of a more gentle nature continually encountered in development work, splitting of pillars, and movement of the extraction line.

Stress relief by violent bumping has been experienced at depths of cover as shallow as 500 feet in some coals. As mining operations are pushed deeper, their occurrence is observed to increase in frequency. For example consider figure 16, which illustrates the observed relation of cover interval and frequency of occurrence of violent bumps in the 1 East mine, Coal Creek. For graphical presentation, all violent bumps in a given 200 foot cover interval are grouped together and plotted against the odd hundreds of feet of cover. It is interesting to note that no occurrences were reported between 1800 and 2000 feet of cover. There is no sure means of assessing this anomaly because of the complex relation between mining practices and variations in physical properties of the coal. Moreover all the deeper workings of this mine were abandoned some years ago.

In contrast to violent bumping recorded from the 1 East mine, stresses at depth in the Number 2 seam, Coleman, have been released in general by continual bumping of a less severe nature. As mentioned above it was at a cover interval of approximately 2300 feet in the McGillivray mine that bumping of a serious nature occurred. Whereas the coal at depth in the 1 East mine is reported to be structurally

RELATIONSHIP OF FREQUENCY OF OCCURRENCE OF VIOLENT BUMPS TO DEPTH OF COVER

NUMBER I EAST MINE COAL CREEK, BRITISH COLUMBIA

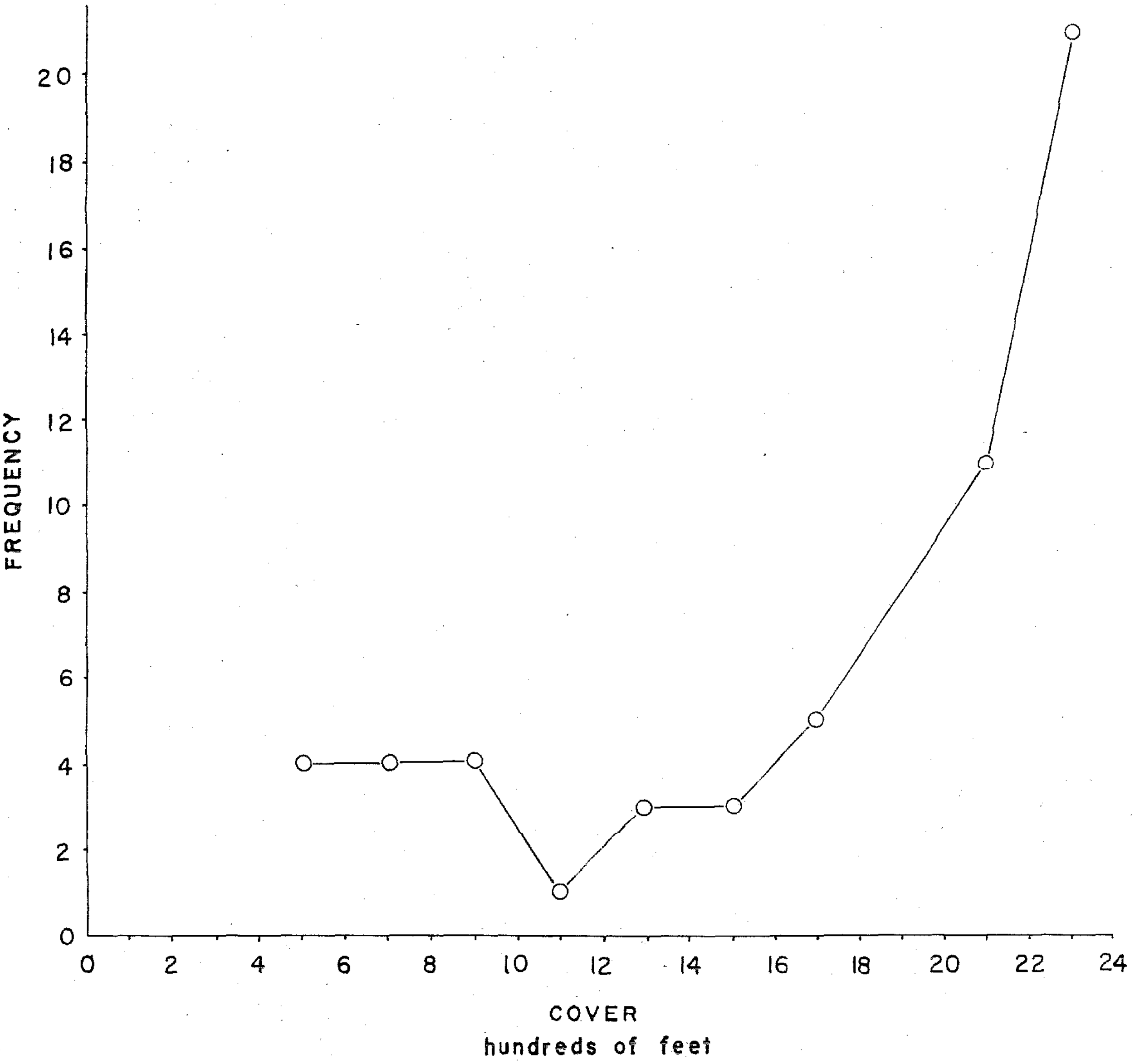


Figure 16.

strong, that in the McGillivray mine is considerably more fractured and in many places moderately sheared. Extensive and gradual heaving of the soft, carbonaceous shale floor in the deeper workings of both mines is indicative of the capability of pillars consisting of either blocky or fractured coals to transmit loading stresses to the floor. A cessation of this heaving is oftentimes a forerunner of a violent bump. This is a natural course of events as the slow heaving of the floor is a means of relief of the stresses pent up in the pillars. In the event that stress cannot be relieved by this means, bursting of the pillars must result.

Some of the most serious bumps occur during the splitting of pillars in close proximity to extensive gobs. The bump of 1950 in the McGillivray mine will illustrate this point. Prior to the occurrence, Number 75 room was being driven up the dip from Five Level in firm, brittle, dull coal. The seam to the rise of Number 4 Counter Entry had been worked out some ten years earlier, while 150 feet to the north along the strike was an extensive gob resulting from extraction during 1949 and 1950. The coal below Five Level was undeveloped. It is quite apparent that the large extracted areas above and to the north must have led to an overstressing of the pillars to the point of failure. The abutment zone was doubtless in the immediate vicinity of 75 Room at the time of the bump.

During the process of pillar extraction it is imperative that the pillar line recede or advance at a uniform rate throughout its length. An irregular advance leads to the development of pillar remnants jutting out into the extracted areas. With the convergence of hanging-wall and foot-wall in the gob, the remnants may become overloaded and burst. A very good example of this may be seen in the presently active workings of the 1 East mine, where two violent bumps in 1950 occurred in a pillar remnant of the shape of a frying pan, the coal being mined out completely on three sides (Ann. Rept., Minister of Mines, B. C., 1950, p. 254). During a visit by the writer in the Spring of 1952 when the mine officials were attempting a skip off one side, incessant bumping and cracking of the strong, blocky coal was an obvious indication of the highly stressed condition of the remnant.

Minor bumping in strong coals is commonly associated with driving of headings and drawing of pillars under a cover of four to five hundred feet. It is indicative of a gentle release of accumulating stress. Many of the incidents cited from the 1 East mine in part V took place during the driving of headings when not more than 15 to 20 per cent of the coal was extracted. The more violent of these bumps at the working face conform with Herd's interpretation of face bumps. They are for the most part induced by blasting.

Experience has shown that the faster the rate of extraction the more violent is this minor bumping. In the extreme case a violent bump may be induced by this means. Moreover by reducing the rate of advance of a heading or extraction line in highly stressed coal the occurrence of a violent bump may oftentimes be avoided (Ann. Rept., Minister of Mines, B. C., p. 129, 1940). This would be expected as the slower rate would allow the accumulating stresses through load redistribution to be released by degrees. In addition it is characteristically found that when a highly stressed pillar remains quiet for a while the next release of stress by bumping is much more violent. Prior to a violent bump the pillars may be quiet for several days, then without warning fail almost instantaneously. Associated with the crushing of a pillar, coal may be ejected from the ribs with violence, but unlike blowouts, the coal is not intensely fragmented. Accompanying the dislodgment of coal from the ribs is a correspondingly large release of gas. As will be seen in the case of blowouts, the volume of gas released is estimated to be in proportion to the amount of coal loosened from the pillars.

Associated with the instantaneous crushing of a pillar there may be a contemporaneous general heaving of the floor and settling of the roof over large areas of the workings. This type of occurrence would fit Herd's interpretation of district bumps. That there has been a large scale upward movement of the floor during the bump is substantiated by the necessity for regrading of haulage ways during cleaning up operations. Take for example one of the bumps which occurred in 1950 in the pillar remnant in the 1 East mine and discussed on page 70. In this instance mine track was heaved 12 to 14 inches. It is worthwhile noting here that autopses of bump victims reveal in a large number of cases intense shattering of the leg bones at angles of about 45 degrees, suggesting a sharp blow from beneath.

A natural sequel to this violent roof and floor motion is extensive shattering of props and closing of haulage ways to the point of flattening mine cars against the roof. The main roof is rarely broken, although the cap rock may be shaken down in profusion and constitute a very serious hazard in blocking exits from the bump area. An excellent example of this roof condition may be seen in the McGillivray mine between Four and Five levels at the northern end of the workings. Because of interspersed carbonaceous matter in the three foot shale capping, the immediate roof is of a rubbly nature and quite unable to support itself over the mine openings. The slightest jar, as from a bump, sends down hundreds of tons of highly fragmented rock into the crosscuts and rooms, in places completely blocking them.

The more violent and extensive bumps (district bumps) are frequently felt on the surface, causing moderate property damage. For example, pictures have been thrown from walls and dishes from shelves at Coal Creek, as a result of violent bumps underground.

There is no apparent relation between the occurrence of bumps and the proximity of faults. Structural maps of the inner workings of the 1 East mine are nonexistent so that one is dependent entirely on reports of bump occurrences to the Minister of Mines for such data. However all evidence both here and elsewhere gives no positive indication of such a relation. Overloading of strong coals is apparently the prime requisite for a bump condition.

Blowouts

By far the most detail on the characteristics of blowout phenomena was gained from studies in the Upper Marsh and Number 4 seams at Canmore. Since the problem is a relatively new one at Canmore a large proportion of the sites of violent relief of stress in the two seams are still open and available for study.

In contrast to the highly sheared coals of the Upper Marsh, blocky coal similar to that in the 1 East mine is extensively worked in the Number 4 seam. Unlike the 1 East mine however, the Number 4 workings have suffered no serious occurrences of violent relief of stress by bumping up to a cover interval of approximately 1450 feet (the present maximum). Minor bumping is of course experienced in development work.

Since blowouts and pushouts show merging characteristics (although distinguishable in their extremes), it was considered advisable to group them together for a statistical analysis of violent stress relief data from the Number 4 seam. The occurrences in the Upper Marsh are all considered to be pushouts. Unlike data for the 1 East mine which gave merely the time and place of occurrence of the various bumps and blowouts, detailed records for all occurrences of violent relief of stress in the mines at Canmore were kept. Characteristics of stress relief occurrences in the Number 4 and Upper Marsh seams are tabulated in tables 2 and 3 respectively.

As indicated in figure 17, there is a minimum cover interval of roughly 400 feet at which blowouts are encountered in the 1 East mine. A peak frequency has been found at about 700 feet of cover, below which there is a trend toward decreasing frequency to the point where no blowouts were recorded at cover intervals greater than 1900 feet. It is interesting to note that a similar trend is found in the Number 4 seam (fig. 18), beginning at a minimum cover of roughly 600 feet, increasing to a peak frequency at 1100 feet, and then decreasing to a minimum at between 1400 and 1500 feet, the present maximum depth of cover.

Apparently then below a certain critical cover interval depth no longer plays a significant role in the frequency of occurrence of blowouts. It may be argued that if limited operations were carried on at large cover intervals there should be a tendency toward decreasing frequency in the deeper workings. However, that being the case, one would

RELATIONSHIP OF FREQUENCY OF OCCURRENCE OF BLOWOUTS TO DEPTH OF COVER

NUMBER I EAST MINE COAL CREEK, BRITISH COLUMBIA

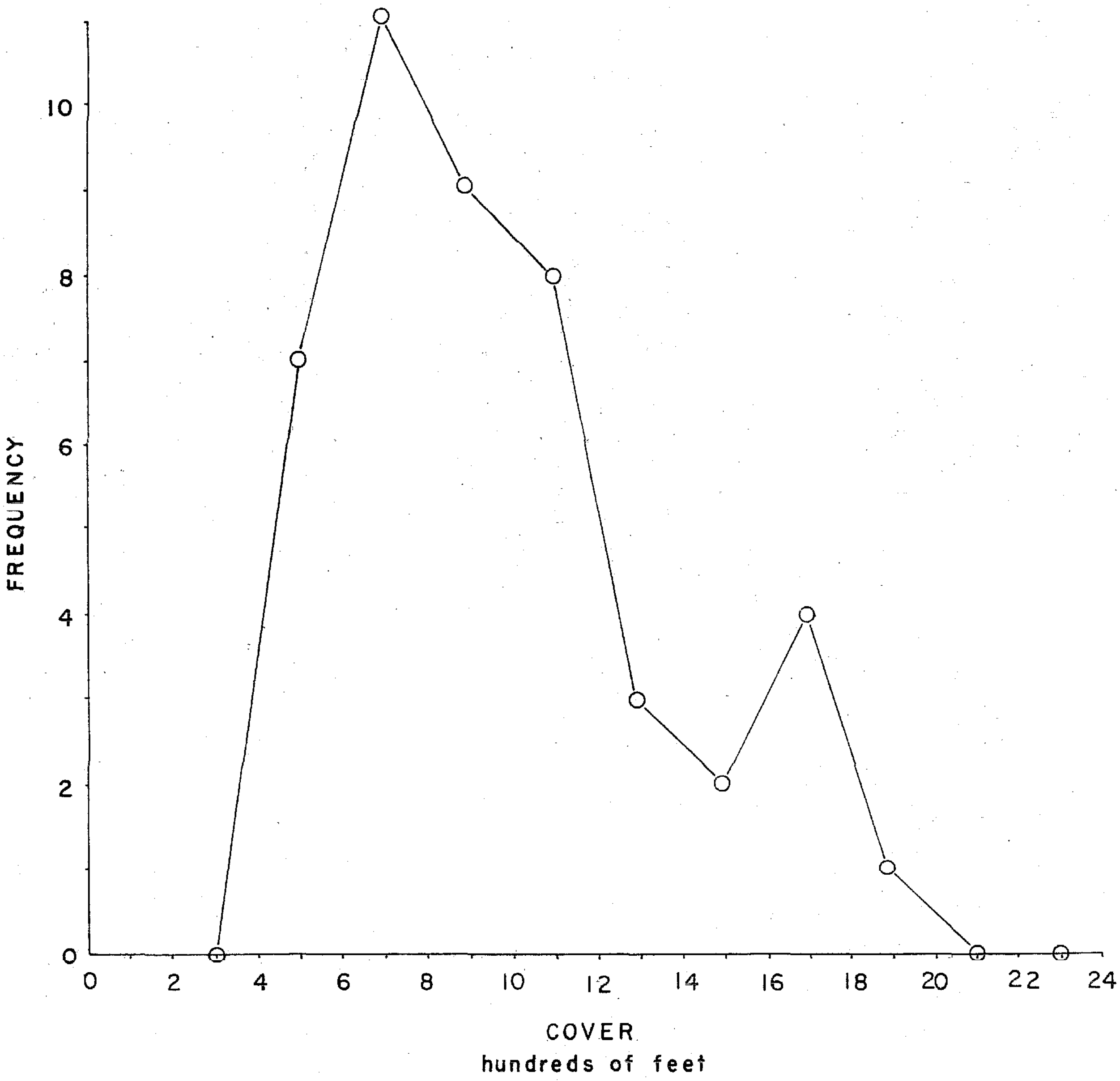


Figure 17.

