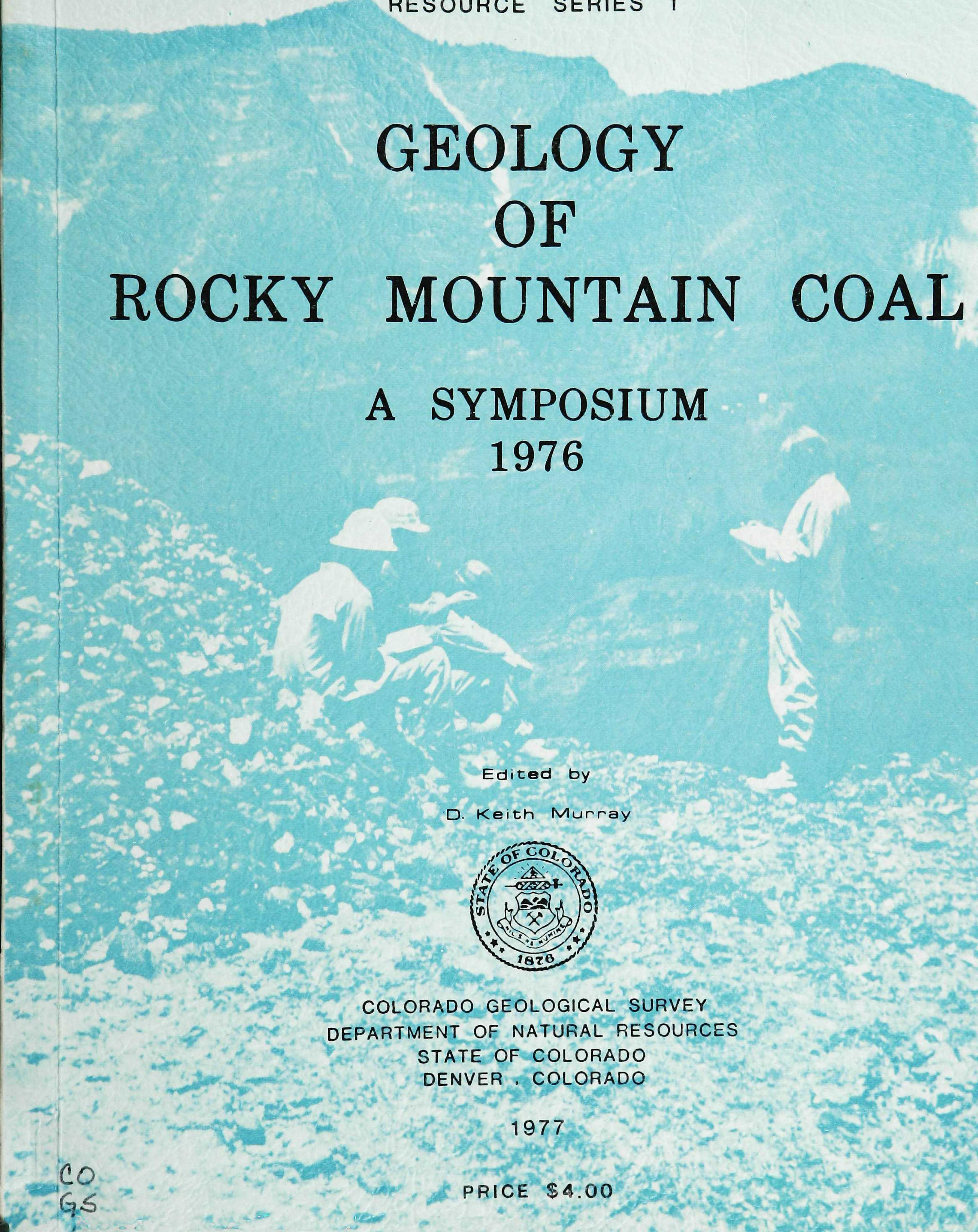
RESOURCE SERIES 1

GEOLOGY OF ROCKY MOUNTAIN COAL

A SYMPOSIUM 1976



Edited by

D. Keith Murray

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
STATE OF COLORADO
DENVER, COLORADO

1977

PRICE $4.00

STATE OF COLORADO
Richard D. Lamm, Governor

DEPARTMENT OF NATURAL RESOURCES
Harris D. Sherman,
Executive Director

COLORADO GEOLOGICAL SURVEY
John W. Rold, Director
and State Geologist

MISSION OF THE COLORADO GEOLOGICAL SURVEY

The Colorado Geological Survey was legislatively re-established in February 1969 to meet the geologic needs of the citizens, governmental agencies, and mineral industries of Colorado. This modern legislation is aimed at applying geologic knowledge toward the solution of today's and tomorrow's problems of an expanding population, mounting environmental concern, and the growing demand for mineral resources.

SPECIFIC LEGISLATIVE CHARGES ARE:

"Assist, consult with and advise state and local governmental agencies on geologic problems."

"Promote economic development of mineral resources."

"Evaluate the physical features of Colorado with reference to present and potential human and animal use."

"Conduct studies to develop geological information."

"Inventory the State's mineral resources."

"Collect, preserve and distribute geologic information."

"Determine areas of geologic hazard that could affect the safety of or economic loss to the citizens of Colorado."

"Prepare, publish and distribute geologic reports, maps and bulletins."

"Evaluate the geologic factors affecting all new subdivisions in unincorporated areas of the State."

"Promulgate model geologic hazard area control regulation."

"Provide technical assistance to local governments concerning designation of and guidelines for matters of State interest in geologic hazard areas and the identification of mineral resource areas."

"To provide other governmental agencies with technical assistance regarding geothermal resources."

Cover photo: Coal Basin, Pitkin County, Colorado

RESOURCE SERIES 1

GEOLOGY OF ROCKY MOUNTAIN COAL

PROCEEDINGS OF THE 1976 SYMPOSIUM

Edited by

D. Keith Murray

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
STATE OF COLORADO
DENVER, COLORADO

1977

PRICE $4.00

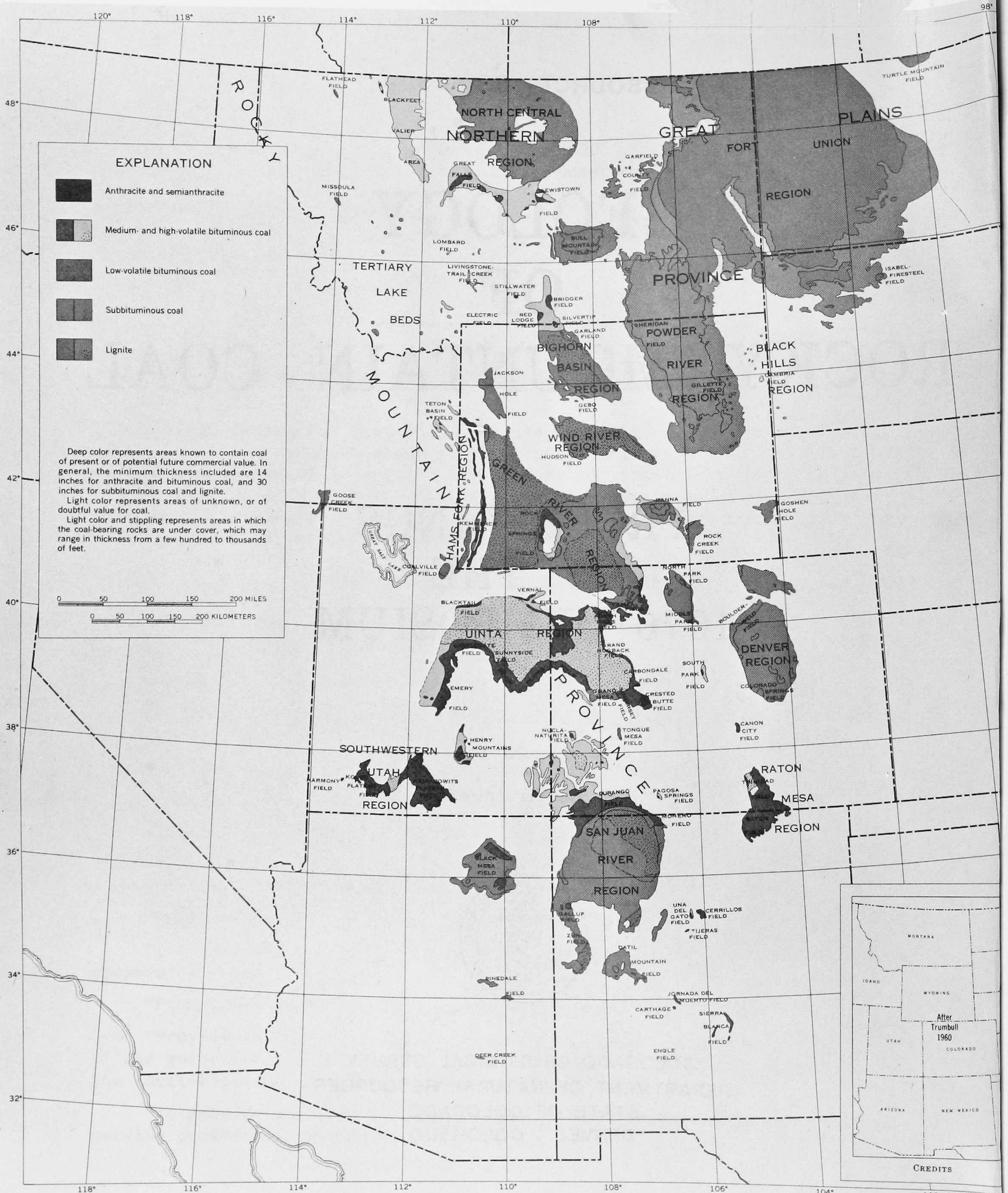


Figure 3:
COAL FIELDS

Coal-bearing regions of the Rocky Mountains (from Geologic Atlas of the Rocky Mountain Region, Rocky Mountain Association of Geologists, 1972)

TABLE OF CONTENTS

FOREWORD

The "1976 Symposium on the Geology of Rocky Mountain Coal," the first of what we hope will be an annual event, was held on April 26 and 27 at the Cecil H. and Ida Green Graduate and Professional Center on the campus of the Colorado School of Mines, in Golden. Over 400 people registered for the meeting, with over 200 coming from out of state and from Canada. The theme of this symposium, and of future ones in this series, is "Geology is the key." Without a doubt, coal is the answer to our short- and medium-term energy requirements, and geology is the key to a better understanding of coal -- of its origin, chemistry, and ultimate utilization.

The 1976 Symposium was sponsored by the Colorado Geological Survey and the Colorado School of Mines, with valuable and much appreciated support from the U.S. Geological Survey, U.S. Bureau of Mines, The Denver Coal Club, and Rocky Mountain Association of Geologists. Without the assistance of many individuals from these agencies and organizations, together with that of numerous energy-related companies, this conference never would have materialized. Finally, the success of the symposium was assured by the speakers themselves, who contributed their time and effort in presenting a number of excellent papers.

The symposium was organized into four technical sessions: (1) Basic coal geology and geochemistry, (2) Rocky Mountain coal deposits, (3) Coal exploration techniques, and (4) Geologic aspects of coal mining and utilization. The technical sessions commenced with an excellent talk by Dr. William Spackman, Jr., of The Pennsylvania State University, on "Coal-forming processes in the swamps and marshes of Georgia and Florida," and finished with a challenging discussion by Dr. Allen G. Thurman, of D'Appolonia Consulting Engineers, entitled "Geologic aspects of environmental planning and reclamation." Thus the entire gamut was spanned, from the early genesis of coal in the peat swamps to the important responsibility of industry to suitably reclaim the land from which the coal has been extracted. We believe our goal -- to acquaint the coal geologist with the myriad aspects of exploration, development, marketing, and utilization of coal -- was attained with the presentation of 19 papers in the four technical sessions. An additional benefit achieved was the bringing together, for periods of informal discussions, concerned individuals representing a broad spectrum of the coal business -- broad in the sense both of specialty and of geography. To round out the conference, two prominent geologists presented excellent talks at our Monday luncheon and dinner sessions: Dr. William L. Fisher, then Assistant Secretary, Minerals and Energy, U.S. Department of the Interior, spoke on an "Update on Federal coal policy"; and Paul Averitt, now retired from the U.S. Geological Survey, presented a thought-provoking discourse on "The way we must go."

Woven throughout the symposium was the thesis that Western coal is playing an increasingly important role in the Nation's energy supply picture. According to data published by the U.S. Geological Survey, the Western States (including Alaska and Washington) contain over 75 percent of the total estimated coal resources remaining in the ground in the United States, or approximately 2.995 trillion tons, as of January 1, 1974.

In sum, this symposium filled a very important need, the need to find out more about our "Black Ace in the Hole" -- coal, a resource about which there is more ignorance than knowledge, more confusion than fact. To quote from "The Americans: 1976," by Irving Kristol and Paul Weaver:

> "To understand our confusion is to achieve a minor but crucial triumph over that confusion. Even to understand our confusion as confusion, rather than as something else, is no negligible achievement."

The sponsors of this symposium attempted to obtain manuscripts from the author(s) of each of the technical papers presented. The majority of the authors did submit manuscripts for the *Proceedings* in a timely fashion: 14 of the papers presented are reproduced in their entirety; of the remaining five, only their abstracts are included in this volume.

The papers included in the *Proceedings* were, for the most part, given only a modest amount of editing and, as a consequence, their style is not necessarily in accordance with that of the usual publications of the Colorado Geological Survey.

The Editor was given considerable assistance in the preparation of this publication by the following individuals, to whom he expresses his sincere appreciation: Meredith Y. Curtin, Wanda Reh, and Janet E. Schultz. However, the undersigned assumes full responsibility for any errors, inconsistencies, or shortcomings of these *Proceedings*, as well as for the regrettable delay in their publication.

D. Keith Murray
Symposium Co-Chairman
Chief, Mineral Fuels Section

April 1977

1976 SYMPOSIUM
ON THE GEOLOGY
OF ROCKY MOUNTAIN COAL

STEERING COMMITTEE

D. Keith Murray, Co-Chairman
Colorado Geological Survey

Karl R. Newman, Co-Chairman
Colorado School of Mines

Paul Averitt
U.S. Geological Survey

Graham R. Curtis
Gulf Mineral Resources *

Joseph R. Hatch
U.S. Geological Survey

Edwin R. Landis
U.S. Geological Survey

Charles L. Pillmore
U.S. Geological Survey

Frederick R. Scheerer
Atlantic Richfield Company

Joseph B. Smith
U.S. Bureau of Mines

Doss H. White, Jr.
U.S. Bureau of Mines

*Consultant,
formerly with Gulf Mineral Resources

WHY ARE WE HERE?

JOHN W. ROLD: State Geologist and Director
Colorado Geological Survey
Denver, Colorado 80203

As we evaluate the question, "Why are we here?", we could approach the subject from many different angles. The evaluation certainly must include the "Energy Crisis." I guess if we ask the question, "Why are we here?", some people would answer, "We are here because some Arab was greedy and was trying not only to make more money, but to use oil as a political tool to dominate the world." Some would answer, "We are here because of governmental bungling, because government was not able to solve future energy problems ahead of time; was not able to provide enough energy in the form of oil and gas and, therefore, allowed lines at service stations during the highly visible 'crisis' of 1973." Others would answer, "We are here because the oil companies are a bunch of money-grubbing corporations trying to hold up the American public, and we are here as a result of that." Maybe we are here because people are like rabbits. At least, they are increasing like rabbits, not only in the United States, but all over the world. Every one in that rapidly increasing populace has an increasing appetite and, particularly, an increasing appetite and need for energy. They have begun to realize that energy is what makes the world go 'round. It's what gives us our standard of living. It's what allows us to achieve a society such as we enjoy today. I don't believe things are going to change. Human nature, human wants, and human desires are going to remain pretty much the same in the foreseeable future. This will force an ever-increasing demand for energy.

Also, I've never been around a group of people that didn't have meetings almost as a ritual. I guess one could answer that a group of people with common interests always bands together to carry out the old tribal custom of getting together and having a meeting. We've probably gathered here for a combination of all the above reasons.

Certainly, down the road some place, at some time, historians are going to look back on the Fossil-Fuel Age just like we look back on the Stone Age, the Bronze Age, and the Iron Age. My hope is that we, as geologists, will be able to furnish enough fossil-fuel energy so that the transition out of the Fossil-Fuel Age into some other yet possibly unknown, unthought-of, age will be an orderly transition; that the human society, as we know it, will be able to survive that transition from the Fossil-Fuel Age to some other. I see coal providing some of the energy to drive and to fuel that transition.

What are some of the problems as we go out of the Fossil-Fuel Age? Certainly, Project Independence was an attempt by one governmental agency to give us a blueprint and to tell us how we might be able to get out of the Fossil-Fuel Age alive. Of course, everyone doesn't agree with their blueprint, and many people have contended we should change certain parts of the blueprint. Obviously, many parts of the blueprint are just not attainable. There is no way that it could be totally achieved, but certainly it is an indication of the national and societal needs for energy over the next decades and proposes one possible solution. Whatever blueprint one might choose to solve society's energy problem must give coal a major role over the next several decades.

Let's look at some of coal's competition. Oil and gas has traditionally been cheaper, cleaner, and definitely advantageous over coal for many uses. However, many serious problems constrict our reliance on oil and gas. Many of you probably are aware that we recently passed quite a milestone in oil and gas production and consumption in America. We just recently moved into the unenviable position where we are importing more oil into the United States than we are producing. Over 50 percent of our total oil consumption is now imported. That is quite a milestone in my mind. But, notably, the only publicity I saw on it was back on pages 17 and 27. To me, that fact should have made front page headlines. The press' handling of that significant information itself truly indicates the depth of our problem. The Arab oil embargo affected us severely when we were only importing somewhat less than one-third of our consumed oil. I wonder what an embargo will be like when we are consuming 75 percent foreign oil.

Also, oil and gas are too precious to burn. The current and future needs of society for petrochemicals and lubrication are so great that I think it ought to be a hanging offense to burn natural gas or fuel oil to produce electricity. All people, of course, don't agree, but I really think that if you look at the long-range needs of society, it should be considered a crime to burn natural gas and oil for electrical power.

Nuclear, of course, has many problems; some real and some imagined. A combination of the two is going to hold that competition down. Oil shale is seriously affected by what I call the "Big Triple E" - the problems of Economics, Environment, and Emotion. These have been the subject of many specific meetings.

Coal, undoubtedly, provides a large part of the answer to the energy dilemma, and is already undergoing increased demand. Each of you has your own figures in the back of your mind to document that increasing demand. As an example, Gary Glass' predictions of future coal production in Wyoming look like they are almost asymptotic to the vertical axis as they are plotted. One wonders if it is possible to actually dig that much coal, but when one starts looking at the facts and the figures, it's not only possible, it's probable that coal production in Wyoming is going to go through the roof. In Colorado, we likewise are seeing a tremendous increase. Back in 1963, Colorado's production was 3.7 million tons. In 1975, it was in excess of 8 million tons. Predictions are similar, though smaller in scale, to Wyoming's.

The most recent attempt to try to predict the future was made by the Subcommittee to Expedite Energy Development, Joseph B. Smith, Chairman (U.S. Bureau of Mines), and the Socioeconomic Impacts of Natural Resource Development Committee, Russell W. Fitch, Chairman (U.S. Environmental Protection Agency), in their publication, *A Listing of Proposed, Planned or Under Construction Energy Projects in Federal Region VIII, A Joint Report* (August 1975). These committees are part of the larger Committee on Energy and Environment of the Denver Federal Executive Board, Dudley E. Favor, Chairman. This report indicates that 33 new coal mines are planned and programmed for the state of Colorado. A simple addition of their productive capacities comes up with 36 million tons of coal production in Colorado in the 1980-82 range. Even if these figures are accurate by only a factor of 50 percent, they certainly document the tremendous need for coal.

As geologists, we're going to have to provide the leadership to find and produce this coal in a means which is economically sound and which is environmentally sound. We'll also have to provide some of the leadership to strip that third "E" from the problem - the Emotion. These questions then lead to this meeting. Where are geologists going to develop the expertise that is going to be needed? Most coal geologists are retreads like myself. They didn't start out from school as coal geologists - they started out as something else. Universities are not turning out coal geologists in large numbers. Probably only a handful of geology departments in the United States turn out graduates who would look upon themselves as qualified to be coal geologists without a tremendous amount of additional work and training. Even if the universities were now beginning to train coal geologists, the educational lag time to turn these people out is almost as long as the lag time to develop a new strip mine. There are very few specific courses in the universities, at least in this part of the country, that are oriented towards coal. Take stratigraphy as an example. Everybody who is teaching stratigraphy, if they have any industrial experience at all, related it to oil geology, with possibly a smattering of mining. As a little experiment here, I would like to see the hands of those people who were trained as coal geologists in the university, and when they left the university, actually planned on being a coal geologist. Can I see the hands? Obviously, they certainly represent a small minority. So that is really the reason for having this meeting. It is to provide a painless retread process to a bunch of old, broken-down oil geologists like myself, so that we can learn something about coal geology.

I noticed this type of deficiency in myself and in my own staff. Last year, I spent what I thought was a sizeable chunk of Colorado Survey budget money and sent Keith Murray back to a one-week coal geology short-course in West Virginia. Keith returned and said he'd learned more about coal geology in that week than he thought he ever wanted to know. Regretably, very little of that meeting was closely applicable to Rocky Mountain coal geology. He didn't think he needed to know too much about Pennsylvania and West Virginia coal geology, particularly in those Pennsylvanian rocks. That discussion was the germ of the idea of having this meeting. Of course, kicking off a meeting or thinking about it is an awful lot like a man's having a baby. The conception and the initial idea is just a heck of a lot of fun. Then, you turn the project over to somebody else who goes through several months of labor and pain to bring forth a meeting like this. Hopefully, the parents of this offspring will all be proud, and it will grow up to be a strapping young adult, or at least adolescent, before the next few days have passed.

The thrust of this meeting was to try to collect the leading experts in their field, assign them a topic and ask them to share their knowledge with those of us who aren't as experienced and maybe aren't as smart. It was planned as an educational "bootstrap" operation.

The turnout of the people that the committee invited to talk to and with you has been excellent. The participation in terms of numbers, in terms of the distance that people were willing to come, in terms of the broad spread of industry, academic institutions, and governmental agencies from all over the country, not only indicates the tremendous interest in Rocky Mountain coal, but certainly ratifies our reasoning in having this meeting. I trust that it will be successful, and that at the end of the meeting, my feelings and your feelings will be as great as my expectations are now.

COAL PALYNOLOGY AND PETROLOGY

ROBERT M. KOSANKE: U.S. Geological Survey
Denver, Colorado 80225

ABSTRACT: Palynological and petrological studies of coal have been closely related aspects of coal geological investigations for many years. The use of palynology to help resolve Paleozoic coal correlation problems in United States, Canada, and Europe is well known. The use of petrology to evaluate blends of coal to produce metallurgical coke of optimum quality is likewise well known.

More recently, both palynology and petrology have been used to evaluate oil and gas potential. Color change in spores and pollen grains, extracted by the maceration process, has been related to depth of burial or thermal alteration. Similarly, reflectance of organic matter can be measured and related to thermal alteration.

In response to increasing demands for low-sulfur coal, emphasis has shifted from Paleozoic coal deposits of eastern United States to the vast Mesozoic and Cenozoic coal resources of western United States. Palynology undoubtedly will play a major role in solving geological problems encountered in these deposits.

INTRODUCTION

Henry Witham (1833) of England published some drawings of organisms observed in thin sections of cannel coal. Witham was uncertain as to what these organisms were, but thought they were of plant origin (vessels). The organisms shown in one of Witham's drawings and in Figure 1 are spores assigned to the genus *Densosporites*. Species of this genus have been reported from Devonian, Mississippian, and Pennsylvanian rocks from many places in the world. Franz Schulze (1855) in Germany discovered that coal could be macerated using chemicals so that undamaged spores, pollen grains, cuticle, resin rodlets, and other plant remains were recovered in the residue. The maceration method consists of two phases: the partial oxidation of coal and the dispersal of humic matter. The resistant plant debris is thus freed and can be isolated for microscopic examination. Oxygen from Schulze's solution, which is a mixture of nitric acid and a saturated aqueous solution of potassium chlorate, can be used to partially oxidize the coal, forming oxides of carbon, water, soluble acids, humic acids, etc. Other oxidizing agents may be used but Schulze's solution is the most common. The speed of the reaction of Schulze's solution with coal can be altered by heat or by increasing the concentration of the nitric acid. The oxidized coal is then washed with water to remove the acid. In the second phase of the maceration process, the partially oxidized coal is covered with a 10 percent solution of potassium hydroxide; this phase results in a release of humic matter (heavy brown liquid) and an insoluble portion containing the preserved botanic ingredients.

Paulus F. Reinsch (1884) reported on the occurrence of organisms found in coal from Russia and Saxony. He believed the organisms were of algal origin, but Bennie and Kidston (1886) concluded in their report on the Carboniferous coals of Scotland that the organisms in coal were spores and not of algal origin. Further, Bennie and Kidston reported the "...traces of orginization..." of Witham (1833) were likewise spores. It is now well known that Bennie and Kidston were correct, although the presence of algae in coals subsequently became known. As a matter of fact, algal coals or boghead coals as they are called, are known from Alaska, Australia, France, Scotland, South America, and United States. Another name applied to algal coals is torbanite.

Figure 2 shows a thin section of a Pennsylvanian coal from Illinois (Kosanke, 1951) in which opaque attritus forms the matrix around a large algal colony. These algae have attracted attention over the years because the nature of their thick walls is such that oil can be distilled. Blackburn and Temperley (1936) have shown that algae of this type are in fact identifiable with the modern species *Botryococcus braunii*. This alga is widely distributed throughout the lakes of United States. Traverse (1955) reviewed the occurrence of *Botryococcus* in lignite and other Tertiary sediments and mentioned older occurrences, including David White's (1906) report on the presence of algae in oil shale of Ordovician age from Illinois. *Botryococcus* is a fossil of considerable antiquity whether or not is is present in the Ordovician of Illinois.

Reinhardt Thiessen, in his work with the U.S. Bureau of Mines from about 1910 to 1938, studied structure and correlation of Paleozoic coals. Thiessen and his colleagues, during their early studies, refined the coal-thin-section method for petrographic and palynological analyses. From these studies, together with carbonizing properties of coal, much basic data were obtained. Thiessen (1918) suggested the possibility of correlating coals by the presence of characteristic exines. Thiessen and Staud (1923) further discussed this topic; and Thiessen and Wilson (1924, p. 20) concluded after a series of intensive studies of coal thin sections from various coal beds that, "As a result of this investigation it has been found possible to correlate each bed by means of spores and other structures found therein." Thiessen and Wilson

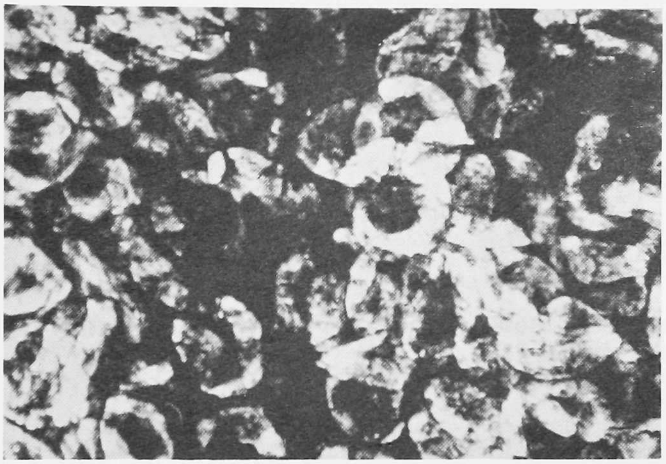


Fig. 1 Thin section of the Reynoldsburg coal, Lower Pennsylvanianof Illinois, with abundant specimens of *Densosporites* (X440).

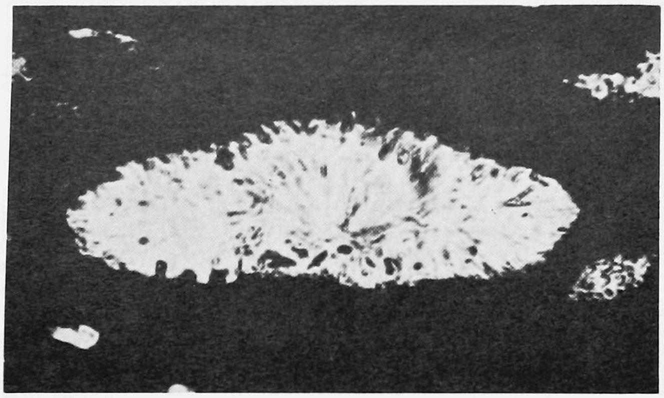


Fig. 2. A large algal colony of *Botryococcus braunii* in a groundmass of opaque attritus (X425) from a Pennsylvanian coal in the Abbott Formation of the McCormick Group of Illinois.

(1924) characterized the Pittsburgh No. 8 coal by the presence of the "Pittsburgh" spore and the "Pittsburgh" megaspore. Thiessen (1932) referred the "Pittsburgh" spore to the "Pittsburgh" microspore for which Kosanke (1943) proposed the formal name *Laevigatosporites thiessenii* (Fig. 4-A). Today this species is known as *Thymospora thiessenii* (see Wilson and Venkatachala, 1963). This spore is small, generally less than 25 microns in maximum diameter, with a thick, distinctive spore coat and a monolete aperture. The "Pittsburgh" microspore of Thiessen is indeed an abundant guide fossil to the Pittsburgh No. 8 coal, but we now know from Clendening (1974) and others that this species is not restricted to the Pittsburgh No. 8 coal. It occurs sparsely in other coals in this part of the stratigraphic column. The work of Thiessen and his associates demonstrated the use of coal thin sections for petrology and palynology. Thiessen and Staud (1923, p. 20) reported, "The spores may be separated out of coal by digesting the coal with Schulze's reage and subsequently treating with dilute ammonia." The maceration method was known to Thiessen but apparently was not used extensively. Today the maceration method is used in palynological studies because it permits study of complete specimens.

We have discussed the maceration method used t extract plant microfossils from coal, but not the collection and preparation of samples. Coal cores are ideal samples when they are available and are cut in half with a carborundum saw (dry). A small segment of one-half of a core (Fig. 3) is cut off the entire length of the core. This complete ribbon or bed-profile sample is subdivided into bench samples, usually not more than 12 in. (30 cm) in length (Fig. 3). The remaining portion of this half of the core can serve as a reserve sample or be used for petrographic analysis. The other half of the core can be used for chemical analysis. Collection of outcrop samples (Fig. 3) should be a continuous ribbon or bed-profile sample. It is often necessary to reduce the size of these samples for maceration, and thi can be accomplished through the use of a riffle.

Our primary Paleozoic coal resources are of Pennsylvanian age. Coal of Devonian and Mississippian age is not very common, although it can provide important information about past plant life. Pennsylvanian rocks, according to Wanless (1969, p. 294-297) are widely distributed on the North American continent from Ellesmere Island in the north to southern Mexico and central Guatemala on the south. The eastern

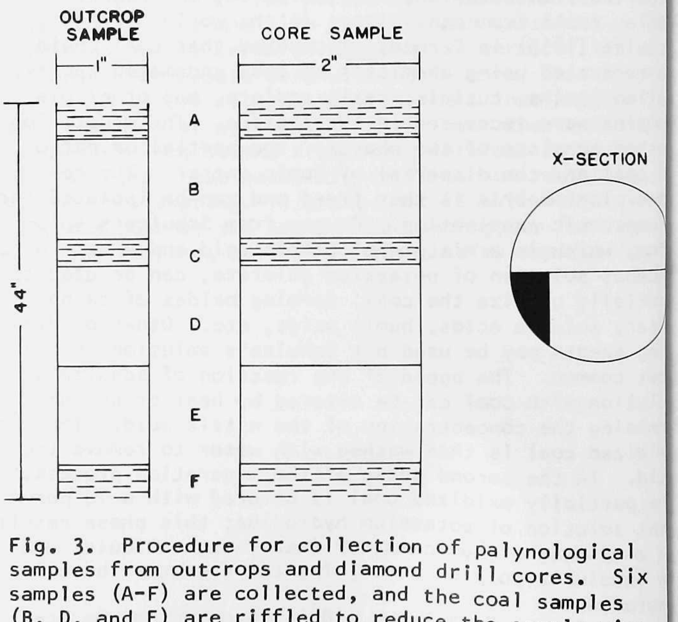
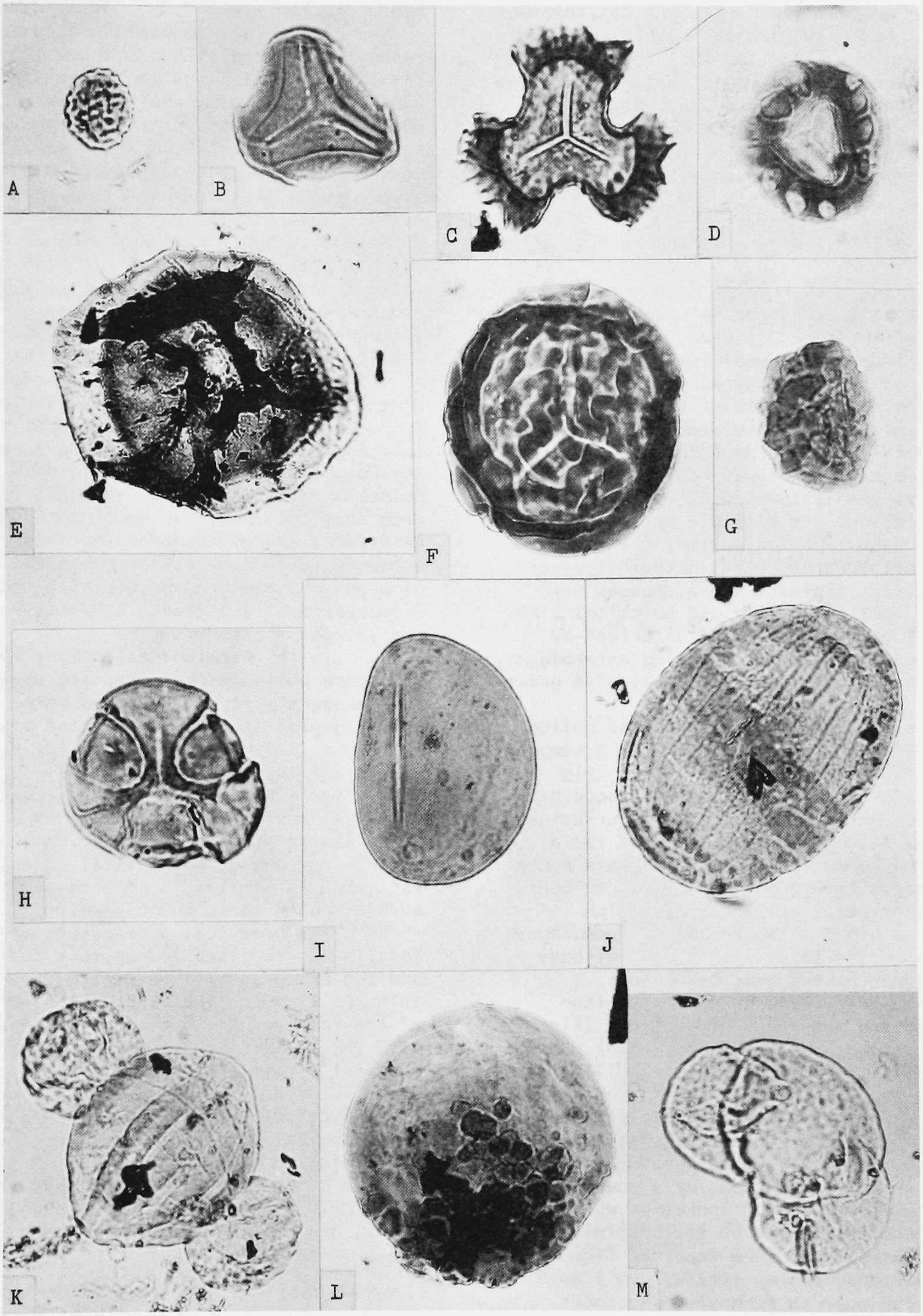


Fig. 3. Procedure for collection of palynological samples from outcrops and diamond drill cores. Six samples (A-F) are collected, and the coal samples (B, D, and E) are riffled to reduce the sample size to the proper amount for maceration. A similar set of samples from a core is obtained by cutting the core in half and then slicing off a part as shown (black). A continuous ribbon of coal or a bed-profil sample is macerated. For additional information on sampling coal beds, see Schopf (1960).



g. 4. Spores and pollen grains from Mississippian, Pennsylvanian, and Permian rocks. A.--*Thymospora thiessenii* (X710), B.--*Rotospora fracta* (X710), C.--*Tripartites vetustus* (X710), D.--*Densosporites irregularis* (X710), E.--*andispora spinosa* (X450), F.--*Punctatisporites sinuatus* (X450), G.--*Thymospora pseudothiessenii* (X710), H.--*rinidulus diamphidios* (X710), I.--*Laevigatosporites ovalis* (X710), J.--*Vittatina costabilis* (X710), K.-- *Hamiapollenites perisporites* (X710), L.--*Schopfites diamorphus* (X450), and M.--*Pityosporites communis* (X710).

margin of Pennsylvanian rocks is in Nova Scotia southward through Canada to Boston and Narragansett basins in Massachusetts and Rhode Island to the Appalachian basin from western Pennsylvania to Alabama. Pennsylvanian rocks occur westward to Nevada and California, with isolated occurrences in Oregon, Washington, and western Canada. Wanless (1969, p. 296) reported that the thickness of Pennsylvanian rocks varied from a few feet to 25,000 ft (a few meters to 7,500 m). Pennsylvanian coals are largely confined to eastern United States. A few coals of Permian age are known but they are not of much commercial importance.

DISTRIBUTION AND APPLICATION OF SELECTED PALEOZOIC PALYNOMORPHS

The use of palynology for Paleozoic coal correlations in United States, Canada, and Europe is well known. Knowledge of its usefulness is based on information gathered for the most part during the past 25 to 30 years. As a result of this accumulation of data, it was possible to postulate, for a recent lecture, selected palynomorph range zones for a new coal program in the state of Iowa. This is something that could not have been attempted 25 years ago. The reason coal correlations are possible results from the fact that, thoughout geologic time, changes in plants occurred that are reflected in their recoverable spores and pollen grains. These changes with geologic time are sometimes rapid and sometimes slow. As a consequence, some coals are characterized by significant changes in their spore-pollen assemblages, whereas other coals can be identified only with great difficulty.

A few Mississippian guide spores and pollen grains are *Tripartites vetustus* (Fig. 4,C), *Rotaspora fracta* (Fig. 4, B), and *Grandispora spinosa* (Fig. 4,E). *Tripartites vetustus* is a radial, trilete spore having concave interradial margins and prominent auriculae that are fluted or folded and widest at the radial margin. *Rotaspora fracta* is a radial, trilete spore having a more or less triangular body which is concave or convex interradially with a zona which is narrow radially and broad interradially. *Grandispora spinosa* is radial and trilete, with a central body enclosed by a bladder having numerous spines.

Two species that span the Mississippian-Pennsylvanian boundary are *Schulzospora rara* (Fig. 7,A) and *Densosporites irregularis* (Fig. 4,D). *Schulzospora rara* is radial, trilete, and elliptical in outline. The body is spherical and surrounded by a bladder, and both body and bladder have a punctate sculpture. *Densosporites irregularis* is radial and trilete, and the body is surrounded equatorially by a dense cingulum which thins irregularly toward the margin, having the appearance of spokes of a wheel. Perhaps the next species should be included with the previous two, because it has been reported from Mississippian and Pennsylvanian strata, but I have observed it thus far only in Pennsylvanian rocks. This is *Punctatisporites sinuatus* (Fig. 4,F), which was originally described by Artüz (1957) from Turkey. *Trinidulus diamphidios* is an unusual species originally described by Felix and Paden (1964) from Lower Pennsylvanian rocks of Oklahoma and Texas. This species (Fig. 4,H) has been observed in a roof shale of a coal bed in the Pennsylvanian part of the Lee Formation of eastern Kentucky. *Lycospora pseudoannulata* is a radial, trilete spore with an equatoria structure (cingulum). This species is present more or less continuously from Mississippian to Middle Pennsylvanian time.

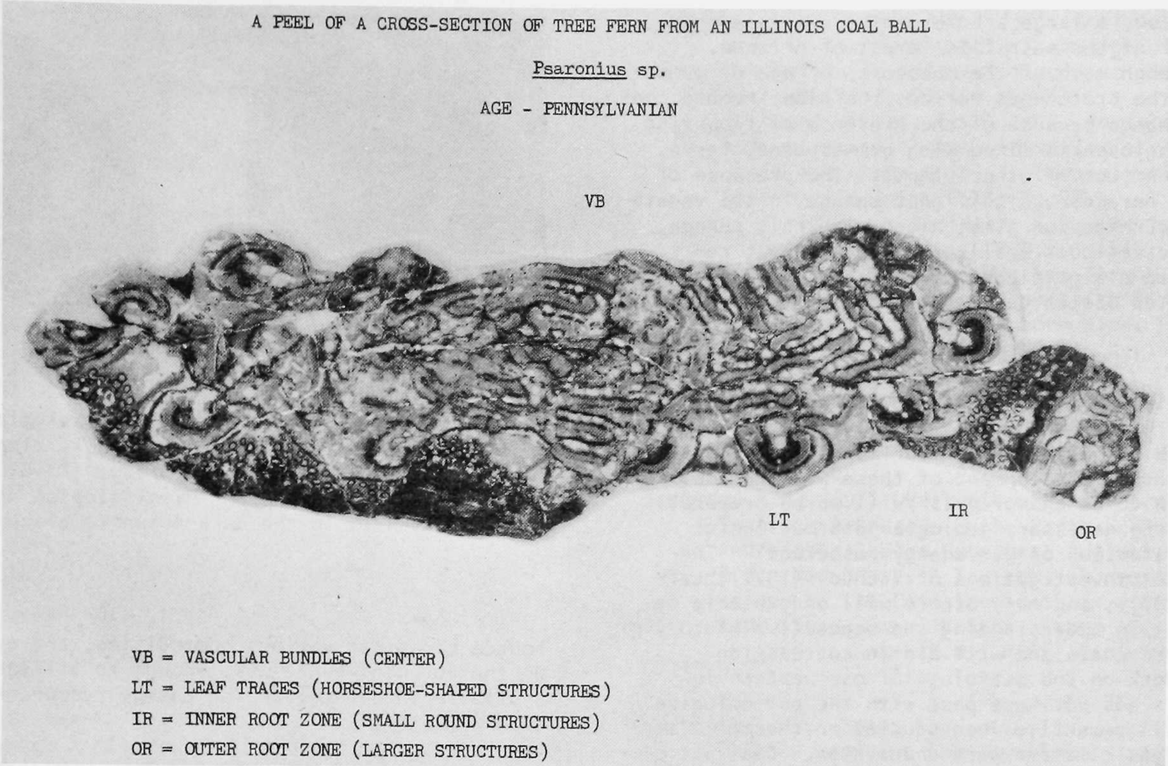
Bilateral, monolete spores are common in many Pennsylvanian coals, and *Laevigatosporites ovalis* (Fig. 4, I) will serve to illustrate this type of spore. In the space available it is not possible to do more than paint a picture with a broad brush. Kosanke (1950) described a new genus from the Colchester (No. 2) coal and named it *Schopfites*. The type species, *S. dimorphus* (Fig. 4,L) is radial, is trilete, and has dimorphic ornamentation; that is, different types of ornamentation on proximal and distal surfaces of the spore. It also has a restricted range zone, being found in a narrow band of Middle Pennsylvanian coals, and thus has value for correlation purposes. *Thymospora pseudothiessenii* (Fig. 4,G) is similar to *T. thiessenii* (Fig. 4,A) but is significantly and consistently larger and occurs in Middle rather than Upper Pennsylvanian coals. *T. pseudothiessenii* has a reasonably short range zone in coals. It is restricted to a zone from just below the Colchester (No. 2) coal and ends at about the Des Moinesian-Missourian boundary. It is at about this time that the lycopsids decline and pteridosperms or seed ferns and gymnosperms increase. *Pityosporites communis* (Fig. 4,M) is morphologically similar to mod pine pollen, even to the distally inclined bladders. *Pityosporites* is present in Pennsylvanian, Permian, and younger rocks.

In the Permian Period many more changes in the spore-pollen assemblages are obvious. Only two such changes will be mentioned here. Striate bisacca pollen grains are now common, and a special taxon of this type is *Hamiapollenites* (Fig. 4,K). The grooves or striations are on the proximal surface and the re tively small bladders are not distally inclined. *Vittatina costabilis* (Fig. 4,J) is a common Permian taxon having grooves or striations on the proximal surface and one or more distal bands. Morphologicall *Vittatina* is similar in some respects to *Welwitschia*, a rare modern xeric gymnosperm.

The practical application of the use of guid fossils has resulted in numerous coal correlations, and two examples will be mentioned here (see Kosanke 1974, P. 12-19). The first example is the correlati of the Princess No. 6 coal of northeastern Kentucky with the Lower Kittanning coal of Ohio, Pennsylvania and West Virginia. Wanless (1939, p. 72) correlated the Colchester (No. 2) coal of Illinois with the Low Kittanning coal, and although there are some minor palynological differences between these two coals, a correlation seems reasonable. A palynological com parison of the Princess No. 7 coal from eastern Kentucky with the Middle Kittanning coal of Ohio, Pennsylvania, and West Virginia suggests a correlation between these two coals.

DISCUSSION OF SELECTED PALEOZOIC AND MESOZOIC PLANTS

Along with increased interest in Pennsylvani spore-pollen assemblages from coals, there has been commensurate interest in fructifications or the plan organs that originally produced the spores and polle grains. These fructifications may occur in coal bal



g. 5. Coal ball peel of a portion of a tree fern (*Psaronius* sp.) from an Upper Pennsylvanian coal of Illinois bout eight-tenths natural size).

they may be preserved as compression fossils. The ores or pollen grains described from fructifications e sometimes indistinguishable from some of the spersed spores and pollen grains isolated from coals. is suggests a relationship of these dispersed units specific fructifications. A Middle Pennsylvanian ndscape might consist of an abundance of *Lepidoden-on, sigillaria,* and *Cordaites,* followed by various rns, seed ferns, *Calamites,* and *Sphenophyllum,* king a mixture of arborescent and herbaceous plants at have contributed to our coals.

How do we know what these plants looked like? mpression fossils found in roof shales and iron-one concretions are helpful and have provided much formation. Coal balls, formed in coal, provide ch important information on the anatomical details these plants. These coal balls or concretions are ten largely composed of calcium carbonate; or, in me instances, they are siliceous. Coal balls are t, ground smooth, etched with acid, and covered with rlodion or an acetate film. When dry, the parlodion acetate film can be peeled off the coal ball, re-ving a thin layer of plant material in the process. gure 5 is a photograph of a peel of an Upper Pennsyl-nian coal ball from Illinois. This coal ball is portion of a stem of a tree fern named *Psaronius.* vascular bundles, leaf traces, and inner and outer t zones are preserved. Calcareous fillings of *diocarpon* seeds (Fig. 6) were commonly observed m within a Middle Pennsylvanian coal of eastern sas some years ago. The hard outer seed layers ear to have been coalified.

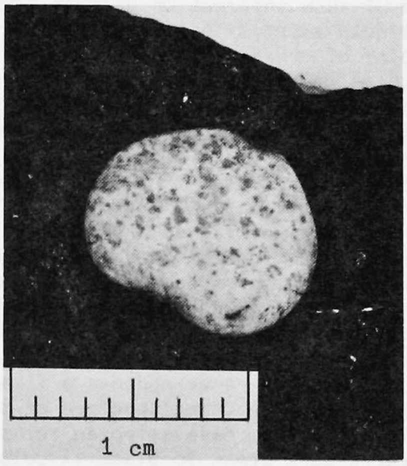


Fig. 6. Calcareous filling of a *Cardiocarpon* sp. seed from within a Middle Pennsylvanian coal of eastern Kansas.

The Triassic and Jurassic plant record reveals a vastly different scene from that of the Pennsylvanian Period. The major contributors to Lower and Middle Pennsylvanian coals, the lycopsids, are reduced in number and importance; they are replaced by the sphenopsids, ferns, seed ferns, and gymnosperms, including the cycads and *Araucarioxylon arizonicum.*

Araucarioxylon, a large arborescent tree, is a prominent member of the petrified forest of Arizona. Passing through much of the Mesozoic, or age of gymnosperms, to the Cretaceous Period, the plant record continues to change because of the presence of flowering plants or angiosperms mixed with gymnosperms, ferns, and a minor amount of other plants. The presence of angiosperms heralds a significant change in the vegetation during Cretaceous time; along with this change, angiospermic residues (pollen and other plant remains) become a significant part of the coals of western United States during late Mesozoic and Cenozoic time.

RESEARCH ON ENERGY RESOURCES OF WESTERN UNITED STATES

With increased demand for low-sulfur coals, we will see further development of these western coals. The question to be answered is "Will we be prepared to provide the necessary geologic information for maximum utilization of our energy resources?" The palynological investigations of Tschudy (1971), Leffingwell (1971), and many others will undoubtedly be most helpful in understanding the vegetative history of these western coals and will aid in correlation studies. Work on the petrology of our western low-sulfur coals has not kept pace with the palynological studies until recently, when studies on thermal alteration of organic matter were undertaken. Coal petrologists have known for many years that in the coalification process, as coal advances in rank, spores and pollen grains change color from light yellow to orange to reddish brown, etc. The process of variable coalification is discussed in detail by Schopf (1948). In our search for energy resources, the application of such information becomes a useful tool to locate liquid energy. Burgess (1974) indicated that the color of organic matter extracted from rocks correlates with the fixed carbon content. Hacquebard and Donaldson (1970) in Canada, and Wilson (1961), Bostick (1971), and others from the United States are seeking answers along these lines. In addition, Epstein (1976) has discovered that a similar color change occurs in conodonts.

I have been working on a project with Forrest Poole of the U.S. Geological Survey, Denver, concerned with thermal alteration of spores, pollen grains, and other organic matter in western Paleozoic rocks as evidenced by color changes. *Schulzospora rara* (Fig. 7,A) from Mississippian rocks of western United States is in the orange color range and has a fixed carbon value of 50 to 55 percent. Another specimen of this same species (Fig. 7,B) from Mississippian rocks of western United States is dark brown to black in color, indicating a fixed carbon content of 65 percent or more, which suggests that these rocks have little or no petroleum potential.

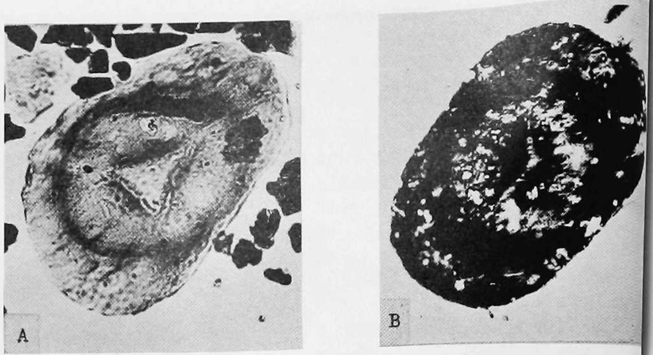


Fig. 7. *Schulzospora rara* from Mississippian rocks western United States. A.--Specimen is clearly tran lucent in the yellow to orange range (X710). B.-- Same species from different Mississippian sample; this specimen is in the dark-brown to black range.

SUMMARY

Palynology and petrology have a contribution to make in exploration of our western energy resource rocks. This may be in the form of coal correlations, coal resource evaluations, study of coal and other rocks to understand unusual mineral distribution patterns, paleoenvironmental assessments of potential source rocks for various commodities, and other area Whether or not we are wise enough to utilize the too available in our search for energy resources, only time will tell.

ACKNOWLEDGMENTS

James M. Schopf and Robert H. Tschudy have viewed the manuscript and offered valuable suggesti for which I am most grateful. Figures 1 and 2 are reproduced with permission of the Illinois State Geological Survey, and Figures 4J, 4K, and 4M are taken from Tschudy and Kosanke (1966).

REFERENCES

Artüz, S., 1957, Die Sporae dispersae der Türkische Steinkohle vom Zonguldak-Gebiet: Instanb. Ün Fen. Fak. Mecm., Ser. B, v. 12, Pt. 4, p. 239-263.

Bennie, James, and Kidston, Robert, 1886, On the oc currence of spores in the Carboniferous Forma of Scotland: Royal Phys. Soc. Edinburgh Proc v. 9, p. 82-117.

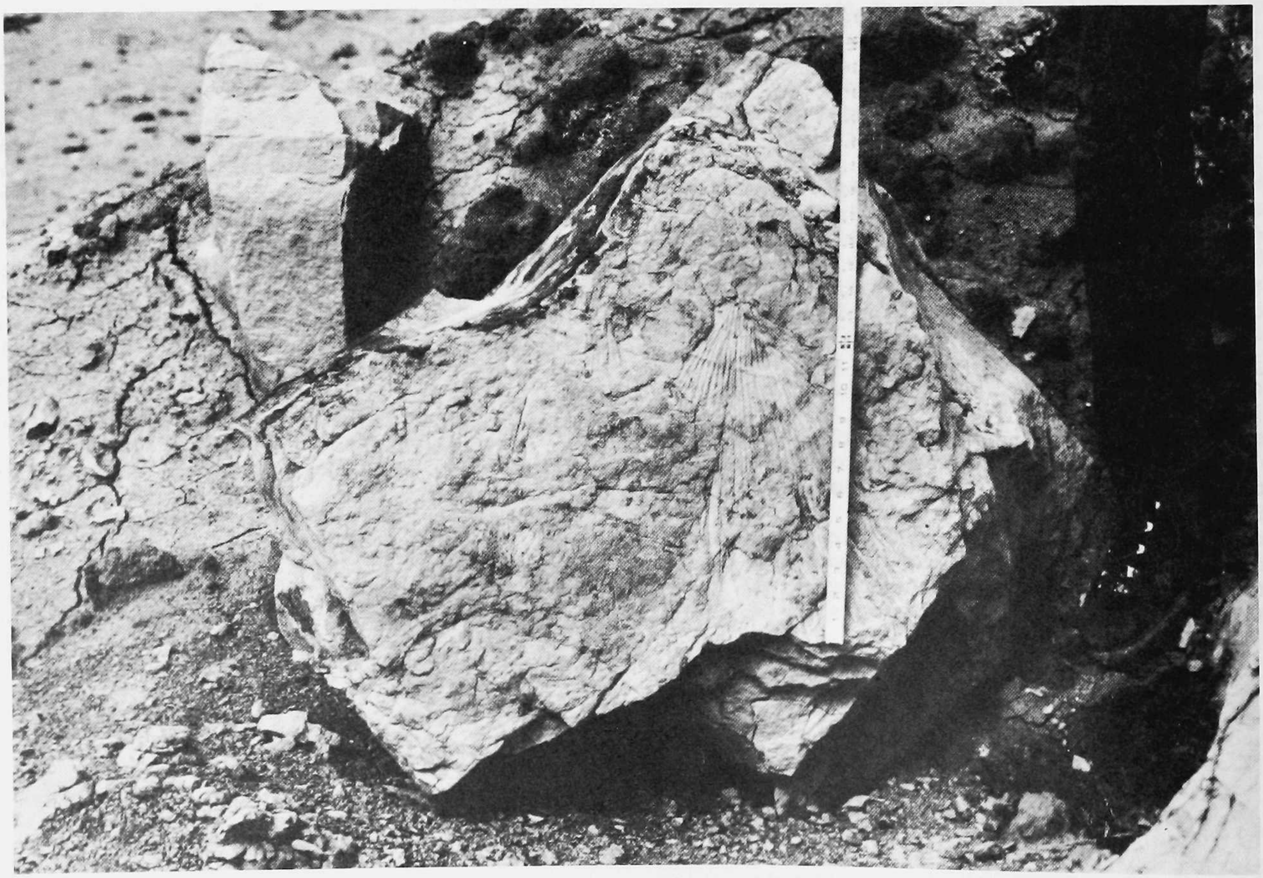
Blackburn, K.B., and Temperley, B.N., 1936, *Botryoc cus* and the algal coals: Royal Soc. Edinburg Trans., v. 58, p. 841-868.

Bostick, N.H., 1971, Thermal alteration of clastic organic particles as an indicator of contact burial metamorphism in sedimentary rocks: Ba Rouge, Louisiana State Univ., Geoscience and Man, v. 3, p. 83-92.

Burgess, J.D., 1974, Microscopic examination of ker gen (dispersed organic matter) in petroleum e ploration: Geol. Soc. America Spec. Paper 15 p. 19-30.

Clendening, J.A., 1974, Palynological evidence for a Pennsylvanian age assignment of the Dunkard Group in the Appalachian Basin, Part II: Wes Virginia Geol. Econ. Survey, Coal-Geology Bul n. 3, 107 p.

Epstein, A.G., 1976, Conodont color alteration--an index to incipient through garnet-grade metamorphism (abs.): Geol. Soc. America Abstracts with programs, Northeast-Southeast Sec. Mtg. v. 8, n. 2, p. 167.
elix, C.J., and Paden, P., 1964, A new Lower Pennsylvanian spore genus: Micropaleontology, v. 10, n. 3, p. 330-332.
acquebard, P.A., and Donaldson, J.R., 1970, Coal metamorphism and hydrocarbon potential in the Upper Paleozoic of the Atlantic provinces, Canada: Canadian Jour. Earth Sci., v. 9, n. 4, p. 1139-1163.
osanke, R.M., 1943, The characteristic plant microfossils of the Pittsburgh and Pomeroy coals of Ohio: American Mid. Nat., v. 29, n. 1, p. 119-132.
__________ 1950, Pennsylvanian spores of Illinois and their use in correlation: Illinois State Geol. Survey Bull. 74, 128 p.
__________ 1951, A type of boghead coal from Illinois: Am. Jour. Sci., v. 249, p. 444-450.
__________ 1974, Palynological studies of the coals of the Princess Reserve district in northeastern Kentucky: U.S. Geol. Survey Prof. Paper 839, 22 p.
ffingwell, H.A., 1971, Palynology of the Lance (Late Cretaceous) and Fort Union (Paleocene) Formations of the Type Lance Area, Wyoming, *in* Kosanke, R.M., and Cross, A.T., eds., Symposium on Palynology of the Late Cretaceous and Early Tertiary: Geol. Soc. America Spec. Paper 127, p. 1-64.
insch, P.F., 1884, Micro-Palaeophytologia formationis carboniferae: v. 1, Continens Trileteas et Stelideas, Erlangae, Germania, Theo. Krische, p. vii + 80.
hopf, J.M., 1948, Variable coalfification: The process involved in coal formation: Econ. Geology, v. 43, n. 3, p. 207-225.
__________ 1960, Field description and sampling of coal beds: U.S. Geol. Survey Bull. 1111-B, 70 p.
hulze, Franz, 1855, Über das Vorkommen wohlerhaltener Cellulose in Braunkohle und Steinkohle: K. preuss. Akad. Wiss., Berlin Math-phys. Kl., Sitzungersber., p. 676-678.
iessen, Reinhardt, 1918, The determination of the stratigraphic position of coal seams by means of their spore-exines (abs.): Science, v. 47, p. 469.
__________ and Staud, J.N., 1923, Correlation of coal beds in the Monongahela Formation of Ohio, Pennsylvania, and West Virginia: Carnegie Inst. Tech. Bull. 9, 64 p.
__________ and Wilson, F.E., 1924, Correlation of coal beds of the Allegheny Formation of western Pennsylvania and eastern Ohio: Carnegie Inst. Tech., Coal-mining Inv., Bull 10, 56 p.
__________ 1932, *in* Fieldner, A.C., Davis, J.D., Thiessen, R., Kester, E.B., Selvig, W.A., Reynolds, D.A., Jung, F.W., and Sprunk, G.C., Carbonizing properties and constitution of Pittsburgh coal bed from Edenborn Mine, Fayette County, Pa.: U.S. Dept. Com., Bur. Mines Tech. Paper 525, 60 p.
Traverse, Alfred, 1955, Occurrence of the oil-forming alga *Botryococcus* in lignites and other Tertiary sediments: Micropaleontology, v. 1, no. 4, p. 343-350.
Tschudy, R.H., 1971, Palynology of the Cretaceous-Tertiary Boundary in the Northern Rocky Mountain and Mississippian Embayment Regions, *in* Kosanke, R.M., and Cross, A.T., eds., Symposium on palynology of the Late Cretaceous and Early Tertiary: Geol. Soc. America Spec. Paper 127, p. 65-111.
__________ and Kosanke, R.M., 1966, Early Permian vesiculate pollen from Texas, U.S.A.: The Palaeobotanist, v. 15, n. 1-2, p. 59-71.
Wanless, H. R., 1939, Pennsylvanian correlations in the Eastern Interior and Appalachian coal fields: Geol. Soc. America Spec. Paper 17, 130 p.
__________ 1969, Marine and non-marine facies of the Upper Carboniferous of North America: Sixième Congrès International de Stratigraphie et de Géologie de Carbonifère, Compte Rendu, v. 1, p. 293-336.
White, David, 1906, *in* Bain, H.F., Zinc and lead deposits of the Upper Mississippi Valley: U.S. Geol. Survey Bull. 294, 155 p.
Wilson, L.R., 1961, Palynological fossil response to low-grade metamorphism in the Arkoma Basin: Tulsa Geol. Soc. Digest, v. 29, p. 131-140.
__________ and Venkatachala, B.S., 1963, Morphological variation of *Thymospora pseudothiessenii* (Kosanke) Wilson and Venkatachala: Oklahoma Geology Notes, v. 23, n. 5, p. 125-132.
Witham, Henry T.M., 1833, The internal structure of fossil vegetables found in the Carboniferous and oolitic deposits of Great Britain: Adam and Charles Black, Edinburgh, and Longman, Rees, Orme, Grown, Green and Longman, London, 84 p.



Fossil plant in Vermejo Formation (Paleocene age), Canon City coal field
Fremont County, Colorado

STRATIGRAPHY AND TECTONICS OF WESTERN COALS

ROBERT J. WEIMER: Colorado School of Mines

Golden, Colorado 80401

ABSTRACT: The Cretaceous and Tertiary strata of the Rocky Mountain region contain extensive coal deposits that accumulated in coastal plain and alluvial environments. The common swamp and marsh environments of *in situ* coal are channel margin swamps, coastal marshes, and channel-fill swamps. Channel margin coal environments are of two general types: (1) areally restricted back-levee swamps that parallel channels and also are the site a deposition of light-colored leached kaolinitic claystone; and (2) more extensive flood basin swamps which are commonly associated with lacustrine deposits. Thin lenticular coals, derived from the accumulation of transported organic material, can be found in both nonmarine and shallow marine environments.

The critical factors necessary for the formation of commercial thicknesses of coal are: (1) fresh, clear water; (2) accumulation of land-derived organics only, (3) balance between ground water table and depositional interface; (4) favorable climate; and (5) persistance of conditions in time and space, and a favorable basin-wide and/or local tectonic influence on sedimentation. These conditions are most commonly found in alluvial and delta plain depositional environments.

The occurrence of penecontemporaneous (growth) faults may influence swamp environments and control the thickness of peat accumulation. Detailed geological and geophysical investigations along the west margin of the Denver basin indicate two types of growth faults are present in an Upper Cretaceous deltaic sequence: (1) deep-seated basement faults, and (2) shallow-listric normal faults. The latter type was a primary control on sedimentation in the coal-bearing Laramie Formation and determined whether or not the coal beds are of commercial thickness. The lateral continuity of coal in the Laramie is interrupted by growth faults, with most of the minable thicknesses of coal occurring only in graben structures.

INTRODUCTION

Coal resources in the Rocky Mountain region are one of the great energy reserves in the world. Coal occurs in rocks of Cretaceous and early Tertiary age spanning the time interval from 95 to 50 million years b.p. Despite mining activities for more than 100 years, details of the sedimentology of coal are not well known. When thick low-rank coals are strip-mined, the geology may be relatively unimportant in exploration and development. But in the more common exploration programs for coal beds 3 to 8 ft thick, geology becomes extremely important in understanding the control on thickness variations and areal distribution. This paper discusses four aspects of the geology of western coals: 1) factors controlling the formation of commercial thicknesses of coal; 2) modern environments of peat accumulation; 3) environments of deposition of western coals; and 4) tectonic influence on coal thickness in the Denver basin.

Cretaceous coals were deposited in a paleogeographic setting along the western margin of an ancient sea that spanned the Western Interior of the North American Continent (Fig. 1). Coal swamps formed on coastal plains between highlands in the Cordilleran region and the marine basin on the east. Rivers discharged into the marine basin, forming large deltas. Figure 2 shows the regional paleogeography for the Late Cretaceous and the location of the major rivers. Shoreline movement along the western margin of the marine basin was dominantly regressive--a response to larger sediment input than rates of basin subsidence would accommodate (Fig. 3). However, the overall shoreline regression was interrupted periodically by widespread transgressions of the shoreline. The resulting major transgressive and regressive cycles are indicated on Figure 3. The eastern terminus of each of four major regressive cycles is shown on Figure 2. Coals are normally found just inland from still-stand positions where thick shoreline sandstones accumulated. Although the nonmarine coal-bearing facies may be thousands of feet in thickness (Fig. 3), the coals of commercial thickness are normally found within the first 100 ft of nonmarine section above marine shale and sandstone deposits.

Beginning in the Late Cretaceous and continuing throughout the Paleocene and Eocene, the Laramide orogeny broke the region into uplifts separated by intermontane basins (Fig. 4). The stratigraphic setting of the lower Tertiary coals is related to fluvial systems draining across the fresh water dominated intermontane basins. The outlines of these fluvial depositional basins are similar to the outlines of the present day structural basins.

Factors Controlling the Formation of Commercial Coal

The explorationist should ask the following questions about the geology of any coal deposit: (1) Where is coal located stratigraphically? (2) What were the environments of deposition that favored the development and preservation of peat? (3) What is the coal thickness and why did the peat accumulate to a sufficient thickness to form a commercial coal? (4) What is its rank and grade? (5) How deep is it? (6) What is the structure (steep or low dip)? (7) What

1976 Symposium on the Geology of Rocky Mountain Coal, p. 9-27

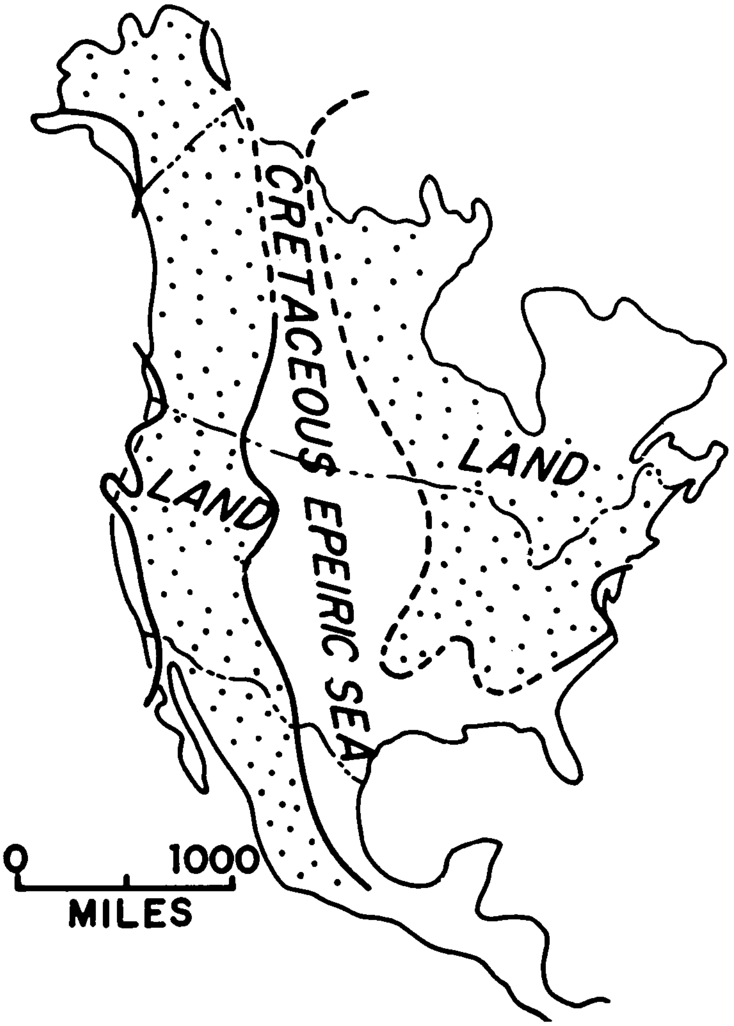


Fig. 1. Map of Cretaceous basin of deposition in which coals were deposited (*after* Gill and Cobban, 1966)

are the thickness and lithology of the roof rock? The following discussion is presented to provide answers to the first 3 questions about Cretaceous and Tertiary coals.

In both the Cretaceous and lower Tertiary, coal is a common lithology, but it represents only a small percent of the total stratigraphic sequence. Shale, siltstone, and sandstone are dominant lithologies. Of prime importance is not just the occurrence of coal, but the geologic factors that controlled the development of commercial thickness of coal, i.e., coals with a quality and thickness to make mining an economic possibility at the present time, or in the near future.

For the western coals a number of constraints can be identified that must be satisfied in order to have a commercial coal bed (Table 1). First, the peat must accumulate in dominantly fresh, clear water environments. Clear water is very important because if muddy water containing abundant suspended clay is carried to the depositional site, the resulting deposi will form carbonaceous shale or coal of poor quality. Peat swamps form in topographically low areas where th ground surface is below the groundwater table, hence they are continuously covered by water. They must be isolated from river waters or tidal channels, because Cretaceous and lower Tertiary depositional models indicate that these channels carried a high suspended lo of clay and silt.

A second constraint is the accumulation only of land-derived organics. No evidence has been presented to substantiate a significant contribution to western coals from marine or brackish water plants.

Third, the balance between the groundwater table and the depositional interface is extremely important. This relationship will be discussed in deta in a later section. If organic matter comes in conta with the atmosphere because of a drop in the level of the ground water table, the organics will be oxidized and little or no peat will accumulate. If the groundwater table is too high, a lake or bay forms an the swamp vegetation cannot grow. Therefore, a delicate balance must be maintained between the depositional interface and groundwater table.

Fourth, a favorable climate for the high productivity of vegetation must be present. The Jurassi was a time of dry desert climate in the Western Interior. A sub-tropical to tropical climate developed sometime in the Early Cretaceous and persisted until near the end of the Eocene. During the mid- to late Tertiary, a drier climate returned. Thus, for about 45 million yrs the climate was favorable for the prolific accumulation of organic matter in swamps. Coleman and others (1970) report an overall accumulation rate of 0.33 ft of peat per century in a large fresh water swamp on the Klang-Langat delta of Malays The maximum rate was 20 ft of peat in about 4500 yrs. Similar rates of peat accumulation are likely to have occurred in the Cretaceous and early Tertiary.

Fifth, the persistance of the above condition in time and space is essential to develop thick coal. This factor is sometimes difficult to evaluate from t study of modern swamps and marshes and even more diffi cult in ancient sequences. Coal thickness is a function of many variables; however, the influence of tectonics on sedimentation is a largely overlooked, but extremely important factor in the development of thick coals. If the above constraints are accepted, thick Cretaceous and lower Tertiary coal beds require a delicate balance between rates of peat accumulatio and rates of subsidence. Even thin coals are sensitive indicators of a local or regional tectonic influence on sedimentation. If a conversion factor of 5 ft of peat compacting to 1 ft of bituminous coal is used, a 5 ft thick coal bed must have formed from 25 ft of peat. Ting (1972, p. 24) reports a compressio factor of 4.3 in a study of a Paleocene lignite in North Dakota.

MODERN ENVIRONMENTS OF PEAT ACCUMULATION

Modern peat accumulates in a wide range of deposition environments. Research in recent years by many workers indicates that the commercial coals of the Cretaceous and Tertiary accumulated in alluvia and delta plain environments. For the sake of brevit

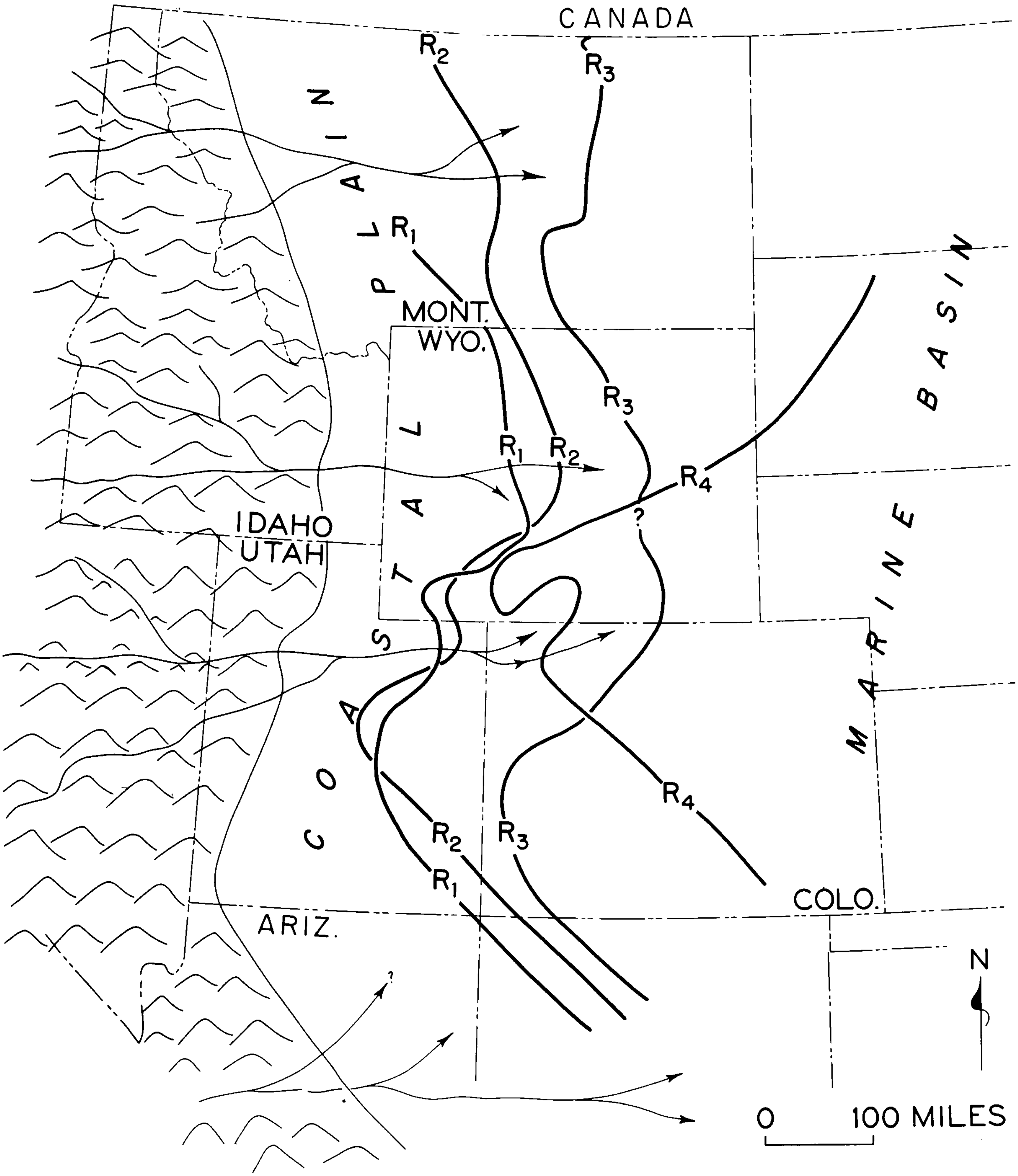


Fig. 2. Position of shorelines during major regressive cycles in Upper Cretaceous of Rocky Mountain region. R_1 is oldest. Refer to Fig. 4 for stratigraphic setting of coals (*after* Weimer, 1970).

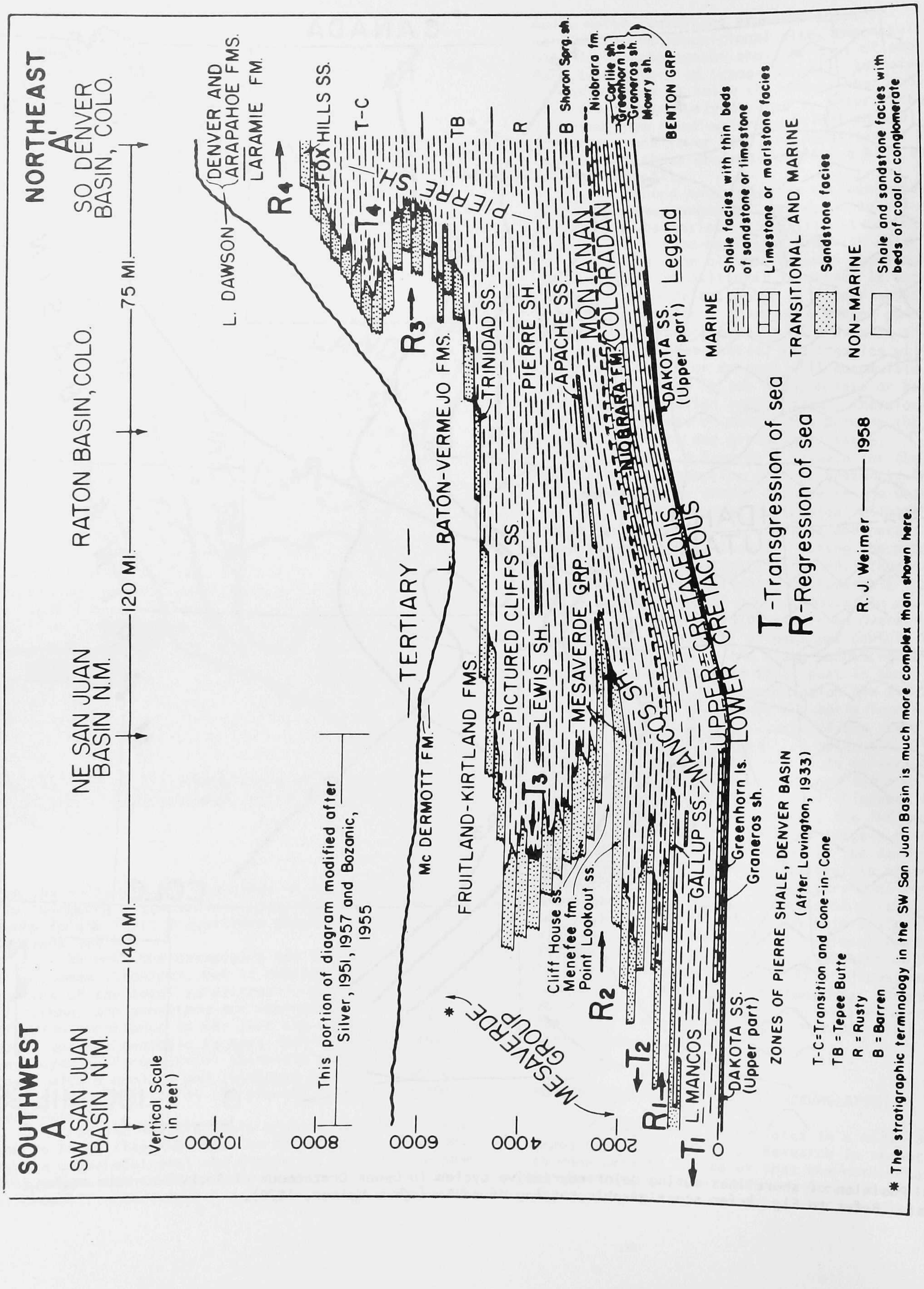


Fig. 3. Restored stratigraphic section across western portion of Cretaceous depositional basin, showing stratigraphic distribution of coal-bearing facies (*after* Weimer, 1960). Line of section shown on Fig. 4.

only the important processes relating to peat accumulation in these environments are considered, and discussion is omitted of the peat-forming environments of modern coastal plains which are judged to be of lesser importance in the origin of western coals.

The terminology most commonly used for the different components of modern alluvial--delta systems is shown on Figure 5 (Gagliano and McIntire, 1968). Frazier and Osanik (1969) describe Holocene peat deposits of the Louisiana coastal plain which are generally associated with shifting deltaic lobes of the Mississippi River. Coleman (1966) discusses the depositional environments of peat associated with freshwater clays in the Mississippi River alluvial valley. From these and other papers, the processes operating within the lower alluvial valley and upper delta plain (Fig. 5) seem the most likely ones to produce the thick peat accumulations necessary to form commercial coal. The channel-margin and flood basin (marginal basin) sub-environments are the loci of peat deposition.

Depositional processes operating on the margin of a large active river are summarized on Figures 6 and 7. Vertical levee growth occurs when fine sand, silt, and clay carried in suspended load are deposited during the time the levee is submerged during the high floods. Repeated flooding, with accompanying deposition, results in the channel and levee system standing topographically above the flood basin of the river. Swamps form marginal to the levee and lakes or bays may develop further into the flood basins.

Two types of swamps--poorly drained and well drained--have been reported in the channel margin area of the modern Mississippi River by Coleman (1966). The type of swamp is controlled by the level of the groundwater table in relation to the depositional interface. When the river floods and the groundwater table rises in the channel margin area (Fig. 6), the depositional interface is covered by water in the entire swamp area. During dry periods, the river level and groundwater table are lower and water drains from the topographically high well-drained swamps. Water continuously covers the topographically low, poorly drained swamps. In areas where the groundwater table is too high above the deposition interface to permit abundant growth of vegetation, the swamps give way to lakes or bays. Under favorable conditions, poorly drained swamps may extend over large areas of the flood basin and widespread layers of peat accumulate.

The position of groundwater table relative to the depositional interface is critical in the preservation of organic material. In the poorly drained

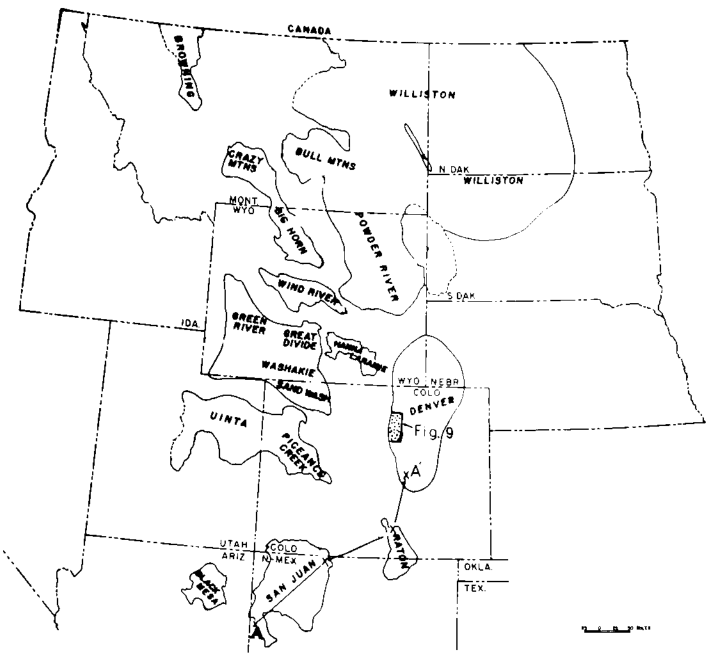


Fig. 4. Map showing major intermontane basins of Rocky Mountain region in which Cretaceous and Tertiary coal-bearing strata are present (*after* Weimer, 1960).

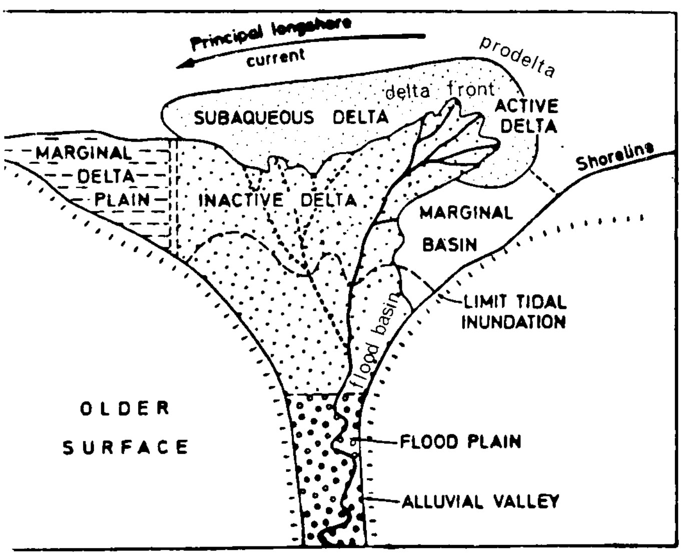


Fig. 5. Major physiographic components of an alluvial-delta system (*modified after* Gagliano and McIntire, 1968).

Table 1. Factors controlling formation of commercial thickness of coal.

1. FRESH, CLEAR WATER
2. ACCUMULATION OF LAND-DERIVED ORGANICS ONLY
3. BALANCE BETWEEN GROUND WATER TABLE AND DEPOSITIONAL INTERFACE
4. FAVORABLE CLIMATE
5. PERSISTANCE OF CONDITIONS IN TIME AND SPACE

(TECTONIC INFLUENCE ON SEDIMENTATION)

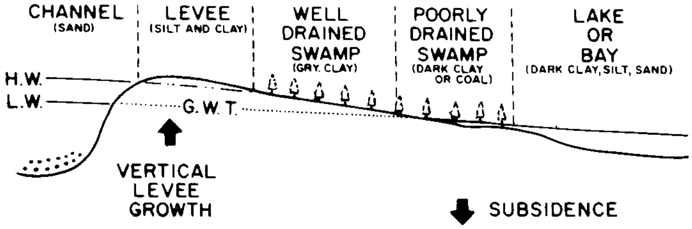


Fig. 6. Environments of deposition and processes occurring in channel--channel margin areas (*after* Weimer, 1973).

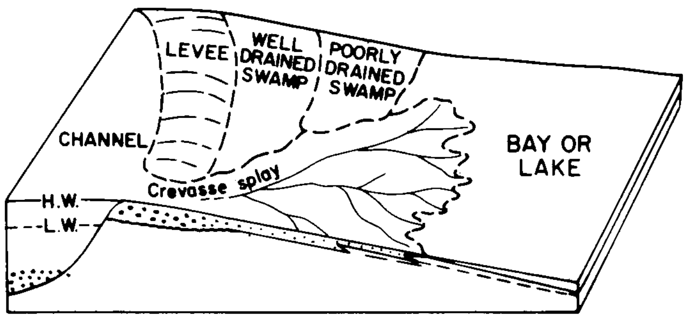


Fig. 7. Relationship of crevasse splay to other channel margin environments (*after* Weimer, 1973).

Table 2. Major environments of deposition of peat during Cretaceous and Tertiary.

IN-SITU COAL
1. CHANNEL MARGIN
   BACK-LEVEE SWAMPS
   FLOOD BASIN SWAMPS
2. CHANNEL-FILL SWAMPS
3. COASTAL SWAMPS (OR MARSHES)

TRANSPORTED COAL

swamps where organic material accumulates rapidly and the depositional interface is continuously covered with water little oxidation occurs and peat forms. However, in the well-drained swamps the accumulating organic material is exposed to the atmosphere for several months a year, which is adequate time to allow for oxidation and removal. If clay is present, alteration to kaolinite may occur, and pyrite may change to siderite, or to one of the iron oxides.

The above processes are illustrated on Figures 6 and 7. Breaks in the levee, or crevasses, result in the suspended load of the river being carried into swamps, bays or lakes, and small crevasse-splay deltas (or lacustrine deltas) are formed. If a major channel is cut off by avulsion and detrital sedimentation ceases, poorly drained swamps may rapidly expand, resulting in the deposition of peat over all other types of deposits. Light-colored kaolinitic, leached clays deposited in well-drained swamps may then form the underclay or seat rock of a peat bed, a condition commonly observed with the Cretaceous and Tertiary coals. This relationship may be important in identifying an ancient coal as a channel-margin coal associated with well drained back-levee swamps.

All depositional systems must operate in time and space. The alluvial-delta system has two major phases of activity (Fig. 5 and 8). Sedimentation occurs when the trunk channel and distributary channels are under active flow. An inactive phase develops when avulsion, or river cut off, occurs and the center of sedimentation shifts to another portion of the delta plain. The development of delta lobes through progradation and distributary abandonment are illustrated by Frazier and Osanik (Fig. 8). The occurrence of peat in this framework is illustrated both in the active and inactive phases of detrital sedimentation. By alternation of these processes, cyclic sedimentation occurs, a condition commonly observed in coal-bearing sequences of the alluvial-delta setting.

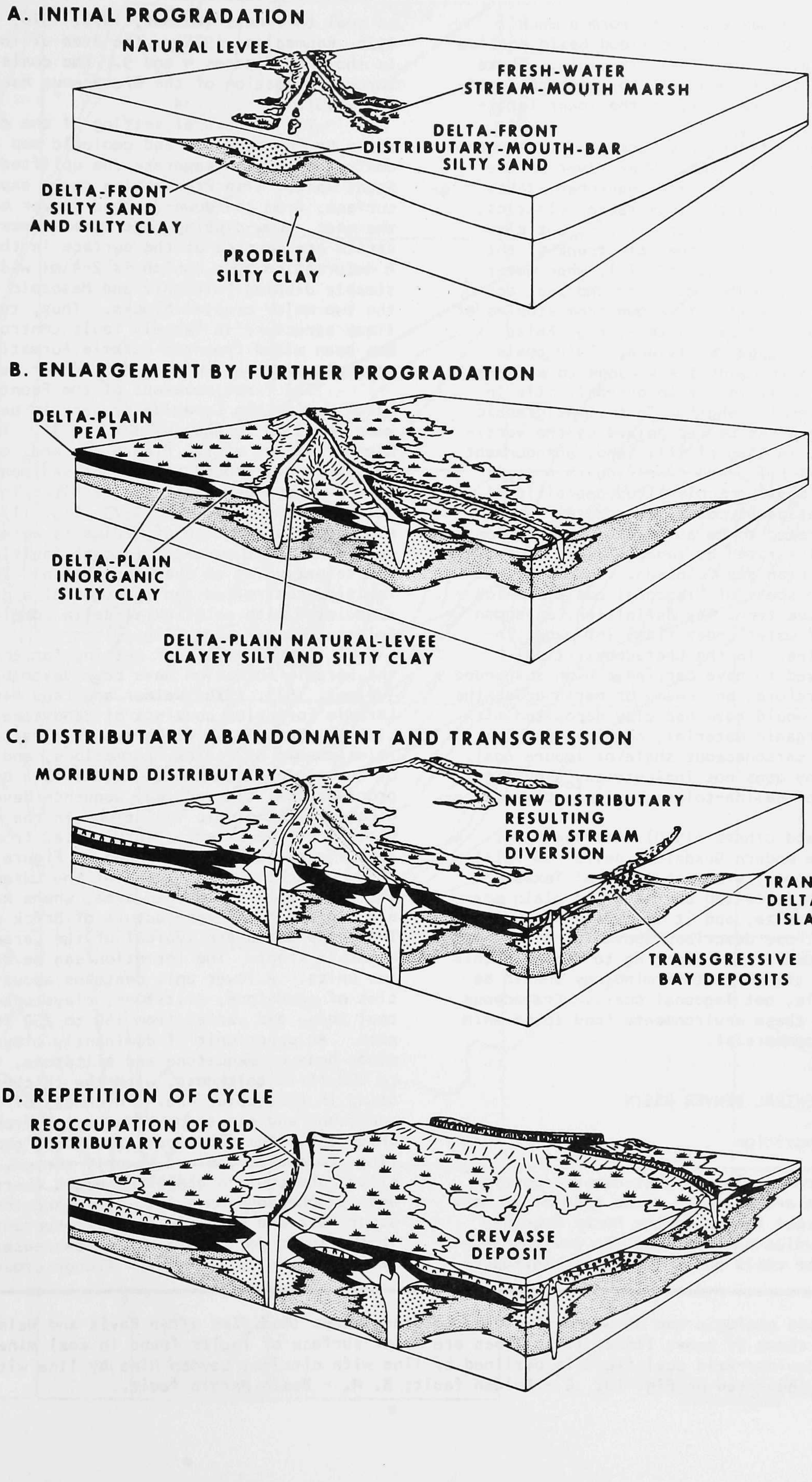
COMMON ENVIRONMENTS OF WESTERN COALS

From recent work by students and myself in several of the major coal basins of the Rocky Mountain region, and from published work of others, the common environments of western coals can be identified (Table 2). The two major categories are *in-situ* coal and transported coal. *In-situ* coals formed in place in swamps and marshes as evidenced by underlying root zones. These coals are of primary interest in coal exploration. Transported coals formed from compaction of organic material that was transported by water from swamps or marshes to another depositional site. These coals do not have associated root zones, are thin with limited geographic distribution, and generally are not of economic interest.

In-situ coals form largely in three environments (Table 2). The most important for the western coals are back-levee or flood basin (marginal basin) swamps that form marginal to a leveed channel. Back-levee swamps are generally linear and parallel to the

Fig. 8. Relationship of peat occurrence to delta processes during active and inactive phases of detrital sedimentation in Mississippi Delta region (*after* Frazier and Osanik, 1969). Published with permission of the Geological Society of America.

→


A. INITIAL PROGRADATION
NATURAL LEVEE
FRESH-WATER STREAM-MOUTH MARSH
DELTA-FRONT DISTRIBUTARY-MOUTH-BAR SILTY SAND
DELTA-FRONT SILTY SAND AND SILTY CLAY
PRODELTA SILTY CLAY
B. ENLARGEMENT BY FURTHER PROGRADATION
DELTA-PLAIN PEAT
DELTA-PLAIN INORGANIC SILTY CLAY
DELTA-PLAIN NATURAL-LEVEE CLAYEY SILT AND SILTY CLAY
C. DISTRIBUTARY ABANDONMENT AND TRANSGRESSION
MORIBUND DISTRIBUTARY
NEW DISTRIBUTARY RESULTING FROM STREAM DIVERSION
TRANSGRESSIVE DELTA-MARGIN-ISLAND SAND
TRANSGRESSIVE BAY DEPOSITS
D. REPETITION OF CYCLE
REOCCUPATION OF OLD DISTRIBUTARY COURSE
CREVASSE DEPOSIT

channel. These swamps may expand to form a much larger swamp occupying much of the flood basin portion of an alluvial valley or upper deltaic plain. These conditions are believed responsible for geographically widespread coal beds, especially in the lower Tertiary.

