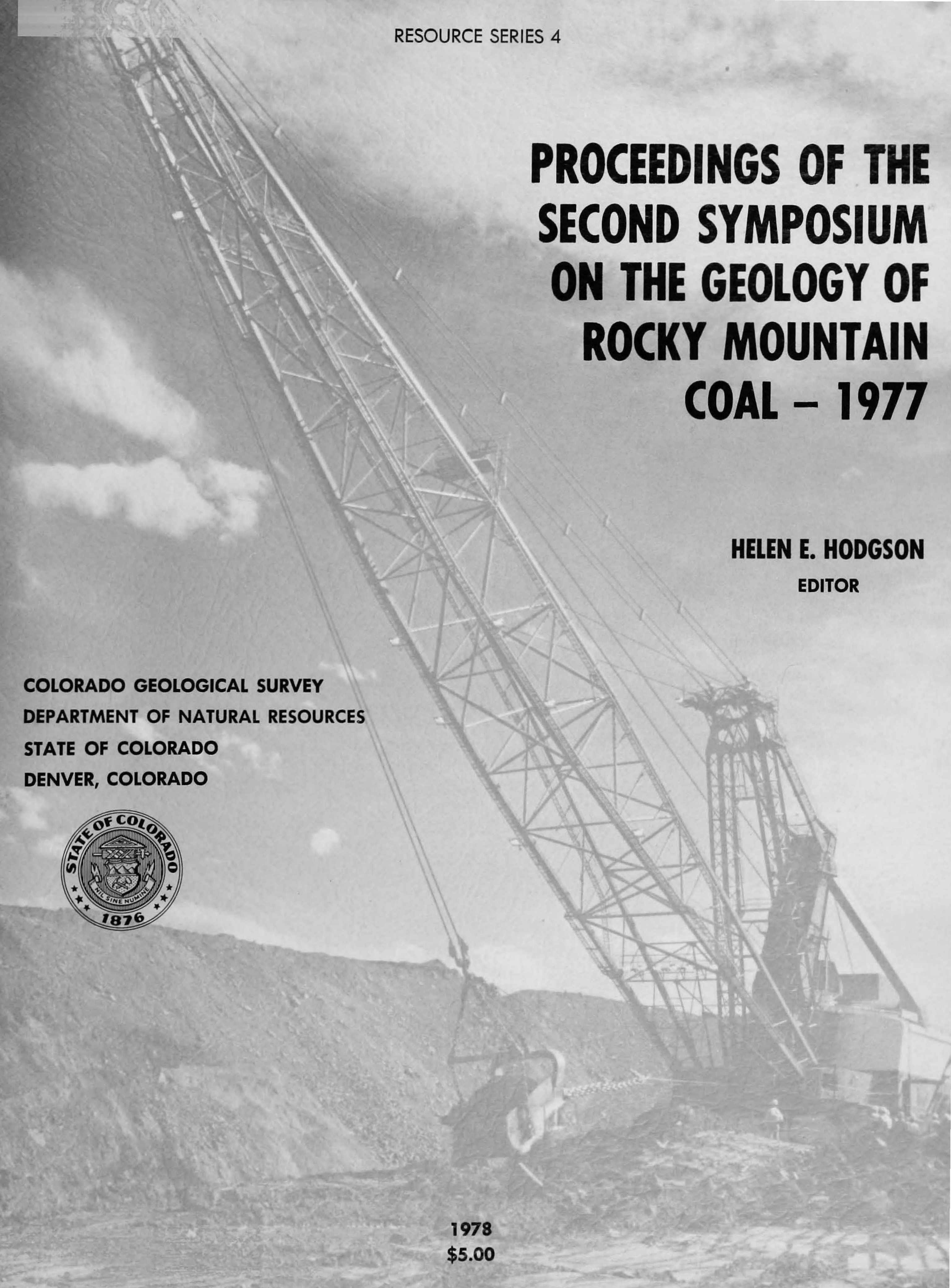

RESOURCE SERIES 4

PROCEEDINGS OF THE SECOND SYMPOSIUM ON THE GEOLOGY OF ROCKY MOUNTAIN COAL – 1977

HELEN E. HODGSON

EDITOR

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

1978
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RESOURCE SERIES 04

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SPONSORED BY COLORADO GEOLOGICAL SURVEY
AND U.S. GEOLOGICAL SURVEY

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

1978

STATE OF COLORADO

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DEPARTMENT OF NATURAL RESOURCES
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COLORADO GEOLOGICAL SURVEY
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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."

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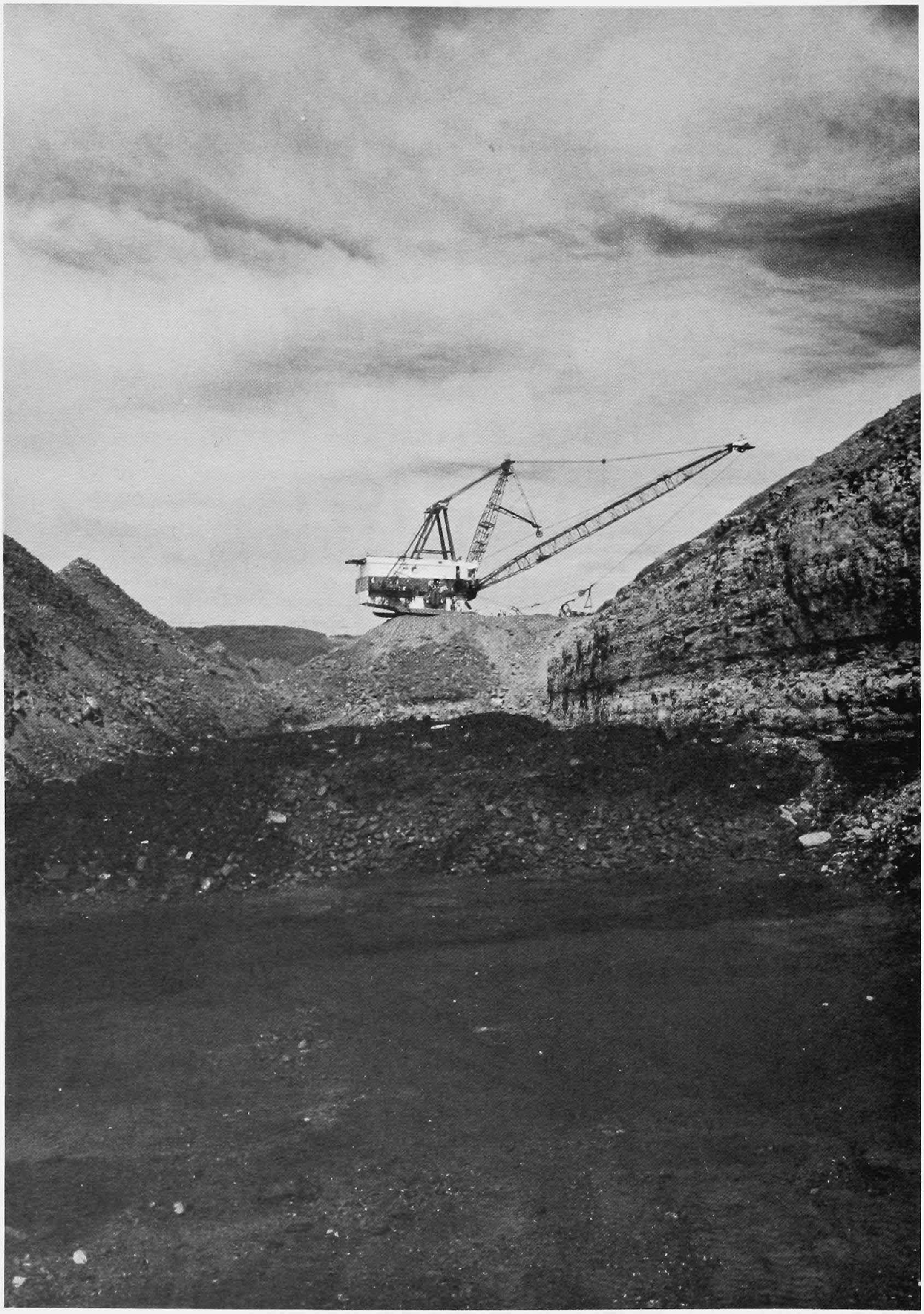
"Promulgate model geologic hazard area control regulation."

"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: Marion 8050 dragline at the Energy Fuels mine, Routt County, Colorado. Photograph taken by Harold H. Arndt.



RoMoCoal Field Trip Photograph by Harold H. Arndt, U.S. Geological Survey

Frontispiece.--Energy Fuels Corporation pit no. 1-A showing coal of the Wadge bed piled and ready for loading in the foreground and a Bucyrus Erie 770, 21-yard-capacity dragline that was visited by participants of the RoMoCoal field trip on the skyline.

Foreword

The 1977 Symposium on the Geology of Rocky Mountain Coal was held May 9 and 10 on the campus of the Colorado School of Mines in Golden. Approximately 400 people from various parts of the United States and Canada attended this second annual symposium. The 1977 Symposium steering committee and its sponsors--the Colorado Geological Survey and the U.S. Geological Survey--hope that this meeting will be an annual spring event to be held in various cities in the Rocky Mountain area.

The 1977 Symposium was a success because of the excellent session speakers and workshop and field trip leaders, and also because of the significant contribution of members of the following agencies and organizations: Colorado Geological Survey, U.S. Geological Survey, U.S. Bureau of Mines, the Denver Coal Club, and the Rocky Mountain Association of Geologists. The 1977 steering committee, composed of members of these organizations, did an outstanding job in formulating and assembling the program; organizing the post-Symposium field trip; and handling the logistics of registration, housing, food service, publicity, exhibits, entertainment, and transportation. Credit should also be given for the excellent educational exhibits set up by a number of Federal agencies and State geological surveys.

This symposium series is designed primarily for the geologist exploring for and developing the coal resources of the Rocky Mountain region, from Montana to New Mexico, and from Colorado to Utah. The 1977 Program Chairman, Mark Wilkerson, concentrated on the importance of depositional environments to coal geology in creating the program; his ideas can be summarized as follows:

> To cover all the facets of the ever-changing discipline of coal geology would require a symposium every year for as long as the demand for coal exists. One very important and often overlooked aspect of coal geology is the role of depositional environments in the understanding of the occurrence, geometry, correlation, and character of coal seams. Examination of interrelated depositional events removes some of the guesswork from our geologic interpretation. This type of study can be applied to on-site field mapping and core-hole logging of potential coal exploration areas.

Wilkerson did a commendable job in assembling the formal papers, which were followed each afternoon by interesting workshops in which participants could examine complete cores of coal-bearing sequences; examine coal thin sections through a petrographic microscope; and observe firsthand how coal data can be efficiently computerized, as exemplified through interaction of computers at the University of South Carolina and the office of the Atlantic Richfield Company in Los Angeles, California.

The 1977 Symposium consisted of four technical sessions:

I: Depositional Models for Coal Exploration in the Rocky Mountain Cretaceous
II: Stratigraphy and Depositional Environments of Rocky Mountain Tertiary Coal Deposits
III: Depositional Models for Coal Exploration in non-Rocky Mountain Regions
IV: Application of Geology to Coal Mining and Coal Mine Planning

In addition to these technical sessions and the three concurrent workshops, the following people addressed luncheon and banquet meetings:

Raymond C. Lowrie (Chief, Intermountain Field Operations Center, U.S. Bureau of Mines, Denver): "An Overview of Western Coal Development"

Beatrice E. Willard (Professor of Environmental Science, Colorado School of Mines, Golden; former member of the President's Council on Environmental Quality): "Can the Coal Geologist Harmonize His Activities with the Environment?"