RELATIONSHIP OF FREQUENCY OF OCCURRENCE OF BLOWOUTS TO DEPTH OF COVER

NUMBER 4 MINE CANMORE, ALBERTA

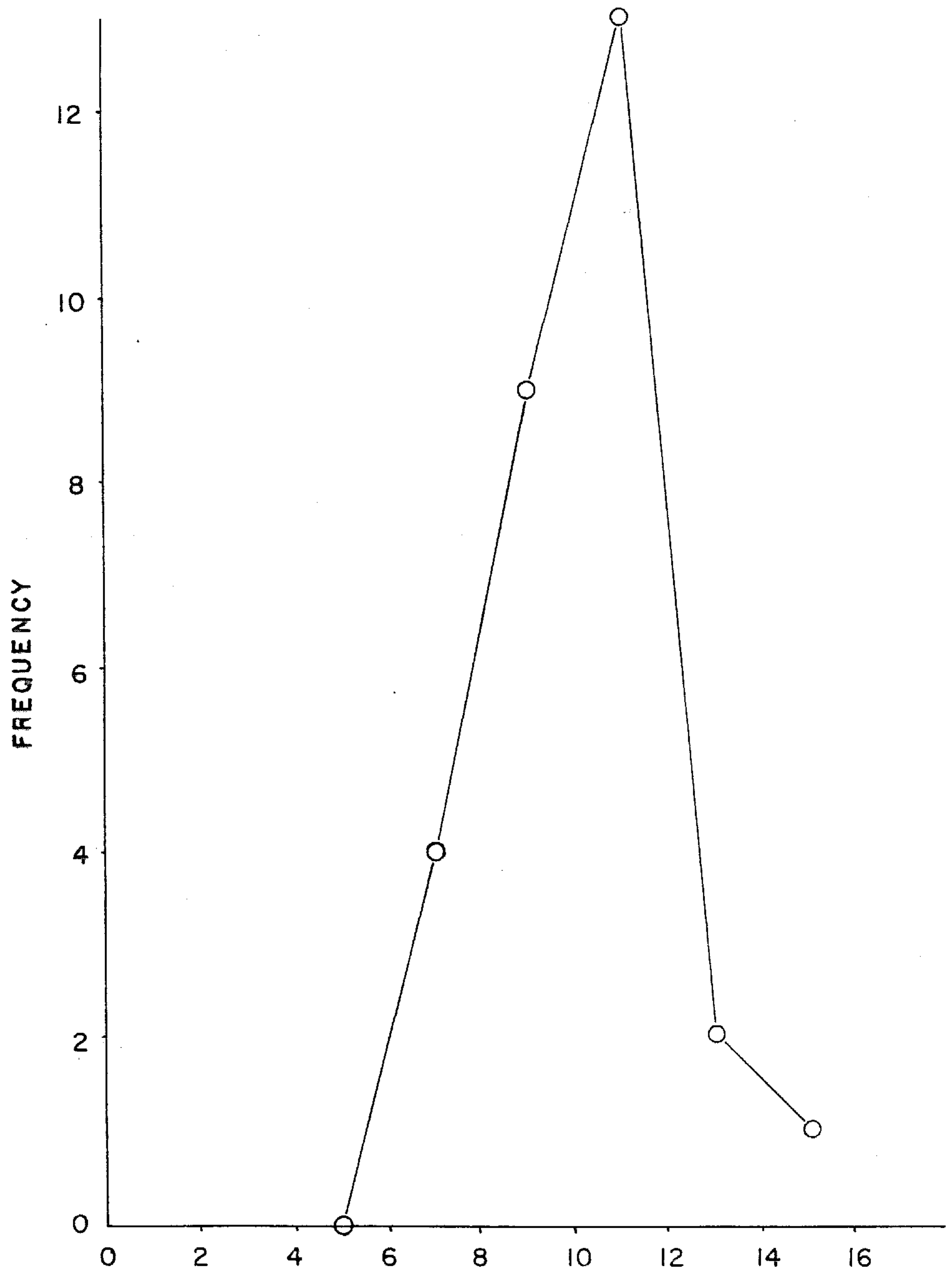


Figure 18.

expect the bump frequency to drop off equally as rapidly. As pointed out with reference to figure 16, this is not so. It was the alarming frequency of occurrence of bumps, not blowouts, in the 1 East mine which was responsible for the curtailment of operations at depth.

The question arises as to the possible relation between cover interval and violence of stress relief within any given seam. The only feasible means of classifying the phenomena by violence was to consider them in terms of the number of tons of coal ejected, the reported force of ejection and the degree of disintegration of the dislodged coal. These three criteria are of primary significance in distinguishing blowouts from pushouts.

With these ideas in mind the scatter diagram (fig. 19) for the Number 4 seam was constructed from the data in table 2. Note that both pushout and blowout occurrences are distributed through all depths at which violent stress relief is encountered. Moreover blowouts eject varying tonnages at a given cover interval. By the very nature of the differentiation of pushouts from blowouts, the former are suppressed to the lower portions of the diagram. There is no apparent relation between tons of coal ejected and the cover interval.

Unlike bumps, blowouts are localized to small volumes of coal. They characteristically occur during development work when in general not more than 15 to 20 per

THE RELATION OF TONS OF COAL EJECTED TO DEPTH OF COVER IN BLOWOUTS AND PUSHOUTS IN THE NUMBER 4 SEAM CANMORE ALBERTA

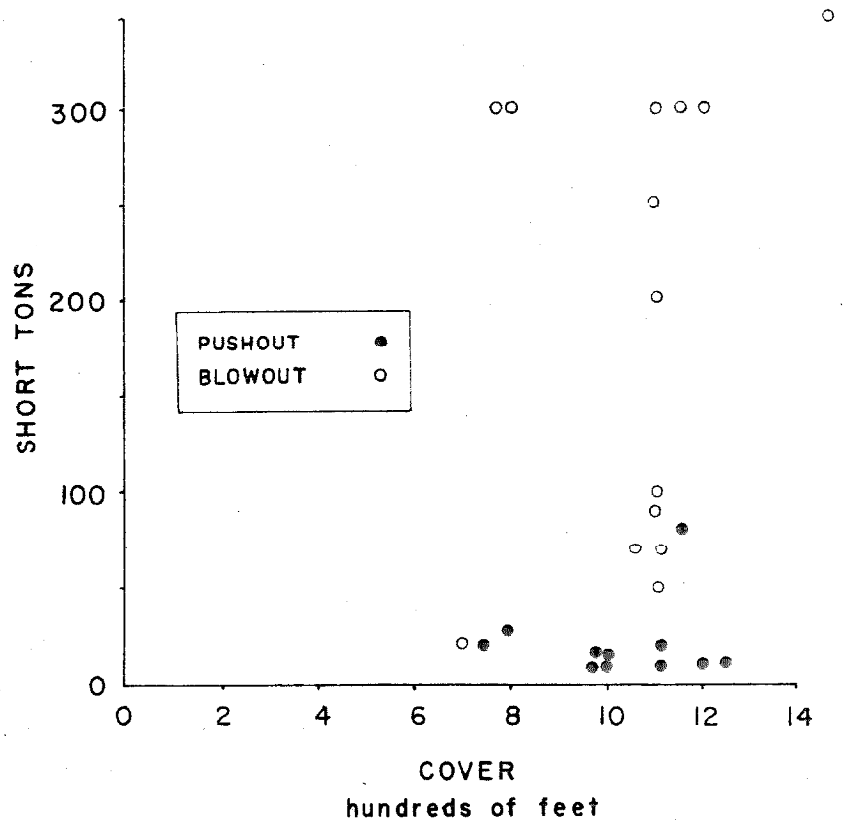


Figure 19.

cent of the coal is being removed. An examination of table 2 will show that of 14 recorded blowouts in the Number 4 seam, Canmore, 12 occurred during cutting of the seam into pillars and the remaining two during the splitting of pillars prior to their being extracted. Furthermore a survey of the reports to the British Columbia Minister of Mines reveals that without exception blowouts occurred only during development work in the 1 East mine.

It is consistently found that when blowouts take place in an inclined seam they inevitably come from the top corner of the working face or the top of the high side rib in close proximity to it. This point is borne out from detailed examination of blowout sites in the Number 4 seam (see tab. 2), as well as from innumerable occurrences cited in the literature.

As the working face approaches a blowout point the coal oftentimes shows obvious signs of being in a high state of stress. In many instances the face is observed to freeze, or tighten up, or as the miners say 'to become dead', sometimes at a considerable distance from the actual point at which the blowout occurs. The strained condition of the tightened coal is somewhat relieved by spontaneous shattering of the coal in the face, as evidenced by continual cracking and minor bumping. Associated with this expansion and crushing of the coal there is some release of gas although much of it is believed to be held back because of the impermeability of the coal. An occasional more violent bump may temporarily relieve the stressed condition, and the cracking noises momentarily subside. When the coal is in a highly strained condition, even a gentle touch of the miner's pick will result in the forceful ejection of small fragments of coal from the working face, quite analogous to the surficial fragmentation of a rock specimen in a laboratory crushing machine.

To illustrate the influence of mining on the occurrence of a blowout, it has been consistently observed that when a working place shows the above mentioned signs of approaching a blowout site, the time of occurrence of the phenomenon may be controlled by the rate of advance of the working face. By progressing slowly or temporarily stopping work, the occurrence may be delayed but not avoided. Moreover tests in the Pumpquart seam, Ponthenry, Wales (Roblings, 1926), revealed the practicability of inducing outbursts by volley firing at points where their occurrence was imminent. Touhey (Coal Age, 1923), cites an interesting example from the Nanaimo coal field in which a face showing signs of an outburst condition was left idle for about 100 hours, but five hours after work was resumed at the place a blowout of unusual violence occurred.

The imminence of a blowout is often indicated by an increase in frequency of bumping and accelerated running of the coal at the face. According to mine officials who have closely observed the phenomena to within a few seconds of the final disruption, the coal begins to disintegrate to the point where it flows like a fluid down the working face.

The final bursting out of the disintegrated material is as through a dam at its weakest point, oftentimes producing a peculiarly shaped cavity. In one instance the cavity was bottle-shaped, becoming wider inside the aperture through which the coal came (Ann. Rept., Minister of Mines, B. C., 1918, p. 336); in another instance a funnel-shaped opening extending for several tens of feet into the solid was developed (Ann. Rept., Minister of Mines, B. C., 1928, pp. 411-414). Blowout cavities in the Number 4 and Upper Marsh seams, Canmore, were cone-shaped with a flat side against the hanging-wall and the apex into the solid coal. Such peculiarly shaped cavities suggest an anomalous stress redistribution in the coal about the mine opening.

The instantly released large volume of gas is believed to be the transporting medium for the dislodged coal. The elastic energy released in the initial fragmentation of the coal is then only partially responsible for the forceful ejection of the fragmented material. The sudden release of stress in combination with the attrition of the coal fragments being transported in the rapidly moving gas results in a disintegration of some of the coal to the consistency of flour. It is believed to be an action of comminution somewhat comparable to that of the projection of coal through an orfice at high velocities in pulverized coal combustion.

Definite evidence that prior to a blowout the overstressed coal is bearing a considerable portion of the redistributed stresses is indicated by roof adjustments during and after the phenomenon. Toward the climax of the blowout the roof strata are heard to crack and rumble, and those sets not dislodged by the momentum of the ejected coal are observed to tighten and frequently to break.

In the case of the two seams investigated at Canmore, it was observed that the tonnages of coal dislodged and their force of ejection were apparently related to the strength of the coal in the pillar. The hard, blocky, bright coal of the Number 4 seam is in obvious contrast to the intensely sheared, platy coal of the Upper Marsh. In the former seam blowouts, frequently of a very severe nature and forcefully ejecting hundreds of tons of finely disintegrated coal, have been experienced, whereas in the latter (compare tab. 2 and 3 for tonnages) seldom more than 50 tons of loose coal have been pushed out from the high side rib or corner of the working face.

The gas released in blowouts and pushouts in the mines examined was for the most part methane. However in certain collieries of the Lower Silesian coal field, Germany, and the Gard Basin, France, outbursts releasing enormous volumes of carbon dioxide are of frequent occurrence (Rice, 1931). Estimates of the amount of gas released per ton of coal mined under normal conditions reveal nothing incongruous with estimates of the volume of gas released per ton of coal dislodged in a blowout or pushout (Jarlier, 1923, 1935; Riffaud, 1946). The displacement of air in the mine workings in close proximity to the site of a blowout by the sudden influx of these gases frequently results in a temporary reversal of the air-current through the workings.

Continued operations in areas susceptible to blowouts confirm the view that a single instance of violent stress relief does not eliminate the possibility of further occurrences in the district. For example, in the 1 East mine, Coal Creek, five outbursts, 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. Note moreover in figures 4 and 13 that blowout phenomena in the Number 3 mine, Elk River, and the Number 4 seam, Canmore, cluster together, rather than occur sporadically throughout the seams. This would further emphasize that a blowout is not due to a simple condition of overloading as in the case of bumps. A violent bump in a given sector of a seam completely alleviates the danger of recurrences in the immediate vicinity.

Blowouts are not found to be characteristically associated with faults in any of the accessible parts of the mines studied. Although few or no geologic data were recorded for the sections of the collieries at Coal Creek notorious for blowouts, the literature consistently reaffirms the view that there was no apparent localization of blowouts at faults (Wilson, 1947). However the Number 4 seam, Canmore, afforded excellent opportunity for a study of this aspect of the problem. It will be noted from table 2 that of 15 recorded blowouts in this seam only six were found to have any relation to faults; the remaining nine took place in unfaulted ground.

Because of the comparatively uniform dip of the Number 4 and Upper Marsh seams there was no means of establishing a possible relation between the dip and the frequency of occurrence of blowouts. However 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 steeply than 50 degrees. It is apparent that a steeper dip favors the occurrence of blowouts.

Frequently it has been stated that it is impossible to restore the ejected coal from a blowout to the cavity from which it came (Miard, 1926; Jarlier, 1923). The volume of the dislodged coal is found to exceed that of the cavity by a factor of as much as five.

Take for example the blowout of November 1, 1951, at the face of 24 Slope in the Number 4 mine, Canmore (no. 24, Tab. 2). From a cavity whose volume measured 3.5×10^3 cubic feet was ejected 230 cars of coal. Since the average volume of material transported in a mine car is 40 cubic feet, the volume of the blowout coal was approximately 9.2×10^3 cubic feet. Thus the volume of the dislodged coal exceeded that of the cavity from which it came by factor of approximately 2.6.

The volume occupied by the loose but unejected coal is estimated at 9.1×10^3 cubic feet on the basis of careful examination of the coal in the ribs on the high side of the blowout cavity. The low side of the cavity is the fault plane.

It has been found that in the process of mining the "Number 4" coal, the volume of this coal in the face is increased by fifty per cent. For the coal in the solid there are approximately 25 cubic feet per short ton whereas the mined coal occupies approximately 38 cubic feet per short ton.

Hence the volume of the loose but unejected coal when in place would be approximately $9.1 \times 10^3/1.5$ cubic feet or 6.1×10^3 cubic feet. The corrected volume of the blowout cavity (neglecting roof and floor convergence, and the cubical expansion of the coal) is then approximately 6.5×10^3 cubic feet. Moreover the volume of the ejected coal corrected to what it would be prior to the blowout is approximately $9.2 \times 10^3/1.5$ cubic feet or 6.1×10^3 cubic feet. Thus the apparent anomaly between the volume of the blowout cavity and the ejected coal is removed.

There are a number of sources of error in this calculation of which the following are the most significant:

1. Measurement of the size of the blowout cavity.
2. Measurement of the volume of the loose but unejected coal.
3. The neglect of the closing of the cavity through roof and floor movement associated with stress release.
4. The neglect of the cubical expansion of all the coal involved in the occurrence.

The measurement of the size of the blowout cavity is fairly accurate whereas the estimate of the volume of loose but unejected coal must be considered with some reservation as the boundary of the destressed coal is gradational and not sharp. As for the closing of the blowout cavity through convergence of the roof and floor, no quantitative data are available. However it was observed that no timbers were broken through load redistribution subsequent to the blowout so that the maximum convergence could be only a few inches and the concomitant error in the calculation only a few per cent. The neglect of the cubical expansion factor is not serious as it is small in comparison with the approximation of the 50 per cent compaction factor involved in the calculation.

Although the agreement in the above is remarkably good in view of the approximations necessary, the writer wishes to point out only that there is nothing incongruous about the volumetric relations of the ejected coal to the blowout cavity.

Pushouts

As mentioned above pushouts are considered to be a form of blowout in the sense that coal and gas are spontaneously dislodged in intimate association with the working face. This form of stress relief shows all gradations into features characteristic of blowouts, in rapidity of movement, degree of fragmentation and tonnages of dislodged coal.