A common depositional environment for western coals is the channel-fill swamp. When river meander loops or distributary channels are abandoned, lakes develop which are filled with fine-grained clastics, normally derived from the adjacent levees, but also from occasional flooding from the main trunk of the river. As a last stage of channel-fill, when water depths become shallow, swamps may form and peat accumulates. This process is well known from studies of "oxbow" lakes in modern river systems, e.g. False River north of Baton Rouge, Louisiana. Thin coals deposited in this environment are sinuous to arcuate in outline and are normally less than one-half mile in width and a few miles in length. This stratigraphic setting of coal can often be recognized by the vertical sequence of active channel fill sand, abandonment fine-grained channel fill, and overlying thin coal.

One of the most commonly cited depositional environments of Cretaceous coals are coastal swamps and marshes interpreted to be associated with lagoons. This concept is illustrated by Young's (1955) work in the Book Cliffs of Utah and Colorado. This work has led some authors to speak of "lagoonal coals," which is a poor descriptive term. By definition, a lagoon is a saline body of water under tidal influence inland from a shoreline. In the Cretaceous, tidal currents are believed to have carried a high suspended load of clay. Therefore, any swamp or marsh under the influence of tides would have had clay deposited with the accumulating organic material, conditions which would give rise to carbonaceous shale or impure coal. Further, paleobotany does not indicate any significant contribution of saline-tolerant plants to Cretaceous coals.

Donaldson and others (1970) described peat associated with the modern Guadalupe delta now filling San Antonio Bay (lagoon) along the central Texas coast. The peat is deposited on the delta plain portion of a lagoonal delta, and it is related to processes similar to those described above for large alluvial-delta systems. In referring to coals in this setting, I believe the correct terminology should be lagoonal-delta coals, not lagoonal coals. Cretaceous coals deposited in these environments tend to be thin and generally non-commercial.

COAL IN THE WEST-CENTRAL DENVER BASIN

Environments of Deposition

Coal occurrences in the west-central portion of the Denver basin are believed to be typical of many of the Cretaceous coal fields in the Rocky Mountain region. Recent studies have defined the environments of deposition of the coals and the tectonic influence on coal thickness (Weimer, 1973, 1976; Davis, 1974, 1976, Rahmanian, 1975). The area of investigation is shown on Figures 4 and 9. The coals occur in the Laramie Formation of the Cretaceous Maestrichtian Stage (Fig. 10).

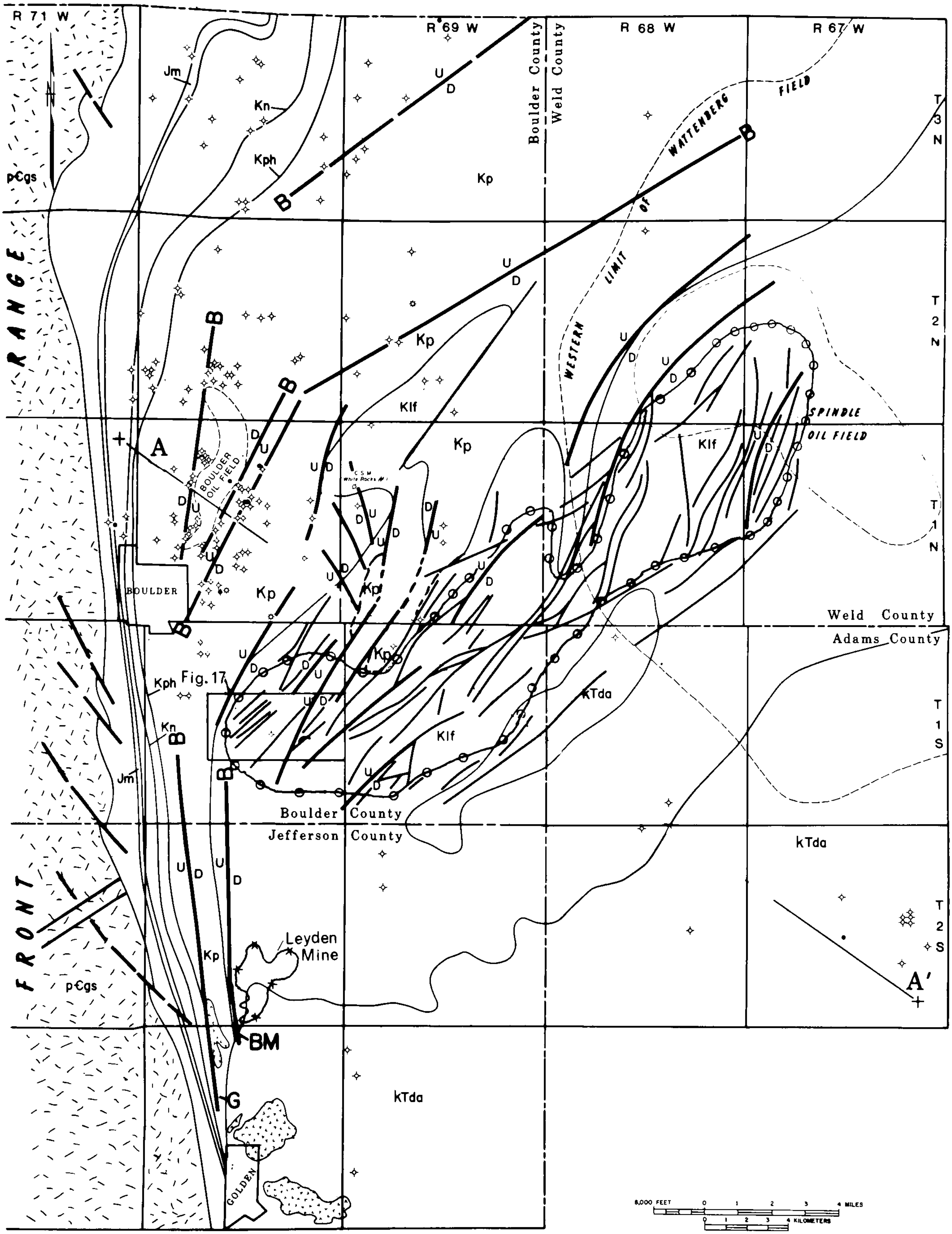
The structural setting of the coal fields is shown by the tectonic and geologic map (Fig. 9). Basin-controlled faults separate the uplifted block of the Front Range, with Precambrian rocks exposed at the surface, from the down-dropped Denver basin block to the east. Low-dipping Upper Cretaceous and Paleocene strata are exposed at the surface in the Denver basin. A deformation zone, which is 2-4 mi wide and contains steeply dipping Paleozoic and Mesozoic strata, separates the two major crustal blocks. Thus, the mountain flank structure is largely fault controlled. Coal has been mined from the Laramie Formation along the mountain flank and within the Denver basin (Fig. 9).

The first movement of the Front Range crustal block during the Laramide orogeny is believed to have been about 70 my ago (Weimer, 1973). The uplifted block rose out of the Pierre sea and, once above sea level, rivers eroded Cretaceous sediment from the land area and deposited the detritus in several small deltas (Weimer and Land, 1975, Fig. 11). The thickness and distribution of sediments were controlled by recurrent fault movement (growth faulting) along faults extending to the Precambrian. This basement faulting controlled the location of a depocenter, associated with an alluvial-delta complex, in the Golden--Boulder area (Fig. 9).

The depositional setting for the coals of the Laramie Formation have been described in detail (Weimer, 1973, 1976; Weimer and Land, 1975). The Laramie Formation consists of sandstone, siltstone, claystone, and coal deposited on a delta plain. The relationship of facies, formations, and environments of deposition is shown on Figure 12. By eastward progradation, the vertical sequence developed as indicated. Lithologic variations in the coal-bearing portion of the Laramie, interpreted from surface and subsurface studies, are shown on Figure 13.

Excellent exposures of the Laramie Formation are present in the Golden area, where kaolinitic clays are mined for the manufacture of brick and tile. These exposures are typical of the Laramie along the mountain front. The formation can be divided into two units. A lower unit contains about equal quantities of sandstone, siltstone, claystone, and thin coal beds, and varies from 150 to 250 ft in thickness. An upper unit of dominantly claystone, with minor beds of sandstone and siltstone, varies from 200 to 800 ft in thickness, with the thicker sections being in the subsurface. Thickness of individual sandstone and claystone beds varies from 20-40 ft (Fig. 13). The sandstones are light gray to buff, fine- to coarse-grained, poorly sorted, subangular, silty, and contain grains of black chert, clay, mica, and carbonaceous material. The sandstones have a scour base and commonly contain abundant clay clasts in the lower part. Grain size decreases upward from medium and coarse to fine. Trough cross-stratification

Fig. 9. Tectonic and geologic map of Golden-Boulder, Colorado, area (*modified after* Davis and Weimer, 1976). Seismic faults are shown by heavy lines; light lines are major surface or faults found in coal mines. B indicates basement faults. Boulder-Weld coal field is outlined by line with circles; Leyden Mine by line with x's. Symbols for formations are indicated on Fig. 10. G - Golden fault; B. M. - Basin Margin fault. →


R 71 W
R 69 W
R 68 W
R 67 W
T 3 N
T 2 N
T 1 N
T 1 S
T 2 S
FRONT RANGE
Boulder County
Weld County
Adams County
Jefferson County
WESTERN LIMIT OF WATTENBERG FIELD
SPINDLE OIL FIELD
BOULDER OIL FIELD
BOULDER
GOLDEN
Leyden Mine
Fig. 17
A
A'
BM
G
pЄgs
Jm
Kn
Kph
Kp
Klf
kTda
U
D
B
8,000 FEET
MILES
KILOMETERS

with sets as much as 8 in. thick, is common in the lower part of the sandstone units, and ripple lamination is prevalent in the upper part. Large-scale load casts are common along the contact of the sandstone units with underlying claystone. The bases of the load casts have a bulbous shape 10-50 ft across, and claystone has been pierced vertically as much as 10 ft. Concentrations of log imprints are present along the base and within the sandstones. The logs average 12 in. in diameter and are commonly 10-20 ft in length. Directional studies of cross-stratification, orientation of logs, and clay clast imbrication indicate an east-southeast transport direction. Minor sets of fractures, some with observable offsets of as much as several feet, are present in the upper part of the sandstone units.

The kaolinitic claystone units of the lower Laramie contain several lithologies. Light- to medium-gray, blocky-weathering claystone is the dominant lithology, with lesser quantities of dark-gray to black carbonaceous claystone and thin coal streaks. Several thin layers are shades of pink, light red, yellow, and tan in color. Iron-rich concretionary siltstone layers (ironstone) from one to four in. thick are common. The claystone is generally structureless, but in a few occurrences light gray claystone contains conchoidal fractures with grooving and polishing similar to slickensides. These breaks are referred to as "clay skins" and may be caused by expansion of roots which were later removed by oxidation. Plant remains in the form of leaf imprints and stem, branch and twig impressions are common. Palm fronds were collected when the clay mining was active in the area. The color of the claystone is a function of the amount of carbonaceous material present and the state of the iron, reduced or oxidized. The claystone in the lower Laramie is dominantly kaolinite of a quality suitable for brick and tile.

The upper Laramie in the Golden area has an outcrop thickness of 160-200 ft and is similar in lithology to the lower Laramie, except that the sandstone units are much thinner (less than 15 ft thick) and are finer grained. Coal and carbonaceous shale is absent in the upper Laramie claystone. Some parts of the claystone show fine laminations instead of having a uniform blocky appearance.

The only fossils found in the Laramie Formation in the Golden area are plant or tree impressions and root zones. Claystones from the Golden area were washed and examined for foraminifera in the course of this study, but none was observed. The Laramie Formation in the Golden area is indicated to have a fresh water origin.

To the north in the Boulder area, molluscan faunas are reported from the lower Laramie by Spencer (1961). Rahmanian (1975) reported trace fossils and oysters in the lower Laramie southeast of Boulder, suggesting brackish to marine water incursions.

The repetitive lithologies of the coal-bearing lower Laramie are related to environments of deposition (see Table 3). The coals mined in the Golden and Leyden areas are interpreted to be deposits of back-levee, poorly drained swamps. The light-colored and pink, kaolinitic claystones are oxidized and leached deposits of the well-drained swamps. Sandstones were deposited as crevasse splays and in major river channels. The medium- to dark-gray, laminated claystones and shales are deposits of lake or bay environments.

Coals in the Boulder area are interpreted to be back-levee (poorly drained swamp) or flood basin deposits. The Boulder-Weld coal field appears to be located on the north margin of the alluvial-delta complex centered in the Golden-Leyden area (Figs. 9 and 13). This interpretation is based on the absence of major channel sandstones and the presence of intercalated marine to brackish water deposits, possibly originating in marginal or flood basins.

Tectonic Influence on Coal Thickness

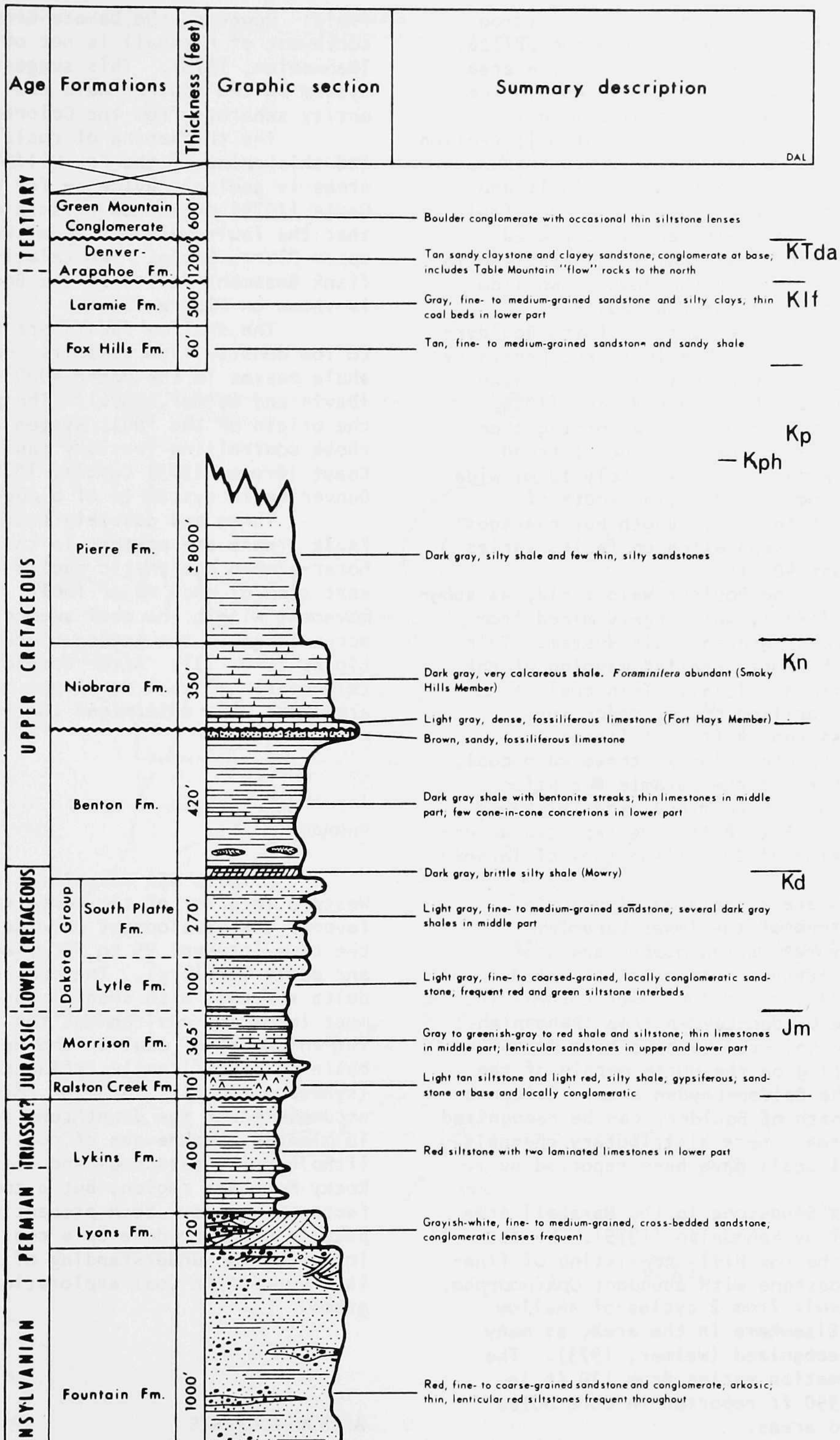
Two major coal areas in the west-central Denver basin show a tectonic influence on coal thickness. Growth faulting (syndepositional), which influenced the thickness of the Fox Hills and Laramie Formations, has been described by Weimer (1973, 1976), in the Golden-Leyden area; and by Rahmanian (1975) and Davis and Weimer (1976) in the Boulder-Weld coal field. Two types of faulting are recognized. Deep-seated basement-controlled faulting is observed in the Leyden Mine area and, this type, together with shallow listric normal faulting, are found in the area of the Boulder-Weld coal field.

Structurally, the Leyden Mine (Fig. 9) is located in the Denver basin block just east of the mountain flank deformation zone which contains nearly vertical-dipping beds (Fig. 14). The Leyden Mine was shut down in 1952; since that time, however, Public Service Company of Colorado has converted the old mine to an underground natural gas storage facility.

The Leyden Mine extracted coal from 2 beds ("veins") at depths varying from 800 to 1000 ft. The stratigraphically higher A coal is separated from the underlying B coal by a claystone and siltstone interval. From north to south across the mine area, this interval thickens from 20 to 80 ft (Camacho, 1969). The B coal is 100 to 150 ft above the Laramie-Fox Hills contact. The total mined area is between 2 and [illegible] sq mi. Core hole data indicate that the A coal, where mined, varied in thickness from 4 to 8 ft, and that the more extensive B coal varied from 6 to 11 ft. The coals are thinner in the surface outcrop than in the mined area, either because of depositional thinning controlled by faulting, or because of thinning of the coals by attenuation in the nearly vertical outcrops. The disappearance of the coal at the north edge of the mine is interpreted by Camacho (1969) to be a result of channel cut-out (Fig. 13). To the south, disappearance of the coal results from facies change to channel-levee deposits.

The total thickness of the Laramie Formation east of the outcrop is in excess of 1000 ft, as determined from the old mine shafts and wells drilled by the Public Service Company for gas storage in the abandoned Leyden Mine. As shown on the map and structure section (Figs. 9 and 14), the Basin Margin fault is interpreted to be present between the nearly vertical beds of the Laramie hogback and the low structural dip in the area of the Leyden Mine. The fault is necessary

Fig. 10. Generalized stratigraphic column for Golden area (*after* LeRoy and Weimer, 1971). →


Age
Formations
Thickness (feet)
Graphic section
Summary description
DAL
TERTIARY
Green Mountain Conglomerate
600'
Boulder conglomerate with occasional thin siltstone lenses
Denver-Arapahoe Fm.
1200'
Tan sandy claystone and clayey sandstone; conglomerate at base; includes Table Mountain "flow" rocks to the north
KTda
Laramie Fm.
500'
Gray, fine- to medium-grained sandstone and silty clays; thin coal beds in lower part
Klf
Fox Hills Fm.
60'
Tan, fine- to medium-grained sandstone and sandy shale
UPPER CRETACEOUS
Kp
— Kph
Pierre Fm.
±8000'
Dark gray, silty shale and few thin, silty sandstones
Kn
Niobrara Fm.
350'
Dark gray, very calcareous shale. Foraminifera abundant (Smoky Hills Member)
Light gray, dense, fossiliferous limestone (Fort Hays Member)
Brown, sandy, fossiliferous limestone
Benton Fm.
420'
Dark gray shale with bentonite streaks, thin limestones in middle part, few cone-in-cone concretions in lower part
Dark gray, brittle silty shale (Mowry)
Kd
LOWER CRETACEOUS
Dakota Group
South Platte Fm.
270'
Light gray, fine- to medium-grained sandstone; several dark gray shales in middle part
Lytle Fm.
100'
Light gray, fine- to coarsed-grained, locally conglomeratic sandstone, frequent red and green siltstone interbeds
JURASSIC
Jm
Morrison Fm.
365'
Gray to greenish-gray to red shale and siltstone; thin limestones in middle part; lenticular sandstones in upper and lower part
Ralston Creek Fm.
110'
Light tan siltstone and light red, silty shale, gypsiferous; sandstone at base and locally conglomeratic
TRIASSIC?
PERMIAN
Lykins Fm.
400'
Red siltstone with two laminated limestones in lower part
Lyons Fm.
120'
Grayish-white, fine- to medium-grained, cross-bedded sandstone; conglomeratic lenses frequent
PENNSYLVANIAN
Fountain Fm.
1000'
Red, fine- to coarse-grained sandstone and conglomerate, arkosic; thin, lenticular red siltstones frequent throughout
PRECAMBRIAN
p€gs
Gneiss, schist, and small granitic intrusions

to account for the thickness and dip of the outcrop sections relative to the thickness in the subsurface. An east-west seismic section in the Leyden Mine area indicates that the Basin Margin fault extends to the Precambrian (T.L. Davis, 1976, personal commun.). Figure 15 is an east-west restored stratigraphic section across the Leyden Mine area showing observed thickness variation of coal across the Basin Margin fault and a hypothetical interpretation across the Golden fault to the west (Fig. 9). The faults are interpreted to have cut the back-levee coal swamps and resulted in greater accumulation of peat on the downthrown side compared to the upthrown side of the faults.

The stratigraphy and structure of the Boulder-Weld coal field has been described in recent papers by Spencer (1961), Colton and Lowrie (1973), Rahmanian (1975), Weimer (1976), and Davis and Weimer (1976). The coal field is located in a complex horst-graben fault system which has a dominant northeast trend (Fig. 9). The fault zone is approximately 10 mi wide and 25 mi long. The coal field, lying south of Boulder Creek, is about the same length but averages 4 mi in width. Vertical separation on faults varies from a few feet to over 400 ft.

Laramie coal in the Boulder-Weld field, as shown by Colton and Lowrie (1973), was largely mined from graben areas in the horst-graben fault system. This association is shown by more detailed mapping of the Marshall area by Rahmanian (1975). Thin coal is present in core holes drilled on the major horst blocks (generally less than 4 ft in thickness).

According to Spencer (1961), three main coal beds in the lower 125 ft of the Laramie Formation were mined in the area. Where mined, the thickness of the beds varied from 5 to 8 ft. He reported an estimated total production of 20 million tons of largely subbituminous B coal.

The coal beds are associated with shale, siltstone, and sandstone of the lower Laramie. Occurrences of the oyster *Ostrea glabra* and some highly burrowed beds suggest more brackish water environments of deposition for the lower Laramie in this area than in the Golden-Leyden area (Rahmanian, 1975). The coals are believed to have been deposited on a delta-plain setting on the north margin of the delta described in the Golden-Leyden area. Evidence for another delta, north of Boulder, can be recognized in the White Rocks area, where distributary channels and thin channel-fill coals have been reported by Weimer (1973, 1976).

The Fox Hills Sandstone in the Marshall area was studied in detail by Rahmanian (1975). He described two units in the Fox Hills consisting of fine- to medium-grained sandstone with abundant *Ophiomorpha*.

The units result from 2 cycles of shallow marine deposition. Elsewhere in the area, as many as 4 cycles can be recognized (Weimer, 1973). The thickness of the formation varies from 120 ft in surface outcrops to 350 ft reported in core holes in the graben faulted areas.

Previous workers (e.g., Spencer, 1961) suggested that northeast-trending shear zones in the Precambrian, associated with the Colorado Mineral Belt, may project into the area of Boulder-Weld coal field. However, the Dakota Group in the hogback southwest of Marshall is not offset by faulting (Rahmanian, 1975). This suggests that the fault system in the Boulder-Weld coal field area is an entity separate from the Colorado Mineral Belt.

The thickening of coals in the lower Laramie and thickening of the Fox Hills Sandstone in graben areas is geologic evidence for growth fault movement. Davis (1974) presented seismic evidence indicating that the faults die out at a shallow depth in the upper Pierre Shale. The relationship of the mountain flank basement faults to the Boulder-Weld fault zone is shown on Figure 16.

The shallow faults are believed to be related to low density, low velocity, possibly overpressured, shale masses in the upper 4000 ft of the Pierre Shale (Davis and Weimer, 1976). The processes controlling the origin of the fault system appear similar to those controlling Tertiary fault systems in the Gulf Coast (Bruce, 1973; Curtis, 1970); however, the Denver basin system is of a much smaller magnitude.

Three and possibly four major listric normal fault trends are present in the fault zone. Secondary horst-graben antithetic faults are found on the southeast side of each major fault. Because of fault movement within the coal swamps, more organic material accumulated in the graben blocks than over the horst blocks (Fig. 17). After compaction, commercial thicknesses of coal developed mainly in the graben areas and thus determined the location of underground mining.

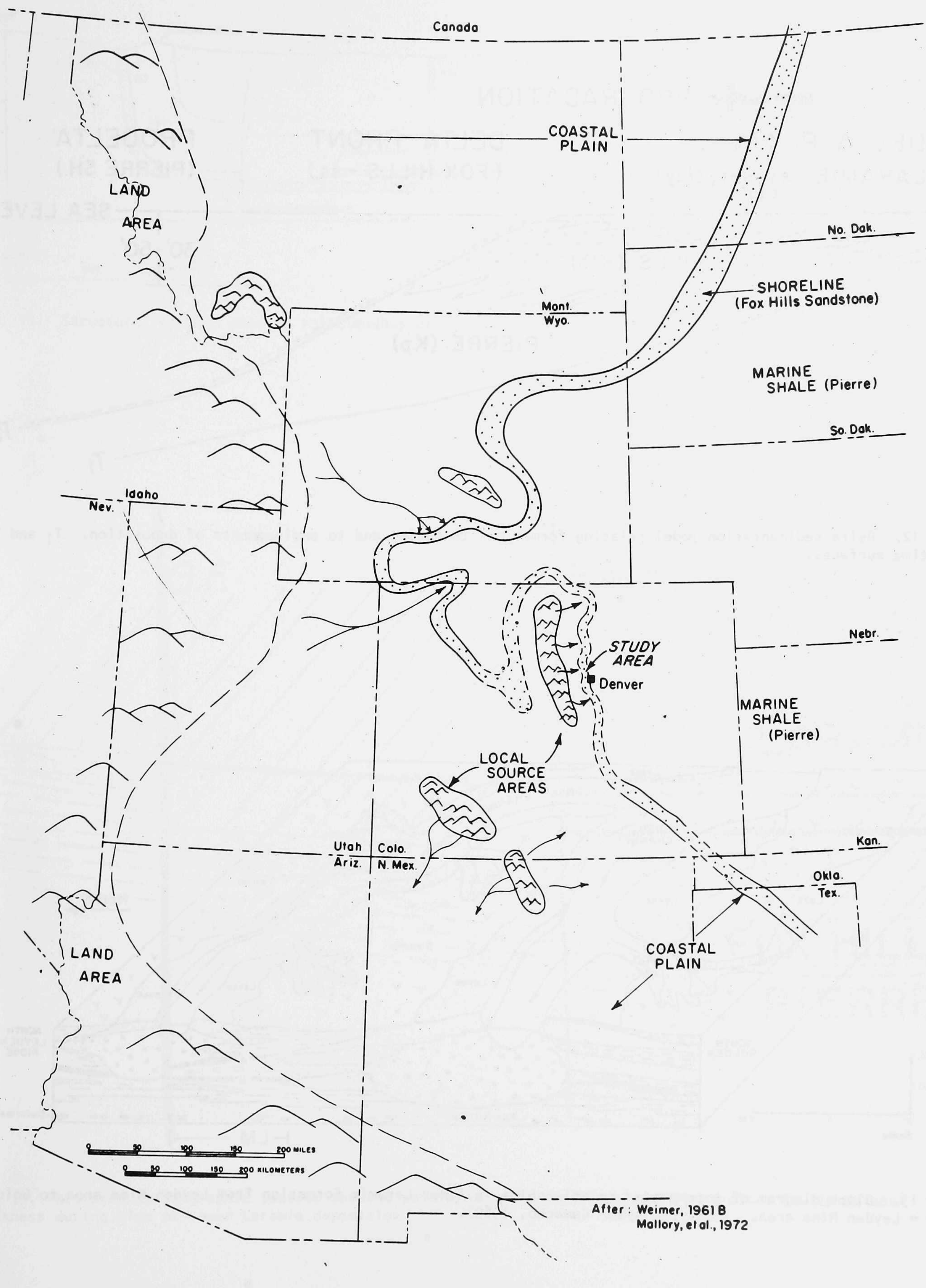
SUMMARY

Climate and deposition conditions in the Western Interior of the North American Continent favored the development of widespread coal swamps for the time interval 95 to 50 my ago (Late Cretaceous and early Tertiary). The coal swamps formed in fluvial delta systems, with channel margin swamps being the most important environment for development of coal. The thickness of coal in the west-central Denver basin is significantly influenced by growth faulting (syndepositional). Greater thicknesses of peat accumulated on the downthrown side of faults, resulting in minable thicknesses of coal. Coal is a widespread lithology in Cretaceous and Tertiary strata in the Rocky Mountain region, but a combination of geologic factors must have been present during deposition of peat in order to develop a coal thickness of economic interest. An understanding of these geologic factors is important in coal exploration and development programs.

ACKNOWLEDGMENTS

I express sincere appreciation to Cooper B. Land and John D. Haun for valuable suggestions for improving the content and format of this paper.

Fig. 11. Regional index map showing study area and paleo environments during late Fox Hills deposition--near end of time of *Baculites clinolobatus* range zone (*after* Weimer and Land, 1975). →


Canada
COASTAL PLAIN
LAND AREA
No. Dak.
SHORELINE (Fox Hills Sandstone)
Mont.
Wyo.
MARINE SHALE (Pierre)
So. Dak.
Idaho
Nev.
STUDY AREA
Denver
Nebr.
MARINE SHALE (Pierre)
LOCAL SOURCE AREAS
Utah
Ariz.
Colo.
N. Mex.
Kan.
Okla.
Tex.
COASTAL PLAIN
LAND AREA
0 50 100 150 200 MILES
0 50 100 150 200 KILOMETERS
After: Weimer, 1961B
Mallory, et al., 1972

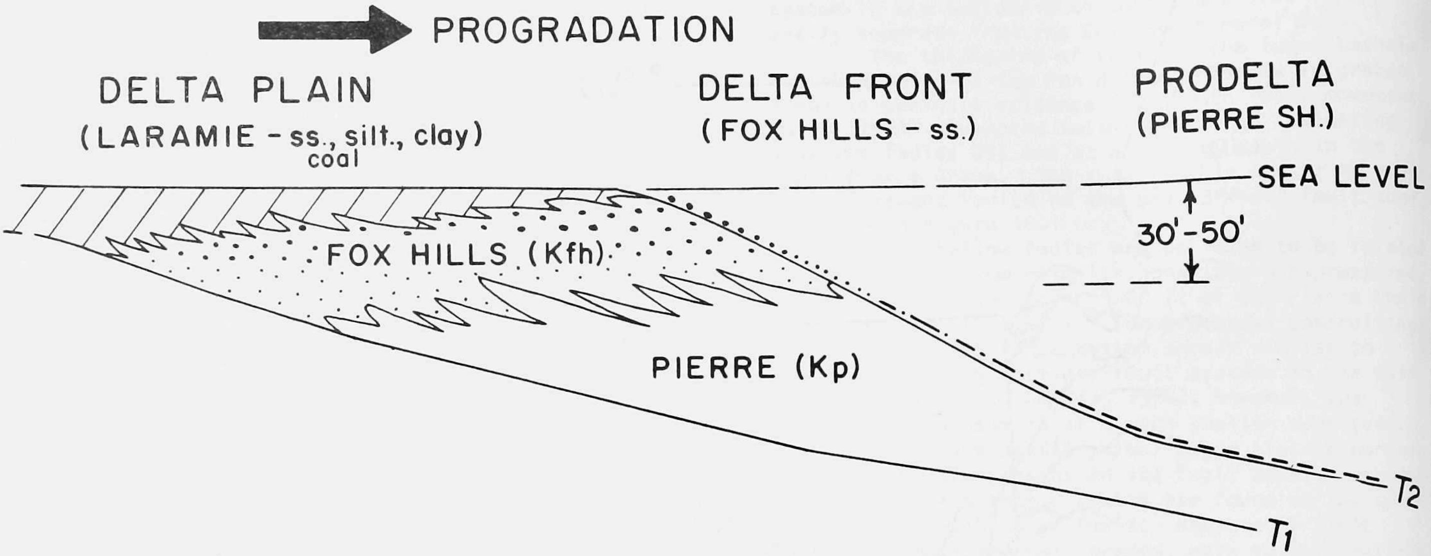


Fig. 12. Delta sedimentation model relating formations to facies and to environments of deposition. T_1 and T_2 are time surfaces.

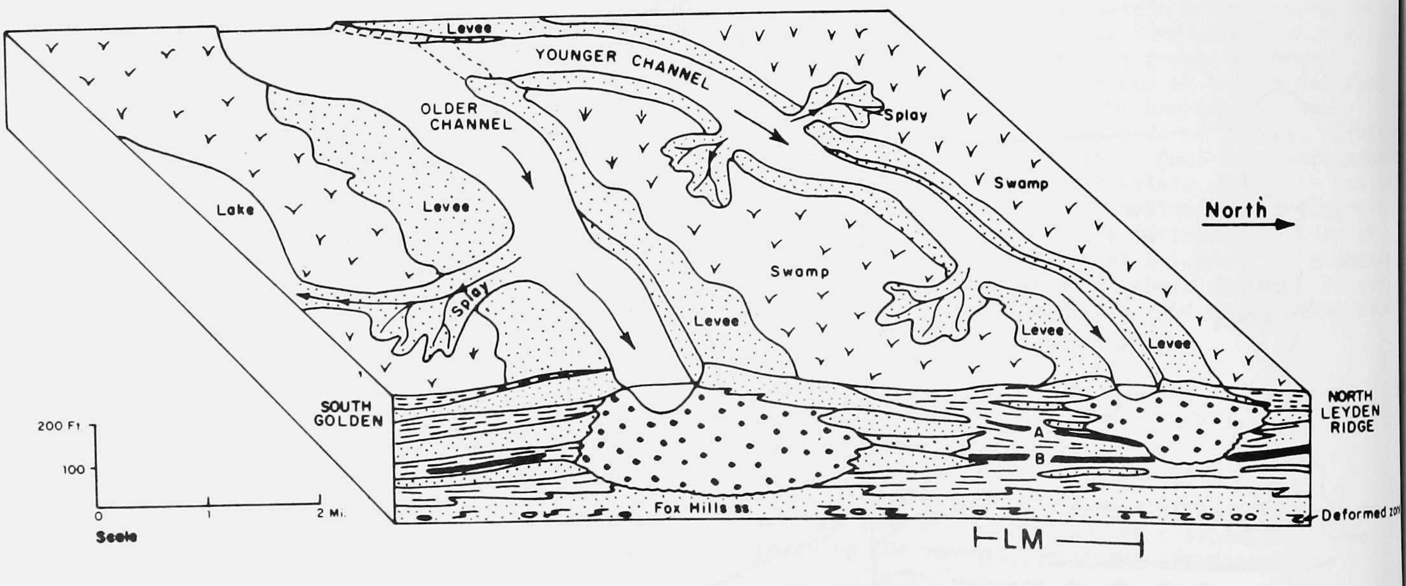


Fig. 13. Block diagram of interpreted relationships in lower Laramie Formation from Leyden Mine area to Golden. L.M. = Leyden Mine area. (*modified after* Camacho, 1969).

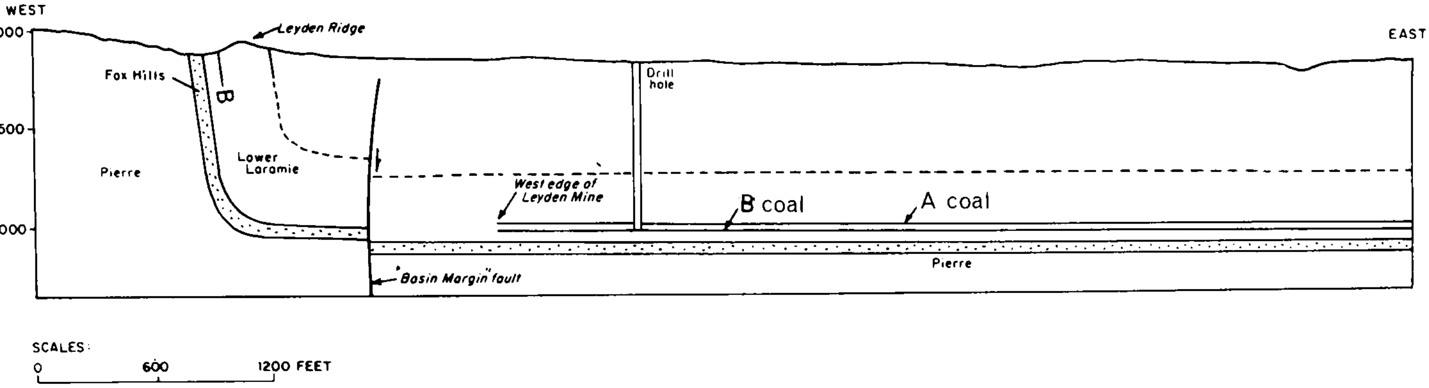


Fig. 14. Structural section showing relationship of Leyden coal mine to outcrop along Leyden Road.

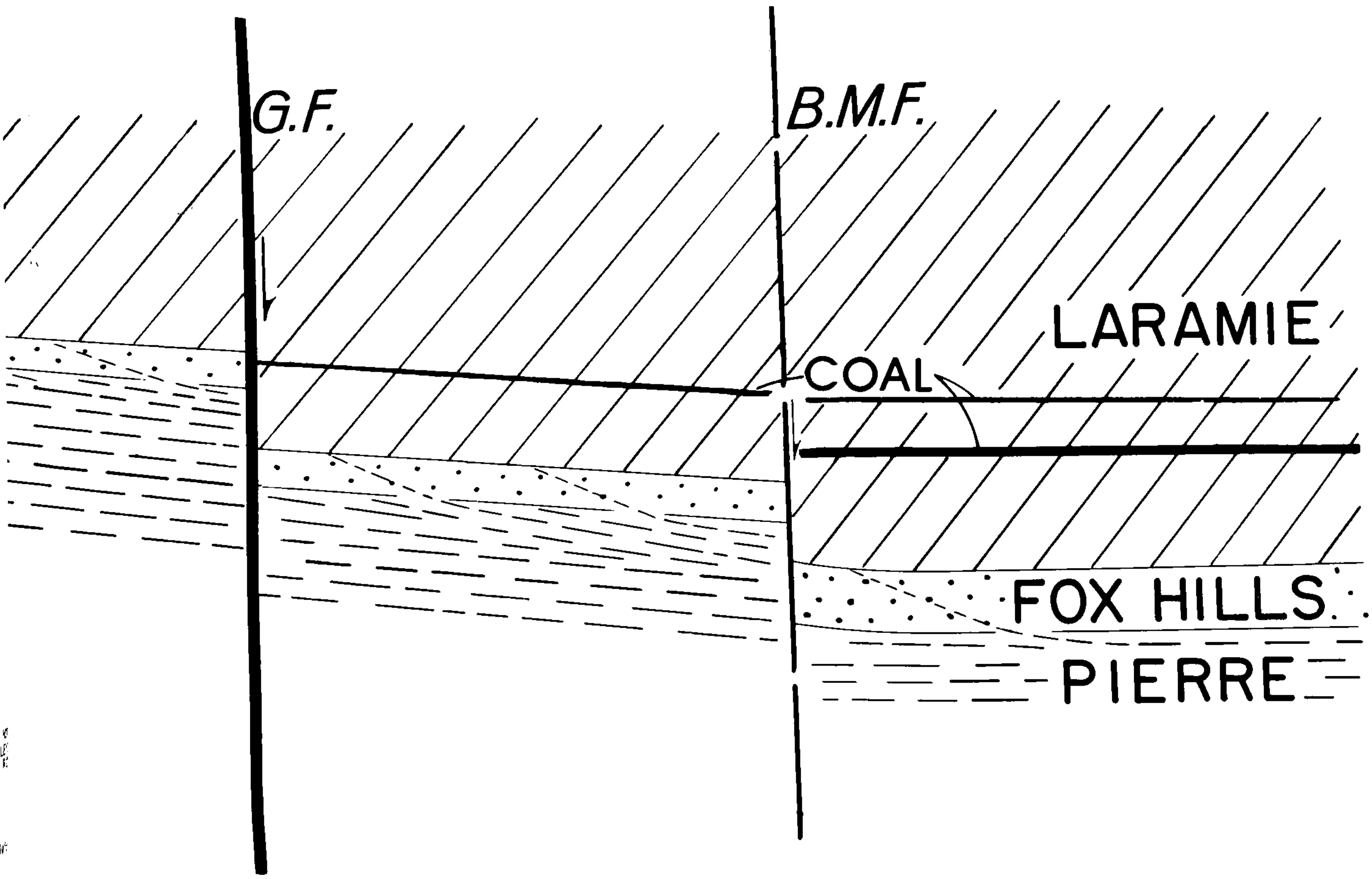


Fig. 15. Restored stratigraphic section showing posulated influence of basement-controlled faults on coal thickness during time of lower Laramie deposition.

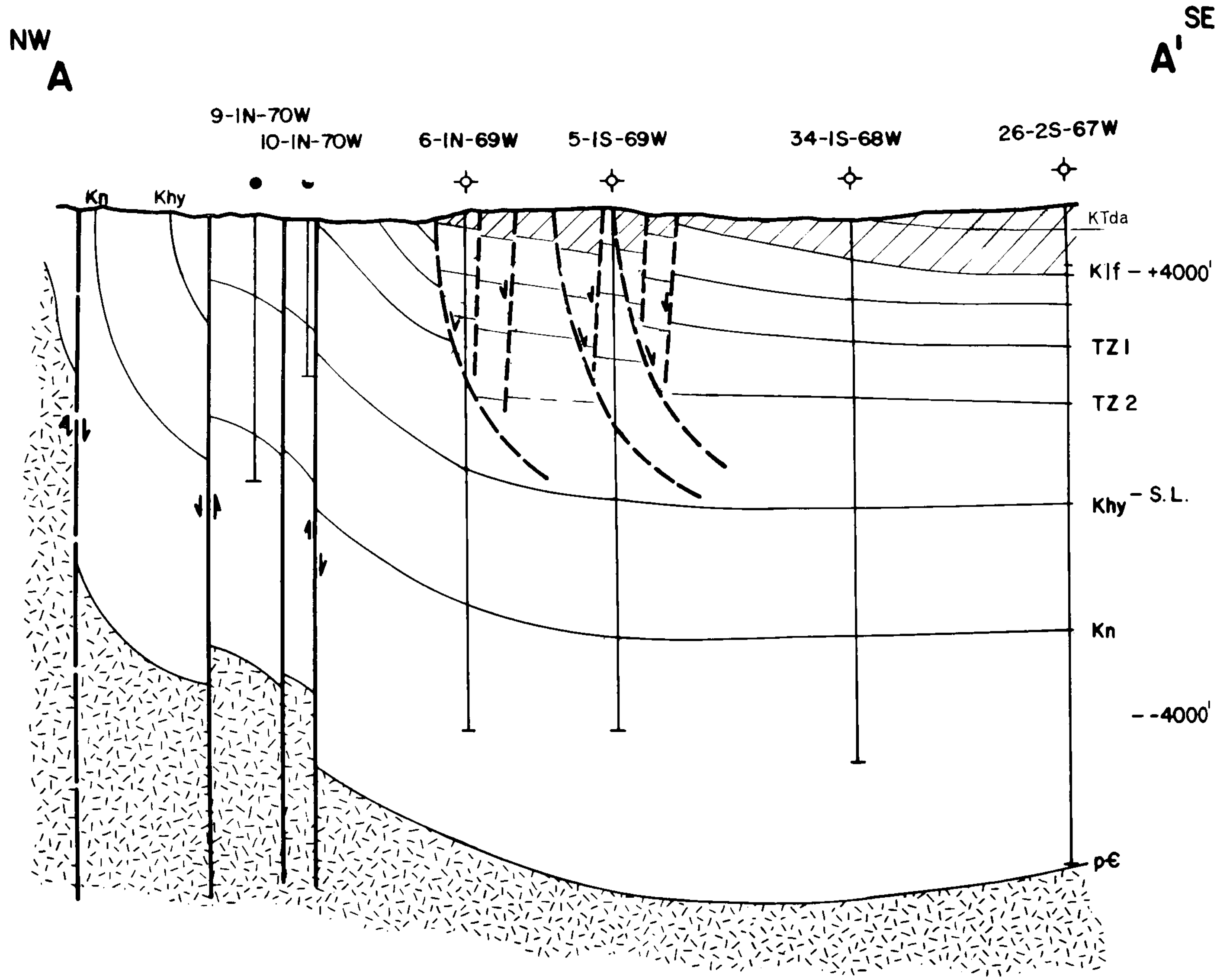


Fig. 16. Composite diagrammatic structural section across Boulder-Weld coal field reconstructed from regional seismic sections and well data. Diagonal ruling indicates coal-bearing interval. Symbols are indicated on Fig. 10. Line of section shown on Fig. 9. (*modified after* Davis, 1974).

REFERENCES CITED

Bruce, C.H., 1973, Pressured shale and related sediment deformation: mechanism for development of regional contemporaneous faults: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 878-886.

Camacho, R., 1969, Stratigraphy of the upper Pierre Shale, Fox Hills Sandstone, and lower Laramie Formation (Upper Cretaceous), Leyden Gulch area, Jefferson County, Colorado [M.S. Thesis]: Golden, Colorado School Mines, 84 p.

Coleman, J.M., 1966, Ecological changes in a massive fresh-water clay sequence: Trans. Gulf Coast Assoc. Geol. Soc., v. 15, p. 159-174.

__________, Gagliano, S.M., and Smith, W.G., 1970, Sedimentation in a Malaysian high tide tropical delta: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 15, p. 185-197.

Colton, R.B., and Lowrie, R.L., 1973, Map showing mined areas of the Boulder-Weld coal field, Colo.: U.S. Geol. Survey Misc. Field Studies Map MF-513.

Curtis, D.M., 1970, Miocene deltaic sedimentation, Louisiana Gulf Coast: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 15, p. 293-308.

Davis, T.L., 1974, Seismic investigation of Late Cretaceous faulting along east flank of Central Front Range, Colorado [Ph.D. Thesis]: Golden, Colorado School Mines, 65 p.

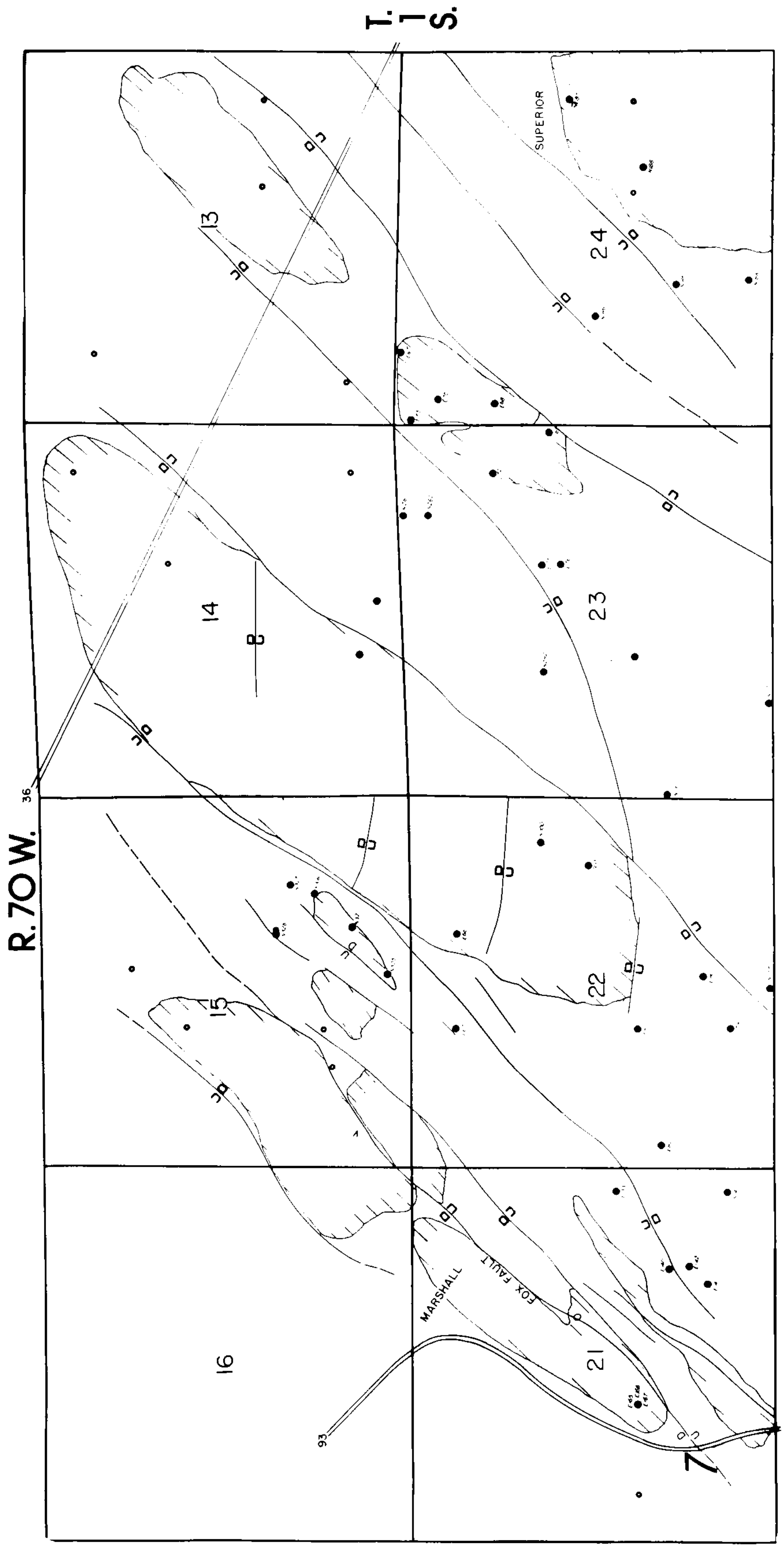


Fig. 17. Map of area 3 miles southeast of Boulder showing a horst-graben faulting and mined areas in Boulder-Weld coal field (*modified after* Rahmanian, 1975).

Table 3. Summary of diagnostic characteristics of Laramie Formation, Golden, Colorado.

	Channel[1]	Swamp well-drained	Swamp poorly drained	Lacustrine	Splay sandstone
Lithology	Gray to brown fine to coarse-grained sandstone with clay clasts near base. Fining upward grain size. Large-scale load casts along base. Clay grains common. Scour base.	Light gray and pink kaolinite claystones with iron-rich concretionary layers 1 to 3 in. thick.	Dark gray to black kaolinite claystonel, carbonaceous shale and thin coal seams.	Medium to dark gray claystone and organic rich shale with minor siltstone and very fine-grained sandstone layers.	Gray to brown fine- to medium grained sandstone. Texture fining upward; scour base near main channel; sharp or transitional base away from channel. Sandstone thins and becomes finer-grained away from main channel.
Stratification	Trough cross strata with sets up to 2 ft in thickness in lower part. Ripple microcross-lamination in upper part.	Generally, massive appearing; "clay skin" fracturing by root system expansion is common.	Laminations of bedding present in carbonaceous rich strata.	Generally well laminated or bedded.	Dominantly ripple microcross-lamination; trough cross-stratification common in lower part.
Fossils	Log and leaf imprints common along base.	Occasional carbonized plant fragment or imprint; root systems.	Carbonized plant remains and imprints; root systems	Leaf and plant fragment imprints.	Numerous log imprints as "log jams" common along base; palm fronds and leaf imprints in upper part.

[1]Levees have not been specifically identified in outcrop sections in Golden area.

__________, and Weimer, R.J., 1976, Late Cretaceous growth faulting, Denver basin, Colorado, *in* Studies in Colorado field geology, Epis, R.C. and Weimer, R.J.: Colorado School Mines Prof. Contrib. 8.

Donaldson, A.C., Martin, R.H., and Kanes, W.H., 1970, Holocene Gualalupe delta of Texas Gulf Coast: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 15, p. 107-137.

Frazier, D.E., and Osanik, Alex, 1969, Recent peat deposits--Louisiana coastal plain, *in* Environments of coal deposition, E.C. Dapples and M.E. Hopkins, editors: Geol. Soc. America Spec. Paper 114, p. 63-85.

Gagliano, S.M., and McIntire, W.G., 1968, Reports on the Mekong River Delta: Louisiana State Univ., Coastal Studies Inst. Tech. Rept. 57, 143 p.

Gill, J.R., and Cobban, W.A., 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geol. Survey Prof. Paper 393A, p. 1-73.

Leroy, L.W., and Weimer, R.J., Geology of the Interstate 70 road cut, Jefferson County, Colorado: Colorado School Mines Prof. Contrib. 7.

Rahmanian, V.D., 1975, Deltaic sedimentation and structure of the Fox Hills and Laramie Formation, Upper Cretaceous, southeast of Boulder, Colorado [M.S. Thesis]: Golden, Colorado School Mines, 83 p.

Spencer, F.D., 1961, Bedrock geology of the Louisville quadrangle: U.S. Geol. Survey Quad. Map GQ-151.

Ting, F.T.C., and others, 1972, Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Surv. Misc. Ser. 50, p. 1-30.

Weimer, R.J., 1960, Upper Cretaceous stratigraphy, Rocky Mountain area: Am. Assoc. Petroleum Geologists Bull., v. 44, p. 1-20.

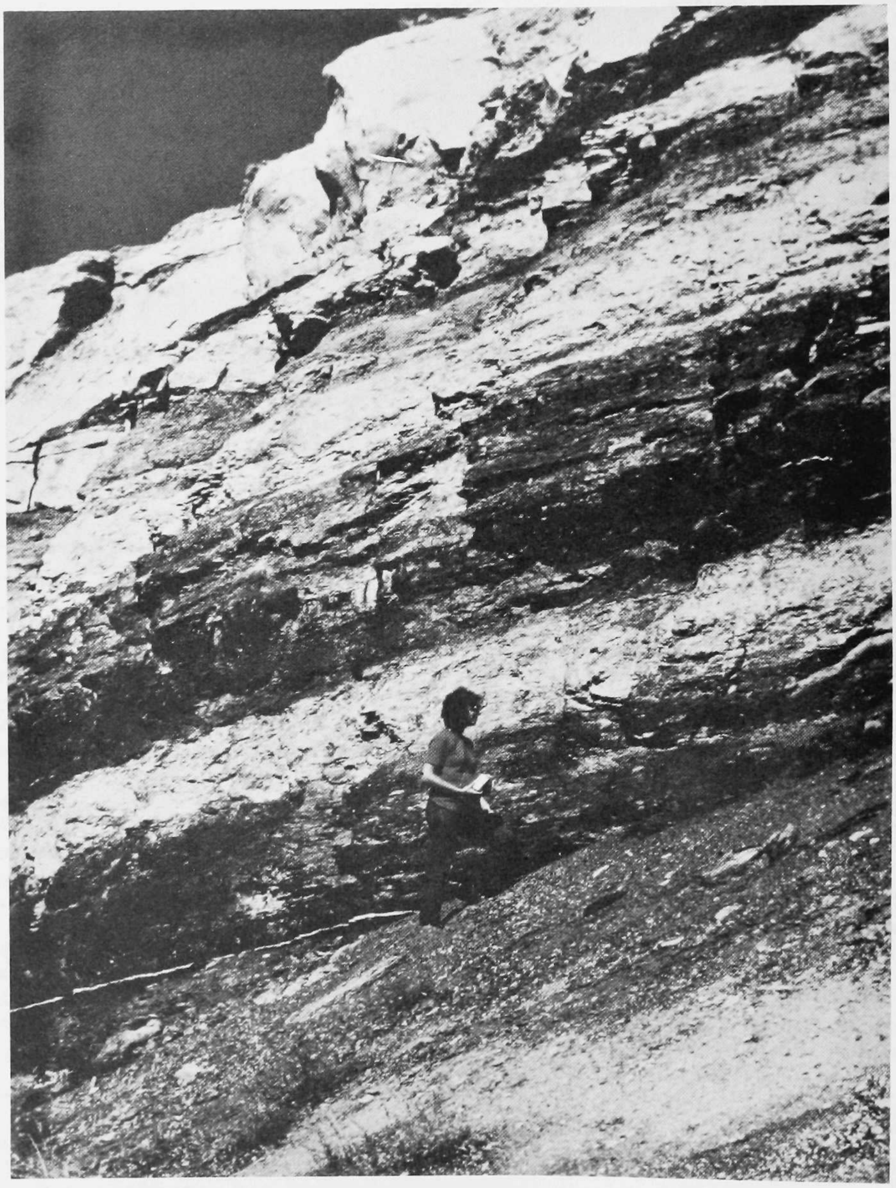
__________, 1970, Rates of deltaic sedimentation and intrabasin deformation, Upper Cretaceous of Rocky Mountain Region: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 15, p. 270-291.

__________, 1973, A guide to upper most Cretaceous stratigraphy, central Front Range: deltaic sedimentation, growth faulting and early Laramide deformation: Mtn. Geologist, v. 10, p. 53-97.

__________, 1976, Cretaceous stratigraphy, tectonics and energy resources, western Denver Basin, *in* Studies in Colorado Field Geology, Epis, R.C. and Weimer, R.J.: Colorado School Mines Prof. Contrib. 8.

__________, and Land, C.B., 1975, Maestrichtian deltaic and interdeltaic sedimentation in the Rocky Mountain region of the United States, *in* The Cretaceous system in the western interior of North America, Caldwell, W.G.E., ed.: Geol. Assoc. Canada Spec. Paper 13, p. 633-666.

Young, R.G., 1955, Sedimentary facies and intertonguing in the Upper Cretaceous of the Book Cliffs, Utah-Colorado: Geol. Soc. America Bull., v. 66, p. 177-202.



Coal in Mesaverde Group, Book Cliffs field, Mesa County, Colorado

COAL DEPOSITS OF THE EASTERN PICEANCE BASIN

BRUCE A. COLLINS: Mid-Continent Coal and Coke Company

Carbondale, Colorado 81623

ABSTRACT: The coalfields of the eastern Piceance Creek basin contain a conservatively estimated 3,129 million tons of bituminous coal and anthracite. At least 800 million tons are of metallurgical quality. These coals occur in the Iles and Williams Fork Formations, which together make up the Mesaverde Group. The Mesaverde sediments were deposited by a southeastward-prograding delta-deltaic plain complex. Intertonguing of marine and nonmarine deposits were caused primarily by compaction, shifting depocenters, and varying sediment supply. The coals are mostly of freshwater origin, and were formed in subtropical to warm-temperate forest swamps.

Rank varies from high-volatile C bituminous to anthracite and locally graphite. While those coals occurring north of Four Mile Creek owe their rank entirely to depth of burial, the higher-rank coals south of Four Mile have been subjected to abnormally high geothermal gradients, the result of heat from the intrusions of the Elk and West Elk Mountains. The coking quality of the coals, while secondarily dependent on peat type and swamp conditions, is primarily a function of rank.

Large-scale mining is presently limited to the coking coals in the southern part of the area. Modern mining in much of the rest of the region awaits the development of economic methods to cope with steep formation dips and other geologic problems.

INTRODUCTION

The Piceance Creek basin is the largest structural basin in northwestern Colorado, covering an area of about 7,225 sq mi as measured around the base of the Upper Cretaceous Mesaverde Group (Fig. 1). Within the basin, the total coal resource, in beds over 42 in. thick, is estimated by the author to be approximately 123.8 billion tons. To put this number in some perspective, the total remaining reserve in the entire state of West Virginia is 102.1 billion tons (Ashcraft, 1974, p. 15).

The Carbondale, Grand Hogback, and southern Danforth Hills coal fields contain a conservatively estimated 3.13 billion tons of high-quality bituminous coal and anthracite (Landis, 1959, tables 8-11) in an area approximately 90 mi long and 1 to 10 mi wide. This reserve is in seams over 42 in. in thickness and under less than 3,000 ft of cover.

The Piceance Creek basin has a maximum structural relief of 27,000 ft, as measured on top of the Precambrian. The basin is asymmetrical to the east, with only 30 mi separating the low point along Piceance Creek near Rio Blanco and Precambrian exposures on the White River uplift (Murray, 1966, p. 192), while 100 mi separate Rio Blanco from the Uncompahgre uplift to the southwest (Haun, 1962, p. 12). The basin is bounded by the Uinta uplift on the north, by the White River uplift and Elk Mountains on the east and southeast, by the Elk and West Elk Mountains and the Gunnison uplift on the south, by the Uncompahgre uplift on the southwest, and by the Douglas Creek arch on the west.

STRUCTURAL GEOLOGY

The Grand Hogback is the most striking physiographic feature of the eastern Piceance Creek basin. The hogback is a westerly dipping monocline composed primarily of the coal-bearing Mesaverde Group of Upper Cretaceous age. The structure can be traced from near Marble on the south to north of Meeker, a distance of over 90 mi. Dips vary from nearly flat to overturned.

Faulting within the coal-bearing rocks appears to be relatively minor, although more extensive mining might prove otherwise. Faulting is most common in the southern part of the area and in association with major bends in the hogback. Most known faults are high-angle normal. Except for shearing associated with bedding-plane movements, faulting has had no noticeable effect on the quality of the coals.

Folding is also relatively minor, aside from the monocline of the hogback itself, and is concentrated in the southern part of the area around the large Tertiary intrusives of the Elk and West Elk Mountains. The southernmost of these is the Chair Mountain uplift, where coal in the surrounding upturned sediments has been metamorphosed to anthracite and locally to high-grade graphite. The Coal Basin anticline is 5 mi north of Chair Mountain, and is thought to be the result of a similar but much smaller laccolithic intrusive in the subsurface. The Divide Creek anticline occurs about 15 mi northwest along the same structural trend, and may have had a similar origin. The Sulphur Creek syncline north of Meeker separates the Grand Hogback to the south from the

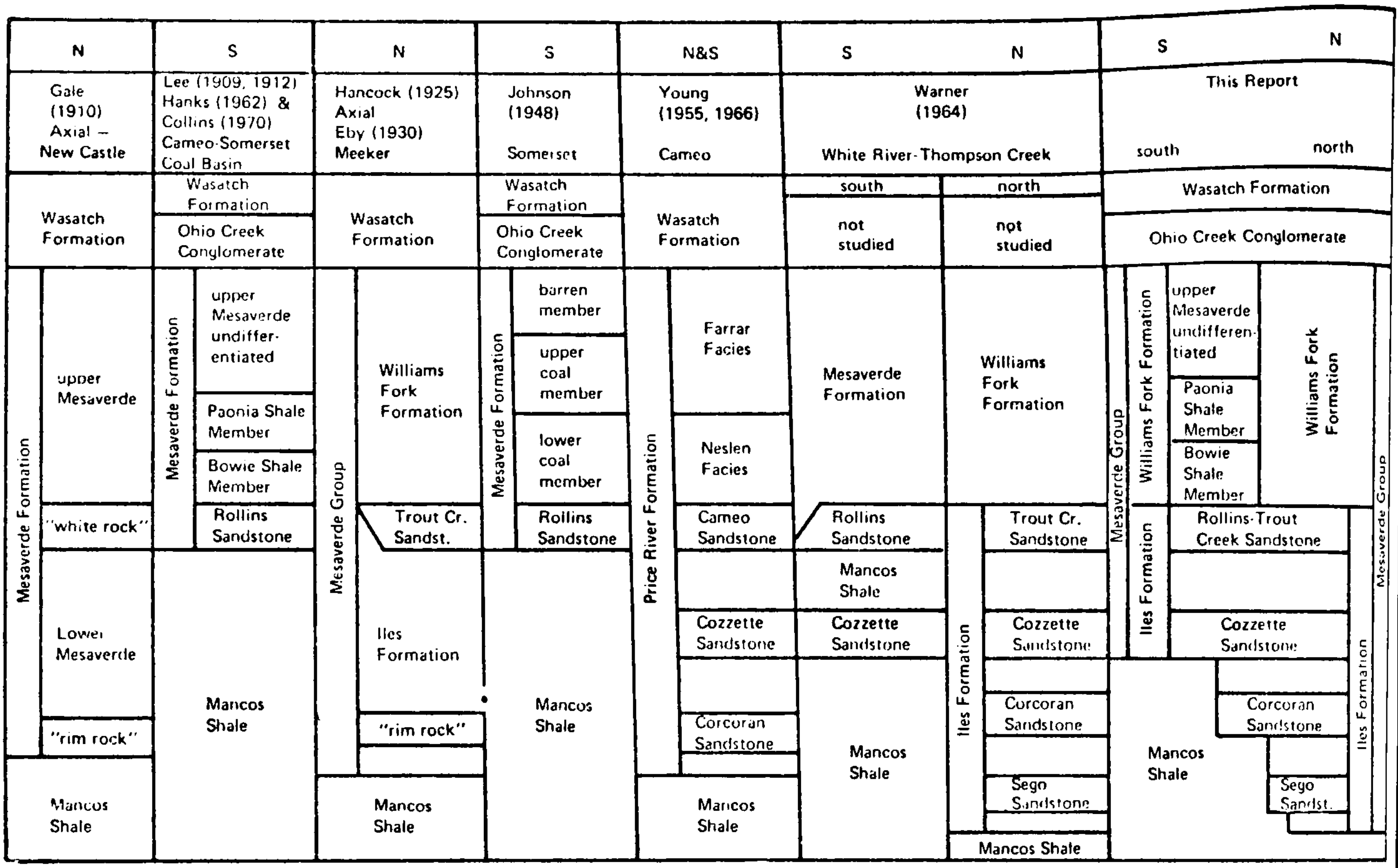


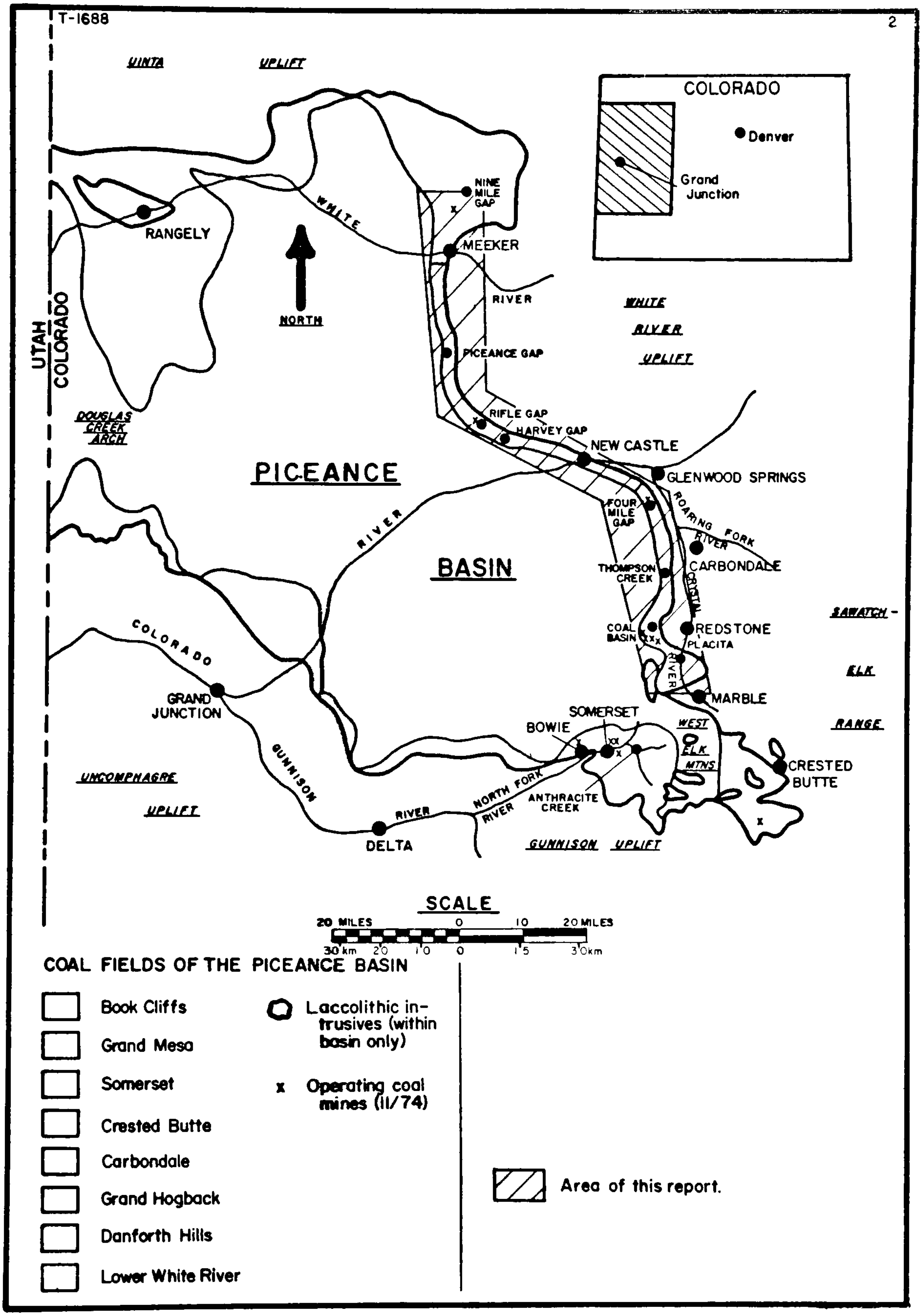
Fig. 2. Nomenclature used by various writers for Upper Cretaceous and early Tertiary rocks in the eastern and southern Piceance basin. Linearity of the Rollins - Trout Creek - Cameo Sandstone zone across the diagram indicates lithogentic equivalency only.

Danforth Hills to the north and the Yellow Jacket anticline to the east (Murray, 1966, chp. II, pl. I). There are a few other minor folds along the hogback, together with drag folding near faults and evidence of plastic flowage in the Mancos Shale.

Igneous intrusives affecting coal-bearing rocks are limited to that part of the area south of Coal Creek, in western Pitkin County. Several laccoliths, one phacolith, several sills, and numerous dikes, all of varying composition, are present within the coal-bearing interval. The Mount Sopris laccolith does not directly affect Mesaverde rocks, but heat from the intrusive was probably responsible for the higher rank coals from Fourmile Creek to the Middle Thompson Creek area. The Chair Mountain laccolith is composed of quartz-monzonite porphyry (Murray, 1966, p. 101; Godwin, 1968, map) and is the largest intrusive in the area directly affecting coal-bearing rocks. Coal seams on both the east and west sides of the mountain have been locally altered to anthracite, and massive graphite deposits are reported near the Genter Mine, northwest of Marble in Gunnison County. A small laccolith in the subsurface is thought to have formed the Coal Basin anticline and to be responsible for the higher rank coals in that area. Laccoliths studied by others in the West Elk Mountains were found to be floored in or above Wasatch sediments, suggesting a post-early Eocene age (Lee, 1912, p. 54-55; Murray, 1966, 102).

Dikes found in the area vary in composition from basalt (Hanks, 1962, p. 148; Godwin, 1968, map) to dacite porphyry and in thickness from feather edges to 50 ft or more. They are best exposed in Coal Basin, where they have coked the coals that they cut up to 50 ft from the contacts. The dikes do not, as a rule, follow faults. They do appear to be texturally and possibly compositionally dependent on the rocks that they cut. The known sills within the area are related to major dikes and are not well developed. Extrusive igneous rocks are limited to basalt flows between Middle Thompson Creek and South Canyon, and are not known to have affected the coals.

Fig. 1. Index map of the Piceance basin showing the thesis area in relationship to the towns, coal fields, operating coal mines, major structural features, and localities referred to in the text. In general, the coal fields boundaries correspond to "Mesaverde" exposures. →


T-1688
2
UINTA UPLIFT
COLORADO
Denver
Grand Junction
RANGELY
NORTH
WHITE
NINE MILE GAP
MEEKER
RIVER
WHITE RIVER UPLIFT
PICEANCE GAP
UTAH
COLORADO
DOUGLAS CREEK ARCH
RIFLE GAP
HARVEY GAP
NEW CASTLE
GLENWOOD SPRINGS
PICEANCE
BASIN
RIVER
FOUR MILE GAP
ROARING FORK RIVER
CARBONDALE
THOMPSON CREEK
CRYSTAL
COAL BASIN
REDSTONE
PLACITA
RIVER
SAWATCH -
ELK
RANGE
COLORADO
GRAND JUNCTION
MARBLE
SOMERSET
BOWIE
WEST ELK MTNS
CRESTED BUTTE
GUNNISON
UNCOMPHAGRE UPLIFT
RIVER
NORTH FORK RIVER
ANTHRACITE CREEK
DELTA
GUNNISON UPLIFT
SCALE
20 MILES 0 10 20 MILES
30 km 20 10 0 15 30 km
COAL FIELDS OF THE PICEANCE BASIN
Book Cliffs
Grand Mesa
Somerset
Crested Butte
Carbondale
Grand Hogback
Danforth Hills
Lower White River
Laccolithic intrusives (within basin only)
x Operating coal mines (11/74)
Area of this report.

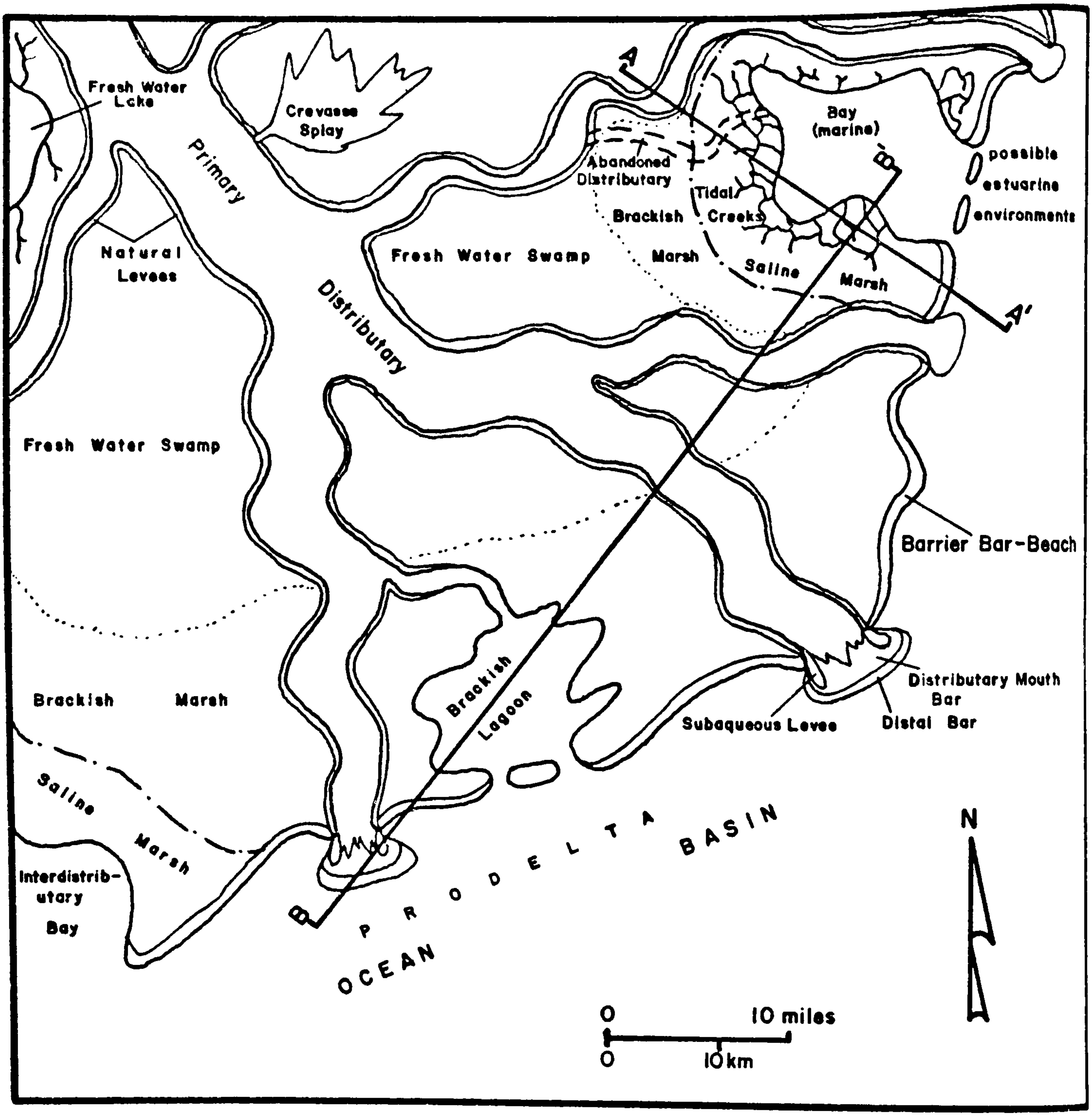


Fig. 3. Plan view of the depositional framework of the Piceance delta during deposition of Trout Creek - Rollins Sandstone and related rocks. Width of channels, levees, and so on exaggerated for clarity. Not all of the features shown here have been definitely identified in the study area. Scale is somewhat arbitrary. Cross sections A - A' and B - B' are shown on Fig. 4.

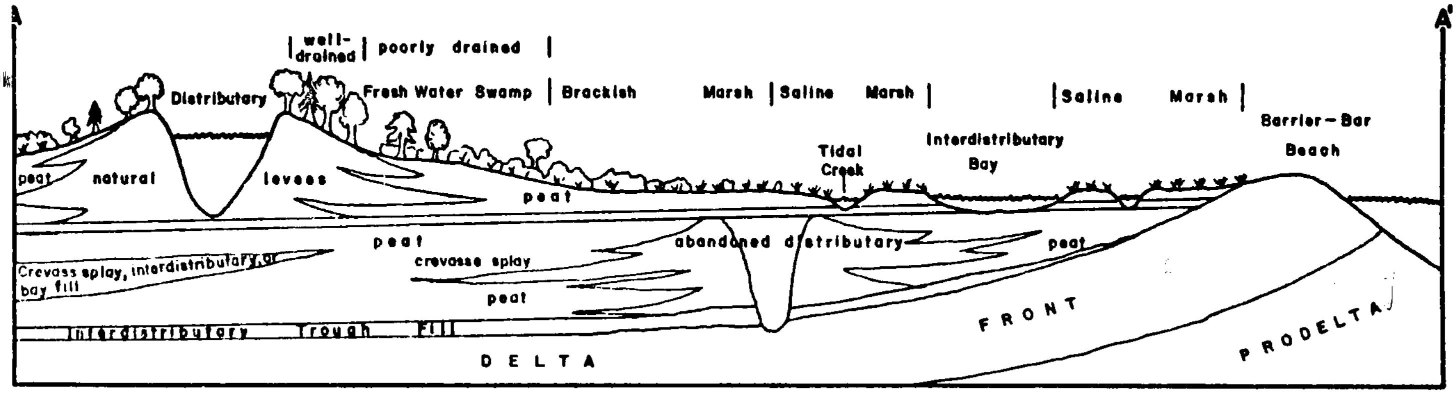
Fig. 4. Cross sections of depositional framework of the Piceance delta; see Fig. 3 for lines of section. Vertical and horizontal scales are arbitrary and exaggerated for clarity. →

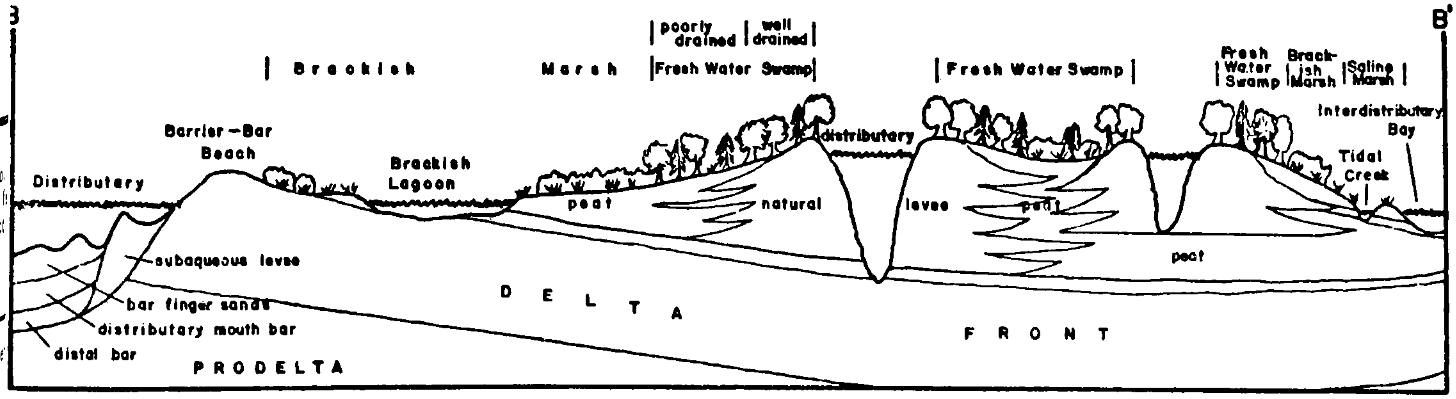
STRATIGRAPHY

The Mesaverde was named on the northern edge of the San Juan basin (Holmes, 1877, pp. 245, 248), and the term has since been extended throughout northwestern Colorado, eastern Utah, and southwestern Wyoming on the basis of lithologic similarity (see, for example, Fenneman and Gale, 1906). The name is used here only because of its customary application (Fig. 2). The group is divided into the Iles and Williams Fork Formations, and varies from 4,595 ft in thickness near Placita, northwest of Marble, to over 6,500 ft near Meeker. Thickness variations are due to variations in marine and nonmarine sediments, primarily in the Iles Formation, and, near Meeker, to marginal marine Lewis Shale equivalents in the Williams Fork (Newman, 1965, Fig. 2 and p. 138).

The Iles Formation is 1,600 ft thick at Meeker, is predominantly nonmarine, and contains economic coals in the Black Diamond coal group. The Mancos Shale tongue present in the formation at Meeker becomes more predominant to the south as basal sandstones pass by facies change into the Mancos Shale. The Iles is 1,175 ft thick at Coal Basin, where the basal Cozette Sandstone, the Mancos tongue, and the Rollins Sandstone make up the entire Iles Formation. The Cozette disappears between Coal Basin and Placita, where the Rollins remains the only representation of the Iles. The Trout Creek and Rollins Sandstones, which are lithogenetic equivalents (Warner, 1964, p. 1099), and which form prominent cliffs and ridges throughout most of the area, occur at the top of the Iles.

The Williams Fork Formation, which varies in thickness from 3,600 ft at South Canyon to 5,780 ft near Meeker, contains most of the area's economic coal beds. The Williams Fork is predominantly nonmarine, although tongues of Mancos Shale, which thin from south to north, occur near the bottom, and tongues of marginal marine sediments equivalent to the Lewis Shale occur in the middle in the Meeker area (Newman, 1965). In the southern part of the area, from Marble to North Thompson Creek, the Williams Fork has been subdivided into the Bowie Shale and Paonia Shale members and an upper, undifferentiated member (Hanks, 1962; Collins, 1970, 1975, 1976). The Bowie Shale contains two major coal groups: the lower, or Fairfield, which is named after Hancock and Eby's Fairfield (1930, p. 206), named near Meeker, to which it is only partially equivalent; and the South Canyon Group, which is 300 to 600 ft above the Fairfield. Although basically nonmarine, Bowie equivalents contain significant marine intervals at least as far north as New Castle. The Paonia Shale and equivalents contain one significant coal group, the Coal Ridge, and a few isolated locally thick coals in the upper part. The undifferentiated sequence contains several





locally correlated coal groups, including the Keystone near New Castle and the Lion Canyon near Meeker. Coals in the upper Williams Fork are highly irregular in thickness, extent, and quality compared to the lower groups, particularly the Fairfield Group seams. Although the Paonia and undifferentiated members and their equivalents are predominantly nonmarine, they do contain some marginal marine Lewis equivalent sediments in the Meeker area.

The Mesaverde Group as exposed in the eastern Piceance Creek basin was deposited by a generally southeastward prograding lobate delta, similar in some respects to the modern Niger delta (see Allen, 1970). Intertonguing of marine and nonmarine sediments was caused by hinge-line faulting on a regional scale, and by compaction and variations in sediment supply on a more local level. A hypothetical model of deltaic deposition is presented in plan view on Figure 3, in cross section on Figure 4.

As many as 7 cycles of marine-nonmarine deposition are locally identifiable, although these vary in number and character, indicating that regional tectonism--that is, basinal lowering--had little or nothing to do with controlling cyclic sedimentation in this area. Cycles can be generally described as follows: prodelta sands and silts spread out over ocean basin deposits, as indicated by thick Mancos Shale sequences which grade upward into somewhat erratic sandy siltstones and fine-grained sandstones. Delta-front sediments are represented by complex sandstones, including the Sego, Corcoran, Cozette, and the Trout Creek-Rollins, each of which forms the base of the Iles from north to south, respectively. These sandstones include distributary-mouth bar, bar-finger, subaqueous levee, barrier-beach, and lower distributary environments. Lower deltaic-plain environments are represented by lagoonal, paludal, flood-plain, and lacustrine deposits, and contain most of the more important coal zones of the Bowie Shale and equivalents. Boundaries between these sediments and overlying prodelta marine deposits in areas of cyclic sedimentation are often abrupt and highly irregular in extent and position, as are the units themselves, again indicating local as opposed to regional control. Upper deltaic plain deposits are represented by generally well-defined channel sandstones, overbank and flood-plain sediments, and minor coals in the upper Paonia Shale and undifferentiated members and equivalents. Deltaic sedimentation is further indicated by current features in several of these environments, particularly in prodelta and delta front deposits. Flow rolls and ball-and-pillow structures are common in the upper Mancos tongues in the Iles; and various load features, clay galls, and contorted bedding occur in the deltaic plain facies of the Williams Fork. In addition, several growth faults have been tentatively identified.

QUALITY OF EASTERN PICEANCE CREEK BASIN COALS

Analysis of the coals of the eastern Piceance Creek basin indicates a wide range of physical and chemical characteristics. Rank varies from high volatile C to anthracite and graphite. Coal thicknesses range up to 60 ft. with from 2 to as many as 15 seams of mineable thickness in any one area.

During a recent study of the coals of this area (Collins, 1975, 1976), a number of samples were collected and subjected to a variety of tests, including petrographic, proximate and ultimate analysis, and ash and X-ray analysis. Lithotype analysis was carried out on a limited number of samples and on in-place coal seams, and indicates that the high-quality coking coals of the southern part of the area generally have a higher vitrain content, in thicker bands, than those seams farther north. Because the number of samples was small, these conclusions may not be statistically valid. Durain contents were found to be slightly higher in the middle portion of the region. Fusain is present throughout the area but rarely in bands thick enough to measure.

Microscopically, 54 samples were examined, although only 19 in detail. Collinite was found to be the predominant vitrinite maceral, although telinite was always present and usually well developed. Sporinite, cutinite, and resinite were all common representatives of the exinite group, but alginite was not identified at all. Fusinite was the most common inertinite, with micrinite somewhat less abundant. Sclerotinite and semifusinite were often well developed, but rare. Overall average maceral group distribution was 71.8 percent vitrinite, 13.7 percent exinite, 11.3 percent inertinite, and 3.1 percent mineral matter, the latter consisting primarily of quartz grains, crystalline and amorphous pyrite, and clays.

The 1.6 specific gravity sink material from 19 samples was examined microscopically to determine how ash materials occur in these coals. Silty and shaley coal or coaly siltstone predominated, usually well mixed but occasionally layered. This material is generally referred to as "bone" when identified megascopically. Quartz grains, calcite, selenite gypsum, clay fragments, and limonite were fairly common, but pyrite and feldspar grains were relatively rare.

The proximate analysis includes, for the purpose of this report, moisture, ash, volatile matter, fixed carbon, Btu, free-swelling index, and ash-softening temperature. In the fresh coal samples tested, moisture varied from less than 2 percent at Coal Basin to over 11 percent north of Meeker. Moisture is useful as an indirect measure of weathering or oxidation, with oxidized coals running as high as 20.5 percent.

As-received Btu, shown on Figure 5, reflects moisture content and is, therefore, not very useful in comparing coals. It is an important commercial value because it indicates the Btu content to be expected from the mine. As can be seen, as-received Btu generally increases from north to south, along with increasing rank.

Volatile matter (dry values shown on Fig. 6) consists of steam and various aromatic and aliphatic decomposition products. The weight loss of the sample on heating is volatile matter plus moisture, while the remaining char is fixed carbon plus ash. Volatile matter decreases markedly from north to south, again

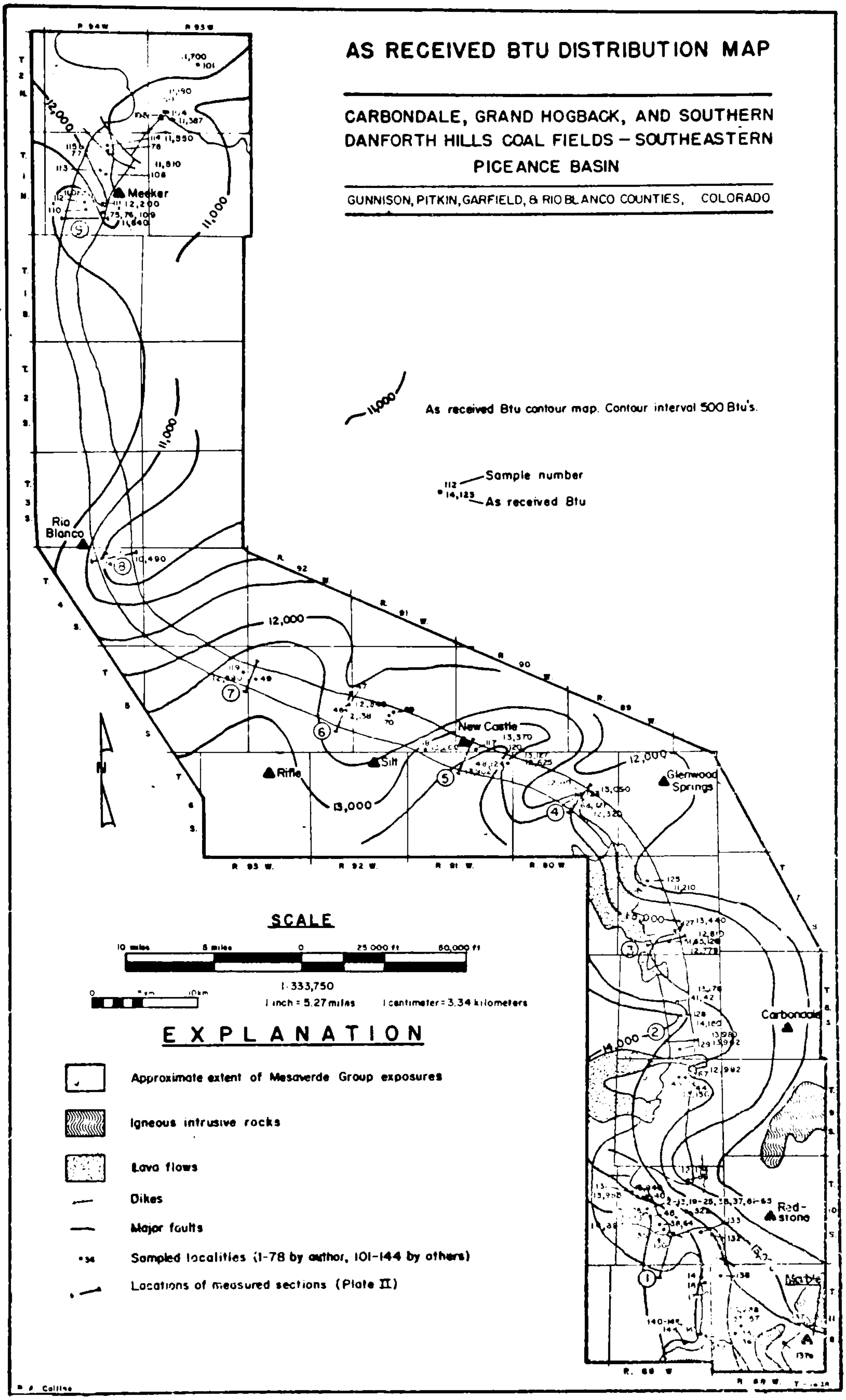


Fig. 5. As-received BTU contour map.

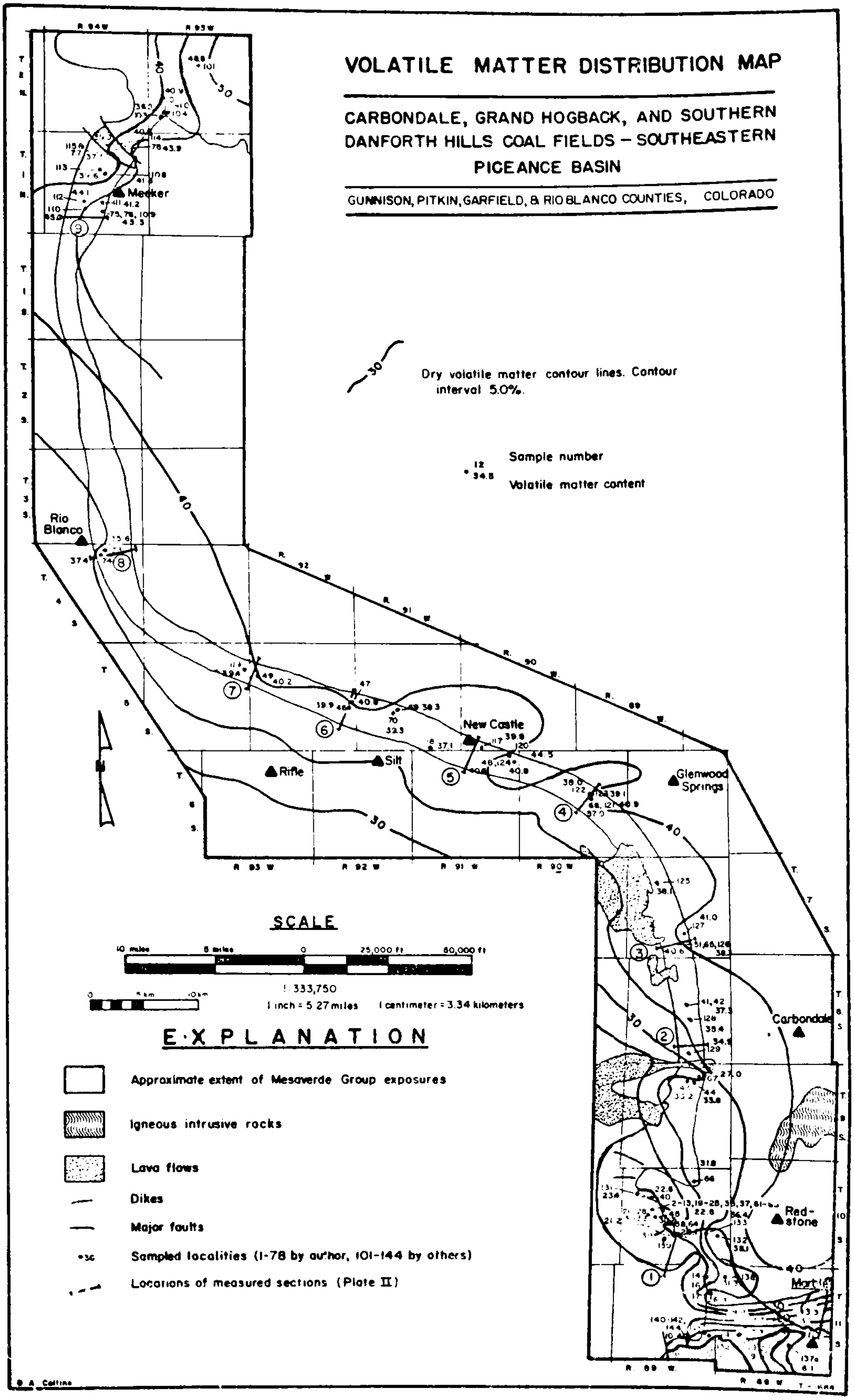


Fig. 6. Volatile matter distribution map.

