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Aspects of Coal Geology, Northwest Colorado Plateau
Some Geologic Aspects of Coal Accumulation, Alteration, and Mining
In Western North America: A Symposium

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Metamorphic Patterns in Western Cretaceous Coals and Their Geoenvironmental Implications

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ABSTRACT.—In late Mesozoic time a long geosynclinal trough was formed, connecting the Gulf of Mexico with the Arctic Ocean. Thick peat deposits formed in many areas along the coastal plains as the geosynclinal basin filled with debris from the great ranges on the west. Individual peat deposits formed behind regressive beaches, or between meandering delta channel levees. Mostly the peat bogs occupied areas of less than 100 square miles; few were larger.

The main purpose of this paper is to suggest that, within limits, the volatile contents of bituminous and higher rank coals reflect the paleogeothermal trends that have affected them; and to present field evidence. In some areas there are downward decreases in volatile content related to stratigraphic position; in others there is little, if any, such downward decrease of volatile content. In Canada, there are strong lateral differences of rank that seem unrelated to the intensity of deformation. The evidence is particularly convincing in western Alberta and southeastern British Columbia.

Washed coal from many gassy mines continues to emit methane, suggesting solid solution. Demethanation is probably an equilibrium-type reaction that is motivated by rising temperatures, and restrained by the confinement of the methane in the coal-bearing strata. The volatile content of pure coal may well represent a relict maximum thermometer, recording within limits the maximum temperature of the coal. Canadian data suggest the present rank of the coal was achieved prior to thrusting, and that neither rock nor coal temperatures were greatly increased by friction heating during thrusting.

GENERAL STATEMENT

The writer first became interested in the metamorphism of coal in the 1940's, while working among the small intrusions of the West Elk Mountains in Colorado. The rapid lateral gradations of volatile content, and their patterns, are in marked contrast with the ideas advanced by Stadnichenko and Dapples in the preceding decade. Metamorphic halos around some of the West Elk intrusives were limited to a few hundred feet from the contacts.

Subsequent studies in coal regions of Utah and western Canada revealed that field relations do not support the hypothesis of stress, or gravity loading, metamorphism. In Canada the correlation is essentially negative.

The publication of D. W. van Krevelen's book, *Coal Science* (1957), and Irving Breger's results from differential thermal analysis studies on coal (1951) both provided laboratory evidence of the role of heat in the process of coalification. The writer has been collecting field evidence of the effects of heat in the process of coalification. Some of the results of this research are presented here.

CANADIAN STRATIGRAPHY AND PALEOENVIRONMENT

The reader will better understand the implications of some of the following discussions if he is aware of the time and space relations of the Cretaceous coal fields in Canada to those in the United States.

In Canada the areas containing distinctly bituminous coal of metallurgical quality are limited to the foothills and thrust belt of western Alberta and adjoining parts of British Columbia. The oldest of these coal-bearing units is known as the Kootenay Formation; it is coal-bearing from the U.S. border northward for about 200 miles. Beyond that point contemporary sediments are marine.

The Kootenay overlies the soft Jurassic marine Fernie Shale and, in ascending order, generally consists of four identifiable units: the basal littoral sandstone, known as the Moose Mountain Sandstone, overlain by the 200- to 350-foot Adanac Shale Member which contains most of the coal, the generally littoral Hillcrest Sandstone (100 to 300 feet), and the upper part of the formation, mostly channel sandstones and finer sediments, known as the Mutz Member.

The thickest part of the Kootenay Formation lies along its western edge, where it is up to 2,000 feet thick, and locally contains as many as 15 coal beds in an interval of 1,800 feet. The Mutz Member is not present east of the Lewis Fault, in the Crowsnest Pass.

The Kootenay was apparently bevelled by wave action from the east, and a layer of clean sand and chert pebbles was deposited. This is variously known as the Cadomin Conglomerate, or the basal conglomerate of the Blairmore Formation. The Cadomin corresponds roughly in age to the Kootenai sandstones of western Montana, and possibly the Dakota of eastern Utah.

The second episode of peat deposition was in the post-Cadomin Luscar Formation whose type locality is in the famous Cadomin-Luscar district west of Edmonton. Spectacular thicknesses of coal are being mined at Cadomin, Luscar, and Mountain Park. The Luscar is coal-bearing from the vicinity of the Clearwater River, northerly to the Smoky River and the Kakwa River. Northerly, from Grande Prairie in Alberta, these strata grade into marine formations, but westerly around Ft. St. John, British Columbia, there are deltaic combinations known as the Moose-bar and Gething Formations which contain many lenticular beds of coal.

Younger Cretaceous formations in the plains region of Alberta contain lenticular beds of coal; the ranks range from high-volatile B to lignite. The westernmost of these deposits are intensely folded, but they are still very high-volatile to sub-bituminous in rank.