Although pushouts occur most frequently during mining operations at depth (cover intervals greater than 500 feet) in friable or sheared coals, they are occasionally experienced in the hard, blocky varieties (c.f. the Number 4 seam, Canmore). During the advance of the face of the main gangway in the intensely sheared coals of the Upper Marsh seam, stress relief manifestations of this sort are continually encountered (tab. 3). Moreover in the Number 3 mine of the Brazeau Collieries, Nordegg, pushouts in the Sixth Level district have become a daily occurrence, even though a cover interval of only 450 feet has been attained. Here the intensely sheared seam pinches to three feet in places and swells to 25 feet in others. The coal has been so completely disintegrated through differential movement between beds that there is immediate convergence of roof and floor in development work. Associated with this movement is the creation of a non-uniform stress condition in the coal at the face.

That the coal at the working face is in a stressed condition immediately prior to a pushout is indicated by its tightening or freezing, a feature so common in the case of blowouts. Moreover the sets are noted to tighten and take on weight during and after a pushout, indicating that adjacent to the excavation such coals are capable of carrying load.

The coal is pushed or eased out from the high side rib or corner of the working face. It is not ejected with any force or to any great distance. However the angle of slope of the dislodged coal is unmistakable evidence that some force of ejection is involved. Characteristically this angle on pushed out coal is up to fifteen degrees more acute than the normal angle of repose (approximately 40 degrees) of the same coal, the angle becoming smaller with more forceful ejection.

Analogous to bumps and in contrast to blowouts there is no apparent change in the size characteristics of the pushed out coal from that produced during normal operations. It is common occurrence to have the whole face or some segment thereof eased forward a few feet en masse.

As the tonnages displaced are relatively low (tab. 3) the volume of gas (largely methane) released is correspondingly small and may result in the gassing out of the pushout site from a few minutes to a few hours.

Pushouts in some mines more than others tend to be localized to points where the workings are being advanced across a fault plane. The occurrences are always in association with immediate load readjustments effected by the advance of the working face. In table 2 note that of 11 occurrences recorded in the Number 4 seam, Canmore, eight took place in intimate association with faults, whereas in table 3 for the Upper Marsh, all eight pushouts manifested themselves in unfaulted sections of the seam. Although no details on the occurrences in the Number 3 mine, Nordegg have been recorded by the mine officials it is quite evident from a tour of the Sixth Level district (presently the deepest part of the mine) that pushouts have been encountered at practically all the faults, as well as at innumerable places where the seam is undisturbed beyond the regional effect of large scale movement of roof over floor.

A type of pushout phenomenon has been observed under normal roof and floor conditions in the highly sheared coals of the southernmost workings of the International mine, Coleman. Here under approximately 1000 feet of cover, the intensely sheared coal literally runs as rooms are being driven up the slope. In many instances no pick work is required in the opening of such rooms; the miners merely keep the sides of the excavation lagged tightly to the face in order to direct the course of the pushout. In contrast to the spontaneous pushing of the coal in the International mine, blasting or bumping frequently induces these minor forms of blowouts in the Upper Marsh seam mentioned above.

The frequent occurrence of these phenomena presents little hazard to the men, but the release of large quantities of gas results in serious reduction of output from those sections of the mine affected, until such workings are cleared. Oftentimes several hours may elapse before the gas content at the face is reduced to safe limits.

It should be emphasized again that pushouts give every indication of being merely a more gentle variety of blowout and that such stress relief manifestations show all gradations from one to the other, in rapidity of movement, degree of fragmentation, and tonnages of dislodged coal.

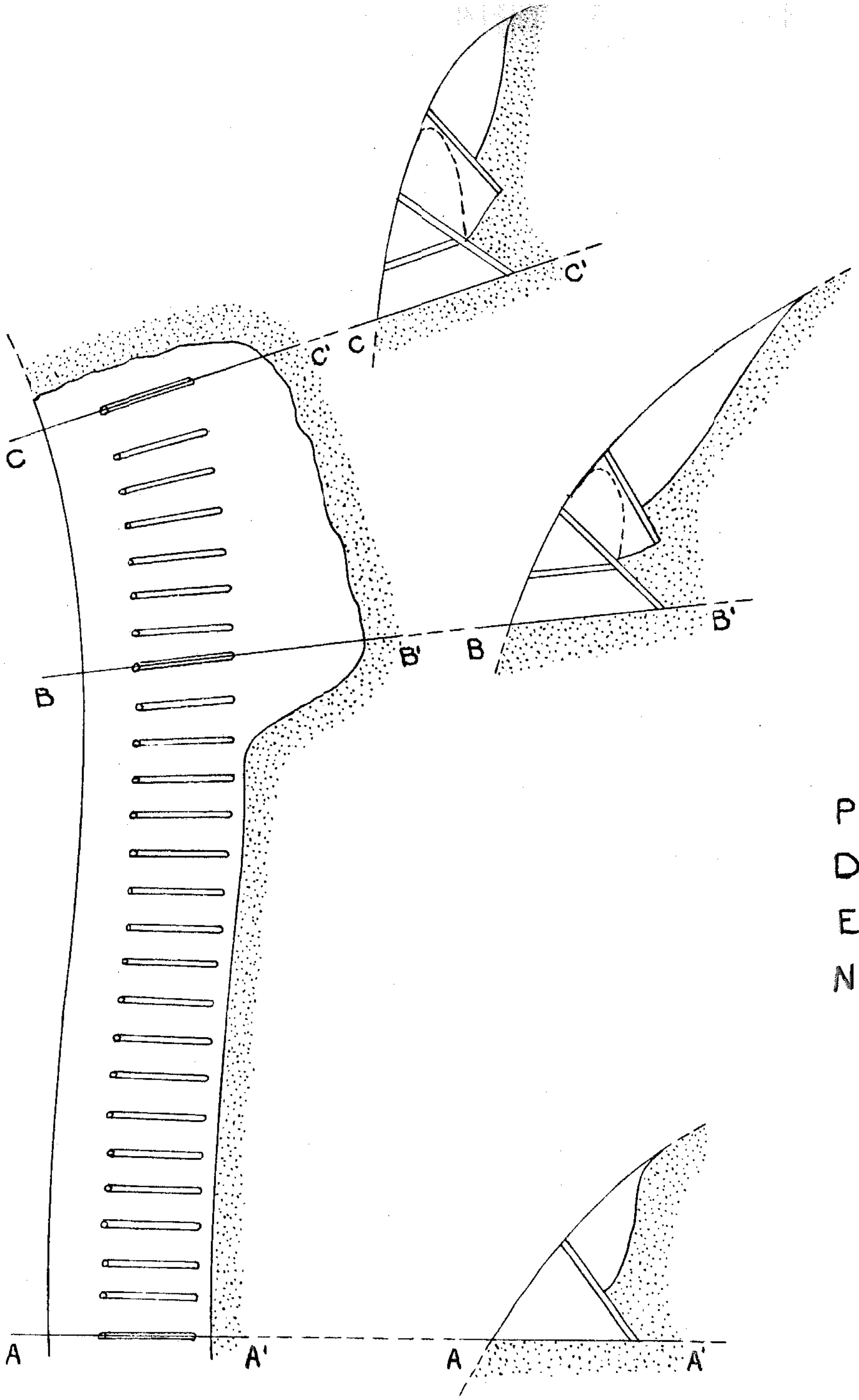
Sloughs

Several instances of a different type of displacement of large tonnages of intensely sheared, soft coal have been erroneously recorded as violent stress relief phenomena. This misinterpretation is doubtless due to a combination of the large tonnages frequently dislodged, and the associated air blast produced by the impact of the displaced material on the floor of the entries.

There are a few cases on record for the Upper Marsh seam, Canmore, (tab. 3) where up to 60 tons have been displaced, while in one outstanding example at the face of the Drainage Level in the Number 3 mine, Elk River, approximately 200 tons of coal were dislodged (fig. 20). This particular instance was regarded by the mine officials as a blowout (Ann. Rept., Minister of Mines, B. C., p. 288, 1949). However in the report of the phenomenon it was stated that the dislodged coal retained its soft, shiny, slickensided nature, and did not differ from the typically soft, and intensely sheared coal of the district. There was no abnormal amount of gas released during the dislodgment.

Difficulty was encountered in holding the coal on the high side rib just outbye of the slough site. Figure 20 displays the steeply inclined condition of the roof, and the dashed outline of the high side rib prior to the slough.

It is not surprising that such phenomena occur in profusion when levels with ribs either vertical or leaning over the mine openings are driven under such conditions. The highly sheared and polished coal fragments of the destressed fringes of the pillars constitute an incoherent mass quite incapable of supporting its own weight. The ribs, in seeking the angle of repose, slough extensively, in particular on the high side where the coal is able to fall free and permit further destressing. In all instances sloughs are developed by continuous but gradual readjustment of the coal surrounding the mine openings. Unlike blowouts and pushouts which occur in intimate association with the advance of the working face, sloughs may occur at any point, and at any time subsequent to development work. The ultimate



Plan and Sections at Face of
Drainage Level, Showing
Extensive High Side Sloughing
Number 3 Mine, Elk River, B.C.
Scale: 20 ft. to 1 in.

Figure 20.

dislodgment of the destressed material is frequently spontaneous, but often is induced by such jarring mechanisms as blasting or minor bumping at the face.

There is neither readjustment of roof and floor immediately following a slough (as evidenced by weighting of the mine props) nor any force of ejection. Moreover sloughs occur at any depth so long as the coal is soft and the seam has a moderate to steep dip. There is no change in size characteristics of the sloughed coal from those of the coal as mined, and no abnormal amount of gas is released.

VIII. REVIEW OF THEORIES OF VIOLENT STRESS RELIEF

A number of different theories have been proposed to explain bump and outburst phenomena. The accompanying outline will acquaint the reader with the theories advanced and where known, with the authors who proposed them.

Type of Phenomenon	Sub-type	Author	Proposed Genesis
Bump	shock	Rice (1918)	rupture and fall of superjacent rock masses
Bump	elastic rebound	Herd (1930	instantaneous reversal of stress regimen (cantilever)
Bump	pressure burst	McCall (1934) Rice (1918)	advance weighting (stress arch) leading to failure of overloaded pillars
Bump	tectonic	-----------	release of strain energy developed by active tectonic stresses

Type of Phenomenon	Sub-type	Author	Proposed Genesis
Blowout	depth	-----------	weighting of cover
Blowout	cavity	-----------	cavities of gas under pressure
Blowout	adsorbtion	Graham and Briggs (1921)	accumulation of powdered coal containing methane under pressure
Blowout	tectonic	Caulfield (1927)	points of excessive strain due to combination of overburden and active tectonic stresses

Note that diverse views have been entertained regarding the genesis of different types of violent stress relief. It is apparent from these views that there is a tendency toward a sharp demarcation between bump and outburst phenomena. The unbalancing of the stresses that gives rise to violent bumping on the one hand is believed to be caused by mining practices. In blowouts on the other hand the stresses are believed to exist prior to mining, in the form of loading, or vestigial or regenerated tectonic stresses, or those arising from the expansive action of pockets of gas at very high pressure.

The Shock Bump Theory

In consequence of the serious bumps of November, 1916, in the 1 East mine, Coal Creek, G. S. Rice was invited to investigate and report on the nature of these phenomena.

From this visit arose the Shock Bump Theory (Rice, 1918). The idea however was expressed some years earlier by W. F. Robertson (1908), former Provincial Mineralogist of the British Columbia Department of Mines.

According to Rice, the prime requisite for a bump condition is the existence of massive, rigid, sandstone, conglomerate or limestone beds some distance above weaker strata in the immediate roof of a seam. With the mining out of a large section of the seam, or the crushing of pillars from the weight of the immediate roof, these weaker strata are believed to subside, and a lens-shaped cavity is produced beneath the strong beds. The areal extent of this cavity spanned by the more rigid beds would depend on the extent of extraction within the seam and the crushability of the pillars. When the lower strata subside over a sufficiently large area (200 to 1000 feet in diameter, say) the massive beds are unable to stand the strain from the superjacent strata, and a large disc-shaped piece is believed to drop through the cavity ("1, 2, or 3 feet, as the case might be") and exert a forceful blow on the immediate roof. To account for various intensities of bumps, different sizes of slabs are presumed to drop out at varying intervals above the seam. Moreover, above any displaced slab, Rice believes, would be a void of essentially the same dimensions so that the stage is set for a second bump in the same area of the workings. With each bump, successively higher voids would become progressively more filled with broken rock, so that later blows would be cushioned and have less effect on the mine workings below. Subsidence of the lower measures through continued crushing of the pillars, or the enlargement of gobs would facilitate the maintenance and growth of the cavities. Great saucer-like masses would continue to drop until a flexible stratum in the superjacent strata or the surface is reached. Rice assumes that the massive strata are free of prominent jointing or faults in the development of his saucer-shaped blocks, as these weaknesses "would modify the character and size of the falling masses." In addition the assumption is made that the strata are inclined at sufficiently low angles that there will be no slippage along the bedding planes. He believes steep dips would radically influence the movement of the falling mass and consequently the nature of the bump. Rice does not attempt to clarify these last two assumptions. In any event the impact sets up tremors in the immediate roof, and the blow is used to account for the breakage of timber, falls of soft roof material, sudden uplifting of the floor, slabbing of coal from the ribs, and the release of large amounts of gas.

The reader need only visit Coal Creek to be impressed with the massive sandstones and conglomerates that are interbedded with and overlie the two uppermost seams in the Kootenay formation. It is doubtless because of the prominence of these beds that Rice's mechanism was conceived.

Considerable energy would be involved in the impact of large saucer-shaped blocks of these highly indurated sediments. As Rice has pointed out the movement need not be very great.

However studies in the Lorraine Basin indicate that massive beds may not be the sole factor in the development of bumps. Pennsylvanian coals of the Basin are overlain by massive Permian and Triassic sandstones and conglomerates, and yet at cover intervals as large as 2500 feet the seams are free of bumps (Coeuillet, 1951).

Continued subsidence of progressively higher strata might lead to sustained bumping localized in certain sections of a mine where convergence of roof and floor is large. Precise leveling surveys on the surface above the workings (in addition to subsidence cracks) reveal that even with cover intervals of 2500 feet there is movement of the superjacent strata above the extracted areas. Moreover bedding-plane slippage throughout the coal-bearing sequence must favor bed separation, especially between units of decidedly different competency.

As the particular section of the 1 East mine in which violent bumps occurred was not accessible at the time of the writer's visit, little can be said of the influence of geologic structure on violent stress relief there. Plans of the old workings are lacking in details regarding faults. It is interesting to note however that frequent reference is made (reports of the District Inspectors of Mines) to the association of such forms of violent stress relief with large pillars left to support the superjacent strata over the principal haulage ways (Miard, 1939). Rarely is any mention made of violent bumps in intimate association with faults.

Much of the fragmentation of the massive sandstone and conglomerate beds in the upper Kootenay is joint controlled. The talus on the slopes of Coal Creek as well as the fragmented roof rock in caved areas underground confirm this. However the fact that some extracted areas hang open for considerable lengths of time after the coal has been mined out suggests that jointing may not play an immediate role in the breaking up of the superjacent strata. Ultimate collapse of the roof rock must be brought about by opening up of these joint systems and not by fragmentation of the strata into large disc-shaped masses.

As Rice lays great emphasis on the presence of massive beds in the production of bumps, is the reader correct in inferring that with such beds extending to the outcrop bumps should be of as great a frequency under shallow cover intervals as at depth? Although this would be a logical deduction from his theory, Rice makes no such implication. In fact he states "bumps are manifestations of pressure, and occur only when mines are at depth, usually exceeding 1000 feet." He uses the pressure aspect of the problem to effect "mine squeeze" and bring about a subsidence of the immediate roof, a mechanism so necessary to produce bumps according to the Shock Theory in areas where only development work has taken place. However with extensively extracted areas next to the outcrop, no such squeezing is necessary so that the setup should be ideal for the development of shock bumps. Surface slumping over these mined out areas close to the outcrop is to be observed everywhere, and yet no forms of violent stress relief whatsoever are experienced. This is particularly well borne out in the International mine, Coleman, where vast extracted areas extending to a cover of roughly 1500 feet underlie the massive sandstones and conglomerates of the basal Blairmore formation. No violent bumps have been experienced in this mine.

Even if the development of lens-shaped cavities and the concomitant dropping out of saucer-shaped masses of sandstone and conglomerate in the superjacent strata were possible, the full impact of the blow should be centered over the gobs, with the resultant destruction of sacrifice pillars, and throwing down of roof rock. However it is consistently found that the center of destruction is in the abutment zone back from the edge of the extracted areas. The gobs are least affected.

At the time violent bumps were first encountered in the 1 East mine only advance work had been conducted, with no more than about 20 per cent of the coal taken out. There was a regular distribution of pillars and no large extracted areas over which extensive subsidence could take place.