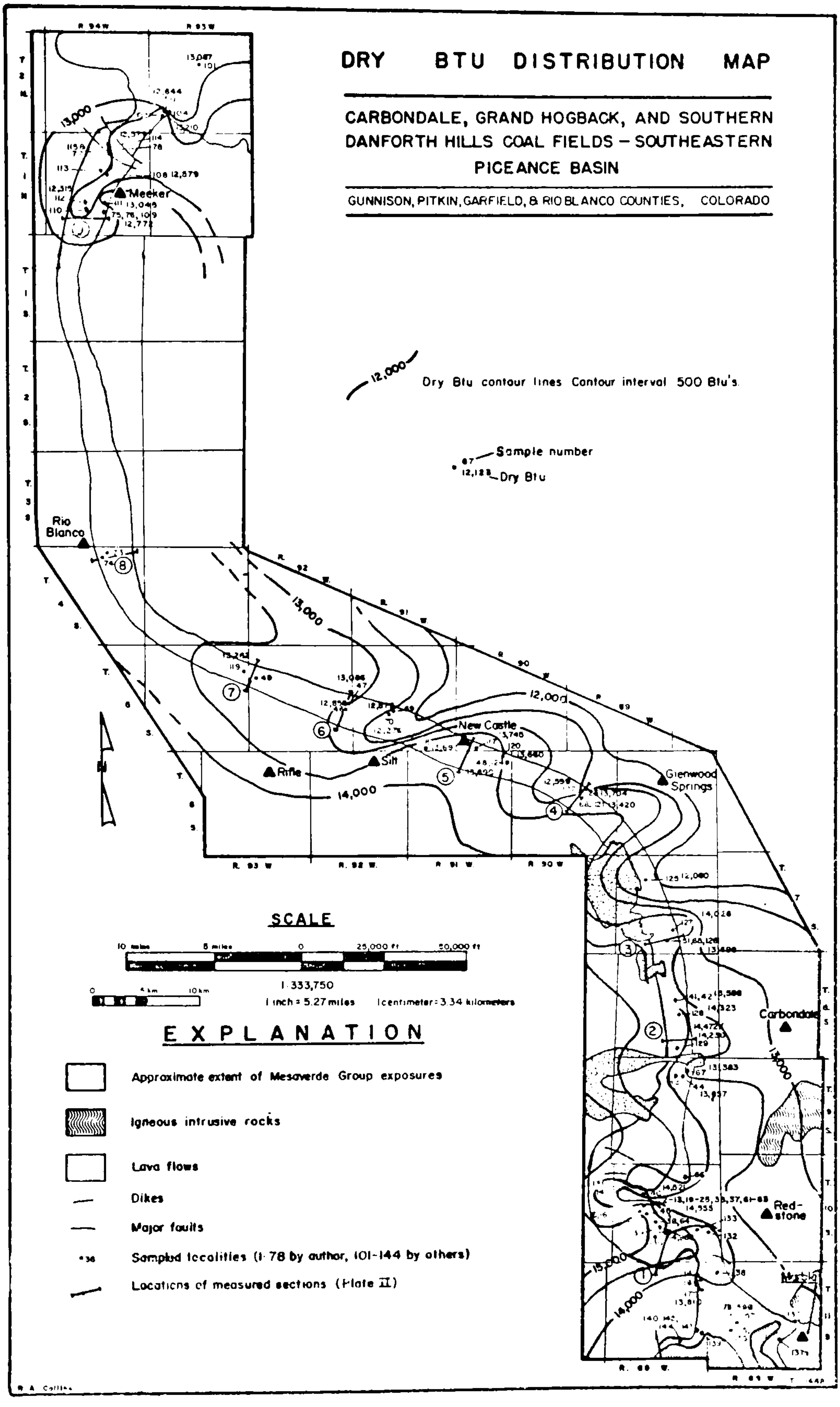


Fig. 7. Dry Btu distribution map

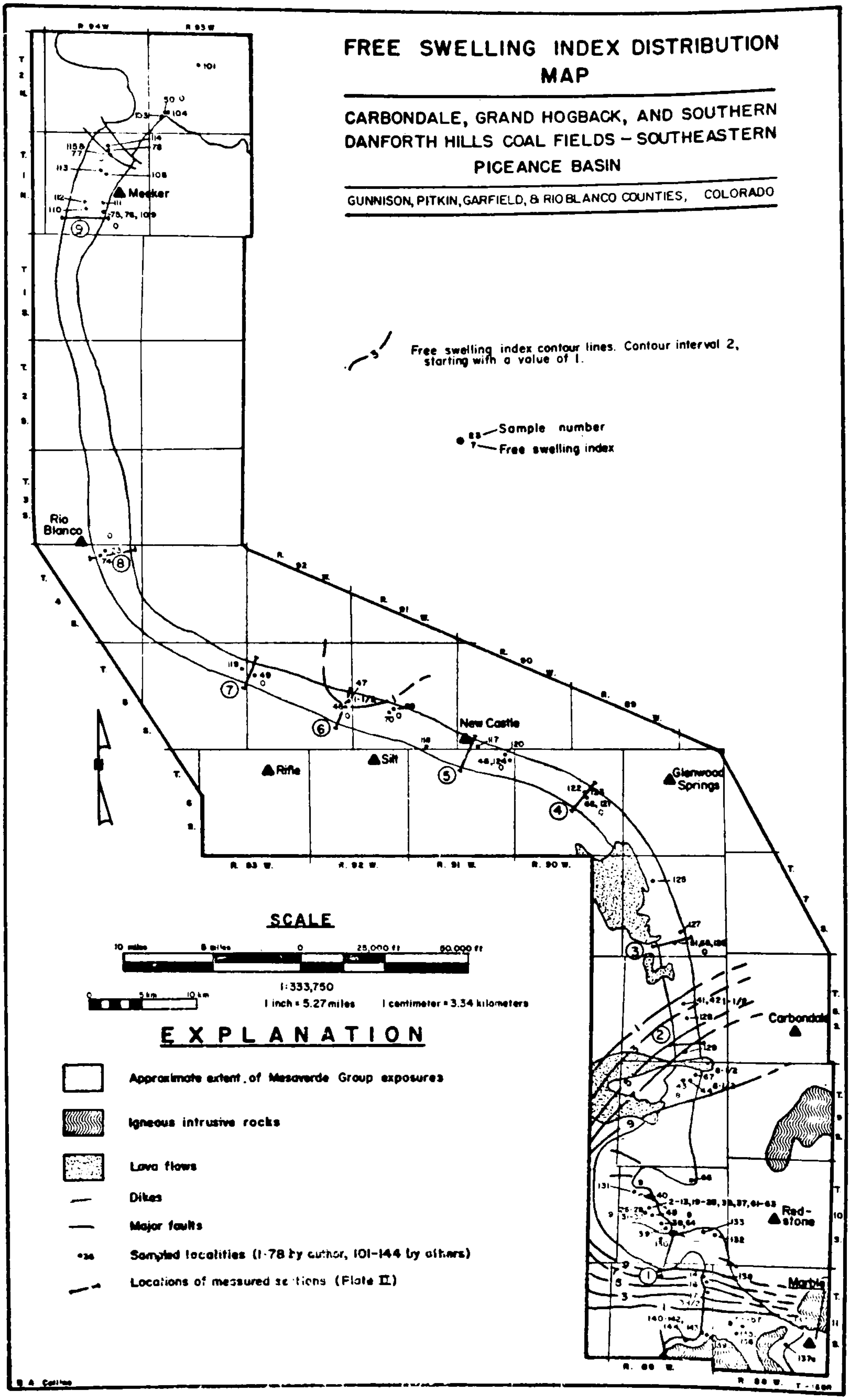


Fig. 8. Free-swelling index distribution map.

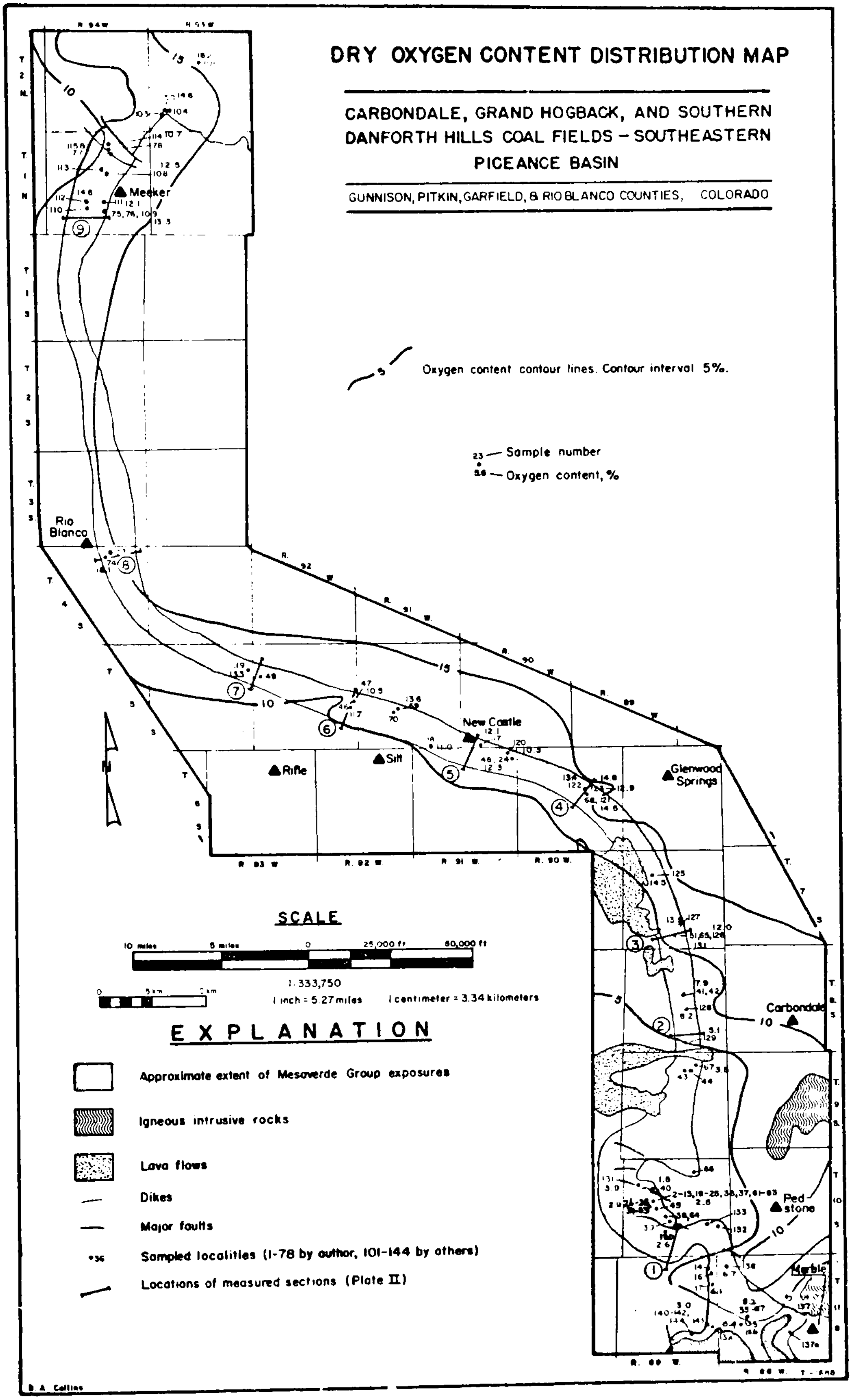


Fig. 9. Dry oxygen content distribution map.

with increasing rank, and varies rapidly in the vicinity of igneous intrusives. Values range from 48.8 percent near Nine Mile Gap to 6.1 percent along Raspberry Creek near Marble. Near a dike in Coal Basin, natural coke had a volatile matter content of 6.5 percent, altered coal 14.2 percent, and unaltered coal 22.6 percent.

Plant ash varies from 1.5 to 3 percent for woody plants and is higher for some grasses and reeds. Sedimentary ash varies from 0 to 100 percent. Ash for samples with Btu rise ranged from 1.7 percent for a lump from the Four Mile Creek area to 90.2 percent for a coaly shale from Coal Basin. Coal seam ash averaged 5 to 8 percent. Although there are definite patterns in local ash distribution, there were no discernible regional ones.

Dry Btu is indirectly dependent on ash content and oxidation. It generally increases with rank up to the low-volatile level, then decreases through the anthracites to graphite. As seen on Figure 7, dry Btu in the area studied varies from less than 12,000 to over 15,000 Btu/lb for unoxidized coal.

The free-swelling index (FSI), shown on Figure 8, gives an indication of the coking nature of a particular coal. It is not an indicator of how well that coal will coke, nor of the quality of the coke produced. Coking coals, that is coals with an FSI of 1 or greater, vary in rank from high-volatile C to low volatile. In the eastern Piceance Creek basin, FSI's varied from 0 for all samples north of Aspen Gulch, except for one from Harvey Gap, to 9 for all Coal Basin samples and for a partial seam sample from Middle Thompson Creek.

Ash fusion temperatures are important in coal utilization studies, with high values indicating potentail slagging problems. For the coals tested, values ranged from 2,170° to 2,730°F, and some were even greater.

Ultimate analysis includes testing for carbon hydrogen, nitrogen, oxygen, and sulfur, although sulfur is often included in the proximate analysis. In the eastern Piceance Creek basin, carbon generally increases from north to south with increasing rank and varies from just under 70 percent to about 85 percent. The hydrogen content was found to be fairly stable over the entire area, averaging about 5 percent. Nitrogen was also fairly constant, ranging from 1.3 to 2.1 percent and averaging 1.7 percent.

Oxygen is present in dry coal from the original plant material and from oxidation by air or by surface or ground water. Oxygen content is an important factor in evaluating coking coals, as it can alter or even destroy the coking properties of otherwise strongly coking coals. Values in the area under study here, shown on Figure 9, varied from 2.5 percent for a medium-volatile sample from Coal Basin to 16 percent for a high-volatile C sample from Nine Mile Gap.

Sulfur was found to be relatively uniform in fresh coal samples, averaging 0.70 percent, with most localities varying from 0.60 to 0.85 percent. Only four samples exceeded 1.0 percent. Nineteen samples were tested for the form of their sulfur content. Sulfate sulfur ranged from 0 to 0.16 percent, organic from 0.34 to 0.62 percent, and pyritic from 0.03 to 0.54 percent. These values are for coal samples only.

All samples collected by the author were subjected to diffraction X-ray analysis. Selected results are given on Figure 10. Intense scattering by complex organic molecules masked virtually all mineral peaks except the strong quartz peak at 26.7°2θ. The selected samples shown do reflect the increased definition of the principal graphite peak at 27.5°2θ quite well. This increase, due to increasing aromatization, is clearly rank dependent.

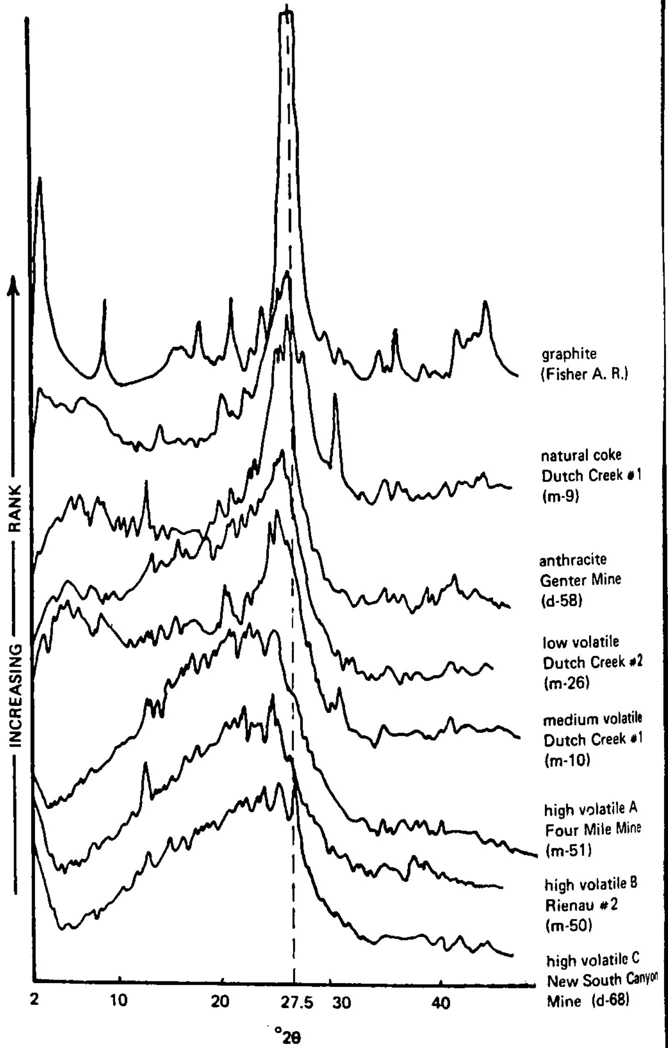


Fig. 10. X-ray powder diffraction patterns of eastern Piceance basin coals. Samples were selected specifically to show variations according to rank increase.

RELATION OF COAL QUALITY TO DEPOSITIONAL ENVIRONMENT

The quality of the coals in the eastern Piceance Creek basin, as in any coal basin, depends on the nature of deposition in the original peat swamp and on the diagenetic changes to which the peat material has been exposed. Both physical and chemical conditions are important in each of these factors, and in many cases the borderline between physical and chemical change is indistinct, as is the boundary between depositional and diagenetic change.

To summarize the depositional environment that produced the coals of the eastern Piceance Creek basin, the peats which led to these coals were deposited as part of a southeastward-prograding delta complex. Most of the peats were of fresh-water origin, although two areas of higher sulfur, higher ash coal closely bounded by lagoonal indicators suggest local accumulations of brackish-water peats. The lower coals in each group, usually higher in ash and sometimes in sulfur, are thought to be of interdistributary marsh origin, and probably developed from grass progenitors and reeds. A generally lower vitrain-vitrinite percentage in these coals at least suggests the sparsity of woody plants. Extreme variations in thickness, lateral extent, and nature of the seams also suggest such an environment.

As the delta prograded, poorly to moderately drained forest swamps developed, with floral assemblages not unlike that of the present Mississippi delta. Rock splits, which are highly variable in thickness, extent, and composition, represent crevasse-splay deposits. Some of the thicker, more regular intervals between seams are due either to interruptions or to increases in deltaic sedimentation which resulted either in submergence and death of the swamp by marine invasion or in choking off of peat accumulation by sediment invasion and by the presence of oxygenated surface waters, respectively.

In the forest swamp itself, water currents were slow moving, except where rock splits represent temporarily higher velocity conditions. Boney partings and layers of higher ash coal indicate slightly higher than normal current conditions where plant debris accumulation was not interrupted. While insufficient work has yet been done in the area to realistically define paleotopography even in the most local sense, some generalizations can be made. Low areas were centers of exinite and inertinite accumulation, fusinite excepted, and were also areas of increased clay deposition in some cases. Thus durain-rich coals now represent low areas in the original swamp, while vitrain and clarain indicate slightly higher areas of accumulation. The generally low fusain content of the thicker coals is interpreted as indicating the absence of ground-cover plants and shrubs, the drying of which would be more conducive to extensive swamp fires than a forest-type assemblage.

Heat due to depth of burial is the most important overall factor in the coalification process. While no widely accepted criteria exist for estimating the depth of burial of a coal seam under all conditions, a combination of methods that have been used, such as Hilt's rule (Mason, 1958, Fig. 39) and some of the Teichmüller studies (see Teichmüller and Teichmüller, 1968), indicates that the coals of the central eastern Piceance Creek basin were probably buried to a depth of 11,200 to 11,700 ft. This agrees reasonably well with the projected total Upper Cretaceous and Tertiary sedimentary record in the area. Samples from the north end of the area, near Nine Mile Gap, indicate burial depths of as little as 8,000 ft, and other local variations occur north of Four Mile Creek. The coals to the south of Four Mile have been elevated in rank solely by their proximity to the igneous intrusions in the area, such as Chair Mountain and Mt. Sopris.

The coking quality of the coals of the southern part of the eastern Piceance Creek basin is predominantly rank dependent, and, therefore, is diagenetically dependent. Coals with very similar petrographic profiles from the Coal Basin and Meeker areas have drastically different coking character. However, the importance of vitrinite and exinite content is also clear, and such content is controlled solely by the sedimentary environment in the original swamp. Vitrinite, which represents the remains of woody plants, is the most reactive maceral in coking, and coals with high vitrinite contents generally make the best cokes. Exinites, which consist of the remains of pollen and spores, leaf cuticles, plant resin and waxes, and algae, are higher in volatile matter than the vitrinite in the same sample. They froth more when heated in the coke oven, and lead to a more open, porous structure than does vitrinite alone. This is desirable up to a point, but a high exinite content coupled with low vitrinite may lead to a soft, weak coke, regardless of rank. The inertinites, primarily micrinite and fusinite, take little or no part in the coking process. From this it is clear that, while sedimentary controls on coking characteristics would appear to be subordinate to rank, or degree of metamorphism, the original swamp environment does indeed affect the nature of the coking coal produced by subsequent changes through time.

COAL PRODUCTION IN THE EASTERN PICEANCE CREEK BASIN

The eastern Piceance Creek basin coal fields were opened in the mid 1880's and have produced continuously ever since. Total production to January 1, 1976, is approximately 22 million tons. From the first production until 1916, several large mines were in operation, primarily in the Spring Gulch-Four Mile and South Canyon-New Castle areas. These mines were served by the Colorado Midland Railroad; when the Midland was abandoned in 1916, large-scale coal production ceased. Production picked up again in the 1950's with the opening of mines on North Thompson Creek and in Coal Basin. While the early years of this century saw the greatest number of mines producing and number of men employed, 1975 was the year of greatest production, approximately 1 million tons.

While coals with a wide range of utility, industrial, and commercial applications obviously exist in the eastern Piceance Creek basin, modern mining has been limited to the metallurgical coals found south of Spring Gulch, in the Thompson Creek and Coal Basin areas. The obvious question at this point, then, is why has there not been further development in this area? The answer is simply that geologic problems encountered in the area prohibit economic mining with present-day techniques. The most obvious geologic problem is dip. At Mid-Continent's Coal Basin operations, ordinary continuous mining techniques are utilized on an average dip of 13°, or 23 percent; dips occasionally exceed 15°. This is in spite of the fact that most mining textbooks state that such equipment cannot be used on dips exceeding 7 to 8°. At Thompson Creek, dips average slightly over 30°; specialized equipment and mining techniques will be used in these mines, which currently are being reopened by Anchutz Coal Company, when full production is resumed. Most of the remainder of the area south of Sulphur Creek, just north of Meeker, exhibits dips in excess of 40°, and in some places the coal beds are actually vertical or overturned. These areas await specialized mining techniques to allow economic extraction on anything approaching large scale. Dip increase also results in rapidly increasing cover.

Faulting is another geologic problem that has in the past determined mining limits in several mines in the area. In general, a fault with a throw up to the thickness of the coal seam causes little difficulty in entry development. Faulting is often accompanied by other problems, however, such as soft or broken top, excessive amounts of water or gas, and, under certain conditions, relict stresses that can cause bumps or outbursts. Many of the faults in the southern part of the area have a rotational component, complicating mining somewhat where large faults are encountered.

In the southern part of the area, where coal rank has been elevated by thermal processes, excessive amounts of methane gas have been generated and, in large part, trapped in the coal. Gas has been a problem in all of the mines opened south of Four Mile Creek. In the Coal Basin area, methane emission rates of up to 2,000 cu ft/ton have been estimated.

In the New Castle area in particular, spontaneous combustion in pillars during pillar extraction and the presence of unusually highly explosive dust have caused problems. Virtually every major mine in this district has suffered at least one fire or explosion. A series of such accidents near the turn of the century took a large number of lives.

SUMMARY

In summary, the eastern Piceance Creek basin contains at least 3.13 billion tons of high-grade bituminous coal and anthracite, much of this coal being considerably higher in quality than most other Western coal. While sedimentary environment has had some influence on coal quality, the principal determining factor is an abnormally high geothermal gradient caused by the presence of numerous igneous intrusives in the southern portion of the area. Geologic conditions, known mining techniques, health and safety laws, and economics have limited modern mining to the coking coals found from Spring Gulch south. Exploitation of the high-grade steam coals found in much of the area awaits practical solutions to these problems.

REFERENCES

Allen, J.R.L., 1970, Sediments of the modern Niger delta: a summary and review, *in* Deltaic sedimentation modern and ancient: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 15, p. 138-151.

Ashcraft, John, 1975, State of West Virginia Department of Mines, Annual Report-1974: Charleston, 77 p.

Collins, B.A., 1970, Geology of the coal-bearing Mesaverde Formation (Cretaceous), Coal Basin area, Pitkin County, Colorado: Colorado School Mines, M.Sc. Thesis T-1284, 116 p.

__________, 1975, Geology of the coal deposits of the Carbondale, Grand Hogback, and southern Danforth Hills coal fields, southeastern Piceance basin, Colorado: Colorado School Mines, Ph.D. Thesis T-1688, 218 p.

__________, 1976, Coal deposits of the Carbondale, Grand Hogback, and southern Danforth Hills coal fields, eastern Piceance basin, Colorado: Colorado School Mines Quart., v. 71, no. 1, 138 p.

Fenneman, N.M., and Gale, H.S., 1906, The Yampa coal field, Routt County, Colorado: U.S. Geol. Survey Bull. 297, 96 p.

Gale, H.S., 1910, Coal fields of northwestern Colorado and northeastern Utah: U.S. Geol. Survey Bull. 415, 265 p.

Godwin, L.H., 1968, Geologic map of the Chair Mountain quadrangle, Gunnison and Pitkin Counties, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-704.

Hancock, E.T., 1925, Geology and coal resources of the Axial and Monument Butte quadrangles, Moffat County, Colorado: U.S. Geol. Survey Bull. 757, p. 1-134.

__________, and Eby, J.B., 1930, Geology and coal resources of the Meeker quadrangle, Moffat and Rio Blanco Counties, Colorado: U.S. Geol. Survey Bull. 812-C, p. 191-242.

Hanks, T.L., 1962, Geology and coal deposits, Ragged-Chair Mountain area, Pitkin and Gunnison Counties, Colorado: Brigham Young Univ. Geol. Studies, v. 9, pt. 2, p. 137-160.

Haun, J.D., 1962, Introduction to the geology of northwest Colorado, *in* Exploration for oil and gas in northwestern Colorado: Rocky Mtn. Assoc. Geologists, p. 7-14.

Holmes, W.H., 1877, Report on the San Juan district: U.S. Geol. and Geog. Survey Terr. 9th Ann. Rept., p. 237-276.

Johnson, V.H., 1948, Geology of the Paonia coal field, Delta and Gunnison Counties, Colorado: U.S. Geol. Survey Coal Inventory Map.

Landis, E.R., 1959, Coal reserves of Colorado: U.S. Geol. Survey Bull. 1072-C, p. 131-232.

Lee, W.T., 1909, The Grand Mesa coal field, Colorado: U.S. Geol. Survey Bull. 341, pt. 2, p. 316-334.

__________, 1912, Coal fields of Grand Mesa and the West Elk Mountains, Colorado: U.S. Geol. Survey Bull. 510, 237 p.

Mason, B., 1958, Principles of geochemistry: New York, John Wiley and Sons, 310 p.

Murray, F.N., 1966, The stratigraphy and structural geology of the Grand Hogback monocline: Univ. Colorado, Ph.D. Thesis, 219 p.

Newman, K.R., 1965, Mancos to Wasatch measured section in Meeker-Rio Blanco area, northwestern Colorado: Mtn. Geologist, v. 2, n. 3, p. 135-139.

Teichmüller, M., and Teichmüller, R., 1968, Geological spects of coal metamorphism, *in* Coal and coal-bearing strata: New York, American Elsevier, p. 233-267.

Warner, D.L., 1964, Mancos-Mesaverde (Upper Cretaceous) intertonguing relations, southeast Piceance Basin, Colorado: Am Assoc. Petroleum Geologists Bull., v. 48, no. 7, p. 1091-1107.

Young, R.G., 1955, Sedimentary facies and intertonguing in the Upper Cretaceous of the Book Cliffs, Utah-Colorado: Geol. Soc. America Bull., v. 55, p. 177-202.

__________, 1966, Stratigraphy of coal-bearing rocks in the Book Cliffs, Utah-Colorado, *in* Central Utah coals: Utah Geol. and Mineralog. Survey Bull. 80, p. 7-20.

Tipples and thermal dryer, underground coal mine, Coal Basin, Pitkin County, Colorado

TRINIDAD — RATON BASINS:

A MODEL COAL RESOURCE EVALUATION PROGRAM

CURTIS L. AMUEDO: Amuedo and Ivey, Consultants
Denver, Colorado 80209

RICHARD S. BRYSON: Consulting Geologist
Lakewood, Colorado 80226

ABSTRACT: A model coal resources evaluation of a complete basin is presented, using the Trinidad-Raton basin as an example. This approach is recommended to avoid excessive exploration drilling costs, and to minimize followup costs of property acquisition and mine development. The objective of the *total basin evaluation concept* is not only to establish a comprehensive baseline analysis of the coal resources, but also an analysis of the economic factors involved if development of the resource is to be undertaken. The basic data for an assessment of this type must be sufficient to answer many diverse questions. Some of these questions are: (1) which areas have the highest reserve potentials and can justify exploration expenses?; (2) what is the mineral ownership picture?; (3) where are the markets for this coal and what is the best way to transport the coal?; (4) how much would it cost to develop a mine in the area?; (5) is an on-site electric generating plant feasible?; (6) what about an on-site gasification plant?; (7) what are the competing energy minerals in the area?; (8) what is the present land-use status?; (9) what are the environmental-ecological considerations?; and (10) is sufficient water available?

NTRODUCTION

We believe the best method to explore for coal s to locate several favorable areas for exploration ithin a basin by studying the basin as a whole. We all this approach the *basin evaluation concept* which as been used successfully for many years by oil companies to discover new oil and gas fields. Only recently is this method being applied to coal exploration. ome companies, particularly certain coal companies, elieve that exploration is the drilling of one or two ore holes a quarter of a mile away from a producing oal mine.

The *basin evaluation concept* includes much more han knowing the depositional history, depth, and hickness of the coal beds. Many other considerations re necessary by private industry before a *"go" or "no-go" decision* can be made to commit exploration ollars and to estimate the long-range capital investent costs. Many diverse questions should be answered. e will discuss some of the obvious ones. It is only fter these simple questions are answered that a comany can make a sound decision. The *basin evaluation oncept* should include at least the following 10 basic uestions:

1. What is the history of coal production from the area?
2. What is the quality of the coal?
3. Where are the largest potential undeveloped coal resources in the basin where core drilling and other expenses might be justified?
4. What is the mineral ownership picture, and what is the present status of land use?
5. Is sufficient water available for domestic as well as increased industrial use?
6. Where would the markets be for the coal, and what are the shipping considerations?
7. Would it make sense to develop a mine-mouth energy complex rather than to ship coal out of the area?
8. How much would it cost to develop a mine in the area?
9. What are the other energy minerals in the area, and would they be competitive?
10. What are the environmental and ecological considerations?

Ideally, the above questions should be answered about any basin before committing exploration dollars.

To demonstrate the *basin evaluation concept* and to answer these questions, we have chosen the Trinidad-Raton basin as a model.

HISTORY OF COAL PRODUCTION

Coal was first reported in the Trinidad-Raton basin in 1848 (Fig. 1). Mining began in 1873 and reached a peak production of 71 million tons during

976 *Symposium on the Geology*
f Rocky Mountain Coal, p. 45-60

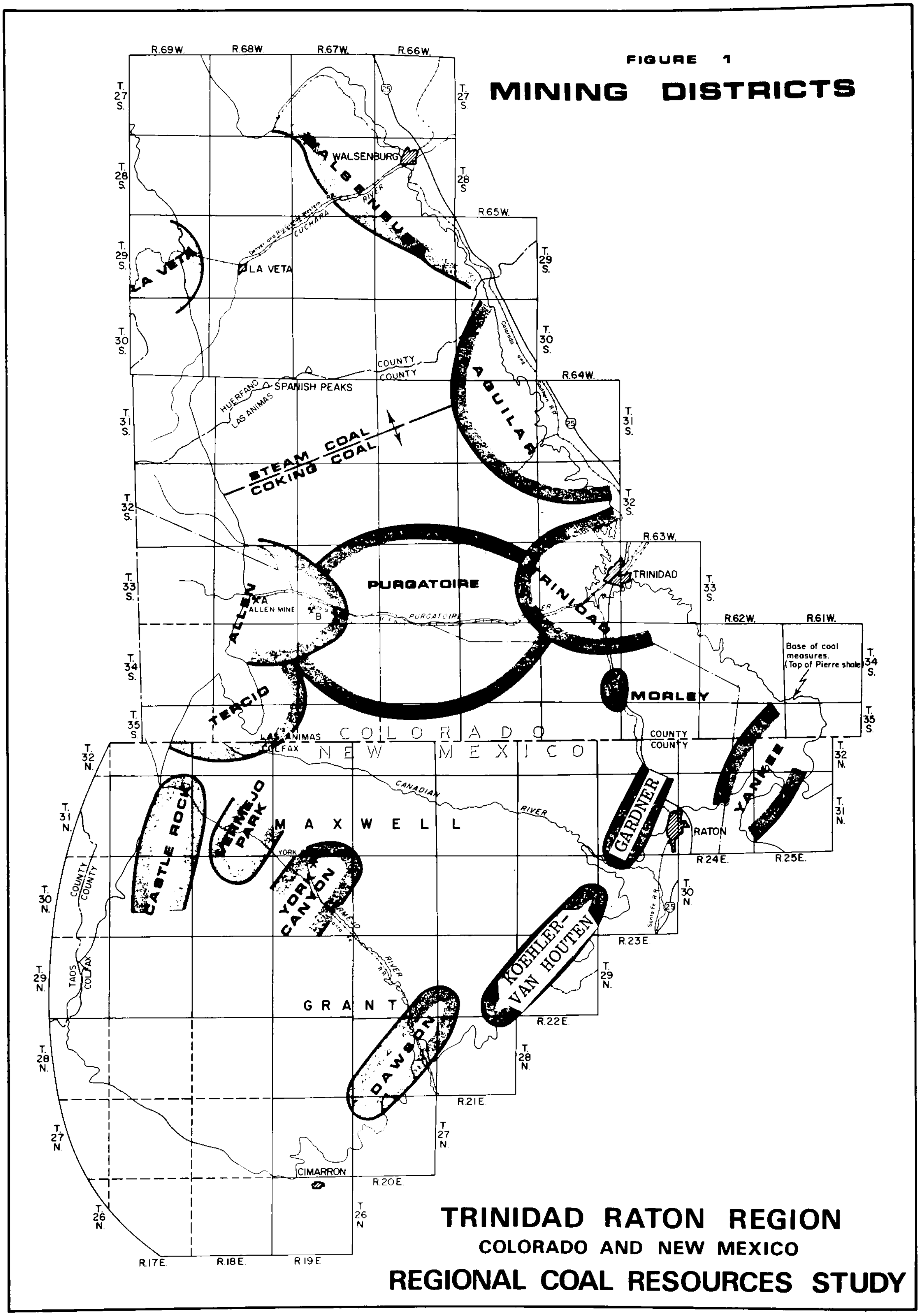


Fig. 1. Trinidad-Raton basin mining districts.

he 10-year period from 1911-20, averaging 5.6 million ons annually in Colorado and 1.5 million tons in New lexico. Cumulative production through 1975 for the ntire basin, from available records, is estimated to e 325.5 million tons--247.5 million for the Colorado ortion, and 78 million from New Mexico. In 1975, otal production in the basin was about 1.6 million ons, approximately 600,000 tons in Colorado and one iillion tons in New Mexico.

On Figure 1, and on all subsequent illustrations, he top of the Upper Cretaceous Trinidad Sandstone outrop is indicated, marking the base of the coal measures, nd enclosing about 2100 sq mi of coal-bearing rocks.

The Trinidad-Raton basin straddles the Colorado-lew Mexico State line. The area is mountainous on the estern side, where the average elevations range from bout 9,000 to 13,000 ft above sea level in the Sangre le Cristo Mountains. West Spanish Peak (elevation 13,600 ft) is the highest point in the area. The topoyraphy becomes more gentle, but dissected, as it slopes eastward to the base of the coal measures' outcrop, here elevations are usually about 7,000 ft. The largest towns in the Colorado part of the basin are Valsenburg (population ±5,000) and Trinidad (±10,000). In New Mexico, Raton has approximately 7,500 inhabitants.

All of the coals within the basin are found in ate Cretaceous and early Tertiary age rocks, from the surface to more than 3,000 ft in depth. The coal is found in the Vermejo and Raton Formations. All of the coals in these formations were deposited in discrete lenses up to 10 ft thick, which cannot be correlated throughout the basin.

Coals of similar age in other Rocky Mountain basins are normally subbituminous to lignite in rank. However, due to the regional igneous activity in the Trinidad-Raton basin, the coals have been upgraded to bituminous rank, averaging about 13,000 Btu/lb. North of a line just south of Spanish Peaks, the coal is of steam quality; south of this line, the coal is high-quality metallurgical-grade coking coal. The 15 separately named mining districts are outlined on Figure 1. There are only 2 large active mines in the basin, the Kaiser Steel York Canyon Mine in New Mexico, and the CF&I Allen Mine in Colorado. A small strip mine was opened in late 1975 north of Trinidad, near the town of Aguilar. During 1975, the York Canyon mine produced approximately 1 million tons of coal, and the Allen produced 632,000 tons.

The new CF&I Maxwell mine is presently under development about 3 mi east of the older Allen mine and is scheduled to reach a production level of about 2,000 tons/day in the spring of 1978. The new mine will cost about 10 million dollars, depending upon the operating level.

QUALITY OF THE COAL

The coals of the Trinidad-Raton basin are similar in quality to eastern coals, being high-volatile, bituminous C through A in rank (Table 1).

Generally, the Btu values of the coal in the basin increase from north to south (Fig. 2). All values greater than 13,000 Btu/lb are underlined on Figure 2. Although these coal beds are not as thick as those of the Powder River basin, Wyoming, their Btu content is about 40 percent higher than Powder River basin coal.

The ash content of the coal ranges from about

TABLE I

REPRESENTATIVE ANALYSES OF SELECTED COALS FROM THE TRINIDAD-RATON BASIN

	Mine or Location	Coal Bed	Formation	Moisture	Volatile Matter	Fixed Carbon	Ash	Sulfur	Btu
1.	Alamo	Raton	Vermejo	7.5	37.4	46.6	8.5	0.6	11,710
2.	Allen	Allen	Raton	4.3	38.3	49.2	8.2	0.5	13,100
3.	Ancho Canyon	Ancho Canyon	Raton		36.3	54.0	8.6	0.5	13,835(1
4.	Boncarbo	Boncarbo	Raton	2.9	32.1	49.0	16.0	0.6	12,210
5.	Brilliant	Tin Pan	Raton	-	37.0	46.5	16.5	0.6	12,470*
6.	Chimney Divide	Chimney Divide	Raton		38.4	47.6	13.4	0.5	13,980(1
7.	Cokedale	Cokedale	Vermejo	2.3	25.8	54.6	17.3	0.5	12,340
8.	Dawson No. 3	Raton	Vermejo	-	38.2	49.3	12.5	0.8	13,230*
9.	Frederick	Frederick	Raton	2.0	30.3	58.3	9.4	0.6	13,790
10.	Koehler No. 1	Raton	Vermejo	-	37.5	50.1	12.4	0.7	13,100*
11.	Morely	Morley	Vermejo	1.9	31.9	53.1	13.1	0.6	12,990
12.	Oakdale	Mannoth	Vermejo	7.8	38.5	44.8	8.9	0.5	11,540
13.	Primero	Primero	Raton	2.3	29.8	58.7	9.2	0.5	13,780
14.	Red Robin	Turner	Raton	2.3	36.1	47.0	14.6	0.6	12,530
15.	Robinson No. 1	Walsen	Vermejo	3.9	37.6	47.7	10.8	0.6	12,340
6.	Sopris	Piedmont	Vermejo	2.1	28.3	51.9	17.7	0.7	12,360
7.	Van Houten	Raton	Vermejo	-	37.1	51.6	11.3	0.9	13,220*
8.	Yankee No. 3	Yankee	Raton	-	38.7	48.7	12.6	0.6	12,700*
9.	York Canyon	York Canyon	Raton	-	35.7	57.2	7.1	0.4	15,150*
:0.	Delagua No. 2	Delagua	Raton	2.9	36.3	53.0	7.8	0.5	13,240

*Dry basis
(1 - Bulk core sample, washed

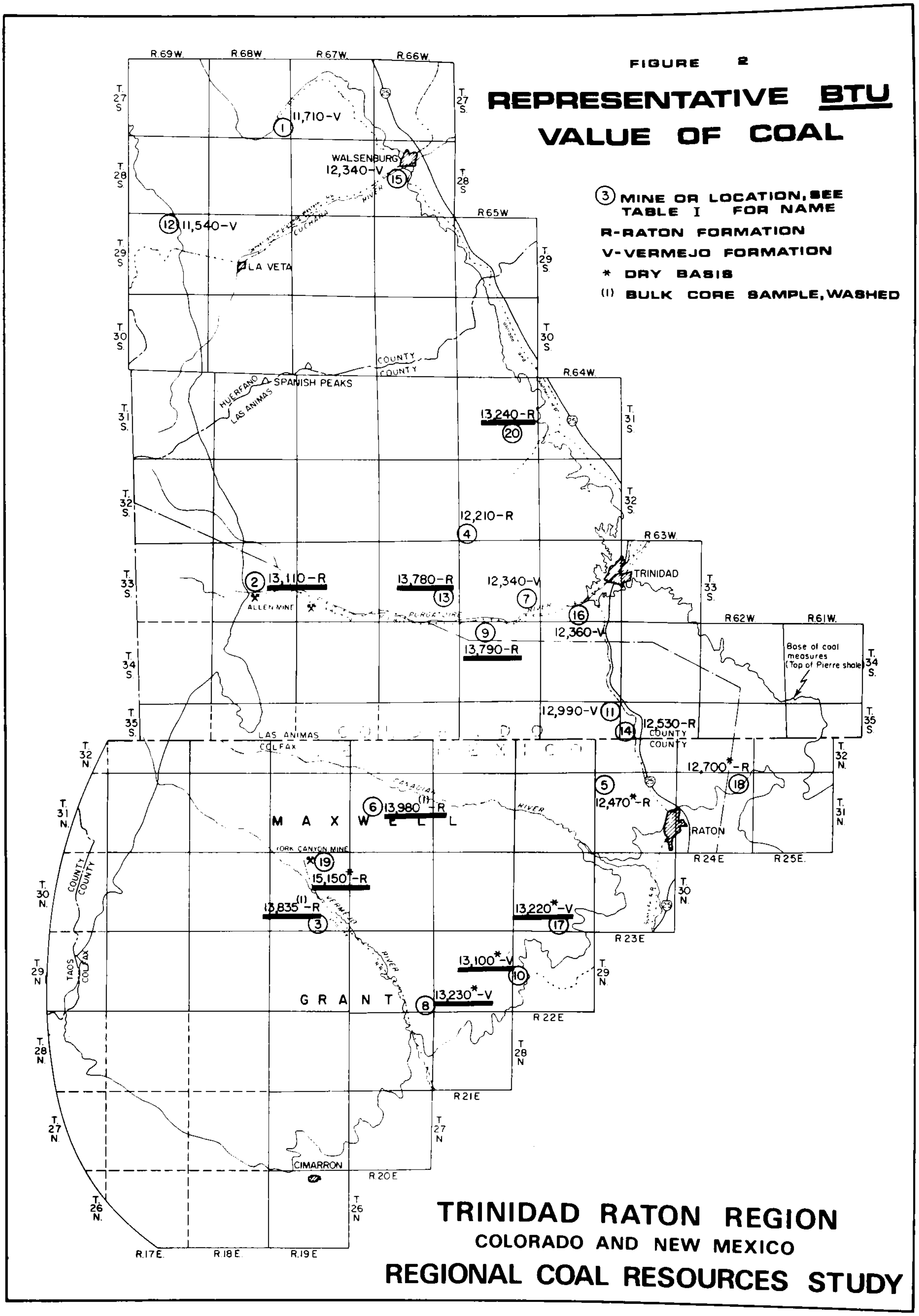


Fig. 2. Representative Btu content.

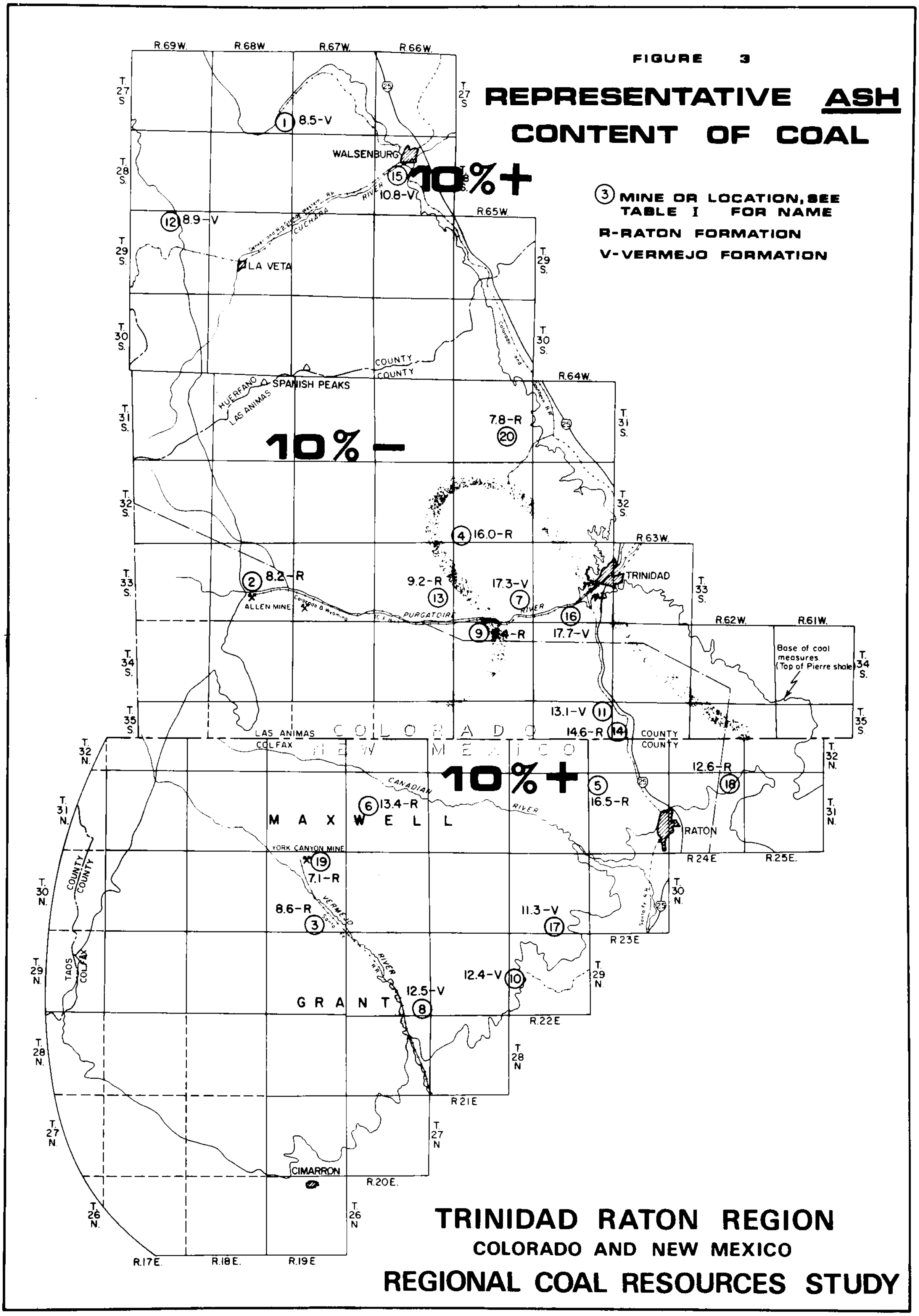


Fig. 3. Representative ash content of coal.

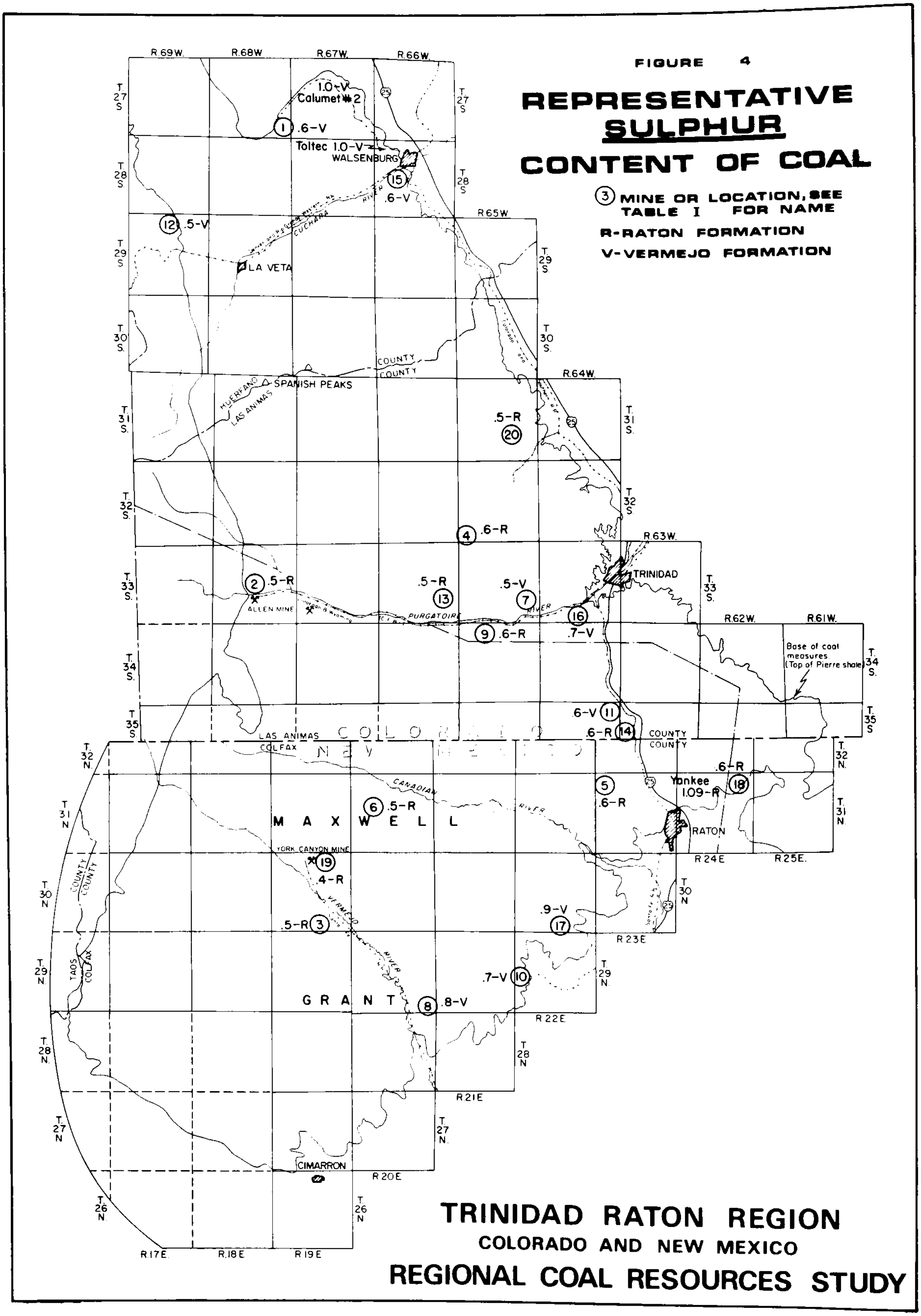


Fig. 4. Representative sulphur content of coal.

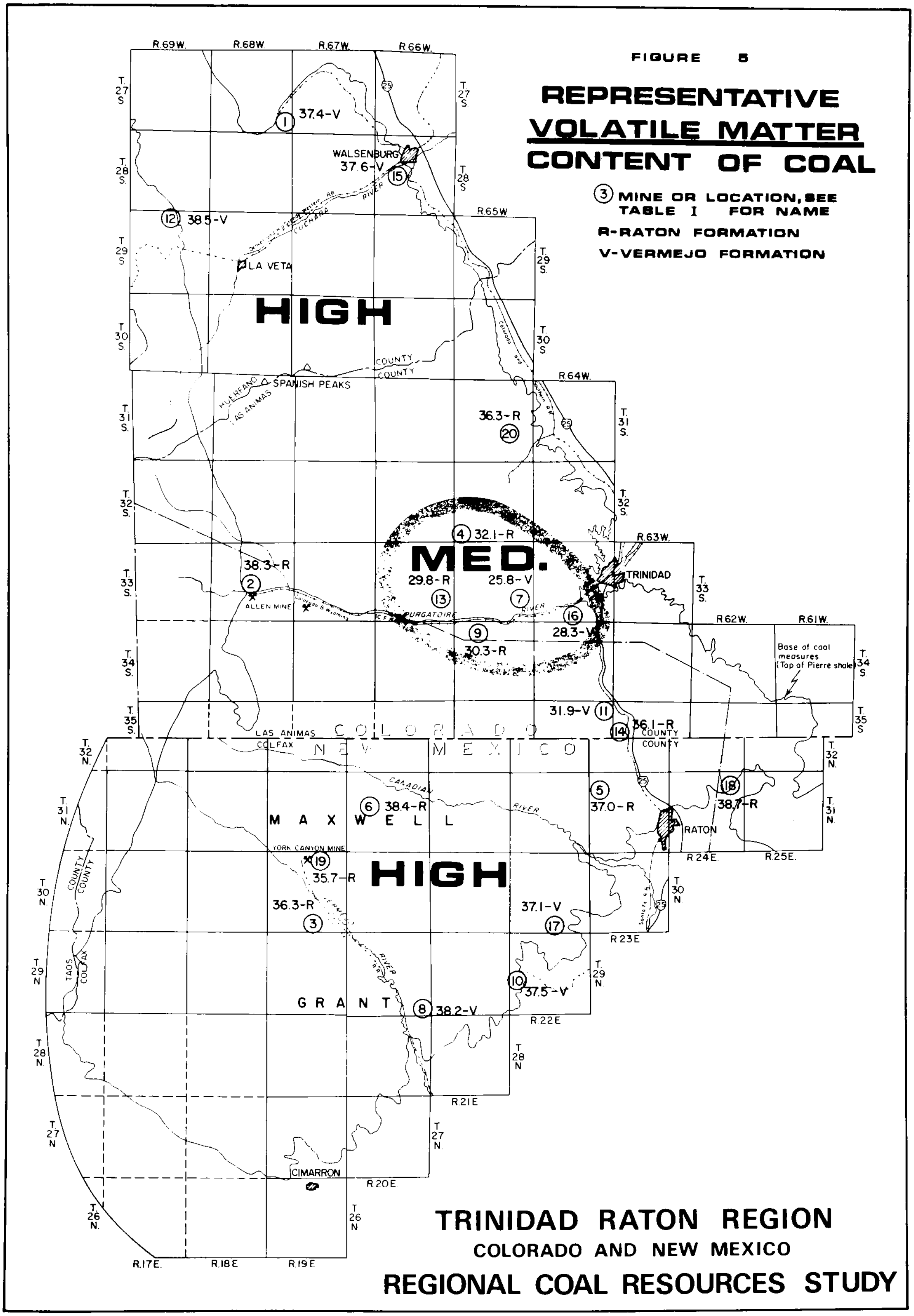


Fig. 5. Representative volatile matter content of coal.

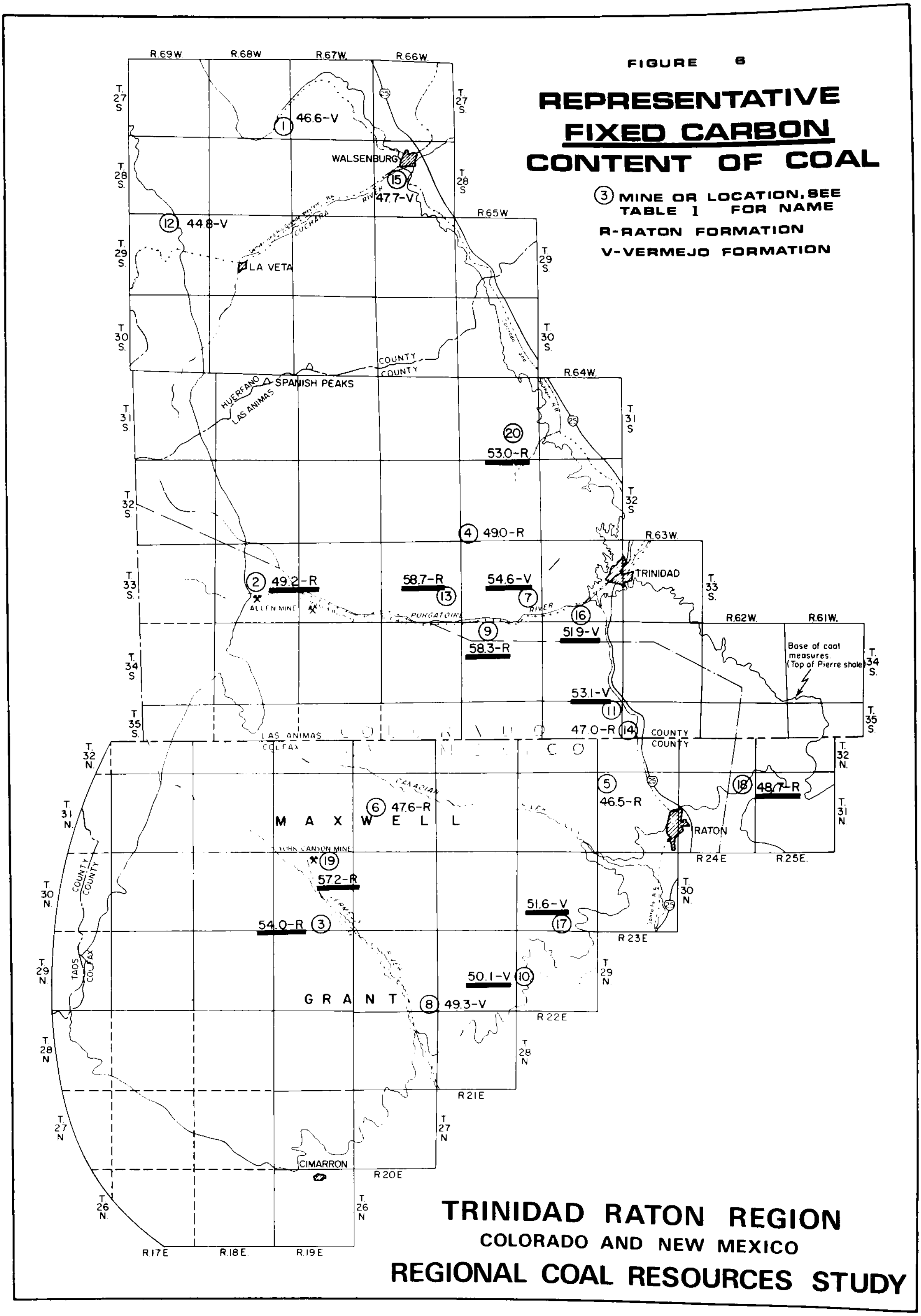


Fig. 6. Representative fixed carbon content of coal.

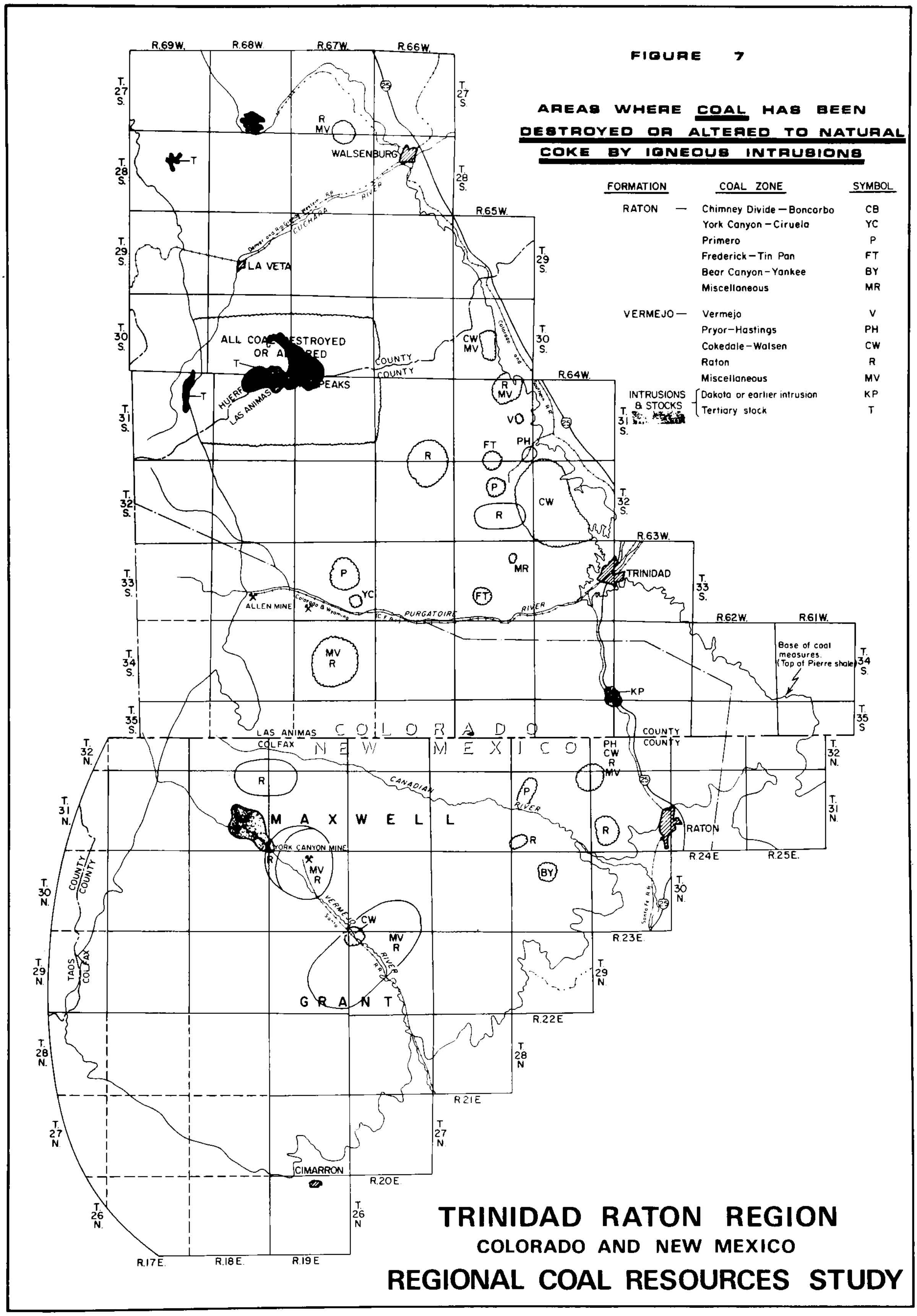


Fig. 7. Areas where coal has been destroyed or altered to natural coke by igneous intrusions.

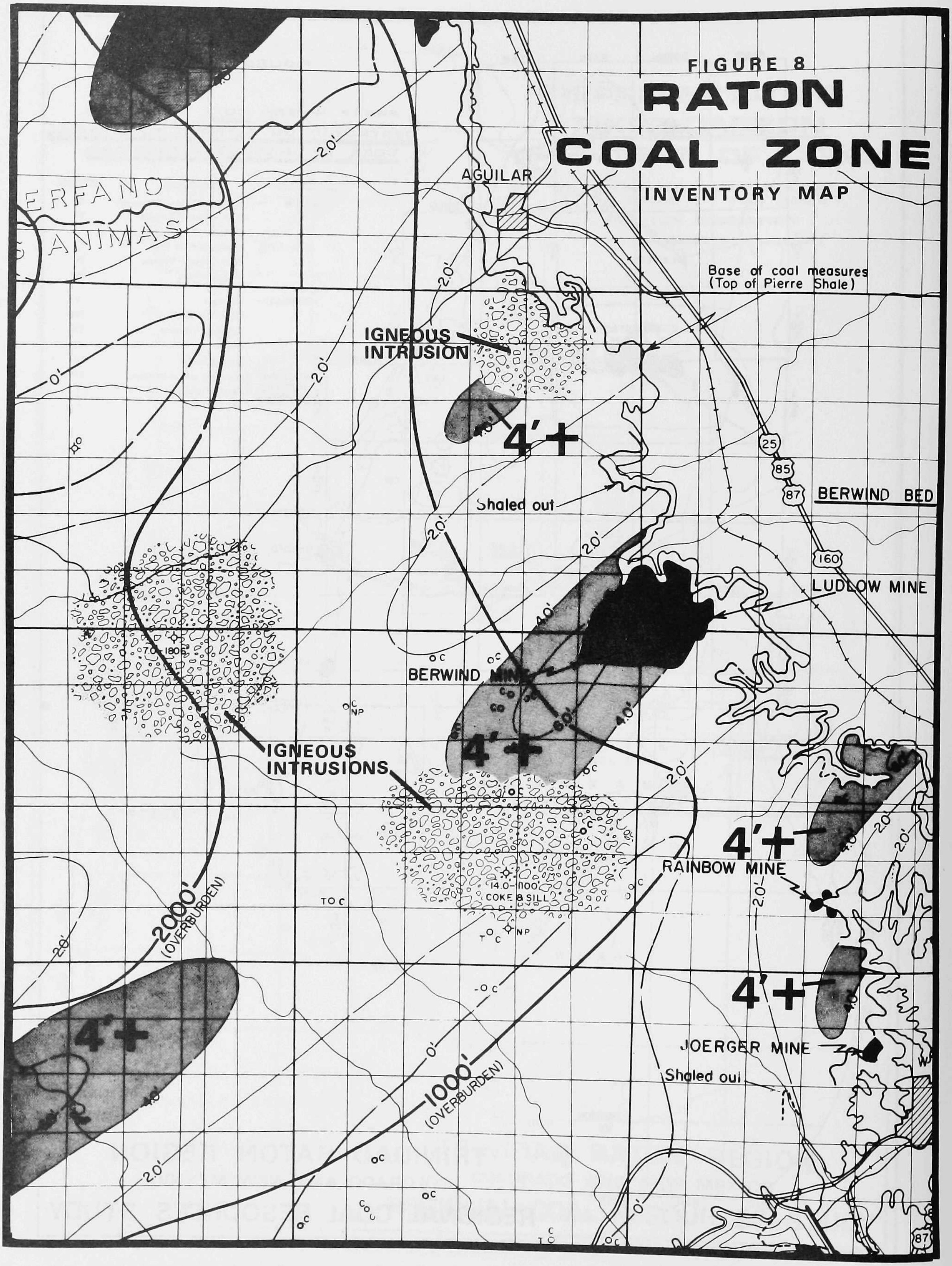


Fig. 8. Raton coal zone.

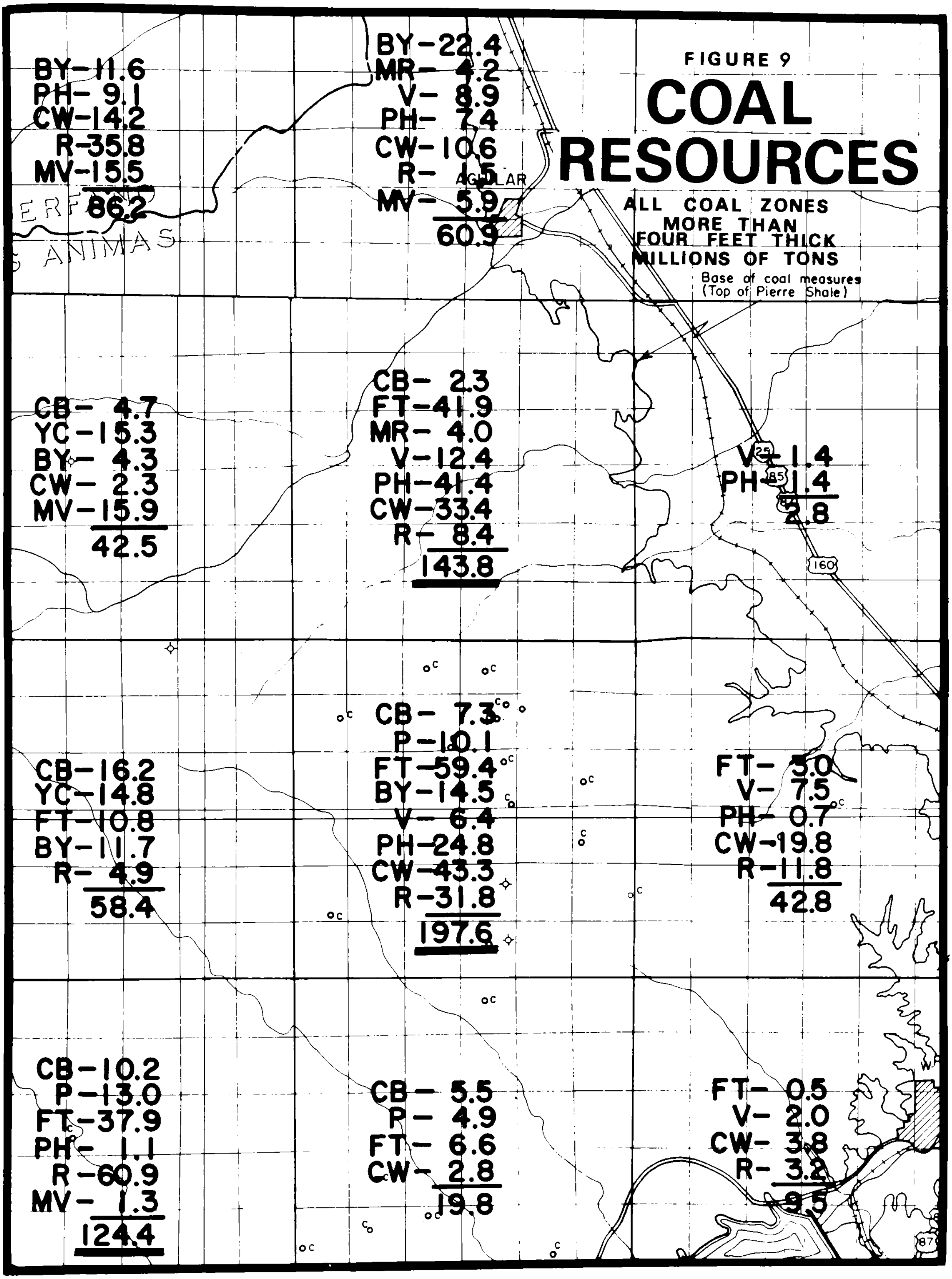


Fig. 9. Coal resources.

7 to 18 percent (Fig. 3). Two areas on Figure 3 show where the content is greater than 10 percent. For the remainder of the area, the coals contain less than 10 percent ash, which is quite low compared with most western coals.

The coals of the Trinidad-Raton basin have low sulfur content, averaging between 0.5 and 0.7 percent (Fig. 4). Local mines near the towns of Raton and Walsenburg have reported coals with up to 1 percent sulfur, mostly in the form of pyrites.

Most of the coal is high-volatile, ranging from about 33 to 39 percent (Fig. 5). One area of medium-volatile coal lies just west of Trinidad, where the volatile content drops to as low as 28 percent.

Generally, Trinidad-Raton basin coals have high fixed-carbon content (Fig. 6). All of the values 50 percent of better are underlined on Figure 5. As in the case of the Btu values, the fixed-carbon values also increase from north to south.

In a number of places within the Trinidad-Raton basin, the coal has been destroyed or altered to natural coke by igneous intrusions (Fig. 7). The Spanish Peaks represent a major Tertiary-age stock. The laccoliths at Moreley and Vermejo Park have intruded into sediments below the coal measures. In numerous instances, sills locally have intruded into coal beds. This igneous activity has upgraded the coal in the area to bituminous rank.

LOCATING THE LARGEST *UNDEVELOPED* POTENTIAL COAL RESERVES

We know that the quality of the coal is high, and that the Trinidad-Raton basin has been, and still is in 1976, a significant coal-producing area. The next step, then, is to delineate the largest areas of potential coal development where core drilling and other exploration expenses might be justified.

The first step is to inventory all available geological data and to start compiling a set of maps at an acceptable scale. In the case of the Trinidad-Raton basin, the scale of 1 in. = 8,000 ft was chosen because the entire basin conveniently fits on one map.

We have examined and correlated considerable data and have identified 9 separate coal zones in this basin. An inventory map of each coal zone was prepared. Figure 8 shows a portion of the Raton Coal Zone Inventory Map. All of the data, with the exception of the coal bed isopachs and thickness of overburden (both of which are our interpretation), were compiled from such sources as the U.S. Geological Survey, U.S. Bureau of Mines, state geological surveys, trade publications, professional association journals, and available logs from oil and gas tests, water wells, and core holes.

Our experience indicates that in exploring for bituminous coal, 4 ft is the minimum thickness likely to support economic development. These areas are indicated on Figure 8. It is also desirable to know the approximate thickness of overburden and where the coal has been destroyed or altered to natural coke by igneous intrusions. It is the sills that destroy the coal, not the well-known dikes that radiate from the Spanish Peaks which, in fact, cause very little alteration.

From this series of inventory maps, one for each coal zone, it is easy to estimate the coal resources in each township for beds greater than 4 ft thick, and to select prospect areas for further evaluation.

Figure 9 is a diagram showing the individual townships and our estimates of their coal resources by individual coal zone. Where the combined resources exceed 100 million tons, they are underscored. This provides a convenient way to determine areas of substantial coal resources. However, it should be recognized that such estimates are limited by the available data.

STATUS OF MINERAL OWNERSHIP

It is now necessary to answer the question about mineral ownership and the present status of land use. The information on Figure 10 was compiled at the same map scale as the inventory maps; so direct comparison is possible by overlaying one map on the other. The mineral ownership map shows the same area as the Raton Coal Zone Inventory Map (Fig. 8). The various stippled and cross-hatched areas identify Federal lands, State lands, and major fee land owners, such as CF&I Steel. The white areas indicate smaller parcels of fee lands. The mineral ownership map should also include any National parks, Indian lands, military reservations, other areas of lands withdrawn from occupancy, and, of course, the outline of any producing oil or gas field that may interfere with future mining activity. A quick examination of this information tells us that considerable fee acreage exists in the basin. However, mineral ownership is not the only land consideration that must be made.

What about the present status of land use? From the land-status map (Fig. 11), we now discover two problems, illustrated by the large tract of land plotted for subdivision development, and the tract classified as recreational land. Large areas of woodlands and rangeland also exist in the basin.

AVAILABILITY OF WATER FOR DOMESTIC AND INDUSTRIAL USE

Water is usually a problem in the West because there are basically two kinds of water. One is saline, the other is fresh, and in either case there are problems. With saline water, one may have disposal problems. With fresh water, enough is needed for plant use and local communities, and enough must be available for future growth of these communities. Present average consumption in Trinidad is about 6 million gal/day, and 2 million gal/day in Walsenburg. Industrial and mine-waste waters must be properly handled in order to avoid contamination not only of surface waters but also of underground waters. In the Trinidad-Raton basin, surface water generally is in short supply. Underground water resources have not been fully evaluated. Transmountain water diversion into this area is not possible because the Rio Grande River drainage west of the Sangre de Cristo Mountains already is in short supply at the State line for downstream users in New Mexico, Texas, and Mexico. Water availability will be a problem for any on-site coal conversion facility in the Trinidad-Raton basin.

MARKETS AND SHIPPING

What about potential markets and shipping? A considerable amount of coal in this area was previously used as steam coal for the railroads and for local consumption; however, the two principal active mines in the basin produce high-quality metallurgical-grade

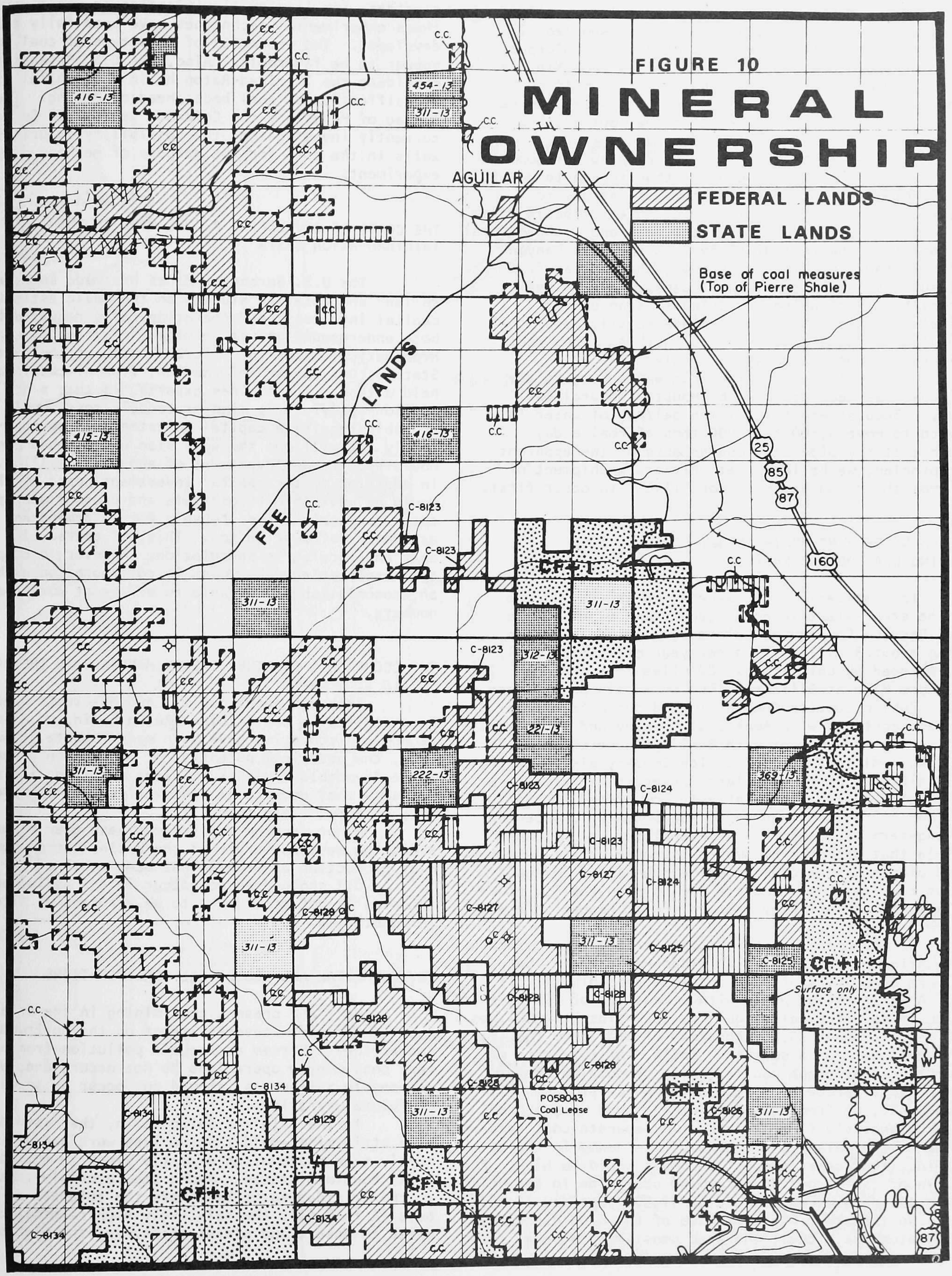


Fig. 10. Mineral ownership.

coking coal. Both of these are captive mines. All of the production from the Allen Mine is transported 121 mi by rail to the CF&I steel mill at Pueblo, Colorado; and all of the production from the York Canyon Mine is shipped 1069 mi by rail to the Kaiser Steel mill at Fontana, California. Unit train operations seem to be the most efficient way to transport coal out of the Trinidad-Raton basin.

The coal in this area is lower in sulfur content and slightly higher in ash content than the eastern U.S. coals. Possibly, with only minor modifications to existing eastern power plants, Trinidad-Raton basin steam coals could be utilized in Mid-Continent and south-central U.S. markets. The rail distance from the York Canyon mine to Fontana, California is about the same as from Trinidad to Chicago or to New Orleans. This raises the possibility of using New Orleans as an export terminal for shipments of high-grade metallurgical coal to foreign markets, especially to South America, where metallurgical coal is in short supply.

A coal-slurry pipeline from Walsenburg to the Gulf Coast has been proposed by Houston Natural Gas Company. Because about 1 million gal/day of water is required to move 3,500 to 4,000 tons of coal a day through a slurry pipeline, and because of the apparent water problem, we believe that unit-train shipment of coal from the Raton basin is more likely to occur first.

DEVELOPMENT OF MINE-MOUTH ENERGY COMPLEX vs EXPORTING COAL OUT OF BASIN

In considering this aspect, we ask why is the Comanche steam-electric power generating plant of the Public Service Company of Colorado, located in Pueblo, burning about 3 million tons per year of Wyoming coal, being shipped by unit trains 600 miles from the Amax Belle Ayre Mine at Gillette? The answer is purely economic. Public Service Company worked out a favorable long-term contract with Amax Coal Company and negotiated a unit train arrangement with Burlington Northern Railroad. In addition, Public Service Company also owns the unit train coal cars. The large reserves at Belle Ayre were readily available, relatively low priced at the time, and sufficiently large to guarantee an uninterrupted long-term fuel supply. Nevertheless, it does seem feasible that one or more smaller steam-electric generating plants using local coal could be sited in the area at the time that electric demand requires it; however, it appears unlikely that this will happen in the near term.

We have looked into the possibility of mine-mouth gasification plants for the Trinidad-Raton basin, but this form of conversion does not seem feasible at this time. A gasification plant with a capacity of 250 million cu ft/day of pipeline-quality (900 plus Btu/MCF) gas would require about 20,000 tons/day of coal from the Trinidad-Raton basin on a sustained basis. At this rate of consumption, the plant would require production from two or more large (probably underground) mines producing simultaneously, or from one large underground mine producing simultaneously from at least two separate coal beds because of the relative thinness of the seams in the basin. In either case, production costs would be high. For comparison, the largest underground coal mine in the United States produced an average of 11,300 tons/day in 1975.

On the other hand, because of the high Btu values of the Raton basin coal, the area does seem to be a candidate for in-situ liquification or gasification once these experimental techniques have been fully tested and developed. The economics of this type of coal conversion appear to be favorable. Also, the U.S. Bureau of Mines considers the Trinidad-Raton basin a potential site for degasification of coal beds ahead of mining. The Bureau of Mines and the Colorado Geological Survey are currently investigating the possibility of drilling test wells in the area for the purpose of methane drainage experiments.

THE COSTS OF DEVELOPING A COAL MINE IN THE TRINIDAD-RATON BASIN

The U.S. Bureau of Mines has made some excellent and detailed studies on the basic estimated capital investment and operating costs required for both underground and strip mines, covering mines of hypothetical sizes in different parts of the United States. Our latest information, from discussions held with Bureau of Mines experts, is that a one million-ton/yr strip mine at today's costs would probably require a capital investment of approximately $15 million; the same size underground mine would require an investment of about $24 million. In addition to the capital investment cost, it also would be advisable to estimate and project operating costs/ton against the probable future demand and estimated sales price/ton. This, of course, is only an exercise in speculation. However, a competent engineering department in collaboration with an economist should be able to arrive at workable numbers.

THE OCCURRENCE OF OTHER ENERGY MINERALS IN THE BASIN

Although about 160 oil and gas tests have been drilled in the Trinidad-Raton basin, no major economic discoveries have been made to date. However, the petroleum potential of the region appears to be favorable. With sufficient drilling, it is probable that commercial discoveries will be made--of gas, more likely than oil.

Minor uranium occurrences have been reported along the western margin of the basin, but no commercial production of uranium has been attained.

Oil shale does not occur in the basin, and the area is not considered to be a potential site for geothermal power.

ENVIRONMENTAL AND ECOLOGICAL CONSIDERATIONS

Past and present coal mining in the area has had a minimum adverse impact on the environment and ecology. Stream and/or air pollution from present coal mining operations do not occur, and, with reasonable safeguards, should not occur as a result of future operations.

In the Trinidad-Raton basin, the restoration of a strip mine would involve less work and be less costly than restoration of strip mines in the northern Rocky Mountain states. Among the favorable factors in the Trinidad-Raton basin are the thinness of coal beds (4 to 8 ft), the relatively high rainfall compared to desert and plains areas, and the high per-

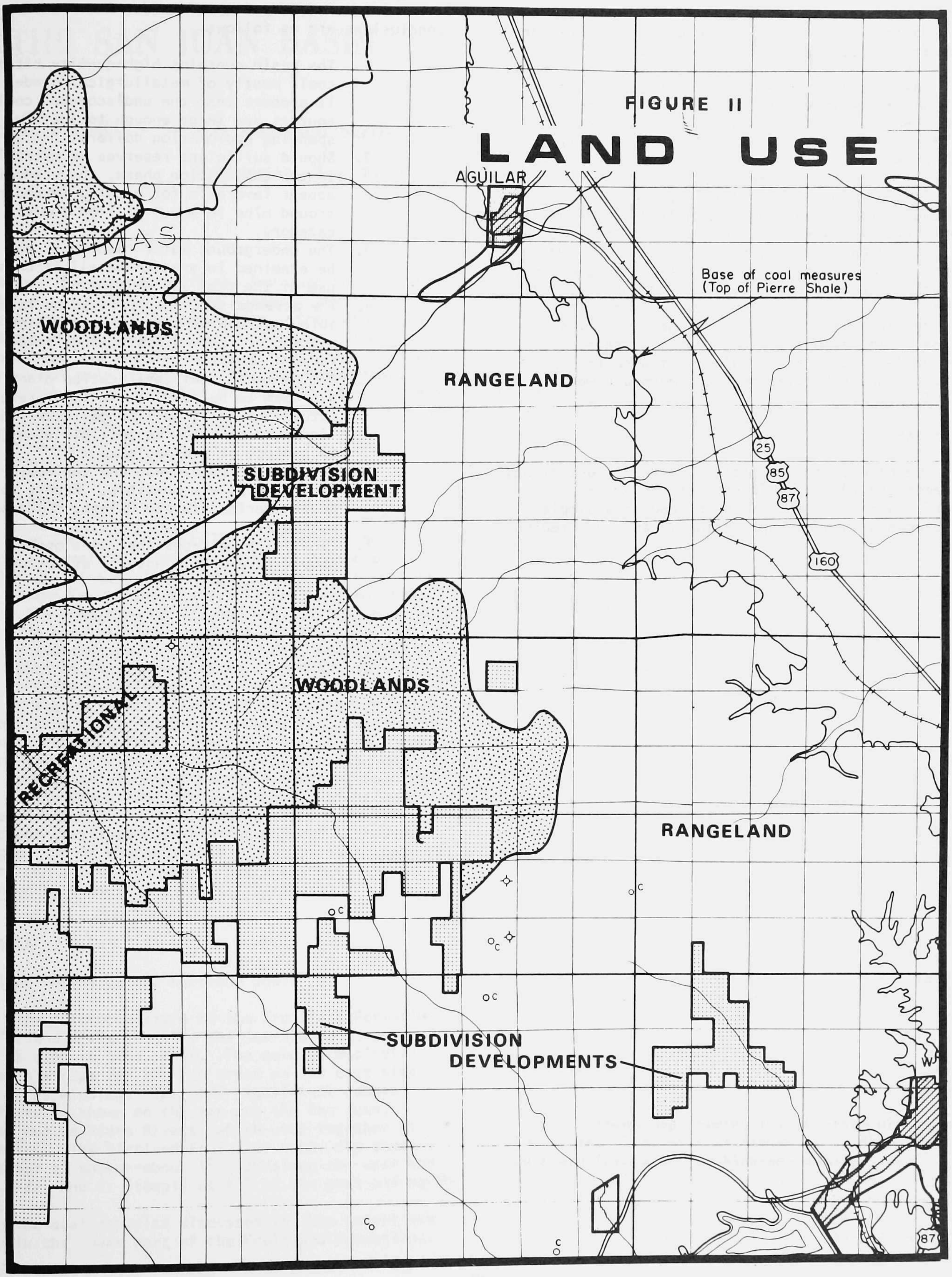


Fig. 11. Land use.

centage of rangeland and woodland. The high rainfall factor would provide more than adequate moisture for revegetation practices, and the rangeland and woodland in this area would be relatively easy to restore.

Restoration procedures now utilized at the waste coal dumps at Kaiser Steel Corporation's York Canyon mine are excellent and could be used as a model for the restoration of any future strip mines in the area. In the case of underground mines, little restoration would be necessary.

There is abundant wildlife in the area, concentrated mainly in the upper rangeland, woodland, and higher elevations west of Walsenburg and Trinidad, Colorado, and Raton and north of Cimarron, in New Mexico. The main species in the basin are mule deer, elk, turkey, bear, band tail pigeon, mountain lions, bobcats, and coyotes. Antelope are common on the plains to the east. Rare and endangered species reported in the area are black-footed ferrets, peregrine falcons, prairie falcons, the southern bald eagle, and probably the Rocky Mountain wolf.

CONCLUSIONS

We hope that our information and illustrations have demonstrated the usefulness of the *basin evaluation concept*, which we recommend as a simple first-step approach to exploration of any coal region.

In the case of the Trinidad-Raton basin, our conclusions are as follows:

1. The basin contains high-quality bituminous coal, mostly of metallurgical grade, and it appears that the undiscovered coal resources are large enough to justify spending exploration dollars.
2. Should sufficient reserves be established in the exploration phase, the economics appear favorable for opening an underground mine in the 1 million ton/yr category.
3. The underground water resources need to be examined in greater detail if on-site use of the coal is anticipated.
4. The acreage status appears to be favorable inasmuch as there exists a high percentage of fee and State lands relative to Federal lands.
5. A mine-mouth coal gasification plant does not seem to be feasible in the foreseeable future; however, in-situ gasification or liquefaction might be possible when the technology is available.
6. Markets in the Midwest and the south-central U.S. are possible. Export to South America via New Orleans *might* be possible.
7. Finally, a well-designed mine operation should have little adverse effect on the environment.

STRATIGRAPHY OF THE COALS OF THE SAN JUAN BASIN

JAMES E. FASSETT: U.S. Geological Survey
Farmington, New Mexico 87401

ABSTRACT: The coal beds of the San Juan basin of New Mexico and Colorado were deposited in the SCI-SWO (sea came in -- sea went out zones; Fassett, 1974) at the west margin of the epicontinental seaway that bisected North America during Late Cretaceous time. Coal deposition was closely related to regressions and transgressions of the shoreline; thus, coal beds occur close to littoral sandstone beds laid down near the margin of the Cretaceous sea. The thickness and lateral continuity of these coal beds apparently are a function of a combination of events occurring not only at the site of coal deposition, but also, in some instances, half-a-world away. If some of these events can be isolated and studied, then perhaps the origin of thick or widespread coal beds can be more easily understood. The coal-bearing rocks of the Fruitland Formation are used as a model for examination of some of the facets of coal formation.

INTRODUCTION

The San Juan basin is in northwestern New Mexico and southwestern Colorado, near the common corner of Colorado, Utah, Arizona, and New Mexico in what is known as the Four Corners area; it encloses an area of about 7,500 square miles (19,400 km^2) and is about 100 miles (161 km) long (north-south) and 90 miles (145 km) wide (east-west). The Navajo, Ute, and Apache Indian Reservations occupy parts of the basin. The basin contains a series of coal-bearing Upper Cretaceous strata which are associated with either regressive or transgressive shoreline deposits. These coal-bearing units are, from oldest to youngest, the Lower (?) and Upper Cretaceous Dakota Sandstone and the Upper Cretaceous Dilco and Gibson Members of the Crevasse Canyon Formation, the upper and lower parts of the Menefee Formation, and the Fruitland Formation. This paper describes the stratigraphy and environment of deposition of the Fruitland Formation coal deposits. Most of the material in this report was previously presented by Fassett and Hinds (1971).