John W. Hand (Vice President, Cameron Engineers, Denver): "The Watkins [Colorado] Lignite Project"

The technical meeting was followed by the RoMoCoal field trip, a two-day excursion to view coal deposits and mining operations in the Yampa coal field, Routt and Moffat Counties, northwest Colorado. This area contains the largest surface coal mines in the State; it produces about two-thirds of Colorado's total annual production. Charles L. Pillmore, Helen E. Hodgson, and John O. Maberry, U.S. Geological Survey, did an outstanding job of organizing and conducting the RoMoCoal field trip. Glen A. Izett, Edwin R. Landis, Robert B. Raup, Jr., and Thomas A. Ryer provided commentaries at selected points of interest along the route. Personnel from the Edna, Energy Fuels, and ColoWyo surface mines gave the group informative tours of the efficient mining and mined-land reclamation programs being carried out in this rugged and scenic part of Colorado.

This Proceedings volume contains all but two of the papers presented at the 1977 Symposium, along with the abstracts of the remaining two. In addition, informative reports from the three workshops are included. A paper on geophysics as related to coal, given at the 1976 Symposium but not published in the Proceedings volume from that meeting, has been included here. Photographs showing highlights of the field trip have been interspersed throughout the volume. In this volume, the primary goals of the 1977 Symposium have been met: "To focus on a basic stratigraphic-framework approach to coal exploration and mine planning. . .[and] to include other important facets of exploration and mine planning which may be conducted by the geologist in the field, lab, or office."

D. Keith Murray
Chairman, 1977 Symposium

March 1978

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1977 Symposium on the Geology of Rocky Mountain Coal

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The RoMoCoal Field Trip Revisited

The Rocky Mountain Coal Symposium (RoMoCoal) field trip was considered a highlight of the meeting and, because many attendees of the Symposium were unable to participate, a fairly complete description of the trip and a map showing the trip route are included here. The trip began on Tuesday afternoon, May 10, after the Symposium ended; and the buses returned to Denver late on Thursday evening. The complete cost of the trip was $75 per person and 106 people participated.

The RoMoCoal field trip left the Green Center by bus and proceeded into the mountains through Idaho Springs, over Berthoud Pass, to Winter Park Ski Area. A roast beef dinner buffet, complete with wine, was served to the group at High County Inn, a ski lodge directly across the valley from the ski area. Following the meal, we drove through Middle Park, down the Colorado River through Hot Sulphur Springs to Kremmling, and turned north at Kremmling. We stopped for a late evening discussion of the geology of the Kremmling area by Glen Izett at an overlook at the junction of Colorado 134 (the Gore Pass road), a few miles north of Kremmling. After this stop we continued on Highway 40 over Rabbit Ears Pass to the Steamboat Village Inn at Steamboat Springs.

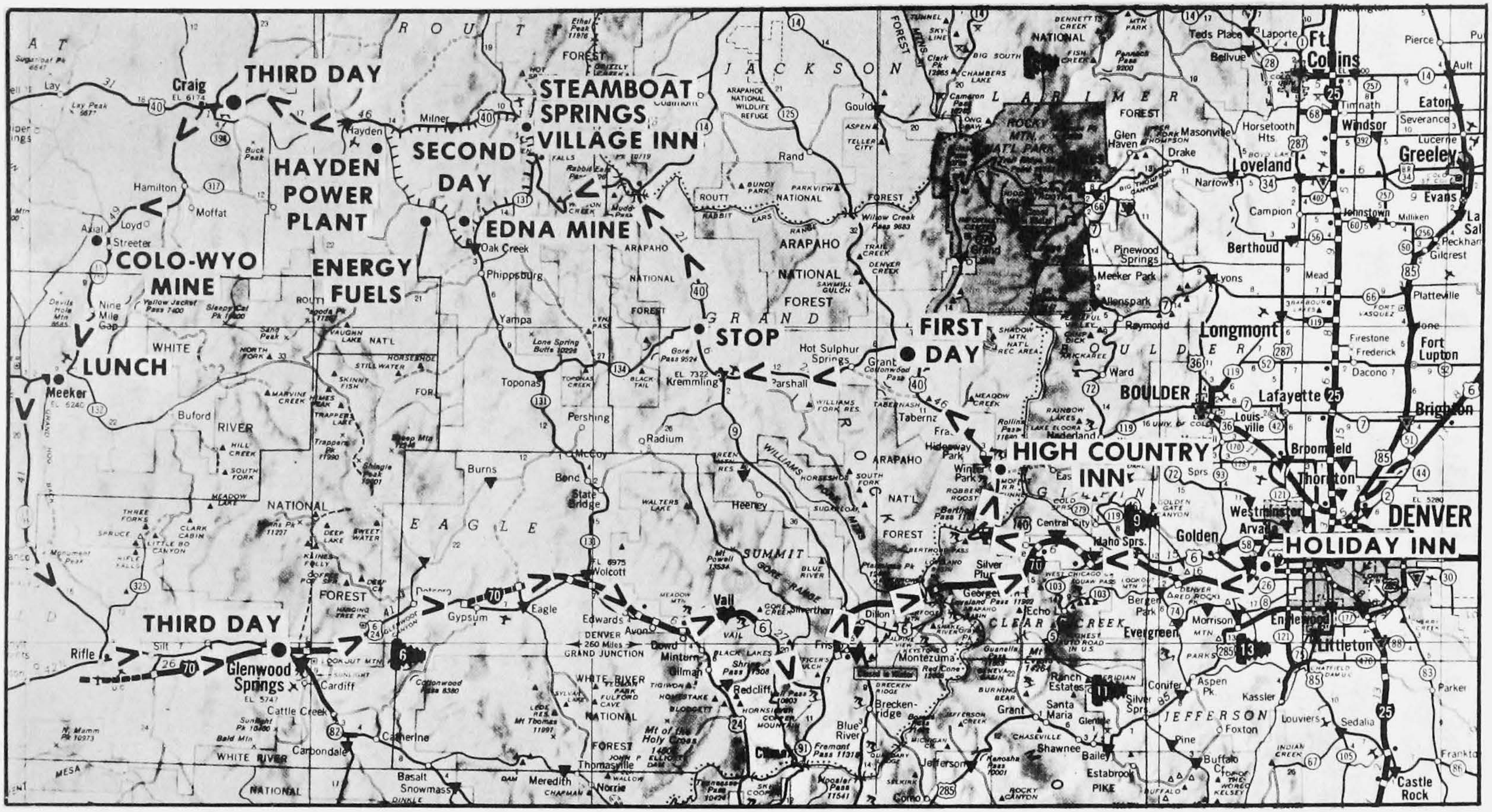
The second day began with an early morning breakfast buffet in the Robbers Roost dining room at the Inn. Following breakfast, and after much confusion and doubling up caused by a bus that malfunctioned, we finally departed and proceeded south on Colorado 131 from Steamboat Springs, turned west at Oak Creek, and then continued northwest to the entrance of the Pittsburgh-Midway Edna mine. Here we left the highway and the buses climbed up the steep grade of the mine road to a lookout point from which we viewed the mining and reclamation activities and listened to a presentation by company officials of the Edna mine. We then walked back down the hill, studying roadcuts and environments of deposition of rocks of the Williams Fork Formation along the way, and met the buses at the bottom. We proceeded on past the Energy Fuels mine to Fish Creek Canyon for further examination of the coal-bearing rocks of the Iles and Williams Fork Formations. A walk through the section was led by Glen Izett, Ed Landis, and Tom Ryer, author of U.S. Geological Survey Open-File Report 77-303, a study of the Foidel Creek EMRIA site that was included in the field trip packet. We then reboarded the buses shortly after noon and returned to a nearby park area for a chicken and beef-rib barbeque lunch that had been prepared in the field by the Steamboat Village Inn team. After lunch a replacement bus arrived, and we visited the Energy Fuels mine to view the coal in the pits; to hear discussions of the mine operations by Gary Myers, Gordon Wren, and others of the staff; and to tour one of the big draglines. On the return trip to Steamboat Springs, we stopped at the Hayden Power Plant, where Robert B. Raup, Jr., of the U.S. Geological Survey, discussed some aspects of coal development and future plans for power generation in the area. We then returned via the Yampa River Canyon to the Village Inn for a cocktail party, followed by a steakfry on the patio.

The third day began with another enormous buffet breakfast, after which we departed and proceeded west from Steamboat Springs on Highway 40, down the Yampa River to Craig, and then south on Highway 13 toward Meeker. We stopped at the ColoWyo mine near Streeter, about 27 miles south of Craig, for discussions of the mining history of the area, an examination of one of the upper beds of coal in a pit being mined, and an overview of the mine site. Ira McKeever, who is in charge of the operation, led our tour and also discussed future plans for mining eight coal seams at this site. After leaving ColoWyo mine, we proceeded south to Meeker for a lunch stop hosted by Colonel Sanders at Meeker City Park. After lunch we continued south to Rifle and joined Interstate 70, which follows the Colorado River past Newcastle and Glenwood Springs and then enters Glenwood Canyon. There, we made a final stop to view the spectacular exposures of Paleozoic and Precambrian rocks in the canyon. At Dotsero we left the Colorado River and proceeded up the Eagle River past the Vail ski resort, over Vail Pass, through the Eisenhower Tunnel beneath the Continental Divide, and then on to Denver.

Response to the RoMoCoal field trip was highly enthusiastic and, for those who care to reminisce, photographs showing some of the highlights of the trip, taken by Harold H. Arndt of the U.S. Geological Survey, are interspersed through the volume.

March 1978

Charles L. Pillmore and John O. Maberry
RoMoCoal Field Trip Co-Chairmen



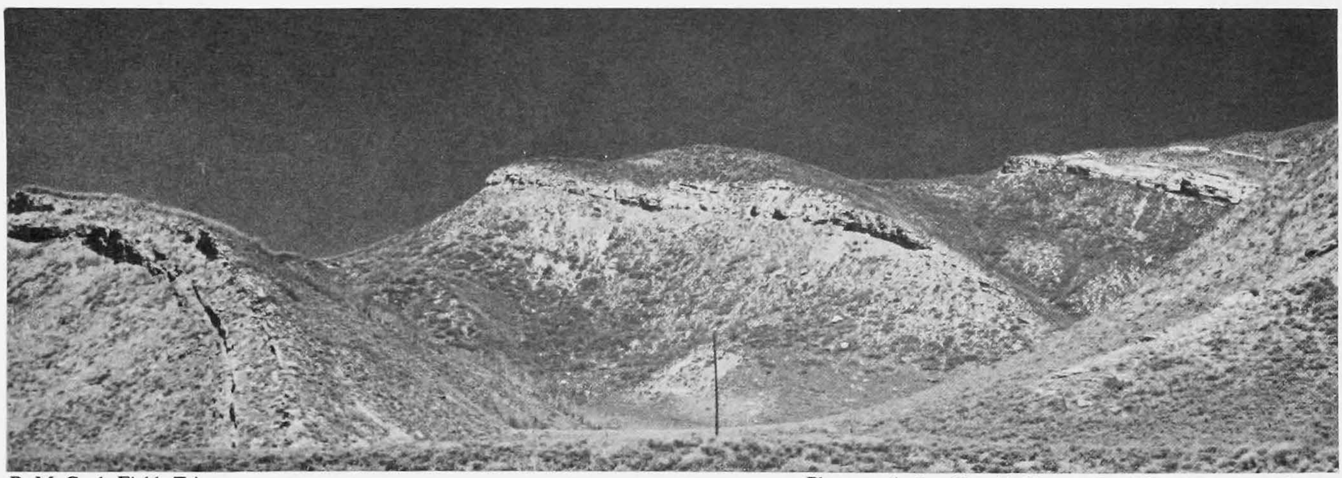
Map showing the route taken by the RoMoCoal field trip.