Some high-volatile B coals are reported at the base of the coal-bearing section near Lethbridge; they are undisturbed and flat-lying.

TECTONICS

Near the close of the Cretaceous there was renewed tectonic activity. Strong uplift occurred along a line running from about Cedar City, Utah, northward through eastern Idaho and around Missoula, Montana; it continued along the present Rocky Mountain trench and into the Yukon. On the eastern flanks of these mountains is a line of overthrusting that extends from the Wasatch Mountains northward.

The Hubbert-Rubey hypothesis is the only mechanism that seems to explain how such massive gliding-thrusting could be accomplished without greater crushing, and without producing obvious high temperature friction effects around the planes of movement. Evidence of elevated temperatures in the glide planes and rubble zones of these great thrusts is notably lacking. There are few, if any, recognized high temperature minerals.

In the western states, from New Mexico to Montana, the old basin was broken by the emergence of a number of mountain ranges, and the coal-bearing formations were locally tilted into steeply dipping structures. Accompanying intrusions have locally affected the rank of the coal in the vicinities of Grand Mesa, Raton Mesa, and west of Steamboat Springs in Colorado.

GEOLOGIC ENVIRONMENT VERSUS METAMORPHIC TRENDS

These discussions deal only with the processes and related evidence for metamorphism of bituminous coal into (or towards) anthracitic rank. In western Canada, these coals are found mostly in the thrust belt, and the differences in volatile contents present some challenges to the older concepts.

In areas where thicker sections of the Kootenay Formation have been preserved there are some surprisingly consistent upward-increasing gradients of volatile content—increases ranging from 0.6% to 0.9% of volatile per 100 feet of stratigraphic interval. Because of these, and because many of the older published assays are seldom assigned to a bed, one must exercise utmost caution in attempting to interpret regional differences of rank. With this in mind, the writer has made comparisons of analysis only of coals whose stratigraphic position is specified and correlative, or for which he knows the sampled horizon. In the Crowsnest Pass area lateral comparisons are made of coals within the lower 500 feet of Kootenay, above the basal Moose Mountain Sandstone. These trends are believed to be significant in respect to the geothermal maxima of past time.

In the western part of the United States the metamorphism of most of the higher-rank coals is directly attributable to heat from intrusions and the effects are limited to the vicinity of those intrusions.

Elk River Region, British Columbia

The Elk River coal fields are in the southeastern corner of British Columbia between the Elk River and the Continental Divide. The field is 70 miles long and 5 to 20 miles wide. It is broken into three distinct smaller units which are separated by minor thrust faults in which the harder Paleozoic strata are arched to form mountains. The hard Moose Mountain Sandstone has helped to preserve the coal-bearing formations. The southernmost district is the Fernie Basin which includes the old coal mining towns of Morrissey, Fernie, Sparwood and Michel on the west side, and Corbin on the east side about 18 miles from Fernie.

On the west side of the Fernie Basin the coal-bearing Kootenay Formation is nearly 2,000 feet thick, with about 1,800 feet between the upper and lower coal beds. Interestingly, the volatile content increases upward from 19% in the lowest beds to 34% in the uppermost bed, or an average increase of 0.83% per 100 feet of stratigraphic interval (note that all analytical data are cited for pure, or MAF basis). The lowest coals are in the 300-foot ± Adanac Shale Member, and the intricately intertonguing system of coal beds is known as the Balmer at Sparwood, where it is 50 to 60 feet thick, and as the Number 1 at Fernie. The term Balmer will be used to correlate other deposits in the region.

For the most part, the beds on the west side plunge steeply into a broad syncline that is broken by some tear-faulting and secondary folds. On the east side the Kootenay beds are complexly folded and contorted.

In the Upper Elk River district some 50 to 60 miles north of Sparwood, most of the Kootenay section is preserved in a west-dipping monoclinal struc-