In view of the violent bumps in the underlying Number 2 mine (approximately 150 feet vertically below 1 East), there should have been abundant bed separation in the strata below and above Number 10 seam worked by the 1 East mine. Hence in the advance of the latter mine, the stage should have been set for bumps of a very severe nature according to the Shock Theory. The mine passed over the bump area of the underlying Number 2 workings without noticeable effect, and it was not until the headings were 300 to 400 feet beyond the face-line of the Number 2 mine that violent bumps were encountered (Ann. Rept., Minister of Mines, B. C., 1916). Apparently the Number 2 workings destressed to some extent the stratigraphic sequence in the vicinity of 10 Seam. It was not until the 1 East mine entered those areas where the full loading effect of the superjacent 2000 feet of strata was borne by the pillars that violent bumps began to occur.

If squeezing out of pillars is essential to the creation of voids in the superjacent strata, then bumps should be encountered in other seams within which there has been ample evidence of squeeze. The 8 Incline section of the Number 9 mine, Elk River, and the 3 Left section from the main slope in the Number 3 mine, underlying Number 9, fully comply with Rice's concept of a bump regimen. There has been ample opportunity for bed separation between the massive units and underlying less competent beds in view of the sheared condition of the coal, the high percentage extraction and the concomitant convergence of roof and floor in the two mines. In neither instance have violent bumps occurred.

Prior to the occurrence of face bumps, hard, blocky coal is almost always observed to become lively. Continual bursting of small pieces of coal from the ribs and face is indicative of the strained condition of the coal. Characteristically the final bump comes without further warning. The fact that the violence of a bump as well as its time of occurrence is dependent on the rate of advance of the face is imcompatible with the Shock Theory.

Where a high percentage of extraction is practised, the occurrence according to the Shock Theory should be independent of the nature of the coal. Subsidence of the roof in the gob would develop the necessary cavities under the rigid sandstone and conglomerates above. On the other hand if the concept of simple overstressing of pillars is applicable, structurally strong coals are a prime requisite for a bump condition. Strain energy must be accumulated in the pillars before violent stress relief can take place. A comparative study of the physical characteristics of the coals in those collieries affected by violent bumps has consistently revealed that bumps manifest themselves only in structurally strong coals.

In association with the settling of the roof there is an instantaneous upheaval of even greater magnitude of the floor. The direct blow on the mine roof is, according to Rice, transmitted to the floor where the coal in the pillars is strong, and results in a sudden upward movement of the floor in the entries and rooms. It is believed that he is implying an instantaneous mass movement of the immediate substratum from under the pillars into the openings.

Continual heaving of the carbonaceous shale floors in mine openings at cover intervals greater than about 800 feet confirms the view of a gradual transfer of material from under the pillars. Where the floor is subject to heaving, use is made of this transfer to tighten sets. The posts are placed to lean out slightly over the entries so that within a few weeks their bases are moved into the vertical, and the posts are held firmly in position. If they are leaned too far when first put in they frequently break prior to their being twisted into the vertical. At the other extreme, the foot of the post is carried out beyond the top and the timber falls out. It is apparent that in order to effect slow movement of the floor rock, pillars must be of sufficient strength to transmit the loading stresses to the substratum. However it is difficult to conceive how coals whose crushing strength is only one-third to one-half of that of the floor rock could transmit a sudden dynamic blow from above and effect the aforesaid instantaneous displacement of the carbonaceous shale in the floor.

In the bump of 1950 in the 1 East mine (see p. 72) in which the floor was heaved from 12 to 14 inches, there was no evidence of an instantaneous mass movement of the floor from under the pillars into the openings. The floor appeared to be normal in every respect except that it was lifted off grade. It appeared that the floor had arched in the entries and rooms by a simple rise, not by thickening through movement of rock from under the pillars. The intensely crushed condition of the pillars and the unshattered state of the main roof and floor strongly suggested that the pillars had merely burst under the load. With the pillars then unable to keep the roof away from the floor, the latter sprang up and the roof settled to a condition of equilibrium. Although Rice does not accept the concept of pillar bursting at Coal Creek, he does entertain that view for some of the bumps in the Carbonado mine in the state of Washington.

In those mines in which precise leveling surveys have been carried out (McGillivray, International, and Canmore Number 4) it has been found that there is considerable resilience in the underlying strata. In the Number 4 mine, Canmore, for instance, surveys in an area in which only sacrifice pillars remain (7 Slope below 2 Gangway East), revealed that, in the closing of the opening from a height of 10 feet to 1 foot, 6 feet of this convergence was due to uplift of the floor, and the remaining 3 feet to subsidence of the roof. Thus a springing up of the foot-wall in association with a violent bump is certainly feasible in terms of a pillar failure concept.

Little has been said on the problem of bumps at Springhill, Nova Scotia. However the literature on bumps in this field contained an interesting point pertinent to the discussion of the Shock Theory. Violent bumps in these mines are believed to be intimately related to the thickening and thinning of a massive sandstone bed in the superjacent strata. At the 5100 foot wall, under a cover of approximately 2200 feet, and with an extensive gob to the high side, shock shooting was attempted in the roof to induce a bump in the coal below the 5400 foot level. While subsidence of the immediate roof should have created the necessary bed separation beneath the massive sandstone, it was thought that the blast would rupture the bed artificially and allow some of it to drop to the immediate roof. Shock shooting produced no apparent results. Moreover shooting in the seam produced no violent relief of stress. The stress in the pillar was partly released by a flowage of coal into the holes, making it impossible to drill.

In summarizing, there are many inconsistencies in the Shock Bump Theory which are readily explained by consideration of a pillar strain concept. It is true that thick, rigid beds play a significant role in violent bumps, but only in the sense that they enable a transfer of loading stresses to the unmined coal. The behavior of the roof rock in caved areas as well as the effects of violent bumps on the mine workings is very suggestive that the mechanism proposed by Rice is inadequate.

The Elastic Rebound Theory of Bumps

The development of the Elastic Rebound Theory is due in large part to the late Walter Herd, through his studies of violent stress relief in the Number 2 mine, Springhill, Nova Scotia (Herd, 1930).

According to Herd it has been consistently found that violent bumps do not occur where overhead drilling has revealed the discontinuance of a massive sandstone bed above the Number 2 mine or where the floor is weak enough to heave in the roadways. A characteristic feature of the Cumberland coal field is the lenticular nature of this massive sandstone, thinning to nothing and thickening to 75 feet within a few hundred feet. From 10 to 20 feet of shale forms the immediate roof of the Number 2 seam.

As a given section of the seam is mined out, the immediate roof (shale) falls out fairly rapidly, while the massive sandstone is believed to span the void as a beam for several hundred feet. The beam fulcrums on the caved material at the inbye section of the gob and on the coal within a few hundred feet of the face. On the assumption that the massive sandstone bed is elastically deformed by the loading of the superjacent strata, there is an upward thrust in the region immediately outbye of the highly stressed coal (the abutment) near the face. The elastic properties of the coal and immediate roof in this sector would permit a dilatation.

With the retreat of the extraction line, the massive sandstone is strained to the point of rupture, the cantilever effect ceases, and the theory postulates an instantaneous reversal in the stress regimen in the zone of dilatation -- a rebound. This hammerlike blow, exaggerated by the weight of the overhead strata, is believed by Herd to be responsible for bursting of the coal into the roadways, heaving of the floor, splitting of pillars, and the shaking down of roof rock. Serious damage from a bump always occurs a few hundred feet back from the extraction line and rarely at the working face. McCall (1934, p. 59) attributes this characteristic to crushing of the coal in proximity to the face by advance-weighting. The crushed coal is then unable to accumulate strain energy.

The Elastic Rebound Theory as applied to violent stress relief phenomena in the Springhill Number 2 mine has much in its favor. Surface outcrops and cross-measure tunnels substantiate the view that the aforementioned sandstone bed is massive, unfaulted and joint-free. It is probably quite capable of spanning large areas of extracted ground.

Convergence studies reveal that the roof rock develops a moderately sharp abutment zone immediately outbye of the extraction line (McCall, 1934). With the retreat of the longwall the abutment zone migrates accordingly, and there is a corresponding increase in convergence at any given station. One would have expected however that if the massive sandstone bed above the seam was acting as an elastic beam, convergence surveys should have revealed a migratory zone of dilatation as well as a compressive zone from the abutment, because of the postulated upwarp in the superjacent strata. While McCall's convergence data were inconclusive in this regard, the survey did indicate a steady convergence of roof and floor, the rate of convergence increasing noticeably as the longwall approached the station. That it would have been impossible for bed-separation between the sandstone and the immediate roof to mask out this wave motion follows from the fact that 15 to 20 feet of shale could not of its own weight account for this steady convergence.

With a loading of approximately 2500 p.s.i. on the sandstone beam, one would expect that failure would lead to a collapse of the bed into the gob. However theory demands a springing up of the broken end of that segment of the beam extending over the solid coal in order to cause an instantaneous reversal of the stress regimen back from the face. In all instances of violent bumps, the gob has given no indication of any unusual movement having taken place in the superjacent strata.

Highly stressed coal is frequently encountered in driving headings in virgin ground or in splitting pillars prior to extraction. Tightening of the face along with spasmodic minor bumps is definite indication of the strained condition of the coal. As pointed out on page 71, a bump may be induced by increasing the rate of mining under such circumstances. It is difficult to reconcile this feature with the Elastic Rebound Theory which demands that the area subject to a bump be in a relative state of relaxation prior to the violent relief of stress.

In addition, the hundreds of violent bumps in the deeper workings of the Number 2 mine, Springhill, demand considerable breaking up of the superjacent strata to produce the necessary rebounds. Subsidence surveys (Herd, 1930), reveal no surface movement in association with the breaking up of the massive sandstone bed.

Briefly then, the prerequisites for a bump condition according to the Elastic Rebound Theory are a strong shale roof and floor, a massive sandstone bed over the immediate roof, and a considerable cover interval. Like the Shock Bump Theory this concept postulates a mechanism which is independent of the strain characteristics of the coal.

The Pressure Burst Theory of Bumps

In his discussion of the genesis of bump phenomena in the Carbonado mines, Washington, G. S. Rice (1918) drew attention to the possibility of failure of large pillars at cover intervals in the vicinity of 2000 feet. He emphasized that under the prevailing unsystematic practice of drawing the irregular-sized pillars, some of the remaining pillars, particularly the larger ones, were forced to bear the burden of the redistributed stresses. The ultimate failure of overstressed pillars was considered by Rice to be the cause of these violent bumps.

The bursting of pillars under increased load was discussed again by T. L. McCall (1934) in his detailed treatise on bumps at Springhill. His idea was that the cantilevering of the massive sandstone member in the roof over the extracted area to the rise and inbye of the longwall face led to the sudden failure of the abutment pillars when their bearing strength was exceeded. The concept is quite analogous to that in the Elastic Rebound Theory, except that in this instance the pillars fail rather than the massive sandstone.

C. T. Holland (1942a) expanded on the theories of Rice and McCall by pointing out the variations in the physical properties of coal in different sections of a seam, and even in different parts of the same pillar. Strong coals, having a low elastic modulus, are capable of storing larger amounts of strain energy than those with low ultimate strengths and a high modulus of elasticity (Philips, 1948). Hence even with a uniform load applied to a given pillar, there would not necessarily be a uniform distribution of strain energy, particularly around the free faces of the pillars.

It has been a problem to explain why violent bumps should be of such frequent occurrence immediately outbye of the extraction line of the Number 2 seam in the McGillivray mine and yet practically unheard of under similar mining conditions in the International mine. In both workings the room and pillar method of developing the seam is practised. By means of a retreating extraction line the seam is systematically mined out between any two levels before the coal in the next lower level is drawn. Moreover in the particular sections of the two mines now under discussion there is approximately the same cover interval (2300 feet). As pointed out on page 25, one outstanding characteristic of the Number 2 seam is the variation along the strike of the amount of soft, sheared coal (see also fig. 9). The northern sector of the McGillivray workings has consistently higher proportions of strong, blocky coal. Violent bumps are localized in those sections of the seam where the overall strength of the pillars is the greatest.

This point serves only to emphasize the significance of Holland's findings on the physical properties of coal in relation to bumps. In the process of developing or extracting a seam, those segments which are structurally stronger will tend to carry a larger proportion of the load. Naturally then highly stressed areas are established. An overstressing of these coals is believed to give rise to a bump condition.

The reader will recall the difficulty encountered in trying to explain the absence of bumps in areas of intensely sheared coals by the Shock Bump Theory (p. 100). The squeeze associated with such coals even under relatively shallow depths of cover (400 feet at Nordegg) merely indicates the inability of these coals to accumulate strain energy. On the other hand two violent bumps (referred to on p. 70) experienced in the strong, blocky coals of the 1 East mine were the result of overstressing a pillar remnant. All evidence points to the dependency of bumps on the strain characteristics of the coal -- the ability of the coal to accumulate redistributed stresses associated with mining and to release them with violence.

In explanation of bumps in close proximity to extracted areas, the Shock and the Elastic Rebound theories demand excessive movement of the main roof in the gobs. This movement is rarely observed. A consideration of the overstressing of strong coals through its buttressing the superjacent strata leads to a simple solution of the incongruity. The only motion of the roof necessary is that associated with the settling of the overhead strata on the crushed pillars. Failure of the pillars permits an instantaneous rise of the remarkably resilient subjacent strata. It is not necessary to consider the transfer of material by means of an impact transmitted from the roof through the coal (whose crushing strength is considerably less than that of the rocks either above or below) to the floor.

In the course of investigating strain characteristics of selected pillars, it is necessary to drill holes into the pillar cores. Frequently such blocks of coal bump violently while the drilling is in progress. As this mechanism of inducing bumps is independent of large scale movement in the superjacent strata neither the Shock nor the Elastic Rebound theories can readily apply.

Although Rice, Herd, and McCall recognize that loading is all important in violent stress relief by bumping, their mechanisms fail to apply when the superjacent strata are intensely fractured and no large overhang or cantilever is possible. In the McGillivray and International mines for instance, strong jointing and an abundance of faults are considered to render the overhead strata non-elastic. Precise leveling surveys reveal no persistent pattern of compressive and dilatory zones accompanying the migration of the extraction line. Simple overstressing of pillars to the point of rupture, however, does not require a large scale transfer of load if the cover interval is adequate.

With increasing load at progressively greater depths, it would be expected that with the same seam characteristics there should be an increase in frequency of violent bumps regardless of the ability of the superjacent strata to act as beams. The Shock and Elastic Rebound theories on the other hand imply that beyond a critical cover interval (roughly 1000 feet), the frequency of bumps would be dependent solely on the ability of the massive beds in the superjacent strata to behave as beams. The relation between cover interval and frequency of occurrence of violent bumps as revealed in figure 16 favors the pressure burst hypothesis.

In the ultimate analysis a bump is the result of overstress. The problem is to evaluate the available data and decide whether the strain energy released is accumulated in the coal, in the associated rocks, or in both. Moreover it is fundamental to know the source of this energy, whether through anomalous redistribution of loading stresses, perhaps localized by geologic structure, or whether vestigial or regenerated tectonic stresses might be contributory. Available data on the influence of the redistribution of mining stresses on the coal seams and associated rocks strongly favors the acceptance of the Pressure Burst Theory for violent relief of stress by bumping. The writer should emphasize that his scope has been limited to selected collieries of the Canadian Cordillera. The observational data on which the above appraisals of current bump theories were made will doubtless be tempered by further studies in eastern North America and abroad.

The Tectonic Theory of Bumps

The fact that faults in some instances cited in the literature tended to localize the occurrences of bumps led many authors to believe that active tectonic stresses have developed concentrations of strain energy in the strata prior to mining. This mechanism has proved ideal in metal mines in explaining rockbursts at shallow depths (2000 feet), and in coal mines in explaining district bumps under 500 feet of cover and face bumps in development work at greater depths. There is no instrumental evidence as to whether such faults are undergoing secular strain. However precise leveling surveys of strata movement at an extension fault in close proximity to the extraction line in the McGillivray mine has suggested that such a zone is 'dead'. In other words the roof strata do not behave as beams in the sense that adjustments associated with movement of the extraction line are transmitted across the fault. The blocks on either side behave as entities. It may be then that the occurrence of bumps in close proximity to a fault is due to anomalous overloading of the coal in the vicinity.

Note moreover that conditions were perfectly normal in the cutting into pillars of that section of the Number 2 seam in the McGillivray mine which has been folded (p. 25). Certainly if tectonic stresses were presently active, this region would be the most likely of any in the seam at which stress might be accumulated.