Contents

RoMoCoal Field Trip

Photograph by Harold H. Arndt, U.S. Geological Survey

Exposure of the Trout Creek Sandstone Member of the Iles Formation, Mesa Verde Group, along the north wall of Fish Creek Canyon, Routt County, Colo. The steep slope above the Trout Creek Sandstone is underlain by the lower coal-bearing member of the Williams Fork Formation.



RoMoCoal Field Trip

Photograph by Harold H. Arndt, U.S. Geological Survey

View on the north side of Fish Creek Canyon showing dipping sandstones of the Iles Formation.

Generation of a Simplified Working Depositional Model for Repetitive Coal-Bearing Sequences Using Field Data: An Example from the Upper Cretaceous Menefee Formation (Mesaverde Group), Northwestern New Mexico

CHARLES T. SIEMERS[1]

ABSTRACT

The Menefee Formation of northwestern New Mexico (San Juan Basin) is the middle, nonmarine, coal-bearing unit of the Mesaverde Group. The stratigraphic section is a confusing repetitive vertical sequence of a few different lithologic types. Using a simple mathematical device, simplified working depositional models for the repetitive sequence have been objectively generated.

Two depositional models were generated for the Menefee Formation, one for the coal-bearing upper and lower parts and another for the middle barren interval. The coal-bearing model consists of (1) a lower, 3-m-thick, fining-upward active-channel-fill sandbody that has a scour base, and (2) an overlying, 12-m-thick repetitive sequence of inactive-channel-fill mudstone, channel-margin levee and flood-plain mudstone and splay sandstone, and well to poorly drained humate- and coal-depositing swamps. Two thin (0.3- to 0.5-m-thick) coal beds generally occur in the sequence, and coal represents an "end-member" of the sequence, commonly being overlain by another channel sandstone. Three or four thin (0.4- to 0.8-m-thick) humate beds and three (0.7- to 1.5-m-thick) splay sandstone beds also occur interbedded with six to seven 0.5- to 2.0-m-thick mudstone units and coal seams. The model for the barren Menefee interval consists of (1) a basal, 6.5-m-thick, multistory channel sandbody and (2) an overlying, 8.5-m-thick repetitive sequence of inactive-channel-fill sediments, flood-plain mudstone and sandstones, and well-drained humate-depositing swamps. These models can be summarized generally as "typical genetic sequences" for middle- to lower-delta-plain (coal-bearing model) and upper- to middle-delta-plain (barren model) sedimentation.

Such model lithologic sequences may never be represented exactly in the observed stratigraphic sections; however, they can be used as "norms" for interpreting outcrops and subsurface data and for making predictions as to the extent and character of lithologic units (including coal) to be expected in a particular area. The significant features of the simple mathematical models are that they are generated using observed data (that is, one lets the data dictate the model), not according to some Holocene depositional environment, and that they are easy to generate and apply in the field.

INTRODUCTION

The Menefee Formation of northwestern New Mexico (San Juan Basin) is the middle, nonmarine, coal-bearing unit of the tripartite Upper Cretaceous Mesaverde Group. During recent investigations of Menefee humate (brownish-colored mudstone in humic matter) by Siemers and Wadell (1975, 1977) and of Menefee lithofacies in general by Mannhard (1976) and S. D. Wallace (written and oral communications, 1975-1977), several hundred meters of Menefee outcrop were measured and described in detail. Such descriptions have provided the data necessary to document the complex character of the Menefee. Only a few different types of lithologic units are present, but they occur in complex repetitive vertical sequences. In order to objectively "boil down" the repetitive sequences into their basic "building blocks" and paleoenvironmental "genetic units," a simple mathematical device was used to generate model lithologic sequences for the coal-bearing and barren (non-coal-bearing) parts of the Menefee. The model vertical sequences provide a basic framework for further understanding of coal-bearing sequences such as those

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of the Menefee.

The purpose of this paper is to describe the simple mathematical device used to simplify repetitive stratigraphic sequences. Emphasis is placed on demonstrating the simplicity, objectivity, and utility of the approach. The model lithologic sequences are generated directly using field data obtained from detailed analysis of outcrops; the same approach can be used on core and wire-line log data. Such models represent "normal" genetic units which can be interpreted in terms of process-product sedimentological concepts. They also can be used as "norms" for making predictions as to the extent and character of lithologic units (including coal) to be expected in a particular area.

STRATIGRAPHY AND LITHOLOGY OF THE MENEFEE FORMATION

The Mesaverde Group in northwestern New Mexico, consisting in its simplest form of the Point Lookout Sandstone, Menefee Formation, and Cliff House Sandstone, is a classic regressive-transgressive sequence (Hollenshead and Pritchard, 1961; Beaumont and others, 1956; Fassett, 1974, 1977; Molenaar, 1977). The general spatial relationships of these stratigraphic units across the San Juan Basin are shown in figure 1. The Point Lookout Sandstone is composed of nearshore marine sandstones (Siemers and others, 1975, p. 67-70) representing an extensive regional northeastward regression across the San Juan Basin area; the Point Lookout has been traced for over 210 km in a dip direction (Molenaar, 1977), and it merges with the Cliff House Sandstone to the northeast (fig. 1). The Cliff House Sandstone is composed of destructional delta-front and nearshore marine sandstones (Mannhard, 1976; Siemers and King, 1974); it occurs in a transgressive stratigraphic position between the nonmarine Menefee below and marine Lewis Shale above. However, the Cliff House is complexly intertongued with the Menefee and Lewis, and most sand buildups (for example, the La Ventana Tongue) represent local prograding shorelines developed during shoreline stillstands and are truly regressive sands (in a sedimentological sense).

The Menefee Formation represents, in general, nonmarine alluvial-plain, deltaic, and coastal-plain deposition landward from the Point Lookout and Cliff House shorelines. The Menefee thickens southwestward from a pinch-out edge on the northeast to about 610 m in the area of the landward extent of the overlying Cliff House (Molenaar, 1977) (fig. 1). In the study area in the southeastern part of the San Juan Basin (fig. 2), the Menefee ranges from 140 to 280 m in thickness. Coal beds occur mainly in the lower and upper parts of the formation, with the middle portion commonly lacking coal but containing abundant carbonaceous mudstone.

Measured Sections and Lithologic Units

The Menefee Formation is well exposed in the southeastern part of the San Juan Basin. Three complete outcrop intervals and one partial interval of the Menefee were measured and described in detail by the author with the assistance of J. S. Wadell and S. D. Wallace. Those sections were supplemented with several short intervals of the upper part of the Menefee that were measured and described by Mannhard (1976). Locations of principal outcrop sections are listed in table 1 and shown in general in figure 2. Measured outcrop sections are illustrated in figures 3-6. Relatively fresh (nonweathered) Menefee lithologies were also observed in two cores of the lower part of the formation in the South Hospah area (see Siemers, this volume); however, analysis of those sequences has not been included in this paper.

The complex repetitive nature of the Menefee is well displayed in the measured sections illustrated in figures 3-6. Only a few lithologic types are present, but they recur numerous times throughout the vertical sequence. Five major lithologic units are easily delineated (table 2): (1) relatively thick crossbedded sandstone units having sharp scour bases and

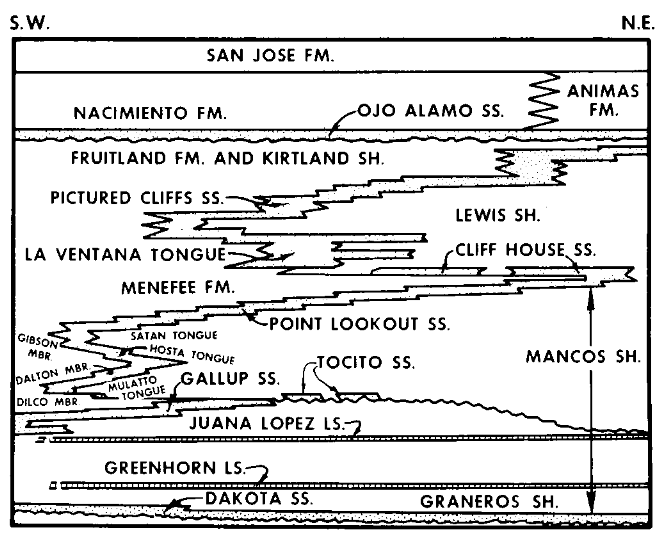


Figure 1.--Diagrammatic stratigraphic cross section of Cretaceous and Tertiary rocks of the San Juan Basin, northwestern New Mexico; vertical exaggeration is about X150. In this study, the Menefee Formation was analyzed from where it is overlain by the La Ventana Tongue of the Cliff House Sandstone to where it is relatively thin toward the northeast. The cross section is modified from an illustration by Fassett (1974, fig. 1).

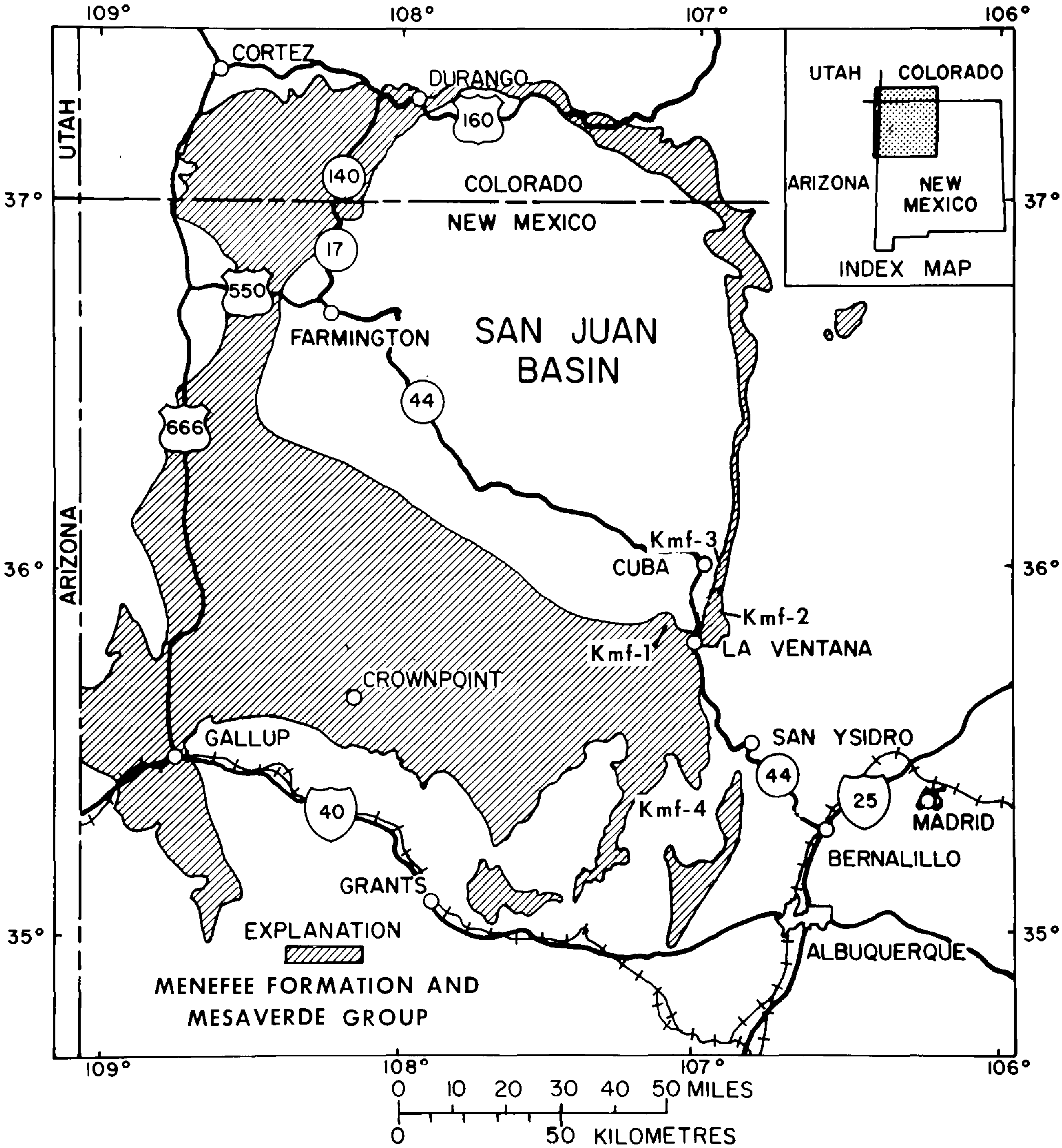


Figure 2.--Index map of the San Juan Basin area showing the location of measured sections (Kmf-1 through Kmf-4) and the area of the Menefee Formation and Mesaverde Group outcrop in northwestern New Mexico and southwestern Colorado. Map modified from Shomaker and Hiss (1974).