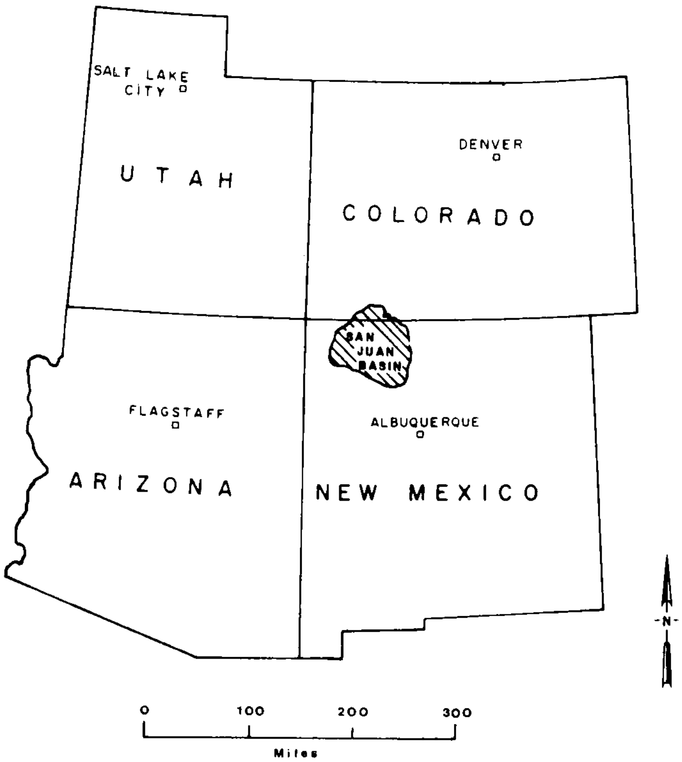


Fig. 1. Index map showing the location of the San Juan basin. The basin is rimmed by outcropping Fruitland Formation and Kirtland Shale.

STRATIGRAPHY

Fruitland Formation and Kirtland Shale

The outcrop pattern of the Fruitland Formation and Kirtland Shale (Fig. 2) defines the San Juan basin as used in this paper. The outcrop encircles the basin except for the two areas on the east side where it is missing. The most significant geographic features shown on the map are the San Juan, Animas, and La Plata Rivers, which come together at Farmington. The Kirtland-Fruitland rocks dip toward the center of basin--about 1° - 2° along the west and south sides and as steeply as 45° on the east and north sides.

The coal deposits discussed in this report are mainly in the lower part of the Fruitland Formation.

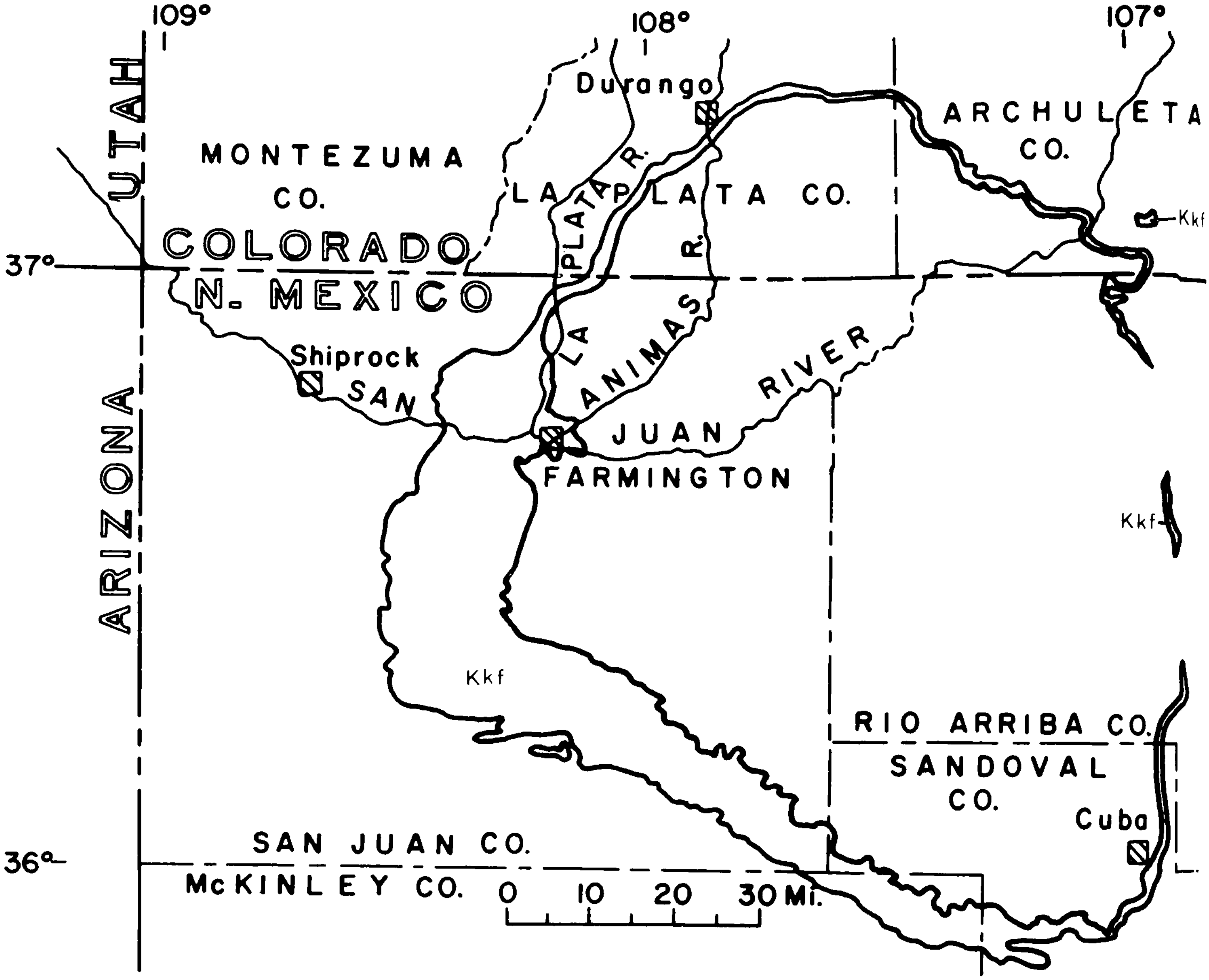


Fig. 2. Map showing distribution of the undivided Fruitland Formation and Kirtland Shale in the San Juan basin. The outcropping rocks shown bounding the basin are the Fruitland Formation and the Kirtland Shale, undivided (Kkf).

The relation of the Fruitland to overlying and underlying rock units and their ages are shown on Figure 3. The marine Lewis Shale contains the Huerfanito Bentonite Bed, which represents a volcanic ashfall into the Lewis sea and is used as a datum for some of the cross sections in this report; the Pictured Cliffs Sandstone represents, for the most part, a regressive beach and littoral deposit that marks the final regression of the sea from the San Juan basin area; the Fruitland Formation comprises paludal and fluvial deposits; the Kirtland Shale is depositionally similar to the Fruitland Formation but contains no coal; and the Ojo Alamo Sandstone represents fluvial deposits and unconformably overlies progressively older rocks from west to east across the basin.

STRUCTURE

The basin is clearly asymmetric (Fig. 4); the rocks on the east side dip steeply west, whereas those on the west side dip gently to the east.

COAL DEPOSITION

The Fruitland Formation coal resources in the San Juan basin are closely related to the Pictured Cliffs Sandstone; thus, a reconstruction of the geologic history of the Pictured Cliffs is helpful in determining the environment of deposition of the Fruitland coals. Figure 5 shows the position of the San Juan basin area relative to the epeiric sea which

SERIES	FORMATION	ENVIRONMENT
PALEOCENE	OJO ALAMO SANDSTONE	FLUVIAL
UPPER CRETACEOUS	KIRTLAND SHALE	FLUVIAL
	FRUITLAND FORMATION	FLUVIAL & PALUDAL
	PICTURED CLIFFS SANDSTONE	LITTORAL MARINE
	LEWIS SHALE HUERFANITO BENTONITE BED	MARINE

Fig. 3. Stratigraphic column showing the age and environments of deposition of the Fruitland Formation and associated rocks.

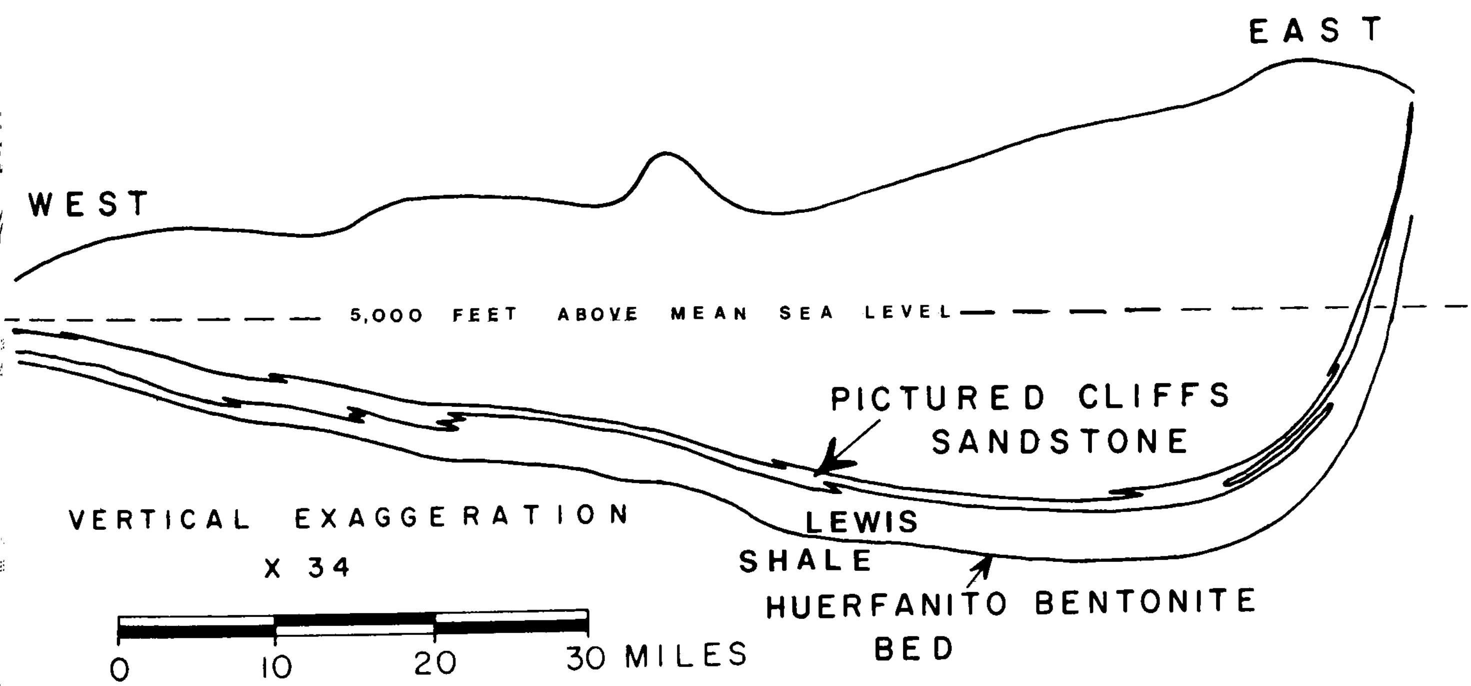


Fig. 4. Structural cross section across the San Juan basin. On this cross section rocks occupying the interval from the top of the Pictured Cliffs Sandstone to the surface have not been subdivided. The thickness of the rocks from the Huerfanito Bentonite Bed to the surface in the structurally deepest part of the basin is about 4,500 ft (1,370 m).

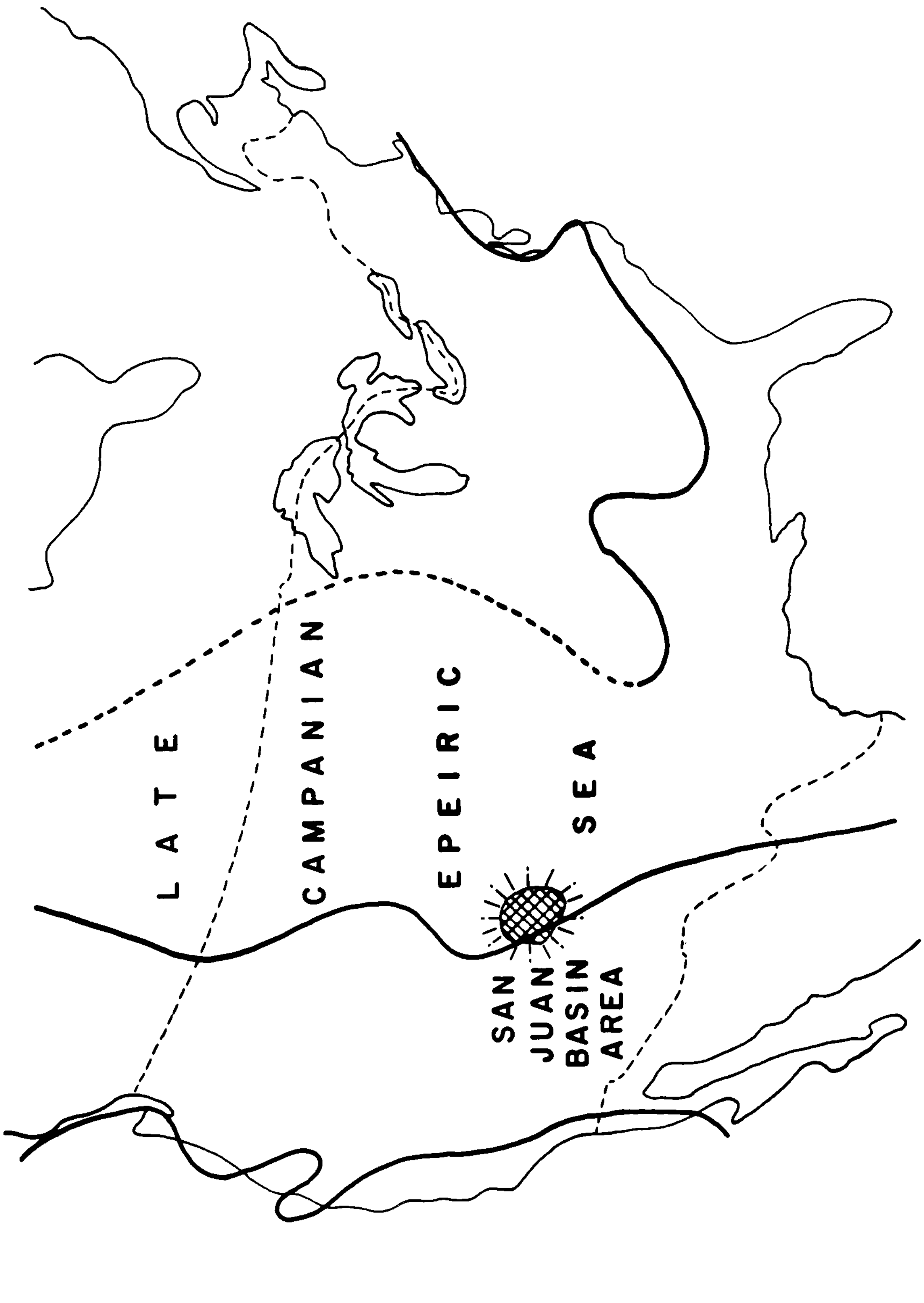
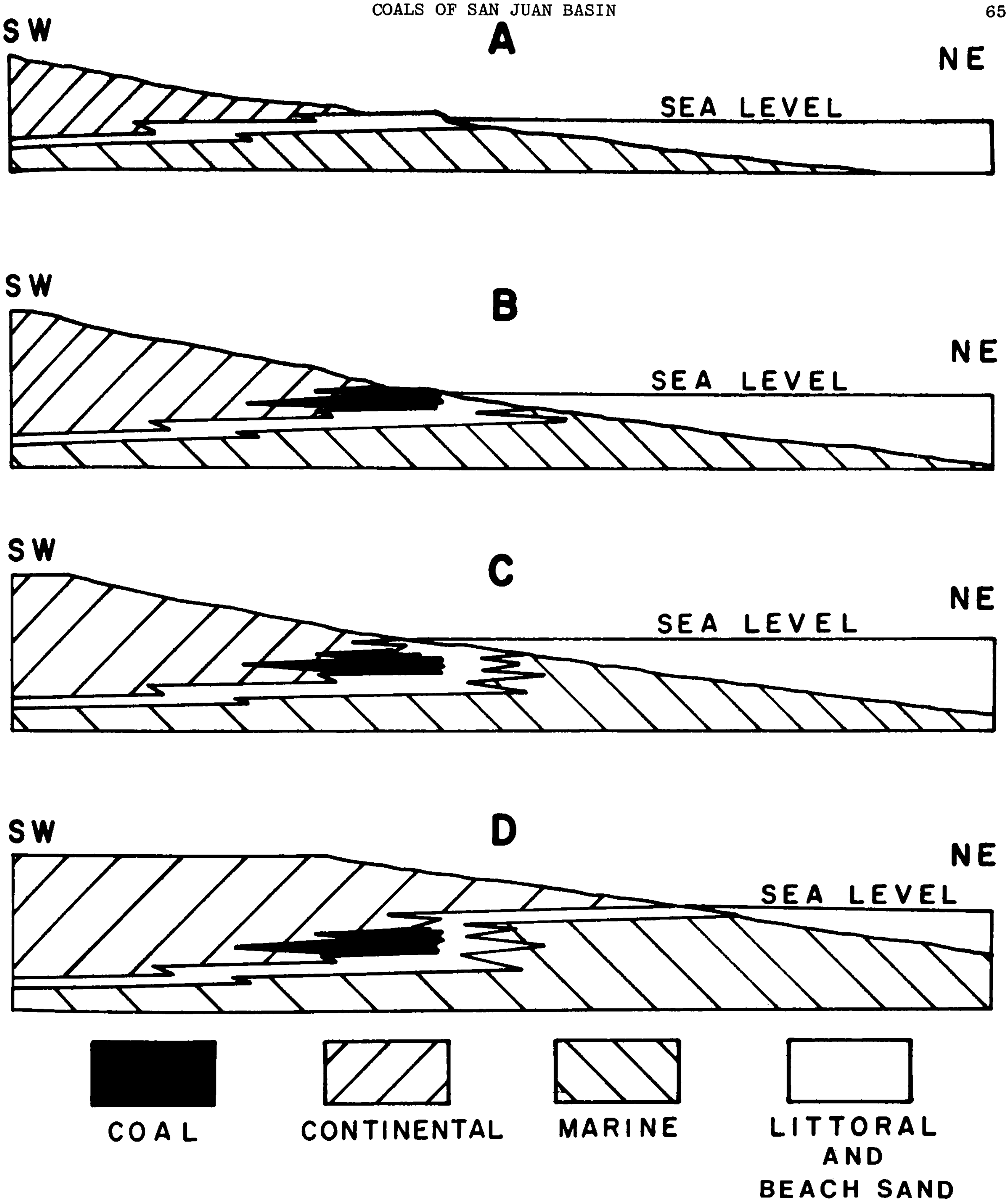


Fig. 5. Configuration of the epicontinental western interior seaway during late Campanian time showing the position of the San Juan basin (from Gill and Cobban, 1966, Fig. 15).



ig. 6. Diagrammatic cross sections showing the relations of the continental, beach, and marine deposits of ictured Cliffs time after (A) shoreline regression, (B) shoreline stability, (C) shoreline transgression, and D) shoreline regression.

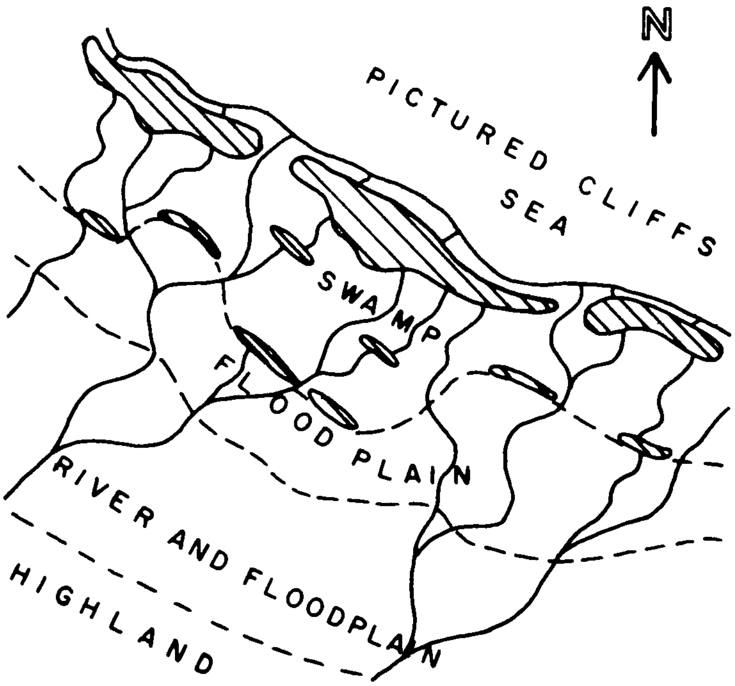


Fig. 7. Paleogeographic sketch map of part of the San Juan basin area during deposition of the Pictured Cliffs Sandstone and the Fruitland Formation and Kirtland Shale. The scale normal to the shoreline is obviously greatly compressed. Hachured areas represent coal swamps.

bisected the North America continent during Late Cretaceous time (Gill and Cobban, 1966). Because the basin was on the western margin of the sea in the SCI-SWO zone, it received alternately marine and nonmarine sediments as the shoreline retreated and advanced.

The four cross sections in Figure 6 represent progressively younger times in the history of the basin area. Overall, the Pictured Cliffs is a regressive sandstone with minor transgressive layers. The sea regressed from the basin area because of infilling by sediments along the western margin of a continuously subsiding trough. The rate of migration of the shoreline was directly related to a balance between the rate of subsidence of the seaway and the rate of sediment influx. At first (Fig. 6A), sedimentation exceeded subsidence; thus, the shoreline shifted to the northeast. In this situation any back-shore coal swamps that might have developed would have been buried rather rapidly by continental deposits and resultant coal beds would be relatively thin. Then (Fig. 6B), the rates of sediment influx and subsidence were about equal, resulting in a vertical upbuilding of littoral sandstone. The coastal swamps thus would have been geographically stable, allowing for a large vertical buildup of vegetal matter yielding thick coal beds. After sediment influx was less rapid than seaway subsidence (Fig. 6C), the shoreline advanced over previously deposited continental sediments. In this situation coastal swamps would have been filled by marine sediments and vegetal matter buildup would have ceased, limiting the thickness of the coal. After sedimentation had exceeded subsidence (Fig. 6D), the shoreline regressed northeastward and there was regression and little or no coal buildup.

Paleogeography of Pictured Cliffs Time

A paleogeographic map of part of the San Juan basin area (Fig. 7), constructed at the time of cross section B (Fig. 6), shows the environments of deposition which paralleled the shoreline during Pictured Cliffs time. The sea is to the northeast; the coastal swamp environment lies just inland from the shoreline; farther inland are floodplain and river and floodplain environments of deposition; and to the southwest a rising highland furnishes sediments that are being carried to the sea. The highland most certainly was hundreds of miles from the sea. The lateral extent of coastal swamps is limited by rivers that cut through the swamp environment to the sea. Clearly, a delicate balance is necessary for the ultimate buildup of thick coal beds. An increase in the influx of continental sediment would fill the coastal swamps; conversely, a decrease would result in the sea moving inland, filling the coastal swamps with marine sediments.

Deposition of Pictured Cliffs Sandstone

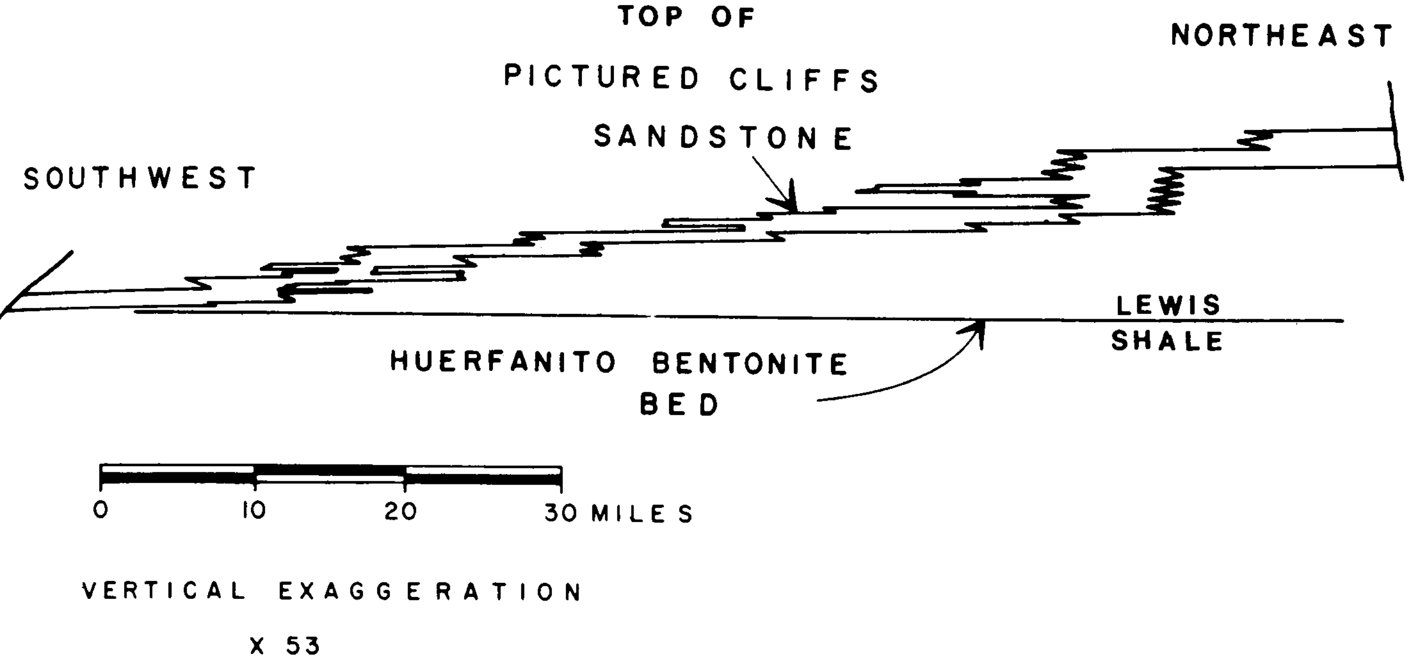
A stratigraphic cross section (Fig. 8) constructed across the San Juan basin from southwest to northeast shows the stratigraphic rise of the Pictured Cliffs Sandstone across the basin relative to the Huerfanito Bentonite Bed. From the previous discussion, the thickest coal beds of the Fruitland Formation would be expected southwest of the largest stratigraphic rises in the position of the Pictured Cliffs Sandstone.

The isopach map (Fig. 9) of the interval between the Huerfanito Bentonite Bed and the top of the Pictured Cliffs rises from southwest to northeast across the San Juan basin; it is only 200 ft (61m) above the Huerfanito Bentonite Bed in the southwest, whereas it is 1,200 ft (366m) above this datum in the northeast. The area where the 800-, 900-, and 1,000-ft isopachs are grouped together represents the largest stratigraphic rise of the Pictured Cliffs; thus, one might expect to find the thickest Fruitland coal beds southwest of this area. Also, these isopach lines presumably closely parallel old shorelines of the Pictured Cliffs sea and thus should furnish a clue as to the orientation of thick Fruitland coal beds, which also should parallel those shorelines.

FRUITLAND FORMATION COAL

Thickness

Figure 10 is an isopach map showing total thickness of coal deposits in the Fruitland Formation throughout the San Juan basin. Subsurface control for this map is based on geophysical logs of several hundred oil and gas wells. The logs used to pick the coals were mostly electric logs, but where available, gamma ray-neutron logs and drilling-rate records were



ig. 8. Stratigraphic cross section across the San Juan basin using the Huerfanito Bentonite Bed, a marker bed ı the Lewis Shale, as a datum (section constructed from subsurface well-log control).

ıed to confirm the electric-log coal picks. As this ıp shows, total coal thickness ranges from less than) ft (3 m) to more than 70 ft (21 m). In the areas thinner coal, only one coal bed may be present. ıe area of thickest coal -- 70 ft (21 m) -- in the ın Juan basin is southwest of the largest strati-aphic rise of the Pictured Cliffs Sandstone, as ıown on Figure 9. Another area of thick coal --) ft (9 m) -- is present in the southwest part of the ısin.

ıality

An important part of the Fruitland Formation ıal study was the collection of more than 60 coal ımples from wells being drilled throughout the San an basin. The method of collecting and processing ese coal samples was described by Hinds (1964). The al samples were analyzed by the U. S. Bureau of nes and had as-received heating values ranging from 000 Btu/lb to more than 13,000 Btu/lb. The as-ceived values were not amenable to the construction an iso-Btu map, although generally the highest lues were clustered in the northwest part of the sin. The moisture- and ash-free Btu values, however, rmed a uniform pattern when contoured, ranging from ,500 Btu/lb in the southwest to 15,500 Btu/lb in the rth (Fig. 11). The values may decrease from the ,500 Btu line northeast toward the edge of the sin; however, Btu control for this part of the sin is scarce. The reason for this pattern is not own; it could result from deep burial of the coal, or it could be related to climatic changes or other unknown environmental conditions existing during Fruitland Formation coal deposition.

The Fruitland Formation coal resources (from Fassett and Hinds, 1971) are shown on Table 1 in several thickness-of-overburden categories. The total coal resources for the Fruitland Formation in the San Juan basin are 201.136 billion tons (182.5 billion metric tons). Of these 200-plus billion tons (180-plus billion metric tons) of coal present in the Fruitland Formation, only about one-half of the 14.6 billion tons (13.24 billion metric tons) in the 0-500-ft (0-152-m) overburden category is recoverable by current strip-mining techniques.

SUMMARY

The Upper Cretaceous Fruitland Formation contains vast coal resources in the San Juan basin of New Mexico and Colorado. These coals are concentrated in the lowermost part of the Fruitland Formation, and individual coal beds usually have their long dimension oriented parallel to ancient Pictured Cliffs shorelines --northwest--in most of the basin area. In addition, the thickest total coal -- 70 ft (21 m) -- is southwest of the largest stratigraphic rise in the position of the Pictured Cliffs Sandstone. Perhaps recognition of similar environments of deposition in coal basins where control is less abundant than in the San Juan basin may help in exploration for thick coal deposits.

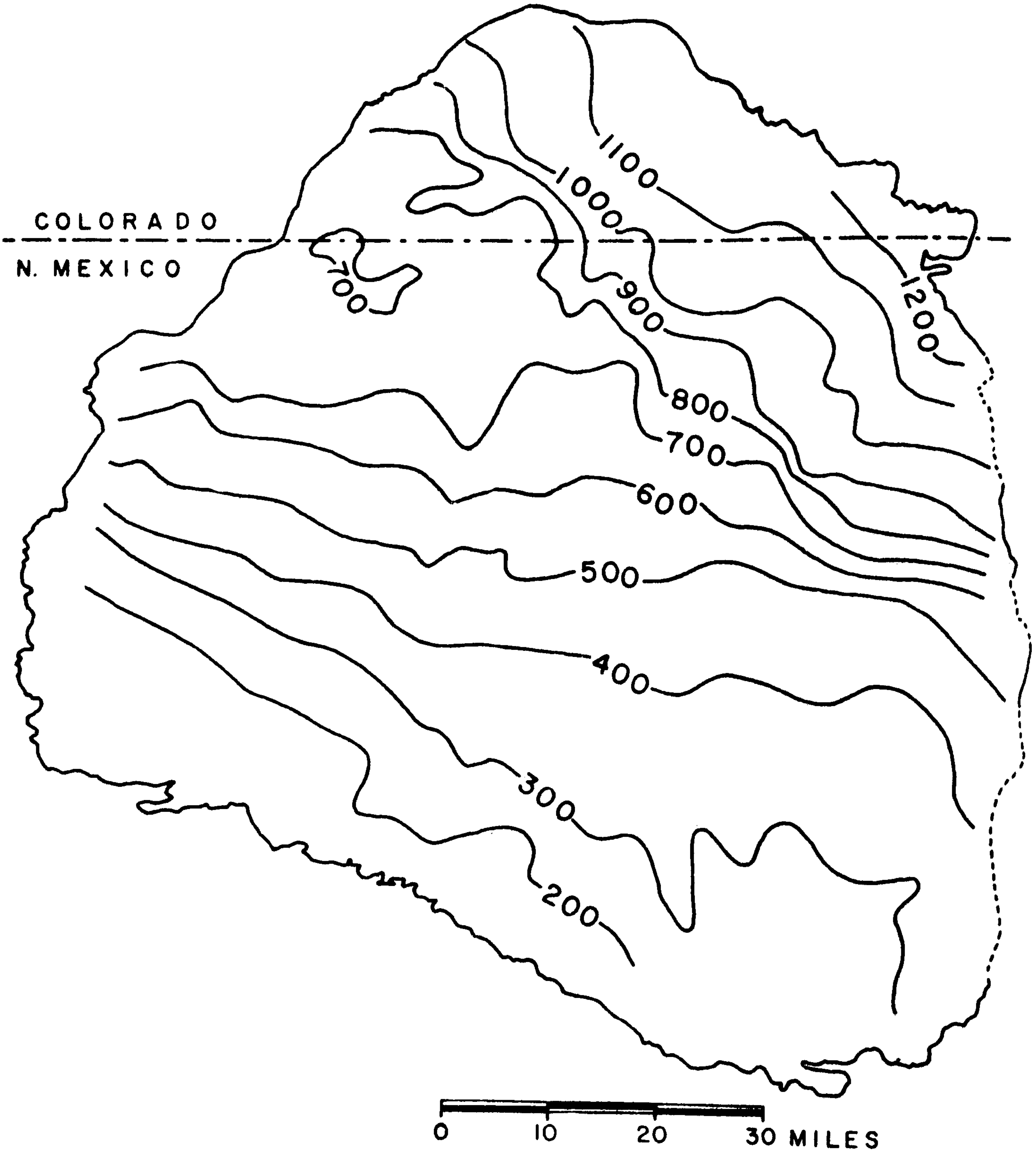
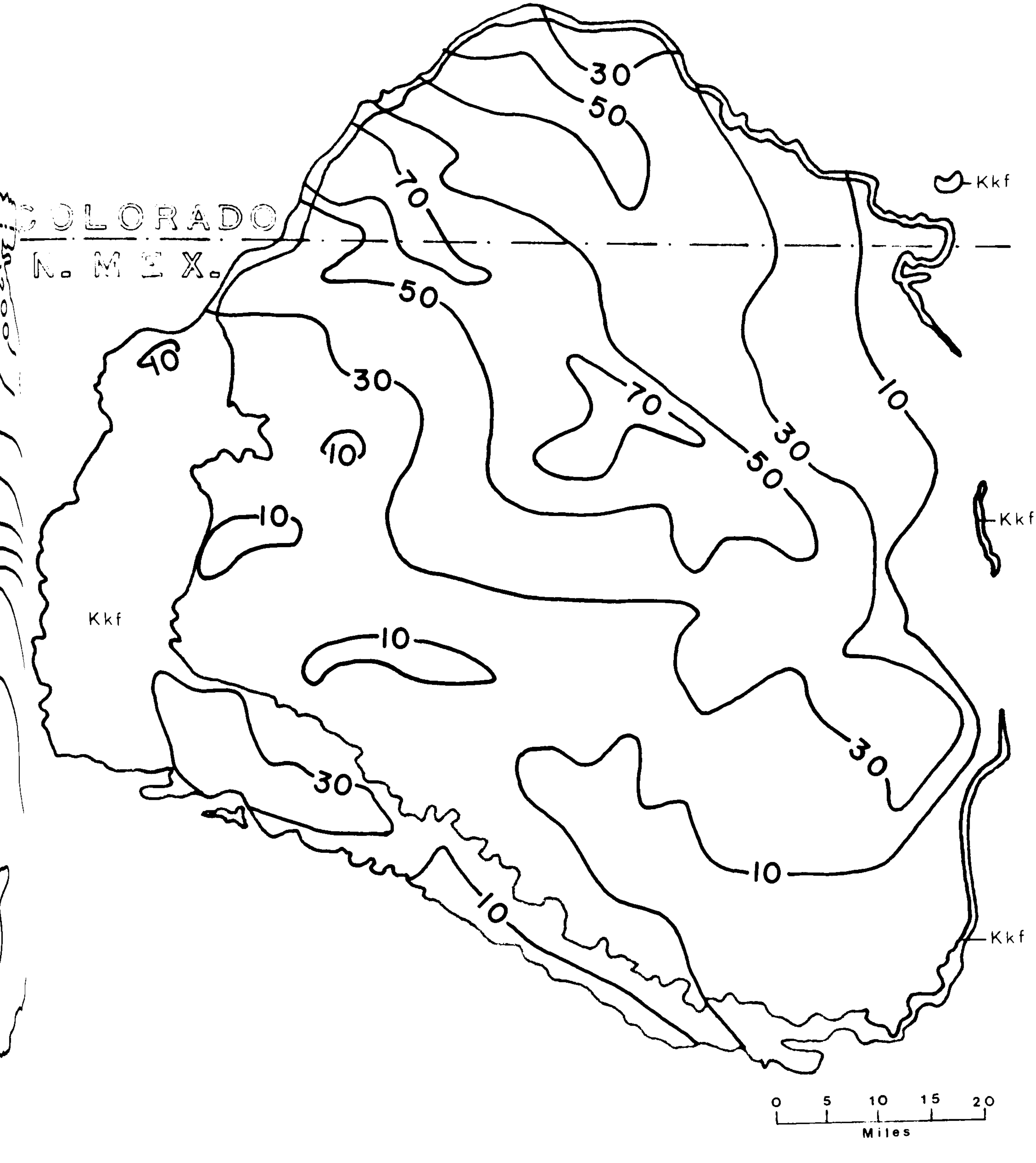


Fig. 9. Isopach map showing the interval from the Huerfanito Bentonite Bed to the top of the Pictured Cliffs Sandstone. Contours show thickness of the interval in 100-ft (30-m) increments. The line bounding the basin is the base of the Fruitland Formation.



g. 10. Isopach map showing the total thickness of Fruitland Formation coal beds. Contours show coal thickness 20-ft (6-m) increments. The outcropping rocks shown bounding the basin are the Fruitland Formation and Kirtland Shale, undivided (Kkf).

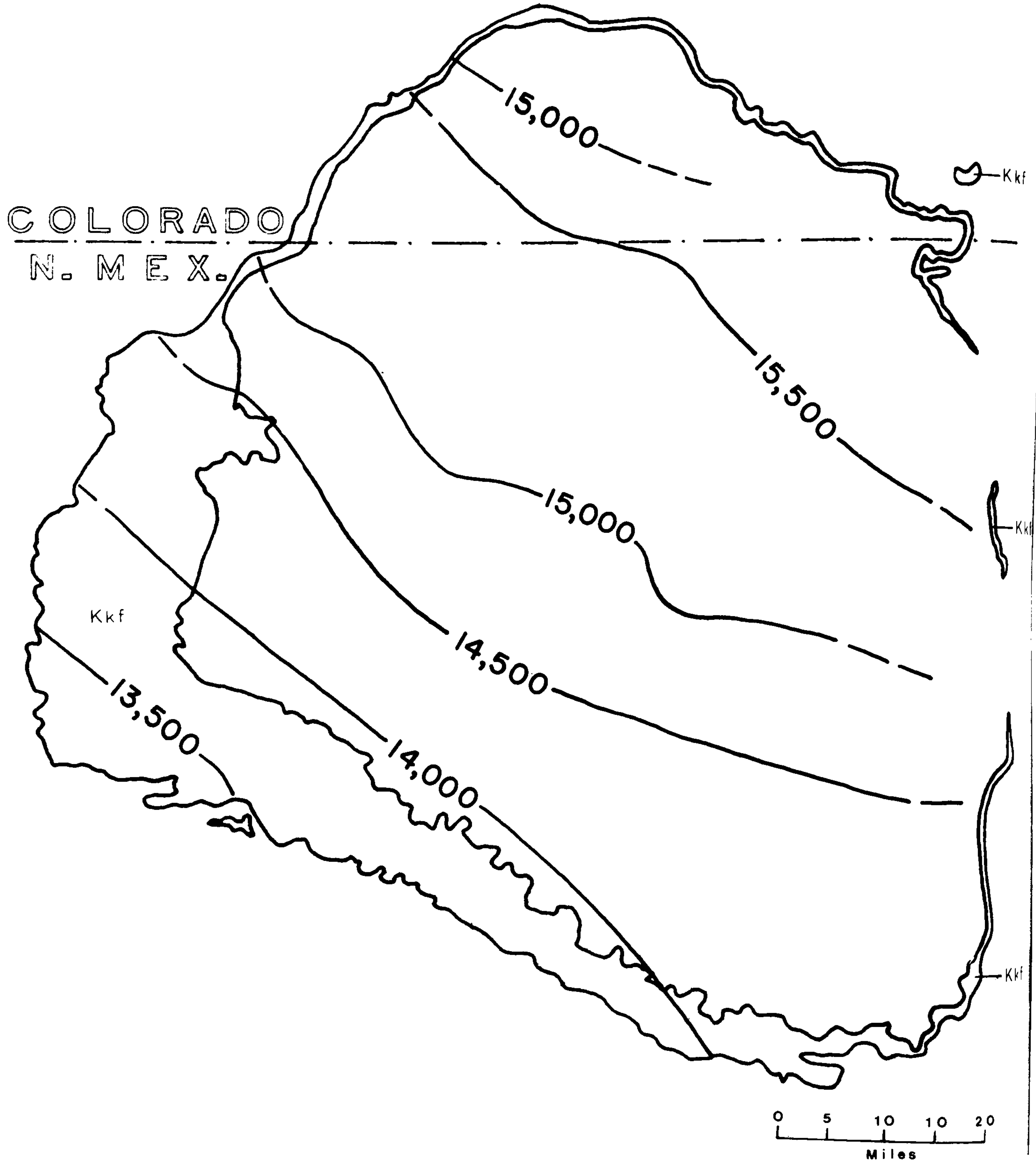


Fig. 11. Map showing contours of equal Btu values (moisture- and ash-free) for Fruitland Formation coal across the San Juan basin. Outcropping rocks bounding the basin are the Fruitland Formation and Kirtland Shale, undivided (Kkf).

Table 1.--*Fruitland Formation coal resources occurring in various overburden categories in the San Juan basin (Fassett and Hinds, 1971)*

Overburden thickness (ft)	Coal, in millions of short tons
0-500..............	14,638
500-1,000............	13,868
1,000-2,000............	27,937
2,000-3,000............	58,808
3,000-4,000............	82,824
Over 4,000.............	3,061
Total...............	201,136

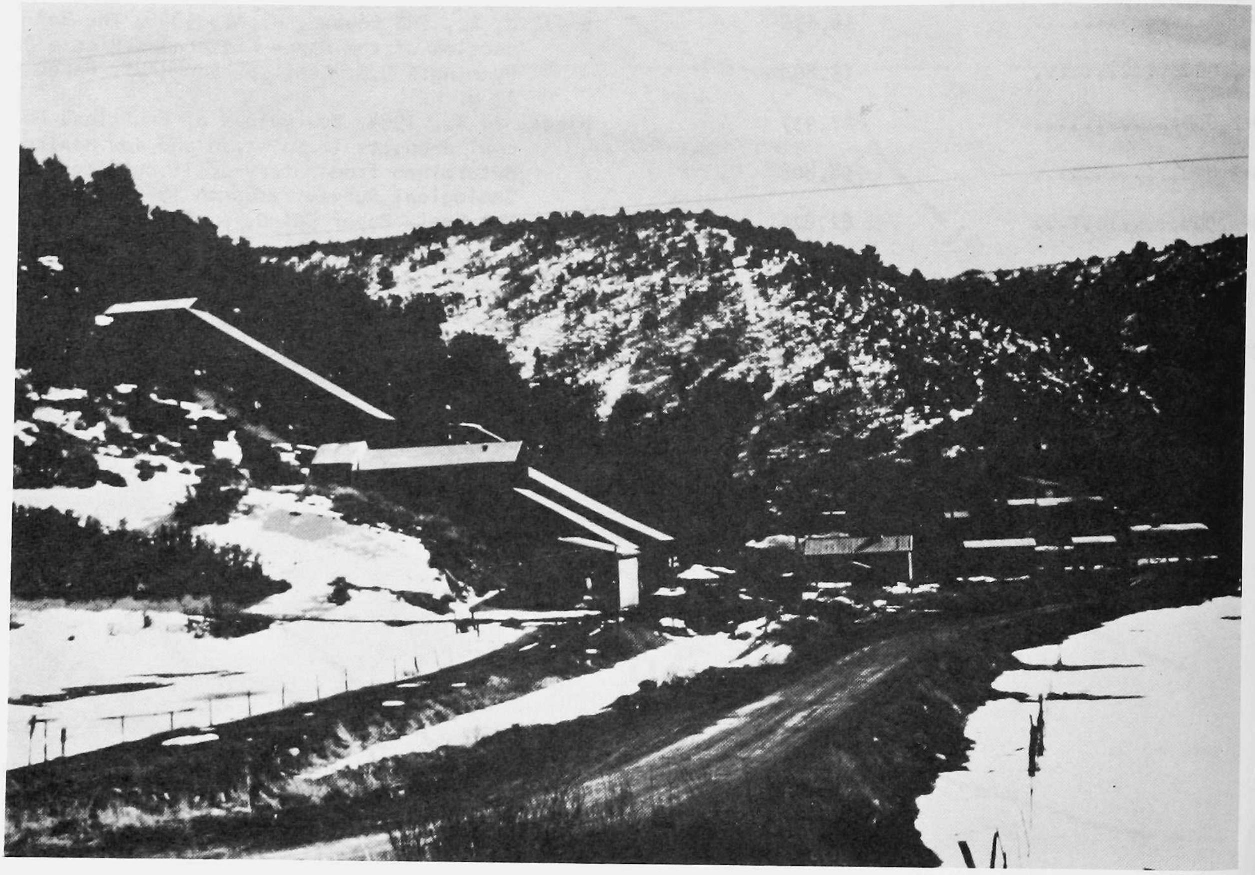
REFERENCES

Fassett, J. E., 1974, Cretaceous and Tertiary rocks of the eastern San Juan basin, New Mexico and Colorado, *in* Ghost Ranch, New Mexico Geol. Soc. Guidebook, 25th Field Conf., 1974: p. 225-230.

Fassett, J. E., and Hinds, J. S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan basin, New Mexico and Colorado: U.S. Geol. Survey Prof. Paper 676, 76 p.

Gill, J. R., and Cobban, W. A., 1966, The Red Bird section of the Upper Cretaceous Pierre Shale in Wyoming: U.S. Geol. Survey Prof. Paper 393-A, 73 p.

Hinds, J. S., 1964, Btu values of Fruitland Formation coal deposits in Colorado and New Mexico, as determined from rotary-drill cuttings, *in* Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501-D, p. D90-D94.



Underground coal mine, Durango field, La Plata County. Colorado

WYOMING COAL DEPOSITS

GARY B. GLASS: The Geological Survey of Wyoming

Laramie, Wyoming 82071

ABSTRACT: Wyoming has nearly a trillion tons of coal underlying about 41 percent of its land area. This coal occurs in Cretaceous and Tertiary coal-bearing rocks which crop out in 10 major basins, regions, or fields scattered across the State. While mountain building, folding, and subsequent erosion has restricted many Cretaceous outcrops to narrow bands around the margins of the coal-bearing areas, younger Tertiary rocks unconformably overlie them in the more central portions of the basins. Tertiary rocks are often nearly flat-lying, while Cretaceous rocks exhibit steeper dips and more complex folding.

Coals within these rocks range from less than 1 ft thick to over 200 ft in thickness, and occur at both shallow and great depths. Cretaceous coals, which seldom exceed 10 ft in thickness, range up to 110 ft thick in western Wyoming. The majority of the Cretaceous coals, especially the thinner ones, probably formed in various nearshore environments (paralic) associated with a widespread Cretaceous seaway. Tertiary coals were developed in intermontane basins and are probably limnic in origin. Tertiary coals often exceed 10 ft in thickness and 70-100 ft thicknesses are common, especially in northeastern Wyoming.

While Cretaceous coals are bituminous to subbituminous in rank, Tertiary coals are either subbituminous or lignitic. These differences in rank alone account for a significant geographic variation in the quality of coals across the State.

INTRODUCTION

With an estimated one trillion tons of coal underlying 41 percent of Wyoming (Averitt, 1975), a short summary of the State's coal deposits is no easy task. Consequently, this review consists of a generalized discussion of the distribution and age of the coal-bearing rocks, followed by brief summaries of the history of coal deposition and selected characteristics of the coals.

By way of background, Wyoming's coal-bearing rocks were deposited during either the Cretaceous Period, some 66-135 million years ago, or during the younger Tertiary Period, 38-66 million years ago. Depositional environments and climates during both of these periods were at least periodically well-suited to the development of densely vegetated swamps that have since been transformed into the coals that underlie much of the State.

The individual geological formations that contain these coals characteristically are thick, each usually ranging from 700-7000 ft in thickness. The Cretaceous formations normally exhibit gradual, regional thickening or thinning across the State. The thicknesses of the various Tertiary formations, however, vary from basin to basin, and are more related to the local tectonic and depositional events that affected each of the coal-bearing areas than they are to larger regional events.

Although Cretaceous rocks are the most widespread coal-bearing rocks in Wyoming, they usually only crop out as narrow bands of upturned rock around the margins of the larger structural basins and uplifted areas of the State or as irregular, linear bands in the thrust belt of western Wyoming. Relatively flat-lying Tertiary rocks, on the other hand, occupy the central portions of most of the coal-bearing areas, where they overlie the older Cretaceous rocks. Even the Tertiary rocks often exhibit steeper dips as they approach the margins of the coal-bearing basins and regions.

Both the Cretaceous and Tertiary coal-bearing formations contain numerous coals separated from each other by as little as a few inches of shale or claystone, up to hundreds of feet of rock that ranges from coarse sandstone or conglomerate to siltstones, claystones, and shales. Although the Cretaceous coals interspersed in these rocks are generally less than 10 ft in thickness, in westernmost Wyoming a few Cretaceous coals are 30-100 ft thick.

The Tertiary coals often exceed 10 ft in thickness, with 30-80-ft-thick coals common. Locally, at least one Tertiary coal reaches 220 ft in thickness.

The quality of Wyoming's coals varies irregularly across the State, often simply because of variations in rank. While the highest ranked coals in the State are bituminous coals of Cretaceous age, some Cretaceous coals are only subbituminous. The Tertiary coals range from subbituminous to lignitic in rank. For this reason, variations in moisture, volatile matter, fixed carbon, and heat values of Wyoming coals equate more to the rank of the coal than to paleodepositional events. Ash and sulfur contents are characteristically low and are related to the depositional histories of the coals rather than to any differences in rank.

Before beginning a more detailed discussion of the coal deposits within the State, it should be noted that correlation of individual coals across most of the coal-bearing areas, or even across a coal field, is seldom documented. For this reason, the correlation of a coal from one coal-bearing area to another is not yet possible. In fact, correlation of some coal-bearing formations from one basin or region to another is speculative.

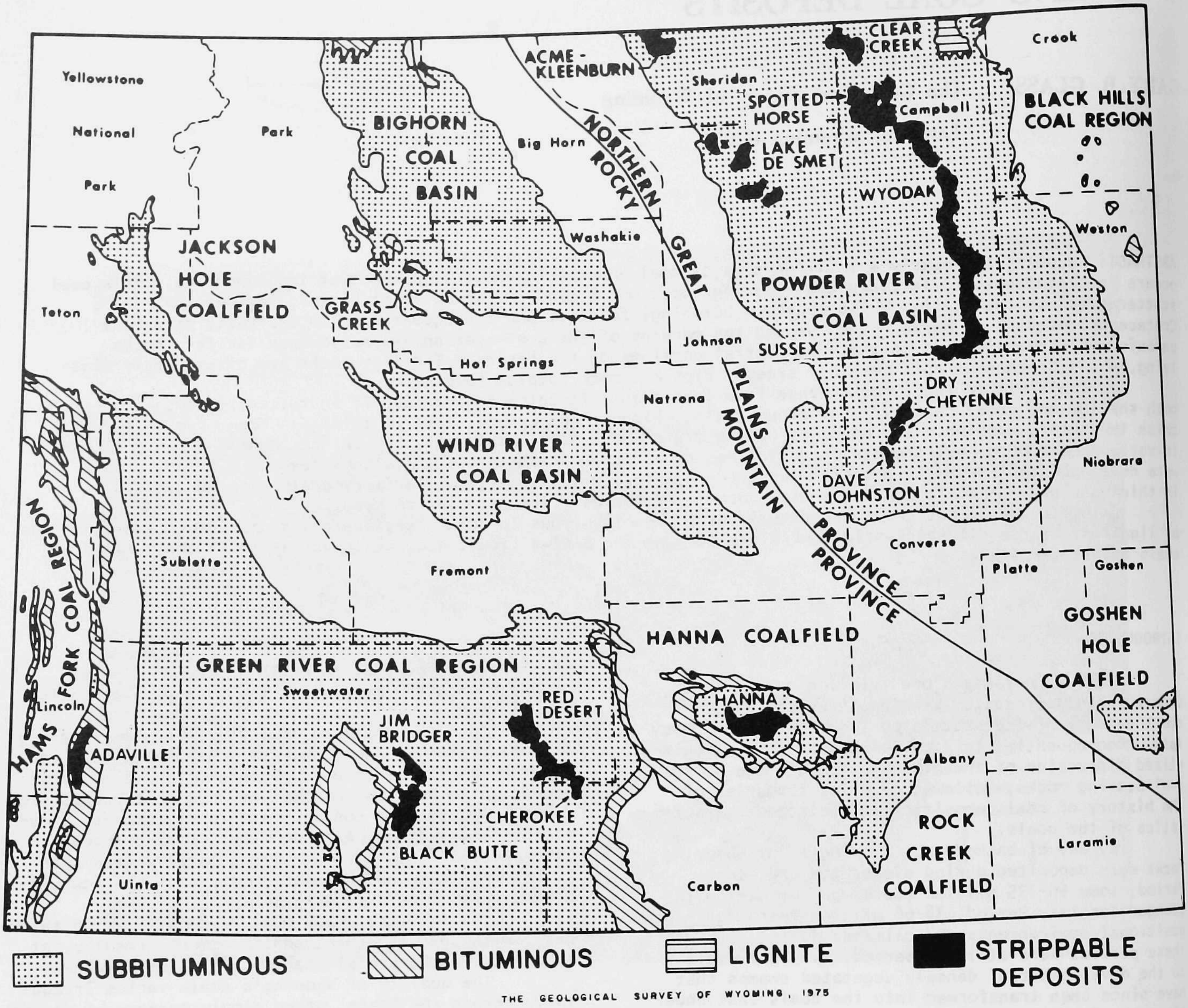


Fig. 1. Coal-bearing areas of Wyoming.

COAL-BEARING AREAS

Coal-bearing rocks presently crop out in 10 major areas of the State. Figure 1 shows that these coal-bearing areas, which are nearly all isolated from one another, are designated as discrete basins, regions, or single coal fields. Each of the basins or regions is divided into numerous smaller coal fields defined over more than a century of mining activity.

Powder River Coal Basin

The Powder River basin is a structural as well as a topographic basin that covers more than 12,000 sq mi of northeastern Wyoming and extends northward into southern Montana. The basin formed during the Tertiary age Laramide Orogeny, when Cretaceous and early Tertiary rocks were folded into an asymmetric syncline that left the older rocks upturned on the flanks of the basin. Even as folding and subsidence occurred, younger Tertiary rocks were deposited, at least from time to time unconformably over the older rocks. Today the Eocene rocks of the basin exhibit almost imperceptible dips. Dips on the Paleocene rocks, which are only 2-5 degrees on the east flank, however, steepen to 7-15 degrees on the west side of the synclinal axis.

Some local faulting is also mapped in the western and northern part of the basin, but faulting is not pronounced.

The Powder River coal basin is the most prolific coal-bearing area in Wyoming, with more than one-half of the State's coal resources, or an estimated 600-700 billion tons of coal lying within its borders. This coal occurs in 4 formations ranging from Upper

Cretaceous to Eocene in age (Fig. 2). Collectively, these coal-bearing rocks account for 7000 ft of the 8000 ft of rock above the Upper Cretaceous Pierre (Steele) Shale.

Although the Upper Cretaceous Mesaverde and Lance (Hell Creek) Formations locally contain some 3-6-ft-thick coals in the southern portion of the basin, the most persistent and thickest coals occur in the upper part of the 2000-3000-ft-thick Paleocene Fort Union Formation (Tongue River Member) and in the 1000-2000-ft-thick Eocene Wasatch Formation. In fact, these two Tertiary formations are probably the most important coal-bearing sequences in Wyoming.

The Fort Union Formation coals, which are best developed in the northern and eastern portions of the basin, consist of 8-12 thick, subbituminous coals (Fig. 3). One, the Wyodak-Anderson coal, frequently ranges between 50 and 100 ft thick. The outcrop of this coal has been mapped for more than 100 mi on the eastern side of the basin. The Wyodak-Anderson coal has also been tentatively correlated into the Sheridan area 60 mi across the basin.

The Wasatch Formation contains as many as 8 persistent, thick coals. The thickest Wasatch coal occurs at Lake DeSmet, on the west side of the basin. There, the Healy coal locally exceeds 200 ft in thickness.

Hanna Coal Field

Up to 23,000 ft of coal-bearing rocks crop out in the Hanna coal field, which occupies a 750-sq-mi

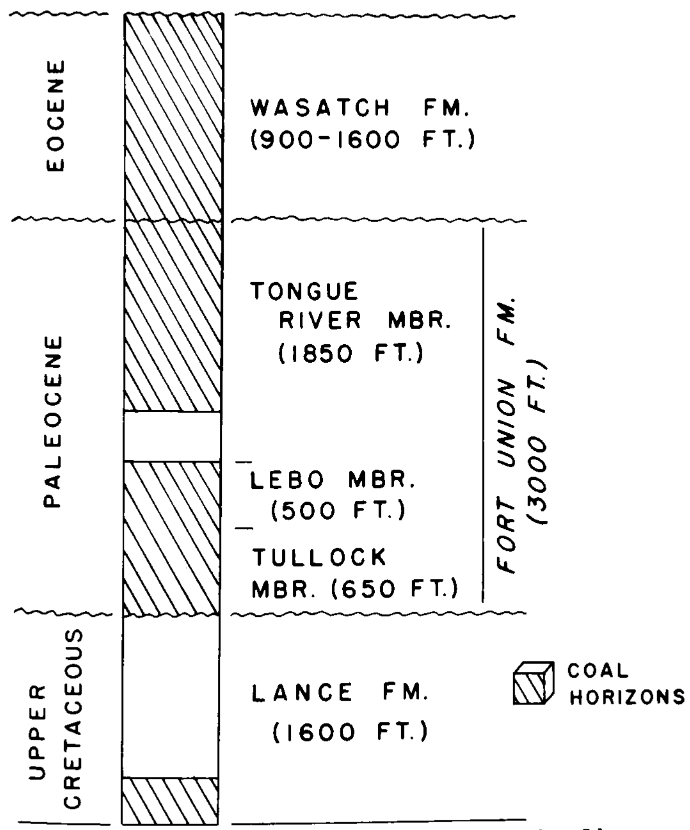


Fig. 2. Coal-bearing formations in the Powder River basin.

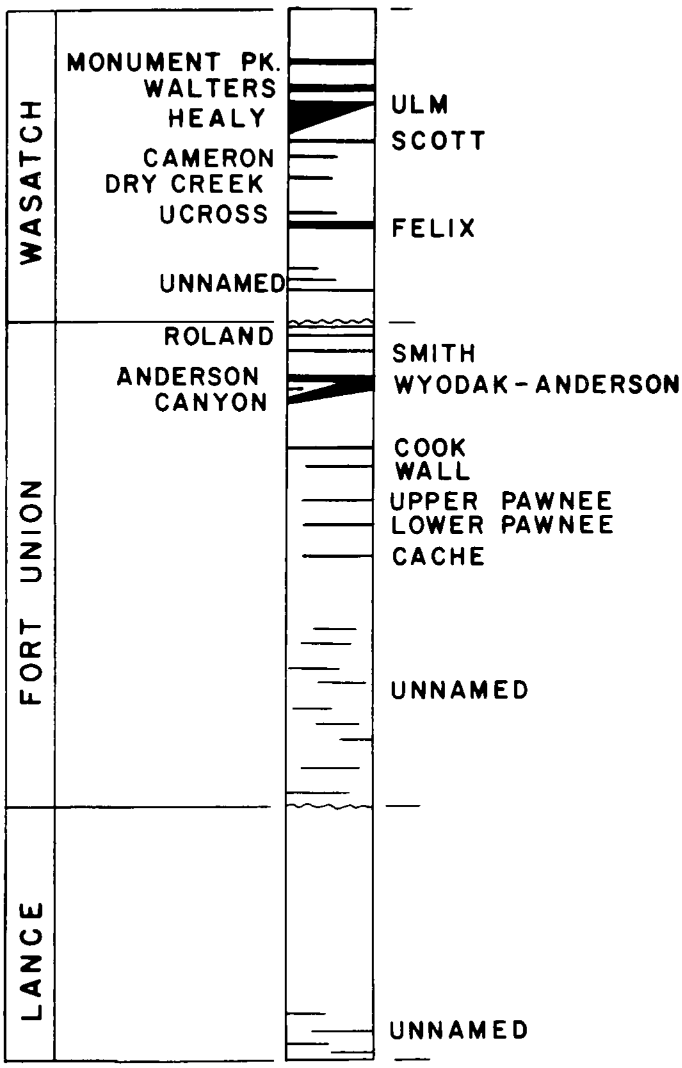


Fig. 3. Coal nomenclature in the Powder River basin.

area of south-central Wyoming. Simply stated, these rocks lie in a deep structural trough that is divided into two separate basins by a large northeast-trending anticline. The Hanna basin lies to the north; the Carbon basin lies to the south. Like other intermontane basins in the State, this trough formed during the Laramide orogeny. The Hanna basin, however, is rather atypical in that it not only is extremely deep for its size, containing 30,000-35,000 ft of sedimentary rock overlying the Precambrian crystalline basement, but also most of these rocks are tightly folded and faulted. Even the Eocene-age rocks steepen to vertical on the flanks of the basin, especially in the north. Flatter dips in the central portion of the Hanna coal field average 5-15 degrees.

Faulting is quite common in the central part of the field, as well as around its flanks. Vertical displacement on high-angle faults in the central part of the Hanna basin varies from a few feet to as much as 400 feet. Cross-faulting between major northwest-southeast trending faults are also abundant, at least in the west-central part of the Hanna basin.

Coals occur in the 2000-2500-ft-thick Upper Cretaceous Mesaverde Group and in the 4000-6500-ft-thick Medicine Bow Formation, as well as in the Tertiary Ferris and Hanna Formations (Fig. 4).

Although the Mesaverde bituminous coals are few in number and thin, as many as 15 Medicine Bow coals of subbituminous rank exceed 3 ft in thickness in the basal portion of that formation. A maximum thickness of 11 ft has been reported. These coals are not particularly persistent.

The oldest major coal-bearing unit is the 7000-ft-thick Cretaceous-Paleocene Ferris Formation, which contains an estimated 45 subbituminous coals (Fig. 5). Twenty of these coals are over 3 ft thick. Although at least one Ferris coal reaches 24 ft in thickness, most Ferris coals, though numerous, are less than 6 ft thick.

While the basal 5000 ft of the overlying Hanna Formation is very probably Paleocene in age, the upper 2000 ft is of Eocene age. The Hanna Formation contains about 20 coals, most of which at least locally exceed 3 ft in thickness. More importantly, the Hanna No. 1, No. 2, and No. 5 coals range up to 30 ft, 36 ft, and 29 ft thick, respectively.

Although outcrops of the more persistent coals in the Ferris and Hanna Formations have been traced for distances up to 15 mi, outcrops of many coals cannot be mapped laterally for more than a few thousand feet.

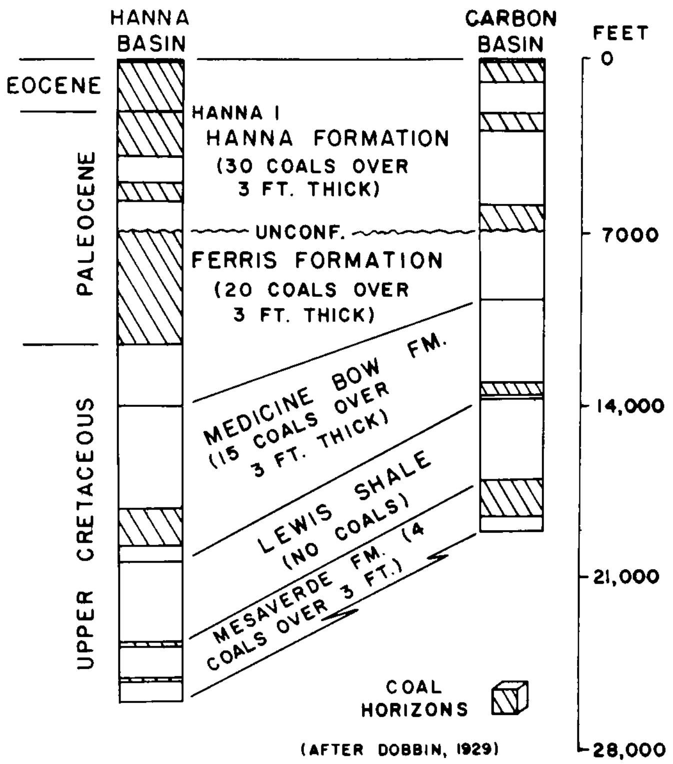


Fig. 4. Coal-bearing rocks in the Hanna coal field.

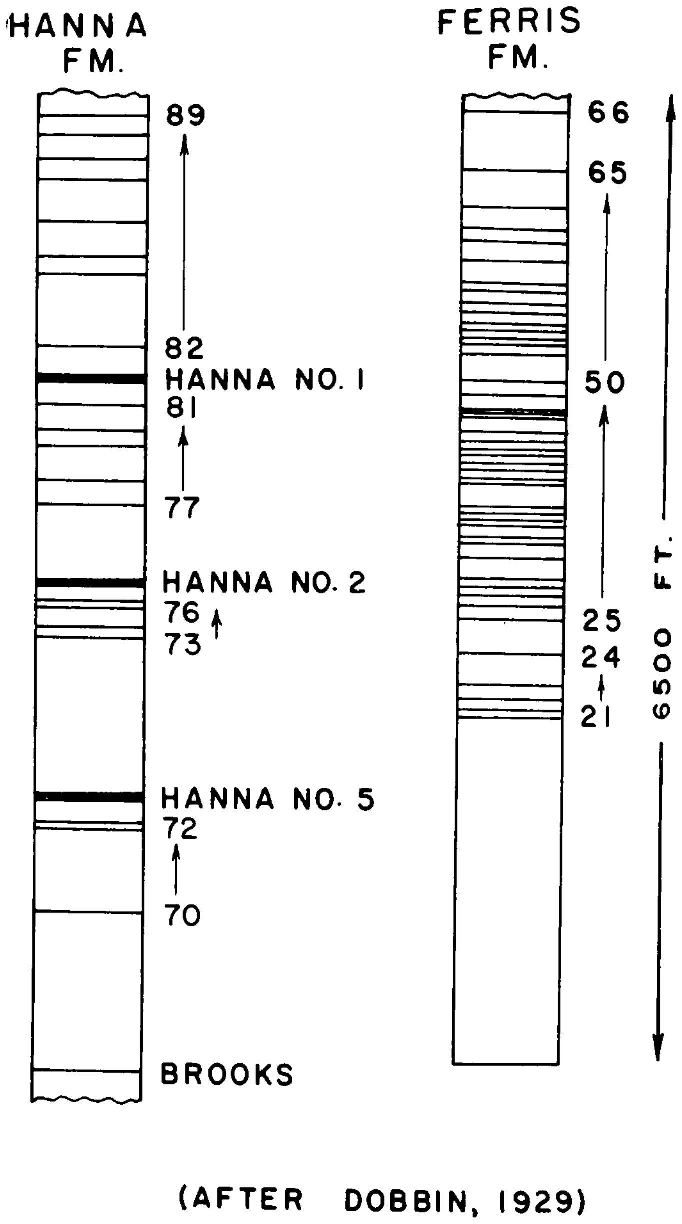


Fig. 5. Coal nomenclature in the Hanna and Ferris Formations of the Hanna coal field.

Green River Coal Region

The Green River Coal Region covers about 15,400 sq mi of southwestern Wyoming. It is structurally complex, with the Rock Springs uplift rising in the south-central portion of the region, thus separating the Green River (or Bridger) basin from the basins east of the uplift. East of the Rock Springs uplift, the low-relief Wamsutter arch divides the Washakie basin from the Great Divide basin to the north.

Cretaceous rocks dip 4-10 degrees on the east flank of the uplift, and increase to 6-20 degrees on the west flank. These same Cretaceous rocks dip 20-60 degrees on the extreme eastern margin of the region. The younger Tertiary rocks are fairly flat-lying except on the eastern side of the region, where the Paleocene rocks, at least, dip up to 12 degrees westward.

Faulting is more pronounced in the Rock Springs area than in the Hanna basin. Faults trend northeast-southwest across the uplift, leaving long, narrow fault blocks bounded on either side by high-angle faults. Vertical displacements on these faults vary from inches to hundreds of feet.

Coals in the Green River region occur in the Mesaverde Group and in the Lance Formation, both of Upper Cretaceous age; in the Fort Union Formation, of Paleocene age; and in the Wasatch Formation, of Eocene age (Fig. 6). The total thickness of all of these coal-bearing rocks in the region is 9,000 ft.

In the Rock Springs area, Mesaverde coals are found in the 1400-ft-thick Rock Springs Formation near the base of the Group and in the 500-ft-thick Almond Formation, which marks the top of the Mesaverde sequence. Rock Springs coals reportedly range up to 10-14 ft thick, but 4-6-ft-thick coals are more common (Fig. 7). Some of the more persistent coals have been traced for 30 mi along the north and west flanks of the uplift. The subbituminous Almond coals, on the other hand, are more numerous, but seldom exceed 8 ft in thickness. Coals in the Mesaverde Group on the eastern side of the Green River region average less than 4 ft thick, but locally reach 16 ft.

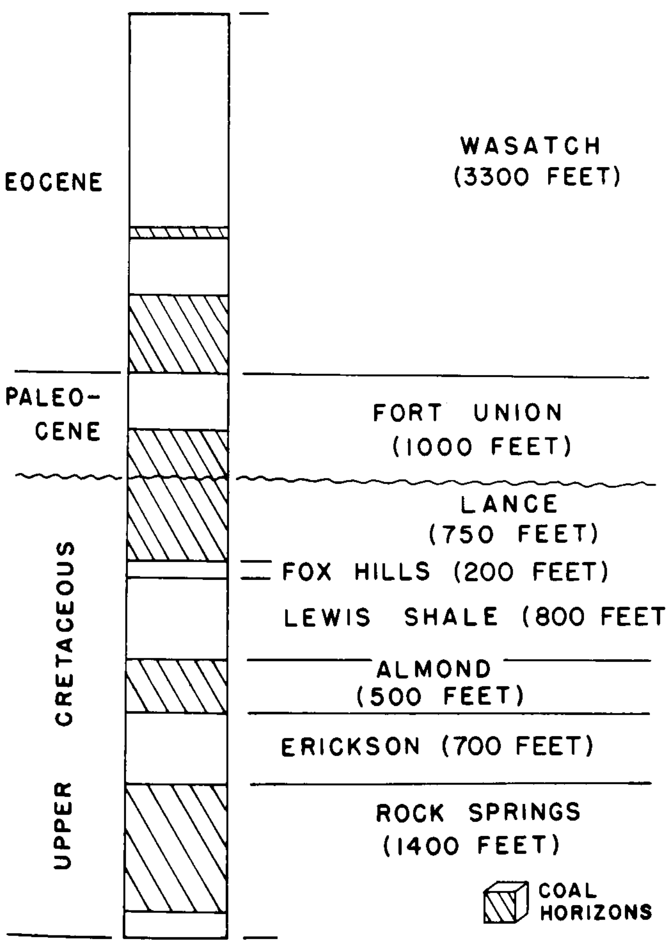


Fig. 6. Coal bearing rocks in the Green River region.

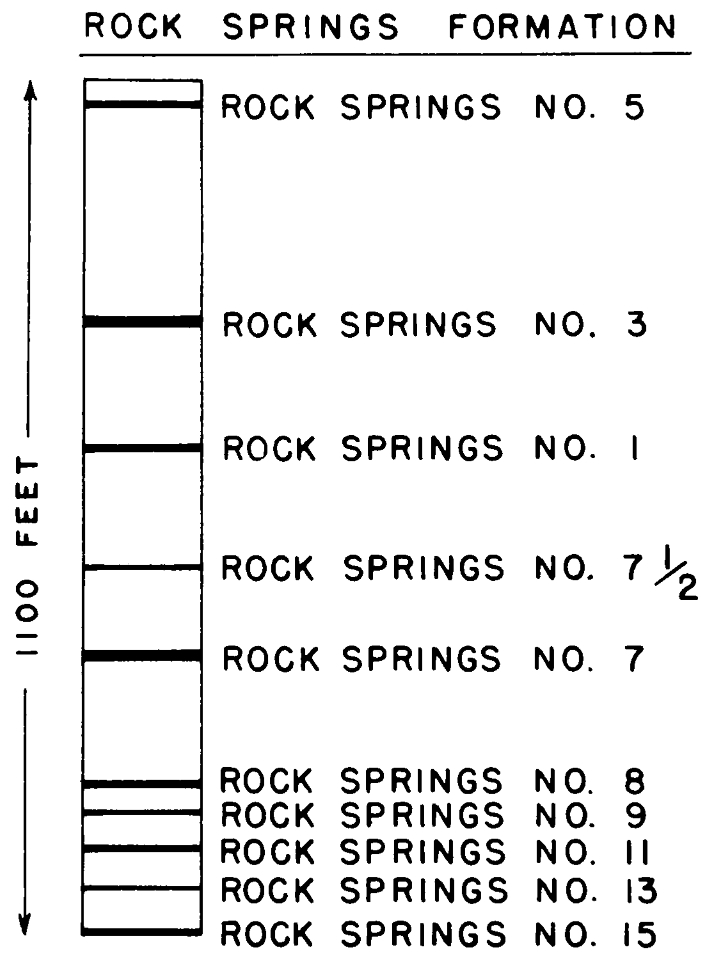


Fig. 7. Coal nomenclature in the Rock Springs Formation of the Green River region.

Subbituminous coals of the Lance Formation are best developed on the east flank of the Rock Springs uplift, where they average 5-10 ft thick. Outcrops on the east side of the Green River region indicate fewer coals in the Lance, but the maximum thickness increases to 20 ft.

Coals occur in the 1000-ft-thick Fort Union Formation and in the 3300-ft-thick Wasatch Formation throughout the basin. Thick accumulations of younger noncoal-bearing rocks, however, overlie these and older rocks over most of the Green River and Washakie basins. Fort Union coals in the western part of the Great Divide basin locally reach 30 ft in thickness. Six-to 16-ft-thick subbituminous coals are described on the east side. Wasatch coals are apparently best developed on the east side of the Great Divide basin, where at least 10 coals, ranging from 5-43 ft thick, have been mapped along outcrop for 6-20 mi. These Wasatch coals are reportedly subbituminous in rank, lenticular, and grade into shale to the east and west.

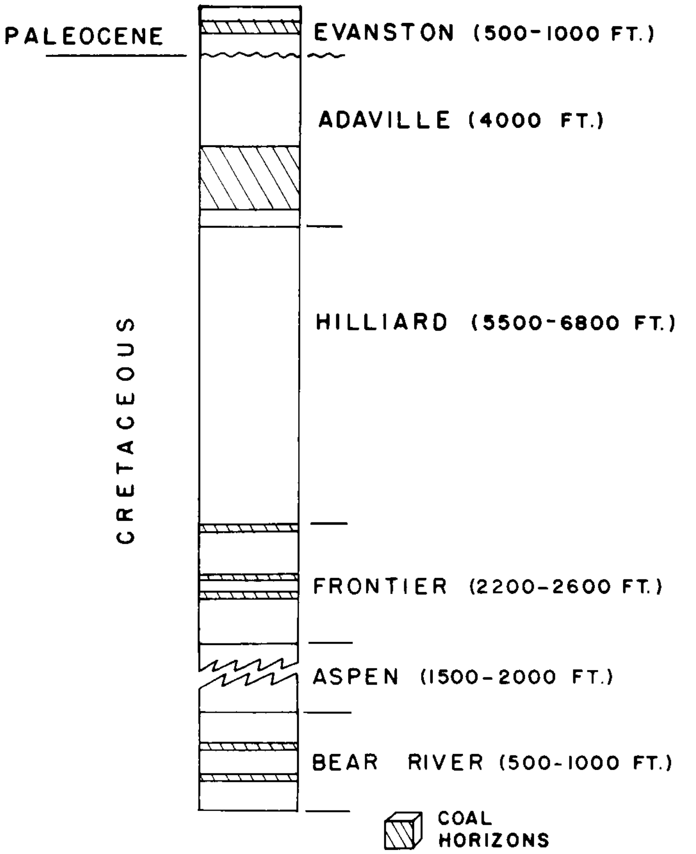
Hams Fork Coal Region

The Hams Fork coal region is unique from the other coal-bearing areas of the State because it is folded and thrust-faulted. It is characterized by a folded Paleozoic and Mesozoic sequence thrust eastward over folded Cretaceous rocks. The youngest Cretaceous and Tertiary rocks of the area were then unconformably deposited on top of the folded and faulted post-Cretaceous and older Cretaceous rocks. Consequently, the coal-bearing rocks in this region now crop out in long, narrow belts bounded by thrust faults, or the flanks of eroded folds.

The coal-bearing rocks of this region are the Bear River, Frontier, and Adaville Formations of Cretaceous age, and the Evanston Formation of Paleocene age (Fig. 8). Collectively, these formations account for a little less than one-half of the estimated 20,000 ft of rocks above the Jurassic.

Of this 9,200 ft of coal-bearing rock, the Bear River and Evanston Formations, which are each 500-1000 ft thick, contain the least amount of coal. The Bear River coals, in particular, are usually thin or absent. The Evanston Formation evidentally contains some thick coals (24-30 ft thick), at least north of Evanston.

The oldest principal coal-bearing formation in the region is the 2200-2600-ft-thick Frontier Formation. Thick and persistent coals apparently are restricted to the middle and top of the formation, where 3-20-ft-thick coals are reported. Most Frontier coals, however, are less than 6 ft thick. In the eastern part of the region, the thicker and more persistent coals can be traced along the outcrop for more than 100 mi.



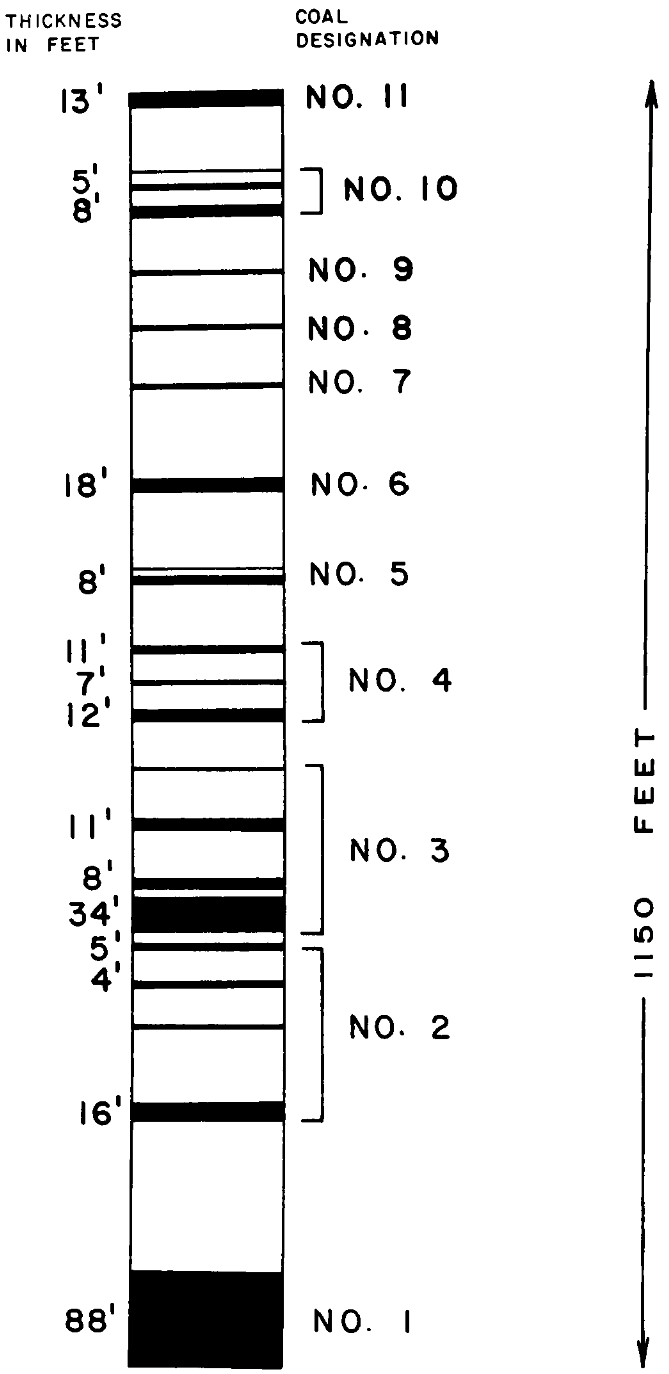


Fig. 9. Coal nomenclature in the Adaville Formation of the Hams Fork region.

Fig. 8. Coal-bearing rocks in the Hams Fork region.

The Adaville Formation, which may be equivalent in age to the Mesaverde, Lewis and Lance Formations of the Green River region, is without question the most important coal-bearing rock unit in the Hams Fork region. Ranging from 2900-4000 ft in thickness, this formation contains more than 32 coals within a 1000 ft interval, many of which are much thicker than the other coals of this age in Wyoming (Fig. 9). Although several of these subbituminous coals are 10-30 ft in thickness, the basal Adaville coal, the Adaville No. 1, is locally 110 ft thick.

Although a zone of Adaville coals can be traced for almost 100 mi, individual coals within the zone are not so persistent. This coal zone perhaps best typifies the variable thickness of individual coals, the splitting and coalescing nature of coals, and the various lithologies associated with coals, ranging from sandstones and conglomerates to siltstones, claystones, and shales (Fig. 10).

Bighorn Coal Basin

The Bighorn coal basin is a broad structural and topographic basin that occupies about 4400 sq mi of north-central Wyoming. Local folding characterizes the flanks of the basin. These small folds create local dips at various angles to the overall synclinal structure of the basin. Dips from 5-50 degrees are common in these border areas. There are also numerous normal faults on the flanks of the syncline, especially in the northern half of the basin. Most of these faults trend northeast-southwest, with vertical displacements up to 250 ft reported.

Principal coal-bearing rocks are the Upper Cretaceous Mesaverde, Meeteetse, and Lance Formations and the Paleocene Polecat Bench (Fort Union) Formation (Fig. 11). These formations, which total 6,000 ft in thickness, crop out in a 3-5-mi-wide zone around the basin. In the central part of the basin, these coal-bearing rocks are buried beneath another 6,000 ft of Eocene rocks, barren of coal except for a few thin lenses of shaly coal or coaly shale.

Most of the Upper Cretaceous coals are described as lenticular and of limited extent, especially along the eastern side of the basin. The Mesaverde coals, which are subbituminous in all but the northern part of the basin, where they become bituminous, are persistent and sufficiently thick in the southern part of the syncline that they can be mapped for up to 3 mi along strike. Most Mesaverde coals are less than 6 ft thick, but they reportedly thicken to 12 ft in places.

Meeteetse coals evidentally thicken to as much as 11 ft when numerous thin coals coalesce into interbedded coal and shale units. In comparison, Lance coals are usually less than 1 ft thick.

The Paleocene Polecat Bench Formation contains the thickest coals in the basin. The maximum thickness for these coals is 38 ft. Usually the Paleocene coals are less than 9 ft thick. The Polecat Bench Formation generally exhibits shallower dips than do the older rocks in the basin.

Wind River Coal Basin

The Wind River coal basin is a large asymmetrical syncline and topographic basin in central Wyoming. Dips are steeper on the northern side than on the southern. Many minor folds and a number of faults complicate the structure of the basin.

Coal-bearing rocks are approximately equivalent to those in the Bighorn basin and consist of the Mesaverde and Meeteetse Formations (Upper Cretaceous) and the Fort Union Formation (Paleocene age). Coals only crop out on the flanks of the syncline, inasmuch as coal-bearing rocks in the central portion of the basin are under considerable cover. All of the Wind River basin coals are believed to be subbituminous in rank.

Jackson Hole Coal Field

The Jackson Hole coal field is an extension of the Green River region into northwestern Wyoming. The field is underlain by coal over an area of 700 sq mi. Subbituminous coals occur in the Upper Cretaceous, Paleocene, and Eocene rocks.

Black Hills Coal Region

This small coal-bearing area is located in extreme northeastern Wyoming. At least one bituminous coal crops out in a narrow, discontinuous belt through the region. The coal belongs to the Lower Cretaceous Lakota Conglomerate. It locally thickens to as much as 10 ft of coal.

Rock Creek Coal Field

The Rock Creek coal field is a small field southeast of the Hanna coal field. Coals occur in the Mesaverde Group of Upper Cretaceous age and in the Hanna Formation of Paleocene and Eocene ages. The thickest and most persistent coals are in the Mesaverde Formation in the northwestern part of the field. One Mesaverde coal reportedly attains a thickness of 17 ft. All of the coals in this field are reportedly subbituminous in rank.

Goshen Hole Coal Field

The Goshen Hole coal field is in the southeastern corner of the State. There reportedly are coals in the Upper Cretaceous Lance Formation, but very little is known about them. Oil and gas well logs suggest that there may be thicker coals in the area than the 2.5-ft-thick coals that have been reported. Much of this field is covered by younger rocks, which contain no coal.

COAL-BEARING FORMATIONS

Lower Cretaceous

In review, the oldest coal-bearing formation in Wyoming is the Lower Cretaceous Lakota Conglomerate (Fig. 12). This formation contains at least one coal in the Black Hills Coal region.

The Bear River Formation of Lower Cretaceous age (Rubey, 1975) is the next younger coal-bearing rock unit above the Lakota. Again, the coals in the Bear River Formation are very local in extent and have only been reported in the Hams Fork coal region.

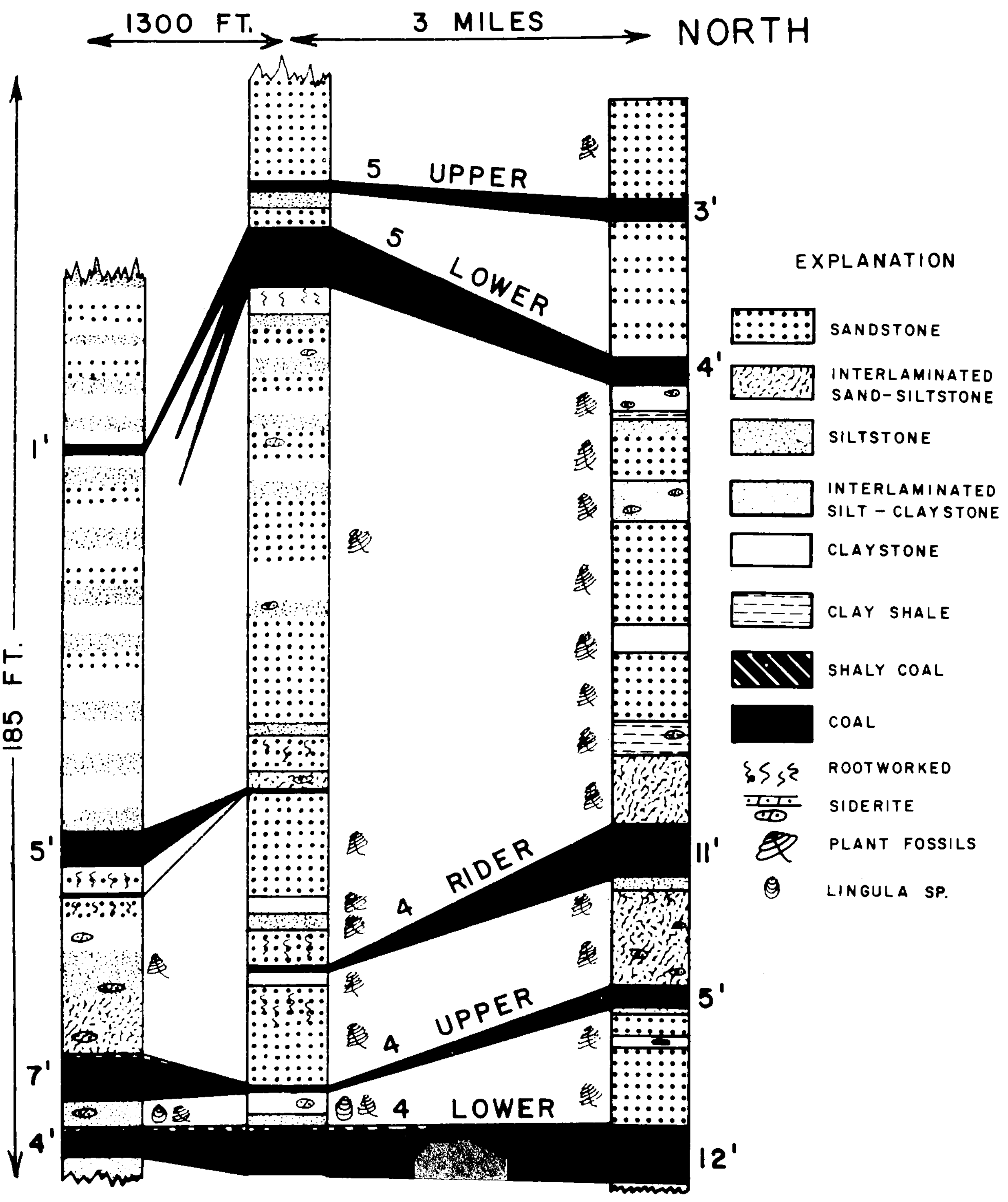


Fig. 10. Correlation of the Adaville No. 4 and No. 5 coals in the Sorensen mine in the Hams Fork region.

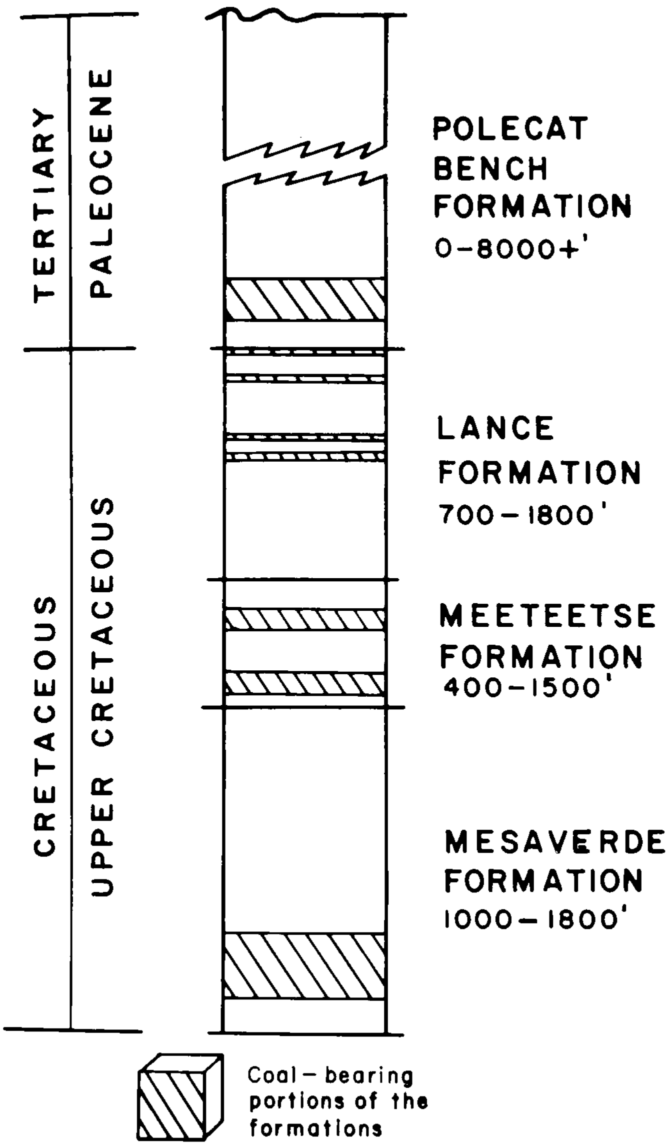


Fig. 11. Coal-bearing rocks in the Bighorn basin.

Upper Cretaceous

Separated from the Bear River by a marine shale, the overlying Frontier Formation contains numerous fairly thick, persistent coals in western Wyoming. Elsewhere, the Frontier coals apparently are thin, shaly, and of very limited extent.

The oldest widespread coal deposits in Wyoming are found in the Mesaverde Group or in its western equivalent; the Adaville Formation. These rocks contain numerous thick to moderately thick coals in the Hams Fork and Green River regions. Mesaverde coals are less numerous and apparently are thinner and more local in extent throughout the rest of the State. The Mesaverde disappears before it is halfway across the Powder River basin, and only exhibits very thin coals on the southern flank of that basin.

The Meeteetse Formation was deposited at about the same time as the Lewis Shale. This formation is recognized in the Wind River and Bighorn basins, where it contains some coals, most of which are thin and discontinuous.

Lance Formation coals are the youngest Upper Cretaceous coals in Wyoming. Although the Lance, or its equivalent, the Medicine Bow Formation of the Hanna field, contains coal throughout the State, Lance coals are best developed in southern Wyoming. There they are numerous, but seldom are more than 10 ft thick.

Paleocene

Paleocene rocks, variously mapped as the Fort Union, Polecat Bench, or Evanston Formations, crop out in all but the Black Hills region and Goshen Hole field. Paleocene rocks invariably contain coals, although they are most prolific in the Powder River basin and Hanna fields. While there are more Paleocene coals in the Ferris and Hanna Formations of the Hanna field, the Fort Union coals of the Powder River basin are often three to four times as thick as the thickest coals in the Hanna field, which are as much as 36 ft thick.

Eocene

The Eocene Wasatch Formation is the youngest coal-bearing rock unit in Wyoming. In the Powder River basin, at least, it rivals the older Paleocene rocks in both the number of coals it contains and in their thickness. In fact, the Wasatch contains the thickest coal in Wyoming, the 220-ft-thick Healy coal. Wasatch or equivalent coals are also abundant and moderately thick in the Great Divide basin of the Green River region and in the Hanna field. Elsewhere in the State, they are thinner and less persistent than many older coals.