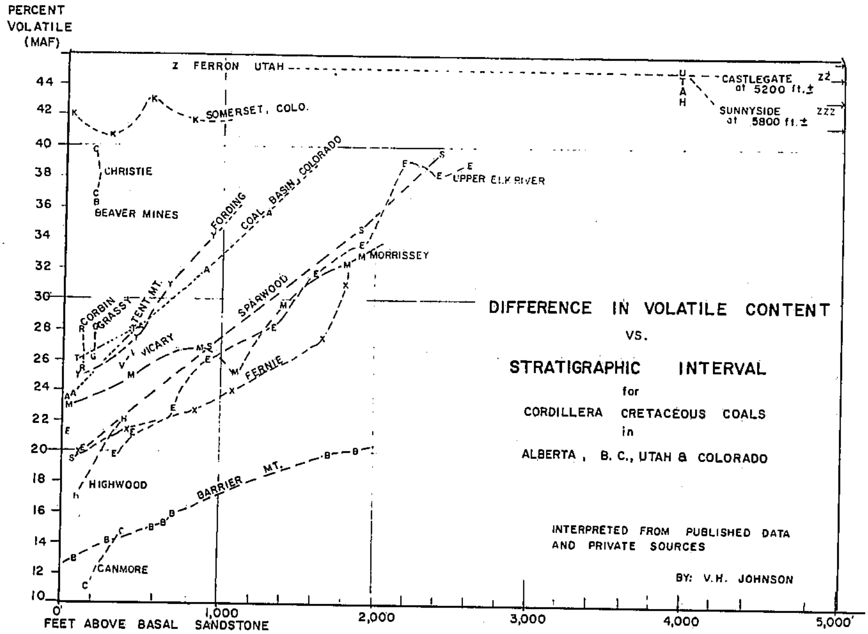


FIGURE 1.—Reprint from Johnson, 1972, p. 4.

ture. This has been explored by Scurry Oil Company and Morrison Knudsen, who report that the Balmer equivalent bed has 19% volatile, and the uppermost bed has around 38% volatile; the stratigraphic interval is reported at 2,500 feet. The gradient is thus 0.76% upward increase in volatile per 100 feet of strata.

On Fording River the available data indicate that only the lower 1,000 feet of Kootenay strata remain. The coals in the Adanac Member have 25% volatile matter as compared with 34% in the top bed. The gradient is thus 0.9% per 100 feet of strata.

Large reserves of coal have been found in steeply folded Kootenay beds on the Fording River. This area is about 40 miles northeast of Sparwood, and on the east side of the Fording Mountain-Loop Ridge Thrust, on which the displacement diminishes southward.

At Tent Mountain, only 18 miles southeast of Sparwood (east of Fernie), the Balmer equivalent coal has a volatile content of 26%, and a coal (4-pit north) about 200 to 300 feet higher has 27% to 28% volatile. The main deposit consists of a 350-foot (vertical) pod of coal in a pocket at the crest of the mountain; this coal is in an asymmetrical synclinal pocket that is overlain and underlain by thrust faults which ruptured the enclosing Moose Mountain Sandstone. The road to the top mine crosses three thrust faults enroute. Despite this very intense mixture of faulting and folding, the Balmer equivalent coal is 5% to 7% higher in volatile content than that at Sparwood. (Note the intense shearing in the accompanying photos.)

Coal Mountain (at Corbin, 3 miles southeast of Tent Mountain) is only one mile wide, but the Moose Mountain Sandstone is folded into at least three deep, narrow synclines. The enclosed Balmer Coal is plastically remobilized and sheared; thicknesses range from 3 feet to more than 300 feet, and the roof rocks are not structurally conformable with the floor rocks. The volatile content is the same as that for the same bed on Tent Mountain, i.e., 26%±.

Both Coal Mountain and Tent Mountain are on the upper plate of the Lewis Thrust. Paleozoic carbonate rocks on the east side are flexed sharply upward to form the Continental Divide, only 3 miles east of Corbin.

A number of small faulted, and steeply tilted, blocks of Kootenay Formation are exposed near Cabin Creek in the Flathead Valley; several thick coal beds are reported but the correlation with standard sections is very vague. Published data show volatile contents of 28% and 30.5% for two beds that are stratigraphically somewhat more than 100 feet apart. Metamorphic forces (i.e., temperatures) would have to have been much lower than in western Fernie Basin if these are Balmer equivalent coals. If the sampled beds were higher in the section, one could not be sure how much of the indicated paleothermal gradients was lateral and how much was vertical.

It is significant, however, that the highly deformed coals at Tent Mountain and Coal Mountain are so much higher in volatile content than the Balmer Coal at Fernie and Sparwood.