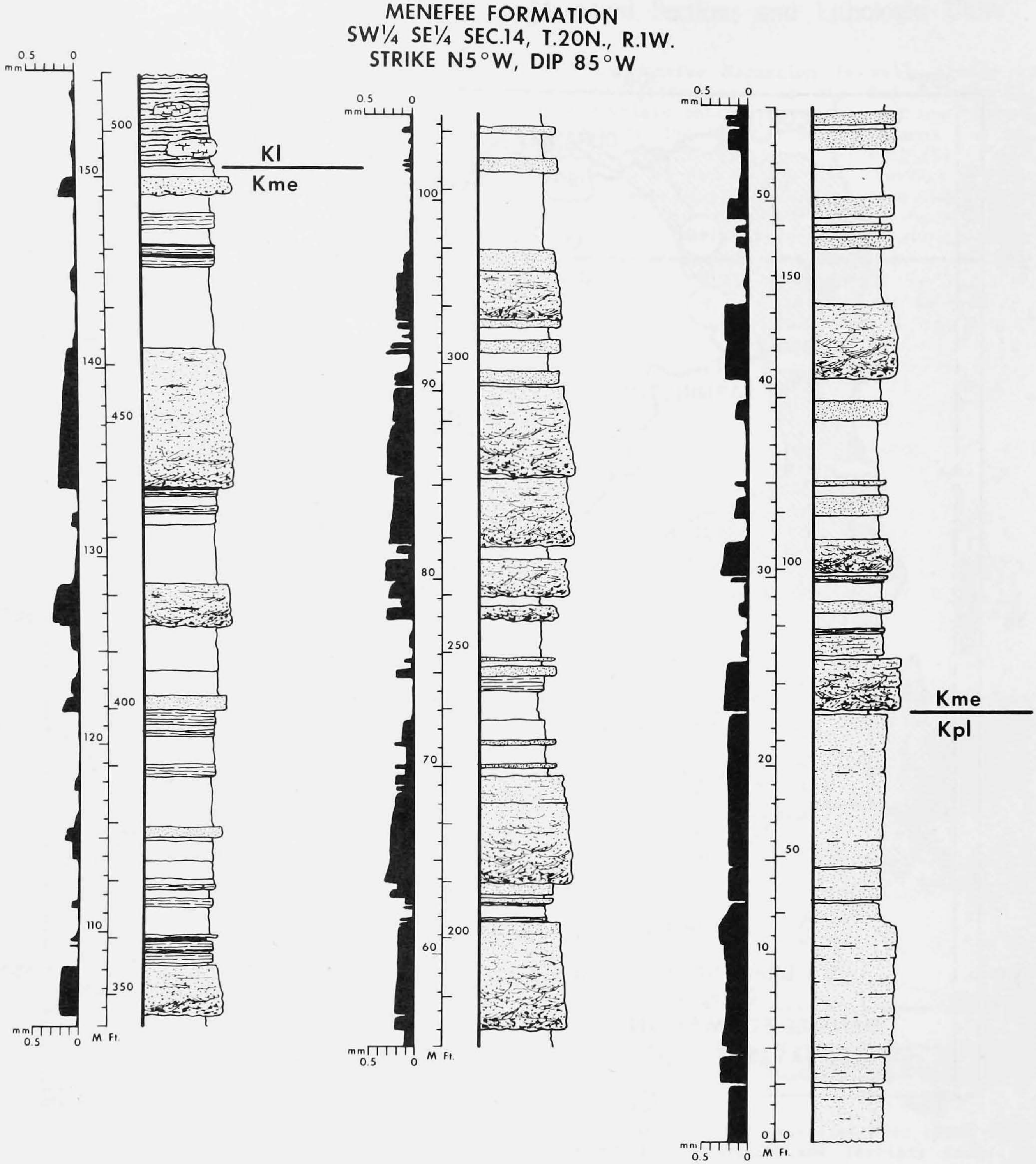


Figure 3.--Measured section Kmf-3 of the Menefee Formation (measured by S. D. Wallace). This is the northernmost section measured; note that the Menefee is 128 m thick here and is overlain by the Lewis Shale. (Cliff House Sandstone is very thin or lacking entirely in this area.) Lithologic symbols used are sandstone, stippled with bedding features sketched; mudstone, nonpatterned; humate, horizontal broken-line pattern; coal, black layers; siderite, discontinuous and disc-shaped black layers. A continuous grain-size plot is shown to the left of each lithologic column. All sections run from base at the lower right to top at the upper left.

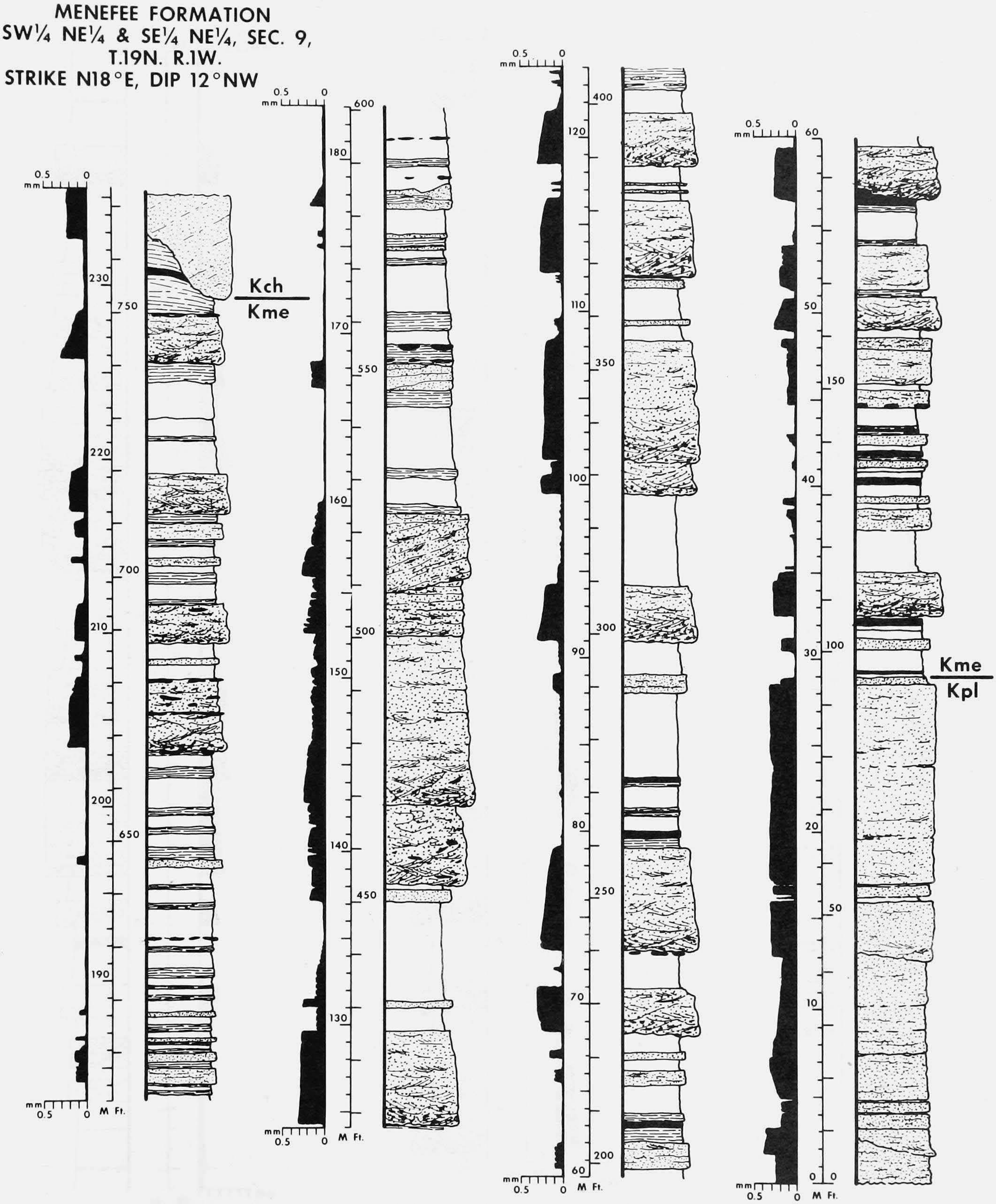


Figure 4.--Measured section Kmf-2 of the Menefee Formation (lower two-thirds of section measured by S. D. Wallace; upper one-third measured by the author and J. S. Wadell). Menefee is approximately 204 m thick here and is overlain by a large rotated slump block of the Cliff House. Lithologic symbols used are sandstone, stippled with bedding features sketched; mudstone, nonpatterned; humate, horizontal broken-line pattern; coal, black layers; siderite, discontinuous and disc-shaped black layers. A continuous grain-size plot is shown to the left of each lithologic column. All sections run from base at the lower r left.