HISTORY OF COAL DEPOSITION

With the possible exceptions of all or part of the Adaville and uppermost Lance coal sequences, Upper Cretaceous coals probably were all derived from paralic swamps--swamps that grew in close proximity to a sea. The Frontier and Mesaverde coals, in particular, are probably the remnants of swamps that grew along or near the shoreline of a widespread Cretaceous seaway that periodically advanced and retreated across vast portions of Wyoming and adjacent states.

Although local regressions of the shoreline periodically interrupted the advance of the Cretaceous sea in Frontier time, this was a major transgressive period now marked by the marine shales that overlie the Frontier Formation.

The coals in the basal portion of the Mesaverde Group represent remnants of swamps that accumulated in response to a major regressive phase of the Cretaceous sea. The swamps that dotted the shoreline of this retreating sea advanced or retreated across the area in response to local transgressive or regressive pulses in the overall regression. The uppermost Mesaverde marks another transgressive sequence, which was followed by the deposition of the marine Lewis Shale or its equivalents over much of the State.

The coal-bearing Upper Cretaceous Meeteetse Formation of the Bighorn and Wind River basins provides

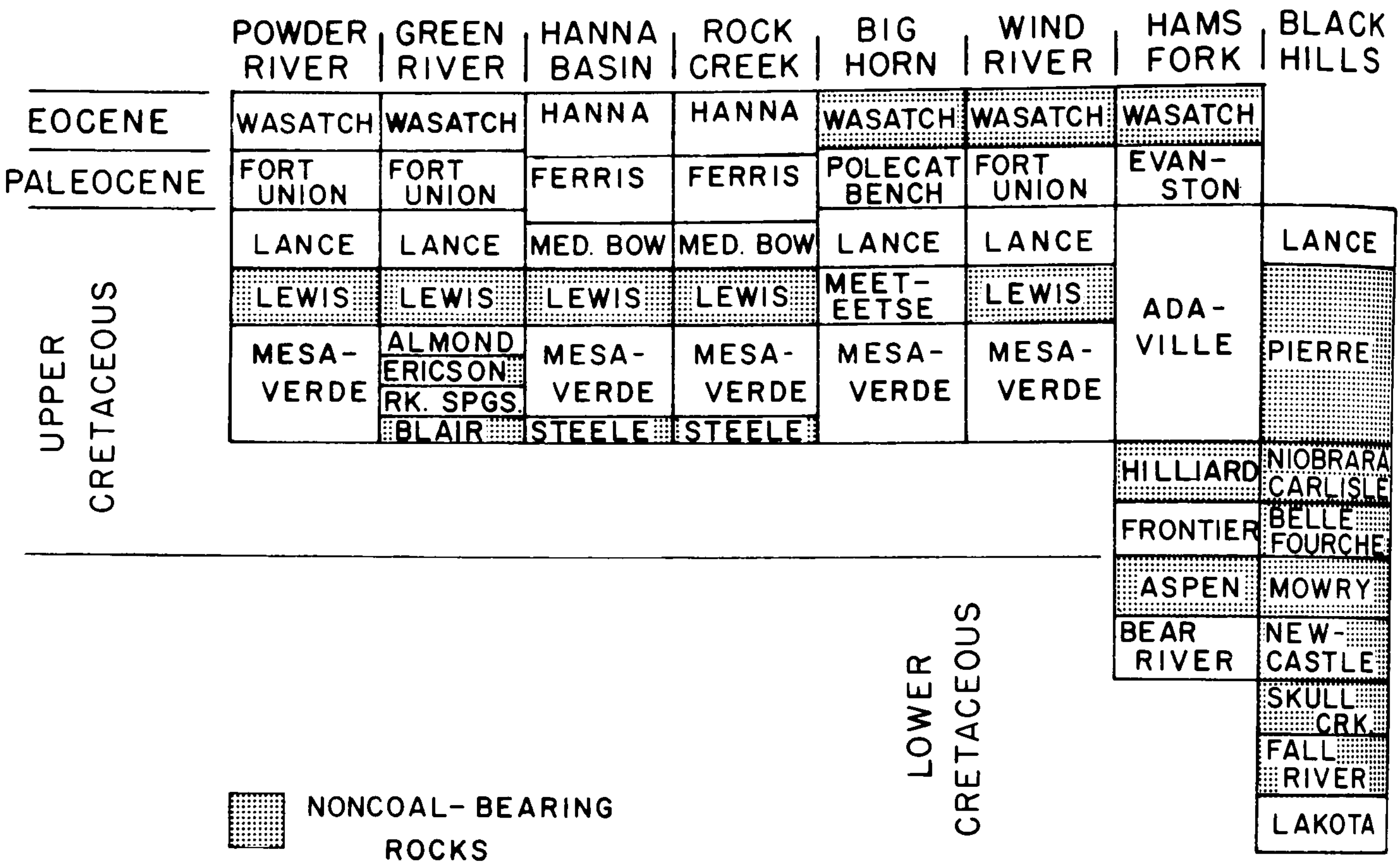


Fig. 12. Major coal-bearing formations in Wyoming.

evidence that the Lewis embayment did not inundate those areas as it did other parts of the State. Meeteetse coal deposits were probably deposited through the transgressive, stationary, and regressive phases of the marine incursion that resulted in deposition of the Lewis Shale.

The Upper Cretaceous Lance, or Medicine Bow, Formations were deposited after the final regression of the Cretaceous sea. Although the coals may have been paralic at the base of the Lance, the upper Lance took on a more terrestrial or limnic character as the sea retreated beyond the borders of Wyoming. The uppermost Lance coals are probably derived from swamps growing on a vast flood plain characterized by meandering streams and freshwater lakes.

Both the exact age and origin of coals in the Upper Cretaceous Adaville Formation of southwestern Wyoming are problematic because their stratigraphic relationship to the coal-bearing rocks in the Green River basin is unclear and because many are atypically thick for paralic Cretaceous-age coals. If they are indeed paralic, they must have been derived from swamps growing adjacent to the Cretaceous sea as it made its final retreat from western Wyoming.

Alternatively, the Adaville coals may have been derived from swamps growing in a subsiding basin generally west of any major marine incursions. The presence of an occasional brackish-water fossil in the upper half of the coal sequence, however, precludes a complete cutoff from the sea. These fossils also suggest that the swamps must have accumulated before or during the last major regression of the sea or possibly in response to a younger heretofore unrecognized marine embayment. The former seems the more likely. In any case, the basal coal swamps may be more continental in origin than are the upper ones.

By Paleocene time, Wyoming was marked by widespread erosion and orogenic activity that partitioned the State into various intermontane basins. The seaways of the Cretaceous had withdrawn, and the Cretaceous rocks were being folded and faulted within the basins as mountains rose around them. Clastic Tertiary sediments carried into the basins by rivers were deposited over the older rocks.

During this period, swamps grew over large areas of the intermontane basins kept moist by the internal drainage that flowed into them. Although most of the Tertiary coal swamps accumulated adjacent to large meandering rivers, others grew along the shores of freshwater lakes. These intermontane areas, therefore, were probably characterized by flood-plain, lacustrine-delta, and even alluvial-fan deposits. In this depositional setting, the coals, as well as the rocks associated with them, record the effects of meandering streams, variations in sediment influx, flooding, climatic fluctuations, differential compaction, and local tectonic events coupled with continuous subsidence.

COAL CHARACTERISTICS

Rank

Wyoming coals range from lignite to bituminous in rank. Lignites, however, are restricted to a small area in the northeastern corner of the Powder River basin that marks a southern extension of the Tertiary lignite deposits of Montana and North Dakota.

Subbituminous coals, which are all either Tertiary or Upper Cretaceous in age, are found in all the coal-bearing areas of the State except the Black Hills region (Fig. 1). Usually the subbituminous coals occupy the more central parts of the coal-bearing areas, although, in the case of the Hams Fork region, subsequent erosion has relegated even the younger subbituminous coal-bearing rocks to narrow bands between faults and eroded folds. In several basins, the subbituminous coals are buried beneath great thicknesses of noncoal-bearing rocks.

Most of the bituminous coals of Wyoming crop out as narrow bands in the Hams Fork region, around the Rock Springs uplift, the eastern edge of the Green River region, and the periphery of the Hanna coal field. The Mesaverde coals in the north end of the Bighorn Basin and the Lower Cretaceous coal of the Black Hills region are also bituminous. Bituminous coals are much more widespread than these outcrops would suggest simply because a great portion of the bituminous coals lie deeply buried beneath younger formations that either contain lower rank coals or no coals at all. All bituminous coals in Wyoming are Cretaceous in age.

Chemical Composition, Heat Value, and Sulfur

Moisture, volatile matter, fixed carbon, and heat values of coals vary widely across the State in direct response to variations in rank. The bituminous and high-rank subbituminous Cretaceous and Tertiary coals on an as-received basis are very similar. Moisture contents are less than 15 percent, volatile matter contents are between 30-40 percent, fixed carbon contents are greater than 40 percent, and heat values are between 10,000-12,000 Btu/lb. In contrast, the lower ranked subbituminous Tertiary coals of the Green River region and the Powder River basin have as-received moisture contents between 20-30 percent, about equal volatile matter and fixed carbon contents, and heat values between 7000-9000 Btu/lb.

Variations in ash and sulfur content are evidentaly more related to events in the depositional history of the original coal swamps than they are related to rank. Consequently, variations in ash content, in particular, are quite irregular. As-received ash contents range from a few percent to more than 50 percent in response to the volume of inorganic debris entering the original coal swamp. Published analyses of various coals sampled across the State, however, suggest that a typical, persistent Wyoming coal of minable thickness contains less than 10 percent ash.

Sulfur contents, on the other hand, show a relationship that varies with the age of the coal. The Cretaceous coals appear to contain slightly more sulfur on a weight-percent basis than do the Tertiary coals. Published analyses of the Cretaceous coals of Wyoming usually range from 0.9-2.0 percent sulfur, compared to a range of 0.3-0.9 percent sulfur in Tertiary coals.

Major and Minor Elements

In Wyoming coals, major elements, which make up more than 0.1 percent of a coal, are silicon, calcium, aluminum, iron and magnesium, usually in that order of abundance. Common minor elements are potassium, sodium, titanium, phosphorous, chlorine, and manganese, in that order.

Silicon, aluminum, calcium and iron all can be present in concentrations greater than 2 percent; silicon concentrations have exceeded 5 percent in some samples. The minor elements rarely exceed 0.1 percent and are best described in thousands or less parts per million.

Based on some recent analyses, Wyoming's Cretaceous and Tertiary coals show similar concentrations of all the major and minor elements except calcium and sodium. The concentration of calcium and sodium in the Tertiary coals are usually four to five times the concentrations normally reported in the Cretaceous coals.

Major and minor elements in 48 Wyoming coal samples in percent on a whole-coal basis (Glass, 1975)

	RANGE	AVERAGE
Silicon	0.41-5.50	1.70
Calcium	0.13-2.10	0.75
Aluminum	0.17-2.50	0.72
Iron	0.15-2.100	0.51
Magnesium	0.026-0.340	0.17
Potassium	0.005-0.370	0.063
Sodium	0.003-0.190	0.044
Titanium	0.001L-0.130	0.038
Phosphorous	0.0021L-0.044	0.0121
Chlorine	0.004-0.026L	0.010L
Manganese	0.0007L-0.0492	0.004

Note: "L" means less than.

Trace Elements

Of the 30 trace elements recognized in some 48 analyses of Wyoming coals, concentrations of the various elements range from a high of 1000 parts per million to a low of 0.004 parts per million. If these elements are grouped according to their average concentrations, 6 elements average less than 1 part per million, 12 elements range between 1-5 parts per million, 11 elements range between 5-100 parts per million, and one element, barium, averages more than 300 parts per million.

With the exception of zinc, which averages 17.9 parts per million, the more common metals--copper, cobalt, nickel, and lead--all occur in concentrations ranging from 1-5 parts per million. While the potentially dangerous elements, arsenic and molybdenum, also average 1-5 parts per million, selenium, cadmium, and mercury normally occur in concentrations of less than one part per million.

Based on these 48 published analyses, Tertiary coals in Wyoming appear to contain higher concentrations of 26 of these trace elements than do the Cretaceous coals. Only boron, beryllium, fluorine, and germanium are higher in the Cretaceous coals.

Average trace element concentrations in 48 Wyoming coal samples in parts per million on a whole-coal basis (Glass, 1975)

ELEMENT	AVERAGE	ELEMENT	AVERAGE
Barium	300	Gallium	3
Strontium	100	Arsenic	<3
Boron	70	Lead	<3
Fluorine	70	Thorium	2.7
Cerium	<20	Cobalt	2
Zinc	17.9	Germanium	<2
Vanadium	15	Neobium	1.5
Zirconium	15	Scandium	1.5
Neodymium	<15	Molybdenum	1.0
Copper	8	Uranium	< 0.9
Chromium	7	Selenium	< 0.8
Lanthanum	<7	Ytterbium	0.5
Nickel	5	Antimony	< 0.4
Yttrium	5	Cadmium	< 0.15
Lithium	4.6	Mercury	0.10

REFERENCES

Averitt, Paul, 1975, Coal resources of the United States, January 1, 1974: U.S. Geol. Survey Bull. 1412, 131 p.

Berryhill, H.L., Jr., and others, 1950, Coal resources of Wyoming: U.S. Geol. Survey Circ. 81, 78 p.

__________ and others, 1951, Coal resources map of Wyoming: U.S. Geol. Survey Coal Invest. Map C-6, scale 1:500,000, colored.

Breckenridge, R.M., Glass, G.B., Root, F.K., and Wendell, W.G., 1974, Campbell County, Wyoming: Geol. Survey of Wyoming County Resource Ser. CRS-3, 9 plates, colored.

Denson, N.M., Keefer, W.R., and Horn, G.H., 1973, Coal resources of the Gillette area, Wyoming: U.S. Geol. Survey Misc. Geologic Invest. Map I-848-C, scale 1:125,000, colored.

Dobbin, C.E., Bowen, C.F., and Hoots, H.W., 1929, Geology and coal and oil resources of the Hanna and Carbon basins, Carbon County, Wyoming: U.S. Geol. Survey Bull. 804, 88 p.

Glass, G.B., 1972, Mining in the Hanna coal field: Geol. Survey of Wyoming Misc. Rep., 45 p.

__________ 1975, Analyses and measured sections of 54 Wyoming coal samples (collected in 1974): Geol. Survey of Wyoming Rept. Invest. No. 11, 219 p.

__________ 1975, Review of Wyoming Coalfields, 1975: Geol. Survey of Wyoming Misc. Rept., 21 p.

__________ and Jones, R.W., 1974, Bibliography of Wyoming coal: Geol. Survey of Wyoming Bull. 58, 163 p.

__________ Wendell, W.G., Root, F.K., and Breckenridge, R.M., 1975, Energy resources map of Wyoming: Geol. Survey of Wyoming Map, scale 1:500,000, colored.

__________, Westervelt, K., and Oviatt, C.G., 1975, Coal mining in the Bighorn coal basin of Wyoming, *in* Wyoming Geol. Assoc. Guidebook: 27th Ann. Field Conf., Bighorn basin, p. 221-228.

Keefer, W.R., 1974, Geologic map of the Northern Great Plains: Open-File Rept. 74-50, 1 sheet, colored.

Love, J.D., Weitz, J.L., and Hose, R.K., 1955, Geological map of Wyoming: U.S. Geol. Survey Map, scale 1:500,000, colored

Mallory, W.W., ed., 1972, Geologic atlas of the Rocky Mountain Region: Rocky Mtn. Assoc. Geologists, Denver, Colorado, 331 p.

Maple, W.J., 1958, Coal in the Powder River basin, *in* Wyoming Geol. Assoc. Guidebook: 13th Ann. Field Conf., Powder River basin, p. 218-224.

Root, F.K., Glass, G.B., and Lane, D.W., 1973, Sweetwater County, Wyoming: geologic map atlas and summary of economic mineral resources: Geol. Survey Wyoming County Resources Ser. CRS-2, 9 plates, colored.

Rubey, W.W., Oriel, S.S., and Tracey, J.I., Jr., 1975, Geology of the Sage and Kemmerer 15-minute quadrangles, Lincoln County, Wyoming: U.S. Geol. Survey Prof. Paper 855, 18 p.

Townsend, D.H., 1960, Economic report on the Kemmerer coal field, *in* Wyoming Geol. Assoc. Guidebook: 15th Ann. Field Conf., Overthrust belt of southwestern Wyoming, p. 251-255.

LAGOONAL ORIGIN OF COALS IN THE ALMOND FORMATION IN THE ROCK SPRINGS UPLIFT, WYOMING

IENRY W. ROEHLER: U.S. Geological Survey

Denver, Colorado 80225

BSTRACT: The Rock Springs uplift in southwest Wyoming is a doubly-plunging asymmetric anticline of Laramide ge. The Almond Formation and other coal-bearing formations of Late Cretaceous age are exposed on the flanks of he uplift.

The Almond Formation is mostly gray sandstone, gray shale, gray and brown carbonaceous shale, thin beds f coal, and minor thin beds of gray siltstone and dolomite. It is 850 ft (259 m) thick on the east flank, but hins and is missing in places on the west flank because of Late Cretaceous erosion. Dinosaur, crocodile, turtle, nd fish fossils collected from the lower 200 ft (61 m) of the formation indicate deposition in freshwater; oysters nd other mollusk fossils collected from the middle 350 ft (107 m) of the formation indicate deposition in brackish ater; and shark teeth and cephalopod fossils collected from the upper 300 ft (91 m) of the formation indicate de- osition in saltwater. The environments of deposition for these fossil intervals are interpreted as coastal swamp, agoon, and mixed barrier bar, lagoon, and marine, respectively. Sedimentary structures permit further subdivision f the barrier bars into lower shoreface, middle shoreface, upper shoreface, sand dune, washover, and flood delta eposits. A model for the depositional environments depicts a marine coastline where lagoons formed behind barrier ars during westward transgressions of a Late Cretaceous sea. Evidence of a lagoonal origin of coal beds is pro- ided by the intertonguing and juxtaposition of the coal beds and the barrier bars, and by the presence of fossil yster beds within coal-bearing sequences.

Eighteen beds of coal, ranging in thickness from 2.5 to 16 ft (.8 to 4.9 m), have been mapped in the lmond Formation. Few of these can be correlated extensively as they characteristically split or wedgeout along utcrops. Almond coals have less than 1 percent sulfur, heating values from 8,800 to 10,850 Btu/lb, and are anked as subbituminous C to subbituminous A. The estimated mineable coal resources are nearly 6 billion short ons. Between 5 and 10 percent of the coal is believed recoverable by strip-mining. Largely ignored in the past, oals of lagoonal origin in the Almond Formation are a vast, undeveloped energy resource.

NTRODUCTION

The Rock Springs uplift is located in southwest yoming, a few miles north of the common boundary of yoming, Colorado, and Utah. The uplift is about 60 mi 96 km) long and 40 mi (64 km) wide. It is bounded on he west by the Green River basin, on the northeast by he Great Divide basin, and on the southeast by the ashakie basin (Fig. 1). The uplift is a north-south rending, doubly plunging, asymmetric anticline of aramide age. Dips on the steep west limb are usually etween 10° and 15°. Dips on the east limb are usually ° to 8°. The Almond Formation and other coal-bearing ormations of Late Cretaceous age are exposed on the lanks of the uplift. The Almond Formation is 850 ft 259 m) thick on the east flank of the uplift, but it iins and is missing in places on the west flank be- ause of Late Cretaceous erosion. Outcrops of the ormation on the east flank are broken up in places / high-angle faults. Coals in the Almond Formation e partly interbedded with fossil oyster beds and are rtly intertongued with and laterally equivalent to rrier bars, which provide evidence that they are of igoonal origin.

STRATIGRAPHY

Depositional environments in the Almond Formation are easily interpreted from the lithologies and fossil occurrences in a measured section located in the southeast part of the Rock Springs uplift, labeled measured section A on Figure 2. The Almond Formation in measured section A is light-gray very fine grained sandstone, interbedded gray shale, gray and brown carbonaceous shale, and coal, with minor thin beds of gray dolomite and siltstone. Fossils collected from the section include dinosaur, crocodile, turtle and fish bones from the lower part, oysters and snails from the middle part, and shark teeth and cephalopods from the upper part. The fossils and lithologies suggest that the lower 200 ft (61 m) of the section were deposited in freshwater coastal swamp environments; the middle 150 ft (46 m) of the section were deposited in brackish water lagoonal environments; and the upper 500 ft (152 m) of the section were deposited mostly in saltwater in barrier bar and shallow marine environments. Fifteen beds of coal, ranging in thickness from less than 1 ft (0.3 m) to more than 6 ft (1.8 m), are present in measured section A. The coals are concen-

76 *Symposium on the Geology Rocky Mountain Coal, p. 85-89*

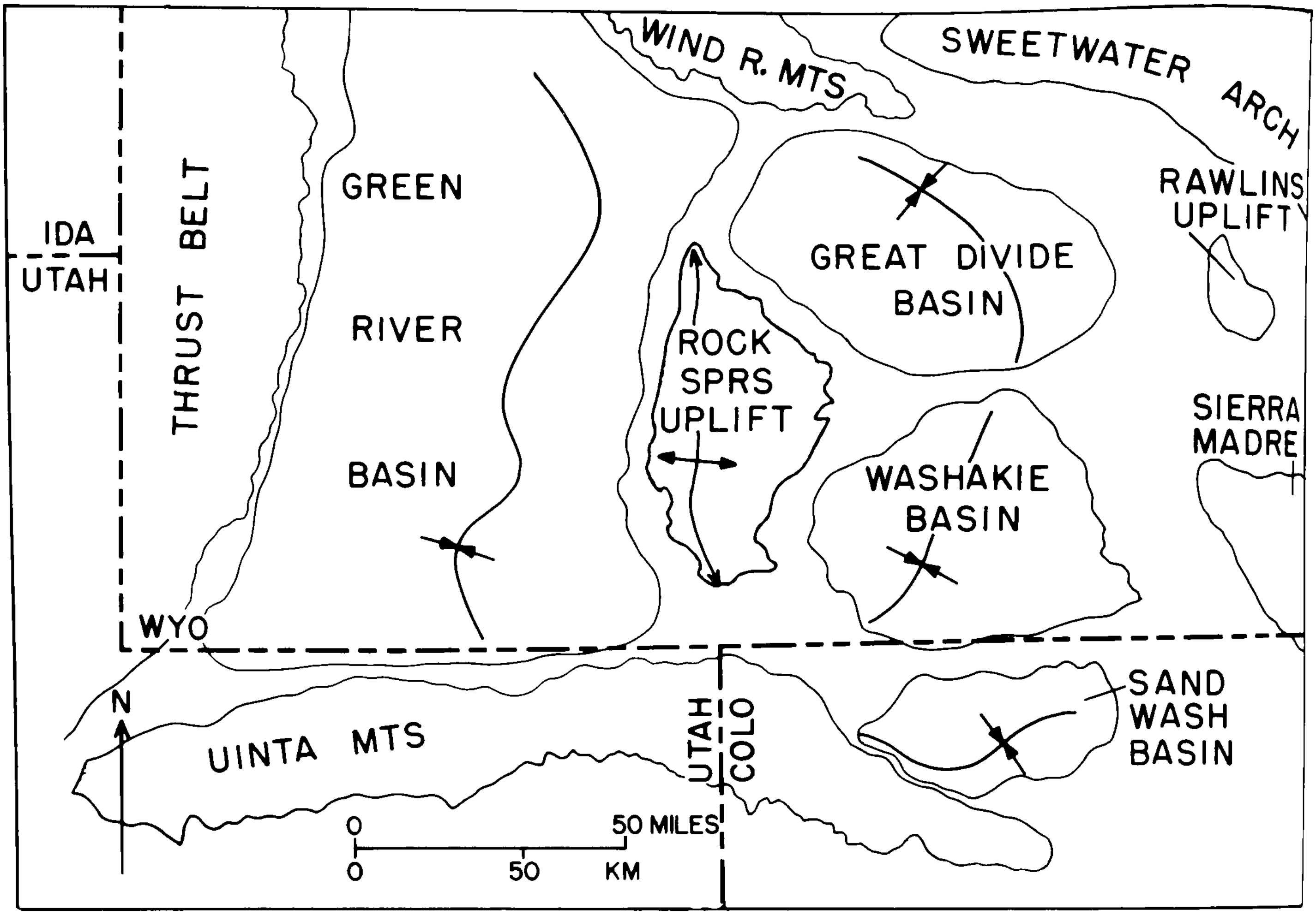


Fig. 1. Map showing the location of the Rock Springs uplift in southwest Wyoming.

trated in lagoonal environments of deposition (Fig. 2).

A model for depositional environments, Figure 3, depicts a coastline where lagoons formed behind barrier bars. Coastal swamps were present in landward directions from the lagoons. Sedimentary structures permit the further subdivision of the barrier bars into lower shoreface, middle shoreface, upper shoreface, dune, washover, and flood-delta sandstone deposits. Coals formed in the swampy parts of lagoons and in swamps that developed on back barrier flats. As Late Cretaceous seas advanced from east to west across the area of measured section A, the environments of deposition, shown on Figure 3, migrated westward. Hence, in the vertical succession of rocks in measured section A, shown on Figure 2, marine rocks overlie barrier bars, barrier bars overlie lagoons, and lagoons overlie coastal swamps.

The environments of deposition interpreted in measured section A can be correlated with other measured sections of the Almond Formation in the Rock Springs uplift. The location of 8 measured sections in the eastern part of the uplift are shown on the upper part of Figure 4. The environments of deposition in these sections are shown on a restored cross section in the lower part of Figure 4. Note that measured section 3 on the cross section is the same as measured section A. The ascending succession of environments of deposition in all 8 sections is persistently coastal swamps, lagoons, barrier bars, and marine shales.

The environments of deposition for one period of time in the Almond Formation are indicated by a dashed line labeled time line G on Figure 4. A paleogeographic map that interprets the environments of deposition at time line G is shown on Figure 5. As indicated on Figure 5, rocks along the eastern edge of the uplift were deposited in a marine environment. A barrier bar crossed the southeast and northeast parts of the uplift. Marineward parts of the exposed barrier bar are shown by fine stippling. Sand dunes situated upon the barrier bar are shown by coarse stippling. The back barrier flat is covered by a swamp. Protruding through the back barrier flat swamp in places are fan-shaped washover sandstones. In the southeast part of the uplift, a tidal channel crossed the barrier bar, and a flood delta was present where the tidal channel entered the lagoon. The lagoon had some open water, but it was partly brackish water ponds and embayments between which were areas of salt marshes and

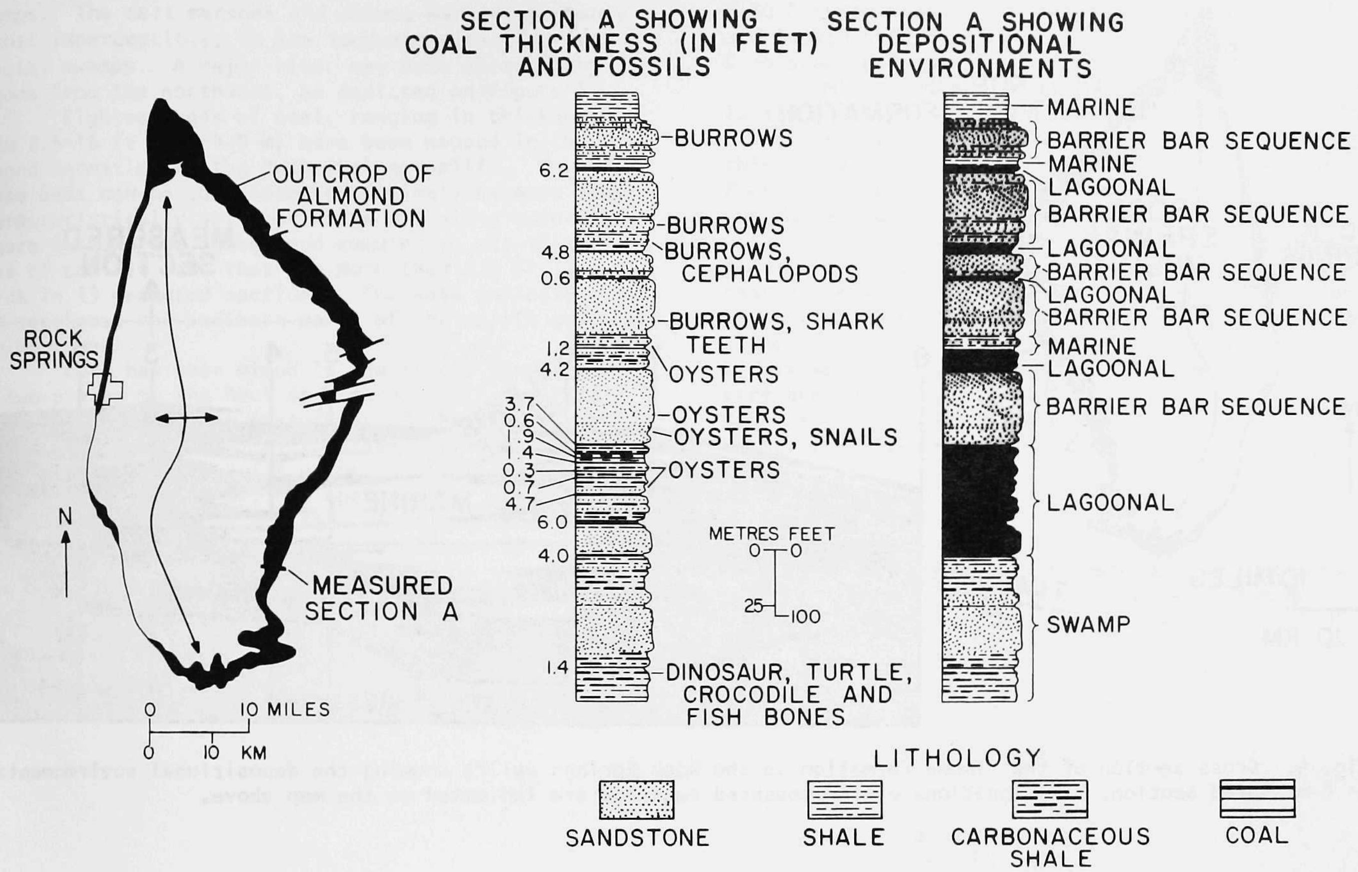


Fig. 2. Lithologies, fossil localities and depositional environments in measured section A of the Almond Formation located in the southeast part of the Rock Springs uplift.

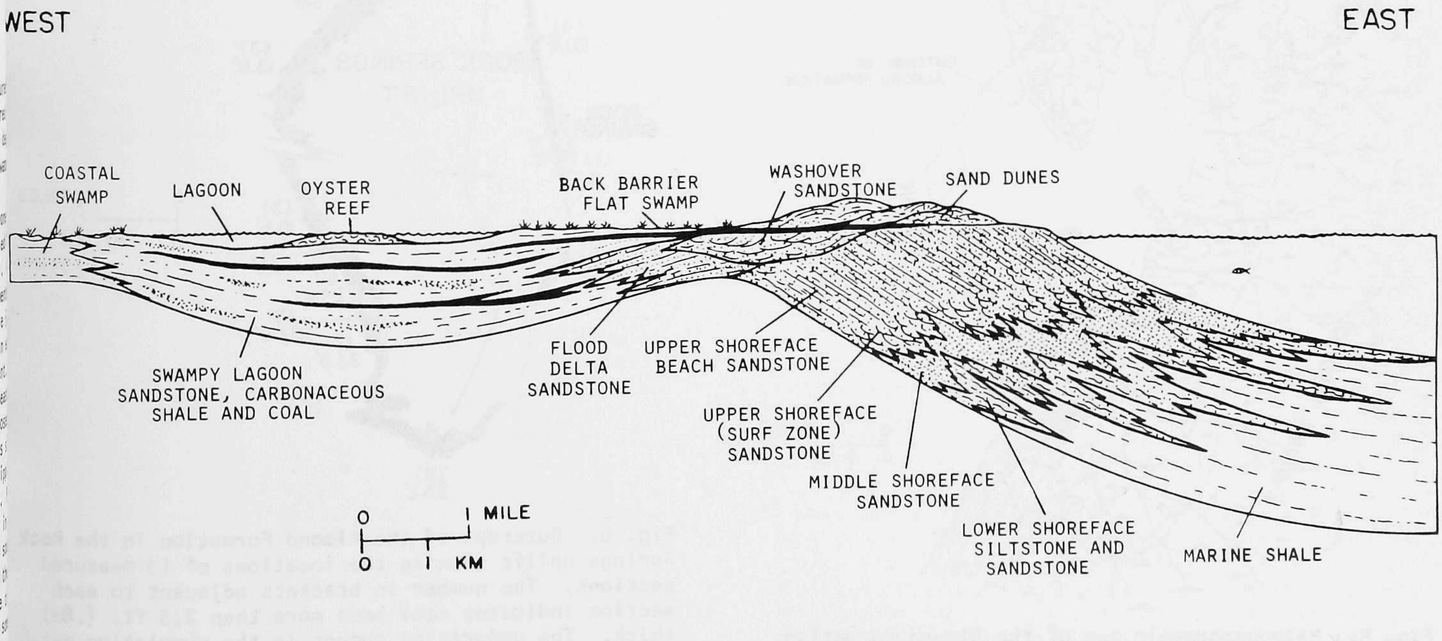


Fig. 3. Model for depositional environments of rocks deposited in the Almond Formation in the Rock Springs uplift.

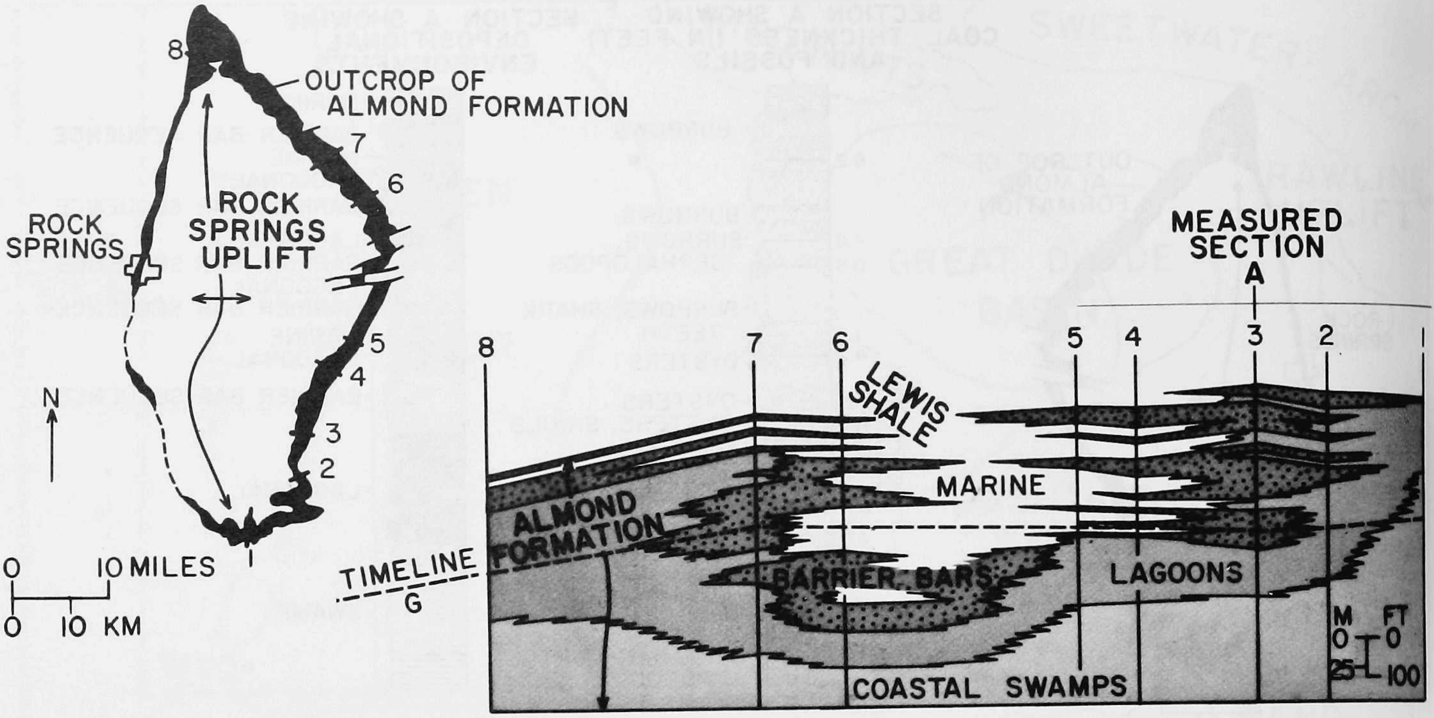


Fig. 4. Cross section of the Almond Formation in the Rock Springs uplift showing the depositional environments in 8 measured section. The locations of the measured sections are indicated on the map above.

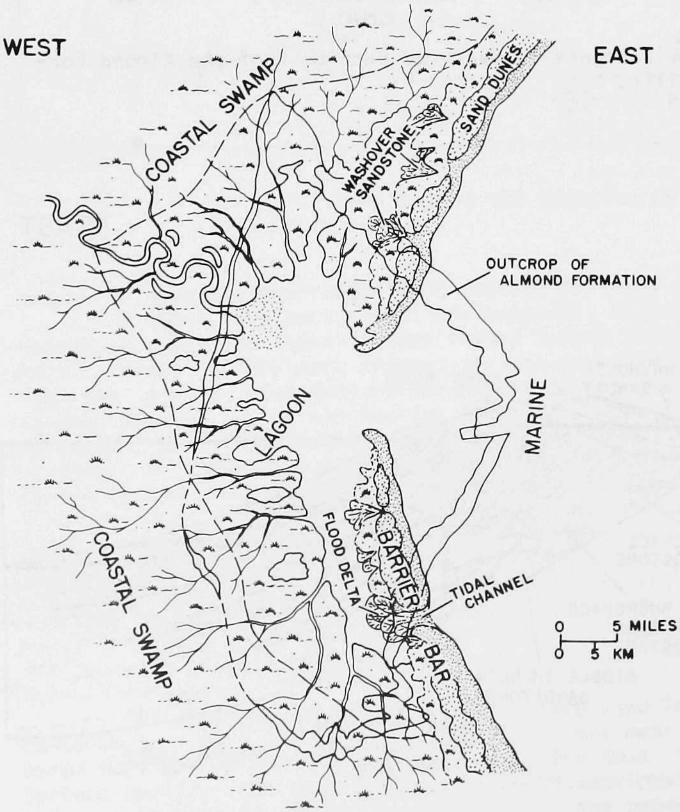


Fig. 5. Paleogeographic map of the Almond Formation in the Rock Springs uplift area at timeline G.

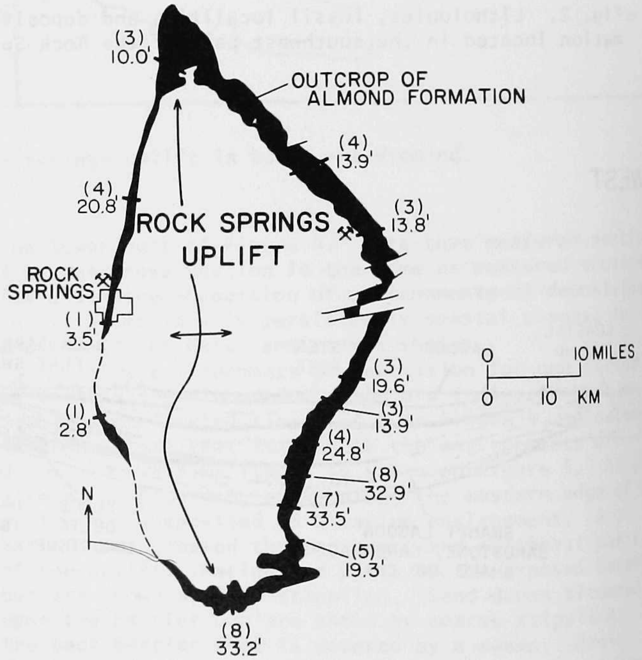


Fig. 6. Outcrops of the Almond Formation in the Rock Springs uplift showing the locations of 13 measured sections. The number in brackets adjacent to each section indicates coal beds more than 2.5 ft. (.8m) thick. The underlying number is the cumulative net thickness of coal in the beds shown in brackets.

swamps. The salt marshes and swamps merged, probably almost imperceptibly, in the landward direction into coastal swamps. A major river may have entered the lagoon from the northwest, as depicted on Figure 5.

Eighteen beds of coal, ranging in thickness from 2.5-16 ft (0.8-4.9 m) have been mapped in the Almond Formation in the Rock Springs uplift. Few of these beds can be correlated extensively because they characteristically split or wedge out along outcrops. Figure 6 shows the number and cumulative net thickness of coal in beds that are more than 2.5 ft (0.8 m) thick in 13 measured sections. The data indicate that the southeast and southern parts of the uplift contain the most coal.

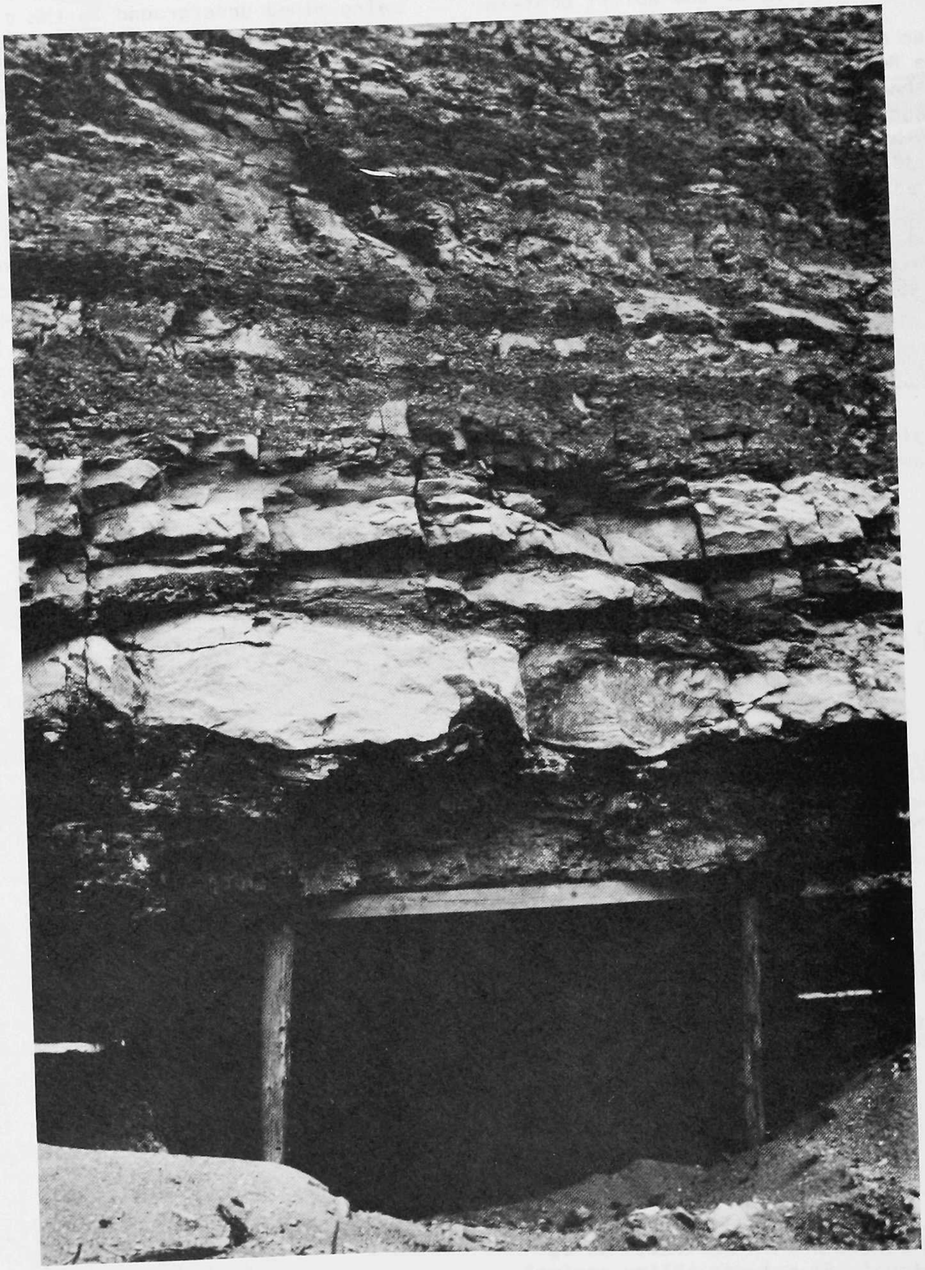
Coal has been mined in the Almond Formation in two places on the Rock Springs uplift. The first mine was opened on the east flank of the uplift near Point of Rocks in 1868, at the time that the Union Pacific Railroad was built across southern Wyoming (Schultz, 1908, p. 230). It operated for about one year and was abandoned in 1869. A second mine, the No. 6 mine, was opened at the City of Rock Springs in 1882. It operated for 4 years and was abandoned in 1886. The coal from these mines analyzed 0.2 to 0.9 percent sulfur, 46 to 51 percent fixed carbon, 3 to 6 percent ash, with heating values between 8,800 and 10,850 Btu/lb. The coal ranks from subbituminous C to subbituminous A.

Mineable coal resources in the Almond Formation in the Rock Springs uplift are estimated to be 5,650 million short tons in beds more than 2.5 ft (0.8 m) thick under less than 3,000 ft (914 m) of overburden. Five to 10 percent of this resource is possibly recoverable locally by strip mining.

Coal is not mined in the Almond Formation presently for two reasons: (1) the coal has a lower heating value than other Upper Cretaceous coals now being mined underground in the vicinity of the City of Rock Springs; and (2) the Almond coals are thin, widely spaced, dip a minimum of 5°, and for the most part are not recoverable by strip mining. Nevertheless, the Almond coals comprise a vast undeveloped energy resource in southwest Wyoming.

REFERENCE CITED

Schultz, A.R., 1908, The southern part of the Rock Springs coal field, Sweetwater County, Wyoming: U.S. Geol. Survey Bull. 381, pt. 2, p. 214-281.



Underground coal mine, Fremont County, Colorado (Vermejo Formation)

GEOLOGY OF THE TONGUE RIVER MEMBER, FORT UNION FORMATION OF EASTERN MONTANA

ROBERT E. MATSON: Montana Bureau of Mines and Geology
Butte, Montana 59701

JOHN M. PINCHOCK: Montana Bureau of Mines and Geology
Butte, Montana 59701

ABSTRACT: The Tongue River Member of the Fort Union Formation contains the largest part of the Nation's low-sulfur coal resources. The Fort Union is Paleocene in age. In Montana, it has been divided into three members: the Tullock (lowest), the Lebo (middle), and the Tongue River (upper). The stratigraphic relations of the members are discussed and compared to similar sections in North Dakota.

The major coal beds of current economic interest in the Tongue River Member are described, correlated, and characterized. These include the Anderson, Dietz, Canyon, Wall, Knobloch and Rosebud coal beds in southeastern Montana, and the Pust coal bed in eastern Montana.

INTRODUCTION

Vast amounts of low-sulfur coal make the Fort Union Formation one of the most important coal-bearing units in the country. As a result, workers have become more interested in this complex unit, and detailed work is beginning. This paper is designed to present an overview of what is known about this unit, and to stimulate further detailed studies of this important but neglected sequence. Because of the broad scope of this report, much of the more detailed information has been omitted; however, a comprehensive list of references is provided. Figure 1 shows the geographic location of the Fort Union Formation in Montana, Wyoming, and the Dakotas.

Many of the coal fields were described and mapped in early U.S. Geological Survey reports. A subject of controversy among early workers was the placement of the Cretaceous-Paleocene boundary. Although the major points have been fairly well resolved, the work is far from completed. The major points of the history of the boundary problem will be discussed here. More details are contained in an account by Brown (1962).

After a review of the Fort Union Formation as a whole, the important coal beds in the Tongue River Member will be discussed. The stratigraphic relationships, areal extent, and chemical analyses of the Anderson, Dietz, Canyon, Wall, Knobloch, Rosebud, and Pust coal beds will be summarized.

HISTORY OF THE CRETACEOUS-PALEOCENE BOUNDARY

The history of the separation of the Fort Union Formation from the Upper Cretaceous has been presented by R.W. Brown (1962). Hayden (1861) first named the coal-bearing rocks of the Rocky Mountain and Great Plains regions the "Great Lignite" group, from field work he and his colleagues undertook in 1854 and the years following. The group was renamed the Fort Union group by Meek and Hayden (1862). Dinosaur fossils collected from various localities in the lower part led workers to agree on a Cretaceous age for at least the lower part. Plant fossils collected from the upper part were identified as Tertiary by Newberry (1868). This was the first indication that the Cretaceous-Paleocene contact was somewhere within the Fort Union.

Newberry's work caused much controversy. Most paleobotanists did not believe that the floras of the upper and lower Fort Union could be distinguished. Newberry (1890) insisted that they could be and stuck to his early conclusions.

Stanton and Knowlton (1897) differentiated the Lance Formation (Upper Cretaceous), which contained dinosaur fossils, from the overlying Fort Union Formation, which did not, in the Lance Creek area of Wyoming. The Fort Union was subdivided on the basis of color. Beginning with the oldest, these subdivisions were named the Hell Creek Member (dark); Tullock Member (light); Lebo Member (dark); Tongue River Member (light); and the Sentinel Butte Member (dark). Eastward from Miles City, Montana, the color differences become very hard to recognize. For this reason, in eastern Montana and the Dakotas the Tullock and Lebo have been placed together to form the Ludlow Member.

Barnum Brown (1907) named the Hell Creek beds from the type area north of Jordan, Montana, and correlated them with the Lance Formation in Wyoming (1914). He placed the Mesozoic-Cenozoic boundary between the Hell Creek and Tullock Members.

Knowlton (1909) divided the sequence above the Fox Hills Sandstone into the upper and lower Fort Union.

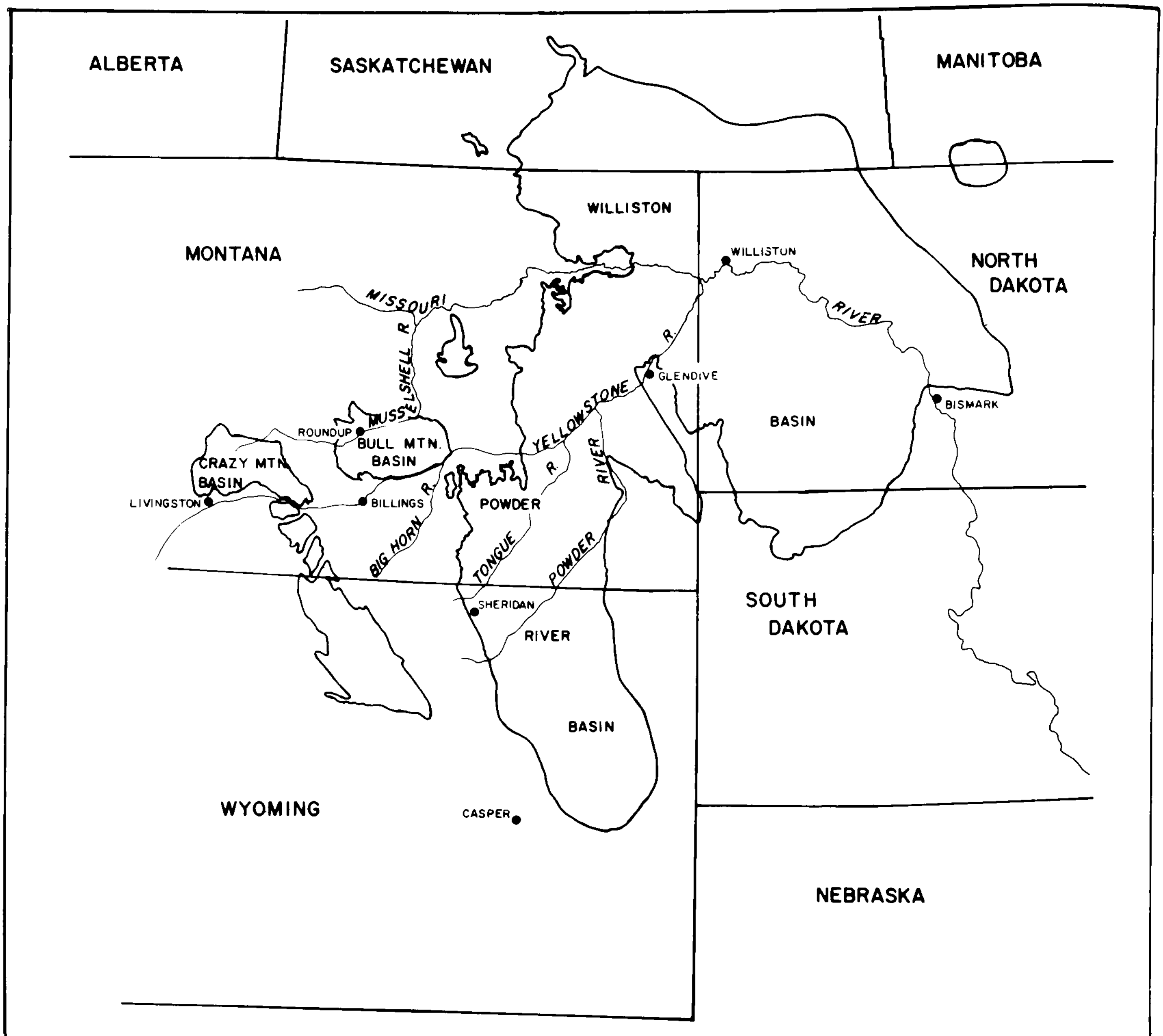


FIGURE 1. Outcrop of the Fort Union Formation, including some areas covered by younger strata

His upper division corresponds to the present Tongue River Member, and his lower with the present Hell Creek, Tullock, and Lebo Members. He did not distinguish the flora of the Hell Creek and the correlative Lance from that of the overlying beds. He did not differentiate between the Hell Creek and Lebo, and he also failed to realize that the Tullock occurred between them. His conclusions further delayed the resolution of the boundary problem.

Placing of the Cretaceous-Paleocene boundary was helped by the discovery of mammal fossils in several locations in the beds above the dinosaur-bearing strata. This information was summarized by Simpson (1937), who published a chart placing the contact between the Hell Creek and what he called the "Bear" beds. He regarded the "Bear" beds as equivalent in part to the Tullock or lower Fort Union in the Crazy Mountains area. R.W. Brown (1962) confirmed that Simpson's "Bear" belonged to the Tertiary and that the contact between it and the Hell Creek marked the Cretaceous-Paleocene boundary.

Leonard (1907) first discovered the oyster beds of the Cannonball Marine Member, which was first thought to be of Cretaceous age (Stanton, 1914, 1921). The Cannonball was found interfingering with the Ludlow, however, which was regarded as Tertiary. This relationship, combined with the lack of ammonites, placed the Cannonball in the Tertiary. Fox and Ross (1940, 1942) found foraminiferal evidence for the Paleocene age of the Cannonball.

The Sentinel Butte Member was first described by Leonard and Smith (1909) in western North Dakota. Thom and Dobbin (1924) regarded it as Wasatch in age, but later paleontological evidence (R.W. Brown, 1948b) placed the unit in the upper part of the Fort Union.

In 1912, Calvert applied the first practical formula for locating the Mesozoic-Cenozoic boundary. While working in the vicinity of Glendive, Montana, he found the latest dinosaur remains just below the "lowest persistent bed of lignite." A color change from the dark Hell Creek to the light Tullock also takes place locally at this level.

This relation can be easily detected and mapped throughout most of the Fort Union (R.W. Brown, 1962). This conclusion has been supported by later paleontological evidence. Dorf (1940, 1942) distinguished marked floral changes across the Lance-Fort Union boundary,

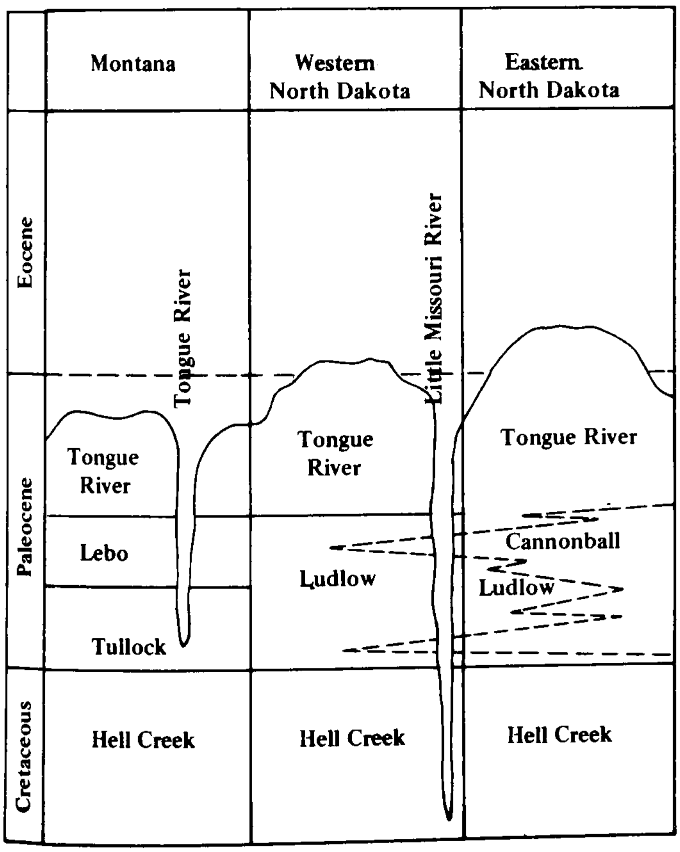


Fig. 2. Correlation of the members of the Fort Union across Montana and North Dakota (after Brown, 1962).

which had not been detected by Knowlton. His work supported that of Newberry and Calvert. Tschudy (1970) and Leffingwell (1970) both observed palynological change across this boundary. The contact is generally marked by lithologic and color changes that become more apparent with familiarity (R.W. Brown, 1962).

PALEOCENE-EOCENE CONTACT

In the Powder River basin of Montana and Wyoming, the Wasatch (Eocene) overlies the Fort Union. The Wasatch consists of conglomerate, sandstone, claystone, shale, and coal seams. The strata resemble those of the Paleocene but tend to be more sandy and varicolored and contain less coal. The Wasatch contains a fossiliferous zone as much as 30 ft thick about 30 ft above the Roland coal bed.

Denson and Chisholm (1971) studied heavy-mineral distributions in the Tertiary and found marked contrast in mineral concentrations across the boundary. In the Paleocene rocks, tourmaline and pinkish-violet zircon predominate. In the lower Eocene rocks, epidote, blue-green hornblende, and garnet are most abundant. The contact is generally marked by lithologic, faunal, floral, and mineralic changes over wide areas. Although certain coal beds may coincide with the boundary in some areas, lithologic and mineralic changes are more reliable in selecting the contact (Denson and Chisholm, 1971).

In North Dakota, the Fort Union is gradational into the Golden Valley Formation (Eocene) in some areas. In other areas it is disconformably overlain by the White River Formation (Oligocene) (Royse, 1967).

FORT UNION DEPOSITION IN THE LIVINGSTON AND BULL MOUNTAIN AREAS

Livingston Area

The earliest deposits of the Fort Union Formation are found in the Livingston area of Montana. The Fort Union conformably overlies the Livingston Group and consists of sandstone and conglomerate interbedded with siltstone and mudstone. This lithology differs from that of the underlying Livingston Group. The Fort Union sediments were derived from sedimentary and metamorphic rocks, whereas the Livingston Group was volcanic in origin. This lithologic difference (and the larger grain size in the Fort Union) suggests that its source was closer than that of the Livingston Group, probably from the Bridger Uplift (Roberts, 1972).

Based on tectonic and paleontological evidence, Roberts (1963, 1965, 1972) placed the basal part of the Fort Union in the Cretaceous and the upper part in the Paleocene.

Bull Mountain Basin

Eastward from the Crazy Mountains basin, the Fort Union Formation grades into what might be called typical Fort Union sandstone, siltstone, claystone, shale, and coal beds. The Bull Mountains form a broad synclinal basin that flattens to nearly horizontal in the east and south. It extends to the north as two folds. Shurr (1972) studied paleocurrent indicators in the Tongue River Member and noticed a general decrease in thickness and grain size to the east, implying a western source.

INDIVIDUAL MEMBERS OF THE FORT UNION

The Fort Union Formation has been subdivided into members. In Montana they are, from oldest to youngest, the Tullock, Lebo, and Tongue River Members. In western North Dakota they are termed the Ludlow, Tongue River, and Sentinel Butte Members. In western North Dakota they are referred to as the Ludlow, Cannonball, and Tongue River Members (Fig. 2).

Tullock Member

The Tullock consists generally of light-colored sandstone, sandy shale, carbonaceous shale, siltstone, clay, and mudstone, together with numerous thin impure coal beds. The type section is in the Tullock Creek area of Montana (Rogers and Lee, 1923). Most of the older reports treated the Tullock as the upper member of the Lance and Hell Creek. The base of the Tullock is defined as the "first persistent bed of lignite" above the dinosaur-bearing beds of the Cretaceous (Calvert, 1912). The contact with the Lebo is taken to be the base of the "Big Dirty" coal bed. Over much of its extent, the top of the Tullock is marked by a resistant bed of calcareous sandstone or siltstone. This bed provides a recognizable contrast to the easily weathered basal shale of the Lebo. In far eastern Montana and the Dakotas, the resistant cap of the Tullock is absent, and the contact with the Lebo is difficult to observe in the field. In these areas, the Tullock and Lebo combined are mapped as the Ludlow. Garrett (1963) believed that the Tullock developed in a coastal plain environment.

Lebo Member

The Lebo consists generally of a dark sequence of shale, mudstone, carbonaceous shale, siltstone, argillaceous sandstone, and lignite. Channel sandstone bodies in the Lebo weather to a light color, in contrast with the rest of the member. In the Crazy Mountains area, the Lebo is composed mainly of andesitic sandstone.

The base of the Lebo Member has been placed at the base of the "Big Dirty" coal bed. More recently, authors (Garrett, 1963; Gerhard, 1967) have suggested that the resistant sandstone marking the top of the Tullock, below the "Big Dirty," forms a better defined boundary. The upper contact with the Tongue River Member is generally based on color changes. In many places, the dark Lebo contrasts strongly with the light Tongue River. Based on color changes, the Lebo thins eastward toward Terry, Montana. Garrett (1963) thought the supposed thinning resulted from the Lebo becoming so light colored as to make the contact with the Tongue River hard to recognize. The Lebo grades eastward into the Ludlow.

Gerhard (1967), working in eastern Montana, divided the Lebo into 3 large cyclic units, separated from each other by unconformities. He noted 5 lithologies, which may be cyclic themselves, as follows: yellow siltstone; brown claystone that weathers light gray; finely fissile brown shale; lignite; and gray to buff limestone that weathers yellow. The limestone, fissile shale, and lignite are probably lateral equivalents. The decrease in grain size from the bottom to the top of each cycle, and the unconformity between units, suggest that each cycle started with an abrupt increase in environmental energy, which then decreased during the cycle. These cycles may be indicative of periodic uplift of the western source. The possible smaller cycles within the units may result from minor energy changes.

Tongue River Member

The Tongue River Member contains most of the economically important coal beds in the Fort Union Formation. It consists of pale-olive to yellow-gray claystone, interbedded claystone and sandstone, interbedded shale and claystone, carbonaceous shale, and thick coal beds. The sandstone and claystone occur in almost equal proportions. A basal sandstone is present in many areas and is used to mark the lower boundary of the member. The top of the Roland coal bed marks the upper contact.

Tongue River Member Depositional Environment

Evidence of cyclic deposition in the Tongue River has been presented by Jacob (1973) and Bryson and Bass (1973). Jacob worked in North Dakota and defined 4 litho-types of a basic cyclic unit. Starting from the base of the cycle, they are: gray claystone and siltstone; lignite; yellow siltstone and clayey sandstone; and calcareous sandstone. He concluded that the sequence was deposited by non-braided, low-sinuosity streams, which formed in the lower, subaerial part of a high-constructive delta. The claystone and siltstone probably were deposited on flood plains. The lignite beds were probably laid down in backswamps. The yellow sandstone and siltstone probably were deposited on natural levees and crevasse splays. A few sandstone bodies that may be point bars are also present.

Bryson and Bass worked in the Moorhead coal field in Montana. The cyclic unit consisted of the following: a basal, massive, faintly crossbedded sandstone; a thin shale and claystone layer; coal; and an upper bed dominated by shale. They concluded that the coal was formed in coastal swamps, at varying distances from the shoreline. The basin was unstable, owing to periodic uplift of the western source. The shale overlying the coal represents either periods of subsidence that moved the shore westward or periods of accelerated deposition from a low-lying source.

Royse (1970) studied the sedimentology of the Tongue River-Sentinel Butte contact in North Dakota. He looked at grain-size distributions in both units and proved that there is a distinctive stratigraphic difference between the two units. Analyses of sediment samples showed the Tongue River sediments to be finer and less well sorted than those of the Sentinel Butte.

The Tongue River Member in this area was deposited by slow-moving streams on a low paleoslope gradient. The sediments were derived from a low-lying source to the west, and transportation eastward was principally by suspension. Near the end of the episode, the altitude of the source was reduced, subsidence exceeded deposition, and swamp conditions prevailed. Backswamp deposits exceed those of transitional and flood plain environments in the Tongue River. The coal beds were deposited in the backswamp. Major channels occur only in the basal part of the Tongue River.

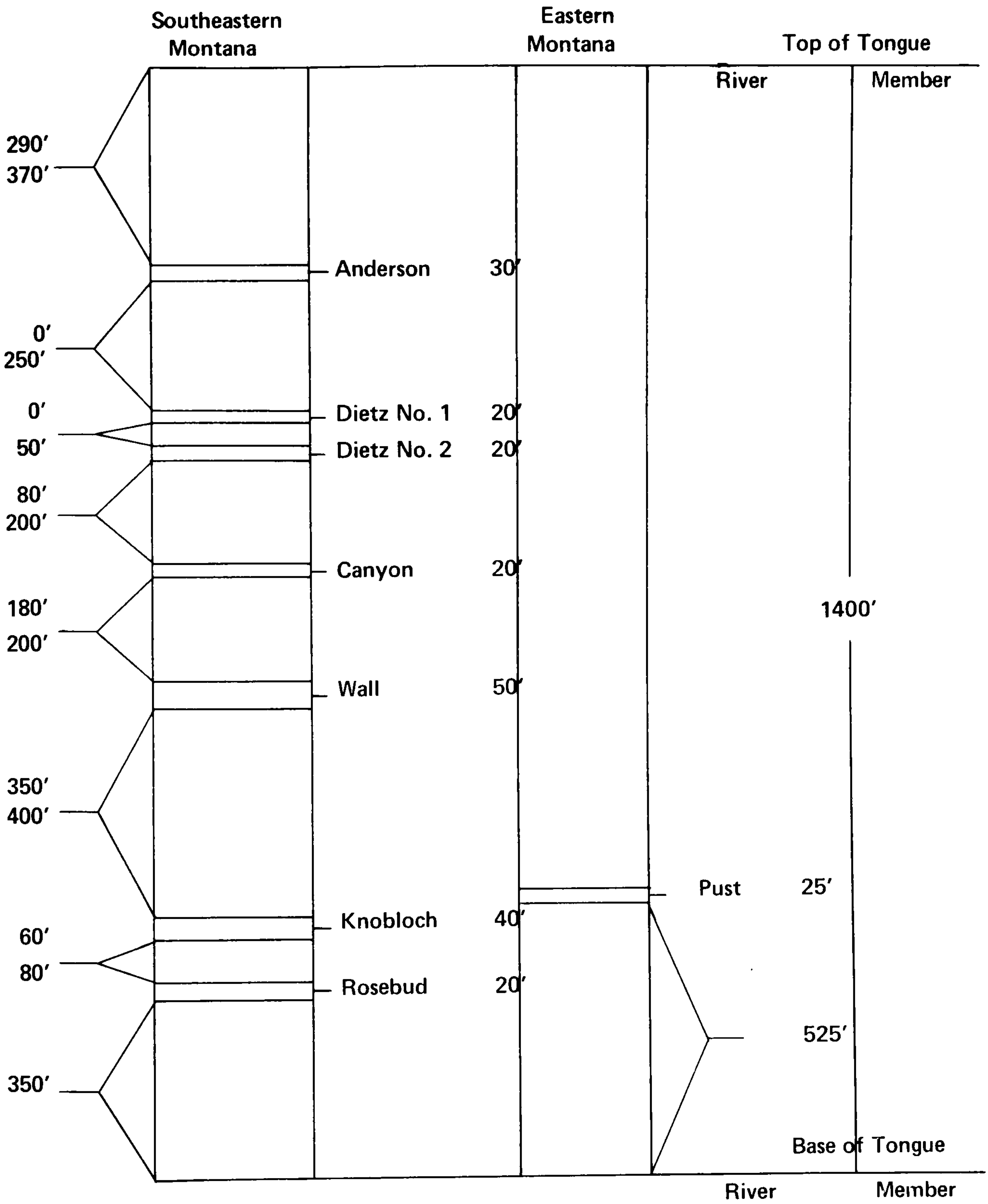


Fig. 3. Stratigraphic relationships of the important coal beds in the Tongue River Member.

Sentinel Butte Member

The strata of the Sentinel Butte are very similar to those of the Tongue River. There has been controversy as to whether the Sentinel Butte should be regarded as a separate member or part of the Tongue River. In North Dakota, where the type section is located, the Sentinel Butte is regarded as a separate member.

The base of the unit is marked by a distinctive basal sandstone (Royse, 1970). Deposition started with the influx of this deltaic sandstone over the swamps of the Tongue River. The source area had changed to the northwest, and the sediments were spread south and eastward. Elevation was increased over base-level. The streams had slightly greater velocities than the Tongue River streams, but transportation was still mainly by suspension. The drainage pattern was less stable and the paleoslope was variable, reflecting tectonism farther west. The sediments were laid down farther upstream than the Tongue River sediments had been. Transitional and flood-plain deposits exceed backswamp deposits. The presence of an upper sand unit suggests rejuvenation of the source.

The unit is disconformably overlain by the White River Formation (Oligocene) in some areas, and grades into the Golden Valley Formation (Eocene) in others.

Most workers have agreed that the Sentinel Butte is missing in the Powder River basin. Carmichael (1967, 1975), after working in the Pumpkin Creek coal field and reviewing the work of Bryson (1952) in the Coalwood coal field, believed that the Sentinel Butte also is present in this area. He believed that the gray shales described by Bryson, between the Mackin-Walker and Stump coal beds, belong in the lower part of the Sentinel Butte. He tentatively placed the Tongue River-Sentinel Butte contact at the base of the Mackin-Walker coal bed.

Ludlow Member

In the Dakotas, the Tullock and Lebo are combined to form the Ludlow Member. Farther eastward, the Ludlow interfingers with the marine Cannonball Member. The Ludlow consists of yellowish-weathering, poorly consolidated sandstone, gray to brown shale, and lignite.

Cannonball Marine Member

The Cannonball was first recognized by Leonard (1907). It is the only Paleocene marine formation in the mid-continent. It is recognized only in western North Dakota and in northwestern South Dakota. It consists of poorly consolidated, grayish-green sandstone, which weathers brown, and gray mudstone that tends to be blocky. The Cannonball Member contains thin beds of marine fossils. Deposition occurred in various environments, which include salt marshes, tidal flats, tidal channels, beaches, and shelf bottoms (Cvancara, 1972). The base of the member is taken as the highest lignite or lignitic shale of the Ludlow. To the west, in interfingers with the Ludlow. The upper contact shows both conformable and disconformable relationships with the basal sand of the Tongue River Member.

CORRELATION OF THE FORT UNION FORMATION

Several authors have noted that the beds of the Fort Union cross time lines (Garrett, 1963; Leffingwell, 1970; Carmichael, 1967, 1975). In a cross section from Billings to south-central North Dakota, Garrett showed the individual members becoming progressively younger to the east. Leffingwell noted that the basal Tongue River in North and South Dakota was older than that in the southern Powder River basin. Carmichael correlated the lower part of the Sentinel Butte in eastern Montana with the Lebo in northeastern Wyoming; the Tongue River with the Tullock; and the Lebo and Tullock with the upper part of the Hell Creek. These observations support the idea that the depositional front of the Fort Union moved in a general south and east direction.

IMPORTANT COAL BEDS OF THE TONGUE RIVER MEMBER

The important coal beds of the Tongue River Member are the Anderson, Dietz, Canyon, Wall, Knobloch, Rosebud, and Pust coal beds. These are important because of the magnitude of the reserves they contain and also the quality of the coal. The general stratigraphic relationship of these coal beds is shown on Figure 3.

All of these beds have wide areal extent (Plate 1-5); and in southeastern Montana, they show variation in quality from subbituminous to lignite, depending on geographic location (Table 1).

The current mapped strippable reserves in these coal beds total 28,000 million tons (Table 2).

Anderson Coal Bed

The Anderson is stratigraphically the highest of the important coal beds in southeastern Montana. It lies 290 to 370 ft below the top of the Tongue River Member. It presently is being mined at the Decker mine and will also be mined at the planned East Decker mine. At the Decker mine, it merges with the Dietz No. 1 bed to form a seam 50 ft thick. Just west of the mine, the Anderson combines with both the Dietz No. 1 and Dietz No. 2 to form an 80-ft-thick seam. Still farther west, the Anderson splits off from the combined Dietz seams. In the Deer Creek coal field, east of the mine, the three beds are separate, and the Anderson is 20 ft thick. In the northern part of the Poker Jim Lookout coal field, the Anderson and Dietz combine for a thickness of 58 ft, but in the southern part of the field they are separate beds. In the West Moorhead coal field, the Anderson is 14 to 30 ft thick and 13 to 81 ft above the Dietz No. 1. In the Hanging Woman Creek coal field, it is 25 to 36 ft thick, thinning to 15 ft in the southwestern part of the area. It lies 50 to 100 ft above the Dietz No. 1.

The highest quality coal from the Anderson bed is found in the Decker deposit. The quality decreases to the east and north from the Decker deposit.

Dietz Coal Beds

Taff (1909) mapped three Dietz beds, about 5 mi north of Sheridan, Wyoming. These were traced northward into the Decker area by Baker (1919). Dietz No. 1 of Taff correlates with the Anderson. The present Dietz

Table 1. Average coal quality of the economically important coal beds. All analyses are on an as-received basis, except where tipple samples are designated.

Deposit	No. of samples	Moisture	Volatile matter	Fixed carbon	Ash	Sulfur	Btu/lb.
			PUST COAL BED				
Burds Creek-Thirteenmile Creek	10	38.846	26.778	26.902	7.828	.654	6138
Savage Mine	Tipple	38.000	27.000	27.000	7.25	.500	6500
			ROSEBUD COAL BED				
Colstrip	16	21.168	29.107	38.852	9.541	.823	8836
Greenleaf Creek-Miller Creek	4	27.175	26.743	37.491	8.592	1.169	8376
Sarpy Creek Mine	Tipple	25.000	29.000	37.000	9.000	.330	8450
Peabody Mine	Tipple	26.300	28.600	34.700	10.400	.750	8450
Western Energy Mine	Tipple	25.500	27.720	38.330	8.450	.800	8750
			KNOBLOCH COAL BED				
Ashland	27	27.664	28.824	37.633	4.828	.153	8420
Otter Creek	28	28.233	29.915	36.712	4.710	.367	8468
Poker Jim Creek-O'dell Creek	6	24.165	30.036	40.695	5.104	.226	8846
Greenleaf Creek-Miller Creek	8	27.405	28.498	37.672	6.424	.540	8580
Beaver Creek-Liscom Creek	12	31.435	28.487	34.532	7.962	.492	8015
Foster Creek	3	31.113	27.740	33.257	7.89	.767	7573
Sand Creek	2	31.835	28.055	33.435	6.675	.300	7340
			WALL COAL BED				
Canyon Creek	42	24.346	30.571	40.429	4.629	.305	9088
Yager Butte	89	32.663	28.03	34.391	4.916	.320	7552
			CANYON COAL BED				
Decker	3	22.863	29.856	39.737	7.544	.418	9104
Poker Jim Lookout	3	30.483	29.466	35.050	5.002	.371	8201
Hanging Woman Creek	4	25.155	29.940	38.542	6.365	.407	8428
Kirby	3	23.780	29.637	40.770	5.817	.240	8789
West Moorhead	12	28.327	29.779	36.550	5.343	.420	8055
Canyon Creek	7	26.829	26.970	35.870	10.328	.786	8192
Diamond Butte	5	35.128	27.921	33.033	3.918	.307	7395
Sonnette	1	36.960	26.709	30.054	6.277	.955	6904
Threemile Buttes	7	37.339	26.378	30.696	5.587	.942	6867
			DIETZ COAL BED				
Decker	4	23.612	25.562	36.563	11.764	.349	8367
Deer Creek	3	23.197	28.705	36.640	11.459	.630	8340
Hanging Woman Creek	4	27.423	29.622	36.811	5.507	.337	8078
Kirby	15	26.780	27.783	37.426	5.870	.590	8442
West Moorhead	4	31.333	29.717	34.823	4.127	.418	7990
			ANDERSON COAL BED				
Decker	8	23.728	29.856	39.634	4.310	.291	9236
Deer Creek	3	23.197	28.705	36.640	11.459	.630	8340
Poker Jim Lookout	8	29.626	30.013	35.084	5.277	.375	7926
Hanging Woman Creek	56	25.990	29.850	38.642	5.133	.293	8503
Kirby	11	26.716	28.085	38.471	4.295	.321	8328
West Moorhead	3	26.233	31.133	37.300	5.333	.367	8297
Decker Mine (Combined Anderson-Dietz)	Tipple	23.0	34.000	39.300	3.7	.400	9600

No. 1 and Dietz No. 2 correspond to the Dietz No. 2 and Dietz No. 3 of Taff. The Dietz is being mined at the Decker mine and will also be mined at the planned East Decker mine.

West of the Decker mine, the Dietz No. 1 and No. 2 combine with the Anderson to form a bed 80 ft thick. Right at the mine, only the Dietz No. 1 combines with the Anderson to form a bed 50 ft thick. In the Deer Creek field, all three beds are separate, and the Dietz beds average 18 ft in thickness. In the southwest part of the Kirby coal field, the Dietz beds combine for a thickness of 50 ft, but they split and thin to the northeast. The Dietz No. 1 has a maximum thickness of 18 ft in the Hanging Woman Creek coal field, but thins to 4 ft in the southwestern corner. In the West Moorhead coal field, it ranges from 6 to 11 ft in thickness, but is thin or absent in the northeast corner.

The best overall coal quality in the Dietz bed is found in the Decker area. The Btu and ash values are better in the Kirby deposit, but the sulfur content is much higher. The quality of the Dietz decreases to the east of these two coal fields.

Canyon Coal Bed

Although not being mined, the Canyon is one of the most widespread coal beds in Montana. The largest coal reserves in the Canyon are found in the West Moorhead and Diamond Butte deposits. In the West Moorhead deposit, the bed ranges from 17 to 24 ft in thickness and lies 67 to 122 ft below the Dietz. It is 16 to 25 ft thick and 180 to 230 ft above the Wall bed in the Kirby coal field. In the Diamond Butte coal field, the Canyon coal is 7 to 16 ft thick and about 200 ft above the Cook bed. It splits into two benches, 4 to 13 ft thick, in the Threemile Buttes deposit. The highest quality coal is in the Decker and Kirby deposits. As with the Anderson and Dietz, the quality diminishes to the east and north.

Wall Coal Bed

Although not presently being mined, the Wall contains large reserves in the Canyon Creek and Kirby deposits, where it is 50 to 60 ft thick. It lies 180 to 230 ft below the Canyon bed. In the Canyon Creek deposit, the Wall is one of the highest-rank coals in eastern Montana.

Knobloch Coal Bed

Although not being mined, the Knobloch contains larger strippable reserves than any other mapped coal bed in the Tongue River Member. It has good potential in the Ashland, Otter Creek, and Poker Jim

Table 2. Strippable reserves by deposit of the economically important beds of the Tongue River Member. All values in million tons.

Deposit	Anderson	Dietz	Canyon	Wall	Knobloch	Rosebud	Pust
Decker	2239.99						
Deer Creek	410.47						
Kirby	216.52	834.35	158.53	473.69			
Canyon Creek				1884.25			
Poker Jim Lookout	872.65						
Hanging Woman Creek	1583.29	1120.96					
West Moorhead	883.74	347.49	690.19				
Poker Jim Creek-O'dell Creek					938.07		
Otter Creek					2075.55		
Ashland					2696.20		
Colstrip						1439.26	
Foster Creek					708.13		
Diamond Butte			418.02				
Yager Butte				496.34			
Threemile Buttes			191.28				
Home Creek Butte			14.61				
Sand Creek					267.34		
Beaver Creek-Liscom Creek					491.62		
Greenleaf Creek-Miller Creek					325.00	76.14	
Burns Creek-Thirteenmile Creek*							4900

*Reserves in this area were calculated to 300 feet of overburden. In all the other areas, reserves were calculated to only 150 feet of overburden.

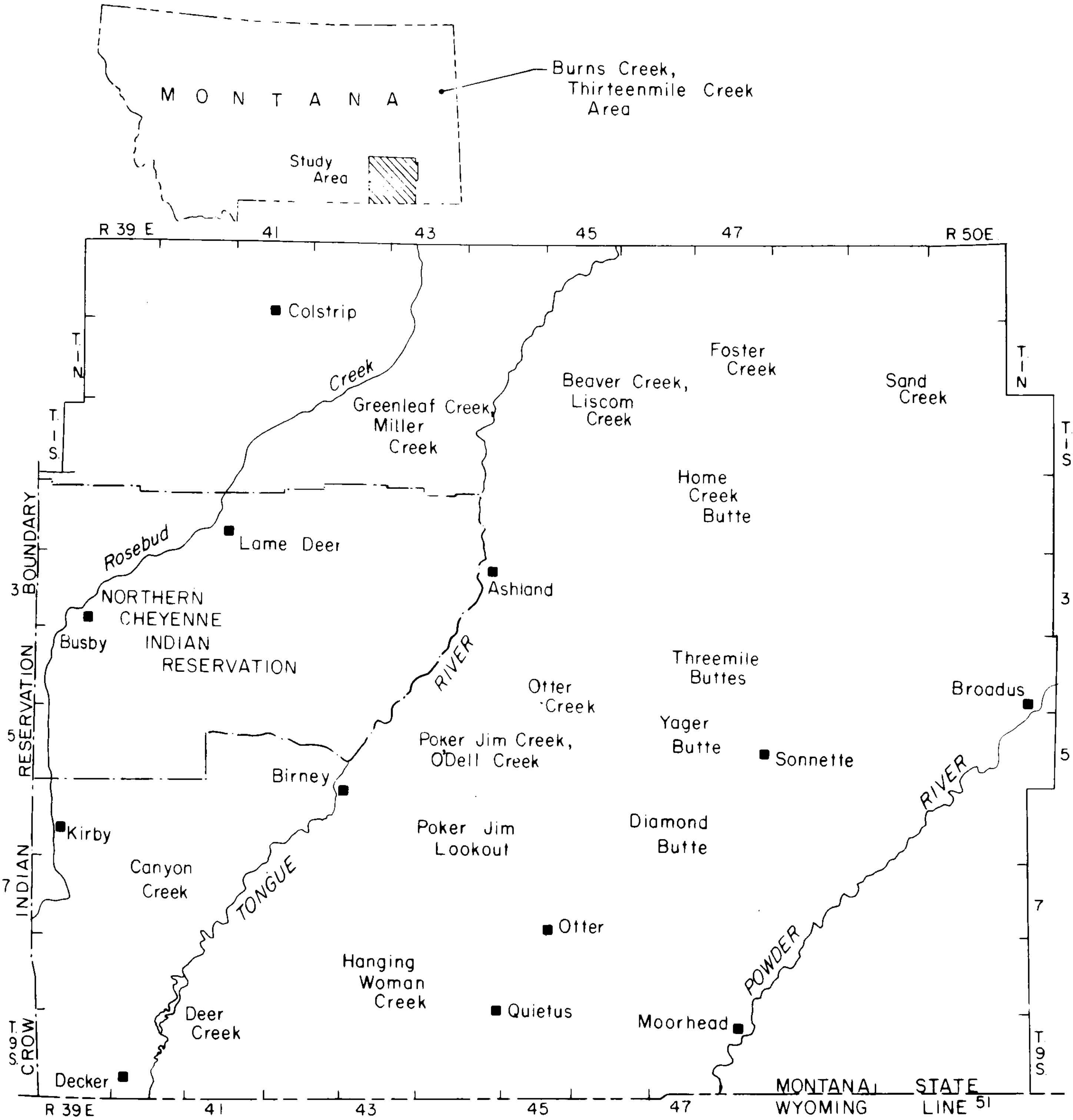


Fig. 4. Locations of discussed coal fields in Montana.

Creek-O'dell Creek deposits, as well as on the Northern Cheyenne Indian Reservation.

Thickness of the Knobloch coal varies throughout its areal extent, and it develops partings and tends to split into two or three seams. It reaches a maximum thickness of 66 ft in the northern part of the Otter Creek and Ashland deposits. Its highest quality is in the Poker Jim Creek-O'dell Creek deposit.

Rosebud Coal Bed

The Rosebud coal bed occurs about 350 ft above the base of the Tongue River Member. It is being mined at Colstrip by Western Energy Company and by Peabody Coal Company, and at Sarpy Creek by Westmoreland Resources Inc. It averages 25 ft in thickness in the Colstrip area. In the east side of the Sarpy Creek area, it is about 15 ft thick and occurs 4 to 36 ft above the McKay. On the west side of Sarpy Creek, it combines with the McKay for a thickness of 25 to 35 ft.

Pust Coal Bed

The Pust coal bed contains the largest reserves and has the greatest areal extent of any of the coal beds in eastern Montana. It is being mined at the Knife River mine. The Pust lies about 525 ft above the base of the Tongue River Member. It reaches a thickness of 44 ft in the eastern part of the Burns Creek-Thirteenmile Creek coal field, but thins to the north and west and averages about 25 ft in thickness. In the eastern part of the field, it forms one bed; however, it splits into two benches as much as 10 ft apart in the western part. The upper bench has a maximum thickness of 25 ft, and the lower has a maximum thickness of 15 ft. The heat values range between 5893 and 6492 Btu/lb, the sulfur between 0.301 and 1.548 percent, and the ash between 4.886 and 11.591 percent. The thicker coal in the eastern part of the area seems to be of slightly better quality than that in the western part.

CONCLUSIONS

The Tongue River Member of the Fort Union Formation (Paleocene age) contains vast amounts of strippable coal reserves in eastern Montana. A major part of these reserves is contained in 7 coal beds--the Anderson, Dietz, Canyon, Wall, Knobloch, and Rosebud in southeastern Montana, and the Pust in eastern Montana.

Generally, the coal that has the highest Btu value and that forms the thickest beds is found in the Decker, Montana area, although thick beds are also found in some of the other deposits.

REFERENCES

Andrews, D.A., 1936, Suggested Lance-Fort Union correlations in adjacent parts of Montana and North and South Dakota [abs.]: Washington Acad. Sci. Jour., v. 26, no. 9, p. 387-388.

Badgley, E.K., Jr., 1953, Correlation of some Late Cretaceous-Early Tertiary sediments in eastern Montana: Univ. Wyoming, M.A. thesis.

Baker, A.A., 1928, The northward extension of the Sheridan coal field, Big Horn and Rosebud Counties, Montana: U.S. Geol. Survey Bull. 806-B, p. 15-67.

Ballard, Norval, 1942, Regional geology of Dakota Basin: Am. Assoc. Petroleum Geologists Bull., v. 26, No. 10, p. 1557-1584.

Barbour, E.H., 1924, Echta coal property, Campbell County: Report for the Nebraska State Railway Commission, Bur. of Securities, Dept. of Trade and Commerce, State of Nebraska, Lincoln: Wyoming Geol. Survey open file, 21 p.

Barclay, C.S.U., 1972, The Tongue River and Sentinel Butte Members of the Fort Union Formation near Glen Ullin, Morton County, North Dakota, *in* Depositional environments of the lignite-bearing strata in western North Dakota, F.T.C. Ting, ed.: North Dakota Geol. Survey Misc. Series 50, p. 76-94.

Bass, N.W., 1932, The Ashland coal field, Rosebud, Powder River, and Custer Counties, Montana: U.S. Geol. Survey Bull. 831, p. 19-105.

Bauer, C.M., 1914, Lignite in the vicinity of Plentywood and Scobey, Sheridan County, Montana: U.S. Geol. Survey Bull. 541, p. 293-315.

__________ 1924, The Ekalaka lignite field, southeastern Montana: U.S. Geol. Survey Bull. 751, p. 231-267.

__________ 1925, Quartzite pebbles at the base of the Lance formation in Montana: Am. Assoc. Petroleum Geologists Bull., v. 9, p. 344-346.

Bauer, C.M., and Herald, F.A., 1922, Lignite in the western part of the Fort Berthold Indian Reservation south of Missouri River, North Dakota: U.S. Geol. Survey Bull. 726, p. 109-172.

Beekly, AL.L., 1912, The Culbertson lignite field, Valley County, Montana: U.S. Geol. Survey Bull. 471-D, p. 319-358.

Beikman, H.M., 1962, Geology of the Powder River Basin, Wyoming and Montana with references to sub-surface disposal of radioactive wastes: U.S. Geol. Survey Trace Element Inv. TEI 823, 85 p.

Bowen, C.F., 1912, The Baker lignite field, Custer County, Montana: U.S. Geol. Survey Bull. 471.

__________ 1914, Coal discovered in a reconnaissance survey between Musselshell and Judith, Montana: U.S. Geol. Survey Bull. 541-H, p. 329-337.

Brown, Andrew, Culbertson, W.C., Dunham, R.J., Kepferle, R.C., and May, P.R., 1954, Strippable coal in Custer and Powder River Counties, Montana: U.S. Geol. Survey Bull. 995-E.

Brown, Barnum, 1907, The Hell Creek beds of the Upper Cretaceous of Montana: Amer. Mus. Nat. Hist. Bull., v. 23, p. 829-834.

__________1914, Cretaceous-Eocene correlation in New Mexico, Wyoming, Montana, Alberta: Geol. Soc. America Bull. 25, p. 355-380.

Brown, R.W., 1938, The Cretaceous-Eocene boundary in Montana and North Dakota [abs.]: Washington Acad. Sci. Jour., v. 28, p. 421-422.

__________1948a, Age of the Kingsbury conglomerate is Eocene: Geol. Soc. American Bull., v. 59, no. 11, p. 1165-1172.

__________1948b, Correlation of Sentinel Butte shale in western North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 1265-1274.

__________1952, Tertiary strata in eastern Montana and western North Dakota and South Dakota: Billings Geol. Soc. Guidebook, 3d Ann. Field Conf., p. 89-92.

__________1958, Fort Union formation in the Powder River basin, Wyoming: Wyoming Geol. Assoc. Guidebook, 13th Ann. Field Conf., p. 111-113.

__________1962, Paleocene flora of the Rocky Mountains and Great Plains: U.S. Geol. Survey Prof. Paper 375, 119 p.

Brown, R.W., and Lemke, R.W., 1948, Newly discovered outcrops of the Cannonball Formation in North Dakota: Science, v. 107, p. 624-625.

Brown, R.W., and Lindvall, Robert, 1953, Fox Hills and Hell Creek strata in the Bearpaw Mountains, Montana: Science, v. 117, p. 39-40.

Brown, R.W., and Pecora, W.T., 1940, Paleocene and Eocene strata in the Bearpaw Mountains, Montana: Science, v. 109, no. 2837, p. 487-489.

Bryson, R.P., 1952, The Coalwood coal field, Powder River County, Montana: U.S. Geol. Survey Bull. 973-B.

Bryson, R.P., and Bass, N.W., 1973, Geology of the Moorhead coal field: U.S. Geol. Survey Bull. 1338.

Calvert, W.R., 1912, Geology of certain lignite fields in eastern Montana: U.S. Geol. Survey Bull. 471, p. 187-201.

Carlson, C.G., 1972, Stratigraphic position of lignite beds in the Tertiary rocks of Mercer and Oliver Counties, *in* Depositional environments of the lignite-bearing strata in western North Dakota, F.T.C Ting, ed.: North Dakota Geol. Survey Misc. Series 50, p. 95-104.

Carmichael, V.W., 1967, The Pumpkin Creek lignite deposit, Powder River County, Montana: Unpub. prof. degree geol. eng. thesis, Idaho Univ.

__________1975, The Sentinel Butte Member of the Fort Union Formation, Powder River County, Montana: Montana Geol. Soc., 22d Ann. Pub., p. 125-142.

Christman, C., 1948, The Fort Union Formation of Montana and adjacent areas: Montana School Mines B.S. thesis, 24 p.

Cobban, W.A., and Reeside, J.B., Jr., 1952, Correlation of the Cretaceous formations of the western interior of the United States: Geol. Soc. America Bull., v. 63, p. 1011-1044.

Collier, A.J., and Smith, C.D., 1909, The Miles City coal field, Montana: U.S. Geol. Survey Bull. 341-A, p. 36-61.

Collier, A.J., 1919, Geology of northeastern Montana: U.S. Geol. Survey Prof. Paper 120-B, p. 17-39.

__________1925, The Scobey lignite field, Valley, Daniels, and Sheridan Counties, Montana: U.S. Geol. Survey Bull. 751-E, p. 157-230.

Collier, A.J., and Knechtel, M.M., 1939, The coal resources of McCone County, Montana: U.S. Geol. Survey Bull. 905, 80 p.

Colton, R.B., 1962, Geology of the Otter Creek quadrangle, Montana: U.S. Geol. Survey Bull. 1111-G, p. 237-288.

Colton, R.B., and Bateman, A.F., Jr., 1956, Geologic and structure contour map of the Fort Peck Indian Reservation and vicinity, Montana: U.S. Geol. Survey Inv. Map I-225.

Culbertson, W.C., 1954, Three deposits of strippable lignite west of the Yellowstone River, Montana: U.S. Geol. Survey Bull. 995-H, p. 292-332.

Curry, W.H., III, 1971, Laramide structural history of the Powder River basin, Wyoming, *in* Wyoming tectonics symposium, 1971: Wyoming Geol. Assoc. Guidebook, 23d Ann. Field Conf., p. 49-60.