The type of mining definitely influences the frequency of occurrence of bumps. It has been found both on this continent and abroad that under large cover intervals a longwall system of mining greatly reduces the occurrences of violent bumps (Holland, 1942b; Bryson, 1936; Walker, 1927). By this system, a seam is developed to a minimum prior to its being extracted and hence there is a more uniform distribution of loading stresses on the unmined coal.

From the foregoing discussion of other theories proposed to explain bumps, it was seen that three factors of prime importance in the development of a bump condition were cover interval, strength of the coal in the pillar, and ability of the floor to resist heave. Under sufficiently great depth of cover violent bumps characteristically occurred in pillar remnants or in the abutment zone back from extracted areas. Moreover a violent bump might be induced by increasing the rate of advance of a heading or extraction line in strong coal.

It is apparent that if secular strain is affecting the coal fields of the southern Canadian Cordillera, its consequence must be of a minor order. As far as can be observed, bumps, whatever their intensity, are due to failure of overstressed coal in zones of redistributed mining stresses.

The Depth Theory of Blowouts

The concept that cover interval alone is responsible for the occurrence of blowouts is now outmoded in view of the complex relation found to exist between such occurrences and cover interval, structural characteristics of the seams and mining practices. Depth of cover is all important since blowouts are unknown at cover intervals less than about 550 feet. However the fact that seams underlying those subject to outburst phenomena are frequently mined without incident is sufficient evidence that depth alone is not responsible for the development of this form of release of strain energy. There are several good examples to illustrate this point: at Coal Creek, Number 2 seam, which is roughly 150 feet lower in the section than Number 1 seam (1 East mine) is entirely free of outbursts; a similar situation is found in the Cevennes Basin, Central France (Quentin, 1952), where the Jeanne seam, 65 feet stratigraphically below the Grande Couche, is free of outbursts; also in the Nanaimo coal field, Vancouver Island (Touhey, 1923), blowouts have been confined to the Douglas seam, which is the uppermost of the three principal seams in that field.

The Cavity Theory of Blowouts

Because of the large volumes of gas characteristically released in blowouts, the idea has been entertained that cavities of gas under excessive pressure exist in the seams. Moreover in boreholes driven ahead of the face, gas pressures of a few pounds per square inch have been recorded, as in the 1 East mine (Rice, 1918).

However in the course of drilling miles of exploratory holes ahead of the working faces, never has any cavity or reservoir of such compressed gases been encountered. This point in itself is sufficient basis for refuting the Cavity Theory.

The Adsorbtion Theory of Blowouts

Following an investigation of the adsorbtion of methane and other gases in coal, Graham and Briggs (1921) proposed an interesting theory of blowouts. They attempted to reproduce the mechanics of such a phenomenon in the laboratory. By experiment they satisfied themselves that lump coal highly charged with methane did not disintegrate to dust when the gas pressure was suddenly released. Hence it was believed that blowout coal must be powdered prior to the instantaneous release of strain energy; and since outbursts were occasionally localized at points where headings were being driven across fault planes, they concluded that outbursts were due to the sudden release of adsorbed gases held under pressure in tectonically fractured and sheared coals.

Whatever the physical relation of the hydrocarbon gases is to the coal, it is true that an abundance of gas is released with the disintegration of the coal in a blowout. The question is whether the gas is the product of this disintegration or the cause.

Innumerable instances of drilling exploratory holes ahead of the working face have never revealed the existence of pockets of soft, fine coal charged with gas under pressure. For that matter the largest tonnages are most forcefully ejected in mining hard, bright, blocky coals (c.f. Canmore, Number 4 seam). Moreover a large number of highly sheared seams is mined in the Nanaimo, Crowsnest and Cascade coal fields, in which no trouble from blowouts is encountered.

The adsorbtion Theory although recognizing the intimate relation between the gases released and the coal disintegrated, fails to distinguish whether these gases are an effect or a cause of the violent release of strain energy in blowouts.

The Tectonic Theory of Blowouts

The influence of active tectonic stresses on the release of strain energy in the mining of coal seams in orogenic belts has been considered both on this continent and abroad. Bernard Caulfield, late superintendent of the Coal Creek mines, was perhaps as familiar as anyone with blowout phenomena. It was he who proposed that in the mine workings there were points of "regional extreme pressure" from a combination of the cover interval and accumulated active tectonic stresses (Caulfield, 1927). According to Caulfield, when these "pressure points" are released, with explosive violence, the forces break up the ejected coal so intimately that the gas is liberated. The principal reason for his advancing the theory was that on occasion outbursts were accompanied by earth tremors which shook the houses in Coal Creek. Moreover, Caulfield drew attention to the occurrence of blowouts at faults, pinches and swells to support the Tectonic Theory.

From a comparative study of coal seams troubled with outbursts, throughout the world, it is immediately apparent that this form of violent release of strain energy is characteristic of mining in orogenic belts. However it is in such regions that the cover interval increases rapidly because of steeply dipping seams and the mountainous terrain. It is universally accepted that there is a minimum depth of cover above which blowouts do not occur. The question immediately arises as to why there should be a minimum cover interval if tectonic stresses exist more or less homogeneously throughout a mountain mass. One would think that in this case there should be equally as great a probability of violent release of strain energy near the outcrop as at depth, other things being equal.

Since blowouts are apparently limited to orogenic belts, if one is to accept the concept of active tectonic stresses, then why are such strain accumulations restricted not only to certain tectonic units within the belt, but also to specific seams within a given unit? In the Crowsnest Pass, for instance, it has been pointed out that blowouts have occurred at Coal Creek, but are unheard of at Coleman. Recall that the Number 2 seam, Coleman, is only

550 feet stratigraphically above the Coleman fault. Moreover, of the seams mined at Coal Creek, only the Number 10 seam is reported to have had releases of strain energy in the form of blowouts.

If one accepts the view that active tectonic stresses are in large part responsible for blowouts, then one must also accept that accumulations of strain energy take place at structural discontinuities such as faults and folds. The most likely place for such an accumulation would be in the axial region of a fold. Such a structure is unbroken and hence there is no ready means of stress relief except by tightening and overturning. A fold is present in the Number 2 seam, Colman (fig. 7), and as already pointed out no blowouts whatsoever were encountered during mining operations in any section of this seam. In the case of faults, blowouts occurred at only a very small number of intersections of headings and fault planes at Canmore (14 out of approximately 275), at no such intersections in the two seams mined at Coleman, and according to the literature at few if any intersections in the 1 East mine, Coal Creek. At the Number 3 mine, Nordegg, however, a mild form of blowout (pushout) is characteristically encountered at intersections of working faces and fault planes. Those occurrences in intimate relation to faults may in part be due to the anomalous redistribution of loading stresses in the course of mining operations.

Considering the relationship of mining practices to blowouts, it has already been emphasized that they occur most frequently during the cutting of a seam into pillars, only occasionally during the splitting of pillars, and rarely during the process of complete extraction. Moreover, blowouts consistently take place in close proximity to the working face, and come either from the top of the high side rib or the top of the high side corner of the face. The time of occurrence may be controlled by the rate of advance of the face; the faster the coal is mined, the sooner will the occurrence of a blowout take place. If tectonic stresses are contributory, blowouts should be independent of depth, of dip of the seam, and of size or shape of the mine openings. The most violent occurrences should always be localized where the workings cross specific geologic structures such as faults or folds. As already pointed out the vast majority of such instances of violent stress relief phenomena in association with faults have been of the least violent type (pushouts).

Briefly then it is believed that the Tectonic Theory of blowouts overemphasizes the importance of secular strain in the rocks of the Canadian Cordillera. If tectonic forces are present at all their influence on the development of a blowout condition is apparently negligible.

IX. STRUCTURE AND VIOLENT STRESS RELIEF

The present physical condition of the seams governs the type, frequency, and intensity of occurrence of violent stress relief. To apply a phrase so common in foreign literature, it is the 'tectonic preparation' (Iete, 1937), which governs the violent stress relief characteristics of the coal.

In part IV it was concluded that forward movement of the overthrust masses was responsible for the faulted and sheared condition of the coal seams. Shouldering of the overthrust masses effected a gentle flexing of the sequence, first one way, then the other, the periods of stretching bringing about extension faults, and the periods of compression, contraction faults. Moreover a tendency toward similar folding in the coal bearing sequence effected considerable destruction of primary features in some seams. The more competent units through bedding-plane slippage superposed on the coal a consistent drag-fold pattern indicating a differential motion between the beds, with upper beds sliding over those lower in the section.

As pointed out in part VI a bump regimen is believed to result from a complex interplay of several factors, cover interval, extent and proximity of extracted areas, variation in physical properties of coal and associated rocks, and rate of advance of headings and extraction lines. Violent bumps occur in deep coal mines whether or not the mines are located in orogenic belts, but they occur only in seams in which there has been a minimum of shearing. Precise leveling surveys tend to suggest that anomalous redistribution of load in the vicinity of a fault may account for the spasmodic localization of bumps in the immediate area.

On the other hand note that not only are blowouts experienced solely during mining of coal in orogenic belts, but also that they are localized to selected seams in a given tectonic unit within a belt.

Two additional factors in the occurrence of blowouts are the dip of the seam and the presence of faults. However as the seams of the Canadian Cordillera subject to blowouts do not differ radically in dip, there is no means of substantiating the statistics of Yarovoi (1948) from the Don Basin on the increase in frequency of blowout phenomena with steepening dip. Moreover blowouts frequently occur in intimate association with faults. Of 34 recorded instances at Canmore, 14 were intimately related to visible faults in the seams. At Morrissey and Coal Creek on the other hand, they apparently occurred without any relation to the occurrence of faulting (Wilson, 1947). The significance of faults in the development of a blowout condition is believed to be no greater than in the case of bumps. Their presence may lead to anomalous stress redistribution.

In the case of blowouts it is apparent that beyond a minimum cover interval depth no longer plays the role so significant in bumps. Moreover the fact that blowout phenomena are intimately related to the advance of headings in virgin ground makes it difficult to accept the belief that these forms of violent stress relief are due solely to an overstressed condition of the coal. Statistics from the Number 4 and Upper Marsh seams, Canmore, show that of 34 instances of blowout phenomena, 32 occurred during the cutting of the seams into pillars, the remaining two during the splitting of pillars prior to their being extracted. There is something subtle about the blowout regimen as opposed to that of a bump.

As far as could be interpreted from a survey of the literature and from a study of violent stress relief phenomena in the two seams at Canmore, beyond a certain critical depth three factors in particular dictate the mechanics of build up and release of stress in a blowout: the redistribution of stresses about a mine opening as it is being driven; the physical properties of the coal; and the physical-chemical relation of the coal and the associated gasses. Without exception those blowout phenomena experienced in driving levels have manifested themselves from the high side corner of the working face or the high side rib immediately adjacent to it. Those occurrences experienced in driving rooms either up or down the dip also occur in intimate association with the advance of the face. In these instances less violent forms (pushouts) frequently result in a dislodgment of the bench coal, while more violent forms characteristically arise from the top corner of the face. Moreover those blowouts experienced in driving openings in flat sections of the 1 East mine, Coal Creek, almost without exception came from either top corner of the working face.

In order to explain the intimacy of blowouts with the corners of the working face an investigation must be made of stress distribution about a given shape of mine opening. As such openings in coal mines rarely assume a simple geometrical form they do not lend themselves readily to such an investigation either on theoretical grounds or by means of models in the laboratory. To complicate matters the assumption of a homogeneous, elastic medium breaks down, and even in the simplest case two media (the coal and the associated rocks) of quite different physical properties must be considered. It is apparent however that a blowout condition must be due in part to the redistribution of stress about the corners of a mine opening. What relation this has to the second factor, the physical properties of the coal, is uncertain.

It has been observed however that the structurally stronger coals of the Number 4 seam, Canmore, are characterized by more violent occurrences -- larger tonnages more forcefully ejected and more highly disintegrated. Crude though the analogy may be, the stronger coals seemingly are better able to dam back the release of strain energy to the point of liberating it almost instantaneously and with great violence.

What part the gas in the coal must play in these phenomena is at present unknown. Is the gas held within the coal at extremely high pressures so that in the final burst out it is responsible for the fragmentation of the ejected coal, or is the gas merely released as a result of intense disintegration of coal in a highly strained condition? Extensive research presently being conducted by the Fuels Division of the Canadian Department of Mines and Technical Surveys has thus far indicated two possible factors in blowout occurrences; one is that the permeability of coals in close proximity to a blowout is apparently less than normal for a seam liable to such occurrences, and secondly that there is a destressing and degassing of a large volume of coal in the immediate vicinity of the cavity at the moment of a blowout. Thus the tonnage ejected is but a small part of the coal involved in the blowout. These points although tentative are introduced here merely to orient the reader to the progress in other aspects of the problem.

Whereas there is every indication that bump phenomena are directly attributable to overstressing of coal in abutment zones, the question of the mechanics of accumulation and release of stress in blowouts remains unanswered. The data thus far suggest that a combination of the physical-chemical relations of the gas to the coal and a nonuniform stress condition in the coal are the prerequisites for a blowout condition.

X. CONCLUSIONS

A study of the structural conditions of the coal fields of the Canadian Cordillera reveals several important conclusions on the relation of structure and mining practices which gives rise to occurrences of violent stress relief.

(1) The structural conditions of the seams in the Disturbed Belt are explicable in terms of the principle of shouldering on bedding-plane thrusts.

(2) The tectonic preparation of the seams is all important in governing their stress relief characteristics.

(3) Secular strain if existent in the Canadian Cordillera is not a primary factor in the development of violent stress relief phenomena.

(4) As far as can be observed bump phenomena are simply the result of failure of overstressed coal in abutment zones.

(5) Revision of mining methods has been found favorable to the reduction of occurrences of violent bumps.

(6) There is a minimum depth level above which neither blowouts nor violent bumps are experienced.

(7) Data from both the 1 East mine, Coal Creek, and the Number 4 seam, Canmore, indicate that beyond a certain cover interval (700 feet in the former mine, 1100 in the latter) the frequency of occurrence of blowout phenomena

drops off sharply.

(8) A blowout is believed to arise from a complex physical-chemical relation of the gas to the coal, and a nonuniform redistribution of stress associated with the advance of the working face in virgin ground.

(9) Much light may be shed on the mechanics of accumulation and release of strain energy in a blowout through further research on the state of association of methane with coal when the two media are in a highly stressed condition.

APPENDIX

References Cited

Beach, H. H. (1943); Moose Mountain and Morley Map-Areas, Alberta; Geol. Surv., Canada, Mem. 236.

Bryson, J. F. (1936); Methods of Eliminating Coal Bumps or Minimizing Their Effects; Am. Inst. Min. Met. Eng. Trans., vol. 119, pp. 40-57.

Caulfield, B. (1927); Outbursts of Gas and Coal in Coal Creek Colliery, British Columbia; Empire Mining and Metallurgical Congress, Proc., Part II Mining, pp. 366-405.

Clark, L. M. (1949); Geology of Rocky Mountain Front Ranges near Bow River, Alberta; Am. Assoc. Petroleum Geologists Bull., vol. 33, no. 4, pp. 614-633.

Coeuillet, R. (1951); Existence or Absence of Bumps; International Conference about Rock Pressure and Support in the Workings (English text); Inichar -- Liege, pp. 419-428.

Crockford, M. B. B. (1949); Geology of Ribbon Creek Area Alberta; Research Council of Alberta, Rept. no. 52.

________ (1951); Geology of Carbondale River Area Alberta; Research Council of Alberta, Rept. no. 59.

Douglas, R. J. W. (1950a); Callum Creek, Langford Creek, and Gap Map-Areas, Alberta; Geol. Surv., Canada, Mem. 250.

________ (1950b); Preliminary map, Mount Head, Alberta; Geol. Surv., Canada, Paper 50-8.

Erdman, O. A. (1950); Alexo and Saunders Map-Areas, Alberta; Geol. Surv., Canada, Mem. 254.

Graham, J. I., and Briggs, H. (1921); Characteristics of Outbursts of Gas in Mines; South Wales Inst. Eng. Proc., vol. 36.

Herd, W.(1930); Bumps in No. 2 Mine, Springhill, Nova Scotia; Am. Inst. Min. Met. Eng. Trans., vol. 88, Coal Division, pp. 151-206.

Holland, C. T. (1942a); Physical Properties of Coal and Associated Rocks as Related to Causes of Bumps in Coal Mines; Am. Inst. Min. Met. Eng. Trans., vol. 149, pp. 75-93.