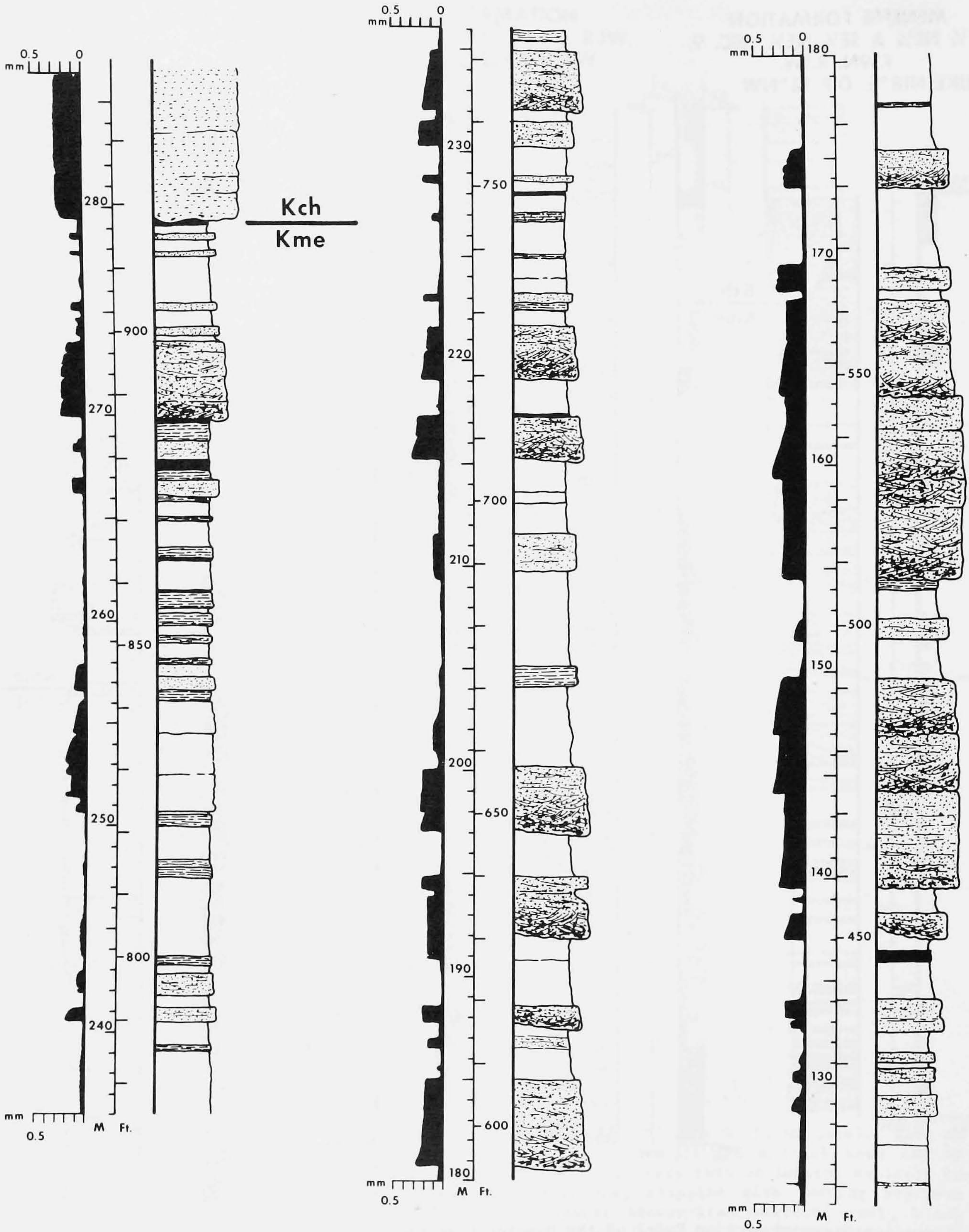
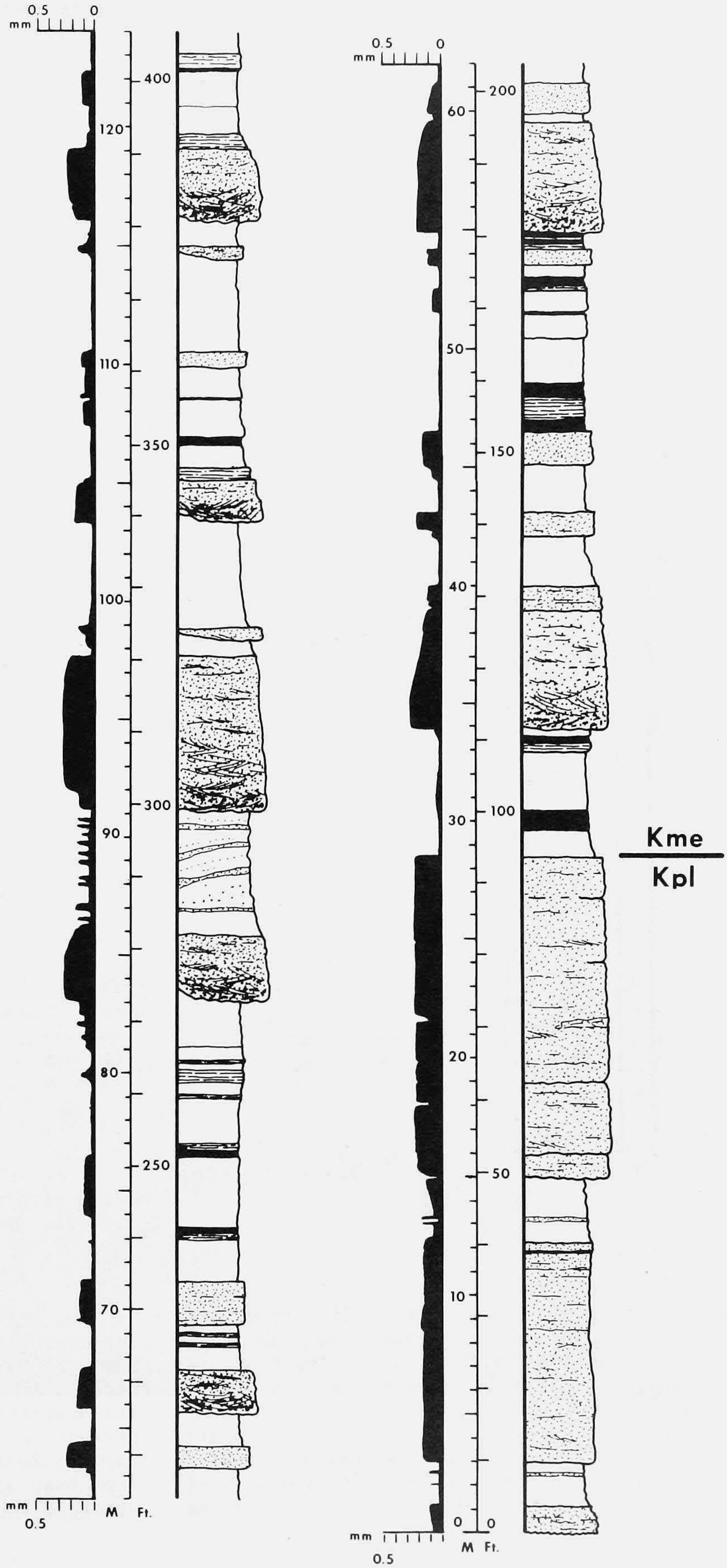


Figure 5.--Measured section Kmf-1 of the Menefee Formation (measured by S. D. Wallace). Menefee is approximately 251 m thick here. Lithologic symbols used are sandstone, stippled with bedding features sketched; mudstone, nonpatterned; humate, horizontal broken-line pattern; coal, black layers; siderite, discontinuous and disc-shaped black layers. A continuous grain-size plot is shown to the left of each lithologic column. All sections run from base at the lower right to top at the upper left.



MENEFEE FORMATION
SW¼ SE¼ SEC.31, T.19N., R.1W.
& NE¼ SEC.36, T.19N., R.2W.
STRIKE N.75°E., DIP 8°NW

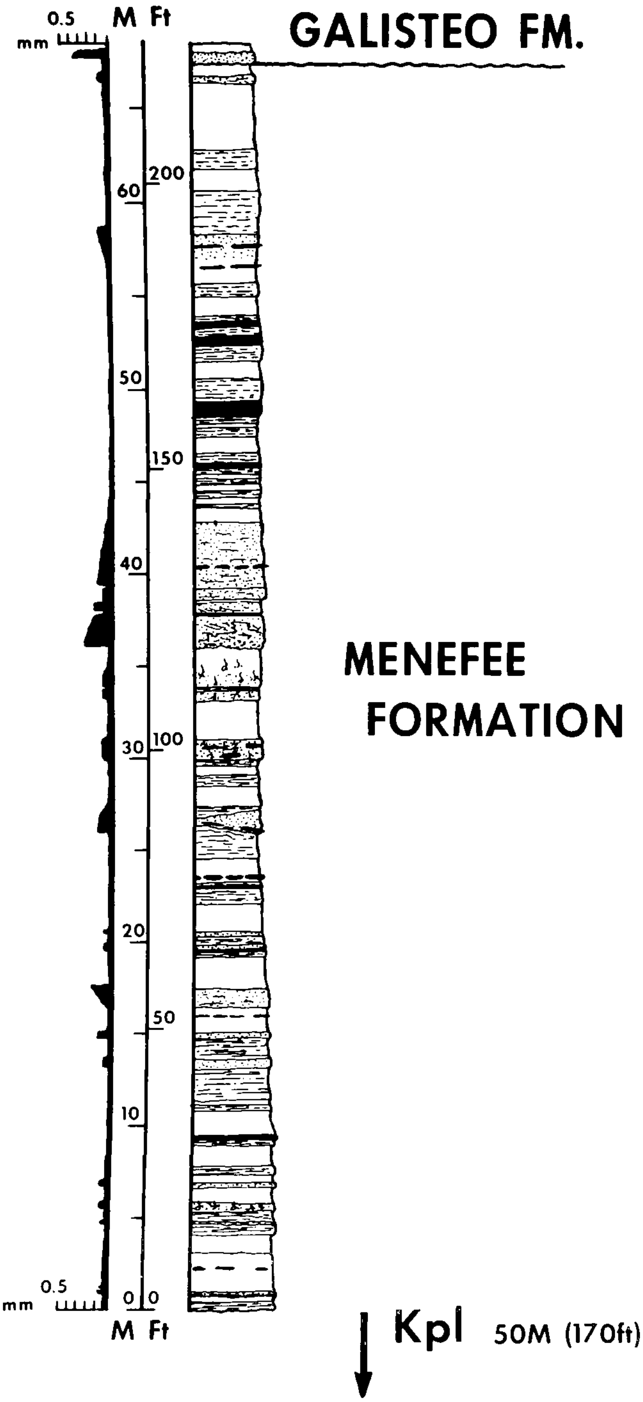


Figure 6.--Measured section Kmf-4 of part of the lower part of the Menefee Formation (section measured by the author and J. S. Wadell). Base of section is about 50 m above the top of the Point Lookout Sandstone. The Eocene Galisteo Formation overlies the Menefee with erosional and angular unconformity here. Lithologic symbols used are sandstone, stippled with bedding features sketched; mudstone, nonpatterned; humate, horizontal broken-line pattern; coal, black layers; siderite, discontinuous and disc-shaped black layers. A continuous grain-size plot is shown to the left of each lithologic column. All sections run from base at the lower right to top at the upper left.

fining-upward grain-size trends; (2) thin, flat- to ripple-bedded sandstone having relatively sharp bases and tops and common *in situ* roots at the top; (3) gray, barren to slightly carbonaceous mudstone; (4) brown, highly carbonaceous humate; and (5) black to brownish-black subbituminous coal. Siderite nodules and septarian concretions are also a common lithologic component. In general, coal beds are most abundant in the lower and upper tens to hundreds of meters of the Menefee, whereas the thick crossbedded sandstone units are best developed through the middle of the formation. Barren mudstone, humate, and thin sandstone units occur at about the same abundance throughout the formation, although humate tends to increase somewhat in coal-bearing intervals.