Cvancara, A.M., 1972, Summary of the Cannonball Formation (Paleocene) in North Dakota, *in* Depositional environments of the lignite-bearing strata in western North Dakota, F.T.C. Ting, ed.: North Dakota Geol. Survey Misc. Series 50, p. 69-75.

Darton, N.H., 1905, Preliminary report on the geology and underwater resources of the central Great Plains: U.S. Geol. Survey Prof. Paper 32, 433 p.

__________1906, Geology of the Bighorn Mountains: U.S. Geol. Survey Prof. Paper 51, 129 p.

Darton, N.H., and Salisbury, R.D., 1906, Cloud Peak-Fort McKinney, Wyoming: U.S. Geol. Survey Geol. Atlas, Cloud Peak-Fort McKinney Folio, no. 142, 16 p.

Davis, J.A., 1912, The Little Powder River coal field, Campbell County, Wyoming: U.S. Geol. Survey Bull. 471, p. 423-440.

Davis, W.M., 1900, The fresh-water Tertiary formations of the Rocky Mountain region: Am. Acad. Arts and Sci. Proc., v. 35, p. 345-373.

Denson, N.M., Bachman, G.O., and Zeller, H.D., 1959, Uranium-bearing lignite in northwestern South Dakota and adjacent states: U.S. Geol. Survey Bull. 1055-B.

Denson, N.M. and Chisholm, W.A., 1971, Summary of mineralogic and lithologic characteristics of Teritary sedimentary rocks in the Middle Rocky Mountains and the northern Great Plains, *in* Geological Survey research 1971: U.S. Geol. Survey Prof. Paper 750-C, p. C117-C126.

Dobbin, C.E., 1929, The Forsyth coal field, Rosebud, Treasure, and Big Horn Counties, Montana: U.S. Geol. Survey Bull. 812, p. 1-55.

Dobbin, C.E., and Barnett, V.H., 1928, The Gillette coal field, northeastern Wyoming: U.S. Geol. Survey Bull. 796, p. 1-50.

Dobbin, C.E., Kramer, W.B., and Horn, G.H., 1957, Geologic and structure map of the southeastern part of the Powder River Basin, Wyoming: U.S. Geol. Survey Oil & Gas Inv. Map OM 185, scale 1:125,000.

Dobbin, C.E., and Reeside, J.B., Jr., 1929, The contact of the Fox Hills and Lance formations: U.S. Geol. Survey Prof. Paper 158, p. 9-25.

Dorf, Erling, 1940, Relationship between floras of type Lance and Fort Union formations: Geol. Soc. America Bull., v. 51, p. 213-236.

__________1942, Upper Cretaceous floras of the Rocky Mountain region; II, Flora of the Lance formation at its type locality, Niobrara County, Wyoming: Carnegie Inst. Washington Pub. 580, p. 79-159.

Douglass, Earl, 1902, A Cretaceous and lower Tertiary section in south central Montana: Am. Philos. Soc. Proc., v. 41, p. 207-224.

Dunlap, C.M., 1958, The Lewis, Fox Hills and Lance formations of Upper Cretaceous age in the Powder River Basin, Wyoming, *in* Powder River Basin, 1958: Wyoming Geol. Assoc. Guidebook, 13th Ann. Field Conf., p. 109-110.

Erdmann, C.E., and Larsen, R.M., 1934, Geologic and structure contour map of the northern half of the Cedar Creek anticline, Dawson, Prairie, Wibaux, and Fallon Counties, Montana: U.S. Geol. Survey.

Evans, G.W., 1916, A report on a portion of the lignite fields of Custer County, Montana, for the Northern Pacific Railway Company, St. Paul, Minnesota: Northern Pacific Railway Company.

Everett, F., and Bowsher, J.A., 1954, Mineral resources (except petroleum and natural gas) of the Powder River Division in southeastern Montana and northeastern Wyoming: U.S. Bur. Mines Prelim. Rept. 94, Missouri River Basin Study.

Falvey, A.E., 1969, Mineral resources of the Tongue River basin, Big Horn, Custer, Powder River, and Rosebud Counties, Montana, and Johnson and Sheridan Counties, Wyoming: U.S. Bur. Mines Prelim. Rept. 175, Missouri River Basin Study, 16 p.

Feldman, R.M., 1972, Stratigraphy and paleoecology of the Fox Hills Formation (Upper Cretaceous) of North Dakota: North Dakota Geol. Survey Bull. 61, 65 p.

Fisher, W.L., and McGowen, J.H., 1969, Depositional systems in Wilcox Group (Eocene) of Texas and their relation to occurrence of oil and gas: Am. Assoc. Petroleum Geologists Bull., v. 53, no. 1, p. 30-54.

Frye, C.I., 1964, Marine tongues in the Hell Creek Formation, North Dakota: The Compass, v. 41, no. 2, p. 167-171.

__________1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geol. Survey Bull. 54, 65 p.

Fox, S.K., Jr., and Ross, R.J., Jr., 1940, Foraminiferal evidence for the Midway (Paleocene) age of the Cannonball formation in North Dakota: Geol. Soc. America Bull., v. 51, no. 12, pt. 2, p. 1970.

__________1942, Foraminiferal evidence for the Midway (Paleocene) age of the Cannonball formation in North Dakota: Jour. Paleontology, v. 16, p. 660-673.

Gale, H.S., and Wegemann, C.H., 1910, The Buffalo coal field, Wyoming: U.S. Geol. Survey Bull. 381, p. 137-169.

Galloway, W.E., 1968, Depositional systems of the lower Wilcox Group, north-central Gulf Coast Basin: Gulf Coast Assoc. Geol. Socs. Trans., v. 18, p. 275-289.

Garrett, H.L., 1963, Fossil slump features of the Tertiary-Paleocene Fort Union: Billings Geol. Soc., 17 p.

Gerhard, L.C., 1963, Cyclic deposition of lower Fort Union Formation in eastern Montana: Compass, v. 40, no. 2, p. 88-96.

__________1967, Surface correlation of lower Fort Union Formation beds in eastern Montana: Mtn. Geologist, v. 4, no. 2, p. 67-72.

Geslin, H.E., and Bromley, C.P., 1957, Preliminary drilling in the Powder River Basin, Converse, Campbell, and Johnson Counties, Wyoming: Atomic Energy Comm. RME-1070 (Rev.), Denver, Colorado, 25 p.

Gilmour, E.H., and Williams, L.A., 1969, Geology and coal resources of the Foster Creek coal deposits, eastern Montana: Montana Bur. Mines and Geology Bull. 73, 9 p.

Glass, G.B., 1972, Review of Wyoming coal fields, 1971: Wyoming Geol. Survey Misc. Rept., 32 p.

Hail, W.J., 1951, Petrology of an early Tertiary sandstone, Powder River Valley, northern Wyoming: M.A. thesis, Washington Univ., Seattle, 54 p.

Hall, J.W., and Norton, N.J., 1967, Palynological evidence of floristic changes across the Cretaceous-Tertiary boundary in eastern Montana (U.S.A.): Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 3, p. 121-131.

Hance, J.H., 1912, The Glendive lignite field, Dawson County, Montana: U.S. Geol. Survey Bull. 471, p. 271-283.

Hares, C.J., 1916, Stratigraphic relations of some of the Cretaceous and Tertiary formations of the Hanna and Powder River basins with those of the Wind River Basin [abs.]: Jour. Washington Acad. Sci., v. 6, no. 9, p. 255-256.

__________1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: U.S. Geol. Survey Bull. 775.

Hay, O.P., 1910, Where do the Lance Creek ("Ceratops") beds belong, in the Cretaceous or in the Tertiary?: Indiana Acad. Sci. Proc. 1909, p. 277-303.

Hayden, F.V., 1861, Sketch of the geology of the country about the headwaters of the Missouri and Yellowstone rivers: Am. Jour. Sci., v. 31, p. 229-245.

Hennen, R.V., 1943, Tertiary geology and oil and gas prospects in Dakota basin of North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 27, p. 1567-1594.

Herald, F.A., 1912, The Terry lignite field, Custer County, Montana: U.S. Geol. Survey Bull. 471, p. 227-270.

Hose, R.K., 1954, Geology of Crazy Woman Creek area, Johnson County, Wyoming: U.S. Geol. Survey Oil and Gas Inv. Map OM-142, scale 1:48,000.

__________1955, Geology of the Crazy Woman area, Johnson County, Wyoming: U.S. Geol. Survey Bull. 1027-B, p. 33-118.

Howard, A.D., 1960, Cenozoic history of northeastern Montana and northwestern North Dakota, with emphasis on the Pleistocene: U.S. Geol. Survey Prof. Paper 326, 107 p. [1961].

Jacob, A.F., 1973, Depositional environments of Paleocene Tongue River Formation, western North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 57, no. 6, p. 1038-1052.

Jeletsky, J.A., 1960, Youngest marine rocks in western interior of North America and the age of the Triceratops beds: with remarks on comparable dinosaur-bearing beds outside North America: Inter. Geol. Cong., Rept. XXIst Sess. Norden, Pt. V, The Cretaceous-Tertiary boundary, Copenhagen, p. 25-40.

Jensen, F.S., and Varnes, H.D., 1964, Geology of the Fort Peck area, Garfield, McCone, and Valley Counties, Montana: U.S. Geol. Survey Prof. Paper 414-F, p. F1-F4.

Jepson, G.L., 1930, Stratigraphy and paleontology of the Paleocene of northeastern Park County, Wyoming: Am. Philos. Soc. Proc., v. 69, no. 7, p. 463-528.

Johnson, W.D., Jr., and Kunkel, R.P., 1959, The Square Buttes coal field, Oliver and Mercer Counties, North Dakota: U.S. Geol. Survey Bull. 1076, 91 p.

Kepferle, R.C., 1954, Selected deposits of strippable coal in central Rosebud County, Montana: U.S. Geol. Survey Bull. 995-I, p. 333-381.

Knowlton, F.H., 1909, The stratigraphic relations and paleontology of "Hell Creek Beds," "Ceratops beds" and equivalents, and their reference to the Fort Union Formation: Washington Acad. Sci. Proc., v. 11, p. 179-238.

__________1911, Further data on the stratigraphic position of the Lance Formation ("Ceratops beds"): Jour. Geol., v. 19, p. 358-376.

__________1914, Cretaceous-Tertiary boundary in the Rocky Mountain region: Geol. Soc. America Bull., v. 25, p. 325-340.

Kohout, F.A., 1957, Geology and groundwater resources of Kaycee Irrigation Project, Johnson County, Wyoming: U.S. Geol. Survey Water-Supply Paper 1360-E, p. 321-374.

Lee, W.T., 1927, Correlation of geologic formations between east-central Colorado, central Wyoming and southern Montana: U.S. Geol. Survey Prof. Paper 149, 79 p.

Leffingwell, H.A., 1970, Palynology of the Lance (Late Cretaceous) and Fort Union (Paleocene) Formations of the type Lance area, Wyoming, *in* Kosanke, R.M., and Cross, A.T., Symposium on palynology of the Late Cretaceous and early Tertiary, San Francisco, California, 1966: Geol. Soc. America Spec. Paper 127, p. 1-64.

Leonard, A.G., 1906, The North Dakota-Montana lignite area: U.S. Geol. Survey Bull. 285, p. 316-330.

__________1907, The coal fields of parts of Dawson, Rosebud, and Custer Counties, Montana: U.S. Geol. Survey Bull. 316-C, p. 194-211.

__________1908, Geology of southwestern North Dakota with special reference to coal: North Dakota Geol. Survey Bienn. Rept. 5, p. 27-114.

__________1911, The Cretaceous and Tertiary formations of western North Dakota and eastern Montana: Jour. Geology, v. 19, p. 507-547.

Leonard, A.G., Babcock, E.J., and Dove, L.P., 1925, The lignite deposits of North Dakota: North

Dakota Geol. Survey Bull. 4, 240 p.

Leonard, A.G., and Smith, C.D., 1909, The Sentinel Butte lignite field, North Dakota and Montana: U.S. Geol. Survey Bull. 341, p. 15-35.

Lindberg, M.L., 1944, Heavy mineral correlation of the Fox Hills, Hell Creek, and Cannonball sediments, Morton and Sioux Counties, North Dakota: Jour. Sed. Petrology, v. 14, p. 131-143.

Littleton, R.T., and Swenson, H.A., 1950, Ground-water conditions in the vicinity of Gillette, Wyoming: U.S. Geol. Survey Circ. 76, 43 p.

Lloyd, E.R., 1914, The Cannonball River lignite field, Morton, Adams, and Hettinger Counties, North Dakota: U.S. Geol. Survey Bull. 541, p. 243-291.

Lloyd, E.R., and Hares, C.J., 1915, The Cannonball marine member of the Lance formation of North and South Dakota and its bearing on the Lance-Laramie problem: Jour. Geology, v. 23, p. 523-547.

Love, J.D., 1960, Cenozoic sedimentation and crustal movement in Wyoming: Am. Jour. Sci., v. 258-A, p. 204-214.

Lowry, M.E., and Cummings, T.R., 1966, Ground-water resources of Sheridan County, Wyoming: U.S. Geol. Survey Water-Supply Paper 1807, 77 p.

Lupton, C.T., 1911, The eastern part of the Bull Mountain coal field, Montana: U.S. Geol. Survey Bull. 421, p. 163-189.

Mapel, W.J., 1954, Geology and coal resources of Lake DeSmet area, Johnson County, Wyoming: U.S. Geol. Survey Coal Inv. Map C 23, scale 1:48,000.

__________1958, Coal in the Powder River Basin, *in* Powder River Basin, 1958: Wyoming Geol. Assoc. Guidebook, 13th Ann. Field Conf., p. 218-224.

__________1959, Geology and coal resources of the Buffalo-Lake DeSmet area, Johnson and Sheridan Counties, Wyoming: U.S. Geol. Survey Bull. 1078, 148 p.

Mapel, W.J., Schopf, J.M., and Gill, J.R., 1953, A Thick coal bed near Lake DeSmet, Johnson County, Wyoming: U.S. Geol. Survey Circ. 228, p. 1-47.

Matson, R.E., 1970, Strippable coal resources, McCone County, Montana: Montana Bur. Mines and Geology Bull. 78, 13 p.

__________1971, Strippable coal in the Moorhead coal field, Montana: Montana Bur. Mines and Geology Bull. 83, 18 p.

Matson, R.E., and Blumer, J.W., Quality and reserves of strippable coal, selected deposits, southeastern Montana: Montana Bur. Mines and Geology Bull. 91, 135 p.

Matthew, W.D., 1914, Evidence of the Paleocene vertebrate fauna on the Cretaceous-Tertiary problem: Geol. Soc. America Bull., v. 25, p. 381-402.

May, P.R., 1954, Strippable lignite deposits, Wibaux area, Montana and North Dakota: U.S. Geol. Survey Bull. 995-G, p. 255-292.

McGrew, P.O., 1971, The Tertiary history of Wyoming: Wyoming Geol. Assoc. Guidebook, 23d Ann. Field Conf., p. 29-34.

Meek, F.B., 1876, A report on the invertebrate Cretaceous and Tertiary fossils of the upper Missouri country: U.S. Geol. Survey Terr. Rept., v. 9, 629 p.

Meek, F.B., and Hayden. F.V., 1862, Descriptions of new lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska..., with some remarks on the rocks from which they were obtained: Philadelphia Acad. Nat. Sci. Proc., 1861, v. 13, p. 415-435.

Miles, W.P., 1955, The geology of the Sumatra quadrangle, Montana: Montana School of Mines unpub. M.S. thesis.

Miller, H.W., Jr., 1960, Correlation of Paleocene and Eocene formations and Cretaceous-Paleocene boundary in New Jersey: Am. Assoc. Petroleum Geologists,v. 40, p. 722-736.

Miner, E.L., 1935, Cretaceous and Tertiary coals from Montana: Am. Midland Naturalist, v. 16, p. 616-621.

Moore, G.W., Melin, R.E., and Kepferle, R.C., 1959, Uranium-bearing lignite in southwestern North Dakota: U.S. Geol. Survey Bull. 1055-E.

Nace, R.L., 1936, Summary of the late Cretaceous and early Tertiary stratigraphy of Wyoming: Wyoming Geol. Survey Bull. 26, 271 p.

Newberry, J.S., 1868, Note on the later extinct floras of North America, with descriptions of some new species of fossil plants from the Cretaceous and Tertiary strata: Lyceum Nat. History New York Annals, v. 9, p. 1-76.

__________1890, The Laramie group: Geol. Soc. American Bull., v. 1, p. 524-532.

Norton, N.J., and Hall, J.W., 1967, Guide sporomorphae in the Upper Cretaceous-Lower Tertiary of eastern Montana (U.S.A.): Rev. Palaeobotany and Palynology, v. 2, p. 99-110, pl. 1.

Olive, W.W., 1953, The Spotted Horse coal field, Sheridan and Campbell Counties, Wyoming: Ph.D. dissert., Louisiana State Univ., Baton Rouge, 77 p.

__________1957, The Spotted Horse coal field, Sheridan and Campbell Counties, Wyoming: U.S. Geol. Survey Bull. 1050, p. 1-83.

Parker, F.S., 1936, The Richey-Lambert coal field, Richland and Dawson Counties, Montana: U.S. Geol. Survey Bull. 847-C, p. 121-174.

Parker, F.S., and Andrews, D.A., 1940, The Mizpah coal field, Custer County, Montana: U.S. Geol. Survey Bull. 906-C, p. 85-133.

Parsons, W.H., 1942, Origin and structure of the Livingston igneous rocks, Montana: Geol. Soc. America Bull., v. 53, no. 8, p. 1175-1185.

Perry, E.S., 1935, Geology and ground-water resources of southeastern Montana: Montana Bur. Mines and Geology Mem. 14, 67 p.

Pierce, W.G., 1936, The Rosebud coal field, Rosebud and Custer Counties, Montana: U.S. Geol. Survey Bull. 847, p. 43-120.

Prichard, G.E., and Landis, E.R., 1955, Geology of the northern part of the Girard coal field, Richland County, Montana: U.S. Geol. Survey Coal Inv. Map C-24.

Renick, B.C., 1929, Geology and ground-water resources of central and southern Rosebud County, Montana: U.S. Geol. Survey Water-Supply Paper 600, 140 p.

Richards, P.W., 1957, Geology of the area east and southeast of Livingston, Park County, Montana: U.S. Geol. Survey Bull. 1021-L, p. 381-438.

Richards, P.W., and Prichard, G.E., 1950, The Livingston formation: Billings Geol. Soc. Guidebook, 1st Ann. Field Conf., p. 49-55.

Richards, R.W., 1910, The central part of the Bull Mountain coal field, Montana: U.S. Geol. Survey Bull. 381-A, p. 60-81.

Roberts, A.E., 1963, The Livingston group of south-central Montana, *in* Geological Survey Research 1963: U.S. Geol. Survey Prof. Paper 475-B, p. B86-B92.

__________1965, Correlation of Cretaceous and lower Tertiary rocks near Livingston, Montana, with those in other areas of Montana and Wyoming, *in* Geological Survey Research 1965: U.S. Geol. Survey Prof. Paper 525-B, p. B54-B63.

__________1972, Cretaceous and early Tertiary depositional and tectonic history of the Livingston area, southwestern Montana: U.S. Geol. Survey Prof. Paper 526-C, p. C1-C120.

Robinson, C.S., Mapel, W.J., and Bergendahl, M.H., 1964, Stratigraphy and structure of the northern and western flanks of the Black Hills uplift, Wyoming, Montana, and South Dakota: U.S. Geol. Survey Prof. Paper 404, 134 p.

Roehler, H.W., 1961, The late Cretaceous-Tertiary boundary in the Rock Springs uplift, Sweetwater County, Wyoming, *in* Symposium on late Cretaceous rocks, Wyoming and adjacent areas, 1961: Wyoming Geol. Assoc. Guidebook, 16th Ann. Field Conf., p. 96-100.

Rogers, G.S., 1913, The Little Sheep Mountain coal field, Dawson, Custer, and Rosebud Counties, Montana: U.S. Geol. Survey Bull. 531-F, p. 159-227.

__________1914, Geology of coal resources of the area southwest of Custer, Yellowstone, and Big Horn Counties, Montana: U.S. Geol. Survey Bull. 541-H, p. 316-328.

Rogers, G.S., and Lee, Wallace, 1923, Geology of the Tullock Creek coal field, Rosebud and Big Horn Counties, Montana: U.S. Geol. Survey Bull. 749, 181 p.

Royse, C.F., Jr., 1967, Tongue River-Sentinel Butte contact: North Dakota Geol. Survey Rept. Inv. 45, 53 p.

__________1970, A sedimentological analysis of the Tongue River-Sentinel Butte interval (Paleocene) of the Williston Basin, western North Dakota: Sed. Geology, v. 4, p. 19-80.

Russell, L.S., 1932a, The Cretaceous-Tertiary transition of Alberta: Royal Soc. Canada Trans., 3d ser., v. 26, sec. 4, p. 121-156.

__________1932b, New data on the Paleocene mammals of Alberta, Canada: Jour. Mammalogy, v. 13, no. 1, p. 48-54.

__________1950, Correlation of the Cretaceous-Tertiary transition in Saskatchewan and Alberta: Geol. Soc. America Bull., v. 61, no. 1, p. 27-42.

__________1953, Tertiary stratigraphy of southwestern Saskatchewan: Billings Geol. Soc. Guidebook, 4th Ann. Field Conf., p. 106-113.

Rutherford, R.L., 1947, The Cretaceous-Tertiary boundary in the foothills of central Alberta: Royal Soc. Canada Trans., v. 41, 3d ser., sec. 4, p. 47-59.

Sandberg, C.A., 1962, Geology of the Williston Basin, North Dakota, Montana, and South Dakota, with reference to subsurface disposal of radioactive wastes: U.S. Geol. Survey Rept. TEI-809, 148 p.

Schuchert, Charles, 1921, Are the Lance and Fort Union formations of Mesozoic time?: Science, v. 53, p. 45-47.

Sharp, R.P., 1948, Early Tertiary fanglomerate, Bighorn Mountains, Wyoming: Jour. Geology, v. 56, p. 1-15.

Sharp, W.N., and others, 1964, Geology and uranium deposits of the Pumpkin Buttes area of the Powder River Basin: U.S. Geol. Survey Bull. 1107, p. 541-638.

Shurr, G.W., 1972, Paleocurrent indicators in Tongue River sandstones of the Bull Mountain syncline, Montana: Montana Geol. Soc., 21st Ann. Field Conf., p. 107-111.

Simpson, G.G., 1928, A new mammalian fauna from the Fort Union of southern Montana: Am. Mus. Novitates, no. 297, 15 p.

__________ 1929, Third contribution to the Fort Union fauna at Bear Creek, Montana: Am. Mus. Novitates, no. 345, 12 p.

__________ 1937, The Fort Union of the Crazy Mountain field, Montana, and its mammalian faunas: U.S. Natl. Mus. Bull. 169, 287 p.

Smith, C.D., 1909, The Fort Peck Indian Reservation lignite field, Montana: U.S. Geol. Survey Bull. 381-A, p. 40-59.

Smith, J.H., 1961, A summary of stratigraphy and paleontology upper Colorado and Montanan groups, southcentral Wyoming, northeastern Utah, and northwestern Colorado, *in* Symposium on Late Cretaceous rocks of Wyoming, 1961: Wyoming Geol. Assoc. Guidebook, 16th Ann. Field Conf., p. 101-112.

__________ 1965, A summary of stratigraphy and paleontology upper Colorado and Montanan groups, southcentral Wyoming, northeastern Utah, and northwestern Colorado, *in* Sedimentation of late Cretaceous and Tertiary outcrops, Rock Springs uplift, 1965: Wyoming Geol. Assoc. Guidebook, 19th Ann. Field Conf., p. 13-26.

Snead, R.G., 1969, Microfloral diagnosis of the Cretaceous-Tertiary boundary, central Alberta: Research Council Alberta Bull. 25, 148 p.

Stanley, E.A., 1965, Upper Cretaceous and Paleocene plant microfossils and Paleocene dinoflagellates and hystrichosphaerids from northwestern South Dakota: Am. Paleont. Bull., v. 49, no. 222, 384 p.

Stanton, T.W., 1909, The age and stratigraphic relations of the "Ceratops beds" of Wyoming and Montana: Washington Acad. Sci. Proc., v. 11, p. 239-293.

__________ 1910, Fox Hills sandstone and Lance Formation ("Ceratops beds") in South Dakota, North Dakota and eastern Wyoming: Am. Jour. Sci., v. 30, p. 172-188.

__________ 1914, Boundary between Cretaceous and Tertiary in North America as indicated by stratigraphy and invertebrate faunas: Geol. Soc. America Bull., v. 25, p. 341-354.

__________ 1921, The fauna of the Cannonball marine member of the Lance formation: U.S. Geol. Survey Prof. Paper 128, p. 1-60.

Stanton, T.W., Hatcher, J.B., and Knowlton, F.H., 1905, Geology and paleontology of the Judith River beds: U.S. Geol. Survey Bull. 257, 128 p.

Stanton, T.W., and Knowlton, F.H., 1897, Stratigraphy and paleontology of the Laramie and related formations in Wyoming: Geol. Soc. America Bull., v. 8, p. 127-156.

Stebinger, Eugene, 1912, The Sidney lignite field, Dawson County, Montana: U.S. Geol. Survey Bull. 471-D, p. 284-318.

Stephenson, L.W., and Reeside, J.B., Jr., 1938, Comparison of Upper Cretaceous deposits of the Gulf region and western interior region: Am. Assoc. Petroleum Geologists Bull., v. 22, no. 12, p. 1629-1638.

Stone, R.W., 1909, Coal near the Crazy Mountains, Montana: U.S. Geol. Survey Bull. 341-A, p. 78-91.

__________ 1912, Coal near the Black Hills, Wyoming-South Dakota: U.S. Geol. Survey Bull. 499, 66 p; [abs.] Washington Acad. Sci. Jour., v. 2, no. 15, p. 389-390.

Stone, R.W., and Calvert, W.R., 1910, Stratigraphic relations of the Livingston formation of Montana: Econ. Geology, v. 5, p. 551-557, 652-669, 741-764.

Stone, R.W., and Lupton, C.T., 1910, The Powder River coal field, Wyoming, adjacent to the Burlington Railroad: U.S. Geol. Survey Bull. 381, p. 115-136

Stow, M.H., 1938, Dating Cretaceous-Eocene tectonic movements in the Big Horn Basin by heavy minerals: Geol. Soc. America Bull., v. 49, no. 5, p. 731-762.

__________ 1947, Results of some heavy mineral studies in the Bighorn Basin, Montana and Wyoming: Wyoming Geol. Assoc. and Yellowstone-Bighorn Research Assoc. Guidebook, 2d Ann. Field Conf., 1947, p. 150-164.

Swenson, F.A., 1955, Geology and ground-water resources of the Missouri River valley in northeastern Montana *with a section on* The quality of the ground water, by W.H. Durum: U.S. Geol. Survey Water-Supply Paper 1263, 128 p. [1956].

Taff, J.A., 1909, The Sheridan coal field: U.S. Geol. Survey Bull. 341, p. 123-150.

Ting, F.T.C., ed., 1972, Depositional environments of the lignite-bearing strata in western North Dakota: North Dakota Geol. Survey Misc. Series 50.

Thom, W.T., Jr., 1928, The Minturn district and the northwestern part of the Gillette field: U.S. Geol. Survey Bull. 796, pl 50-64.

Thom, W.T., and Dobbin, C.E., 1924, Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas: Geol. Soc. America Bull., v. 35, p. 481-505.

Thom, W.T., Jr., Hall, G.M., Wegemann, C.H., and Moulton, C.F., 1935, Geology of Big Horn County and the Crow Indian Reservation, Montana; with special reference to the water, coal, oil, and gas resources: U.S. Geol. Survey Bull. 856, 200 p.

Torrey, A.E., and Kohout, F.A., 1956, Geology and ground-water resources of the lower Yellowstone River valley between Glendive and Sidney, Montana, *with a section on* Chemical quality of the water, by H.A. Swenson: U.S. Geol. Survey Water-Supply Paper 1355, 92 p.

Townsend, R.C., 1950, Deformation of Fort Union formation near Lignite, North Dakota: Am. Assoc. Petroleum Geologists Bull., v. 34, no. 7, p. 1552-1564.

Tozer, E.T., 1953, The Cretaceous-Tertiary transition in southwestern Alberta: Alberta Soc. Petroleum Geologists, 3d Ann. Field Conf. and Symposium, p. 23-32.

Tracey, J.I., and Oriel, S.S., 1959, Uppermost Cretaceous and lower Tertiary rocks of the Fossil Basin, Intermountain Assoc. Petroleum Geologists Guidebook, p. 126-130.

Tromp, S.W., 1949, The determination of the Cretaceous-Eocene boundary by means of quantitative, generic, micro-faunal determinations and the conception "Danian" in the Near East: Jour. Paleontology, v. 23, p. 673-676.

Troyer, M.L., and others, 1954, Summary of investigations of uranium deposits in the Pumpkin Buttes area, Johnson and Campbell Counties, Wyoming: U.S. Geol. Survey Circ. 338, 17 p.

Tschudy, R.H., 1970, Palynology of the Cretaceous-Tertiary boundary in the northern Rocky Mountains and Mississippi Embayment regions, *in* Symposium on Palynology of the Late Cretaceous and Early Tertiary, San Francisco, California, 1966: Geol. Soc. America Spec. Pub. 127, p. 65-111.

Tudor, M.S., 1975, Geologic exploration and development of coal in the Sarpy Creek area, Big Horn County, Montana: Montana Geol. Soc. Guidebook, Ann. Field Conf., "Energy Resources in Montana", p. 159-164.

Van Houten, F.B., 1954a, Early Cenozoic facies in the Rocky Mountain region: Science, v. 101, no. 2626, p. 430-431.

__________1945b, Review of the latest Paleocene and early Eocene mammalian fauncas: Jour. Paleontology, v. 19, no. 5, p. 421-461.

Waage, K.M., 1961, The Fox Hills formation in its type area, central South Dakota, *in* Symposium on Late Cretaceous rocks, Wyoming and adjacent areas: Wyoming Geol. Soc. Guidebook, 16th Ann. Field Conf., p. 229-240.

Warner, D.A., 1946, Geology and ground-water resources of the Ranchester area, Wyoming: Wyoming Geol. Survey open file, 11 p.

Warren, W.C., 1959, Reconnaissance geology of the Birney-Broadus coal field, Rosebud and Powder River Counties, Montana: U.S. Geol. Survey Bull. 1072-J, p. 561-585.

Weed, W.H., 1893, The Laramie and the overlying Livingston formation in Montana, with report on flora by F.H. Knowlton: U.S. Geol. Survey Bull. 105, 68 p.

Wegemann, C.H., 1910, Notes on the coals of the Custer National Forest, Montana: U.S. Geol. Survey Bull, 381-A, p. 108-114.

__________1917, Wasatch fossils in so-called Fort Union beds of the Powder River Basin, Wyoming, and their bearing on the stratigraphy of the region: U.S. Geol. Survey Prof. Paper 108, p. 57-60.

__________1929, The Pumpkin Buttes coal field, Wyoming: U.S. Geol. Survey Bull. 806, p. 1-14.

Wilson, R.A., and Rowe, J.P., 1915, The Bull Mountain coal field: Colliery, England, v. 36, p. 7-11.

Wilson, L.R., 1945, Application of paleoecological method to an early Tertiary coal seam [abs]: Geol. Soc. America Bull., v. 56, no. 12, pt. 2, p. 1212.

Wilson, L.R., and Webster, R.M., 1946, Plant microfossil in a Fort Union coal of Montana: Am. Jour. Botany, v. 33, no. 4, p. 271-278.

Winchester, D.E., Hares, C.J., Lloyd, E.R., and Parks, E.M., 1916, The lignite field of northwestern South Dakota: U.S. Geol. Survey Bull. 627, 169 p.

Wolfe, J.A., and Hopkins, D.M., 1967, Climatic changes recorded by Tertiary land floras in northwestern North America, *in* Tertiary correlations and climatic changes in the Pacific--Pacific Sci. Cong., 11th, Tokyo, 1966, Symposium No. 25: Sasaki Printing and Publishing Co., Sendai, Japan, p. 67-76.

Wood, H.E., and others, 1941, Nomenclature and correlation of the North American continental Tertiary: Geol. Soc. America Bull., v. 52, no. 1, p. 1-48.

Woolsey, L.H., 1909, The Bull Mountain coal field, Montana: U.S. Geol. Survey Bull, 341-A, p. 62-77.

Woolsey, L.H., Richards, R.W., and Lupton, C.T., 1917, The Bull Mountain coal field: U.S. Geol. Survey Bull. 647, 218 p.

Yen, T.C., 1946, Paleocene freshwater mollusks from Sheridan County, Wyoming: Am. Jour. Sci., v. 244, no. 1, p. 31-48.

__________1948, Paleocene fresh-water mollusks from southern Montana: U.S. Geol. Survey Prof. Paper 214, p. 35-50.

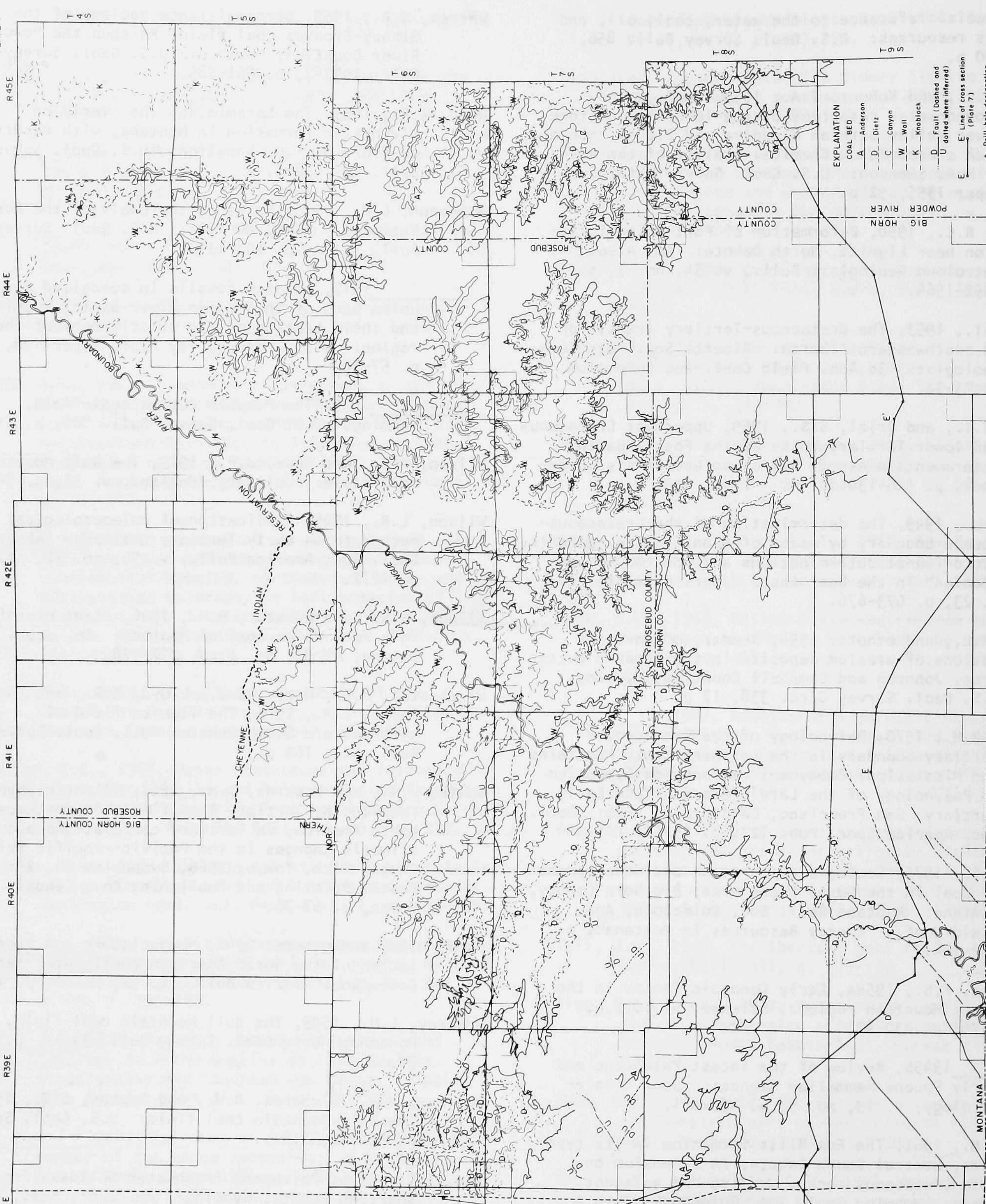


Plate 1. Outcrops of the major coal beds, southeastern Montana.

PLATE 2

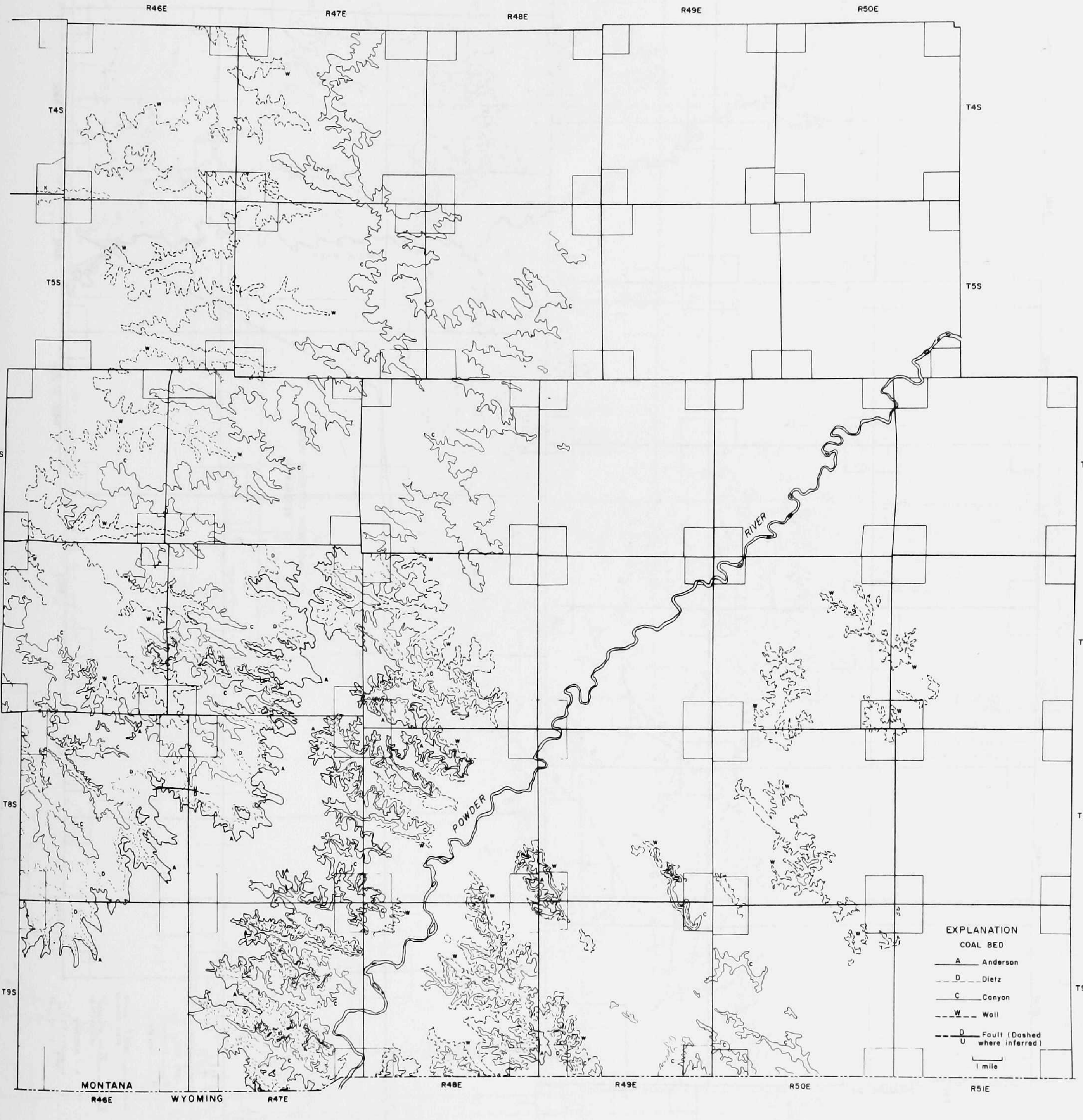


Plate 2. Outcrops of the major coal beds, southeastern Montana.

PLATE 3

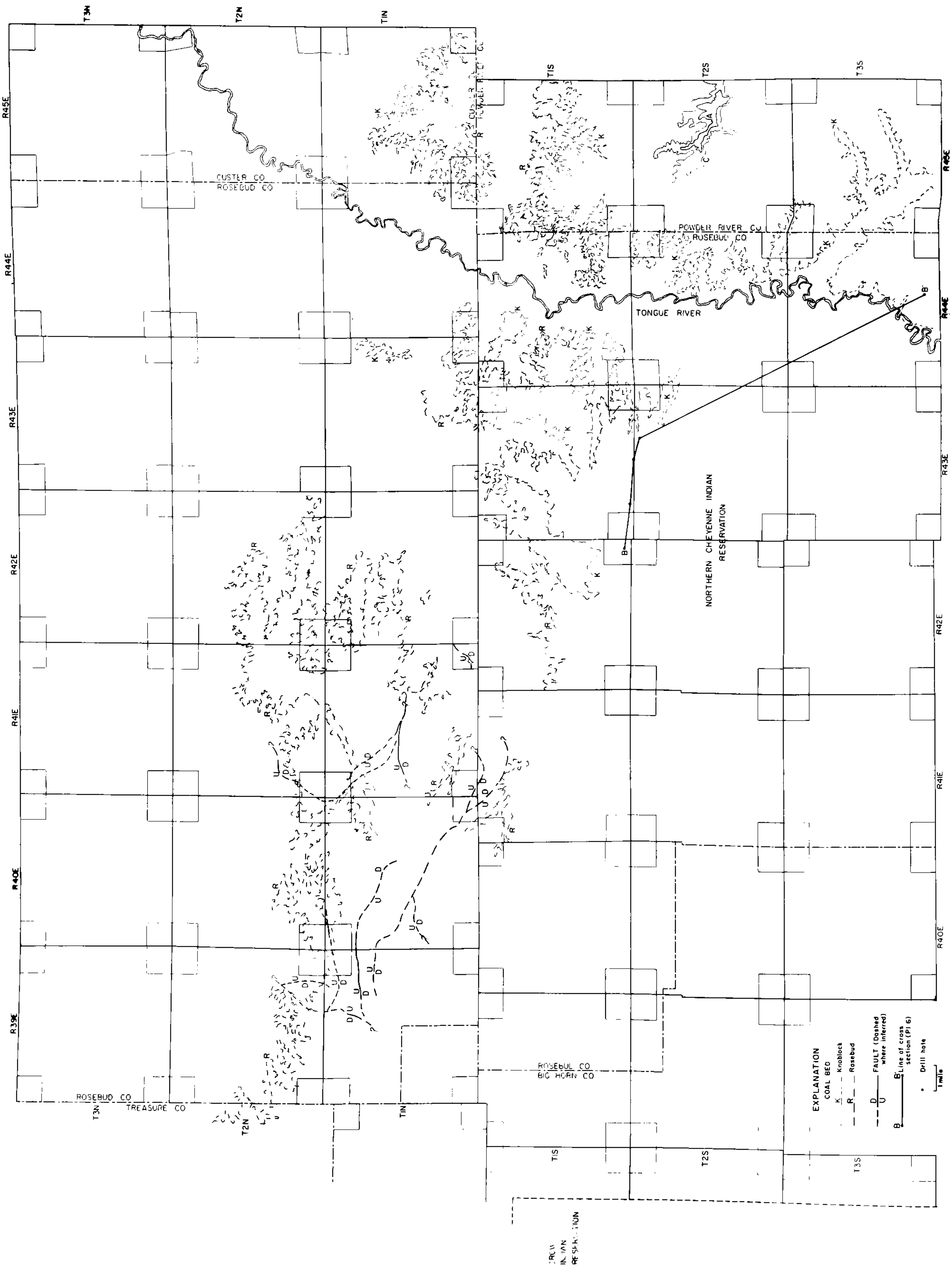
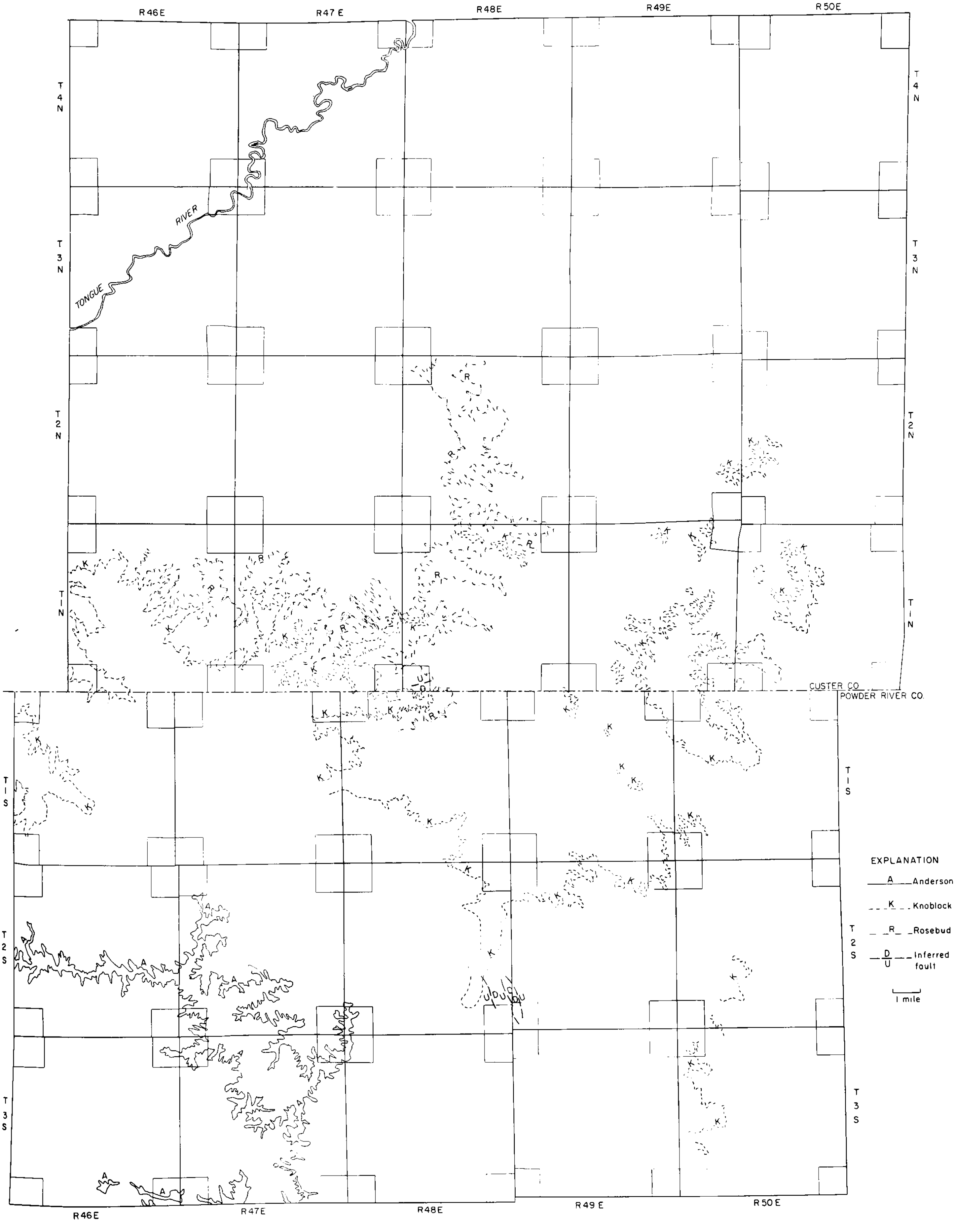


Plate 3. Outcrops of the major coal beds, southeastern Montana.



rops of the major coal beds, southeastern Montana.

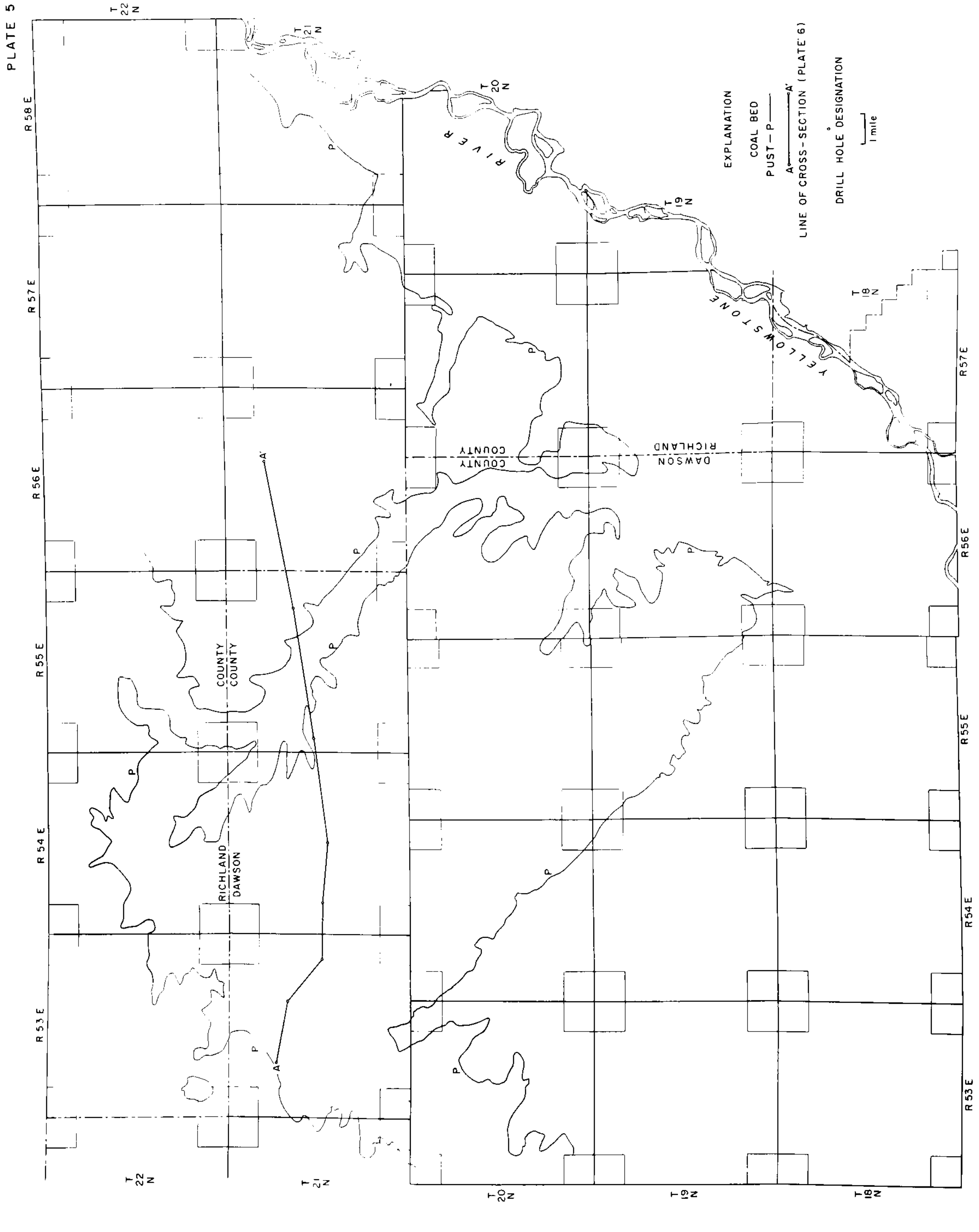


Plate 5. Outcrop of Pust coal bed, eastern Montana.

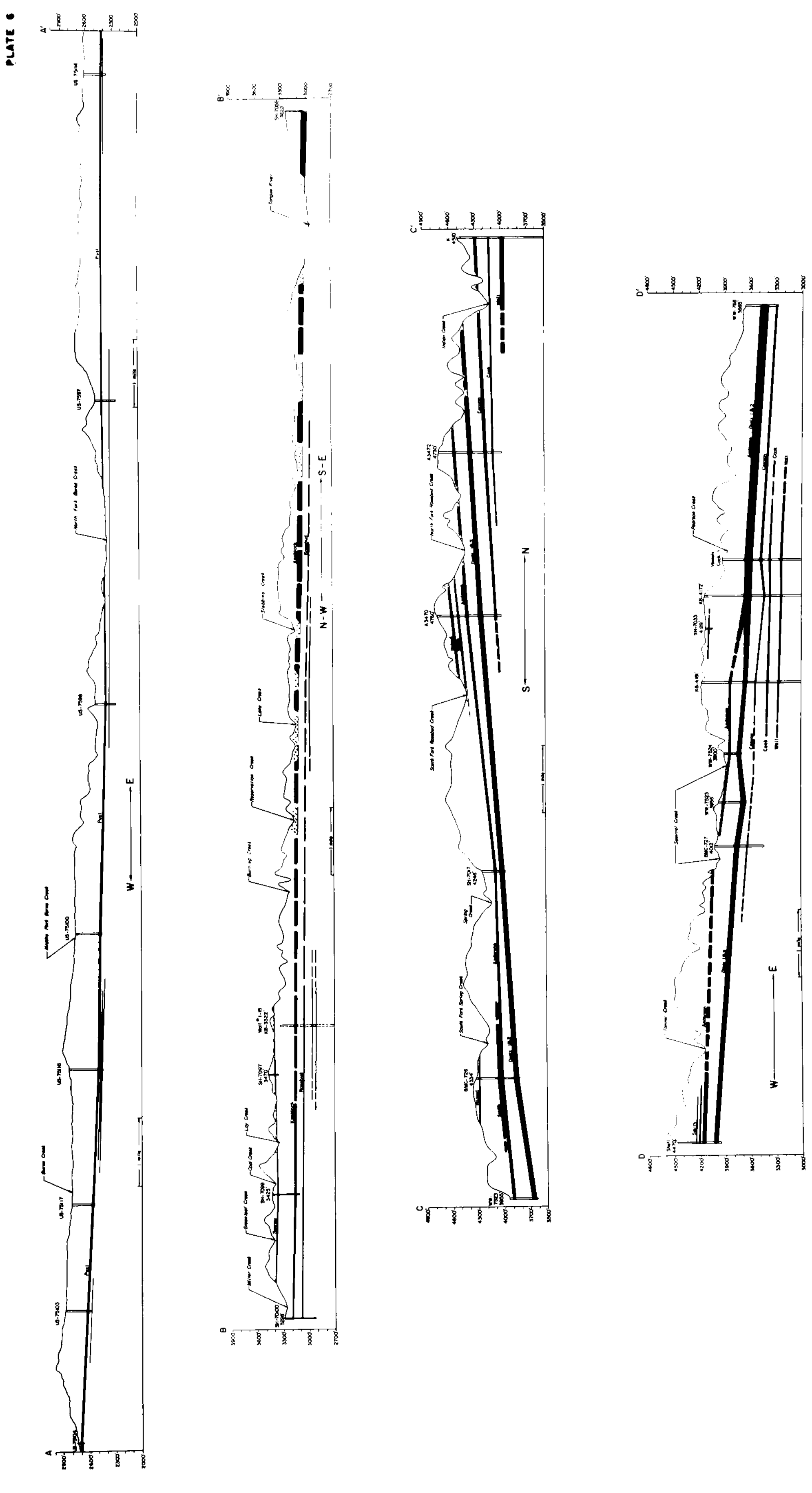


Plate 6. Regional cross-sections showing structure and correlation, Tongue River Member, Fort Union Formation.

PLATE 7

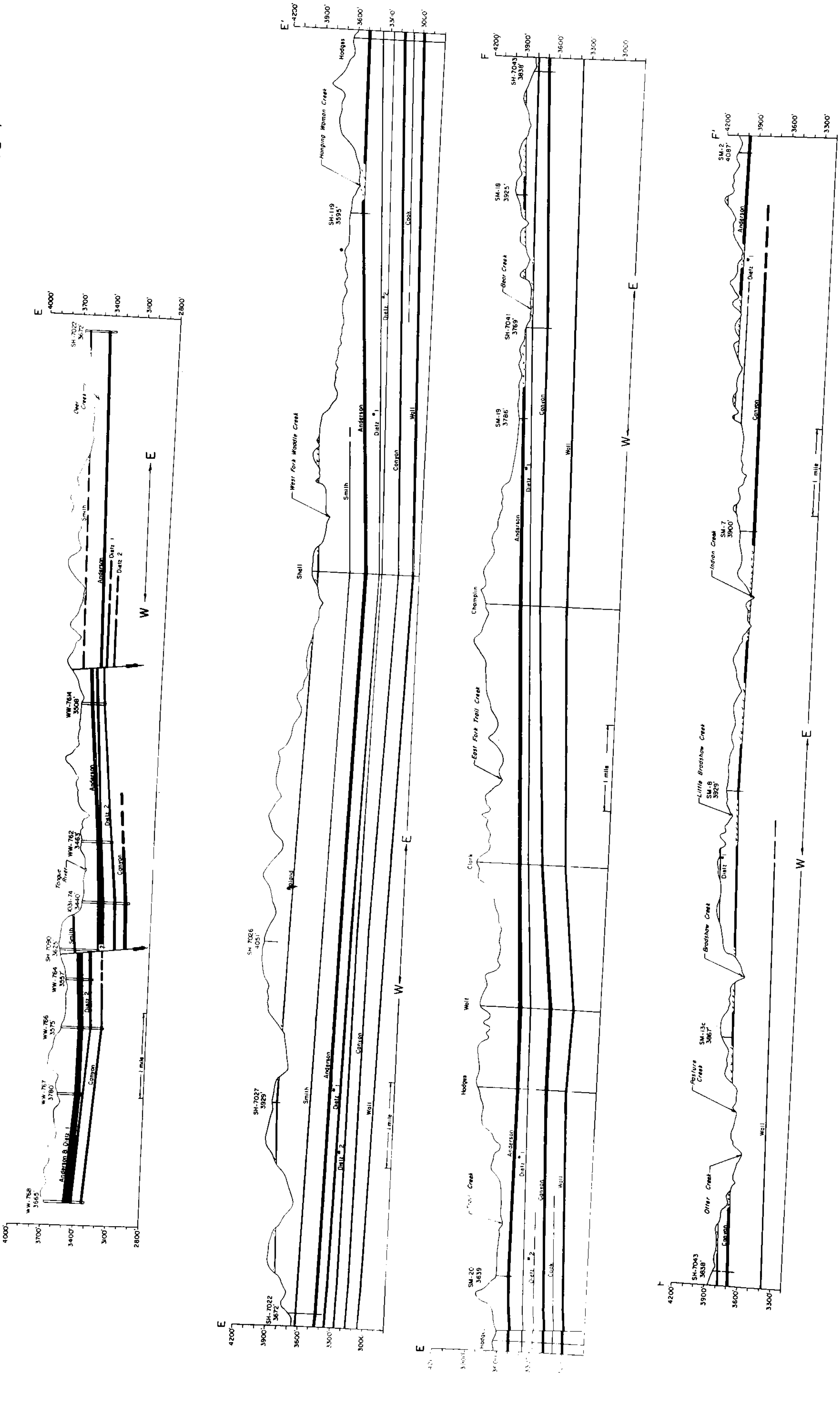


Plate 7. Regional cross-sections showing structure and correlation, Tongue River Member, Fort Union Formation.

GEOPHYSICAL LOGGING OF COAL

DONALD G. DAVIS: Scientific Software Corporation

Denver, Colorado 80202

ABSTRACT: Although computational procedures are available today for the in-situ evaluation of coal, including Btu and ash content, the borehole logs required are not often available in the calibrated form or suites required. The exploration for coal can be enhanced considerably by using the logs available in the well-log libraries if certain fundamental geophysical parameters are considered and the effects of coal compared to other rocks or minerals as seen by the logging tools are understood. This discussion will primarily deal with this latter aspect of geophysical (borehole) measurements.

INTRODUCTION

The accumulation of data recorded by logging instruments in the borehole has been going on for over 30 yr in the Rocky Mountain region. These logs have primarily been recorded for the purpose of petroleum exploration and exploitation. The result, however, has provided a library of data in the form of curve traces that may be used to identify coal seams, and, in some cases, to evaluate the quality of the coal with regard to moisture, ash and sulfur content as well as Btu level on an in-situ basis.

Although simple "rules of thumb" are desirable in any data research project, they generally are plagued by exceptions. Techniques for coal identification definitely fall into this category. General "rules of thumb" are helpful and quite useful if a full understanding of the exceptions are applied.

This paper deals with a study of the effects of coal on various logging or borehole geophysical measurements, including a study of coal bed thickness.

The geophysical measurements to be studied are:

1. Spontaneous potential
2. Resistivity
3. Conductivity
4. Acoustic transit time
5. Bulk density
6. Neutron porosity index

EARLY WELL LOGS

The earliest type of logging device likely to be encountered in any log library is the electrical log. This log consists of a set of measurements recorded as continuous analog traces vs. depth. This log, commonly referred to as the ES log, generally contained the following curve traces:

Spontaneous Potential, or SP
Short Normal - AM = 16"
Long Normal - AM = 64"
Lateral - AO = 18'8"

The SP curve can be quite misleading in that an anomaly or excursion to the left of the base, or shale, line may or may not occur with coal beds. Thus, it is not a reliable indicator of the presence of coal.

Any coal seam is a poor conductor of electric current; thus, high resistivity values are to be expected from resistivity measuring devices. A normal resistivity device, as referred to above, will respond

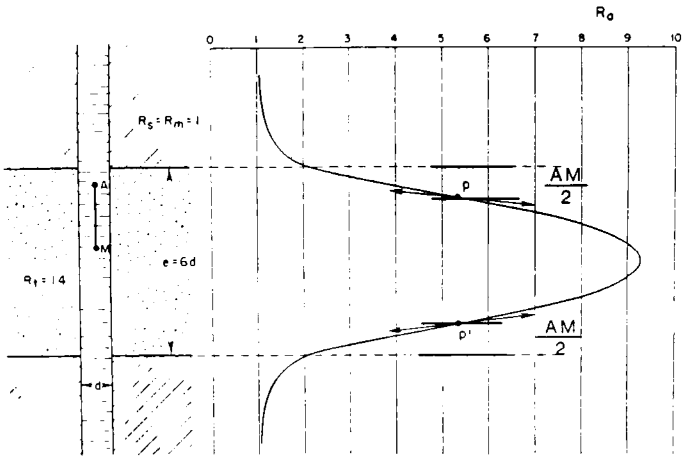


Fig. 1. Response of the normal resistivity device opposite a bed *thicker* than the AM (electrode) spacing (Schlumberger Well Services, 1950).

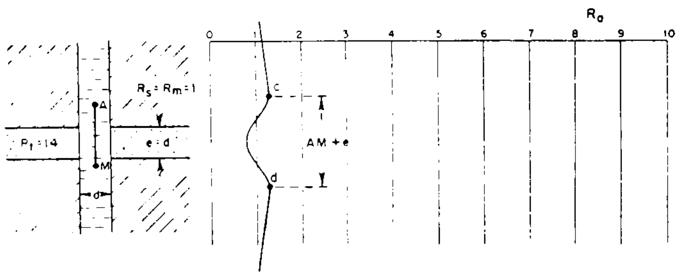


Fig. 2. Response of the normal resistivity device opposite a bed *thinner* than the AM (electrode) spacing (Tixier and Alger, no date).

as shown on Figure 1 if the bed is thicker than the AM spacing (Schlumberger, 1950). If the seam is thin, the effect will show up as indicated on Figure 2 (Tixier and Alger, no date). Consider a coal bed thicker than 16 in. but thinner than 64 in. The short normal will appear as on Figure 1, while the long normal will look like Figure 2.

Also note that the inflection points as shown on Figure 1 are actually one-half the AM spacing inside the bed boundaries; that is, the bed is thicker than the distance between the inflection points by the full AM spacing. In the case of Figure 1, this would amount to adding 16 in. to the bed thickness. In the case of a thicker bed and use of the long normal as a coal bed delineator, the thickness would be underestimated by 64 in., or over 5 ft.

The lateral curve is unique in that it is non-symmetrical with regard to its shape. Should a coal bed be thinner than the spacing of the lateral instrument (18'8"), which is quite likely here in the Rockies, it would exhibit an appearance as noted on Figure 3 (Schlumberger, 1950). Note that the resistivity anomaly is displaced downward, with the peak near the bottom of the bed, and that a "blind" or low reading zone followed by a smaller false peak occurs immediately below the resistive bed--possibly a coal bed. A composite of these curves is shown on Figure 4 (Tixier and Alger, no date).

Our first exception to a "rule of thumb" is now encountered. These coal beds would appear the same if they were tight limestone or sandstone stringers, or thin beds. Their appearance simply means that they do not contain large amounts of water and that they contain little shale. Other log data must be examined before the presence of coal can be established as a certainty. However, nearby core control that establishes that these beds are coal could lead to using these logs on a correlation and thus "most likely" basis of coal identification.

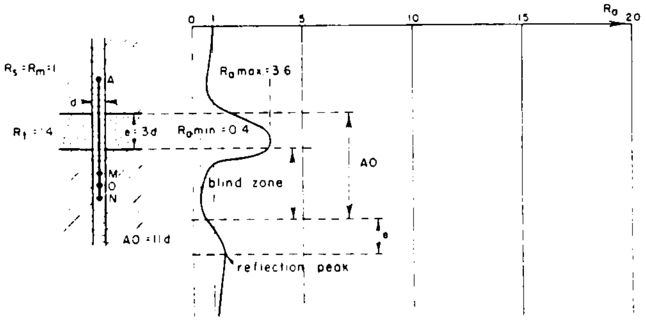
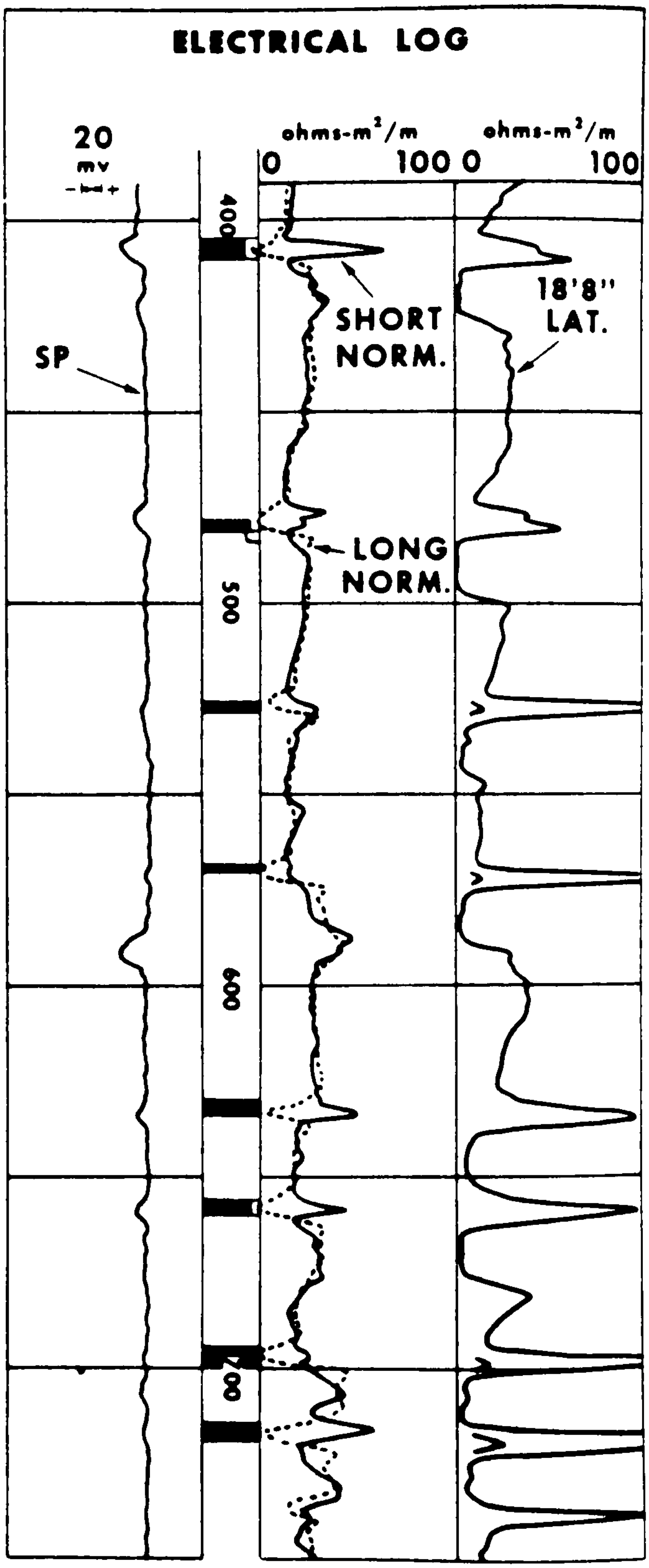


Fig. 3. Response of the lateral resistivity curve opposite a bed *thinner* than the AO (electrode) spacing (Schlumberger Well Services, 1950).

Fig. 4. Responses of short normal, long normal, and lateral curves opposite coal beds on typical electrical log (Tixier and Alger, no date). →



LATEROLOG OR FOCUSED LOG

This was the next commonly used tool on the logging scene. It is often confused with the lateral device discussed above because of the similarity of names, but it is nothing like it. The laterolog employs a technique that forces the current horizontally and thus overcomes many borehole and side-bed distortions. It is a symmetrical device and the inflection points truly represent bed boundaries. But remember, it is also a resistivity device and may react to limestone or sandstone beds as described above.

INDUCTION LOG

This is a conductivity measuring device. Its purpose is the same as the previously mentioned devices; that is, to determine the current-carrying capability of the formations. It works on an entirely different principle than previously described devices but its appearance is the same. Bed thicknesses are measured at the half-way (inflection) point on the conductivity curve. The same limitations of lithology apply with this device as with those described above.

GAMMA RAY LOG

Coal exhibits a low radioactivity level in nearly all cases in the Rockies. The level of natural radiation is in the range of 20 API units, depending on mud weight, hole size, and how the tool is positioned in the hole (i.e., centered or excentered). This is about the same value that a limestone bed would exhibit. However, high concentration of uranium may occur, resulting in high gamma ray readings in certain conditions since carbon actively reduces hexavalent uranium bearing salts in solution to an insoluble tetravalent salt (Tixier and Alger, no date). The lignite found in the Black Hills is an example of this "thumb rule" exception.

SONIC OR ACOUSTIC LOG

Coal beds are extremely poor transmitters of acoustical energy in terms of velocity of transit time. This transit time varies with the type of coal and burial depth of the bed. Coal beds in the Mesaverde Group in southwestern Wyoming show a typical value of about 125 microseconds per ft. This is indicated on Figure 5 (Tixier and Alger, no date). The log responses of several devices opposite coal beds in a well located in Colorado are depicted on Figure 6 (Tixier and Alger, no date). Although these coals are subbituminous A in rank, they exhibit lower values of Δt than expected for their rank because of their depth, 7500-7700 ft. Lignite amd subbituminous coals found at shallow depths in southern Colorado might easily show a value of 140 microseconds per ft. Table 1 provides a range of transit times for various coals.

DENSITY LOG

Densities of coal range from as low as 0.7 gm/cc for some lignites to 1.8 gm/cc for anthracite. Again, Table 1 shows ranges for various coal types. Figure 5 shows a value of 1.45 in a Wyoming well.

One caution should be noted here. The standard "oil field" density tool is very poorly calibrated to measure bulk densities of rocks less than 2 gm/cc. Oftentimes, a back-up curve trace for values lower than 2 gm/cc is not even recorded. A disappearance of the curve to the left might well be interpreted as an indication of coal, other indicators confirming. It is possible to obtain density recordings that are accurate below the 2 gm/cc level if prior notice is given to most logging companies so that proper calibrations may be made.

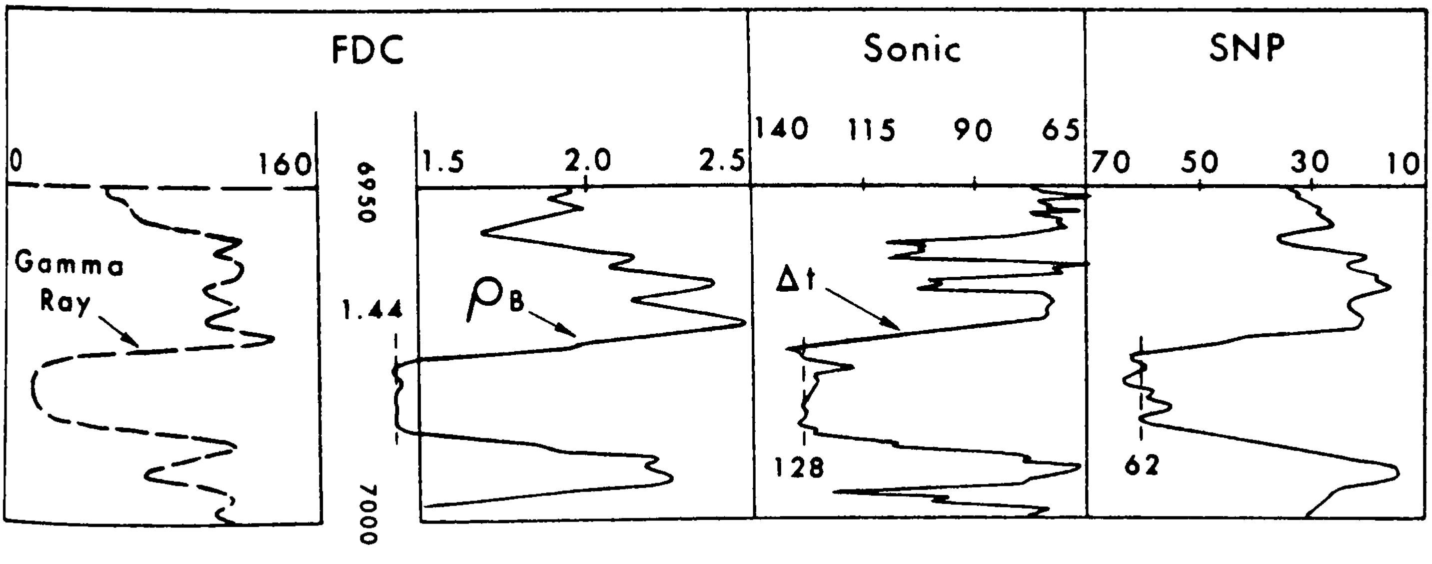


Fig. 5. Responses of formation density, sonic, and sidewall-neutron porosity logs opposite a coal bed in the Mesaverde Group (Upper Cretaceous), southwestern Wyoming (Tixier and Alger, no date).

TABLE 1

LOG TYPE	LIGNITE	BITUMINOUS	ANTHRACITE
Gamma Ray (API Units)[1]	Low 20-25	Low 20-25	Low 20-25
Resistivity (ohm-m)[2]	High 50-2000	High 50-2000	High 50-2000
Transit Time (Microseconds/ft)[3]	130-150	110-140	120 or less
Density (gms/cc)[4]	0.7-1.5	1.2-1.5	1.4-1.8
Neutron (Porosity Index)	Very High 55-70	Very High 55-70	Very High 55-70

[1]Except where uraniferous salts occur (Black Hills)
[2]Varies with moisture
[3]Varies with burial depth
[4]Varies with ash content

Modern logging suites with tools properly calibrated for the range of data expected, coupled with mathematical models and correlation fits to assay values, can lead to accurate evaluations of ash, moisture, and sulfur content and Btu rating of the coal beds under study. In addition, mechanical parameters concerning rock strengths may be calculated to determine fall points and pillar size as assists to good underground mine design. Obviously, these more sophisticated concepts require the application of computer techniques.

NEUTRON LOG

This type of logging device in all its "mutatio and variations is primarily a counter of hydrogen atoms and coal is rich in hydrogen. Thus, a porosity index of over 50 percent is typical. Again, referring to Figure 5, a value of 62 percent is shown on this southwestern Wyoming well.

NOTABLE EXCEPTIONS

The porosity tools listed above all exhibit recordings that would lead to high porosity calculations

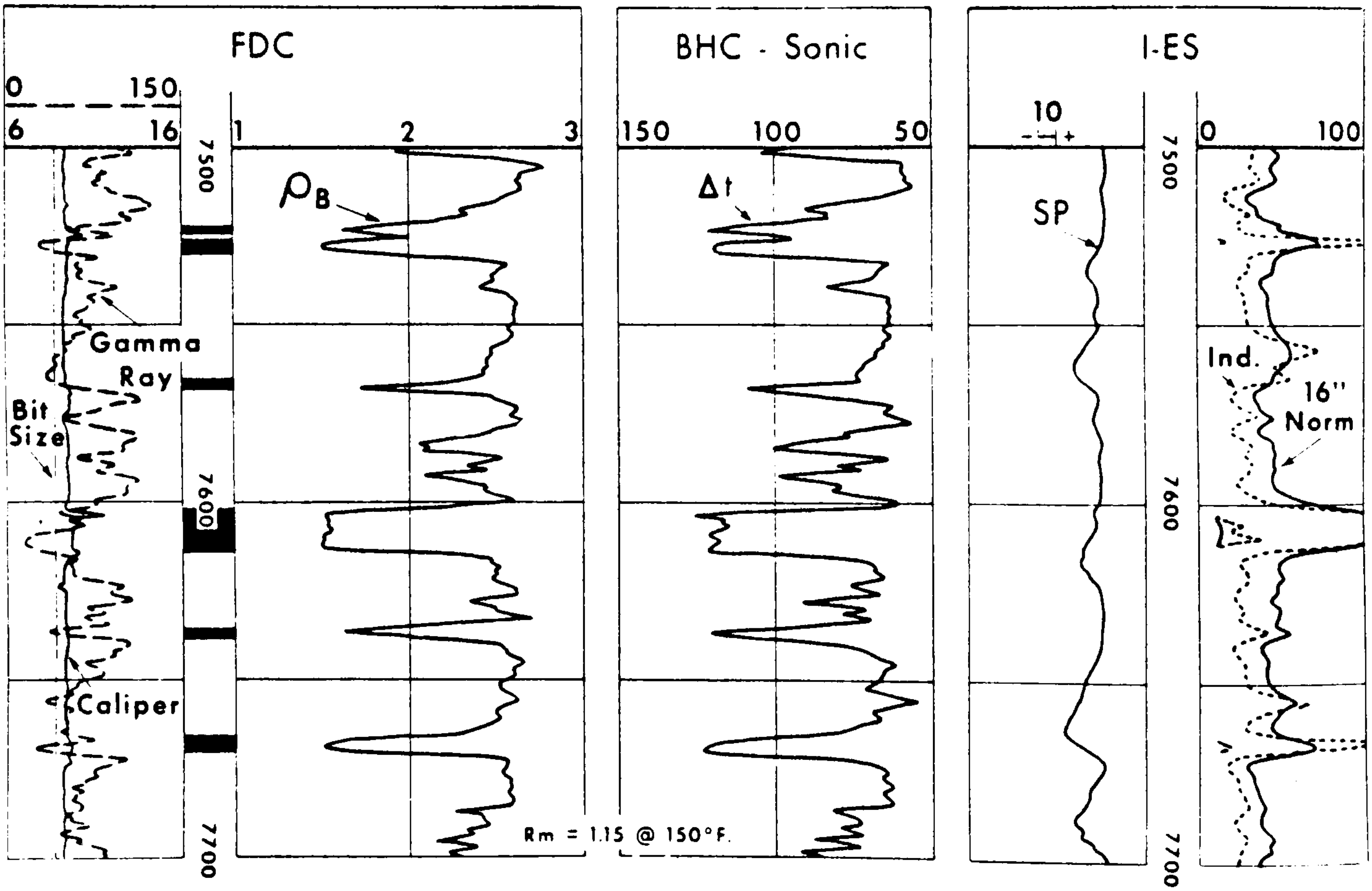


Fig. 6. Responses of formation density, sonic, and resistivity logs in a Colorado well; coal beds are shaded black (Tixier and Alger, no date)

from the recorded values. Unfortunately, coal is not the only rock that gives such high readings. Others in the Rockies are:

- Shales - The apparent porosity level is high only on the sonic and neutron logs, and not nearly so high as coal, even on these logs.
- Bentonite - Long transit times, low densities, high neutron porosity index, but low resistivity.
- Kerogen - Basically the same or greater effects on the porosity devices as soft coal; density values can be as low as 0.95 gm/cc for a pure kerogen bed. However, it seldom is found in pure form; thus, oil shale ore of high grade may indeed appear as a coal bed. After all, oil shale contains solid hydrocarbons.
- Washouts - These effect the contact devices--density logs and sidewall neutron logs--the most. A hole caliper is a great help in these cases. Coals often will tend to cave or show an increase in hole size, particularly toward the bottom of the bed. Large-diameter washouts are rare opposite coal beds.

CONCLUSIONS

Coal beds definitely can be identified by combining the proper logging suite and some knowledge of the geological sequence being studied.

A low gamma ray reading, a very high porosity reading on the 3 so-called porosity tools--acoustic, density or neutron--and a high resistivity reading undoubtedly are reflecting the presence of coal or kerogen. A knowledge of the geological and geographical position of the hole can usually determine the type of bed encountered.

Once positive coal identifications are established, correlations may be made with other wells where comprehensive data may be limited, thus adding to the store of exploration control.

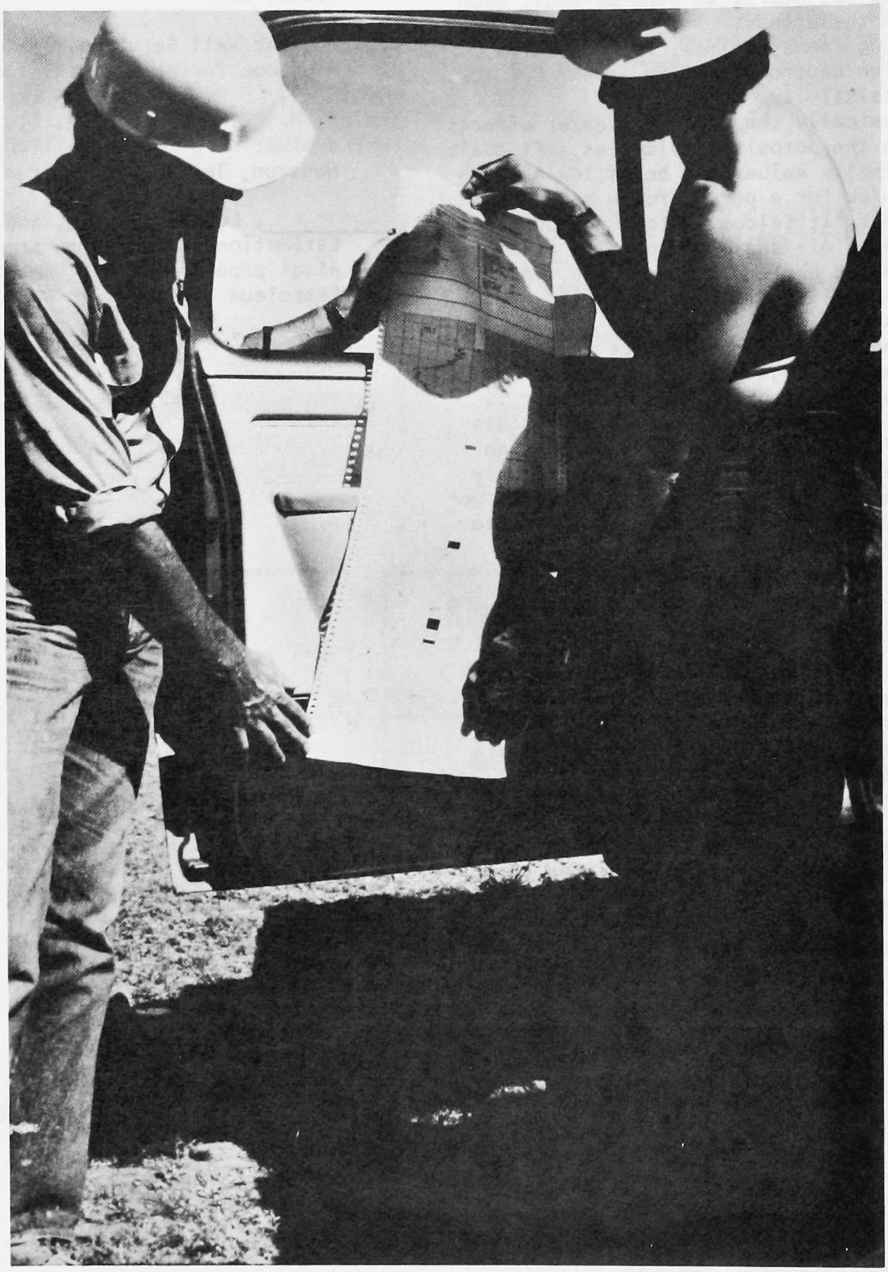
REFERENCES

Bond, L. O., Alger, R. P., and Schmidt, A. W., 1971, Well log applications in coal mining and rock mechanics: Soc. Mining Engineers (AIME) Trans., v.250, Dec.

Schlumberger Well Services, 1950, Interpretations handbook for resistivity logs: Document 8, July.

Tixier, M. P., and Alger, R. P., (undated), Log evaluation of non-metallic mineral deposits: Houston, Texas, Schlumberger Well Services, 23p.

__________, Loveless, G. W. and Anderson, R. A., 1973 Estimation of formation strength from the mechanical properties log: Am. Inst. Mining Metall. Petroleum Engineers.



Examining coal beds recorded on geophysical log, Huerfano County, Colorado

METHANE FROM COAL

CHARLES M. McCULLOCH:[1] U.S. Bureau of Mines[3]

MAURICE DEUL:[2] Pittsburgh, Pennsylvania 15213

ABSTRACT: Subsurface coal mining, except for metallurgical coal, is not commonplace in the Rocky Mountain states. The deeper coalbeds cannot be mined economically in competition with surface mining where coal is to be used only as a fuel. Thus, methane emission from underground mines is presently only a problem with the higher rank coals. Our studies show that the methane content of coalbeds is directly correlatable with rank, all other factors being equal.

The U.S. Bureau of Mines has developed a method to measure directly the gas content of coalbeds by testing cored coals collected in a standard fashion. These direct measurements of the gas content have been related to methane emissions from operating mines. Thus, this method makes it possible to determine the resource base of the gas contained in the coalbed and the effect of the emissions on the contained gas during mining.

It has been found that if there is sufficient gas in the coal to warrant degasification, then there are four methods of draining gas from coalbeds. These are: (1) vertical boreholes; (2) horizontal boreholes; (3) slant holes; and (4) gob degasification holes.

INTRODUCTION

The U.S. Bureau of Mines research to date on the degasification and utilization of methane from coalbeds has been concentrated in the Appalachian coalfields. However, in recent months the program has been expanded, and currently studies are being conducted in Colorado, Utah, and Oklahoma. Most of our work west of the Mississippi is just starting. Studies done in other coalfields, however, can be related to Western coals.

The Bureau has been involved in studying methane gas in coal for about 12 yrs. One of the most serious safety hazards in underground coal mines is the occurrence of methane gas (Humphrey, 1959). The gas emitted from coal requires constant ventilation of the working area; occasionally, when ventilation is inadequate, mining must stop because of the dangers of explosions of methane-air mixtures. Despite the technology developed and knowledge of the causes, there are still ignitions of gas causing explosions and loss of lives. Nine people have lost their lives in Colorado alone in the last 11 years due to methane gas explosions.

To get a better picture of the amount of gas that coal mines ventilate and emit to the atmosphere in the United States, it has been calculated that more than 200 million cu ft of gas per day is being vented into the atmosphere. As of March 16, 1976, mines in Colorado and Utah alone vent 11.4 million cu ft each day. More than 93 billion cu ft of gas is wasted from U.S. mines each year, of which 4.2 billion cu ft is from Colorado and Utah mines. It takes about 450 cu ft of gas per day to heat or cool an average house in Denver. This means that the gas wasted from mines in Utah and Colorado is enough to supply the fuel needs of 25,000 homes in this area each day. This gas could be compressed and pumped to gathering areas, where it could be transmitted by the pipeline system already available, which has lines going through most of the coal regions of Colorado (Fig. 1).

CURRENT WORK

The Bureau of Mines is conducting cooperative studies with the Colorado, Oklahoma, and Utah Geological Surveys. We are collecting data on the coalbeds in these states to determine which coalbeds are the gassiest and thus have the potential for methane drainage ahead of mining.

Our work is conducted in three phases. First, data on the individual coals (including cores) are collected to determine the gas content of important coalbeds. It has been estimated (Landis and Cone, 1971) that approximately 94 percent of the coal of Colorado will be extracted by underground mining systems. In the second phase, a detailed geologic study of selected areas is conducted to determine the potential effect of methane emissions on mining and the possibilities of methane production from the coalbeds. In the third phase, areas will be selected to produce methane so that the gas can be utilized rather than vented to the atmosphere and so that the coal can be mined without danger of explosions of methane-air mixtures. In the Western states, the Bureau is presently in the first phase of the investigation, whereas in Appalachia it is in the third phase.

When a comprehensive methane control research program started 12 yrs ago, we had no clear understanding of the factors that controlled the gas content of coalbeds. Mine disasters caused by explosions of methane-air mixtures provided no meaningful clues. But there was some experience that indicated that the higher rank coals were more gassy.

[1]Geologist

[2]Supervisory Geologist

[3]McCulloch now with Dames & Moore, Cincinnati, Ohio.

STATE OF COLORADO

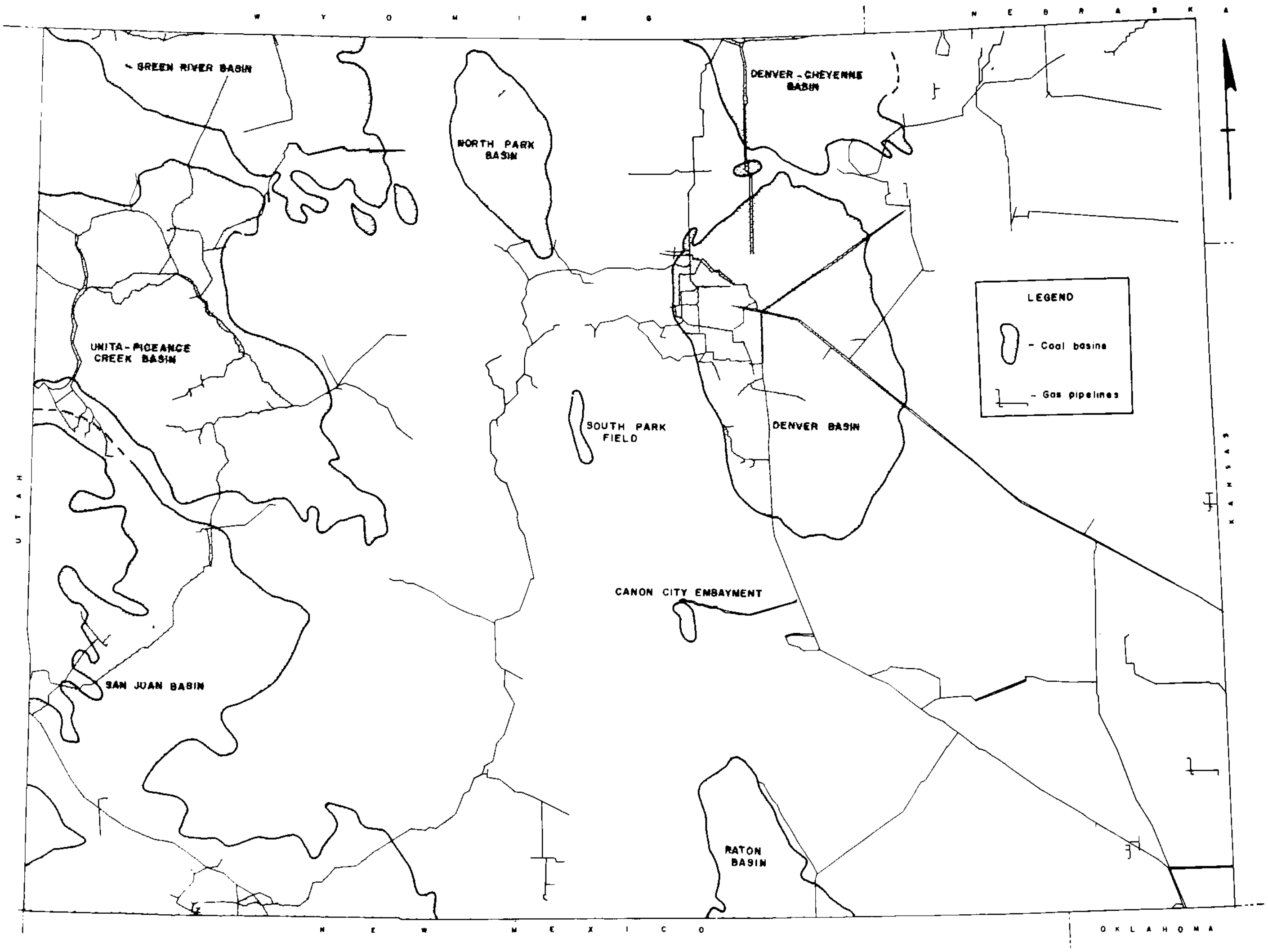


Fig. 1. Gas pipelines in Colorado

WESTERN COALFIELDS

Only about 25 percent of the coal in the Western states is above subbituminous in rank (Fig. 2); until recently, the rest of the coal was considered too low in gas content per ton of coal in place to be concerned about. This was an error, because where a bituminous coal might be 10 ft thick and contain 300 cu ft of gas per ton, a subbituminous coal 100 ft thick, containing 40 cu ft of gas per ton would comprise an even larger resource of gas--and be just as hazerdous to mine underground. Work by the U.S. Geological Survey indicates that gas has been detected in the subbituminous coals. Today, because of high costs, most of the coals being mined underground in the Rocky Mountain region are metallurgical coals. Such coal is of higher rank; hence, more gas is produced per ton mined. This can be seen on Table 1, which shows the methane production of underground mines from Colorado and Utah.

DIRECT METHOD OF DETERMINING GAS CONTENT OF A COALBED

In methane control, it is necessary to predict or accurately estimate the gas content of a given coalbed. Once this is done, it may be possible to understand why certain coal mines at given depths are much gassier than others at the same depth.