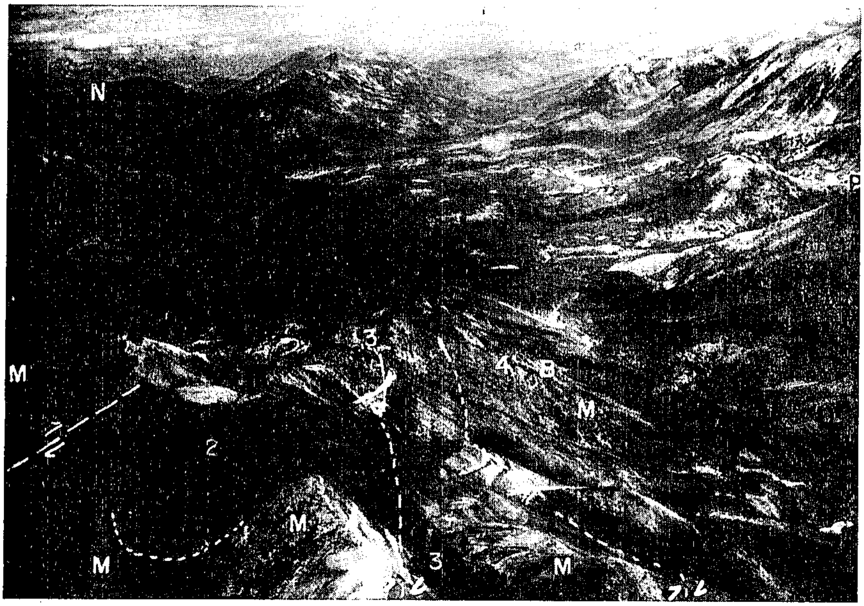
Crowsnest Pass Region

At Coleman, Alberta, the Coleman Thrust brings the coal-bearing lower part of the Kootenay Formation to the surface; this is about 11 miles east of Tent Mountain and 8 miles east of the trace of the Lewis Thrust. The Coleman Thrust has produced about 5,000 feet of stratigraphic displacement, and probably as much as 10 miles of total displacement. Feeder dikes of alkalic lava (Blairmoreite) were encountered in underground mining at Coleman. These fractures transmitted enough lava to produce nearly 1,000 feet of pillow lavas and tuffaceous sediment, yet the thermal effects were confined to a few feet on either side of the dike. The volcanic rocks are about 1,000 feet above the coal, and are known as the Crowsnest Volcanics.

The volatile content of the Vicary Coal (in the lower Hillcrest Sandstone) is 26%–27%, which is very little higher than at Tent Mountain, Corbin, or Fording River. Deformation of the coal is mild to intensely sheared, with no apparent difference of effect on the volatile content of the coal.

At Grassy Mountain, 3 miles east of the Coleman Fault trace, the coals in the Adanac Shale have been mined from a ruptured anticline. South and east of the Grassy mine, the Turtle Mountain Fault is exposed near Hillcrest. Three thousand-plus feet of Paleozoic carbonate rocks overrode the Fernie Formation and nearly vertical coal beds at the Frank mine. Analyses of samples from the Grassy and Frank mines show 28% and 32% volatile matter, respectively. (See photo of Frank slide, Plate 6.)

Coal from the Bellevue mine, just east of Frank, has about the same composition as at Frank. The Beaver Mines operation, 10 to 12 miles south of Bellevue, has produced coal from the Adanac Member which contained 36% volatile matter, and the nearby Christie mine produced coal from the same horizons having 36% to 44% volatile. Both of these are in the footwall plate of the Lewis Thrust fault, and not very far below it. The Kootenay Formation at Beaver mines forms the roof plate of the Livingstone thrust.



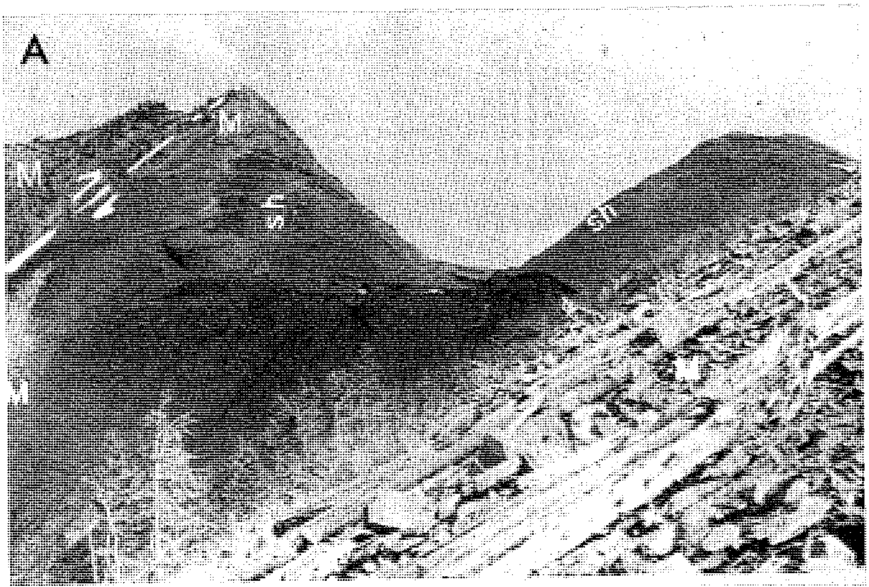
EXPLANATION OF PLATE 1

PLATE 1.—An oblique view of Tent Mountain (1961). This air view, looking northwest, shows Tent Mountain in the foreground and its relation to Natal Ridge, "N," (at the north end of Fernie Basin) near Sparwood, and Fording Valley, "F," (upper center) behind the horizon and separated from Natal Ridge by the limestone thrust block. The "P" at the upper right marks the Crowsnest Pass, where Paleozoic rocks form the upper plate of the Lewis Thrust and the Continental Divide.