Thick Crossbedded Sandstone Lenses

Relatively thick (commonly 2-5 m), lenticular, crossbedded sandstone units are commonly the dominant features of an outcrop (fig. 7), whereas most other lithologies form partly covered slopes above and below. In most cases the lenticular sandstone bodies have sharp (concave-upward) scour bases, which remove or displace the mudstone-humate-coal sequence, and flat gradational tops with overlying mudstone. The lower part of the sandstone bodies contains coarse detritus consisting of claystone clasts, wood and plant debris, and coal and humate fragments (fig. 8). The main body of the sandstone lenses consists of large- to medium-scale cross-stratified, friable, fine-grained, moderately sorted yellowish-gray sandstone. Both large (3- to 7-m-thick), planar, point-bar accretion-surface crossbeds (fig. 7) and medium-scale (0.2- to 0.5-m-thick) trough cross-stratification are common. The upper parts of the sandstone bodies consist of thin, flat- to ripple-bedded, very fine grained silty sandstone with some small-scale trough cross-stratification. Paleocurrent analysis of cross-stratification indicates a predominant unidirectional flow, with small to moderate variation, toward the northeast. In general these sandstone bodies can be interpreted as representing active-channel-fill sand deposition in a meandering-channel system.

Several sandstone samples (8) were analyzed texturally using a combined sieve, pipette, and settling-tube technique. The channel sandstones

Table 1.--Location of measured sections of Menefee Formation used in this study

Notation	Location	Comments
Kmf-1	SW1/4 sec. 31, T. 19 N., R. 1 W. to NE1/4 NE1/4 and E1/2 NE1/4 sec. 36, T. 19 N., R. 2 W.; approx. 1.6 km northwest of La Ventana, N. Mex.	Measured section of Menefee Formation (251 m) by S. D. Wallace.
Kmf-2	S1/2 NE1/4 sec. 9, T. 19 N., R. 1 W.; approx. 14 km south of Cuba, N. Mex., on old New Mexico Highway 44.	Measured section of Menefee Formation (204 m); lower two-thirds (east of old New Mexico Highway 44) measured by S. D. Wallace; upper one-third (west of old New Mexico Highway 44) measured by C. T. Siemers and J. S. Wadell.
Kmf-3	SW1/4 SE1/4 sec. 14, T. 20 N., R. 1 W.; approx. 1.6 km north of San Pable, N. Mex., 10 km south of Cuba, N. Mex.	Measured section of Menefee Formation (128 m) by S. D. Wallace.
Kmf-4	Ctr., E1/2 sec. 3, T. 14 N., R. 1 E.; approx. 14 km southwest of San Ysidro, N. Mex.	Measured section of 67 m of part of lower part of Menefee Formation by C. T. Siemers and J. S. Wadell.

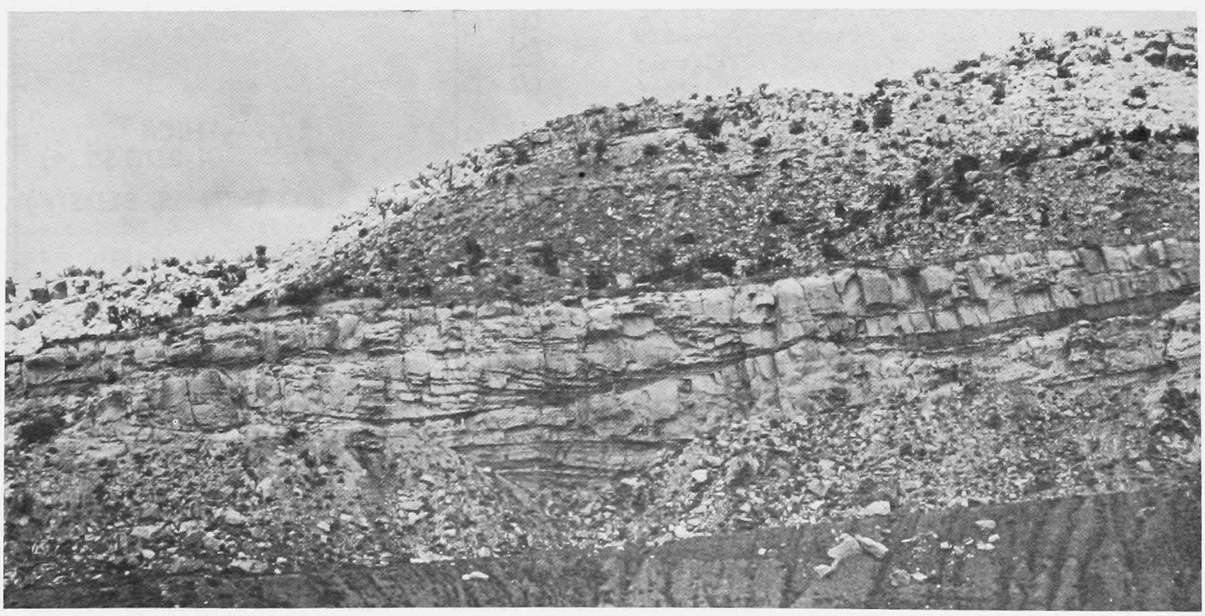


Figure 7.--Exposure of complex (multistory), thick crossbedded channel sandstone in Menefee near measured section Kmf-1. Note large point-bar accretion crossbed sets in lower part of the upper sandstone body. Sandstone sequence is approximately 14 m thick.

Figure 8.--Coarse debris present typically at the base of thick crossbedded channel-sandstone lenses. Large clasts consist of reworked mudstone, humate, and coal, and altered plant and wood fragments.

ranged in mean grain size from 2.68 phi (0.15 mm; fine sand) to 3.63 phi (0.08 mm; very fine sand), and in sorting values from 0.39 phi-units (well sorted) to 1.27 phi-units (poorly sorted). The channel sands are easily distinguished from the barren mudstones but overlap, in terms of grain size and sorting, with the thin sandstone units (fig. 9). Petrographically the channel sands are grain-supported and have a framework/nonframework (void space, matrix, cement) ratio of 64/36 (7.5, 11, 17.5). The framework classifies mostly as arkose to lithic arkose, containing 63-75 percent quartz plus chert, 13-26 percent feldspar (divided equally between orthoclase and plagioclase), and 5-16 percent rock fragments that are mostly granitic and volcanic material (Mannhard, 1976, p. 148-154). The nonframework fraction is mostly detrital silt and clay matrix and authigenic kaolinite clay cement (X-ray diffraction conformation) with locally abundant iron oxide cement.

Thin Sandstone Beds

Thin (0.5-2.5 m), tabular to broadly lenticular sandstone units have sharp, but not scour, basal contacts with mudstone and sharp to slightly gradational tops, commonly with abundant in situ roots. Sieve and pipette analysis of the friable, gray to yellowish- and brownish-gray "sandstone" (7 samples) revealed a mean size of 3.10 phi (0.118 mm; very fine grained sand) to 4.97 phi (0.032 mm; very coarse silt), and sorting of 0.81 phi-units (moderately sorted) to 1.86 phi-units (poorly sorted) (fig. 9). Structures are mostly horizontal and ripple lamination, with some small-scale troughs in the lower parts and climbing ripples randomly distributed. Roots and sparse burrows (insect?) commonly have completely destroyed the primary physical sedimentary structures. Thin mud interlaminae are common, and fine-grained plant and wood debris is usually present. Such thin sandstone units probably represent some type of crevasse splay or levee deposition associated with channel development in flood-plain and deltaic areas.

Barren Mudstone

Olive-gray to brownish-gray, moderately indurated mudstone (silty claystone to clayey siltstone) (fig. 9) is volumetrically the most abundant lithology of the Menefee; however, units are commonly expressed as partly covered slopes on outcrop and are not as noticeable initially as are the more resistant sandstone units (fig. 7). Mudstone units appear to be tabular in shape and are fairly persistent laterally; they are commonly 0.5-1.5 m thick but may be much thicker (over 4.0 m). The mudstone is generally massive in appearance and characterized by its nonfissile (blocky) character (fig. 10), differentiating it from shale which is fissile by definition. Minor lamination may be visible in more silty or slightly sandy units. Root structures are common, but wood and plant debris is sparse. Clay minerals of the mudstones (20 samples

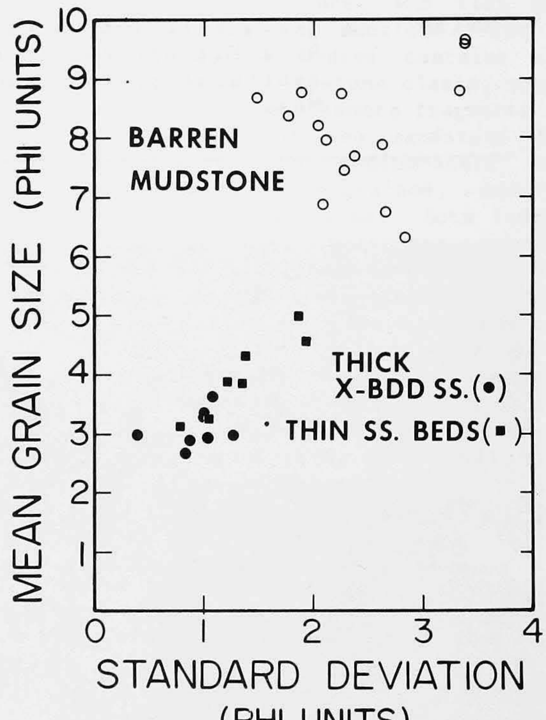


Figure 9.--Bivariate plot of grain-size data for sandstone and mudstone of the Menefee Formation. Note the distinct separation of mudstone and all sandstones, but the overlap of thick crossbedded sandstone and thin sandstone samples.

Figure 10.--Relatively fresh exposure of barren mudstone of Menefee showing characteristic blocky (nonfissile) fabric. Exposure in humate mine pit near measured section Kmf-4.

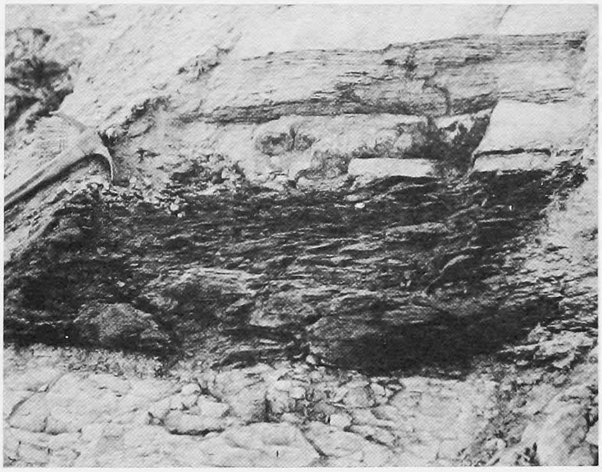


Figure 11.--Trench exposure of blocky, slightly shaley humate bed (dark bed) between barren mudstone below and clayey thin sandstone above. Humate is brown, mudstone is light gray, and sandstone is yellowish gray. Note sharp lithologic contacts. Exposure is in the upper part of the Menefee at locality Kmf-2.

analyzed by X-ray diffraction) are predominantly montmorillonite and mixed-layer montmorillonite-illite with abundant kaolinite. Barren mudstone units probably represent flood-plain deposition in areas that are exposed and oxidized shortly after flood deposition.

Humate

Humate is the dark-brown to brownish-gray, carbonaceous, blocky to slightly fissile mudstone containing abundant wood and plant material, which commonly is aligned and contributes to moderate fissility (figs. 11, 12). (The term "shale" could be correctly applied to some of these units.) The humate in the Menefee of this area has been described in detail and discussed in depth by Siemers and Wadell (1977). Humate units are thin (0.3-0.7 m), uniform in thickness, and laterally persistent, although they may grade laterally into barren mudstone. In a vertical sequence, humate is usually interlayered with barren mudstone or coal (fig. 12). It is important to emphasize that humate is a mudstone composed predominantly of detrital clay-mineral matter, even though it does contain abundant amorphous and structural organic matter. Humate in general probably represents moderately to poorly drained swamps receiving abundant clay-mineral and organic matter.