The Bureau of Mines has developed a method of calculating the gas content of a coalbed from exploration cores (Kissell and others, 1973; McCulloch and others, 1975). The results can be used to estimate the resource potential of the coalbed to produce gas and to design an adequate ventilation system for a coal mine This was an important accomplishment. Now we can estimate methane emission from a mine before it is opened.

The technique is simple, as is the equipment (Fig. 3). Cost for all equipment necessary should be under $100. The testing can be done in the field, with no laboratory work required. It has been adopted

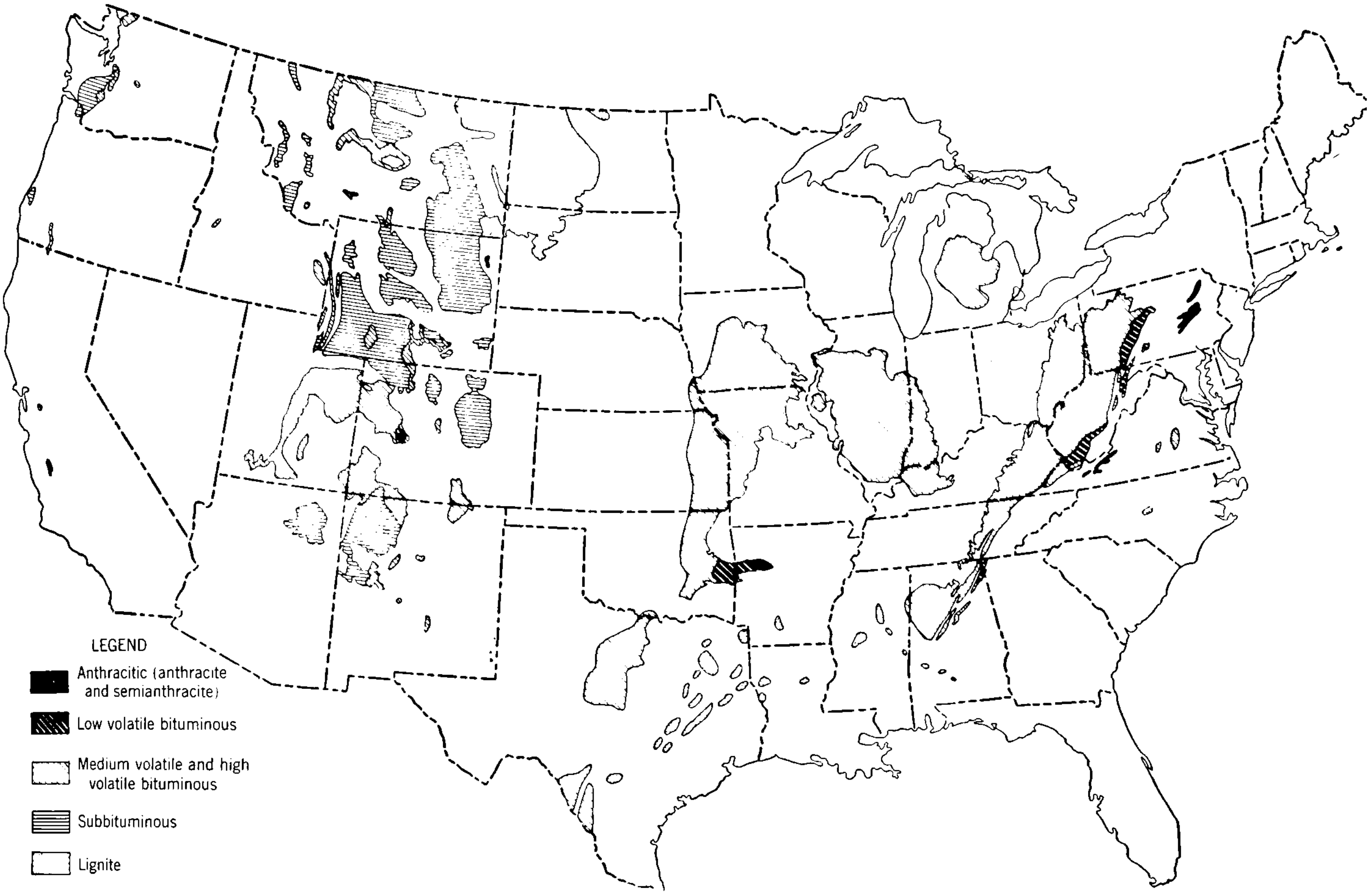


Fig. 2. Coal fields of the United States (prepared by U. S. Geological Survey).

by a number of coal mining and consulting engineering companies and is routinely conducted as part of their exploration programs. Members of both the Colorado and Utah Geological Surveys also can run this test and are willing to assist companies in determining the gas content of their coals. The coal sample necessary for the test can be collected from any type of hole drilled or cored to the coalbed as long as the coal itself is cored. The diameter of the sample can be of any size. The cooling medium used in coring can be air, mist, water, or mud. The only difference this makes is in calculating the gas lost in bringing the sample to the surface. It is important, once the coal is cored, that the core barrel should be removed without delay and the sample placed in the container and the container sealed immediately to minimize the amount of gas lost.

The test can be conducted successfully with as little as 100 g of coal, but more accurate data can be obtained with larger samples of 1,000 g or more.

Once the sample has been sealed in the desorption cannister, the gas pressure will build up; the gas emitted should be released periodically. The initial emissions of gas from the coal are the largest; the emission rate decreases with time. Within a few days, the emission rate is low enough to require only one reading per day.

To measure emission (Fig. 4), the desorbed gas is bled off through a tube attached securely to the valve head into an inverted graduated cylinder filled with water. After the first day, the gas emitted should be measured once a day until the daily emission has fallen below 0.05 $cm^3/g/d$ for 5 consecutive days, as seen in the Pittsburgh and Beckley coalbed samples shown on Figure 5. This normally would take between 3 and 4 weeks. At this time, the coal sample can be taken from the container for analysis. The gas still remaining in the sample can be estimated graphically (McCulloch and others, 1975).

After the total gas content of the sample has been calculated, then simply divide the weight of the sample, and the resultant is the cm^3/g.

USE OF DIRECT METHOD TO DETERMINE IN-PLACE GAS AND VENTILATION NEEDS

Once the gas content of a sample has been determined, then the uses for these data are twofold. They can be used to estimate the volume of air that

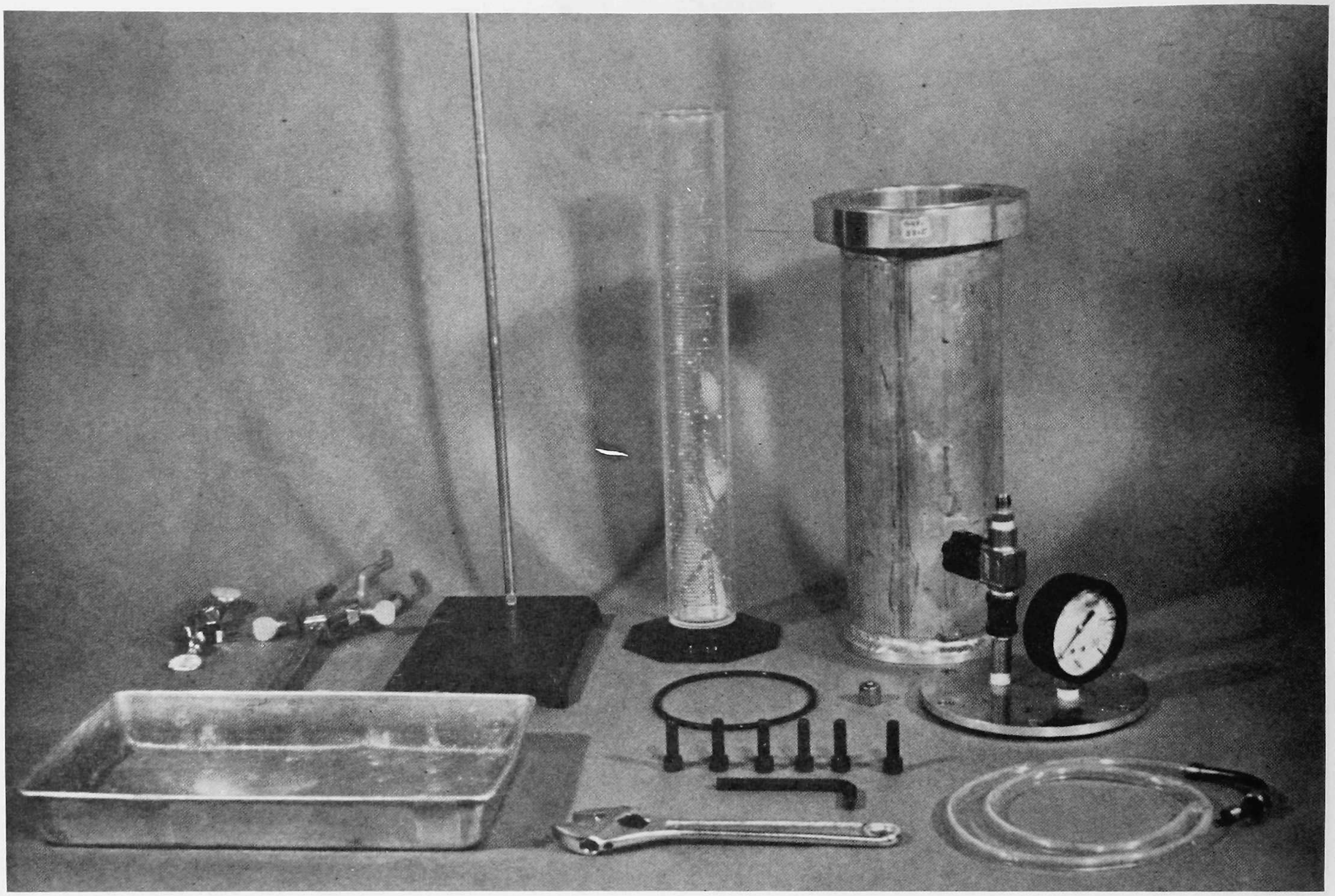


Fig. 3. Desorption equipment disassembled.

will be necessary to ventilate a mine (Fig. 6). This figure shows the relationship of gas emissions from known mines to the cm^3/g of gas measured from samples taken on their property. The correlation is good for mature deep mines that have a sustained coal production of at least several thousand tons per day. New mines emit less methane per ton of coal mined than older mines with extensive old workings and gob areas that still bleed gas.

For example, if a sample from a mine property contains 6 cm^3 of gas per gram of coal, then we would estimate that a mature mine would emit an average of 1,200 cu ft of gas for every ton of coal mined.

Also, and in some cases more importantly, the data can be used to estimate the amount of gas contained in a coalbed to determine its resource potential. This kind of study has been conducted in the Mary Lee group of coals in Alabama (Diamond and others, 1976), and we hope to conduct similar studies in the major coalbeds in the Rocky Mountain states. Figure 7 shows desorption data for 12 samples from the Mary Lee coalbed. These samples were obtained from depths ranging from 620 and 2,200 ft and from high volatile to low volatile in rank, respectively. The relationship of gas content to depth for these samples shows that as depth of cover increases, the gas content increased for a given coalbed.

This relationship holds true only when samples at different depths are taken throughout a coalbed to represent a significant range. Similar relationships also have been found for the Pittsburgh coalbed in West Virginia and Pennsylvania and the Hartshorne coalbed in Oklahoma. Once this relationship is known, an overburden isopach map (Fig. 8) is drawn. By using overburden and coal isopach maps, and knowing the relationship of gas content to depth, the gas resource in a coalbed can be calculated. For example, it has been estimated that more than 1 trillion cu ft of methane is contained in the coals of the Mary Lee group. It also was estimated that approximately 90 percent of the methane occurs at depths greater than 1,000 ft; more than one-half of the gas is contained within only 12 percent of the study area at depths greater than 1,500 ft. This makes this area important not only for coal production but also as a potential source of natural gas.

A plot of overburden versus gas content for all coal samples tested is shown on Figure 9. This plot shows a very poor correlation of gas content with depth, and obviously is not accurate enough to use for prediction of gas content. Therefore, depth alone is

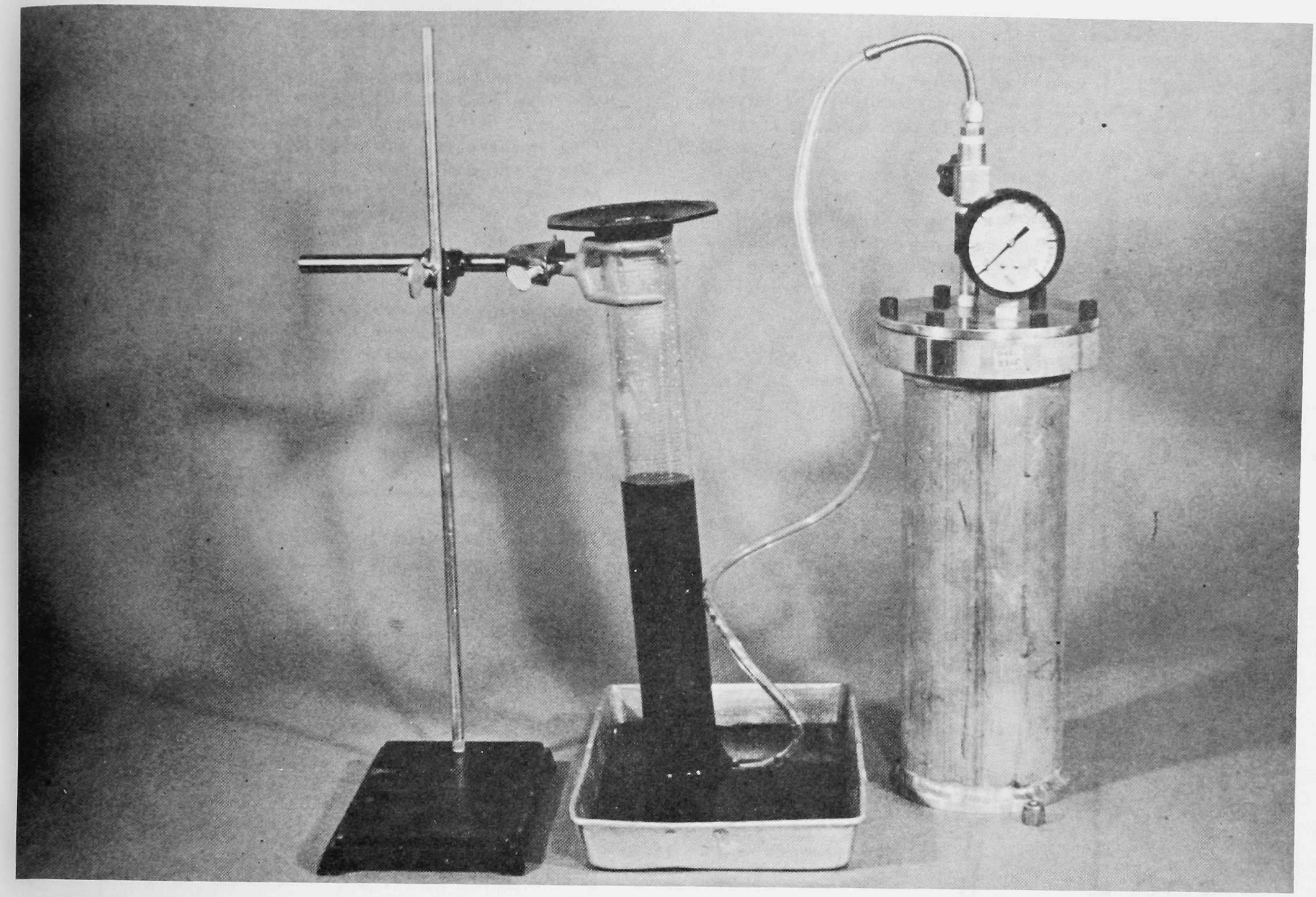


Fig. 4. Desorption equipment assembled for use.

not the controlling factor.

Another graph is shown (Fig. 10) that relates the gas content of a coal to its rank. Fixed carbon (moisture- and ash-free) is used as the rank indicator. High-volatile coals contain little gas, usually on the order of 1 to 6 cm^3/g or 32 to 192 ft^3/ton. The medium-volatile coals contain between 6 and 12 cm^3/g, and the low-volatile coals contain much more gas (between 10 and 19 cm^3/g, or 320 to 608 ft^3/ton). Most of the Western coals are high-volatile, at least around the edges of the basins and under relatively shallow overburdens, so we should not expect much gas; however, in some areas the Western coals are of higher rank and also are buried much deeper. These are the areas where high rates of emission of methane can be anticipated if the coals are to be mined underground.

By using this graph (Fig. 10), it may be possible to estimate the gas content of a coal simply by knowing only the percentage of fixed carbon. After further testing, this type of graph may be used to estimate the gas content of a coal when no samples are available for direct testing. At present, the direct method of testing is still the best and most accurate way to determine the gas content of a coalbed.

The rank of the coals in the 8 coal regions of Colorado has been estimated; the ranges of fixed carbon are shown on Table 2. For example, the Uinta-Piceance Creek basin has a much greater potential gas production than certain other well-defined areas, such as the North Park basin.

But this raises another question. What happens to the rank of a coalbed with greatly increased depth? What happens to a high-volatile coal like the Vermejo coalbed in the Raton basin when its depth increases from 700 to 2,000 to 5,000 ft? There is a strong likelihood that the rank will increase. For example, again relating the Mary Lee coal in Alabama to the Western coals--it is a high-volatile coal under 500 ft of cover, but in two new mines with more than 1,500 ft of cover, the Mary Lee is a low-volatile coal. The mines at a depth of 500 ft have no methane control problem, but those with more than 1,500 ft of cover are emitting more than 3,500 cu ft of gas for every ton of coal mined. This means a mine that will produce 3,000 tons per day must ventilate 10.5 million cu ft of methane. Anyone working in the Rocky Mountain coal-fields should consider this and be concerned as deep mines are planned.

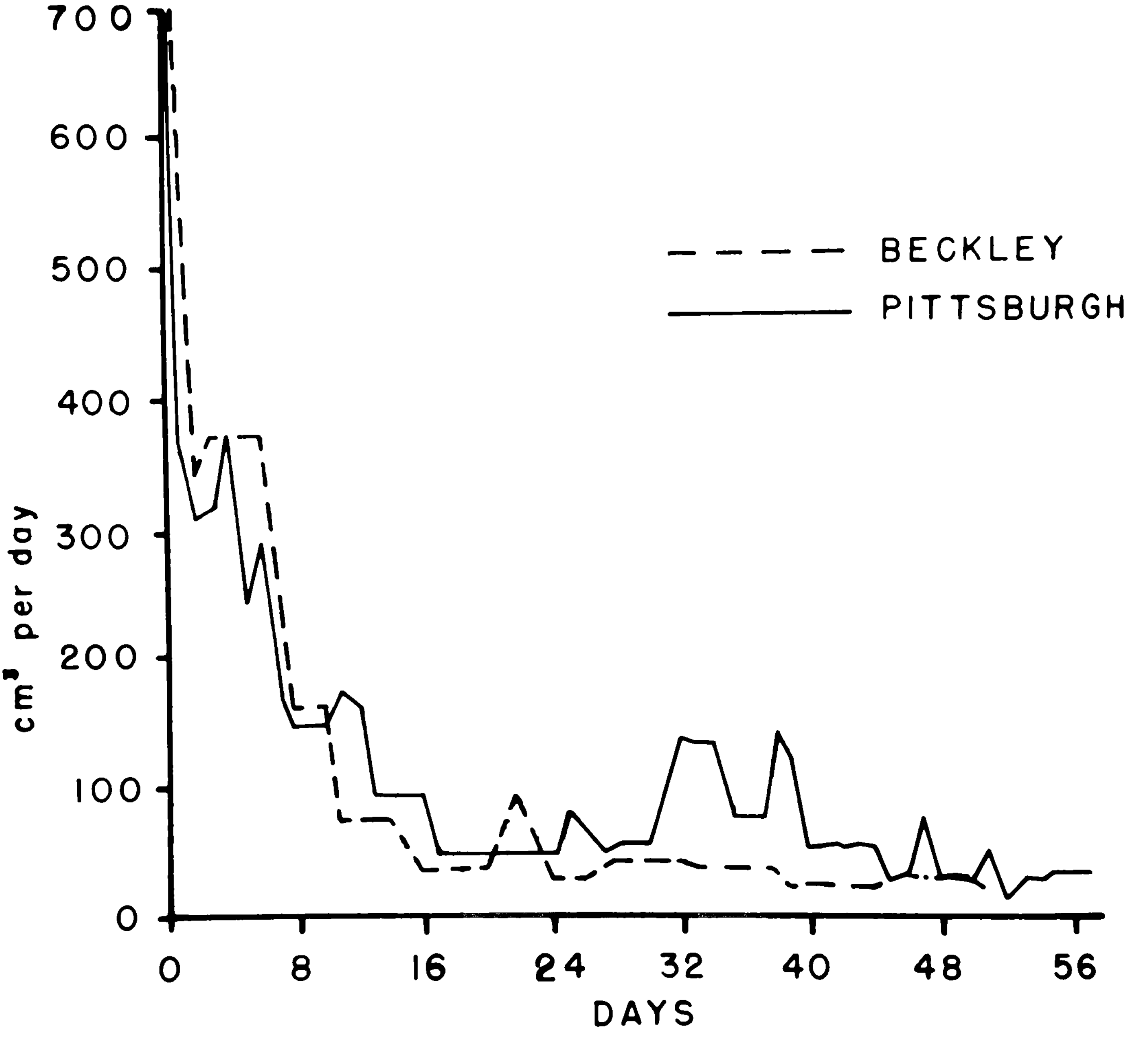


Fig. 5. Decline curves for the Pittsburgh and Beckley coal beds.

FOUR METHODS AVAILABLE FOR DEGASIFICATION

Once the gas content of a coalbed has been determined by the direct method, it must be evaluated as to its potential for producing gas. If it is determined that there is sufficient gas present to warrant some type of degasification, then there are 4 possible methods available today that the Bureau has developed and is constantly modifying.

Vertical Boreholes

The first is degasification through vertical boreholes. These are holes drilled to the coal that are normally of 6-in. diameter, cased to 4-1/2 in., and cemented. It is important that the coal be left free of pipe and cement if possible. Gas flow into a borehole is dependent upon coalbed permeability and formation pressure. Some examples of measured pressures are shown on Table 3. It should be noted that in order for the gas to flow freely, the coalbed must be dewatered. A greater rate of degasification can be achieved by increasing coalbed permeability in the drainage area and by increasing the surface area exposed for more rapid desorption. Hydraulic stimulation is one method of accomplishing this (Elder and Deul, 1975). Figure 11 shows the marked increase due to hydraulic stimulation of the Pittsburgh coalbed (high-volatile) under 400 ft of overburden in Washington County, Pa.

There are several kinds of stimulation treatments available. Normally a 10,000-gal treatment with 5,000 lbs of sand as a propping agent is used. An increase in gas production of between 5 and 20 times the prestimulation flows (Fig. 12) has been observed. If it was anticipated that degasification would be necessary, then it would be possible to lay out the holes in such a way that the holes could be used for degasification initially before mining reached the area, as power-drop or rock-dust supply holes during mining, and as gob degasification holes after retreat mining.

Horizontal Boreholes

A second method available for degasification is the use of horizontal holes drilled into the coalbed from the bottom of a shaft (Fig. 13) or from an advancing entry. This method requires either that a mine already exists or is past the planning stage and shaft sites have been selected (Cervik and others,

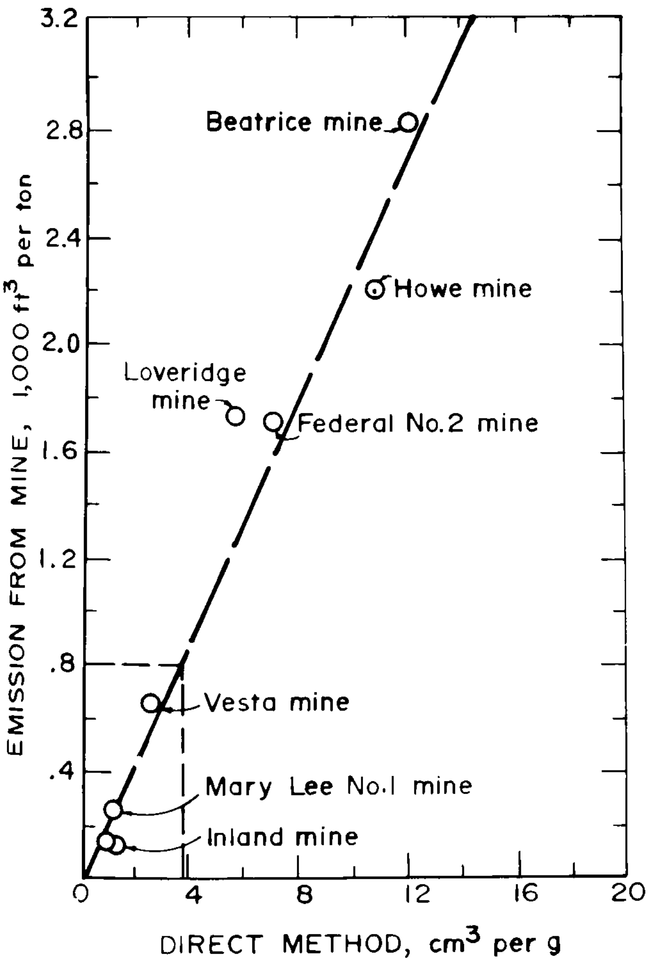


Fig. 6. Gas content of coal versus actual mine emission.

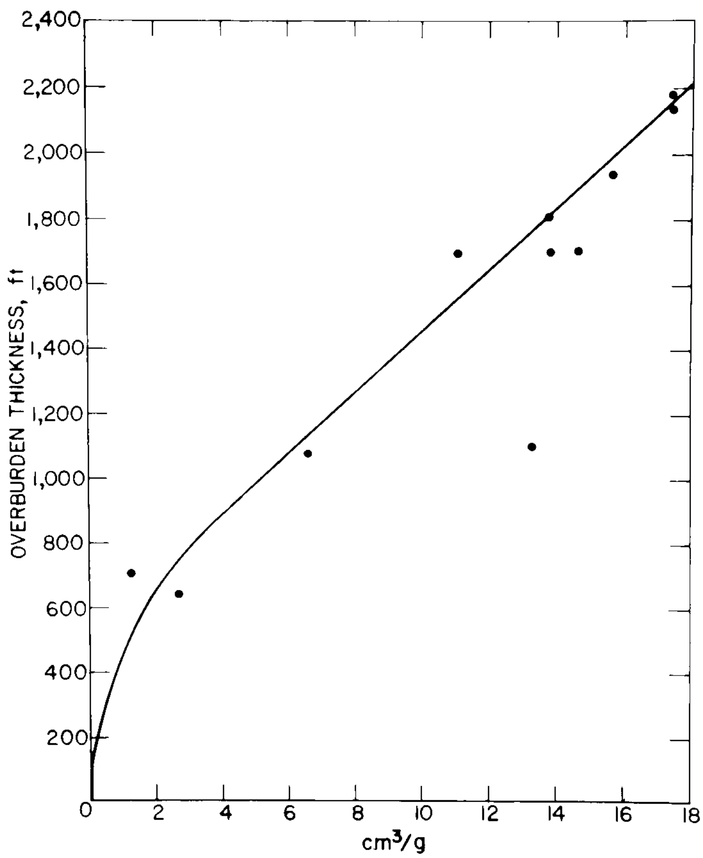


Fig. 7. Gas content of coal samples versus depth of samples from Mary Lee coal bed in Alabama.

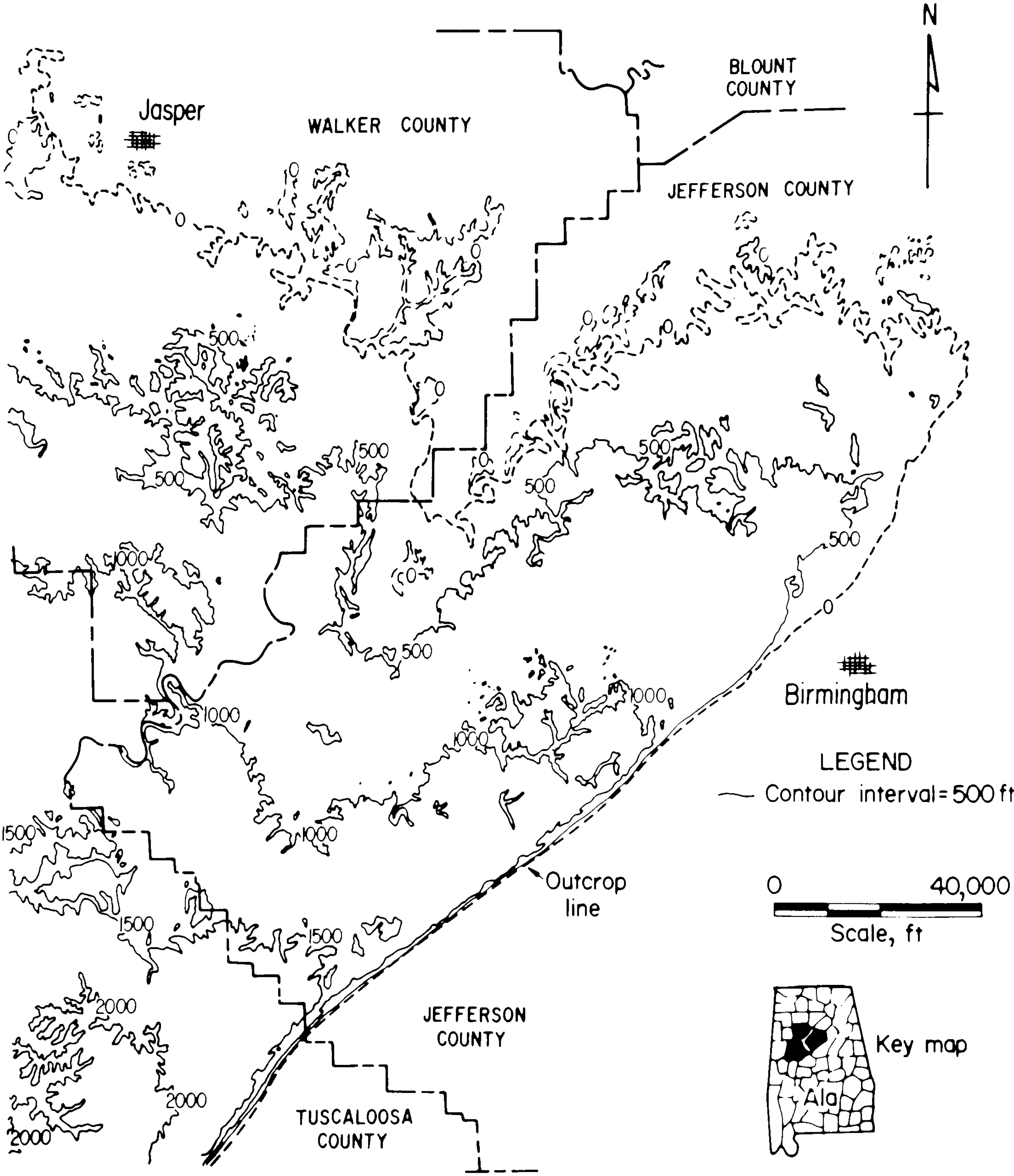


Fig. 8. Overburden isopach for the Mary Lee coal bed, Alabama.

TABLE 1 - Methane emission of underground mines in Colorado and Utah, ft^3/d

State and Mine	
Utah	
Carbon Fuel No. 3	164,000
Soldier Canyon	164,000
Sunnyside No. 1	1,368,000
Sunnyside No. 2	36,000
Sunnyside No. 3	395,000
Emery	105,000
Colorado	
Allen	452,000
Bear	65,000
Coal Basin	1,168,000
Dutch Creek No. 1	1,193,000
Hawk's Nest No. 3	68,560
Hawk's Nest East	6,600
Eagle	7,000
CMC	24,000
Bear Creek	650,000
Somerset	850,000
Dutch Creek No. 2	1,292,000
L. S. Wood	3,338,812

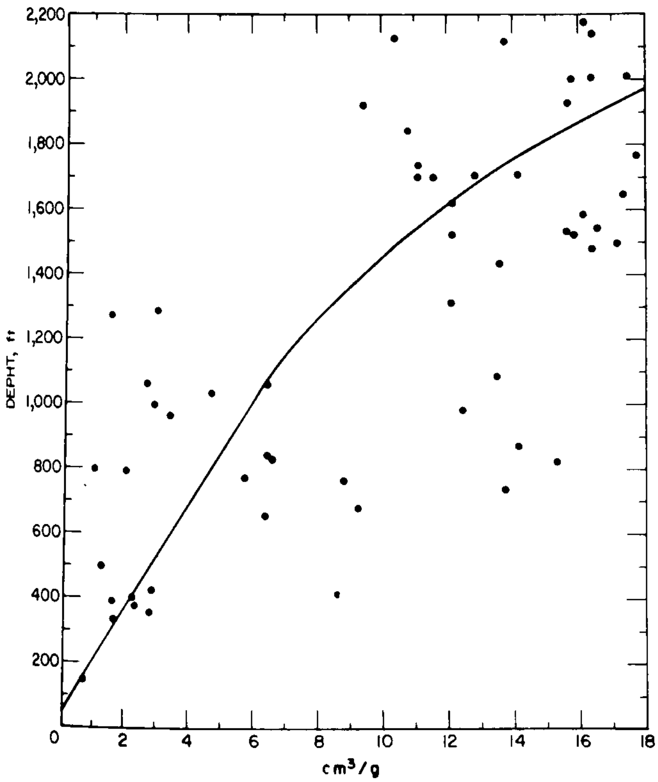


Fig. 9. Gas content versus overburden for all samples tested.

TABLE 2 - Ranges of fixed carbon in Colorado coal regions

Coal-Bearing Region	Fixed carbon (maf) range
Green River	48-59
North Park	38-56
South Park	54?
Canyon City Embayment	40-61
Denver - Cheyenne	46-61
Raton	44-60
Uinta-Piceance	48-86
San Juan	43-61

1975). An example of this is the series of 7 horizontal degasification holes (Fig. 14) drilled into the Pittsburgh coalbed from a small shaft drilled for that purpose (Fields and others, 1973). After 1,267 days of degasification, 741 million cu ft of gas has been removed from the Pittsburgh coalbed. Also 344 million cu ft of this gas had been purchased by a gas company, and, with the use of a compressor, put into their gas lines (Fields and others, 1975). The aggregate length of these 7 holes is 4,325 ft; to date, the gas produced from these holes amounts to 135 cu ft per day per linear ft. This type of work could be done from a mine shaft that had been sunk 5 yrs before it would be needed for ventilation or mining, and the gas so produced should more than pay for the investment, while at the same time making mining safer and more productive.

Another site for degasification from horizontal holes from a shaft bottom, at the Honey Run shaft, also in the Pittsburgh coalbed, has a similar production record. Over 724 million cu ft has been produced in 974 days, as of April 14, 1976. This horizontal hole is averaging over 740,000 cu ft of methane per day. Over 103 million cu ft of this quantity of gas has been placed into a pipeline and sold. The aggregate length of these 5 holes is 5,830 ft; to date, the gas production has been 128 cu ft per day per linear ft.

The other method of using horizontal holes is drilling them in advance of a working section in outside entries. This method would be used to degasify a section of coal underground. The gas drained from the coal would have to be piped through a manifold system to the surface.

Horizontal holes also are used to degasify longwall panels by simply drilling a series of horizontal holes into the panel and allowing it to degasify during development.

Slant-Hole Drilling

The third method is still experimental. Directional drilling is a technique that has been used for some time in the oil and gas industry. We have adopted and modified this technique to drill holes from the vertical on the surface to intersect the coal at a glancing angle and to remain horizontal in the coalbed (Fig. 15). This type of degasification combines the techniques of vertical drilling with horizontal degasification. The first slant hole we

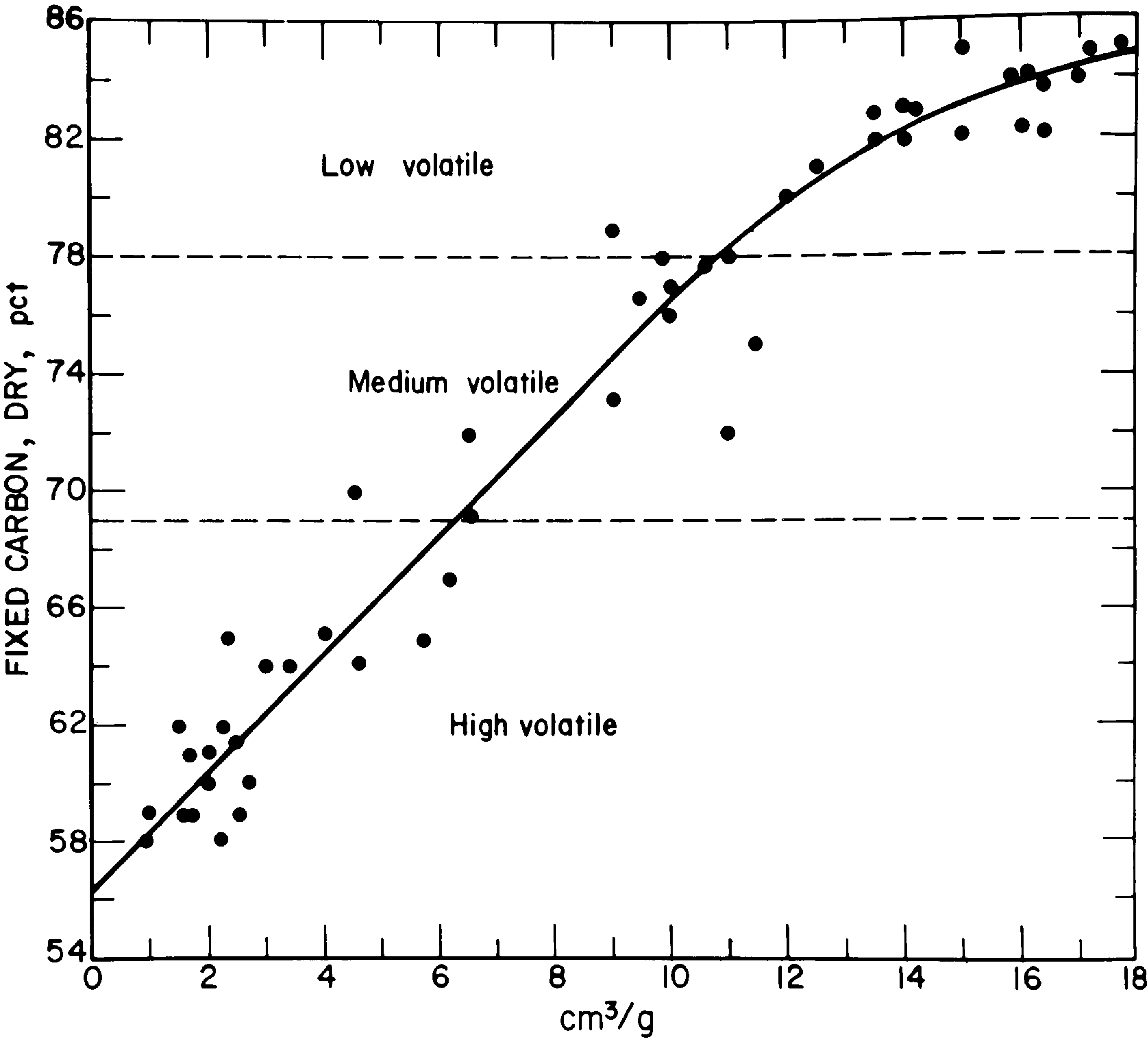


Fig. 10. Gas content versus rank.

attempted was in the Pittsburgh coalbed in West Virginia (Fig. 16). It intersected the coal successfully and drilling continued for 420 ft horizontally in the coal. Pumps and tubing are set up on the site, and gas production should begin by May 1, 1976.

Gob Degasification

The fourth method of degasification for larger mines is gob degasification (Elder and others, 1969; Moore and Zabetakis, 1972). This entails drilling a series of vertical holes into a gob area to bleed gas from the gob (Fig. 17) and hence preventing its entry into the return air. A slotted pipe is used. This technique is the same as that used in vertical holes, except that the rock is not hydraulically fractured. Gob degasification can result in a substantial reduction in the methane content of the ventilation air. Figure 18 shows the reduction of methane from gob degasification in the Pocahontas No. 3 coalbed in Virginia. Monitoring of returns from longwall panels have shown significant reductions of

TABLE 3. - Gas pressures and depths from vertical boreholes

Coalbed	Location, County and State	Pressure measured, lb/in^2	Depth to base of coal, ft
Pittsburgh	Marion, W.Va.	168	930
Do.	Monongalia, W.Va.	250	800
Do.	Washington, Pa.	146	450
Lower Hartshorne	LeFlore, Okla.	253	570
Do.	Haskell, Okla.	670	1,410
Pocahontas No. 3	Wyoming, W.Va.	158	765
Do.	Buchanan, Va.	580	1,415
Mary Lee	Jefferson, Ala.	396	1,050
Castlegate Subseam No. 3	Carbon, Utah	266	980
Illinois No. 6	Jefferson, Ill.	120	735

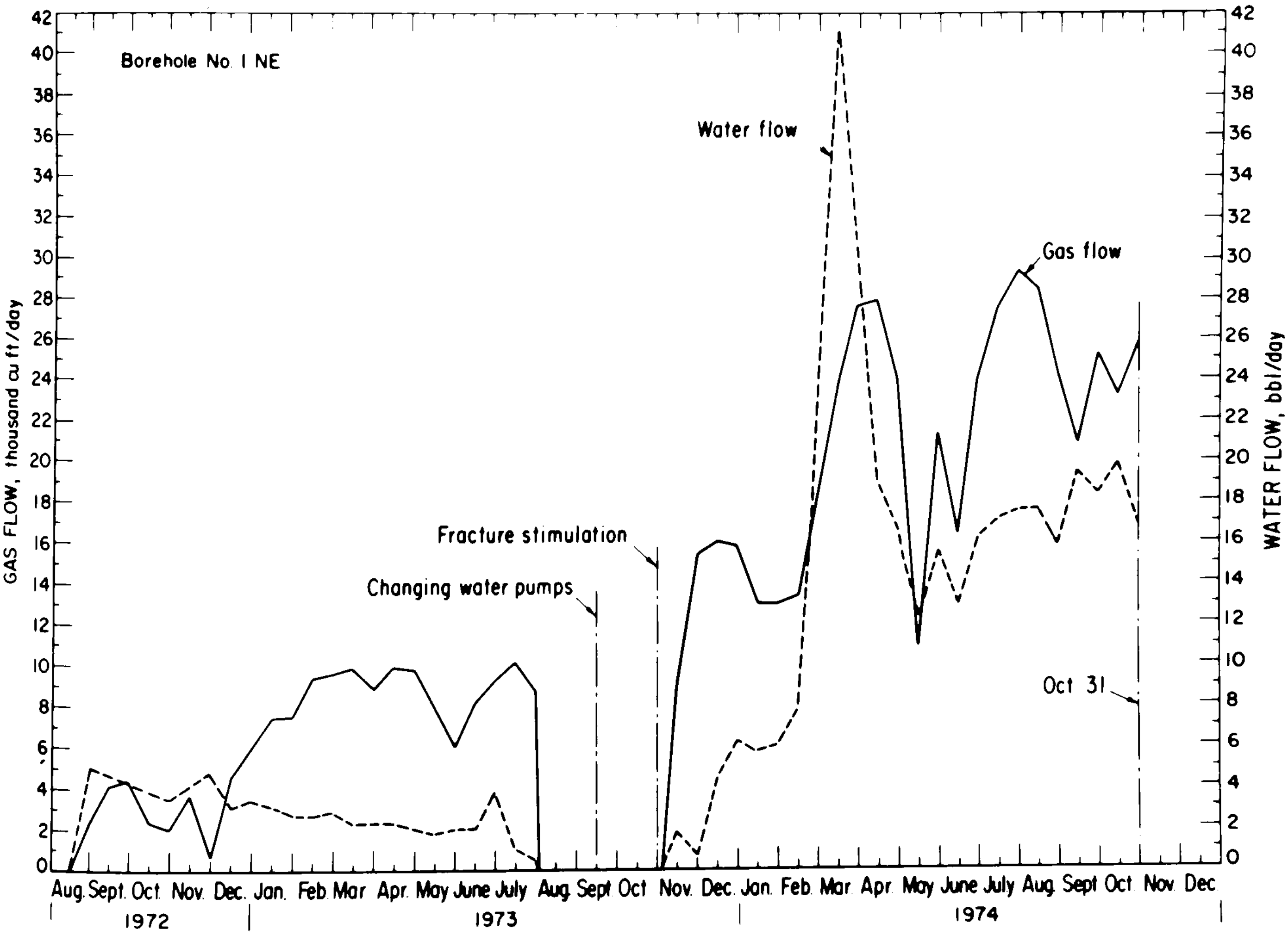


Fig. 11. Increase in gas flow from hydraulic fracturing of the Pittsburgh coal bed.

Effect of Hydraulic Stimulation on Gas and Water Production

Coalbed	Avg gas production rate ft^3/d		Avg water production rate gal/hr	
	Before	After	Before	After
Pocahontas No. 3	600	12,000	1.3	2.9
Pittsburgh	7,000	35,750	5.6	26.3

Fig. 12, Gas production from vertical boreholes before and after hydraulic fracturing.

methane emissions. This reduction would make it possible to mine for longer periods of time without costly shutdowns.

High gas flows have been observed. A hole in the Pocahontas No. 3 coalbed yeilded over 800,000 cu ft of high-purity methane per day under free-flow conditions. More than 179 million cu ft was removed in a 15-month period. The methane concentration of the gas discharged by the borehole during the study period ranged from 77 to 100 percent. This occurred when mining had just progressed past the hole. A year later the methane concentration was still averaging 43 to 45 percent, high enough for use as a fuel.

The chief result of this degasification method is that the methane flow rate decreased underground and large fluctuations in that flow rate were eliminated. This method could be adapted for Western mines using longwall systems that have high gas emissions from their gob.

SUMMARY

The emission of methane is one of the most serious safety hazards faced in underground min'ng today. Mines in Colorado and Utah today emit over 11 million cu ft of gas each day; as mining progresses and as new and deeper mines come into production, the quantity of vented methane will increase.

For a mine to formulate a plan to adequately cope with methane emission from the mined coalbed, the methane content of that coal must be accurately estimated.

A technique has been developed by the U.S. Bureau of Mines to accurately estimate the methane content of a coal core from a drill hole. The equipment is simple and its total cost is less than $100. The tests can be run in the field, and no laboratory work or testing is required. There are two main uses for the results: (1) To estimate the resource potential

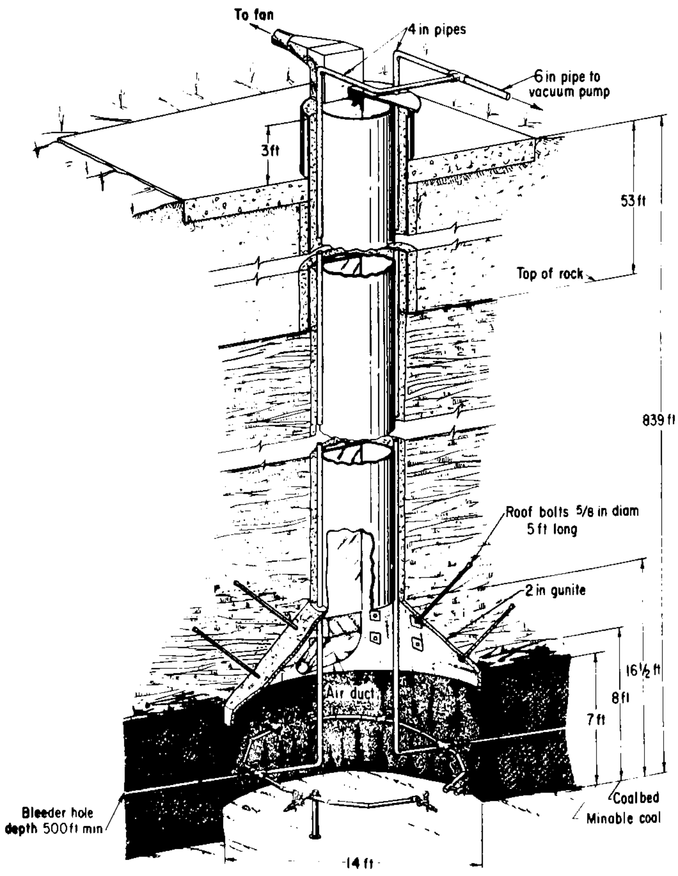


Fig. 13. Mutipurpose borehole.

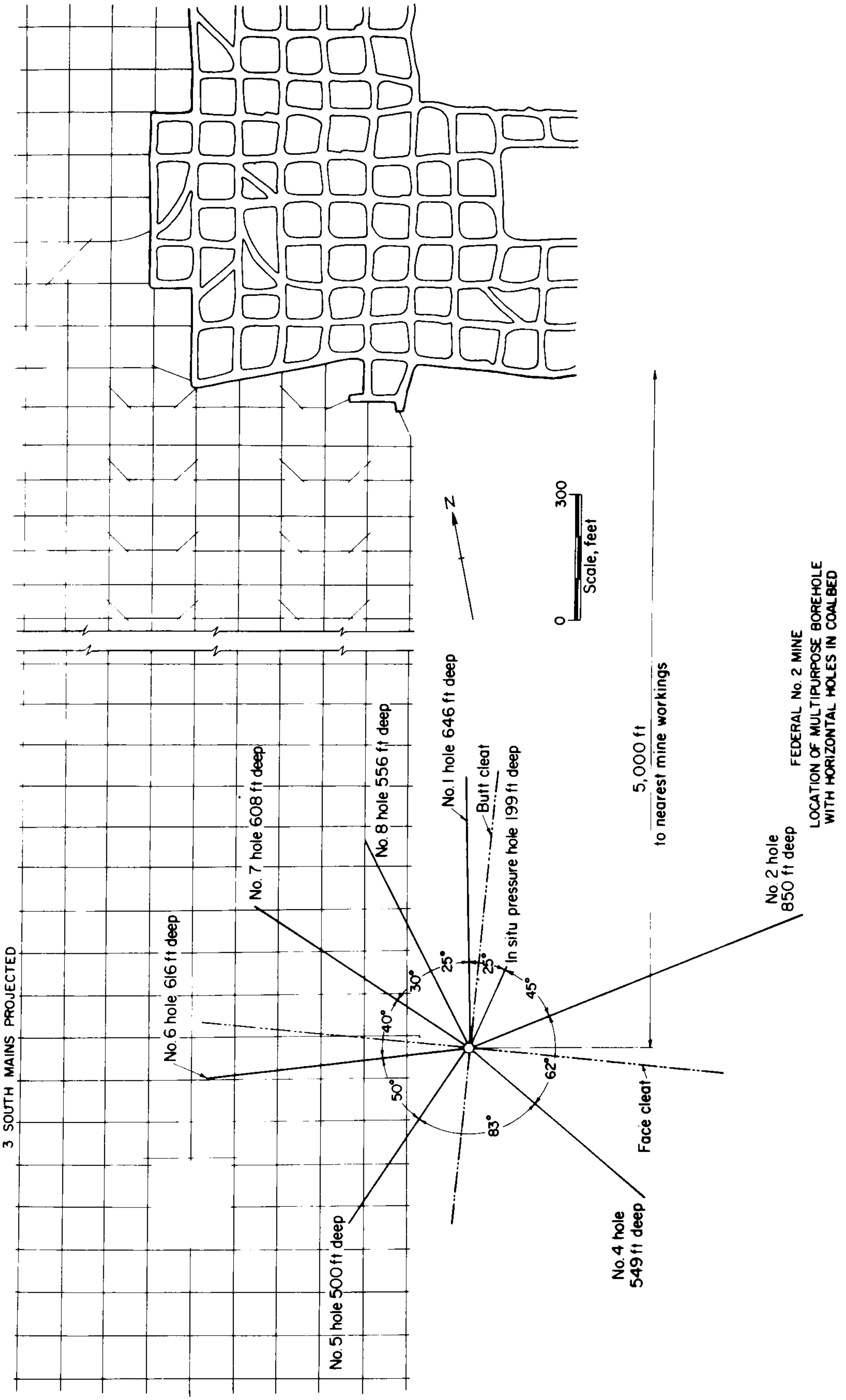


Fig. 14. Plan view of seven horizontal holes from multipurpose borehole.

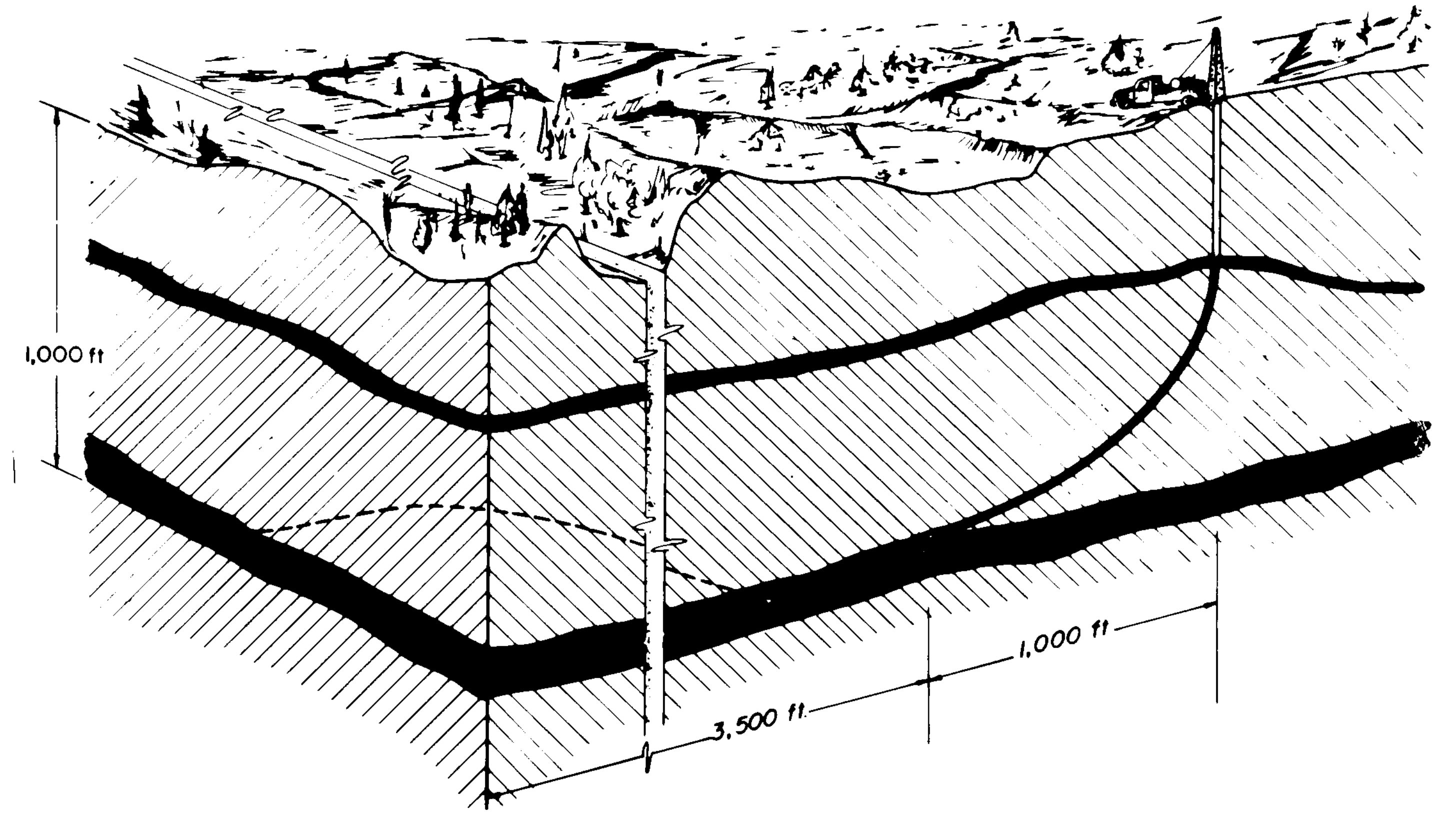


Fig. 15. Plan view of proposed slant hole.

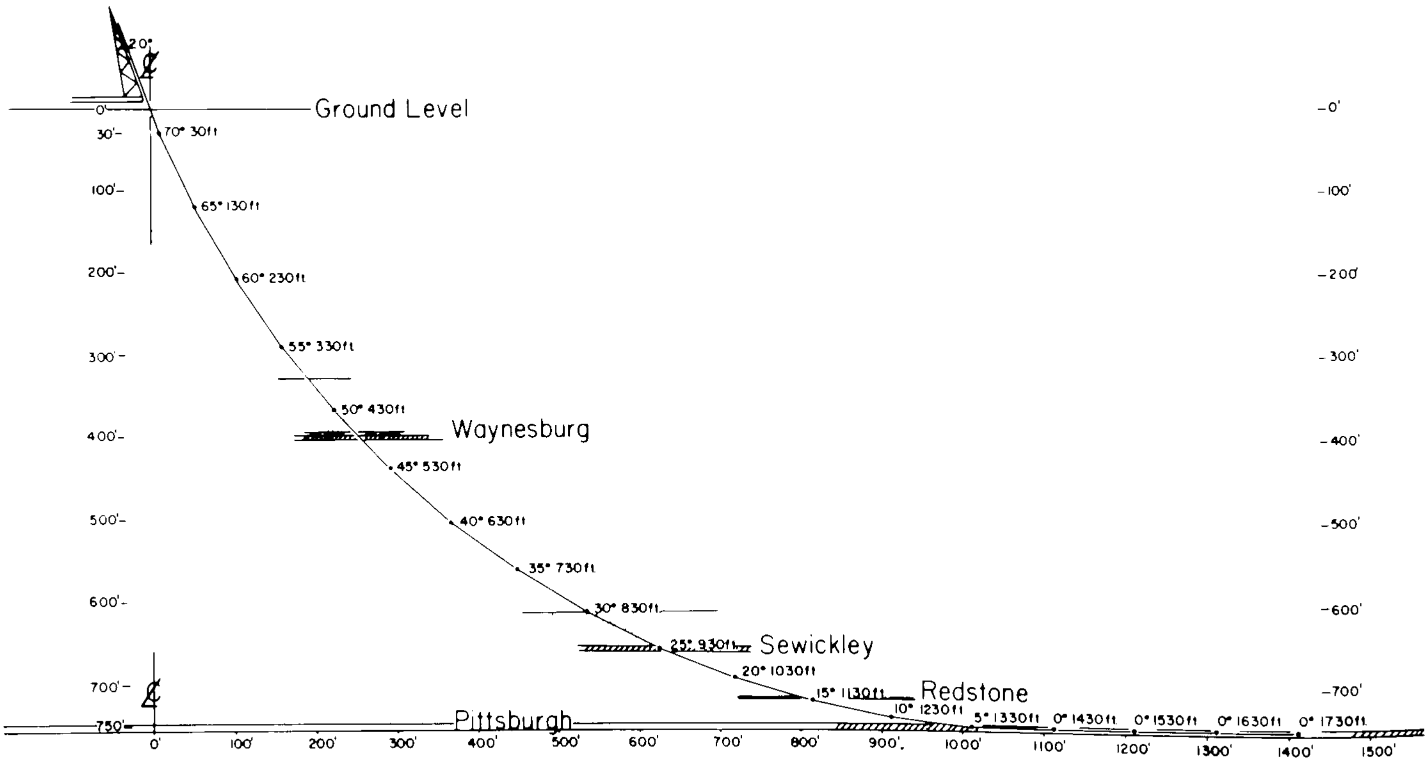


Fig. 16. Slant hole into Pittsburgh coal bed.

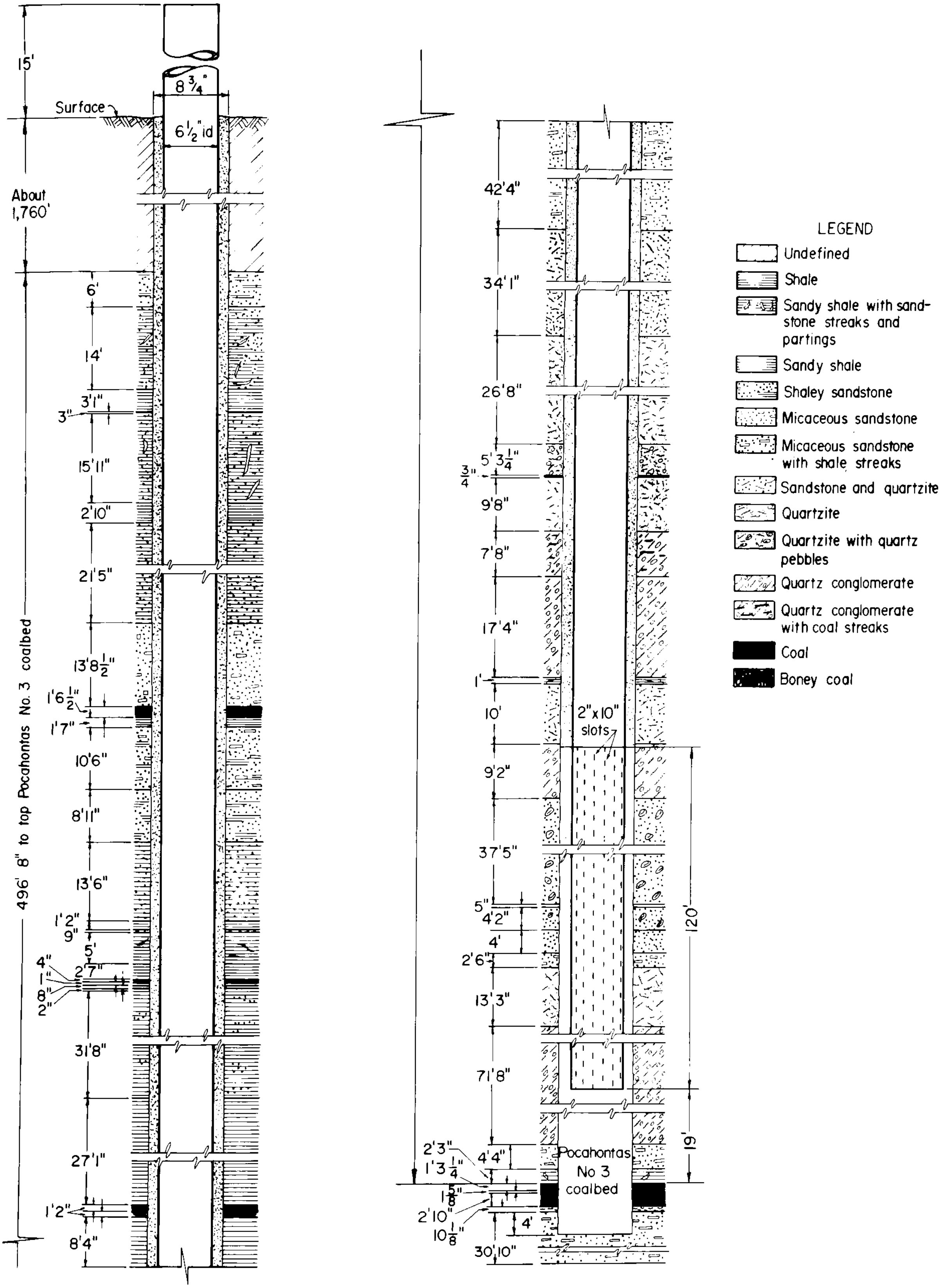


Fig. 17. Strata and slotted pipe for gob degasification.

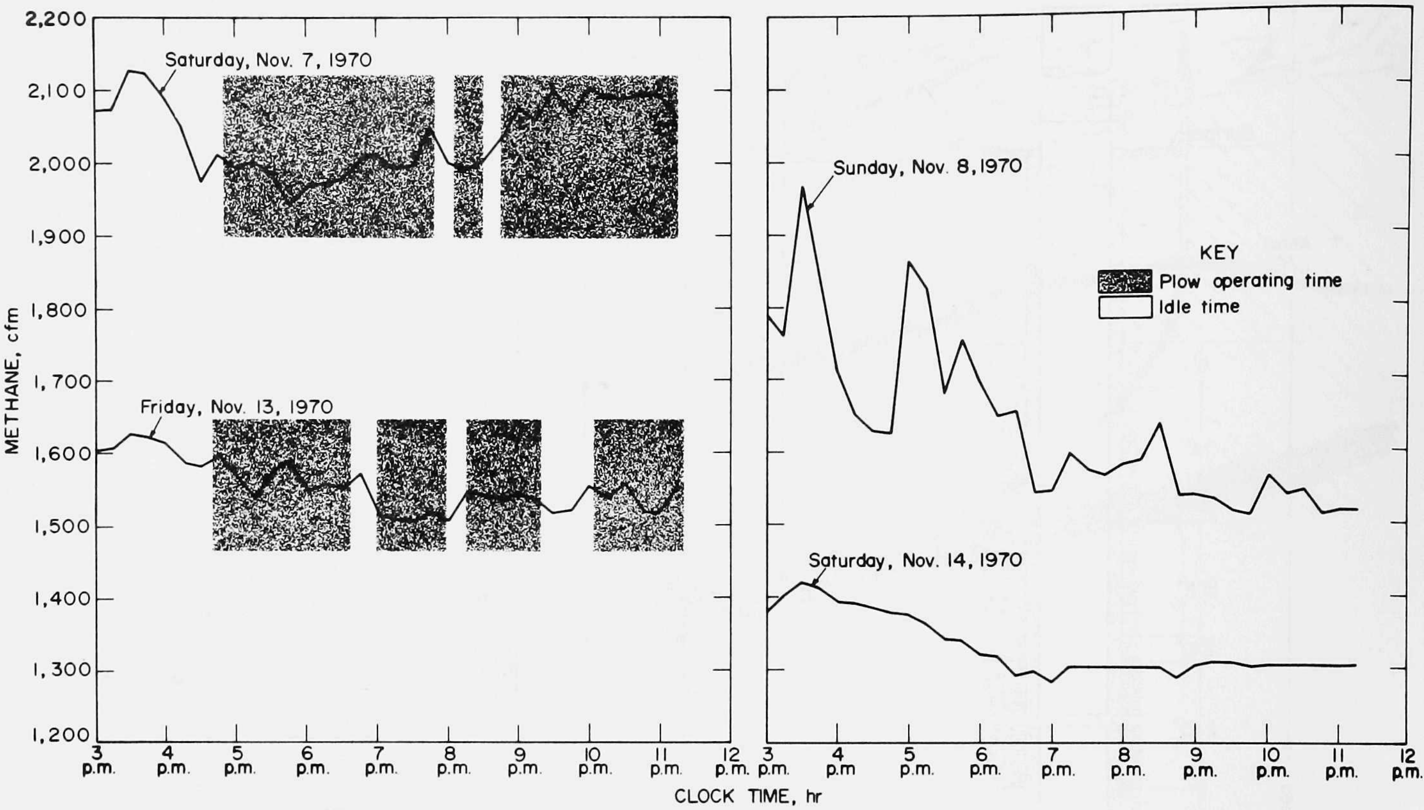


Fig. 18. Reduction of methane in mine workings from gob degasification.

of the coalbed for possible gas production, and (2) to assist in designing an adequate ventilation system to handle the methane emissions anticipated.

If the tests indicate that the methane content is sufficient, then degasification of the coal prior to mining could be planned. There are 4 methods presently available for this. These are: (1) vertical boreholes; (2) horizontal boreholes; (3) slant holes; and (4) gob degasification holes.

The degasification technique ultimately selected will depend upon individual mine conditions. Degasification takes time, so advance planning is essential. The specific techniques to be used also will depend on the need to increase mine safety, mine productivity, and a ready market for the produced gas.

REFERENCES

Cervik, Joseph, Fields, H.H., and Aul, G.N., 1975, Rotary drilling holes in coalbeds for degasification: U.S. Bur. Mines Rept. Inv. 8097, 21 p.

Diamond, W.P., Murrie, G.W., and McCulloch, C.M., 1976, Methane gas content of the Mary Lee group of coalbeds, Jefferson, Tuscaloosa, and Walker Counties, Alabama: U.S. Bur. Mines Rept. Inv. 8117, 9 p.

Elder, C.H., 1969, Use of vertical boreholes for assisting ventilation of longwall gob areas: U.S. Bur. Mines Tech. Progress Rept. 13, 6 p.

__________, and Deul, Maurice, 1975, Hydraulic stimulation increases degasification rate of coalbeds: U.S. Bur. Mines Rept. Inv. 8047, 17 p.

Fields, H.H., Krickovic, S., Sainato, A., and Zabetakis, M.G., 1973, Degasification of virgin Pittsburgh coalbed through a large borehole: U.S. Bur. Mines Rept. Inv. 7800, 27 p.

__________, Perry, J.H., and Deul, Maurice, 1975, Commercial-quality gas from a multipurpose borehole located in the Pittsburgh coalbed: U.S. Bur. Mines Rept. Inv. 8025, 14 p.

Humphrey, H.B., 1959, Historical summary of coal-mine explosions in the United States: U.S. Bur. Mines Info. Circ. 7900, 275 p.

Kissell, F.N., McCulloch, C.M., and Elder, C.H., 1973, The direct method of determining methane content of coalbeds for ventilation design: U.S. Bur. Mines Rept. Inv. 7767, 17 p.

Landis, E.R., and Cone, G.C., 1971, Coal reserves of Colorado tabulated by bed: U.S. Geol. Survey Open-File Rept., 515 p.

McCulloch, C.M., Levine, J.R., Kissell, F.N., and Deul, Maurice, 1975, Measuring the methane content of bituminous coalbeds: U.S. Bur. Mines Rept. Inv. 8043, 22 p.

Moore, T.D., Jr., and Zabetakis, M.G., 1972, Effect of a surface borehole on longwall gob degasification (Pocahontas No. 3 coalbed): U.S. Bur. Mines Rept. Inv. 7657, 9 p.

COAL ANALYSIS:
WHY, WHERE, WHEN, AND HOW

LLOYD W. TAYLOR: Commercial Testing and Engineering Company

Denver, Colorado 80239

ABSTRACT: This paper explains that the why, or need, for coal analyses is due mainly to the heterogeneity of the complex hydrocarbon, coal. It also touches on how the geological formation occurred and affected the final product, coal.

DEVELOPMENT AND NEED FOR COAL CHARACTERIZATION TESTS: Explains the reason, need, and development of our current standarized tests that are used and accepted worldwide. It also recognizes today's organizations that are continually working to develop new tests and update our current ones.

COAL SAMPLING AND PREPARATION PARAMETERS: Covers some of the basic problems and acceptable approaches to sampling and preparing coal samples for laboratory analyses. The parameters governing the sampling of coals by hand or mechanical samplers from bulk storage piles, unit train loadouts, and coal-core drilling programs are given and explained. The basic theory of preparing the gross sample for the desired analyses is also covered.

COAL CHARACTERIZATION TESTS: This outlines the most acceptable and most frequently used coal characterization tests normally performed in the modern coal laboratory today. It also explains how some of these tests are used in evaluating a given coal for a given use by the ultimate consumer.

COAL ANALYSES: WHY?

The basic answer to this question can be summed up into one word. There are a number of good reasons, but the one word that describes it best is *economics*.

In our capitalistic form of government, and I am sure that each of us is aware that it is a capitalistic government, as it definitely has all of the capital--our capital! Economics does and must play a major role in all of our endeavors. It has permitted us to build the greatest nation that ever existed on the face of this God's green earth.

This reminds me of an occurrence a few short years back that points this out quite vividly. I was attending one of the meetings of our local Denver Coal Club, and the speaker was speaking on the various approaches to coal gasification and other coal conversion processes. After his talk, and during the question and answer period, he was asked if there had been developed newer and better parameters, other than the customary and historical parameters currently in use that would better define a specific coal for use in the various gasification or conversion processes. He replied that the current, best basic evaluation was, as in the past, how many Btu's does one get for his dollar.

To review briefly the whys and wherefores of coal, we must define it and consider how coal came into being.

Coal may be defined geologically as a combustible, carbonaceous rock composed principally of carbon, hydrogen, nitrogen, oxygen, sulfur, and mineral matter. It is a highly complex and heterogeneous hydrocarbon, and it has eluded official chemical formulation because of the complex variety of chemical bond structures, and because of variations in the amount of identifiable coal species from coal deposit to coal deposit.

In addition to its chemical heterogeneity, coals contain varying amounts of extraneous mineral matter. Because these variations change both chemical and physical properties, coal characterization analyses are extremely important to producers and consumers of coal.

The chemical and the proximate analyses of coal and of other solid fuels are strictly linked with the chemistry and the technology of the solid natural raw materials used in the generation of power, chemical utilization, and other apparent areas in which coal can and will be used. Analysis yields information concerning the structure, the chemical nature, and other properties of a solid fuel. It is, therefore, not only the basic tool of scientific research on the chemistry of coal, but also, in industrial practice, an indispensable factor without which the preparation and the economic utilization of coal and other solid fuels would be impossible.

The knowledge that we have obtained over the years, regarding the solid fuels, can be attributable to the natural sciences, principally to geology, petrography, and palaeobotany, but above all to chemistry and physical chemistry. The ultimate analyses of coal have shown that the organic matter of the natural solid fuels consists, practically speaking, of only 5 elements: carbon, hydrogen, oxygen, nitrogen, and organic sulfur.

Coal heterogeneity, both chemical and physical, reflects the history of its formation. The major coal deposits of the eastern United States originated approximately 150 to 300 million years ago in the swamp forests of the Carboniferous Period. At that time, the Earth's mild climate encouraged vast growths of primitive trees and vegetation. Approximately 3 to 7 ft of compacted plant material was required to form one ft of bituminous coal. The formation of the coal from these vast growths of vegetation was accomplished by very special chemical and physical transformation under extreme heat and pressure. The progressive alteration from peat through a series of coals ranging from lignite to anthracite was a time-consuming process.

Today, the utilization of this final product--coal--includes the firing of industrial and utility boilers, conversion to coke for chemical and metallurgical purposes, gasification, and liquifaction. It is also a raw material for a wide range of applications in the chemical industry, either directly or as a by-product of other areas of utilization. Because of its heterogeneous and complex composition, not all coals are suitable for these purposes. Even within one of these general classifications, there are subdivisions: For example, coals suitable for grate-type boilers may not be suitable for cyclone firing. If only for these reasons, each coal must be subjected to a number of chemical and physical tests to determine its suitability for a specific use and application to a desired market.

In the early 19th Century, Jedrzej Sniadecki, an outstanding Polish chemist, proposed the following unequivocal views on page 287 in his Volume II, "Introduction to Chemistry":

> "Earth coal, or mineral coal (lithantrax), is found in vast seams, or strata, in younger mountains or in plains made up of the same strata. These coal strata, horizontal or sloping, usually alternate with strata of clay, sandstone, or limestone, and are sometimes situated at very great depths. Coal is always black; its luster is sharp, almost metallic; it is rather hard, and of course made up of flakes; it is difficult to ignition [Sic], but once ignited it gives a very strong fire and burns a long time. [...] Most naturalists see in Earth coal relics of wood, decomposed by sea water and by the organisms dissolved in the sea. Indeed, recognizable plants and trees are often found partly altered into coal overlying the seams. Moreover, the layers of earth and rocks overlying the coal, or alternating with the coal seams, contain shells or the remains of sea fish; this seems to prove that deposits of plant and animal organisms accumulated on the sea floor and subsequently buried in earth constituted the origin of the mineral coal, a fact visibly confirmed by the distillation of coal and the evolution of ammonia by fire. The deposits of Earth coal are thus the work of the sea and the relics of plant as well as animal organisms; in particular, the fatness running through them seems to be of animal rather than plant origin. [...] Not always and not everywhere is Earth coal exactly the same, which is why it has been divided into different species."

In view of the above, it is easy to understand that the demand and subsequent development of analytical techniques suitable for research and development work, as well as the routine tests for use in industrial practice, has resulted in the development and the adoption of a great variety of procedures, some of which are more valuable than others. In research and industrial laboratory practice, many of the methods suggested were rejected from the start, others needed improvements and modifications, while many have proved their great practical value. The development of these acceptable practices, methods, and techniques has thus been a slow and lengthy process.

COAL ANALYSES: WHERE?

This is a very simple question, and it has a very simple answer: In a competent and qualified coal testing laboratory. It cannot be stressed too much that the laboratory must have proper knowledge and background in its field of endeavor. A large number of the tests for coal characteristics are empirical, that is, the test must be run by using the very same type of equipment and the procedures for that specific test must be followed exactly, otherwise the results between different chemists and/or different laboratories will not be compatible. There is no college or university, to my knowledge, that graduates a fully-qualified coal chemist. During the 27 years that I have been involved in coal analyses laboratories and the sampling and the analyses of coal, we have constantly found that the coal chemist must be grown. It is true that a basic understanding of chemistry is a must, but the true coal chemist is only a reality after he has gone through the trial-by-fire training in a competent and qualified coal testing laboratory.

Today, there have been developed standarized coal tests that are accepted industrywide. Also, with the current energy crisis, there is great pressure and demand for additional methods and techniques that will give us a much clearer insight into the evaluation and utilization of the various species and types of coals. There is a great need for much more definitive parameters, especially in those areas dealing with the gasification and liquifaction of coal.

The majority of the standardized coal tests that are currently being used today by the world coal industry have been developed by the American Society for Testing and Materials (ASTM), the International Organization for Standardization (ISO), and the standardization bodies of other nations, of which the Japanese Industrial Standards (JIS) is an example. The ASTM standardization of tests for coal and coke started formally in 1904, and this work continues today under Committee D.05.

Development of characterization tests required the work of many people over a long period. In the United States, test methods emerged from individual work supported by private industry, the U.S. Bureau of Mines (USBM), and several State agencies. These tests are accepted as standards on a consensus basis by ASTM Committee D.05, which is composed of members from 3 groups: (1) Coal producers (owners), (2) consumers, and (3) those actively working with coal (but not owned by a producer or a consumer).

The applicability of proposed standards are carefully evaluated by testing coals of different rank. Comparisons are made within and between ASTM members' laboratories. Once established, these standards are constantly reviewed and improved to meet changing market requirements. Also, new and improved analytical equipment and techniques are reviewed to assure that the best available methods are utilized. Coal characterization tests commonly utilized to determine the suitability of each coal for a particular application are summarized later in this discussion.

COAL ANALYSES: WHEN?

The answer to this question is again one of simplicity and logic: Whenever coal must be used, it must be analyzed. Its quality and adaptability for the considered, planned, or intended use must be known. Again, economics is a basic issue; it would not be wise or economical to use a metallurgical coking coal for steam purposes or in a coal conversion process, nor can a non-agglomerating Western low-rank coal be used to make matallurgical coke.

The initial analyses are usually done to evaluate the coal *in-situ*--before it is mined. The current cost to open and operate a modern mine has grown by leaps and bounds in the past few years, especially since the 1969 Safety and Health Act was passed and made the law of the land. It is imperative that the quality and use of the coal be determined and known so that the necessary investment of the millions of dollars of capital required to develop and mine the coals will have a reasonable modicum of success and develop a reasonable return on the required investment during the life of the mine--normally 20 years or longer.

There are many times that analyses of coal must be made, for example, during the development of the initial mining plan, during the entire life of the mine so that coals of reasonable average or even premium quality can consistently be supplied to the consumer. Whenever a unit train is loaded, it must be determined that the load meets contract specifications, or, on today's market, that it will meet environmental restrictions. Yes, I could enumerate many more instances when coal must be analyzed, but those I have given will give you the basic, logical approach to the answer to this question.

COAL ANALYSES: HOW?

The most important procedure in how to analyze coal is the sampling and sample preparation procedures. If the proper representative sample of the coals under consideration is not obtained and delivered to the laboratory for analyses, it is impossible to obtain a representative and accurate analyses. The coal analyses results are only as good as the sample delivered to the laboratory. It is very similar to the statement about computers--trash in, trash out, or non-representative samples to the laboratory, non-representative analyses out. The very best trained and most competent coal chemist cannot develop a good analyses on a bad or non-representative coal sample.

The obtaining of representative samples from coal-core drilling programs, coal stock piles, mine-loading tipples, railroad cars, transfer points, unit trains, or any other area coal must be subjected to sampling for analyses and quality evaluation, presents many variables and highly complex problems. The task of obtaining a representative sample of reasonable weight to represent the lot of coal under consideration presents a large number of problems and, therefore, dictates the utilization, wherever possible, of standard sampling procedures. ASTM D 2234 introduces the problem with the following statement:

> "Data obtained from coal samples are used in establishing price, controlling mine and cleaning plant operations, allocating production costs, and determining plant or component efficiency. The task of obtaining a sample of reasonable weight to represent an entire lot presents a number of problems and emphasizes the necessity for using standard sampling procedures. Coal is one of the most difficult of materials to sample, varying in composition from noncombustible particles to those which can be burned completely, with all gradations in between. The task is further complicated by the use to be made of the analytical results, the sampling equipment available, the quantity to be represented by the sample, and the degree of precision required.
>
> "These standard methods give the over-all requirements for the collection of coal samples. The wide varieties of coal handling facilities preclude the publication of detailed procedures for every sampling situation. The proper collection of the sample involves an understanding and consideration of the physical character of the coal, the number and weight of increments, and the overall precision required."

Again, the time to evaluate all of the problems associated with coal sampling and preparation are too lengthy and complicated to thoroughly cover in the limited time available, but it is most imperative that you obtain the very best qualified and trained personnel available to sample and/or obtain and prepare the coal samples for you and your organization. It is recommended that you hire and utilize the services of a coal testing laboratory that has proven its competency and expertise in this field, and also utilize the services of consultants, both individuals and/or organizations, that are above question. There is a reasonably large number of these available and known. Automatic or mechanical coal sampling devices require the expertise of those that are knowledgable and experienced in this field. The maintenance, evaluation, operation, and use of automatic coal sampling equipment is a science in itself.

COAL CHARACTERIZATION TESTS

Coal characterization tests commonly utilized to determine the suitability of each coal for quality and/or a particular application are summarized in the following paragraphs. A large number of these tests are empirical, therefore, the exact same procedures and equipment must be used by the various laboratories before acceptable reproducible results can be produced. ASTM methods give the acceptable tolerances allowable between duplicate tests on the same sample, by the same laboratory, and also results obtained by different laboratories on duplicate splits of the same sample.

Proximate analysis, ASTM D 3172 (old standards D 271-70), covers the determination of moisture, volatile matter, and ash, and the calculation of fixed carbon on coals and cokes. Some laboratories, especially Commercial Testing & Engineering Co., also include the Btu and Sulfur determinations as part of the "proximate". The historic term "proximate" is misleading because it could be confused with the word" "approximate", whereas all proximate analysis tests are performed according to rigid specifications and tolerances. Results of these analytical methods may be used (1) to establish the rank of coals, (2) to show the ratio of combustible to incombustible constituents, (3) to provide the basis for buying and selling, (4) to evaluate for beneficiation, and (5) for the basic criteria of coal quality, among other purposes.

The forms of moisture in coal have been studied by a number of investigators, and even today some of them are considered an arbitrary definition. Some forms of moisture are as follows: (1) total moisture, (2) free moisture or adherent moisture, (3) physically bound or inherent moisture (that moisture held by vapor pressure and other physical processes), (4) chemically bound water (water of hydration of "combined" water), and (5) bed moisture (*in-situ* moisture).

Total moisture is determined by a two-step procedure (ASTM D 3302). This procedure involves air-drying for removal of "excess" moisture from the gross sample, size reduction, and thermal determination of residual moisture in the prepared sample (ASTM D 3173). An algebraic calculation is used to obtain the "total" moisture.

The as-received moisture is the total moisture at a given time. This term is commonly used in the trade to indicate the moisture present when the coal is delivered to a point of transfer or to the ultimate consumer.

Recognizing that "total moisture" is of such complexity that it must be defined in terms of its method of measurement, ASTM Committee D.05 has defined "total moisture" as a loss in weight in an air atmosphere under rigidly controlled conditions of temperature, time, and air flow. At least in principle, "total moisture" represents a measurement of all the water not chemically combined. Traditionally, thermal treatment has provided the most commonly used basis for attempting to separate the non-chemically bound water from coal. The absolute separation of absorbed moisture without loss of a portion of chemically bound water is practically impossible. The separation is particularly difficult with coals of lower rank.

In other parts of the world, "organic reflux" moisture tests have been used to determine the residual moisture in the prepared sample (ISO R 348). Studies of organic reflux techniques have been made in the United States (USBM RI 4969). These methods may be used to determine moisture and may be particularly applicable for our Western low-rank coals (subbituminous and lignites).

Equilibrium moisture is the moisture-holding capacity of coal at 30°C in an atmosphere of 97 percent relative humidity (ASTM D 1412). The equilibrium moisture of a sample of coal is considered to be equal to the bed moisture, or *in-situ* moisture, for classification of coal by rank (ASTM D 388). Also, equilibrium moisture results may be used for estimating the surface, or extraneous, moisture of wet coal, especially where there appears to be excessive moisture. The difference between total moisture and equilibrium moisture would be surface moisture added during drilling.

Volatile matter is the gaseous products, exclusive of moisture vapor, driven off during standardized test conditions (ASTM D 3175). The expelled gases may be labeled combustible and non-combustible. The combustible gases are carbon monoxide, hydrogen, methane, and other organic hydrocarbons. Those generally classified as non-combustible are carbon dioxide, ammonia, hydrogen sulfide, and some chlorides. Volatile matter is a derived characteristic and is not a natural component of coal.

Because empirical test methods are used, the details of the test procedure must be rigidly adhered to so that test results between laboratories are meaningful. Using the standard ASTM procedure, it is often difficult to obtain repeatable or reproducible results with many low-rank coals. To overcome these problems, low-rank coals have been blended with certain low-volatile bituminous coals. Due to the increased interest in low-rank coals, ASTM Sub-Committee D.05.21 has formed a task group to further investigate these Western coals. Volatile matter test results are used to establish the rank of coals, to indicate coke yield on carbonization processes, or to establish burning characteristics.

Ash is the non-combustible mineral matter left behind when coal is burned under rigidly controlled conditions of temperature, time, and atmosphere (ASTM D 3174). The resulting ash obtained by this method differs in composition from the inorganic constituents present in the original coal. Burning causes the expulsion of water from the clays and calcium sulfate, of carbon dioxide from carbonates, and the conversion of iron pyrites into ferric oxide. Each of these reactions involves a loss of weight from the original material. Formulas for correcting ash values to the original mineral matter basis are presented in ASTM D 388. Other ways in which ash values are used are the following: (1) to calculate other coal characterization values to an ash free basis, (2) to evaluate the efficiency of coal cleaning or beneficiation processes, and (3) to estimate the amount of residue after coal is commercially burned.

Fixed carbon is the solid residue other than the ash resulting from the volatile matter test. Actually, the value is calculated by subtracting moisture, volatile matter, and ash from 100 percent (ASTM D 3172). The results would be on an "as-received" basis. For a given sample, the fixed carbon is always lower than the total carbon (see *ultimate analysis*).

Another historic term, *ultimate analysis*, refers to the individual elements which are combined in the complex coal molecular structure. As defined in ASTM D 3176, these elements are total carbon, total hydrogen, total sulfur, total nitrogen, and oxygen. Ash is included in ultimate analysis as an estimate of the original mineral matter in coal so that it will be possible to calculate the oxygen content. Some laboratories, of which Commercial Testing & Engineering Co. is one, also include the determination of chlorine as part of the ultimate analysis.

Total carbon is determined by catalytic burning of the sample in oxygen to form carbon dioxide, which can be readily measured (ASTM D 3178). Total carbon includes both organic and carbonate carbon. A *total organic carbon* can be calculated by subtracting the carbonate carbon, as determined by ASTM D 1756, from the total carbon.

Total hydrogen also is determined by the catalyt burning of a sample in oxygen to form water. This water is absorbed in a desiccant and is weighed directly (ASTM D 3178). Hydrogen results, as determined by ASTM D 3178, include the hydrogen present in both the residual sample moisture, and water of hydration. The hydrogen from the residual sample moisture can be removed stoichiometrically (ASTM D 3176). Results can be calculated to other moisture basis according to formulae given in ASTM D 3176.

Total sulfur is another part of the ultimate analysis. Sulfur is generally present in 3 forms, and the sum of these is reported as the total sulfur. Total sulfur can be determined by the following 3 chemical methods (ASTM D 3177): (1) the Eschka method, (2) the bomb-washing method, and (3) the high-temperature combustion method. In the Eschka method, the sample is ignited in a mixture of magnesium oxide and sodium carbonate. The sulfur, now in a soluble form, is leached with water and precipitated from the resulting solution as barium sulfate ($BaSO_4$). The precipitate is filtered, ignited, and weighed. In the bomb-washing method, sulfur is also precipitated as $BaSO_4$ from the oxygen-bomb calorimeter washings. In both instances, the sulfur content can be stoichiometrically calculated. In the high-temperature combustion method, the sample is burned in a tube furnace and sulfur oxides are collected in solution and determined by an acid-base titration.

Total nitrogen is determined by chemical digestion (Kjeldahl-Gunning) methods (ASTM D 3179). Total nitrogen is catalytically converted to ammonia. The ammonia is distilled, absorbed by an acidic solution, and measured by an acid-base titration. While not listed in ASTM D 3179, a semi-micro method has proven to give equally accurate results. A semi-micro method is described in ISO R 333.

Total chlorine is determined by ignition of the sample with Eschka mixture, a mixture of magnesium oxide and sodium carbonate. The chlorine, now in soluble form, is leached with water and precipitated with silver nitrate as silver chloride. The amount of chlorine is determined by a back titration with potassium thiocyanate.

Ash as discussed previously under proximate analysis, is analyzed according to ASTM D 3174.

Since there is no satisfactory direct ASTM method of determining *oxygen*, it is calculated by subtracting total carbon, total hydrogen, total sulfur, total nitrogen, total chlorine, and ash from 100 percent (ASTM D 3176). A method for the direct determination of oxygen is given in U.S. Bureau of Mines RI 6753. However, the method is lengthy, and for most applications, the increased precision is not considered by United States investigators to be in proportion to the effort extended.

Other important chemical and physical tests performed to characterize coal are:

1. Heating value (Btu content)
2. Sulfur forms
3. Ash fusibility temperatures
4. Ash analysis
5. Trace elements
6. Free-swelling index
7. Hardgrove grindability.

The *heating value*, sometimes referred to as calorific value, or Btu/lb, is one of the most important determinations necessary in buyer-seller relationships. Several methods have been proposed, but the most common method is the adiabatic bomb calorimeter (ASTM D 2015). The Btu value is determined by actually burning a coal sample in an oxygen bomb and measuring the temperature rise. The temperature rise is converted to Btu/lb by algebraic comparison with the heating value of a standard pure solid, benzoic acid. Corrections are made for the heat contributed by the ignition wire, the heat of formation of nitric acid, and the heat of formation of sulfuric acid (from the sulfur in the coal). The *gross heating* value is normally reported, which assumes that all the combustion product water vapors are condensed. The *net heating value*, a lower value, is calculated from the gross value by assuming that all water in combustion product remains in vapor form (ASTM D 407).

As I have just pointed out, there are a large number of additional coal characterization tests used in the evaluation of coal for its intended use, but time will not permit me to cover these today. There are also screen or sizing analyses, washability studies used to develop washing plants or beneficiation designed parameters, as well as specific specialized coking tests and others. It is very important that you discuss these additional tests, their need, and application thoroughly with the laboratory before your final analyses program for the evaluation of your specific coal is finalized.

REFERENCES

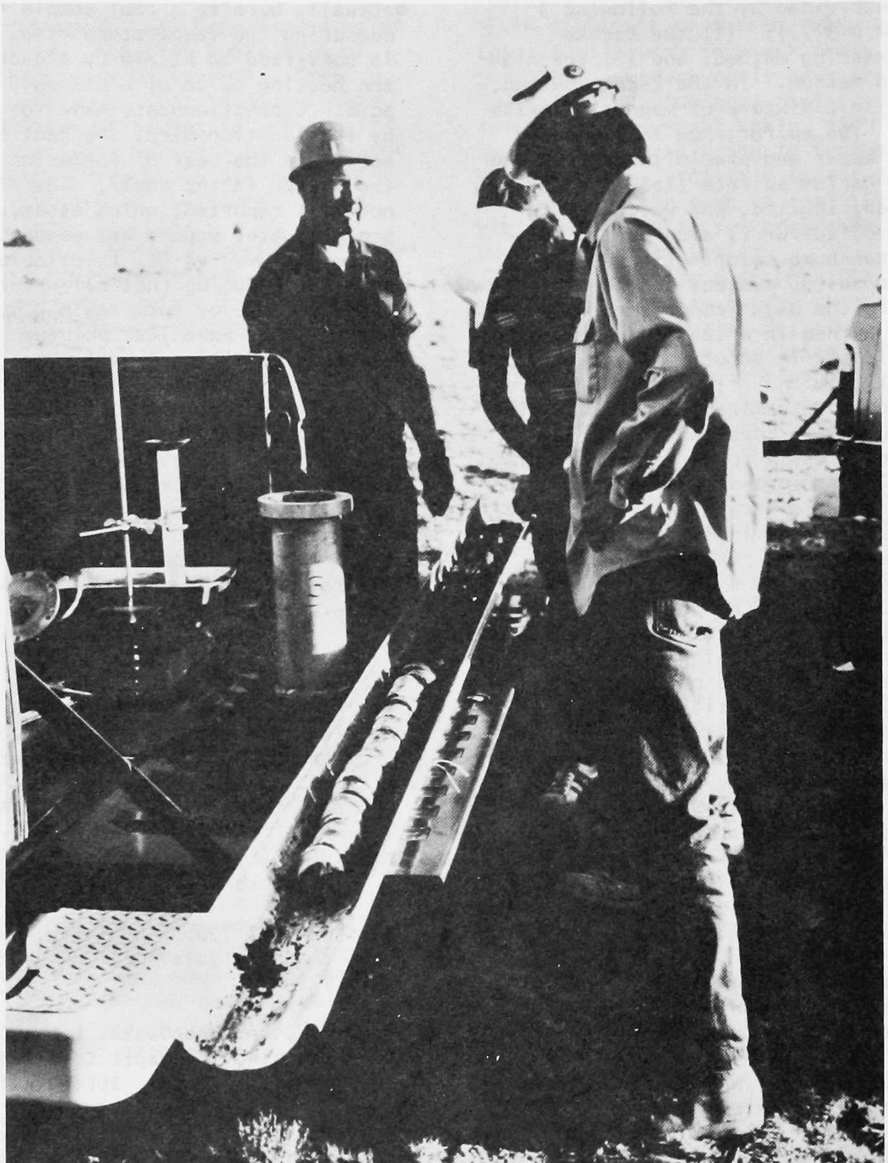
American Society for Testing and Materials, 1975, Annual Book of ASTM Standards, Part 26: Gaseous Fuels; Coal and Coke; Atmospheric Analysis (Coal and Coke, p. 179-428), ASTM, Philadelphia, PA

Krumin, P.O., 1963, The determination of forms of moisture in coal: Ohio State Univ. Bull. 195.