On Tent Mountain the numerous slices of Moose Mountain Sandstone are marked "M"; the Moose Mountain Sandstone and coal are repeated by folding and thrusting. The coals at "2," "3," and "B" are all the same bed, and are Balmer equivalents. The dash-lines show the top of the Moose Mountain Sandstone under "2" pit and the traces of thrust faults.

No. 4 coal is marked by the line of prospect pits beyond "4" to the end of the ridge. This coal is above the Hillcrest Sandstone and is in a southward plunging syncline whose western limb is truncated by the lowest thrust indicated on the lower margin. The Hillcrest Sandstone is visible in the picture between "4" and "B."

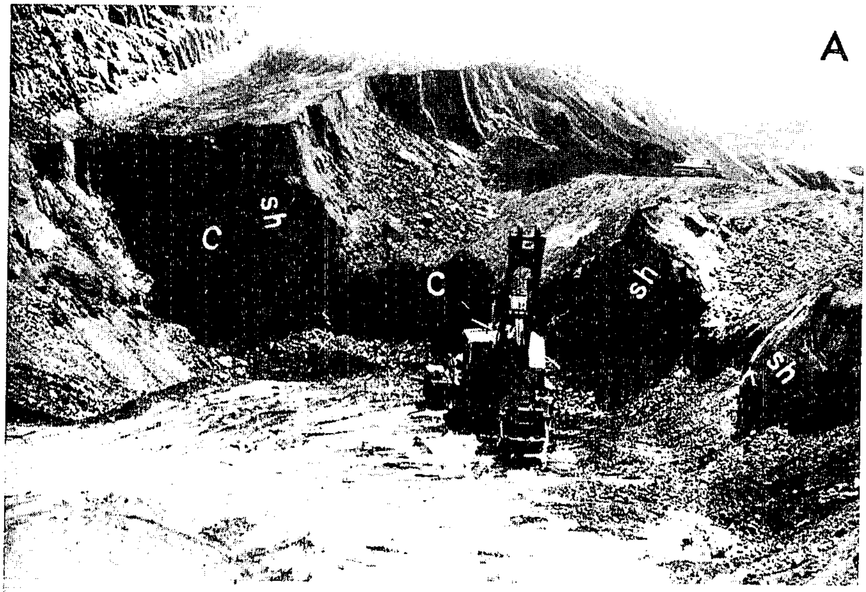
The coal in 3-mine is in a thrust; it is overlain and underlain by Moose Mountain Sandstone.

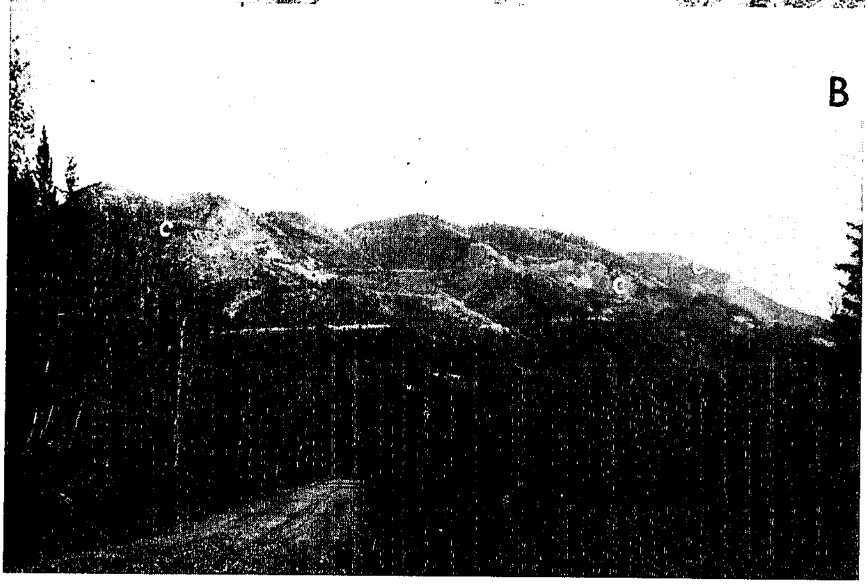


EXPLANATION OF PLATE 2

FIG. A.—A closer view (1966) of the south end of No. 2 pit of Tent Mountain. The Moose Mountain Sandstone is repeated by thrusting on the left, and folded beneath the coal. A 25-foot ± shale parting near the bottom of the coal is marked "sh." This is medium-volatile coal.

FIG. B.—This shows intensely folded coal in No. 2 pit. The shovel is faintly visible in Plate 2A.