__________(1942b); Coal Mine Bumps; Mining Congress Journal, June and July.

Iete, E. C. (1937); The Investigations of Fissuring of Seams Liable to Sudden Outbursts in the Gorlov Anticline; Reports Mak NII, T. IV, ONTl.

Jarlier, Inspector General (1923); Revue de l'Industrie Minerale, no. 49, Feb. 1.

Jarlier, Inspector General (1935); The Mechanism of Outbursts; International Congress of Mines, Metallurgy and Applied Geology, Feb. 22.

MacKay, B. R. (1932); The Mesozoic-Paleozoic Contact and Associated Sediments, Crowsnest District, Alberta and British Columbia; Geol. Surv., Canada, Sum. Rept. 1931, Pt. B, pp. 1-25.

__________(1933); Geology and Coal Deposits of Crowsnest Pass Area, Alberta; Geol. Surv., Canada, Sum. Rept. 1932, Pt. B, pp. 21-67.

__________(1941); Preliminary Map, Brazeau, Alberta; Geol. Surv., Canada, Paper 41-4.

McCall, T. L. (1934); Further Notes on Bumps in No. 2 Mine, Springhill, Nova Scotia; Am. Inst. Min. Eng. Trans., vol. 108, Coal Division, pp. 41-70.

Miard, H. E. (1926); Report to the Chief Inspector of Mines for British Columbia on the Blowout of April 5, 1926, in 1 Left off 14 East Entry, Number 1 East Mine, Coal Creek.

Miard, H. E. (1939); Report of the District Inspector of Mines; Ann. Rept., Minister of Mines, B. C., 1939, pp. 144-45.

Moore, E. S. (1950); Coal; John Wiley and Sons Inc., New York.

Phillips, D. W. (1948); Tectonics of Mining; Colliery Engineering, vol. 25, no. 292, pp. 199-202.

Quentin, H. (1952); Reflexions sur les Degagements Instantanes; Revue de l'Industrie Minerale, Juin.

Rice, G. S. (1918); Bumps and Outbursts of Gas in the Mines of the Crowsnest Pass Coal Field; Dept. of Mines, British Columbia, Bull. no. 2, 31 pp.

Rice, G. S. (1931); Introductory Notes on Origin of Instantaneous Outbursts of Gas in Certain Coal Mines of Europe and Western Canada; Am. Inst. Min. Met. Eng. Trans., vol. 94, Coal Division, pp. 75-87.

Rich, J. L. (1934); Mechanics of Low-Angle Thrusting as Illustrated by Cumberland Thrust Block, Virginia, Kentucky, and Tennessee; Am. Assoc. Pet. Geol., Bull., vol. 18, pp. 1584-1596.

Riffaud, E. (1946); The Origin of Outbursts in Coal Mines; Revue de l'Industrie Minerale, no. 512, July.

Robertson, W. F. (1908); Report on the Bump of July 31, 1908, in the Number 2 Mine, Coal Creek; Ann. Rept., Minister of Mines, B. C., 1908.

Roblings, G. (1926); Outbursts of Gas and Methods of Working Seams Liable to Them; South Wales Institute of Engineers, Proc., vol. 42, no. 5, pp. 465-496.

Touhey, J. B. (1923); Outbursts of Gas and Coal at Cassidy, B. C.; Coal Age, vol. 23.

Walker, H. et al. (1927); Crumps at the Pendleton Colliery; Colliery Guardian, p. 533.

Wilson, W. (1947); History of Recent Blowouts or Outbursts in No. 4 Seam, Canmore, April 17.

Yarovoi, I. M. (1949); Treatise on the Working of Seams Dangerous for Blowouts of Gas and Coal; Moscow Ougltehizdat, Russian Text.

Sources of Thicknesses of Stratigraphic Units

1a. Erdman, O. A., (1950); Alexo and Saunders Map-Areas, Alberta; Geol. Surv., Canada, Mem. 254, p. 14.

1b. ______ (1950); Idem (Mem. 254), p. 12.

2a. MacKay, B. R., (1933); Geol. Surv., Canada, Sum. Rept., Pt. B, P. 41, 1932.

3a. ______ (1932); Geol. Surv., Canada, Sum. Rept., Pt. B, p. 21, 1931.

3b. ______ (1932); Idem (Sum. Rept., 1931), p. 21.

3c. ______ (1932); Idem (Sum. Rept., 1931), p. 7.

3d. ______ (1932); Idem (Sum. Rept., 1931), p. 7.

3e. ______ (1932); Idem (Sum. Rept., 1931), p. 16.

3f. ______ (1932); Idem (Sum. Rept., 1931), p. 7.

3g. ______ (1932); Idem (Sum. Rept., 1931), p. 7.

3h. ______ (1932); Idem (Sum. Rept., 1931), p. 8.

4a. ______ (1941); Geol. Surv., Canada, Paper 41-4.

4b. ______ (1941); Idem (Paper 41-1).

5a. Crockford, M. B. B., (1949); Geology of Ribbon Creek Area Alberta; Research Council of Alberta, Report No. 52, p. 31.

5b. ______ (1949); Idem (Rept. No. 52), p. 23.

5c. ______ (1949); Idem (Rept. No. 52), p. 19.

5d. ______ (1949); Idem (Rept. No. 52), p. 18.

6a. Warren, P. S., (1927); Banff Area, Alberta; Geol. Surv., Canada, Mem. 153, p. 27.

6b. ______ (1927); Idem (Mem. 153), p. 12.

7a. Beach, H. H. (1943); Moose Mountain and Morley Map-Areas, Alberta; Geol. Surv., Canada, Mem. 236, p. 17.

7b. ______ (1943); Idem (Mem. 236), p. 15.

7c. ______ (1943); Idem (Mem. 236), p. 11.

8. Clark, L. M., (1949); Geology of Rocky Mountain Front Ranges Near Bow River, Alberta; Am. Assoc. of Petroleum Geologists Bull., vol. 33, no. 4, p. 624.

Table 2. - Statistics of blowout phenomena in the Number 4 Seam, Canmore, Alberta.

No.	Date	Class	Seam	Mine	Location	Elevation of Location	Surface Elevation	Cover feet	Tons Ejected	Gas Released ft.^{3}	Structural Condition	Warning Signs	% Ht. Mined	Fragmentation of mined coal	Fragmentation of ejected coal	Point of ejection	Inducement	Holes shot prior to occurrence	Mining operation	Dip	General Remarks
1	June, 1944	Pushout	No. 4	No. 4	face Main Slope	3680	4590	710	20	$25x10^3$	fault	none	100	blocky	—	face	Blasting	1	development	9°	coal thrown 20 ft. forward with no appreciable violence.
2	Dec. 28, 1945	Blowout	4	4	33x, 60 Slope	4030	4300	770	300	large	fault	face working	100	blocky	—	h.s. of face along fault	air pick	—	development	25	coal thrown 60 ft.; 12 sets blown out; gas cleared in 1 hr.
3	Feb., 1946	Pushout	4	4	31x, 60 Slope	4050	4775	725	30	small	fault	roof rumble; timbers cracking	100	blocky	—	h.s. of face along fault	blasting	4	development	25	cutting 4th side of pillar; occurred 3 to 4 min. after last shot: rumbling heard 300 ft. away.
4	Mar. 28, 1947	Blowout	4	4	46x, 66 Slope	4030	4800	770	300	$50x10^3$	fault	face working; gas	100	blocky	—	h.s. of face	blasting	5	development	25	coal ejected along roadway 60 ft.
5	Apr. 2, 1947	Blowout	4	4	15 Pitch, 2 Gwy. East	3990	4610	620	16	large	fault	face working	100	blocky	—	face	blasting	2	development	22	face hard, firm prior to blowout; gas cleared in 1 hour.
6	Apr. 1, 1948	Blowout	4	4	7 Slope, 2 Gwy. East	3520	4720	1200	300	$40x10^3$	fault	face working	100	blocky	—	face	shovel	—	development	22	coal ejected 50 ft. up slope; face issuing 200 ft.^{3}/min. prior to blowout.
7	May, 1948	Pushout	4	4	38x. 7 Slope	3545	4675	1130	small	small	normal	—	100	blocky	—	h.s. of face	—	—	—	—	small pushout unreported prior to June 4, 1948.
8	May 4, 1948	Blowout	4	4	34x, 7 Slope	3575	4700	1125	70	small	fault	face working	100	blocky	—	h.s. of face along fault	blasting	2	development	26	coal ejected 25 ft.; face working and blew out 15 min. after 2nd shot.
9	June 6, 1949	Pushout	4	4	50x, 73 Slope	4010	5010	1000	20	moderate	normal	bumping on h. s.	100	blocky	much as mined	h.s. of face	blasting	3	development	24	vigorous bumping after 3rd shot; h.s. coal fragmented and loose.
10	July 25, 1949	Blowout	4	4	60x, 76 Slope	4000	5080	1080	90	large	normal	face working	100	blocky	moderate	face	blasting	1	development	24	face advanced 12 ft. by blowout; gas cleared in 3 hours.
11	Aug. 4, 1949	Blowout	4	4	60x, 76 Slope	4000	5080	1080	150	large	normal	bumping on h. s.	100	blocky	intense	face	air pick	—	development	24	face advanced 30 ft. by blowout; face working with blast- in A.M. shift.
12	Sept. 7, 1949	Blowout	4	4	60x, 76 Slope	4000	5080	1080	100	small	normal	bumping	100	blocky	coarse	h.s. of face	blasting	4	development	24	h.s. of face advanced 8 ft. by blowout; coal not forcefully ejected.
13	Sept. 20, 1949	Blowout	4	4	60x, 76 Slope	4000	5080	1080	50	small	normal	h. s. tight	100	blocky	coarse	h.s. of face	blasting	3	development	24	coal just loosened, not ejected
14	Nov. 17, 1949	Blowout	4	4	62x, 76 Slope	3990	5100	1110	200	small	normal	bumping	100	blocky	coarse	h.s. of face	blasting	3	development	24	face working after A.M. shift; 2 bumps after 2nd shot.
15	Nov. 28, 1949	Blowout	4	4	49x, 73 Slope	4010	5090	1080	70	small	normal	h. s. tight	100	blocky	—	face	blasting	4	development	24	hiss of gas followed by bumping; one timber pushed out and car twisted.
16	Dec. 1, 1949	Pushout	4	4	62x, 76 Slope	3990	5100	1110	80	small	normal	face tight	100	blocky	coarse	face	blasting	5	development	24	bumping and gas after 4th shot.
17	Dec. 21, 1949	Blowout	4	4	62x, 76 Slope	3990	5100	1110	300	moderate	normal	none	100	blocky	moderate	face	blasting	5	development	24	coal ejected 35 ft.; advance holes showed no gas prior to blowout.
18	Dec. 19, 1950	Pushout	4	4	2x, 24 Slope	3690	4775	1085	10	small	fault	face tight	100	blocky	coarse	l.s. of face	blasting	1	development	24	low side shot induced pushout.
19	Apr. 4, 1951	Blowout	4	4	49x, 73 Slope	4010	5090	1080	250	moderate	normal	face working	100	blocky	intense	face	blasting	1	pillar splitting	25	face advanced 35 ft. up dip by blowout; beginning a room.
20	May 11, 1951	Pushout	4	4	9x, 24 Slope	3650	4800	1150	—	moderate	fault	bumping	100	blocky	one large block	face	hand pick	—	development	20	large block of coal (15'x15'x5') eased out; no loose coal; slight roof rumble.
21	Aug. 16, 1951	Pushout	4	4	30 Jig above 3 Gwy. East	3765	4775	1010	5	small	fault	none	100	blocky	coarse	h.s. corner of face	blasting	5	development	16	faulty ground; coal moderately sheared.
22	Aug. 17, 1951	Pushout	4	4	3 East Counter Gwy.	3755	4800	1045	10	small	fault	face working	100	blocky	coarse	h.s. of face	blasting	8	development	16	hole no. 8 at bottom on timbers taking wt. after occurrence.
23	Sept. 13, 1951	Pushout	4	4	face, 3 Counter Gwy.	3755	4810	1055	5	small	fault	bumping with gas	100	blocky	coarse	h.s. of face	blasting	5	development	17	cutting 4th side of pillar; last hole a top shot.
24	Nov. 1, 1951	Blowout	4	4	face, 24 Slope	3520	4980	1460	350	large	fault	none	100	blocky	intense	along fault at face	blasting	2	development	22	both shots in bottom bench; then violent hissing like a broken air line.
25	Feb. 11, 1952	Blowout	4	4	49x, 73 Slope 4 Pitch	4010	5090	1080	300	large	normal	face working; bumping	100	blocky	—	face	air pick	—	pillar splitting	25	two pillars extracted to southeast, with considerable roof movement.
26	Mar. 26, 1952	Pushout	4	4	1x, 30 Slope	3690	4775	1085	—	small	fault	face working	100	blocky	coarse	h.s. of face at fault	blasting	2	development	19	both holes on high side; 3 sets pushed out.

Table 3. - Statistics of blowout phenomena in the Upper Marsh Seam, Canmore, Alberta

1	Mar. 20, 1951	Slough	Upper Marsh	3	face, East Gwy.	4700	5375	676	60	small	normal	h. s. rib soft	100	friable, sheared	unchanged	h.s. rib	blasting	5	development	23	coal not ejected; much sloughing noted; last shot low side bottom.
2	May 3, 1951	Slough	Upper Marsh	3	face, East Gwy.	4700	5475	775	6	small	normal	coal soft	100	friable, sheared	unchanged	h.s. rib	blasting	3	development	25	no indication of coal being thrown or pushed.
3	Aug. 9, 1951	Slough	Upper Marsh	3	face, East Gwy.	4700	5800	1100	—	small	normal	h. s. coal very soft	100	friable, sheared	unchanged	h.s. rib	blasting	2	development	27	much sloughing of h.s. rib.
4	Aug. 21, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5810	1100	2	small	normal	face working	100	friable, sheared	unchanged	h.s. rib	air pick	—	development	27	coal not ejected, just loosened; roof rumbled.
5	Oct. 5, 1951	Slough	Upper Marsh	3	face, East Gwy.	4710	5860	1150	40	small	normal	face working	100	friable, sheared	unchanged	h.s. rib at face	blasting	3	development	26	coal pushed and sloughed from h.s. rib; h.s. rib very soft.
6	Oct. 17, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5860	1150	35	small	normal	roof rumble	100	friable, sheared	unchanged	h.s. rib and face	blasting	2	development	26	2 sets pushed out; both shots on l.s.
7	Nov. 9, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5860	1150	40	small	normal	none	100	friable, sheared	unchanged	h.s. rib and face	blasting	1	development	26	coal loosened and pushed out; ripping noises in face.
8	Nov. 16, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5860	1150	50	small	normal	none	100	friable, sheared	unchanged	h.s. rib and face	blasting	2	development	27	2 shots in middle; ripping noises in face.
9	Nov. 21, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5860	1150	50	small	normal	face bumping	100	friable, sheared	unchanged	h.s. rib and face	blasting	3	development	27	coal just loosened; holes in middle on low side.
10	Nov. 26, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5860	1150	50	small	normal	face bumping	100	friable, sheared	unchanged	h.s. rib and face	blasting	2	development	27	coal just loosened; both holes on low side.
11	Nov. 30, 1951	Pushout	Upper Marsh	3	face, East Gwy.	4710	5860	1150	50	small	normal	slighting bumping	100	friable, sheared	unchanged	h.s. rib and face	air pick	—	development	27	loose coal eased out, not ejected; test holes showed no gas.
12	May 19, 1952	Pushout	Upper Marsh	3	face, East Gwy.	4710	5760	1050	50	small	normal	bumping	100	friable, sheared	unchanged	h.s. rib and face	blasting	2	development	19	coal loosened, not thrown.