Rees, O. W., 1966, Chemistry, uses and limitation of coal analysis: Illinois State Geol. Survey RI 220

Roga, B., and Wnekowska, L., 1965, Analysis of solid fuels: U. S. Dept. Commerce Federal Scientific and Tech. Info., Springfield, VA

Savage, K. I., 1976, Coal testing, *in* Handbook of Energy Technology: New York, McGraw Hill.



Laying out core preparatory to placing coal in methane desorption cylinder, Huerfano County, Colorado

TRACE ELEMENTS IN ROCKY MOUNTAIN COALS

JOSEPH R. HATCH: U.S. Geological Survey
Denver, Colorado 80225

VERNON E. SWANSON: U.S. Geological Survey
Denver, Colorado 80225

ABSTRACT: Since 1971, the U.S. Geological Survey, in cooperation with other Federal and State agencies, educational institutions, and private companies, has collected and chemically analyzed more than 3,100 channel samples of coal beds from 30 States. For each sample, the Survey's analytical laboratories have quantitatively determined the amounts of 24 major, minor, and trace elements (including As, Cd, Cu, F, Hg, Pb, Sb, Se, Th, U, and Zn), and have semiquantitatively determined the concentrations of between 15 and 20 additional trace elements (including B, Be, Cr, Ge, Mo, Ni, and V). In addition, the U.S. Bureau of Mines has performed proximate and ultimate analyses, and Btu and forms-of-sulfur determinations on most of the samples. These analytical data on coal are used for environmental evaluations; assessment of possible coal-mining, coal-preparation, and coal-use problems; estimating byproduct recovery potential; and geological and geochemical interpretations.

Rocky Mountain province and Northern Great Plains province coals, when compared to Interior province coals, have appreciably lower concentrations of most elements of environmental concern. Distinct compositional differences also exist between adjacent coal regions or fields, as shown by data from the Fort Union and Powder River regions and by data from the San Juan River region and Black Mesa field.

INTRODUCTION

Three topics are to be covered in this paper: first, a brief review of the U.S. Geological Survey's program on the composition of coal; second, a discussion on how analysis for major, minor and trace elements are used; and, third, a summary and brief comparison of coal compositional information from the Northern Great Plains, Rocky Mountain, and Interior coal provinces, from the Powder River region and Fort Union region and from the San Juan River region, and Black Mesa field (see Fig. 1).

U.S. Geological Survey's Program on Composition of Coal

One objective of the Survey's program on composition of coal is to provide a detailed data base for evaluating the overall chemical composition of coal in the United States. This program began in 1971 with the U.S. Department of Interior's Southwest Energy study. During the course of this study, major, minor, and trace elements in 71 coal and 16 power plant ash samples from the Southwestern United States were determined (Swanson, 1972).

Since then, some 3,100 samples of coal, power-plant ash, and coal-associated rocks have been submitted to the Survey's analytical laboratories. These samples represent coals from 30 of the 37 States that have coal-bearing rocks and were collected by U.S. Geological Survey personnel, State Geological Survey personnel, and personnel from mining companies and universities.

The geographic distribution of these samples is indicated on Table 1.

Table 1: Geographic distribution of coal and coal-related rock and ash samples.

Area	Number of samples	Area	Number of samples
Eastern province	883	Rocky Mountain province	690
Gulf Coast province	70	Pacific Coast province	10
Interior province	425	Alaska province	90
Northern Great Plains province	920	Total samples	3,088

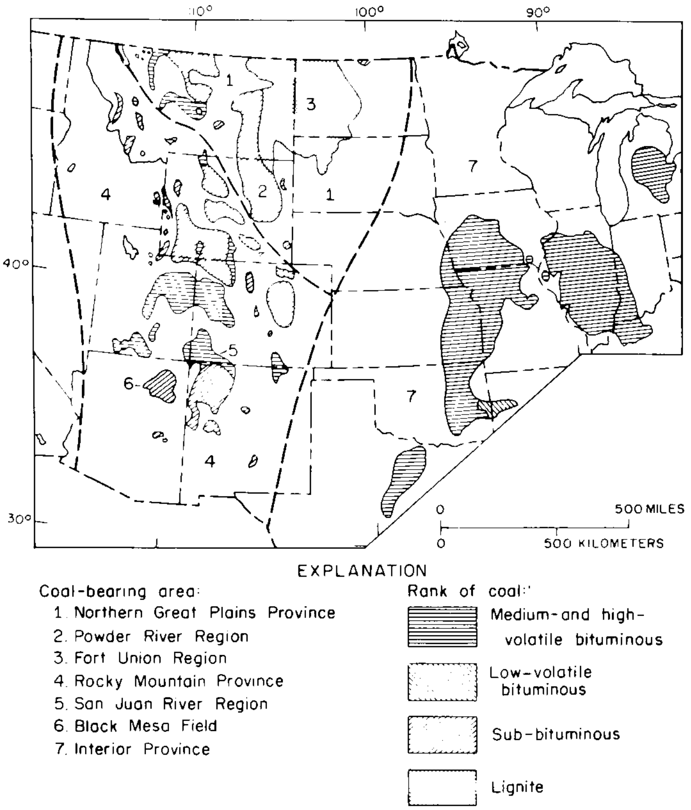


Fig 1: Location of coal-bearing areas discussed in the text. (modified from Trumbull, 1960)

All the different analyses for more than 2,000 of the approximately 3,100 samples have been completed.

The sequence of analyses preformed on samples is shown on Figure 2.

A total of 24 major, minor, and trace elements are determined quantitatively. An additional 15 to 20 elements are determined semiquantitatively.

USEFULNESS OF MAJOR, MINOR, AND TRACE ELEMENT DATA ON COAL

There are four somewhat overlapping reasons for obtaining comprehensive and precise chemical analyses on coal: (1) to assess environmental implications of coal mining and utilization, (2) to determine the most suitable use of coal, (3) to assess possible byproduct recovery, and (4) to provide a base for making geological and geochemical interpretations.

Environmental implications: In concentrated amounts, some trace and minor elements in coal may cause environmental problems. Current interest is focused on the amounts of mercury, arsenic, selenium, antimony, fluorine, cadmium, lead, boron, and beryllium that may be released to the atmosphere during coal combustion or to soils and water from coal ash. The Federal Clean Air Act of 1970 sets SO_2 controls, and indicates that emission standards will be set for both beryllium and mercury. Very likely within the next decade standards also will be set for arsenic, selenium, fluorine, and cadmium.

The concentration level of an element in coal does not directly indicate the concentration level or the form in which an element is emitted from a coal-fired power plant. After combustion, the relative amounts of an element in the bottom ash, fly ash, flue gas, or process water, depend upon many factors, including size and operating temperature of the furnaces, number and efficiency of the scrubbers and precipitators, and the mineralogical composition of the ash. For example, in a study of three power stations by Radian Corporation for EPA, the selenium emission to the atmosphere ranged from a few to almost 65 percent of the selenium initially in the coal (Radian Corporation, 1975).

The first step in evaluating the fate of each element during combustion is to determine how much and in what form each element is in the coal. With this knowledge, preferably obtained before mining and utilization, plans can be made to control, or at least minimize, problems that may arise. Contingency plans may include selective mining, prewashing the coal, or blending with other coal.

Technological use: Trace and minor element composition of the coal can be a factor in plant design, and in the physical preparation of the coal necessary prior to use. Boiler fouling and corrosion are potentially serious problems that are caused primarily by high concentrations of alkali metals (particularly sodium), sulfur, and chlorine. In coking coals, elements such as phosphorous and arsenic tend to lower the steel quality, and their concentrations and distribution have to be considered. If the coal is to be used for coal gasification or liquifaction, the concentration and distribution of possible catalytic poisons, such as vanadium, need to be known. Not every trace or minor element in coal is detrimental, however; for example, high concentrations of cesium and potassium in the coal may be a definite asset if the coal is being considered for a magnetohydrodynamic power plant.

Byproduct recovery: Some elements in coal may be concentrated sufficiently to be of economic interest. The best example is zinc which is locally present as sphalerite (ZnS) in the coal of northwestern Illinois, southeastern Iowa, and northeastern and southwestern Missouri. In the coal of this region, sphalerite occurs with pyrite, calcite, and kaolinite in vertical cleats or fractures. Because of the relatively high sulfur content of this coal, the coal is commonly washed before use to remove most of the sulfide minerals by gravity separation. Thus, the sphalerite is removed and concentrated in the heavy mineral fraction. The maximum content determined in a mineable coal is about 6,000 parts-per-million zinc, calculated on a whole-coal basis, or about 3 percent of the ash. If all of the zinc could be recovered in a coal-washing plant, from a mine producing one million tons of this coal per year, an ore containing about 6,000 tons of elemental zinc could be shipped to a smelter each year. With zinc currently selling for about 37¢ a pound, the 6,000 tons could represent nearly $4.5 million worth of zinc.

Other elements that may be economically recoverable from coal include germanium, selenium, uranium, and vanadium. In the current study, concen-

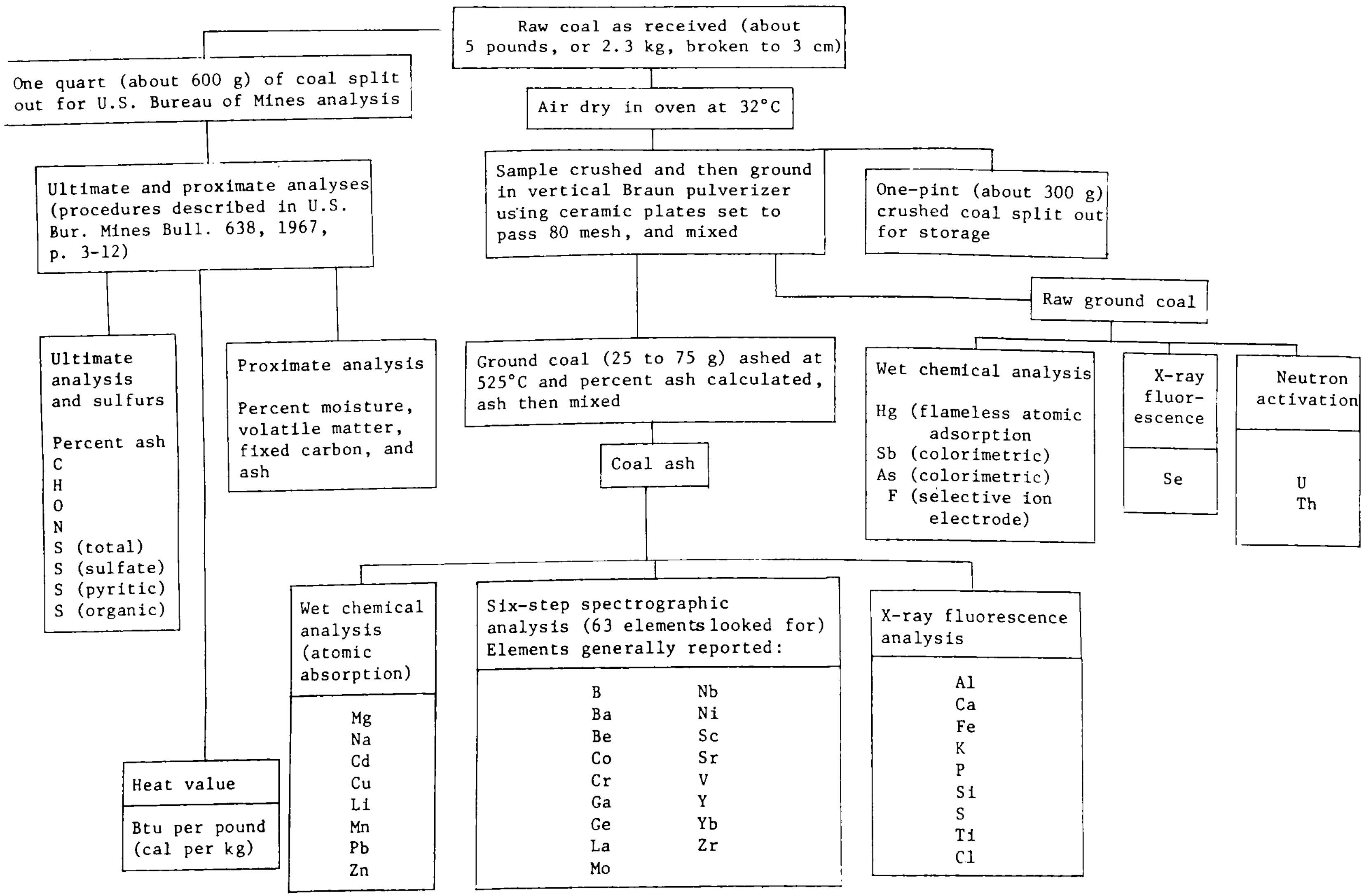


Fig. 2: Flow chart showing sequence of sample preparation and chemical analysis. (from Swanson and Huffman, 1976, Fig. 1)

PRINCIPLE PHASES IN COAL	MAJOR ELEMENTS	MINOR AND TRACE ELEMENTS
A. Organic fraction	C, H, N, O	S, Fe, Ti, B, Ni, V, Cu, Mo, Co, Cr, Ga, Mn, Ge, Be (Na, Ca, Mg, Sr, and Ba in lower rank coals)
B. Silicate fraction		
Clays	Si, Al, K, Mg, Ca, O	B, Ti, Zr, Fe, Cu, V, Cr, Ni, Mn,
Quartz		Pb, Sc, Ga, Li
C. Sulfide fraction		
Pyrite or marcasite	Fe, S	As, Hg, Sb, Cu, Ni, Co, Se, Ag
Sphalerite	Zn, S	Cd, Ge
D. Carbonate fraction	Ca, Mg, Fe, C, O	Mn, Sr, Ba
E. Other mineral fractions		
Phosphate	Ca, P, O	F, U
Sulfate	Ca, Ba, Na, S, O	Sr
Oxide	Ti, Th, Mn, O	

Fig. 3: Association of major, minor and trace elements with each of the principle phases of coal.

trations of germanium in coal ash of up to 1,000 parts-per-million (0.1 percent) have been determined for samples from the eastern United States.

Geochemical interpretations: The fourth reason for chemical analyses of coal is to obtain geochemical information. The geochemical behavior of an element can be better understood through knowledge of its distribution among the several organic and mineral components of coal. Regional, local, and stratigraphic variations in element concentrations or in ratios between elements may lead to a better understanding of paleodepositional processes and subsequent geologic history. It should be emphasized, however, that trace and minor element data by themselves, to date, have supplied few unique geological interpretations. Geologically useful information supplied by element data will more than likely be supplemental to information supplied by detailed stratigraphic and sedimentological studies.

There are two primary problems in basing geologic interpretations on element data only: First, the given element may have been fixed in the coal at several different time periods, and, second, the element may be in the coal in one or more phases. An element may be incorporated in the coal through fixation in the original plant material or brought in with detrital minerals, through adsorption by organic compounds during the peat stage, or through deposition of minerals in cleats or fractures from ground water or hydrothermal solutions moving through the coal. One consequence of multiple depositional processes is that an element may occur in the coal in a variety of phases. Figure 3 illustrates the possible residence sites of many of the major, minor and trace elements in coal. Sources of information summarized in this figure include Clark and Swaine (1962), and Zubovic and others (1960 and 1961).

The principal conclusion to be drawn from Figure 3 is that many elements have more than one possible phase association in the coal. Calcium, for example, may occur in the coal as an insoluble humate (Fuchs, 1935), possibly included in the expandable or mixed-layer clay minerals described in coal by Gluskoter (1967), in calcite or dolomite (Rao and Gluskoter, 1973), in apatite (Ruch and others, 1974, plate 1) or in the gypsum observed on most coal outcrops.

The geological application of trace and minor element data requires knowledge of the concentration level of an element, and also the distribution of that element within the coal bed. An example of the geological use of element data is in the use of boron as a paleosalinity indicator. Many researchers, including Walker (1968), Couch (1971), and Bohor and Gluskoter (1973), have shown that boron concentration in illite is an indicator of the paleosalinity. An analysis of total boron in coal would include the organically bound boron, boron in clays other than illite, as well as boron in other detrital minerals such as tourmaline. Therefore, because of these different boron residence sites, any reported boron analyses of coal will be relatively useless for paleosalinity determinations until the distribution of boron within each coal is carefully determined.

CHEMICAL COMPOSITION OF WESTERN COAL

Statistical summaries are presented for currently available modern U.S. Geological Survey analyses of coal from the Northern Great Plains and Rocky Mountain provinces; from the Fort Union and Powder River regions; and from the San Juan River region and Black Mesa field. For comparison, a statistical summary of Interior Province coal follows those of the Northern Great Plains and Rocky Mountain province. Two tables are given for each of these 7 areas; the first table lists means and ranges of major and minor oxides and 5 trace elements in ash of coal; the second table presents the means and ranges of elements measured directly on whole coal, or calculated from ash analyses to a whole-coal basis, and includes a listing of the average composition of shale (Turekian and Wedepohl, 1961, table 2) for comparison.

Many of the chemical analyses used to compute the statistical summaries presented on Tables 2 through 8 are listed in Swanson (1972), U.S. Geological Survey and Montana Bureau of Mines and Geology (1973, 1974, and 1976), U.S. Bureau of Land Management (1975a, b, and c), Glass (1975), Swanson and others (1974), and Swanson and others (1976).

In this report the geometric mean (GM) is used as the estimate of the most probable concentration (mode); the geometric mean is the antilog of the mean of the logrithm of concentration. The measure of scatter about the mode used here is the geometric deviation (GD) which is the antilog of the standard deviation of the logarithms of concentration. These statistics are used because of the common tendency for the amounts of trace elements in natural materials to exhibit positively skewed frequency distributions; these distributions are normalized by analyzing and summarizing trace element data on a logarithmic basis.

If the frequency distributions are lognormal, the geometric mean is the best estimate of the mode, and the estimated range of the central two-thirds of the observed distribution has a lower limit equal to GM/GD and an upper limit equal to GM·GD. The estimated range of the central 95 percent of the observed distribution has a lower limit equal to $GM/(GD)^2$ and an upper limit equal to $GM \cdot (GD)^2$ (Connor and others, 1976).

Although the geometric mean is, in general, an adequate estimate of the most common concentration, it is, nevertheless, a biased estimate of the arithmetic mean. In the summary tables of data, the estimates of the arithmetic means are Sichel's $\underline{t}$ statistic (Miesch, 1967). In this report the terms arithmetic mean, average value, and abundance are used synonymously.

A common problem in statistical summaries of trace element data arises when the element concentration in one or more of the samples is below the limit of analytical detection, resulting in a censored distribution. Procedures developed by Cohen (1959) were used to compute unbiased estimates of the geometric mean, geometric deviation, and arithmetic mean where the concentration data are censored.

DISCUSSION

A comparison of the average (arithmetic mean) composition of ash of coal from the Northern Great Plains, Rocky Mountain, and Interior provinces (Tables 2a, 3a, and 4a) shows that the CaO, MgO, Na_2O, and SO_3 content of the ash of Northern Great Plains province coal is about two times greater than in the other two provinces. The ash of Rocky Mountain province coal is similarly higher in SiO_2 and Al_2O_3, while the ash of Interior province coal is two times higher in K_2O, Fe_2O_3, and MnO, and Zn, Cd, and Pb are five to 25 times higher. The average ash content of Interior province coal is 50 percent greater than that of Northern Great Plains coal.

When compared on a whole-coal basis, Northern Great Plains province coal has a higher Mg and Sr content, Rocky Mountain province coal is higher in Si and Al, while the Interior province coal is distinctly higher in K, Fe, Mn, As, Cd, Cu, Pb, Sb, Se, U, Zn, Be, Co, Cr, Mo, and Ni.

A comparison of the average composition of coal ash from Fort Union region coal with coal ash from Powder River region coal (Tables 5a and 6a) shows that the Fort Union coal ash contains nearly twice as much MgO and Na_2O, while Powder River region coal ash has a higher content of SiO_2, Al_2O_3, K_2O, Cu, Pb, and Zn. The average ash content of the coal from the two regions is very similar.

When compared on a whole-coal basis (Tables 5b and 6b), Fort Union region coal has a Mg and Na content about twice that of coal in the Powder River region, while Powder River region coal is significantly higher in Si, Al, K, Cu, Th, Zn, Cr, Ni, and V.

A comparison of the composition of coal ash from the San Juan River region with that from the Black Mesa field (Tables 7a and 8a) shows that the San Juan River region coal ash is significantly higher in SiO_2, Al_2O_3, Li, and Pb, while the ash of coal from the Black Mesa field is significantly higher in CaO, MgO, Fe_2O_3, and SO_3.

When a comparison is made on a whole-coal basis (Tables 7b and 8b), San Juan River region coal has significantly higher contents of Si, Al, Na, K, Mn, Ti, Cu, F, Hg, Li, Pb, Th, U, Zn, B, Ga, V, and Zr. Because San Juan River region coal has more than twice the average ash content when compared to Black Mesa field coal (21.1 versus 8.0 percent), many of these elements very likely are associated with detrital minerals in the coal.

SUMMARY OBSERVATIONS

1. When trace element contents in coal from the Northern Great Plains and Rocky Mountain provinces are compared to Interior province coal, the Northern Great Plains and Rocky Mountain coal contains appreciably lesser amounts of most elements of environmental concern. In Western coal one just does not find the 150 ppm Se or 250 ppm As values in the whole coal, or 60,000 ppm Zn or 580 ppm Cd that have been noted in the ash of some Interior or Eastern province samples.

2. Higher concentrations of Mg, and Na are present in Northern Great Plains and Rocky Mountain coal than in Interior province coal. Coal from the Fort Union region is particularly high in these two elements.

3. To date, no concentrations of trace and minor elements in Northern Great Plains and Rocky Mountain coal appear to be sufficiently high to be of economic interest.

4. The average uranium content in mineable coal from the Fort Union region is 1.0 ppm. This information should serve to dispel the mistaken belief that large amounts of uranium could be recovered from lignite being mined in this region.

5. In a comparison of the average trace and minor element contents of coal and shale, only selenium (Se) is consistently enriched in the coal as compared to shale. Coal, as a rock type, is depleted in most other minor and trace elements.

In summary, one can conclude that trace and minor element information will become increasingly

Table 2a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 490 Northern Great Plains province coal samples.

(All samples were ashed at 525°C; L after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range		Geometric mean (expected value)	Geometric deviation
		Minimum	Maximum		
Ash %	9.8	3.2	84.9	9.0	1.5
SiO_2 %	29	1.0 L	69	24	1.8
Al_2O_3 %	14	2.6	30	13	1.5
CaO %	19	.36	49	16	1.8
MgO %	4.59	.28	14.3	4.00	1.7
Na_2O %	2.07	.27	12.4	1.00	3.3
K_2O %	.45	.022	3.1	.22	3.3
Fe_2O_3 %	7.5	.12	77	5.6	2.1
MnO %	.060	.02 L	.45	.034	2.9
TiO_2 %	.67	.082	1.61	.59	1.6
SO_3 %	17	.28	45	15	1.8
Cd ppm	.8	1.0 L	20	.5	2.4
Cu ppm	114	4.6	685	91	2.0
Li ppm	54	5 L	186	40	2.2
Pb ppm	62	25 L	1,660	49	2.0
Zn ppm	186	12	2,480	106	2.8

Table 2b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 490 Northern Great Plains province coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown)

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	1.4	0.01 L	25	1.0	2.3	7.3
Al %	.73	.11	11	.61	1.8	8.0
Ca %	1.2	.086	7.8	1.0	1.6	2.21
Mg %	.238	.013	.758	.218	1.5	1.55
Na %	.122	.001	.672	.067	3.0	.96
K %	.042	.001L	1.2	.018	3.7	2.66
Fe %	.55	.010	14	.36	2.5	4.72
Mn ppm	50	9.0 L	440	33	2.5	850
Ti %	.040	.004	.13	.034	1.7	.46
As ppm	4	1 L	45	2	2.5	13
Cd ppm	.08	.02	2.7	.04	2.8	.3
Cu ppm	10.5	.34	76	8.2	2.0	45
F ppm	47	20 L	340	38	1.9	740
Hg ppm	.11	.01 L	3.8	.08	2.2	.4
Li ppm	5.6	.32 L	49.2	3.6	2.6	66
Pb ppm	5.9	1.2 L	76	4.8	1.9	20
Sb ppm	.6	.1 L	43	.4	2.6	1.5
Se ppm	.9	.1 L	13	.6	2.4	.6
Th ppm	4.3	.04	28	3.4	2.0	12
U ppm	.9	.07	7.5	.6	2.6	3.7
Zn ppm	17.9	1.0	218	9.4	3.1	95
B ppm	70	15	300	70	1.8	100
Ba ppm	500	10	2,000	300	2.3	580
Be ppm	.7	.1 L	15	.5	2.4	3
Co ppm	2	.3 L	20	2	2.1	19
Cr ppm	5	.5	100	3	2.3	90
Ga ppm	2	.5	20	2	1.9	19
Mo ppm	2	.3 L	70	1.5	2.4	2.6
Nb ppm	1.5	.7 L	30	.7	3.3	11
Ni ppm	5	.5 L	300	2	2.5	68
Sc ppm	2	.5 L	20	1.5	1.8	13
Sr ppm	300	15	1,500	200	2.3	300
V ppm	15	1	150	10	2.3	130
Y ppm	5	.7 L	30	3	2.1	26
Yb ppm	.3	.07 L	3	.3	2.0	2.6
Zr ppm	15	2	150	15	1.8	160

Table 3a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 295 Rocky Mountain province coal samples.

(All samples were ashed at 525°C; L after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range		Geometric mean (expected value)	Geometric deviation
		Minimum	Maximum		
Ash %	13.3	1.76	88.2	10.9	1.9
SiO_2 %	46	15	79	44	1.4
Al_2O_3 %	21	4.3	35	19	1.4
CaO %	8.9	.21	35	6.2	2.4
MgO %	1.63	.22	7.10	1.4	1.8
Na_2O %	1.39	.08	8.56	.68	3.3
K_2O %	.65	.05	3.0	.45	2.3
Fe_2O_3 %	7.6	1.1	26	4.5	2.8
MnO %	.049	.004	.55	.029	2.8
TiO_2 %	.89	.02L	1.8	.81	1.6
SO_3 %	8.4	.10L	29	5.1	2.7
Cd ppm	.7	.5 L	4.0	.6	1.9
Cu ppm	87	22	1,260	77	1.6
Li ppm	88	10 L	328	73	1.9
Pb ppm	45	20 L	195	41	1.5
Zn ppm	77	13	1,820	62	1.9

Table 3b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 295 Rocky Mountain province coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F. Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown)

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	3.2	0.9	23	2.3	2.3	7.3
Al %	1.6	.14	13	1.1	2.3	8.0
Ca %	.61	.05	3.7	.48	2.0	2.21
Mg %	.107	.015	.76	.089	1.8	1.55
Na %	.155	.002	.76	.055	4.2	.96
K %	.092	.003	1.7	.041	3.6	2.66
Fe %	.64	.10	4.2	.34	3.1	4.72
Mn ppm	33	2.7	492	20	2.6	850
Ti %	.062	.001L	.54	.047	2.1	.46
As ppm	2	1 L	50	2	2.5	13
Cd ppm	.08	.021	.50	.05	2.7	.3
Cu ppm	10.8	1.3	100	8.4	2.0	45
F ppm	95	20 L	920	69	2.2	740
Hg ppm	.08	.01	1.48	.05	2.4	.4
Li ppm	13	.44 L	82.9	8.0	2.7	66
Pb ppm	6.5	.95	62	4.7	2.2	20
Sb ppm	.4	.05 L	5.2	.3	2.2	1.5
Se ppm	1.6	.10L	5.7	1.2	2.1	.6
Th ppm	4.2	1.7	34.8	2.9	2.5	12
U ppm	1.9	.1	23.8	1.1	2.8	3.7
Zn ppm	10.7	1.0	380	6.8	2.6	95
B ppm	70	7	300	70	2.2	100
Ba ppm	300	3	1,500	150	2.6	580
Be ppm	.7	.05	3	.5	2.3	3
Co ppm	2	.3	10	1.5	2.0	19
Cr ppm	5	.5	70	5	2.2	90
Ga ppm	5	.3	30	3	2.3	19
Mo ppm	2	.2	15	1.5	2.3	2.6
Nb ppm	1	.3	30	.5	2.6	11
Ni ppm	3	.7	20	2	2.1	68
Sc ppm	2	.3	15	1.5	2.0	13
Sr ppm	100	5	700	100	2.1	300
V ppm	15	1.5	100	100	2.1	130
Y ppm	7	.5	30	5	2.1	26
Yb ppm	.7	.03	3	.5	2.2	2.6
Zr ppm	30	3	100	20	2.3	160

Table 4a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 155 Interior province coal samples.

(All samples were ashed at 525°C; L after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range Minimum	Maximum	Geometric mean (expected value)	Geometric deviation
Ash %	15.7	2.1	45.9	12.9	1.9
SiO_2 %	27	3.5	57	24	1.7
Al_2O_3 %	13	1.4	31	11	1.7
CaO %	10	.31	30.	5.4	3.1
MgO %	1.25	.10 L	10	.81	2.6
Na_2O %	.37	.08	3.4	.27	2.2
K_2O %	1.3	.07	3.2	.99	2.0
Fe_2O_3 %	30	3.6	69	26	1.7
MnO %	.12	.010	4.7	.075	2.7
TiO_2 %	.62	.10	1.4	.54	1.7
SO_3 %	7.0	.38	29	4.8	2.4
Cd ppm	48	1 L	580	.8	18.5
Cu ppm	147	26	632	126	1.7
Li ppm	74	10 L	276	54	2.2
Pb ppm	295	25 L	2,700	146	3.3
Zn ppm	2,220	36	60,000	451	6.0

Table 4b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 155 Interior province coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown; G means greater than the value shown)

Element	Arithmetic mean (abundance)	Observed range				Geometric mean (expected value)	Geometric deviation	Average shale
		Minimum		Maximum				
Si %	2.0	.14		9.0		1.4	2.3	7.3
Al %	.97	.15		3.6		.77	2.0	8.0
Ca %	1.2	.025		6.3		.50	3.8	2.21
Mg %	.089	.009		1.0		.063	2.3	1.55
Na %	.035	.002		.21		.026	2.2	.96
K %	.16	.011		.53		.11	2.4	2.66
Fe %	3.3	.23		16		2.3	2.4	4.72
Mn ppm	138	4.4		4,400		72	3.1	850
Ti %	.052	.01		.21		.040	2.1	.46
As ppm	21	1	L	240		12	2.9	13
Cd ppm	7.1	.02	L	100		.12	18.3	.3
Cu ppm	20.2	3.7		158		16.3	1.9	45
F ppm	71	20	L	330		58	1.9	740
Hg ppm	.14	.01	L	.83		.10	2.3	.4
Li ppm	11	.44		80		7.0	2.7	66
Pb ppm	55	.7	L	283		19	4.3	20
Sb ppm	1.7	.1	L	16		.8	3.4	1.5
Se ppm	4.6	.23		75		2.8	2.7	.6
Th ppm	5.2	3.0	L	79		1.6	4.8	12
U ppm	3.3	.2	L	43		1.4	3.8	3.7
Zn ppm	373	1.2		18,000		58	6.9	95
B ppm	100	1.5	L	200		50	3.4	100
Ba ppm	70	5		3,000		30	2.6	580
Be ppm	3	.1	L	5		1.5	3.1	3
Co ppm	7	1		100		7	2.3	19
Cr ppm	15	2		70		10	2.0	90
Ga ppm	5	.5	L	10		3	2.0	19
Mo ppm	5	.7	L	50		2	2.8	2.6
Nb ppm	1.5	.5	L	7		.7	2.6	11
Ni ppm	30	1		200		18	2.4	68
Sc ppm	3	.51		15		3	2.1	13
Sr ppm	50	3		5,000	G	30	2.8	300
V ppm	20	3		150		20	2.1	130
Y ppm	10	1.5	L	70		7	1.9	26
Yb ppm	.7	.2		3		.7	2.0	2.6
Zr ppm	15	2		70		10	2.0	160

Table 5a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 80 Fort Union region coal samples.

(All samples were ashed at 525°C; L shown after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range Minimum	Maximum	Geometric mean (expected value)	Geometric deviation
Ash %	9.5	5.04	25.6	9.0	1.4
SiO_2 %	18	1.0	47	13	2.1
Al_2O_3 %	9.5	2.9	21	8.6	1.5
CaO %	24	6.3	38	22	1.4
MgO %	7.42	2.22	14.3	7.01	1.4
Na_2O %	3.30	.08	12.4	1.43	3.7
K_2O %	.16	.06	1.2	.059	4.1
Fe_2O_3 %	8.9	.12	50	5.0	2.9
MnO %	.041	.036L	.12	.019	3.6
TiO_2 %	.60	.09	1.1	.49	1.9
SO_3 %	22	6.7	45	19	1.6
Cd ppm	1 L	1 L	1	1 L	---
Cu ppm	56	46	132	42	2.1
Li ppm	36	5 L	160	27	2.2
Pb ppm	34	25 L	100	31	1.5
Zn ppm	31	12	272	26	1.9

Table 5b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 80 Fort Union region coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown.)

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	0.85	0.03	5.0	0.55	2.5	7.3
Al %	.48	.11	1.7	.41	1.7	8.0
Ca %	1.5	.78	2.8	1.4	1.3	2.21
Mg %	.393	.171	.668	.380	1.3	1.55
Na %	.223	.006	.672	.095	3.7	.96
K %	.013	.01 L	.15	.006	3.6	2.66
Fe %	.63	.01	8.9	.32	3.3	4.72
Mn ppm	41	20 L	118	29	2.3	850
Ti %	.034	.01	.078	.028	1.8	.46
As ppm	5	1	30	4	2.4	13
Cd ppm	.1 L	.1 L	.2	.1 L	3.6	.3
Cu ppm	5.3	.3	15.4	3.8	2.3	45
F ppm	35	20 L	120	26	2.1	740
Hg ppm	.14	.01 L	.60	.09	2.4	.4
Li ppm	3.7	.3 L	22.6	2.4	2.6	66
Pb ppm	4.4	1.4 L	11.1	3.8	1.7	20
Sb ppm	.4	.1	3.0	.2	2.4	1.5
Se ppm	.7	.1	2.0	.6	1.8	.6
Th ppm	2.8	2.0 L	9.4	2.4	1.9	12
U ppm	1.0	.1 L	5.1	.6	2.6	3.7
Zn ppm	3.0	1.0	27.7	2.3	2.1	95
B ppm	150	15	300	100	1.8	100
Ba ppm	500	15	2,000	300	2.9	580
Be ppm	.5	.2 L	15	.15	4.1	3
Co ppm	2	.3 L	3	1.5	2.2	19
Cr ppm	2	.5	10	1.5	1.9	90
Ga ppm	1.5	.5	7	1.5	1.7	19
Mo ppm	1.5	.3 L	10	1	2.3	2.6
Nb ppm	1.5	1.5 L	5	1	4.0	11
Ni ppm	1.5	.7 L	7	1.5	1.8	68
Sc ppm	2	.5 L	7	1.5	1.9	13
Sr ppm	500	150	1,500	500	1.7	300
V ppm	5	1	30	3	2.2	130
Y ppm	5	1 L	15	3	2.0	26
Yb ppm	.3	.1 L	1.5	.2	1.9	2.6
Zr ppm	15	2	70	10	2.1	160

Table 6a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 410 Powder River region coal samples

(All samples were ashed at 525°C; L after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation
Ash %	9.9	3.2	84.9	9.0	1.5
SiO_2 %	30	5.8	69	28	1.6
Al_2O_3 %	14	2.6	30	14	1.4
CaO %	18	.36	49	15	1.8
MgO %	4.01	.28	12.3	3.56	1.6
Na_2O %	1.85	.03	8.71	.93	3.2
K_2O %	.50	.02 L	3.1	.28	3.0
Fe_2O_3 %	7.3	.39	77	5.8	2.0
MnO %	.062	.020L	.45	.036	2.8
TiO_2 %	.68	.08	1.6	.61	1.6
SO_3 %	17	.28	39	14	1.8
Cd ppm	.8	1 L	20	.6	2.4
Cu ppm	123	30	685	107	1.7
Li ppm	58	1	186	43	2.2
Pb ppm	68	25 L	1,660	54	2.0
Zn ppm	208	16	2,480	141	2.4

Table 6b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 410 Powder River region coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown)

Element	Arithmetic mean (abundance)	Observed range		Geometric mean (expected value)	Geometric deviation	Average shale
		Minimum	Maximum			
Si %	1.5	1.6	25	1.2	2.1	7.3
Al %	.78	1.4	11	.66	1.8	8.0
Ca %	1.1	.086	7.8	.98	1.6	2.21
Mg %	.207	.013	.758	.195	1.4	1.55
Na %	.106	.001	.491	.063	2.8	.96
K %	.048	.001L	1.2	.022	3.5	2.66
Fe %	.54	.051	14	.37	2.4	4.72
Mn ppm	51	10	443	34	2.5	850
Ti %	.041	.004	.12	.035	1.7	.46
As ppm	3	1 L	45	2	2.4	13
Cd ppm	.09	.1 L	2.7	.04	2.8	.3
Cu ppm	11.2	2.4	76	9.5	1.8	45
F ppm	49	20 L	340	40	1.9	740
Hg ppm	.11	.01	3.8	.08	2.1	.4
Li ppm	5.9	.4	32	3.9	2.5	66
Pb ppm	6.4	1.2 L	76	5.1	1.9	20
Sb ppm	.6	.1 L	43	.4	2.6	1.5
Se ppm	1.0	.1 L	13	.7	2.5	.6
Th ppm	4.3	2 L	28.2	3.3	2.1	12
U ppm	.9	.1 L	7.5	.6	2.6	3.7
Zn ppm	20	1.5	218	12.5	2.7	95
B ppm	70	15	150	50	1.6	100
Ba ppm	300	10	2,000	300	2.1	580
Be ppm	.7	.1 L	7	.5	2.3	3
Co ppm	2	.3 L	20	2	2.1	19
Cr ppm	7	.7	100	5	2.2	90
Ga ppm	3	.5	20	2	1.9	19
Mo ppm	2	.3 L	70	1.5	2.4	2.6
Nb ppm	1.5	.7 L	30	1	3.1	11
Ni ppm	5	.5 L	300	3	2.6	68
Sc ppm	2	.5 L	20	1.5	1.8	13
Sr ppm	200	15	700	150	2.2	300
V ppm	15	1.5	150	10	2.0	130
Y ppm	5	.7 L	30	3	2.0	26
Yb ppm	.5	.07 L	3	.3	2.0	2.6
Zr ppm	15	3	150	15	1.7	160

Table 7a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 79 San Juan River region coal samples.

(All samples were ashed at 525°C; L after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range Minimum	Maximum	Geometric mean (expected value)	Geometric deviation
Ash %	21.1	5.1	60	19.4	1.5
SiO_2 %	54	36	79	53	1.1
Al_2O_3 %	24	14	31	24	1.2
CaO %	4.9	.85	19	3.9	2.0
MgO %	.88	.50	1.94	.84	1.3
Na_2O %	1.56	.26	2.85	1.40	1.6
K_2O %	.61	.11	1.6	.54	1.6
Fe_2O_3 %	3.8	1.3	13	3.5	1.5
MnO %	.022	.005	.049	.017	1.9
TiO_2 %	1.0	.49	1.4	.95	1.4
SO_3 %	3.7	1.3	14	3.2	1.7
Cd ppm	.9	.5 L	1.0	.8	1.4
Cu ppm	66	34	210	64	1.3
Li ppm	97	38	198	91	1.4
Pb ppm	66	25	110	63	1.4
Zn ppm	68	22	1,820	57	1.8

Table 7b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 79 San Juan River region coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown)

Element	Arithmetic mean (abundance)	Observed range Minimum	Observed range Maximum	Geometric mean (expected value)	Geometric deviation	Average shale
Si %	5.4	.86	22	4.8	1.6	7.3
Al %	2.7	.45	6.0	2.4	1.6	8.0
Ca %	.67	.10	3.7	.54	2.0	2.21
Mg %	.107	.047	.432	.099	1.5	1.55
Na %	.236	.032	.762	.203	1.7	.96
K %	.16	.012	.79	.088	2.1	2.66
Fe %	.54	.17	1.6	.48	1.6	4.72
Mn ppm	29	7.2	83	23	2.0	850
Ti %	.11	.042	.19	.097	1.5	.46
As ppm	3	1.0 L	40	2	2.5	13
Cd ppm	.2L	.05 L	.4	.2L	1.6	.3
Cu ppm	13.3	4.4	49.0	12.4	1.5	45
F ppm	122	20 L	500	92	2.1	740
Hg ppm	.12	.02	1.20	.08	2.3	.4
Li ppm	19.7	4.3	32.7	17.7	1.6	66
Pb ppm	13.1	1.5	22	11.7	1.6	20
Sb ppm	.5	.1	1.8	.4	1.8	1.5
Se ppm	2.0	1.1	4.0	1.9	1.3	.6
Th ppm	5.9	3.0 L	17.1	4.3	2.2	12
U ppm	2.5	.4	8.2	2.2	1.6	3.7
Zn ppm	15.1	1.8	380	11.1	2.2	95
B ppm	100	30	150	100	1.4	100
Ba ppm	300	70	1,500	300	1.9	580
Be ppm	1	.3	3	1	1.6	3
Co ppm	2	.7 L	7	2	1.6	19
Cr ppm	5	2	15	5	1.5	90
Ga ppm	7	1.5	15	7	1.6	19
Mo ppm	1.5	.7 L	7	1	2.3	2.6
Nb ppm	3	1 L	10	2	1.7	11
Ni ppm	3	1	10	2	2.0	68
Sc ppm	3	1	10	3	1.5	13
Sr ppm	100	30	300	100	1.6	300
V ppm	20	7	100	20	1.5	130
Y ppm	7	3	15	7	1.5	26
Yb ppm	.7	.15	2	.7	1.5	2.6
Zr ppm	50	10	100	50	1.6	160

Table 8a: Arithmetic mean, observed range, geometric mean, and geometric deviation of 15 major and minor oxides and trace elements in the ash of 26 Blask Mesa field coal samples

(All samples were ashed at 525°C; L after a value means less than the value shown)

Oxide or element	Arithmetic mean (abundance)	Observed range		Geometric mean (expected value	Geometric deviation
		Minimum	Maximum		
Ash %	8.0	3.2	13.6	7.4	1.5
SiO_2 %	38	19	59	36	1.4
Al_2O_3 %	15	5.9	28	15	1.4
CaO %	15	3.4	27	13	1.7
MgO %	2.42	.75	6.11	2.20	1.5
Na_2O %	1.9	.39	4.79	1.45	2.1
K_2O %	.49	.1 L	1.3	.38	2.1
Fe_2O %	6.1	2.1	10	6.2	1.3
MnO %	.018	.008	.035	.016	1.5
TiO_2 %	1.0	.78	1.3	.98	1.2
SO_3 %	13	6.0	23	12	1.4
Cd ppm	1 L	1 L	2.0	1 L	3.0
Cu ppm	70	54	127	69	1.2
Li ppm	47	20	89	44	1.4
Pb ppm	31	20 L	75	29	1.5
Zn ppm	67	20	275	54	1.9

Table 8b: Arithmetic mean, observed range, geometric mean, and geometric deviation of 36 elements in 26 Black Mesa coal samples (whole-coal basis). For comparison average shale values are listed (Turekian and Wedepohl, 1961)

(As, F, Hg, Sb, Se, Th, and U values used to calculate the statistics were determined directly on whole-coal. All other values used were calculated from determinations made on coal ash. L means less than the value shown)

Element	Arithmetic mean (abundance)	Observed range		Geometric mean (expected value)	Geometric deviation	Average shale
		Minimum	Maximum			
Si %	1.6	0.28	3.3	1.2	2.0	7.3
Al %	.69	.21	1.8	.57	1.8	8.0
Ca %	.78	.28	1.3	.70	1.6	2.21
Mg %	.104	.046	.245	.098	1.4	1.55
Na %	.093	.025	.166	.079	1.8	.96
K %	.037	.004	.13	.024	2.5	2.66
Fe %	.31	.18	.53	.31	1.2	4.72
Mn ppm	9.7	4.9	16	9.0	1.5	850
Ti %	.046	.021	.078	.042	1.5	.46
As ppm	2	1 L	10	1	1.9	13
Cd ppm	.1 L	.03 L	.23	1 L	1.4	.3
Cu ppm	5.5	2.3	11.7	5.1	1.5	45
F ppm	51	20 L	100	41	1.9	740
Hg ppm	.04	.02	.08	.03	1.6	.4
Li ppm	3.9	1.2	10.5	3.2	1.8	66
Pb ppm	2.7	1.0	5.6	2.4	1.7	20
Sb ppm	.3	.1	.6	.2	1.7	1.5
Se ppm	1.6	.7	3.1	1.5	1.4	.6
Th ppm	2.2	2.1	4.6	2.0	1.6	12
U ppm	.6	.2 L	1.1	.4	2.7	3.7
Zn ppm	5.6	1.1	32.5	4.0	2.3	95
B ppm	20	15	70	20	1.6	100
Ba ppm	300	150	500	300	1.5	580
Be ppm	.5	.15 L	1.5	.3	2.5	3
Co ppm	1.5	.5	7	1	1.9	19
Cr ppm	3	1	10	3	1.7	90
Ga ppm	2	.7	7	2	1.8	19
Mo ppm	1	.3 L	2	.7	1.8	2.6
Nb ppm	1.5	.7	3	1	2.0	11
Ni ppm	2	.7	10	2	1.9	68
Sc ppm	1.5	.5	2	1	1.5	13
Sr ppm	150	30	500	100	1.9	300
V ppm	7	3	20	7	1.6	130
Y ppm	3	1	10	3	1.8	26
Yb ppm	.3	.1	1	.3	1.7	2.6
Zr ppm	15	3	70	15	1.9	160

more important in helping to make the decisions as to which coals will be mined, how a coal will best be utilized, and what engineering designs will have to be included in coal-fired power plants and in coal-conversion plants.

ACKNOWLEDGMENTS

This report summarizes an abundance of sample and analytical data that have been produced only by the cooperative efforts of many scores of people. The contribution of each of these people is gratefully acknowledged, though they are not individually cited here (see Swanson and others, 1976, p 3-5). Special thanks are extended to Claude Huffman, Jr., and the staff of chemists in the laboratories of the U.S. Geological Survey at Lakewood, Colorado, and to Forrest E. Walker and the staff in the laboratories of the U.S. Bureau of Mines at Pittsburgh, Pa. The direct assistance of Scott D. Woodruff, Ricky T. Hildebrand, Jack H. Medlin, and S. Lynn Coleman of the U.S. Geological Survey in preparing data for this report is also appreciated. Costs for many of the analyses summarized in this report were funded under USGS-ERDA Interagency Agreement No. E(49-18)-2005.

REFERENCES

Bohor, B.F., and Gluskoter, H.J., 1973, Boron in illites as an indicator of paleosalinity of Illinois coals: Jour. Sed. Petrology, v. 43, no. 4, p. 945-957.

Clark, M.C., and Swaine, D.J., 1962, Trace elements in coal: Commonwealth [of Australia] Sci. and Ind. Research Org. [C.S.I.R.O.], Division of Coal Reserach, Tech. Commun., no. 42, 52 p.

Cohen, A.C., 1959, Simplified estimators for the normal distribution when samples are singly censored or truncated: Technometrics, v. 1, no. 3, p. 217-237.

Connor, J.J., Keith, J.R., and Anderson, B.M., 1976, Trace-metal variation in soils and sagebrush in the Powder River basin, Wyoming and Montana: U.S. Geol. Survey Jour. Research, v. 4, no. 1, p. 49-59.

Couch, E.L., 1971, Calculations of paleosalinities from boron and clay mineral data: Am. Assoc. Petroleum Geologists Bull., v. 55, no. 10, p. 1829-1937.

Fuchs, W., 1935, Rare elements in German brown coal ashes: Ind. Eng. Chem., v. 27, P. 1099-1100.

Glass, G.B., 1975, Analyses and measured sections of 54 Wyoming coal samples: Wyoming Geol. Survey Rept. Inv. no. 11, 219 p.

Gluskoter, H.J., 1967, Clay minerals in Illinois coals: Jour. Sed. Petrology, v. 37, p. 205-214.

Meisch, A.T., 1967, Methods of computation for estimating geochemical abundances: U.S. Geol. Survey Prof. Paper 574-B, 15 p.

Radian Corporation, 1975, Coal fired power plant trace element study; Volume 1, a three station comparison: Denver, Colo., U.S. Environmental Protection Agency under EPA Contract 68-01-2663, 76 p.

Rao, C.P., and Gluskoter, H.J., 1973, Occurrence and distribution of minerals in Illinois coals: Illinois State Geol. Survey Circ. 476, 56 p.

Ruch, R.R., Gluskoter, H.J., and Shimp, N.F., 1974, Occurrence and distribution of potentially volatile trace elements in coal--a final report: Illinois State Geol. Survey Environmental Geology Notes, no. 72, 96 p.

Staff, Office of the Director of Coal Reserach, 1967, Methods of analyzing and testing coal and coke: U.S. Bur. Mines Bull. 638, 85 p.

Swanson, V.E., 1972, Composition and trace-element content of coal and power plant ash: U.S. Dept. Interior, Pt. 2, Appendix J, Southwest Energy Study Coal Resources Work Group, 61 p.

_________, Huffman, Claude, Jr., and Hamilton, J.C., 1964, Composition and trace-element content of coal, Northern Great Plains area: U.S. Dept. Interior Open-File Rept., Northern Great Plains Resources Program, Mineral Resources Work Group, p. 52-83.

_________ and _________, 1976, Guidelines for sample collecting and analytical methods used in the U.S. Geological Survey for determining chemical composition of coal: U.S. Geol. Survey Circ. 735 (in press).

_________, Medlin, J.H., Hatch, J.R., Coleman, S.L., Wood, G.H., Jr., Woodruff, S.D., and Hildebrand, R.T., 1976, Collection, chemical analysis, and evaluation of coal samples in 1975: U.S. Geol. Survey Open-File Rept. 76-468, 503 p.

Trumbull, J.V.A., 1960, Coal fields of the United States, exclusive of Alaska-Sheet 1: U.S. Geol. Survey Map, scale 1:5,000,000

Turekian, K.K., and Wedepohl, K.H., 1961, Distribution of the elements in some major units of the Earth's crust: Geol. Soc. America Bull., v. 72, no. 2, p. 175-192.

U.S. Bureau of Land Management, 1975a, Trace elements, *in* Otter Creek study site [Powder River County, Mont.]--Resource and potential reclamation evaluation: U.S. Bur. Land Management [Denver, Colo.] EMRIA Rept. 1, p. 61-79.

_________ 1975b, Trace elements, *in* Hanna Basin study site [Carbon County, Wyo.]--Resource and potential reclamation evaluation: U.S. Bur. Land Management [Denver, Colo.] EMRIA Rept. 2, p. 48-59.

_________ 1975c, Composition [of coal], *in* Alton study site [Kane County, Utah]--Resource and potential reclamation evaluation: U.S. Bur. Land Management [Denver, Colo.] EMRIA Rept. 4, p. 75-82.

U.S. Geological Survey and Montana Bureau of Mines and Geology, 1973, Preliminary report of coal drill-hole data and chemical analyses of coal beds in Sheridan and Campbell Counties, Wyoming, and Big Horn County, Montana: U.S. Geol. Survey Open-File Rept., 51 p., 3 tables.

_________ 1974, Preliminary report of coal drill-hole data and chemical analyses of coal beds in Campbell County, Wyoming: U.S. Geol. Survey Open-File Rept. 74-97, 241 p.

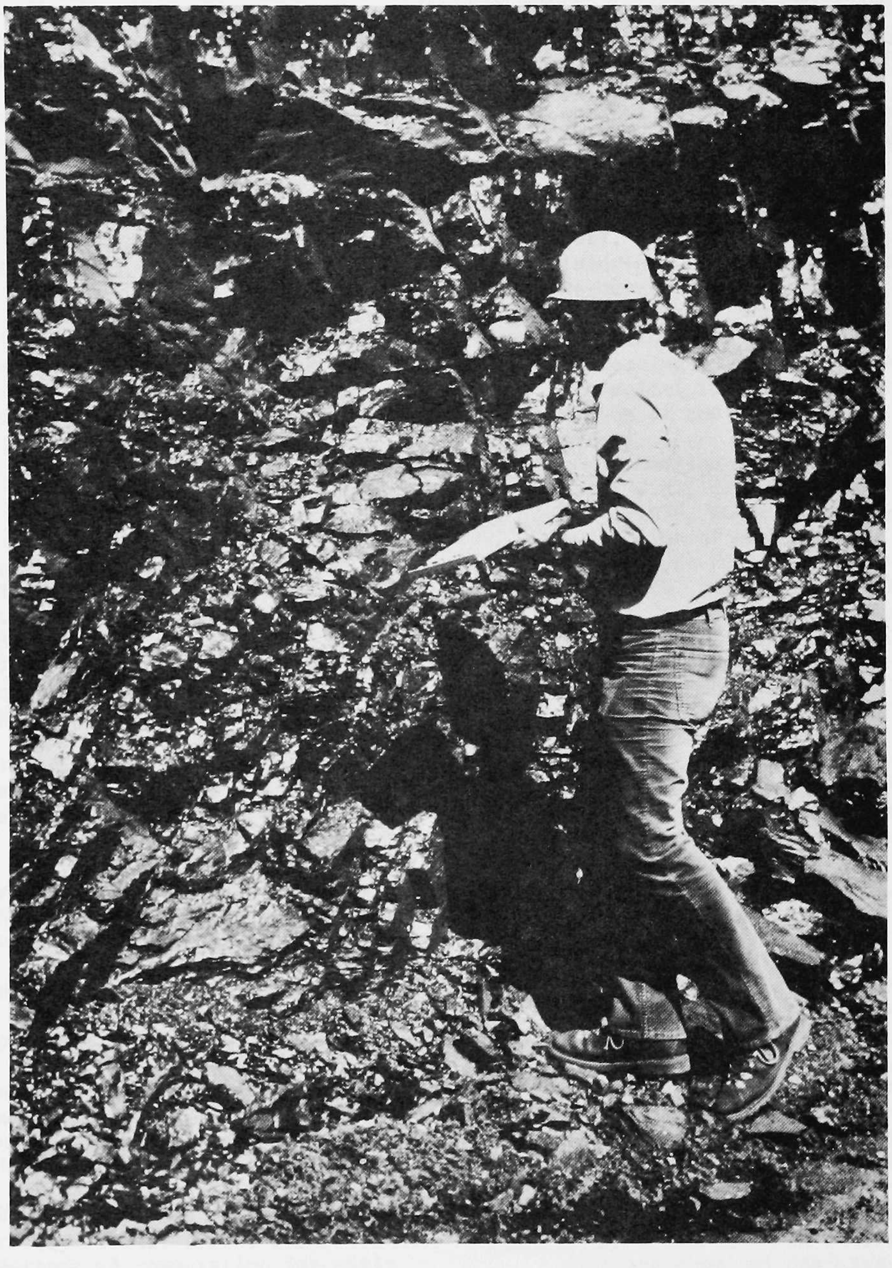
_________ 1976, Preliminary report of coal drill-hole data and chemical analyses of coal beds in Campbell and Sheridan Counties, Wyoming; Custer, Prairie, and Garfield Counties, Montana; and

Mercer County, North Dakota: U.S. Geol. Survey Open-File Rept. 76-319, 377 p.

Walker, C.T., 1968, Evaluation of boron as a paleo-salinity indicator and its application to off-shore prospects: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 751-766.

Zubovic, Peter, Stadnichenko, Taisia, and Sheffey, N.B., 1960, The association of some minor elements with organic and inorganic phases of coal: Art. 41, *in* U.S. Geol. Survey Prof. Paper 400-B, p. B84-B87.

________, 1961, Chemical basis of minor-element associations in coal and other carbonaceous sediments: Art. 411, *in* U.S. Geol. Survey Prof. Paper 424-D, p. D345-D348.



Sampling coal in Coalmont Formation (Paleocene age),
Jackson County, Colorado

THE GEOLOGIST'S ROLE IN COAL MINING

FRANCIS DEFILIPPO: Gates Engineering Company [1]

Denver, Colorado 80222

ABSTRACT: The geologist is usually the first technical person to inspect a coal property for management; therefore, the geologist's role in this initial stage of mining cannot be overemphasized. The geologist must be prepared to plan and execute a drilling, sampling, and mapping program, and to determine reserves and conditions that affect the viability of a mining project. In the construction and operational phase, the geologist will be responsible for monitoring previous conclusions and making changes to the benefit of the operation.

The geologist must lend himself to providing expertise in mine planning, development, additional acquisitions, and other stages of operations that are necessary to a project.

INTRODUCTION

The geologist is usually the first technical person to examine a coal acquisition prospect. Often it is his decision whether or not additional funds are committed to the prospect or that it be dropped. To make sound decisions, the geologist should be familiar with coal mining methods, operations, and economics, as well as being accomplished technically. Also, for better utilization of personnel and to assure success of an operation, the geologist and/or manager should be aware of the assignments in which a geologist can be used. This paper will highlight areas of utilization of the geologist from initial prospect to final reclamation.

EXPLORATION

To determine if a property is suitable for the objectives of management, an exploration program first must be initiated. The following section will deal with the traditional role of the geologist in a coal exploration program.

Planning a Drilling and Sampling Program

Proper planning of a drilling and sampling program will ensure collection of the necessary information at the lowest possible cost. Major elements of this planning are as follows:

1. *Literature search.* The first step in planning a drilling program is to do a thorough literature search. Federal agencies should be checked. Contact the U.S. Geological Survey for open-file reports, maps, published reports, and possible drill-hole data. Check with the U.S. Bureau of Mines for coal analyses, open-file reports, and publications. The U.S. Bureau of Reclamation may be planning a dam and this property could be under 100 ft of water in several years. In addition to data already mentioned, air photos, weather data, seismic activity, and other useful information is available from several federal sources.

State agencies should be checked. The State geological survey may have important information on file. Investigate mine maps on file at the State mine inspector's office. The area of interest could have been mined out or drill-hole information supplied by an outside source may indicate that drilling occurred in pillars of old coal workings.

Private sources should be investigated. Firms such as Petroleum Information or American Stratigraphic Company, both in Denver, often have data (Samples, geophysical logs, well completion cards, etc.) of oil and gas wells drilled in the area that will give the geologist an idea of formation lithology and tops. Examining records of previous drilling and reports by private parties is essential.

2. *Field inspection.* A field inspection is necessary for a properly planned drilling program. Geologic conditions, such as coalbed and marker bed outcrops, should be investigated. Evidence of faulting is another important item to look for. Determine the strike and dip of key beds to help in planning the depths of the drill holes. When large areas are inaccessible, an aerial over-flight is most useful.

An important consideration of an initial field inspection is to determine the amount of surface development. Are there surface structures that would preclude caving of the strata above the coal? Will aquifers supplying municipal, commercial, or domestic water be affected adversely by mining? Such considerations must be taken into account at the early phases of a project to prevent costly and often embarrassing law suits.

3. *Drilling and sampling.* The two main objectives of a drilling program are to obtain coal seam thickness and quality information. Is the coal of steam (boiler) or metallurgical quality? The answer to this question determines the number of core holes to be drilled and types of analyses to be performed. For steam coal, proximate analysis and ash-fusion tests need to be run. Sometimes ultimate analyses also are run. For metallurgical coal, proximate analysis and free-swelling index (F.S.I.) are usually run with other available tests.

The use of geophysical logs are invaluable in determining seam thickness. Also, information as to formation lithology, porosity, and coal quality can be derived from these logs, thereby reducing the number

1976 Symposium on the Geology of Rocky Mountain Coal, p. 165-167

[1]Now with Carbon Fuel Company, Lakewood, Colorado 80228.

of core holes.

The number of core and rotary holes to be drilled and their approximate depths should be determined for bidding purposes. At times when several coal seams are near the surface and close together, it might be more economical to do straight coring. At other times, it pays to rotary drill the hole, ascertain the location of coal seams to be cored, off-set the rotary hole, and then rotary drill to a point immediately above the coal zone, and finally, continuously core the coal, including a portion of the roof and floor rock.

Depending upon coal-seam continuity, drill sites should be planned with approximately 4,000-ft centers. If the seams appear to be lenticular, a closer spacing of drill sites should be considered.

Points of project review should be planned in the drilling program. Say, 50 holes are planned on a regular spacing to cover a property on which little or no drilling has been done. The first commitment should be made to drill from 6 to 10 holes and to evaluate the results of these holes. If the results are favorable, drill another 10 to 14 holes. After results are unfavorable, abandon the project. After the second phase of drilling, go through the evaluation again for a similar "go/no go" decision. When all the holes have been drilled, determine if additional fill-in holes are needed. These decision points should be built into the drilling program before any drilling occurs.

Locating Contractors

Sufficient time should be allowed to receive bids from the major program contractors. By April, many drilling contractors are booked for the summer drilling season. The geologist should be aware of these time constraints and remember that a rushed job often results in additional costs and/or second-best contractors.

Obtaining Permits

Depending upon the ownership of surface and coal rights, Federal, State, or private permission for access may have to be obtained. The geologist may have to prepare permit applications from either the U.S. Geological Survey or the state in question. The information developed in the planning stage of the drilling program will include much of the data required. A geologic background is very important to the proper completion of these applications.

Executing the Drilling and Sampling Program

After the drilling and sampling program is planned, funded, and permitted, and the necessary contractors arranged for, the program must be started.

1. *Road location and construction.* The geologist will locate roads, keeping in mind access via these roads, cost of construction, and minimization of environmental damage. Supervision of the construction and approval of bills for this work is an important role of the geologist.

2. *Site location and preparation.* Usually the geologist can locate drill sites from a topographic map. A level site should be prepared for the drill rig; and an area large enough for the drill rig, water truck, and service vehicles should be cleared. Mud pits of sufficient capacity must be dug. The geologist should ensure that any top soil and vegetativ cover is stockpiled for eventual site reclamation. Upon completion of the drilling program, the drill hole should be properly plugged and the sites surveyed in and reclaimed.

3. *Supervision of the drilling and sampling.* Supervision of the drilling and sampling is the primary role of the geologist in the field. He is require to see that contractors perform their duties properly. Also, the geologist must describe the cuttings and core samples with particular attention to the roof and floor rock and the coal.

When the coal sample is collected, the geologist must see that the sample is representative of the seam to be mined. A knowledge of mining techniques will aid in this job.

4. *Additional sampling.* Although sampling of the coal seam and enclosing strata is the most important job of the geologist during the drilling phase of property development, he must be aware of other aspects of the overall operation so that information can be gathered during this initial phase, rather than later on at additional cost. Some examples are the collectio of samples for overburden removal in surface operations and eventual reclamation. Samples of this nature can b tested for rock strength to identify parameters for either drilling and blasting or ripping. Also, knowledge of the chemical characteristics of the overburden is essential in order to prevent leaching of toxic materials and eventual contamination of the water resources.

During this phase of the operation, sampling and testing of water quantity and quality can be performed by the geologist. Necessary water information can be gathered to aid in planning coal washing plants and for other industrial uses, for bath and domestic-type mine facilities, for reclamation purposes, and for public relations, such as leaving a hole open for a rancher to obtain water for his cattle.

Compiling Drilling Results

As the data are collected and sent in from the field, they must be digested and put in usable form for planning purposes. This compilation is another key role of the geologist. Necessary items are discussed below.

1. *Isopach maps.* To aid in mine planning, the geologist should prepare isopach maps of coal thickness. These maps will give the planner the necessary information for preparing production and machinery estimates.

Isopachs of heat (Btu) content, ash, and sulfur content of the coal should be prepared in order that the marketing people will know the quality of the product and the production personnel will know what blends to make.

Another necessary map in surface mining is a stripping-ratio contour. This map will determine the economic cut-off for the operation.

2. *Geologic maps.* Maps of a geologic nature are the key to planning an efficient coal mining oper-

ation. These maps should include structure contours, the locations of major and minor faults, and rock types. In addition, maps should be prepared displaying such problems as high joint frequency, coal seam splits, excessive water, and poor roof and floor conditions. The availability of these data provides planning personnel with the information necessary to make any adjustment in the mining plan.

3. *Other maps*. The geologist should supervise the mapping, usually by air, of the property. When obtaining topographic coverage, the locations of pipelines, transmission lines, section corners, drill holes, survey-control points, and the like should be included. The scale of the map depends upon the use of the map; therefore, maps with several scales should be made.

DEVELOPMENT

The role of the geologist in this stage of a mining operation is not so intensive as in the exploration stage, but his role nevertheless still is vital.

Additional Drilling and Sampling

Drilling on closer spacing should be conducted by the geologist at this time. Location of coal outcrop burns and any abnormalities not indicated in the exploration stage should be sampled and reported. Drilling and sampling in the areas of the first cuts for surface mines and entry and main haulage ways in underground mines should be done by the geologist, and necessary maps and reports made.

Included in this drilling and sampling phase should be a program of testing for building foundations, sanitary waste disposal, dragline erection pads, and other surface structures. Also, drilling and sampling of possible road-base and building materials should be done at this time.

It may be necessary for the geologist to perform additional overburden testing. This is an important stage in which to answer questions that arose after the close of the exploration phase.

Other Information Gathering

Geologic investigations of necessary mining facilities should be undertaken. Planning of waste enbankments and water storage facilities to minimize cost, environmental damage, and threat to human life and property is the responsibility of the geologist. This planning might include gauging of stream flow, determining water shed areas, anticipating flood frequencies, relocating stream channels, and other pertinent hydrogeologic activities.

Determining the expected water inflow to the mine area can be done by the geologist. Quantity of water should be estimated for the ordering of pumps and coal removal equipment in surface operations.

Finally, the geologist should be available for certain types of surveying. Depending upon the individual operation, his surveying duties may be minimal or extensive.

PRODUCTION

The geologist can make a significant contribution to the production phase of an operation. Several important aspects will be discussed.

Drilling and Sampling

This activity still is an important responsibility of the geologist. Drilling and sampling on closer spacing should be completed to about one year's production reserve ahead of mining. This lead time is to allow for planning and purchasing of additional equipment.

Rock Mechanics

The geologist can assist in the production function by monitoring slope stability and ground subsidence which depends upon the type of mining operation. Determining the safe angle of repose of a high wall will save money and will contribute to the safety of the operation. Accurate records and measurements of ground movement might be required should the mining operation ever be involved in a law suit or similar legal action.

Monitoring of Mining Conditions

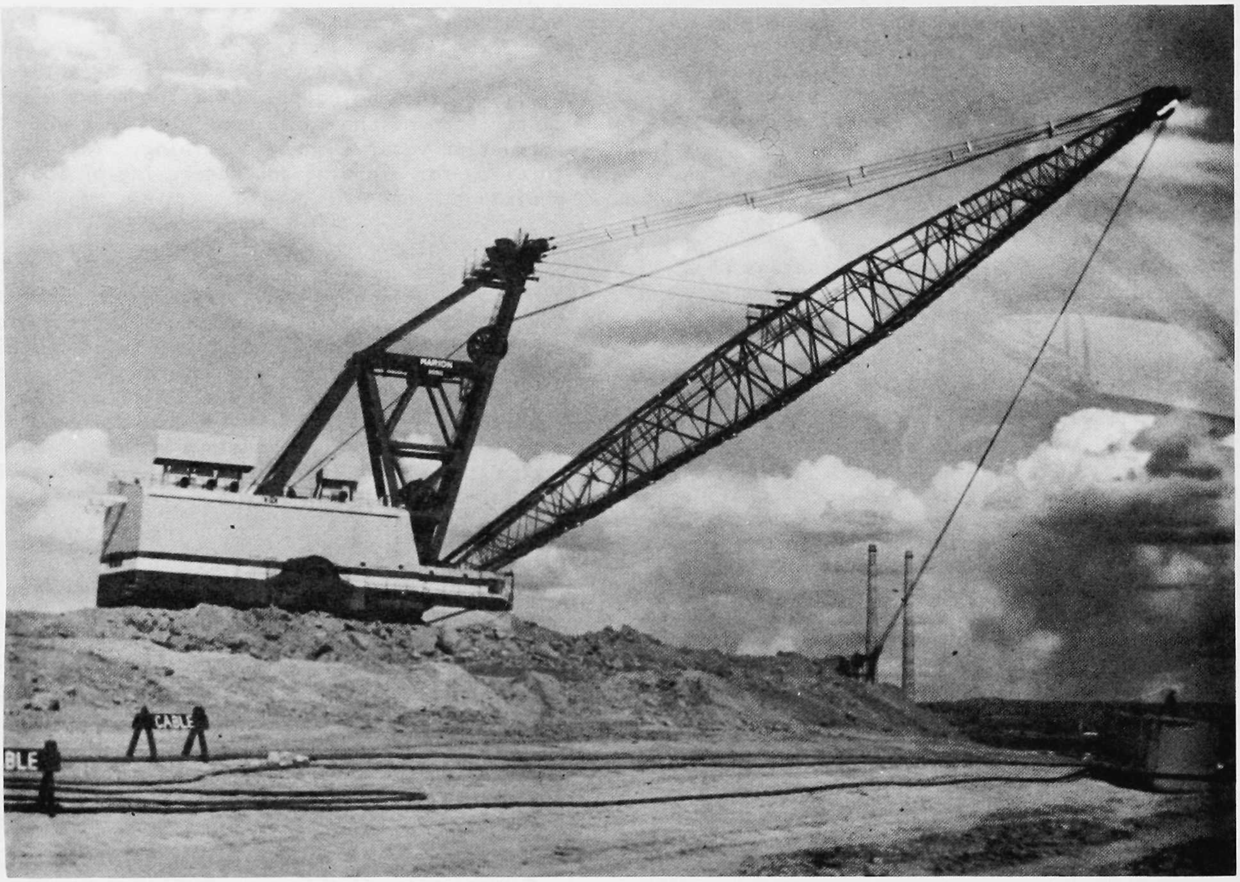
Monitoring of mining conditions to verify previous conclusions by the geologist is another role where he will prove useful. If an unexpected fault is encountered, the geologist should determine its lateral extent and amount of displacement and advise the best position for resumption of mining. Also, any previous mapping should be reviewed to see whether additional corrections to the mining plan are needed.

Land Acquisition

Land acquisition for expansion of the mining property is an activity where the geologist can be of great value. He can advise as to the desirability of the property, can estimate coal reserves, and can prepare acquisition priorities and sequencing.

SUMMARY AND CONCLUSIONS

The geologist should be familiar with coal mining methods, operations, and economics, besides being technically proficient. Traditionally, the primary function of the geologist has been in planning and executing an exploration program and compiling results of that program. The geologist can also play as vital a role in the development and operation of a mining project by gathering and analyzing data necessary for construction and mining activities.



Dragline, Colstrip, Montana

GEOLOGIC ASPECTS OF ENVIRONMENTAL PLANNING AND RECLAMATION

ALLEN G. THURMAN: D'Appolonia Consulting Engineers, Inc.
Denver, Colorado 80237

ABSTRACT: This paper discusses a conflict--the fact that many environmental issues and problems of mining are influenced by geology but that the evaluations and solutions being put forward are seldom obtained from the geologist. An appeal is made to the geologist to play a more active role in questions of environmental planning and reclamation--that the geologist not allow others to usurp this role by his default caused by lack of interest.

Mineral exploration has long been recognized as a geologist's role. Along with a particular category of engineers, the geologist has also been fundamental to the roles of site investigation, mine planning and design, and the extraction of the mineral. Today's society says that these activities must now be done in an "environmentally acceptable" manner. Most geologists accept this. However, the geologist seldom plays a lead role in satisfying this new requirement. Although he is a principal professional during exploration and much of mining, he has generally let others define the scope, plan and implement the steps, and complete the environmental aspects of mining despite the fact that to a very great extent the actual problems and meaningful solutions remain geologic in nature. Specific recommendations are made to reverse this "give away" trend so that the geologist's contributions to environmental planning and reclamation can rank in similar importance to his contributions to other aspects of mining.

INTRODUCTION

For centuries, modern man has satisfied his material needs by the grace of a generous and forgiving Nature--Mother Nature. Minerals, energy, food, and water have been so abundant that they have been used with little concern for the future, for efficiency, or for multiple benefit. More recently, increasing demands for material goods, decreasing natural resource availability, and a population explosion have combined to force today's generation to view Nature from a different perspective.

I believe that this basic premise is no longer debatable: that each thinking American must by now realize that resources are limited; that conservation must be emphasized; that multiple use must be made of our materials; and that the needs of future generations must be considered. However, the extent of required change is still ill defined, and the methods for change remain in hot debate. Guidelines are being espoused, written and rewritten by every politician and agency, by every technical and social discipline, by various professional societies and industries, and by numerous individuals and groups who just seem to feel they must be part of the turmoil whether they have a contribution to make or not.

If this issue had not materialized over such a short period of time, if communications were limited so that "white papers" were not viewed on TV by millions, if we did not have the economic luxuries of today, etc.--I suspect we would sanely be finding meaningful guidelines *and solutions* without turmoil, without confrontation. But such is not the case.

THE MEANING OF ENVIRONMENT

Compounding these and other ifs which confront us, is a simplistic, catchall word which has only recently assumed prominence in our vocabulary, but which is now known by all--the word is *environment*. Webster defines environment as: "All the physical, social and cultural factors and conditions influencing the existence or development of an organism....; that which surrounds." [1] Few words are so all-encompassing--there is something for everybody, and everybody's concept can be embraced.

This gets to the heart of the point I want to make: *environment* covers such breadth that anyone can and does express an opinion, that everyone can be and is involved. However, the word by itself lacks substance until the "physical, social and cultural factors" are defined, and until the "influence on the existence or development of the organism" is understood. And this is where the present common procedures for environmental planning and reclamation break down--industry's plans are often being developed without accurate consideration of important factors, and agency requirements are becoming increasingly demanding with little assurance that the resulting influence will be meaningful or even beneficial.

Because the word *environment* seldom has the same meaning for both the speaker and the listener, it

[1] The English-Language Institute of America, Inc., 1971, The living Webster encyclopedic dictionary of the English language: Chicago, p. 329.

should always be qualified or explained with additional words and phrases. For this reason, I am inclined to drop environment from my vocabulary. I am like President Ford and the word "detente"--a word that gets one in trouble nearly every time it is used should be forgotten. Unfortunately, we must now live with the National Environmental Policy Act, the Environmental Protection Agency, Environmental Impact Statements, etc. Since the word will not go away, the best we can do is to make sure that its use is always clarified by correctly associating and understanding the factors of importance in each particular situation.

THE ROLE OF THE GEOLOGIST

This brings me more directly to my topic: The geologist and his role in environmental planning and reclamation as applied to mining.

Mineral exploration, including coal, has long been recognized as a geologist's role. A few amateurs may develop limited exploration capability. But generally, years of specialized education and field experience are expected qualifications--certainly the urban sociologist or the wildlife biologist does not often presume to have expertise in this aspect of mining.

Along with a particular category of engineers, the geologist has also been fundamental to the roles of site investigation, mine planning and design, and the extraction of the mineral. Again, other professions generally do not claim capabilities fundamental to this aspect of mining.

But the processes of exploration and the extraction of the mineral do not complete the full spectrum of mining as required by today's society. The mining process is no longer considered to be complete until the affected land has been returned to a condition suitable for other purposes. And during mining, neighboring land must not be detrimentally affected. Further, extraction ratios are influenced not only by economics but by the technical limitations of maximum recovery. These concerns of mining are relatively new and are fraught with controversy. And they offer inroads for instant experts of all kinds, few with capability to provide meaningful, realistic solutions.

People characteristically find fault in the actions of others, particularly when the others are a minority, such as mining is now a minority within U.S. industry. Further, people seem to often profess an ability to correct the faults of others if any of the following situations exist:

1. Their own faults are so complex that the faults of others seem to be an area more amenable to correction. Example: Urban ghettos continue to deteriorate mostly as a result of low income, but rather than solve problems at their back door, many sociologists take a stand against new mining because the influx of miners may upset the social structure of the associated community.

2. The fault can be corrected by changing the actions of others rather than changing their own actions. Example: The city resident refuses to change his air-polluting driving habits but he demands zero dust from a rural surface mine.

3. Employment opportunities are at mismatch with the expertise required for more natural correction of the fault. Example: Political scientists abound and tend toward employment positions unfilled because of a shortage of engineers and hard scientists. Another example: The geologist seeks his more historical role of exploration leaving the geologic aspects of reclamation to others by default.

4. Their own discipline is not naturally marketable or recognized as important. Example: The archaeologist or historian recognizes in mining a new financial means to study a tipi ring or homestead.

Each of the above situations and examples suggests that attempts to correct past faults of mining will often be made by people historically outside of mining. While faults too close to home are often not recognized, and while fresh ideas from an outside perspective may often be productive, I submit that meaningful, long lasting, viable corrections of the faults of mining will come from those more familiar with all of the circumstances and limitations which have and will continue to influence mining. Further, corrective action demands major input by those who, in the past and probably in the future, are most intimately committed to the survival of the mining industry.

It seems improbable that the sociologist will comprehend that mining is an integral part, in fact the first part, of other industry. It seems illogical that the biologist will correctly comprehend the physical factors influencing mining and mined land reclamation. It is hard to believe that the historian has more than a cursory interest in any ongoing process. It can be expected that the political scientist will quickly jump to tomorrow's issue when it develops. And where is help from the economist who doesn't comprehend that mining is one of the few industries which create the economic base of the country?

I do not want to imply that these non-geologic, non-engineering disciplines are not important. They may, in fact, appropriately contribute to solutions, or even lead to logical restraints to mining in some areas. However, let us not let the tail continue to wag the dog.

True commitment and expertise will be required if the past faults of mining are to be corrected. To me, this requires the geologist, and those engineers closely associated with geology.

It should be recognized that in addition to the fact that everyone else wants to get into the act, the geologist is suspect. In a general sense, the geologist has been and will remain a part of the mining industry--an industry which has been judged guilty of doing wrong and of having ulterior motives. Although this may make it difficult for the geologist to assume lead roles in the processes of environmental planning and reclamation, I urge, in fact I appeal for his active involvement.

SUBJECTS INVOLVED IN AN ENVIRONMENTAL BASELINE STUDY

I hope the previous discussion has developed a philosophical logic for the geologist's participation in the environmental activities of the new mining ethic. If not, there is probably little I can say that will do so. However, my experience indicates that all too often the specific subjects of environmentally related mining activity are not properly recognized by the geologist as being in his area of expertise. Therefore, let me review the subject which must be covered in a typical environmental baseline study for a surface coal mining operation. For both convenience and emphasis, I have ordered the subject as my experience has shown them to be ordered in importance:

(1) Geology and Mineral Resources. A statement of existing conditions so elementary to the geologist that he ranks it as trivial, yet this topic forms the basis or logic for the mine and, thus, the purpose of the baseline study. Generally, topography should be described within this category also--and topography is usually defined by the geologic conditions.

(2) Surface and Ground Water Hydrology[2]. Since surface hydrology is influenced by topography, and because ground water is associated with geologic formations, who is better qualified to address this issue than the geologist, recognizing that for the hydraulics of flow, engineering may also be required? In fact, can ground water hydrology be defined without the assistance, if not the direct responsibility, of the geologist?

(3) Surface and Ground Water Quality. Since water quality is influenced by the chemistry of the soils and rock which the water is exposed to, this subject is also directly related to the geologist. In fact, as the baseline study advances to assessment, the geochemist must be involved if assessment of environmental impacts due to mining is to be even partially understood. Granted, the biological aspects of water quality must also be measured and evaluated; but unless there will be direct disruption of existing streams, this will be secondary in importance to chemistry and sediment.

(4) Soils. Although the science of soils is basically in the agricultural discipline of agronomy, the geologist can provide significant assistance in the interpretation of soils distribution--particularly if soil chemistry is such that soils at any depth should be buried or topsoiled during reclamation.

(5) Vegetation and Land Use. An important subject not directly related to the geologist. However, conditions of topography, hydrology, and soils allow the geologist to have a good understanding of the factors which influence vegetation and land use, and, therefore, the requirements to reestablish acceptable conditions following mining.

(6) Wildlife. A subject for the specialist. Although topography, vegetation, and land use influence wildlife, the relationships to geologic conditions are obscure. Thus, this is the first subject of the baseline study totally separate from the geologic disciplines.

(7) Socioeconomics. A subject of obvious interest to all who will live in the vicinity of the mine, but not a subject for solution by the geologist.

(8) Climatology and Air Quality. A subject also for others, but one generally having little real interaction with mining unless the mine is associated with a power or gasification plant.

(9) Archaeology, History and Paleontology. Although the latter subject is associated with geology, it will be inconsequential except at the unusual site. The first two are often similarly inconsequential but, as previously mentioned, the specialist has already carved his niche into this aspect of mining.

(10) Marketing, Transportation, Power, etc. Topics which can generally be addressed in sufficient detail by anyone prepared to take the time to do so.

As noted, the first three subjects I have listed (Geology and Mineral Resources, Surface and Ground Water Hydrology, and Surface and Ground Water Quality) are directly related to geology; and the next two (Soils and Vegetation and Land Use) are closely associated with geology. However, this is just the start of a meaningful environmental program. The end result of the baseline study is an inventory of data, generally useless without detailed consideration with respect to the mining operations. And this consideration must be made by people knowledgeable about and sensitive to the procedures and economies of mining. Again, the geologist and his closely associated friends in engineering rise to the top of the qualifications list.

AN APPEAL FOR ACTION

I submit that mining operations that appropriately consider geology, topography, surface and ground water hydrology, water quality and soils--as accurately viewed from the full spectrum of geology--will have minimum environmental impacts. Further, I submit that reclamation, planned and implemented with accurate consideration of these subjects, will be successful. Other subjects, often of more common public concern such as vegetation and wildlife, will be almost automatically controlled in an environmentally acceptable manner if the correct soil is placed in the correct position at the correct slopes, and if surface and ground water is redeveloped in a scientifically controlled manner.

Hopefully, I have convinced you that the geologist can play an important role in the process of environmental planning and reclamation. If so, and you want to know more about the details, the literature is extensive--although you will often have to add the geologic thought process on your own.

More commonly, I recognize that most in this audience will continue to pursue the more historic roles of geology in mining. I do not blame you for this attitude--I, and the company I represent, have a similar interest. However, I appeal to you to play an activist role in the environmental issues of mining.

Accept the need for environmentally sound mining procedures, but insist that the entire subject be kept in perspective. Fight for laws and agency interpretations that make environmental sense compatibly with geology and the process of mining. And when you are responsible for the employment of environmental services, look past the frosting of vegetation, wildlife and air quality to insist on capabilities compatible with the real and total needs. I believe you will find these capabilities only in firms having major strength in the various specialties of geology.

SUMMARY

To summarize, let me come back to the title of my paper: Geologic Aspects of Environmental Planning

[2] Although I have listed this subject second to Geology and Mineral Resources, I hasten to emphasize that Surface and Ground Water Hydrology will be technically the most complex subject. And, except for definition of purpose, it will be environmentally the most important subject in most mining situations.

and Reclamation. What is the geologist's role? I honestly do not know. It is clear that the potential and need are great. But to gain a role, you must assume one--particularly when others are also trying to assume the role. To date, I am afraid that the profession of geology has all too often been guilty of giving this role away--intentionally because of a lack of interest, or by default because their effort is still directed only to the more historic aspects of mining.

Reclaimed surface-mined coal land, Routt County, Colorado

ABSTRACTS

Texts of the following papers were not submitted for publication.

COAL-FORMING PROCESSES IN THE SWAMPS AND MARSHES OF FLORIDA AND GEORGIA

WILLIAM SPACKMAN, JR.: The Pennsylvania State University
University Park, Pennsylvania

ABSTRACT: Many of the structural features and compositional characteristics of coal seams are fixed at the time of accumulation of the precursor sediments. Included in this category are texture, intraseam stratification and coal quality, insofar as ash yield and sulfur contents are concerned. The mineral content and the concentrations of major and trace elements are established to a significant degree, as are certain aspects of maceral composition.

The Okefenokee Swamp of Georgia and the Everglades-Mangrove swamp-marsh complex of southern Florida, provide a variety of environments in which one can evaluate the significance of geological, geochemical and biological processes in determining the nature of the peat sediments. The phenomena of aqueous transgression and regression account for a major portion of the stratification that characterizes the peat blanket, but there are a number of other phenomena which also contribute to the superpositioning of different peat types. In contrast to the common inorganic sediments, the texture of the various peat types is developed largely through the action of biological processes. The development and concentration of such important substances as pyrite and fusinite are favored in certain environments, and the general character of the subsequently developed coal type is determined by the interaction of the geological-geochemical-biological processes which are operating in the particular peat-forming environment involved. Compositional relationships between the Tertiary lignites of Alabama, Dakota and Vermont and the Georgia and Florida peats are beginning to emerge.

MODELS OF COAL DEPOSITION

ALAN C. DONALDSON: West Virginia University
Morgantown, West Virginia

ABSTRACT: The scope of this paper includes the larger depositional system of which the swamp-peat-coal is a part and emphasizes the value of using the present as a key to the past in the analysis of coal measure rocks. The modern setting of most swamps is in areas of temperate to tropical climate and part of the depositional systems of river deltas and inter-delta marine-dominant environments such as strand plain, barrier island-lagoon, and tidal plain.

Three basic models of deposition are useful in understanding the Appalachian coals: (1) marine-dominant delta in an unstable tectonic area (Niger Delta - Pocohontas and New River Group), (2) fluvial-dominant delta in an unstable tectonic area (Mississippi Delta - Kanawha Group), and (3) fluvial-dominant delta in a stable tectonic area (Guadalupe Delta - Conemaugh and Monongahela Groups). The models indicate the factors controlling the position of the coal in the anatomy of the delta in respect to the framing sandstone facies, as well as such coal characteristics as the areal extent, thickness, preferred orientation (trend), splits, want areas, sulfur and ash content, and stacking arrangement. These models also seem appropriate for the Rocky Mountain coals.

GEOPHYSICAL TECHNIQUES FOR COAL EXPLORATION

WILFRED P. HASBROUCK: U.S. Geological Survey
Denver, Colorado 80225

FRANK A. HADSELL: Colorado School of Mines
Golden, Colorado 80401

ABSTRACT: By adapting and using the tools and techniques of oil, mining, engineering, and borehole geophysics, the coal geophysicist, working as part of the exploration team, seeks solutions to coal-related problems that now require an inordinately large number of drilled, cored, and sample-logged holes. For coals of the Western States, two problems are of immediate concern: the establishment of bed correlations, and the mapping of burned facies. Field studies indicate that the combined use of seismic shallow-reflection procedures and seam-wave certification techniques appears to be the method of choice for the bed-correlation problem; magnetic methods work well on the clinker problem. Other geophysical methods that have yielded positive results in coal exploration include (1) the gravity method--used to delineate coaliferous basins and to locate cutouts of thick coals at shallow depth; (2) electrical resistivity methods--used to locate subcrops of steeply dipping coal beds, and (3) borehole methods--used to effect bed correlations and to estimate quality of coal.

EASTERN UTAH COAL FIELDS

HELLMUT H. DOELLING: Utah Geological and Mineral Survey
Salt Lake City, Utah 84108

ABSTRACT: Most of Utah's important coal fields are in the eastern half of the state; those in east-central Utah have been the most important to the state from the standpoint of production. Large reserves are still to be found here, the quality is excellent, environmental problems are less than those experienced in southwestern Utah, and future development and projects are to be expected. A review of the Mount Pleasant, Wasatch Plateau, Book Cliffs, Sego, Henry Mountains, and Emery fields will point out some problems inherent to Utah coal.

COAL AS A MAJOR SOURCE OF DRY NATURAL GAS, WITH EXAMPLES FROM TWO ROCKY MOUNTAIN BASINS (SAN JUAN AND RATON)

FRED F. MEISSNER: Filon Exploration Corporation
Denver, Colorado 80202

ABSTRACT: Modern geochemical theory indicates that oil and most hydrocarbon gases are generated by the thermal alteration (metamorphism) of primary organic material buried in sediments. Observed field relationships and thermodynamic principles show that the process is both a) temperature- and b) time-dependent, and is related to the instability and breakage of molecular bonds in complex solid organic material accompanied by the release of more simple fluid hydrocarbons. The onset of measurable hydrocarbon generation (source-rock "maturity") occurs suddenly at some "critical temperature," which may conveniently be related to burial depth through the earth's geothermal gradient. Relative stages of thermal metamorphism related to "maturity" may be determined by examining certain properties of organic material, such as color, electron-spin resonance, extractable hydrocarbons, etc.

Because coals form a continuous metamorphic series grading from peat to graphite, the "coalification" process applicable to "woody" organic material offers a convenient means of determining and standardizing incremental charges in thermal alteration. Coalification ranks may be conveniently related to depth through the recently proposed "level-of-organic-metamorphism" (LOM) scale. The onset of thermal hydrocarbon generation (maturity) appears to occur at a level-of-organic-metamorphism corresponding to a high-volatile B bituminous coal with a volatile matter content of about 41 percent.

The concept of dry natural gas originating from bedded high-rank coals or disseminated coaly matter has not been widely used as an explanation or prospecting concept for the delineation of major gas producing areas. The observed association of major gas accumulations with coal-measures containing high-rank coals provides a substantial body of empirical evidence relating coal metamorphism to gas generation. The occurrence of methane in certain coal-mining areas serves as further evidence for gas generation from coal. Data suggest the generation of over 6,000 cubic feet of gas for each ton of coal metamorphosed to the anthracite rank.

Coal-bearing strata are found in sediments characterized by sea-coast lagoonal and deltaic flood-plain deposits of uppermost Cretaceous-lowermost Tertiary age in most of the Rocky Mountain structural basins. Basins where these coals achieve high rank in the subsurface are further associated with the presence of large volumes of natural gas in adjacent sandstone reservoirs deposited in transitional shoreline-bar or stream-channel environments. Examples of coal distribution, metamorphism, and associated methane gas accumulation have been investigated in two basins. The San Juan Basin is a rather maturely explored area and contains the second largest gas field complex in the United States. The Raton Basin is non-productive at the present time, but should have tremendous exploration potential based on theory and similarity with proven areas. Semi-quantitative estimates, based on coal extent, thickness, and rank, suggest the Vermejo and Raton Formation coals in the Raton Basin should have reasonably generated 14 trillion cubic feet of gas.

ENERGY-RELATED PUBLICATIONS OF THE COLORADO GEOLOGICAL SURVEY

COAL

RESOURCE SERIES 1--Geology of Rocky Mountain coal, a Symposium, 1976, edited by D. Keith Murray, 1977.

INFORMATION SERIES 1--Coal mines and coal fields of Colorado, by D. C. Jones, 1976, 1 map (scale 1:500,000), $2.50 (active and abandoned surface and underground coal mines).

INFORMATION SERIES 2--Coal mines of Colorado, statistical data, by D. C. Jones and D. K. Murray, 1976, 27 p., $1.00.

INFORMATION SERIES 7--Colorado coal analyses, 1975 (Analyses of 64 samples collected in 1975), by D. L. Boreck, D. C. Jones, D. K. Murray, J. E. Schultz, and D. C. Suek, 1977, 112p., $3.00.

SPECIAL PUBLICATION 9--1975 summary of coal resources in Colorado, by A. L. Hornbaker, R. D. Holt, and D. K. Murray, 1976, 17 p., $1.00.

BULLETIN 34-A--Bibliography, coal resources in Colorado, by R. D. Holt, 1972, 32 p., $1.00.

OPEN-FILE REPORT--Active/licensed coal mines of Colorado, by D. C. Jones, 1976, 1 map (scale 1:1,000,000, Ozalid copy), $2.00.

OIL AND GAS

INFORMATION SERIES 3--Oil and gas fields of Colorado, statistical data, by D. C. Jones and D. K. Murray, 1976, 57 p., $2.00.

GEOTHERMAL ENERGY

BULLETIN 35--Proceedings of a symposium on geothermal energy in Colorado, by R. H. Pearl, ed., 1974, 102 p., $3.00.

SPECIAL PUBLICATION 2--Geothermal resources of Colorado, by R. H. Pearl, 1972, 54 p., $1.00.

INFORMATION SERIES 4--Map showing thermal springs, wells and heat-flow contours in Colorado, by J. K. Barrett and R. H. Pearl, 1976 (scale 1:1,000,000), $1.50.

INFORMATION SERIES 6--Hydrological data of thermal springs and wells in Colorado, by J. K. Barrett and R. H. Pearl, 1976, 124 p., $1.50.

GENERAL

GEOLOGIC MAP OF COLORADO--U.S. Geological Survey, 1935 (1 sheet, multi-colored, scale 1:500,000; reprinted by Colorado Geological Survey, 1975), $5.00 ($6.50 rolled and mailed).

MAP MF 788--Preliminary geologic map of Colorado, compiled by Ogden Tweto, U.S. Geological Survey, 1976 (2 sheets, black and white, scale 1:500,000), $1.50.

MAP I-1039--Energy resources map of Colorado, Compiled by U.S. Geological Survey and Colorado Geological Survey, 1977, U.S.G.S., (1 sheet, multi-color, scale 1:500,000), $2.00.

MAP SERIES 1--Geologic, energy and mineral resources maps of Routt County, Colorado, by A. E. Miller, 1975 (2 maps, scale 1:126,750), $5.00.

MAP SERIES 3--Geology of Moffat County, by A. E. Miller, 1977 (scale 1:126,720) (in press).

MAP SERIES 6--Energy resource development map of Colorado, compiled by D. K. Murray, 1976 (1 sheet, two-color, scale 1:500,000) (out-of-print; to be revised and reissued in 1977).

BULLETIN 37--Bibliography and index of Colorado geology 1875-1975, compiled by American Geological Institute, 1976, $7.50 soft cover, $10.00 hard cover. Mail orders add $1.00 for each copy, postage and handling.

COLORADO STRATIGRAPHIC CORRELATION CHART--by R. H. Pearl and D. K. Murray, 1974, $0.25.

To order publications, specify series and number, title, and quantity desired. Prepayment is requested. Make checks payable to:

Colorado Geological Survey
Room 715, 1313 Sherman Street
Denver, CO 80203
(Telephone: 303/892-2611)