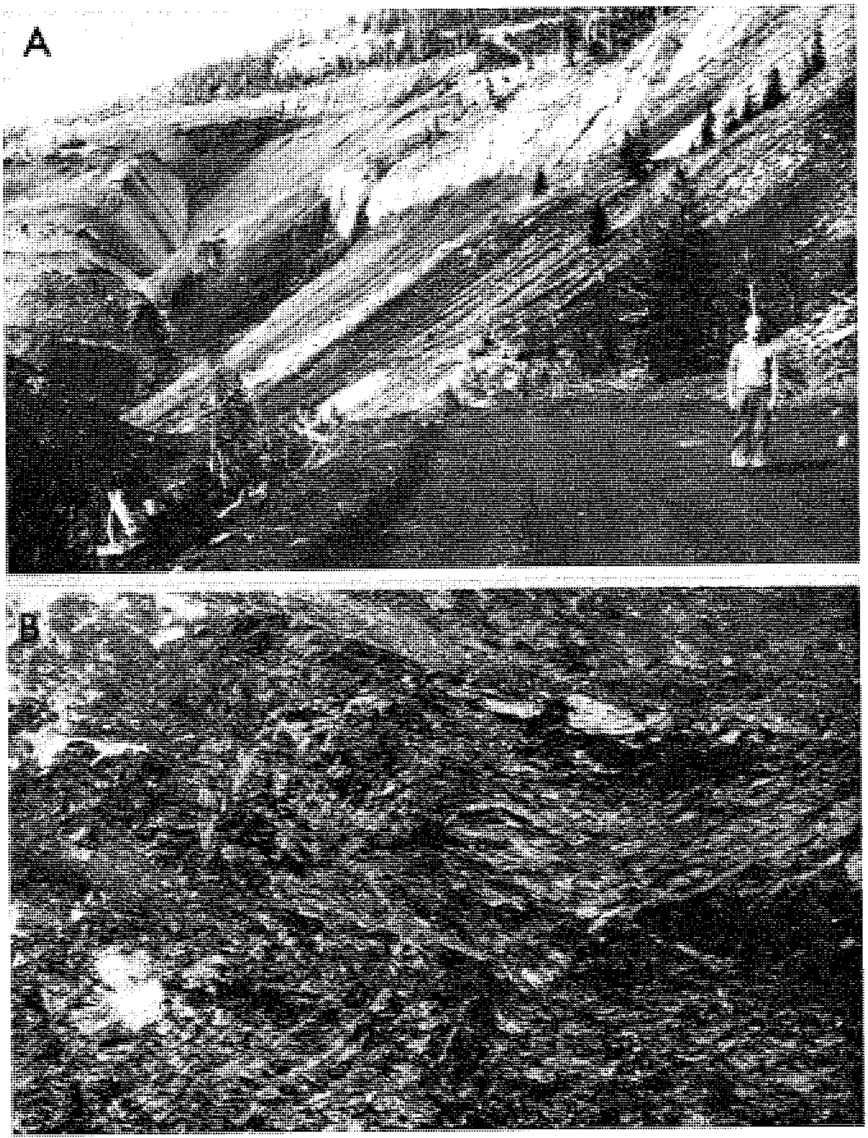




EXPLANATION OF PLATE 3

FIG. A.—Drag-folding of the shale parting and the 20-foot ± lower bench of coal near the synclinal axis at the north end of the same pit. Scale is indicated by the 4-yard shovel. The Moose Mountain Sandstone forms the steep left wall of the pit at the shovel level.

FIG. B.—View of Coal Mountain from the northwest. Coal outcrops in three separate synclinal structures are marked "c." The middle "c" marks the old open pit mine known as No. 3, or the "big show." Plates 4A and 4B are photos taken in this pit.