APPENDIX

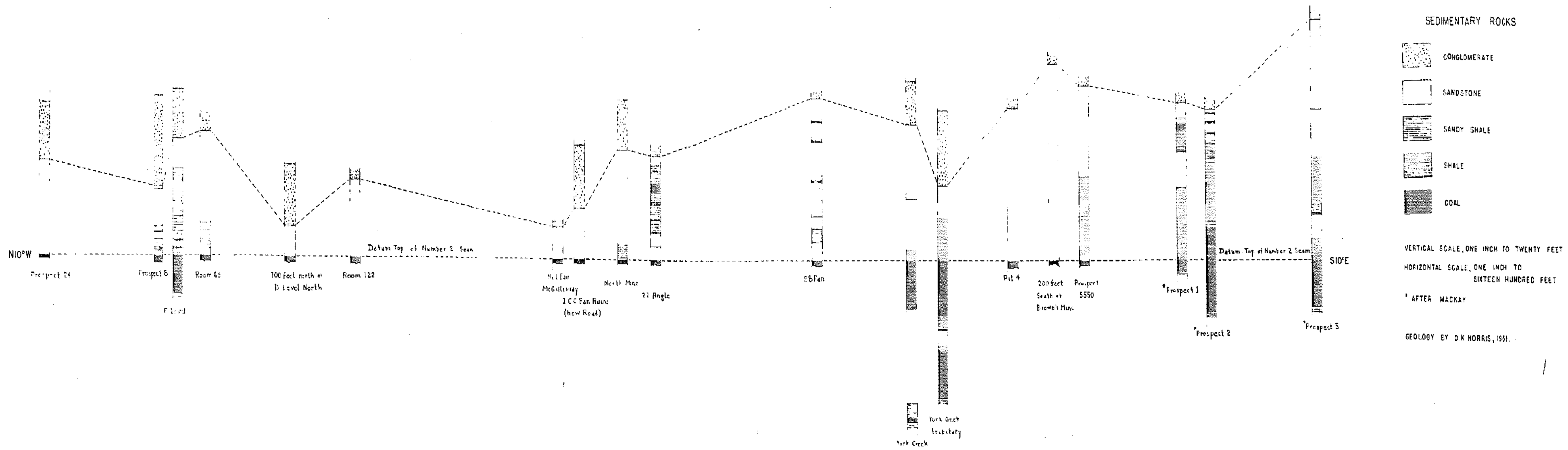
Table 1. - Stratigraphic Units of the Coal Fields of the Southern Canadian Cordillera

ERA	PERIOD or EPOCH	FORMATION or GROUP	LITHOLOGY	THICKNESS feet			
				FERNIE	COLEMAN	CANMORE	NORDEGG
Cenozoic	Paleocene	Paskapoo	non-marine, arkosic sandstones, mudstones, and shales	—	—	—	1900 (1a)
Mesozoic	Upper Cretaceous	Belly River(K_{BR})	non-marine sandstone and shale; coal in upper part	—	4000(2a)	—	—
		Wapiabi(K_{WP})	marine sandstone and shale	—	2000	—	—
		Bighorn(K_{BH})	marine sandy shale and sandstone	—	50-12[illegible]	—	—
		Blackstone(K_{BK})	marine sandstone and shale	—	1100-1400	—	—
	Upper Cretaceous?	Crowsnest(K_{CN})	volcanic agglomerate and tuff	—	400-1[illegible]50	—	—
	Lower Cretaceous	Blairmore(K_{BL})	non-marine sandstone, shale and conglomerate	Elk River cgl. 6000 (3a)	2500	—	Luscar 1700(4a)
		Blairmore(K_{BL})	chert and quartzite pebble conglomerate		10-35	— —	Cadomin 20-40(1b)
		Unconformity					
		Kootenay(K_K)	non-marine sandstone, carbonaceous shale and coal	4000 (3b)	450-565 (3c)	3400 (5a)	Nikanassin 350(4b)
	Jurassic	Fernie(J_F)	marine shale and sandstone, basal conglomerate	—	900 (3d)	10[illegible]5 (5b)	—
		Disconformity?					
	Triassic	Spray River(₱)	limestone, dolomite, quartzite and siltstone	—	undifferentiated 341 (3e)	600 (5c)	—
		Disconformity?					
Paleozoic	Pennsylvanian	Rocky Mountain(₱)	gritty dolomite and chert	—		625 (5d)	—
		Unconformity?					
	Mississippian	Rundle(C_R)	limestone, dolomite and shale	—	4988-1675 (3f)	2400 (6a)	—
		Banff(C_B)	limestone and shale	—	1070 (3g)	1400 (6b)	—
	Mississippian or Devonian	Exshaw(D_{EX})	marine shale	—	45 (3h)	34 (7a)	—
	Upper Devonian	Palliser(D_P)	limestone	—	undifferentiated 2600	800-950 (7b)	—
		Fairholme(D_F)	dolomite	—		1100-1450 (7c)	—
		Disconformity?					
	Devonian?	Ghost River(D_{GR})	gritty dolomite	—	—	150-170 (8)	—
		Unconformity					
	Cambrian	Middle Cambrian(Є)	limestone	—	—	—	—

FIGURE 2

THE KOOTENAY - BLAIRMORE UNCONFORMITY

COLEMAN, ALBERTA



VERTICAL SCALE, ONE INCH TO TWENTY FEET
HORIZONTAL SCALE, ONE INCH TO SIXTEEN HUNDRED FEET

* AFTER MACKAY

GEOLOGY BY D.K. NORRIS, 1951.