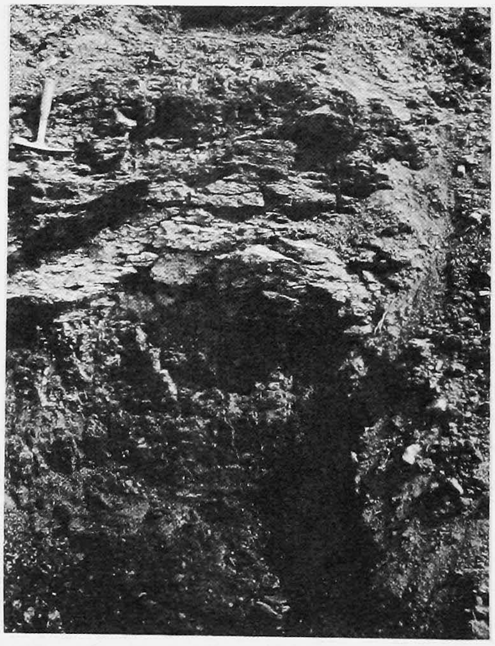


Figure 12.--Trench exposure of highly weathered coal bed (dark zone of lower half of photo) overlain by blocky humate bed (relatively light bed above). Coal is brownish black to black; humate is brown to brownish gray. Note sharp, nongradational contact between coal and humate beds. Exposure is in lower part of Menefee exposed at locality Kmf-4.

Table 2.--Major lithologic units of the Menefee Formation in northwestern New Mexico

Major lithologic units	Description
A. Thick crossbedded sandstones.	Scour base; fines upward.
B. Thin sandstones--	Flat- to ripple-bedded; sharp contacts; *in situ* roots at top.
C. Mudstone---------	Grayish-colored; barren to carbonaceous.
D. Humate-----------	Brownish-colored; highly carbonaceous and lignitic.
E. Coal-------------	Subbituminous.

Coal

The thin (0.2-0.4 m) coal seams in the Menefee of the study area are known to be mostly subbituminous A in rank, but some reach high-volatile bituminous C (Shomaker and others, 1971). In outcrop, the brownish-black to black coal is highly weathered and displays dull to moderately brilliant luster. The coal ranges from soft to quite hard, displays good cleat, contains abundant amber-colored resin, and may contain abundant pyrite or limonite and jarositic iron oxide on bedding planes and fracture surfaces. Thin mudstone and silty sandstone interlayers are moderately common. Coal beds are laterally persistent and may be vertically adjacent to any other Menefee lithology, but most commonly are interbedded with sharp to slightly transitional contacts with humate (fig. 12) and frequently are overlain with sharp scour contact by a thick crossbedded sandstone unit. Coal beds represent poorly drained swamps adjacent to channels and flood-plain deposits in a deltaic setting.

Siderite Nodules and Concretions

Iron nodules and concretions, commonly septarian in part, are present throughout the Menefee, both in outcrops and in subsurface cores. Nodules are generally less than 10 cm thick; septarian concretions may be more than 0.5 m thick (fig. 13). These structures generally consist of a gray, dense core of clayey calcitic siderite (X-ray diffraction confirmation) and a reddish- (geothitic) to yellowish-brown (limonitic), oxidized exterior. Nodules and concretions appear to be most commonly associated with humate and coal, but also are present in sandstone and barren mudstone units. Siderite commonly is developed penecontemporaneously with sedimentation as well as post-depositionally; the nodules and concretions observed in the Menefee may have developed anytime during and following deposition of the enclosing sediment. They were not deposited in the same way that other primary detrital minerals and organic matter were deposited, and are not considered in the depositional models below.

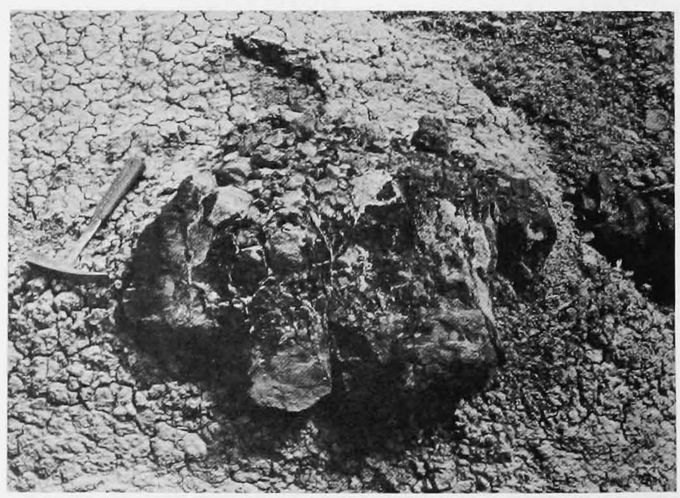


Figure 13.--Large septarian siderite concretion within interval of barren mudstone and humate. Dense core of concretion is clayey, gray siderite; exterior is oxidized brown goethitic siderite; shrinkage cracks are filled with iron-stained calcite. Siderite nodules and concretions are abundant throughout the Menefee, but most are smaller than this one, which occurs in the lower part of measured section Kmf-4.

GENERATION OF THE MODEL LITHOLOGIC SEQUENCES

General Methodology

Any detailed bed-by-bed description of the Menefee, such as that illustrated by the stratigraphic sections shown in figures 3-6, reveals a confusing repetitive sequence of the few lithologic units indicated above (table 2). One can probably assume that such sequences are not totally random and that each lithologic state is probably genetically related to the lithologic states above and below. It is difficult, however, to qualitatively determine the most common lithologic associations within such sequences. (For example, is a humate bed most commonly associated with a coal bed? What are the relationships of the thick crossbedded sandstone unit with any other units such as a coal bed or an interval of barren mudstone?) Ultimately one would like to develop a depositional model to explain the origin of the types and distributions of the lithologies observed.

The two methods most commonly used to interpret the depositional environments of ancient lithologic sequences such as the Menefee are as follows: (1) compare the lithologic sequence with specific depositional models that have previously been generated from the study of modern depositional environments or of other ancient sequences (Model Approach); or (2) interpret the physical, chemical, and biological processes responsible for the formation of each lithologic unit and the contact relationship between successive vertically and laterally adjacent units, and then develop an overall interpretation of the paleoenvironment by combining the "micro-systems" (Process Approach). The most useful depositional models for coal-bearing sequences have been generated from the study of modern dynamic lacustrine swamps and coastal deltaic and marginal-marine depositional environments. An increased understanding of the sedimentary processes in modern deltas, barrier island-lagoon complexes, freshwater swamps, and saltwater marshes has led directly to the development of better dynamic models for the deposition of coal-bearing sequences. However, one of the great difficulties of using models of modern depositional environments for the analysis of ancient systems is that the model never fits exactly, and one is forced to modify the model to fit the field data. In many instances one may become so influenced by these depositional models that objectivity decreases and certain data may be ignored or modified to better fit the model. Such an erroneous procedure can be alleviated to a great extent by using the more refined depositional-process approach (perhaps in conjunction with the model approach); however, one is still greatly influenced by what is known about the geometry and sedimentology of modern depositional systems.

A superior approach is to generate a model lithologic sequence quantitatively, such that the field data have the greatest influence in the development of the model. The approach used to analyze the repetitive lithologic sequences of the Menefee is a modified Markov chain approach, which considers both the vertical succession of lithologic states and the absolute and relative thicknesses of all the lithologic states. A Markov chain is a model that describes a sequence containing both random and deterministic elements; that is, the occurrence of certain elements in the sequence is strongly controlled by the preceding element, whereas other elements occur completely at random throughout the sequence. Krumbein and Dacey (1969) provided a comprehensive list of studies applying the Markov techniques to geologic phenomena. Markov chains and their use are explained in some detail by Harbaugh and Bonham-Carte (1970, p. 98-168). Also of specific interest are the following papers which describe the application of Markov chain or Markov chain-type models for the analysis of repetitive vertical sequences of strata: Selley (1970), Allen (1970), Harms and others (1975, Chapter 4 by Walker, p. 63-79), Doveton (1971), and Beaumont (1977, p. 52-67). The interested reader is urged to carefully digest the information provided in those valuable publications.

The analytical technique demonstrated below is presented in a rather simplified manner in order to emphasize the ease with which the rapid analysis of complex stratigraphic sequences can be performed in the field. Also, the technique includes consideration of the vertical succession of lithologic states as well as the absolute and relative thicknesses and abundance of all lithologic states. The analytical procedure, which is demonstrated in detail below, can be outlined briefly as follows: (1) Measure and describe the lithologic sequence in detail, especially noting all significant vertical changes in lithology as well as unit contact relationships and types and distribution of sedimentary structures. (2) Summarize the repetitive sequence in terms of the major lithologic states. The five major lithologic states described above (excluding siderite) were used in the Menefee analysis. (3) Prepare a tally matrix of the vertical transitions from one lithologic state to another. (4) Using the tally matrix data for observed transitions, calculate an expected-lithologic-transition matrix illustrating a random arrangement of lithologies (calculated for each matrix position by cross-multiplying row and column totals and dividing by total number of transitions). (5) Calculate a difference matrix by subtracting the predicted matrix from the observed matrix. (6) Prepare a flow diagram of the positive lithologic transitions (those transitions which occurred more times than would be expected in a random sequence). (7) Note the relative number and average thicknesses of the lithologic units. (8) Prepare a sketch of the simplified vertical sequence. This sequence can then be interpreted in terms of process-product sedimentological concepts.

The stratigraphic sequences illustrated in figures 3-6 provided most of the data used in generating the model lithologic sequences for the Menefee. Two models were generated, one for coal-bearing intervals and one for intervals lacking coal beds. The five major Menefee lithologic units described above represent the "building blocks" of the Menefee; they are listed in table 2 and referred to by the letters A through C in many of the illustrations.

Model Lithologic Sequence for Coal-Bearing Intervals

The tops and bottoms of coal-bearing intervals are picked at the highest and lowest occurrences of coal beds in an interval containing several coal beds. In the Menefee, extensive barren zones (non-coal-bearing intervals) occur that easily delineate the coal-bearing and barren intervals. It should be noted, however, that the coal-bearing intervals do not necessarily occur in the uppermost and lowermost portions of the Menefee. For example, in section Kmf-1 (fig. 3), no coal was observed in the lower portion of the Menefee, and section Kmf-2 essentially lacked coal in the upper portion of the formation.

Within the stratigraphic intervals to be modeled, each lithologic transition is recorded by starting from the base of the section and noting every change upward from one lithologic state to the next. The transitions are recorded in a tally matrix (fig. 14A). For example, if the lowest unit in the Menefee section is a thick crossbedded sandstone (lithologic state A) and it is overlain by a silty barren mudstone (lithologic state C), then a tally would be made in the matrix location row A, column C; 18 such transitions were noted in the combined coal-bearing intervals of all measured sections of the Menefee (fig. 14A). If the mudstone is in turn overlain by a humate bed (transition from state C to state D), then a tally would be made in the matrix location row C, column D; 62 such transitions were noted (fig. 14A). The tally matrix is complete when all transitions in the desired stratigraphic sequence have been recorded and all row and column totals have been calculated. The total number of transitions noted for the coal-bearing intervals analyzed is 460 (fig. 14A).