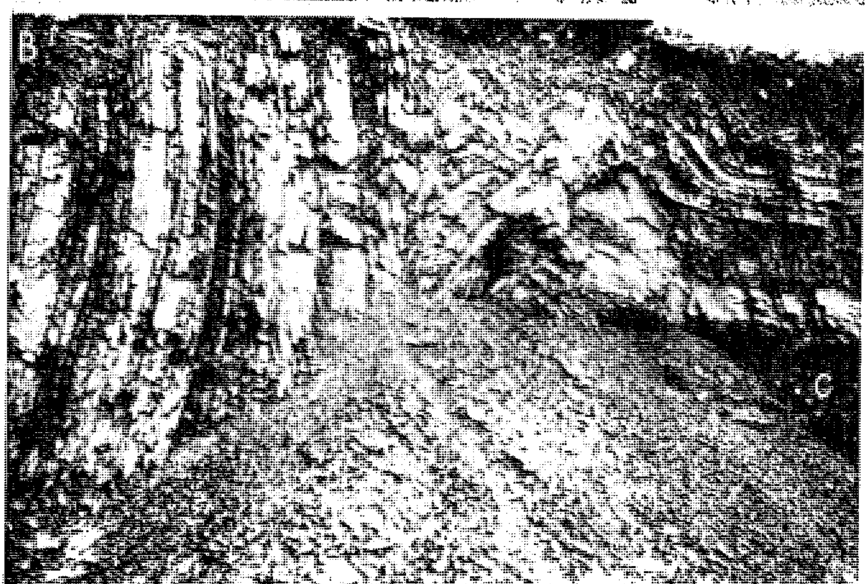


EXPLANATION OF PLATE 4

FIG. A.—View of the "big show" pit from the south end, before renewed mining activity. The coal in the foreground is in a northerly plunging syncline. The light-colored sandstone (upper right) is the Moose Mountain Sandstone on the east limb of the syncline, where it forms a thrust at the ruptured anticline. The roof is visible at the right, and at upper center where the dip is reversed.

Early mining was done with steam shovels and steam locomotive. Stripping was done with fire hoses.

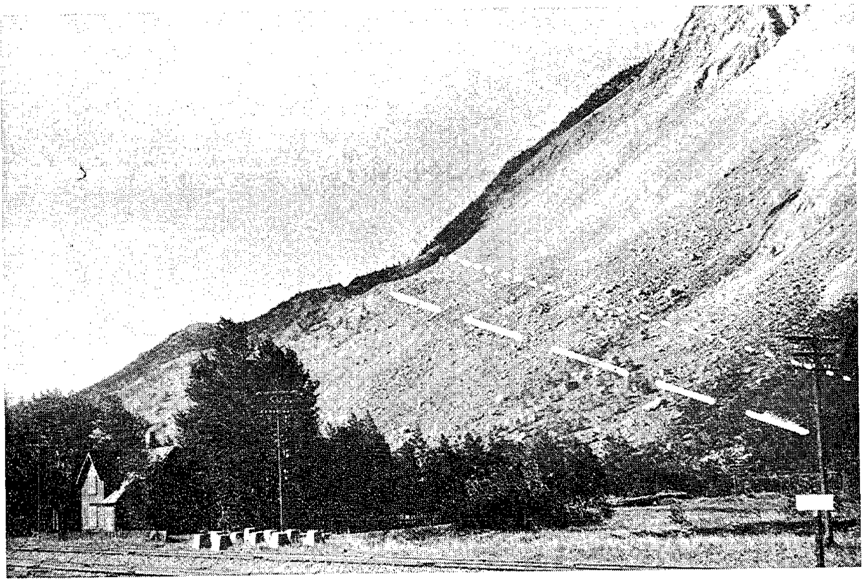
FIG. B.—Contorted coal in the pit. The field of view is about ten feet high. This is medium-volatile coal.



EXPLANATION OF PLATE 5

FIG. A.—Sharp omega-shaped fold in the roof of the Vicary Coal. The floor is not so affected. The rubble at the lower right edge is in the Coleman Thrust fault, as indicated coal is marked "C."

FIG. B.—Ruptured anticlinal local fold in the roof of the coal bed at Grassy Mountain. Coal is marked "C."



EXPLANATION OF PLATE 6

PLATE 6.—View of the famous Frank Slide, looking south. The approximate line of the former coal crop beneath the slide is indicated by the dashed line. A small "glory hole" is visible at the far end of the line (arrow). The volume of this slide is variously estimated at around 90 million tons. Several men working night shift in the mine during the slide in April 1906 escaped. Turtle Mountain is on the right, and the trace of the thrust is indicated by the dotted line.

The abandoned Franco-American mine is located about 2 miles south of the highway, near the pass, and only a few hundred feet below the trace of the Lewis Thrust. Published analyses of this coal in the Belly River Formation, and 5,000 feet stratigraphically above the Kootenay Coal, show a volatile content of 41%, pure coal basis. This coal was dragged and crushed during the faulting, when the more-than-15,000-foot roof plate of the Lewis Thrust slid over it, and probably for 10 miles beyond that point.

Summarizing the observations in the Crowsnest Pass region, there is an eastward increase of 20% in the volatile content of the coals in a distance of less than 40 miles. The 19% coals at Sparwood are in the same member of the Kootenay Formation as the 35% to 39% volatile coals at Beaver Mines and Christie Mine; the trend is progressive, and not related to the intensity of the deformation at any particular point. But, lest we forget, these perimeter points were probably more than 100 miles apart before the thrusting.

There is also a progressive north to south increase in volatile content, extending from Canmore (near Banff) to Waterton. These differences amount to more than 25 percentage points in a distance of around 150 miles along strike of the major structural features.