FIGURE 5

KOOTENAY SECTION ON YORK CREEK

TWO MILES SOUTH OF COLEMAN, ALBERTA

SCALE, ONE INCH TO TWENTY FEET

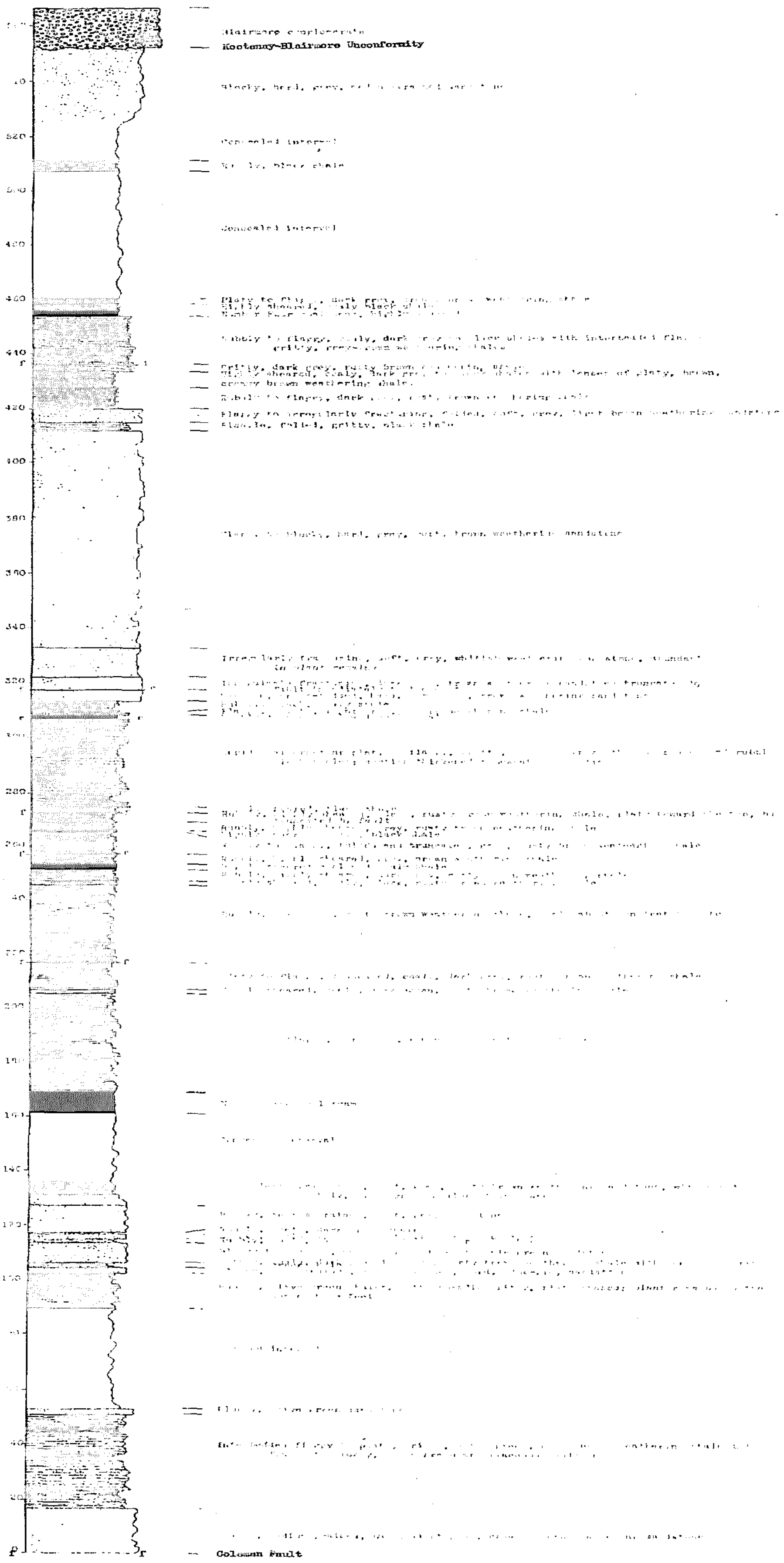


FIGURE 4

STRUCTURE MAP OF THE NUMBER 3 MINE, ELK RIVER COLLIERIES, BRITISH COLUMBIA

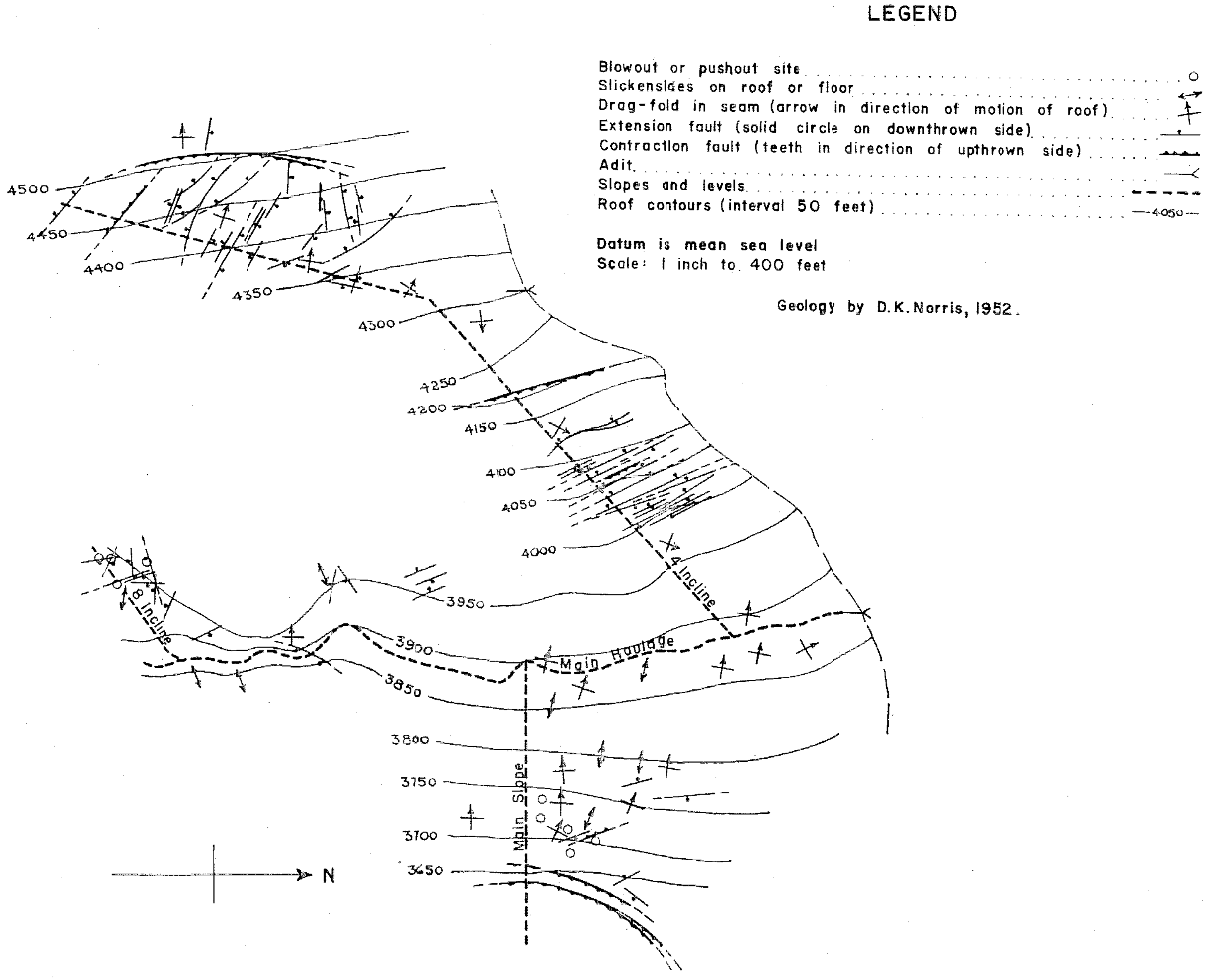


FIGURE 5

STRUCTURE – SECTION OF THE CROWSNEST COAL AREA, ALBERTA

Scale, 1/62,500

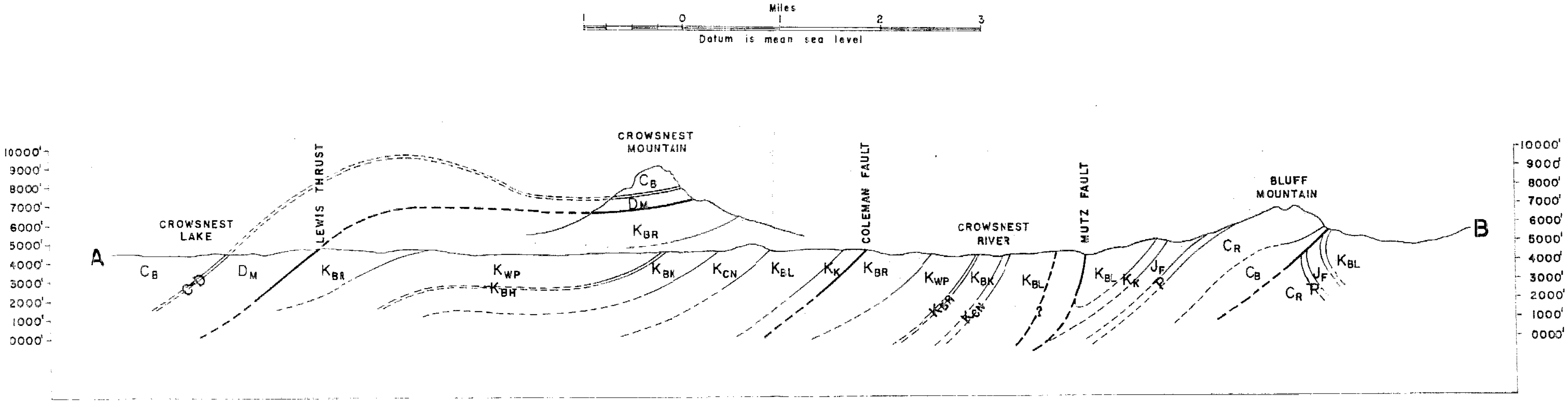


FIGURE 6

GEOLOGIC MAP OF THE KOOTENAY FORMATION

ON THE PROPERTY OF COLEMAN COLLIERIES LIMITED, COLEMAN, ALBERTA

Scale, 1 inch to 1600 feet

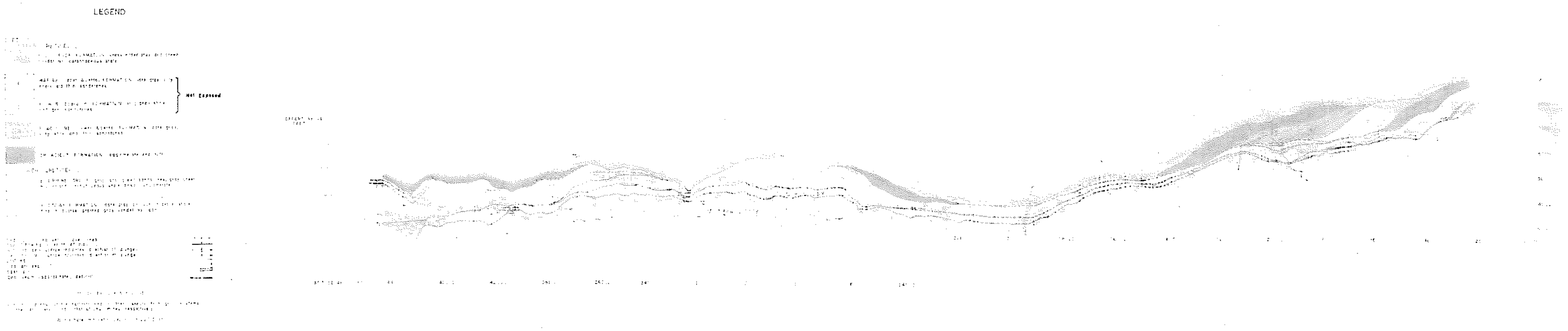


FIGURE 8

STRUCTURE MAP OF THE MAP OF THE NUMBER 2 SEAM INTERNATIONAL MINE, COLEMAN, ALBERTA

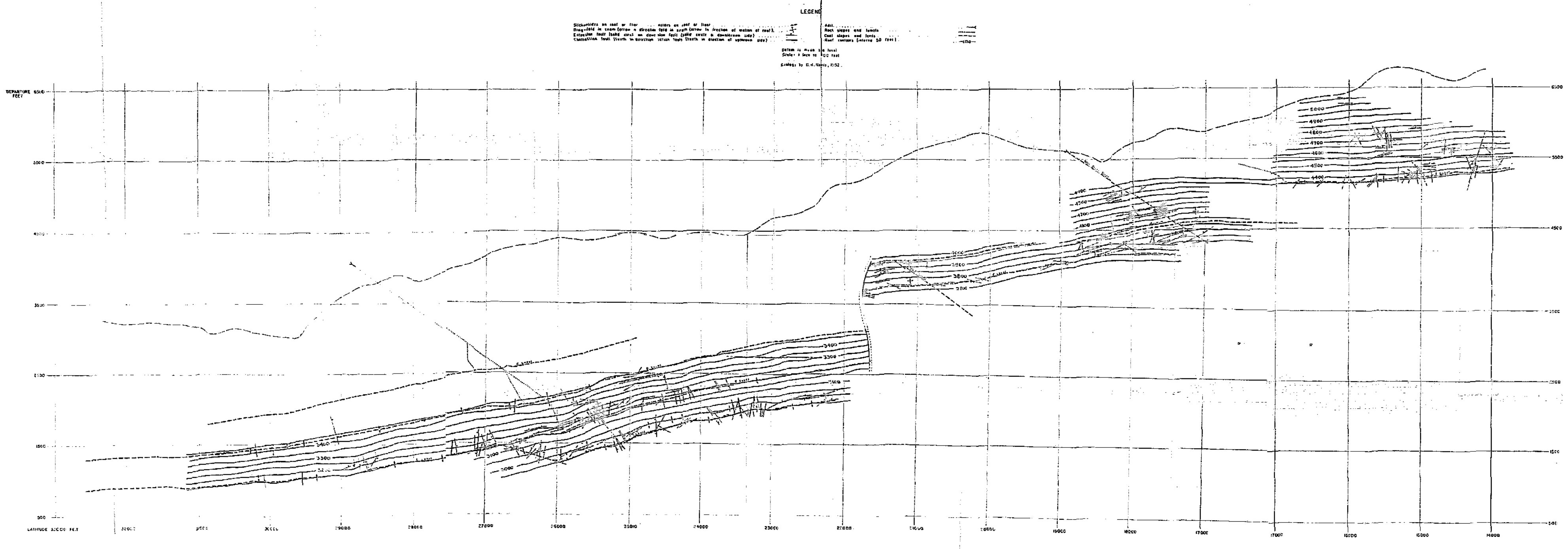


FIGURE 7

STRUCTURE MAP OF THE NUMBER 2 SEAM, MC GILLIVRAY MINE, COLEMAN, ALBERTA

LEGEND

Slickensides on roof or floor		Anticlinal axis	
Drag-fold in seam (arrow in direction of motion of roof)		Synclinal axis	
Extension fault (solid circle on downthrown side)		Adit	
Contraction fault (teeth in direction of upthrown side)		Stopes and levels	
Fault, type unknown		Roof contours (interval 50 feet)	—4150—

Datum is mean sea level
Scale 1 inch to 400 feet

Geology by D. K. Norris, 1952

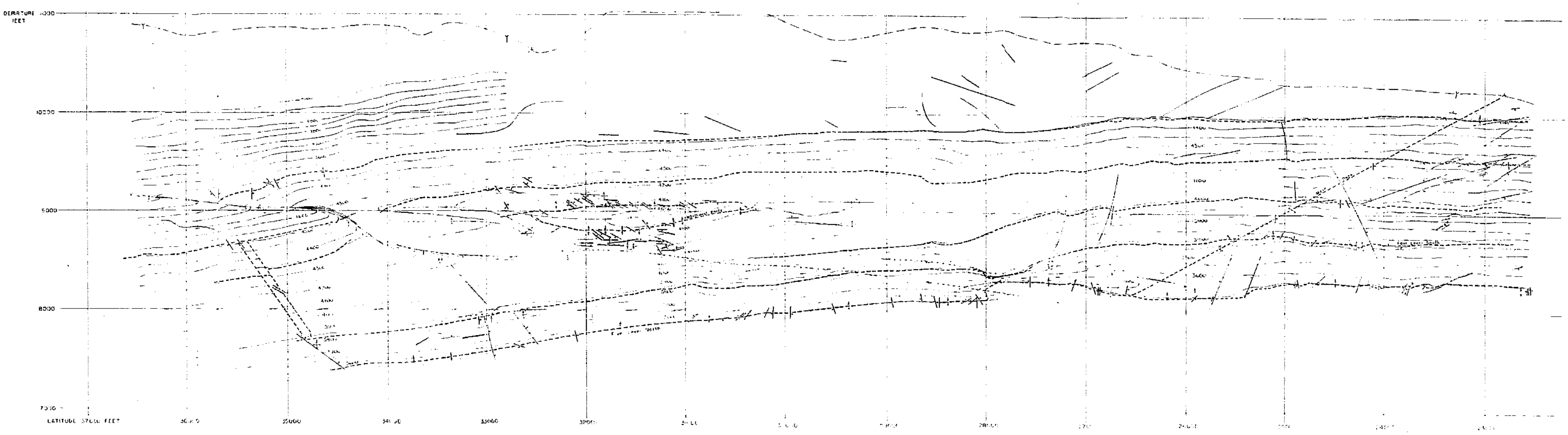


FIGURE 10

STRUCTURE MAP OF A SEGMENT OF THE NUMBER 2 SEAM

MC GILLIVRAY MINE, COLEMAN ALBERTA

SCALE, 1 INCH TO 100 FEET

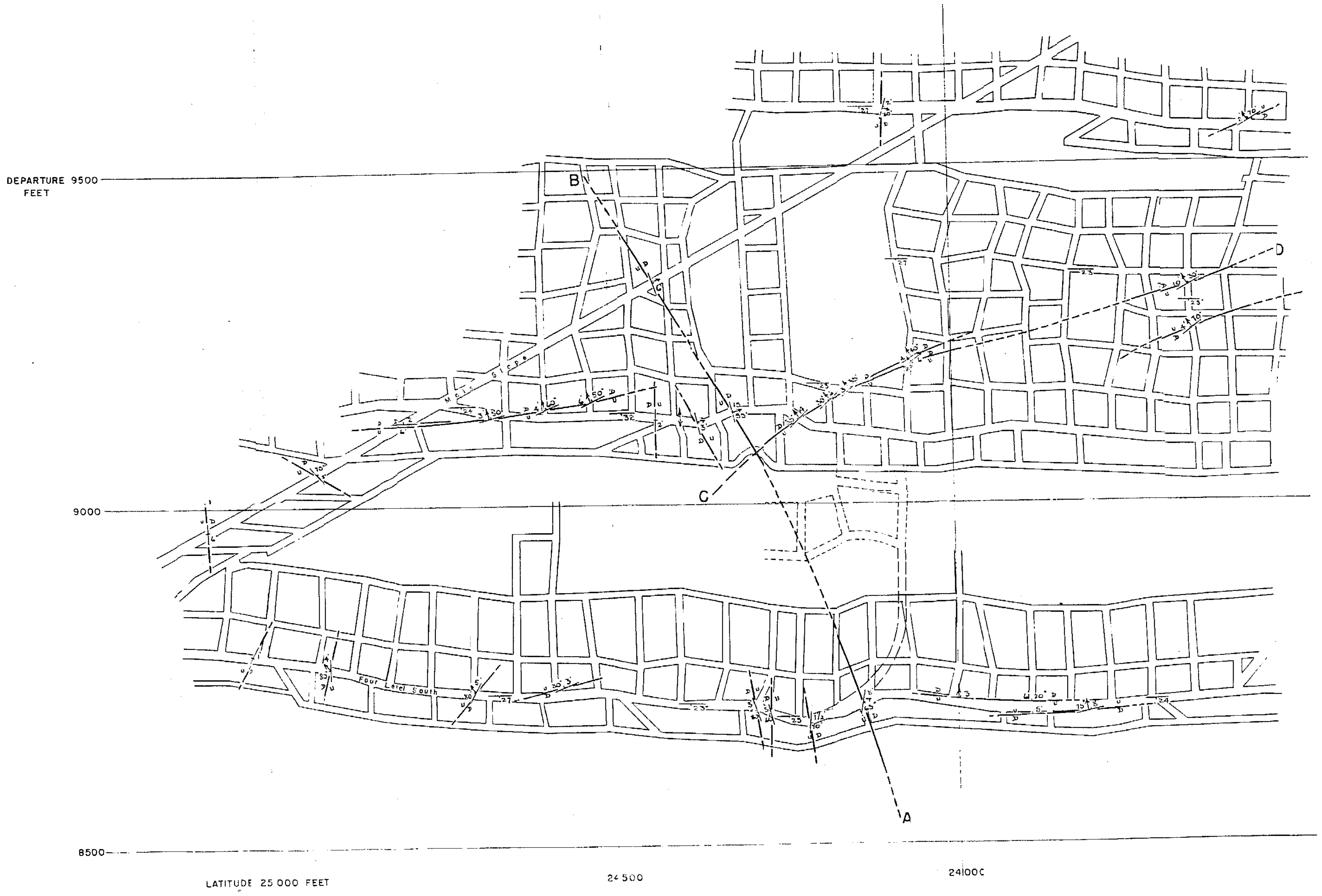


FIGURE II

STRUCTURE MAP OF A SEGMENT OF THE NUMBER 4 SEAM

MC GILLIVRAY MINE, COLEMAN ALBERTA

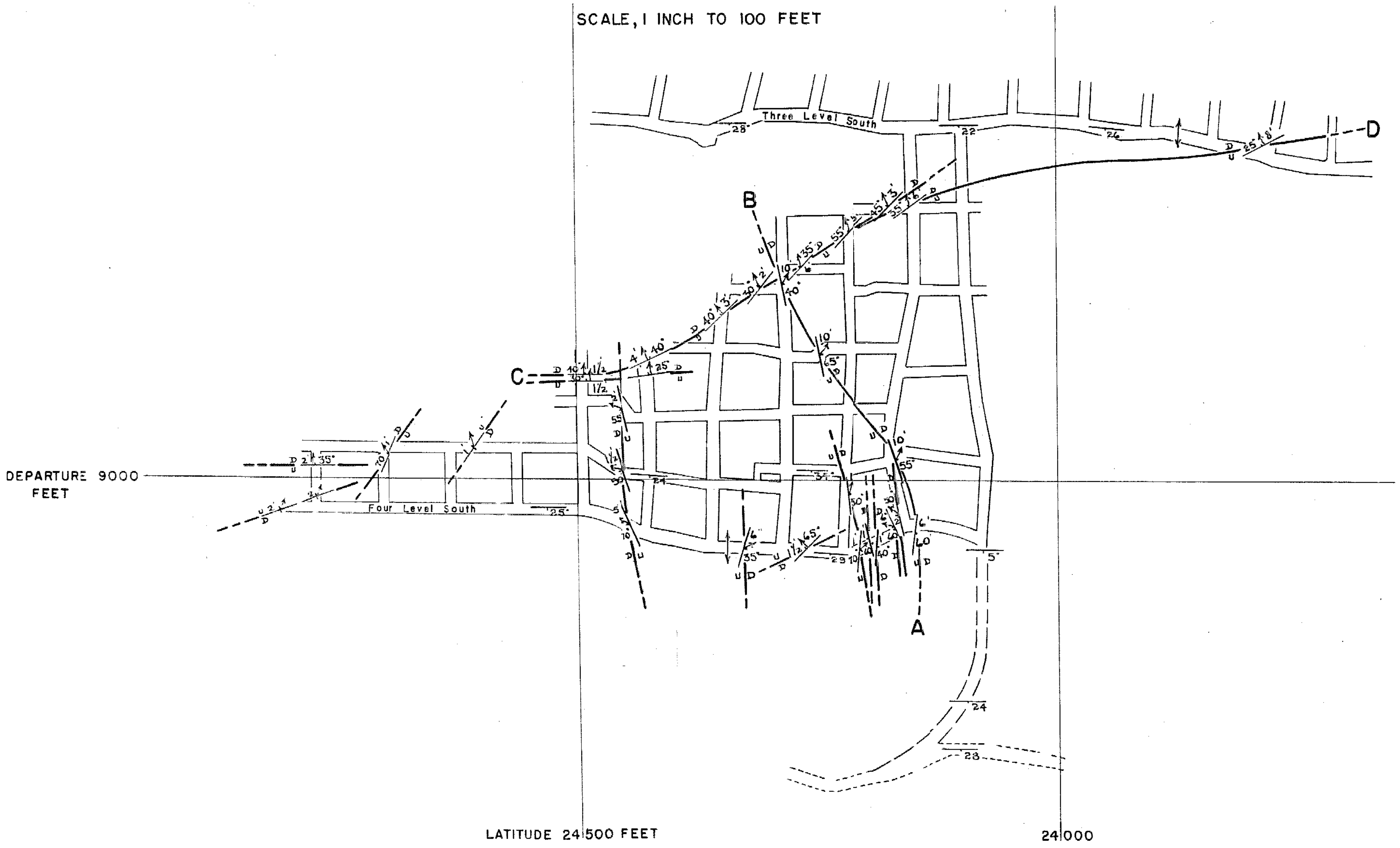


FIGURE 12

STRUCTURE – SECTION OF THE CASCADE COAL AREA, ALBERTA

Scale, 1/62,500

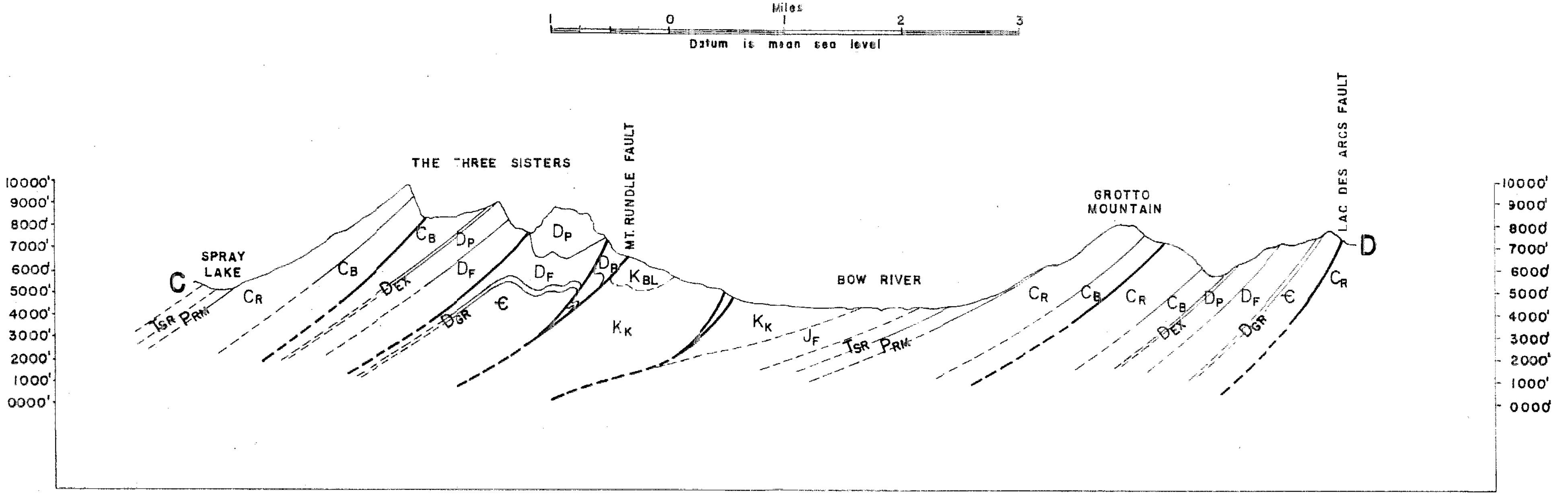


FIGURE 13

STRUCTURE MAP OF THE NUMBER 4 MINE, CANMORE, ALBERTA