There has been bedding plane slippage at all of these localities; almost all of the coal is crushed *in situ.*

Oldman River-Highwood-Kananaskis-Canmore Region

The region from the Crowsnest Pass to Canmore is characterized by a system of interlacing *en echelon* thrust faults that affect the coals in the lower Kootenay Formation. Details regarding the sources of the samples are inadequate to permit detailed analysis as has been presented for the Elk River and Crowsnest Pass regions. There is, however, a steady northward decrease in the volatile content to the vicinity of Canmore, where assays of two beds show 11% and 13% of volatile, respectively.

Most of the coal in this region is in the Adanac Member, beneath the Cadomin Conglomerate.

Canmore-Clearwater Region

This 50-mile segment is north of the Bow River; it is characterized by more open folding and wider spacing of the thrusts, but the lower Kootenay coals along the western edge of this strip are all of semianthracite rank. There is a slight northward increase of volatile content indicated, particularly north of the Red Deer River, and also an increasing trend from west to east.

At Barrier Mountain, between the Panther and Red Deer rivers, there is a zone of sandy-silty strata overlying the Moose Mountain Sandstone. The coal in these beds, though sheared, is not structurally contorted, but the overlying black shale unit is dragged into tight folds by eastward movement of the overlying sandy unit. This upper sandstone unit, which is similar to the Hillcrest Sandstone, is only slightly deformed, but folds in the shale have amplitudes of several hundred feet.

The coal in the lower sandstone contains 13% of volatile matter compared to 20% or more in the upper sandstone. The apparent interval is about 2,000 feet. The coal in all of the beds has been affected by bedding-plane shearing.

The thickness of the shale unit has been at least doubled by the drag folding. If the metamorphism had preceded the faulting and folding, the present upward gradient of volatile (0.35% per 100 feet) would be 0.7% or more, and more nearly in line with gradients observed in the Elk River Valley.

The Luscar Coal Region

The Luscar Formation is coal-bearing for a distance of 200 miles along and within the eastern margins of the thrust belt. The volatile contents of these coals range from 16% to 30%, as indicated by analytical data from Mine Branch Bulletin 831 (Nicolls, 1952). The writer is not sufficiently conversant with the stratigraphy or sample points outside of the main Smoky River district to treat these as has been done for the Kootenay coals.

One interesting situation is noted near the present town of Grande Cache on the Smoky River. Most of the data available to the writer suggest that the vertical gradients of volatile matter in the low-volatile coals of the main area are small. But 12 to 15 miles upstream (up-structure, or up-thrust) there is a coal reported to contain 30% volatile. If these are the same beds as those sampled north of Grande Cache, there is a significant decrease in paleotemperature indicated for the area around the Sulfur River, as compared with the presently mined area.

Western U.S.

By comparison, coals in Carbon and Emery counties in Utah are essentially the same through an interval of more than 5,000 feet. These are faulted and tilted around the San Raphael Swell. Differences of volatile content are more closely related to recent entry of oxygen in groundwater.

There is only one or two percent difference of volatile content in 2,000 feet of Mesaverde at Somerset, Colorado, but the coals in 2,500 feet of section around Coal Basin and Thompson Creek show a range of 21% to 38%. Around Coal Basin there are also some striking lateral differences in the same beds.

In the Meeker field the volatile content of the upper beds is 4% to 5% higher than in beds 4,200 feet lower stratigraphically.

The writer has carefully sampled coals at several points near the intrusive contacts of the West Elk Mountains in the vicinity of Somerset and Crested Butte. It is surprising to find that there are many contacts where the elevated temperatures did not extend more than a few hundred feet from contacts of intrusive bodies having volumes measured in cubic miles. At other places, such as Coal Basin, the volatile content of the coal has been reduced markedly at distances of more than 3,000 feet from the contact, but the effects have a very limited areal extent.

SUMMARY

The lines of reasoning based on the evidence cited above lead the writer to conclude that:

1. The metamorphism was essentially thermal in nature, and the observed patterns of differences of volatile contents in the coals (particularly the Canadian coals) are related to pre-Laramide, or very early Laramide geothermal gradients.

2. It follows that the Lower Cretaceous coals of western Alberta and adjoining areas in British Columbia had achieved essentially their present rank prior to the onset of thrusting.

3. Except for intrusive contact-related situations, the patterns of metamorphism shown by coal analytical data tend to be regional and do not exhibit differences related to the intensity of local stresses or shearing. They do not show the metamorphism that would be expected if high temperatures were produced by friction during thrusting, nor does the fault rubble.

4. It is probable that the volatile content of these coals is representative of the highest temperatures that have affected them, modified slightly by the rates of escape of the methane during the periods of elevated temperature and/or by recent oxidation.

5. More study is needed on the phenomenon of thermal metamorphism of coal, especially the interrelationship of the effects of temperature and confining pressures on the rate of devolatilization and the net effects with time.

ACKNOWLEDGMENTS

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