Using the tally-matrix data, one can then calculate what the matrix would be if the lithologic sequences were completely random in their organization. This matrix is called a transition-probability matrix or the expected matrix (fig. 14B) for a stratigraphic sequence in which all lithologic units represent depositional events totally independent of the lithologic units above and below them in a vertical sequence. Values for each site in the expected matrix are easily calculated by multiplying the row and column totals and dividing by the total number of transitions. For example, the value 2 for matrix location row A, column A was determined by multiplying the row total (28) by the column total (30) and dividing by 460. The resulting value is 1.8, which is rounded off to 2.0. It is probably best to wait until all matrix values have been calculated and recorded to the nearest tenth before rounding them off to whole numbers.

Next, the expected matrix is subtracted from the original tally matrix to generate the difference matrix (fig. 14C), which indicates the lithologic transitions that occur more or less times than would be expected for a random sequence. For example, in matrix location row A, column A, the tally matrix shows a value of 0 and the expected matrix has a value of 2; the difference is -2, which indicates that the transition from state A to state A occurred less than would be expected in a random sequence. The important values in the difference matrix are the positive values (shaded locations in fig. 14C), which indicate the transitions that occur more times than would be expected for a random sequence. These transitions represent the memory, or dependent events, of the depositional sequence.

Most of the lithologic states showed positive transitions to two or three other states. For example, lithologic state C (mudstone) showed positive transitions to B (thin sandstone; +31), D (humate; +20), and A (thick crossbedded sandstone; +3). Such transitions have been rated as to relative strength according to the number values. The relative strengths of all positive transitions for the coal-bearing sequences are summarized in table 3. All of the positive transitions are illustrated diagrammatically by the transition flow diagram in figure 15. Thick crossbedded sandstone units and coal beds appear as "end-members" of the model flow chart; and mudstone, thin sandstone, and humate units appear to represent an internal "subcycle" of the overall model sequence.

Using the transition flow diagram, an idealized vertical sequence can be sketched; however, such a model might not accurately represent the thicknesses and relative number of different lithologic units that should occur in the model sequence. In order to make the model more accurate, one must consider the thickness and number of lithologic units in the measured sections. The absolute lithologic-unit abundance values for the coal-bearing intervals are listed in table 4A. Note that the 22 thick crossbedded sandstone units had an average thickness of 2.97 m, 63 thin sandstone units averaged 0.85 m, 143 mudstone units averaged 1.18 m, 87 humate beds averaged 0.50 m, and 41 coal beds averaged 0.32 m

A. TALLY MATRIX

(OBSERVED TRANSITIONS)

A = THICK X-BEDDED SANDSTONE

B = THIN SANDSTONE

C = MUDSTONE

D = HUMATE

E = COAL

	A	B	C	D	E	
A	0	2	18	7	1	28
B	3	3	49	23	3	81
C	14	59	14	62	12	161
D	6	13	61	1	47	128
E	7	4	25	26	0	62
	30	81	167	119	63	460

B. "EXPECTED" MATRIX

(INDEPENDENT EVENTS)

$$E = \frac{r \times c}{N}$$

E = VALUE FOR EACH MATRIX LOCATION
r&c = ROW AND COLUMN TOTALS
N = TOTAL NUMBER OF TRANSITIONS

	A	B	C	D	E	
A	2	5	10	7	4	28
B	5	14	30	21	11	81
C	11	28	58	42	22	161
D	8	23	46	33	18	128
E	4	11	23	16	8	62
	30	81	167	119	63	460

C. DIFFERENCE MATRIX

(OBSERVED-MINUS-EXPECTED)

	A	B	C	D	E
A	-2	-3	+8	0	-3
B	-2	-11	+19	+2	-8
C	+3	+31	-44	+20	-10
D	-2	-10	+15	-32	+29
E	+3	-7	+2	+10	-8

Figure 14.--Matrices for the coal-bearing intervals of the Menefee Formation. See text for explanation.

Table 3.--List of positive lithologic transitions noted in the difference matrix (see fig. 14C) for the coal-bearing intervals of the Menefee Formation

Lithologic unit	Relative transition strength		
	Strongest	Weakest or intermediate	Weakest
A. Thick crossbedded sandstone.	C, mudstone	------------	---------------
B. Thin sandstone---	C, mudstone	D, humate	---------------
C. Mudstone---------	B, thin sandstone.	D, humate	A, thick cross-bedded sand-stone.
D. Humate-----------	E, coal	C, mudstone	---------------
E. Coal-------------	D, humate	A, thick crossbedded sandstone.	C, mudstone.

thick. More readily usable data for the construction of a model lithologic sequence are the relative lithologic-unit abundance values (table 4B). For example, taking lithologic state A as 1, it can be established that for every thick crossbedded sandstone unit in the measured sections, there are about 3 thin sandstone units, 6 to 7 mudstone units, nearly 4 humate beds, and about 2 coal beds. Using the average thickness of each unit and multiplying it by the relative number, the total thickness of each lithologic type within the model lithologic sequence is generated. The total thickness of the model lithologic sequence is obtained by summing the total thicknesses of the lithologic units; the model lithologic sequence for the coal-bearing

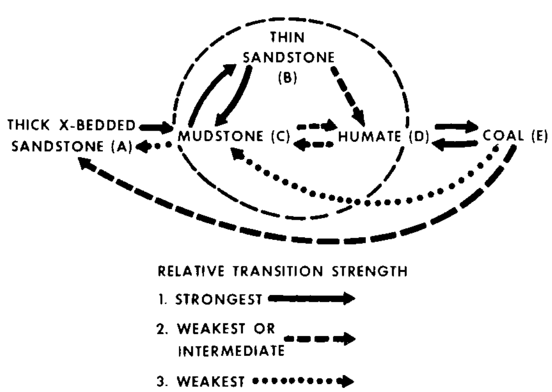


Figure 15.--Transition flow diagram of the lithologic sequence for the coal-bearing model of the Menefee Formation.

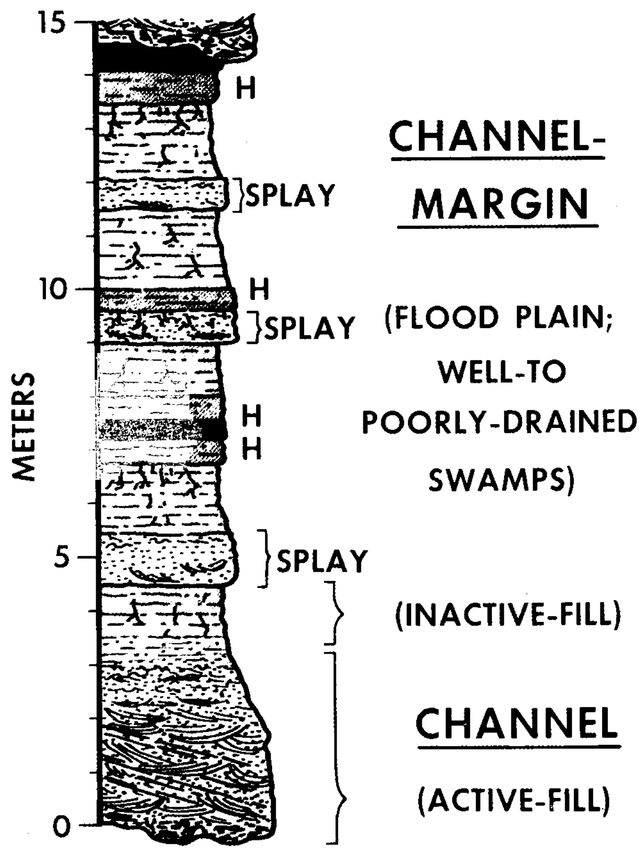


Figure 16.--Model lithologic sequence for the coal-bearing intervals of the Menefee Formation. Lithologies are sandstone, stippled and bedded patterns; barren mudstone, dashed pattern with roots; humate, sparsely dashed pattern marked by H; and coal, black seams.

Table 4.--Absolute and relative lithologic-unit abundance for the coal-bearing intervals of the Menefee Formation

A. Absolute

Lithologic unit	Number of units	Total thickness (m)	Percent of interval	Average thickness (m)	Range in thickness (m)
A. Thick crossbedded sandstone.	22	65.4	19.0	2.97	0.97-6.57
B. Thin sandstone---	63	53.4	15.5	.85	.20-2.25
C. Mudstone---------	143	168.5	49.0	1.18	.20-4.70
D. Humate-----------	87	43.0	12.5	.50	.10-1.65
E. Coal-------------	41	13.0	4.0	.32	.10- .85

B. Relative

Lithologic unit	Relative number	Average thickness (m)	Thickness per relative unit (relative number X average thickness) (m)
A. Thick crossbedded sandstone.	1	2.97	2.97
B. Thin sandstone---	2.86	.85	2.43
C. Mudstone---------	6.50	1.18	7.67
D. Humate-----------	3.95	.50	1.98
E. Coal-------------	1.86	.32	.60
Thickness of relative unit----------------			15.65

intervals has a thickness of 15.65 m (table 4B).

Combination of the transition flow diagram (fig. 15) and relative lithologic-unit abundance (table 4), along with lithologic characteristics of the major units, results in the model lithologic sequence shown in figure 16. The model consists of (1) a lower 3-m-thick, fining-upward, active-channel-fill sandbody having a scour base, and (2) an overlying, 12-m-thick repetitive sequence of inactive-channel-fill mudstone, channel-margin levee and flood-plain mudstone and splay sandstone, and well to poorly drained humate- and coal-depositing swamps. Two thin (0.3-0.5 m) coal beds generally occur in the sequence, and coal represents an "end-member" of the sequence, commonly being overlain by another channel sandstone. Three or four thin (0.4- to 0.8-m-thick) humate beds and three (0.7- to 1.5-m-thick) splay sandstone beds also occur interbedded with six to seven (0.5- to 2.0-m-thick) mudstone units.

Model Lithologic Sequence for Barren Intervals

The model lithologic sequence for the barren (non-coal-bearing) intervals of the Menefee is generated in the same manner as that for the coal-bearing intervals. The data matrices contain only four lithologic states (fig. 17). The positive transitions are emphasized in figure 17C and illustrated in the transition flow diagram (fig. 18). Thick crossbedded sandstone units are thicker and more than twice as abundant in the barren intervals (table 5). Also, because such sandstone units commonly are overlain with scour contact by similar sandstone units (multi-

A. TALLY MATRIX

(OBSERVED TRANSITIONS)

A = THICK X-BEDDED SANDSTONE

B = THIN SANDSTONE

C = MUDSTONE

D = HUMATE

	A	B	C	D	
A	12	4	23	3	42
B	5	0	30	7	42
C	17	30	7	31	85
D	7	7	26	7	47
	41	41	86	48	216

B. "EXPECTED" MATRIX

(INDEPENDENT EVENTS)

$$E = \frac{r \times c}{N}$$

E = VALUE FOR EACH MATRIX LOCATION

r&c = ROW AND COLUMN TOTALS

N = TOTAL NUMBER OF TRANSITIONS

	A	B	C	D	
A	8	8	17	9	42
B	8	8	17	9	42
C	16	16	34	19	85
D	9	9	19	10	47
	41	41	87	47	216

C. DIFFERENCE MATRIX

(OBSERVED-MINUS-EXPECTED)

	A	B	C	D
A	+4	-4	+6	-6
B	-3	-8	+13	-2
C	+1	+14	-27	+12
D	-2	-2	+7	-3

Figure 17.--Matrices for the barren intervals of the Menefee Formation. See text for explanation.

Table 5.--Absolute and relative lithologic-unit abundance for the barren intervals of the Menefee Formation

A. Absolute

Lithologic unit	Number of units	Total thickness (m)	Percent of interval	Average thickness (m)	Range in thickness (m)
A. Thick crossbedded sandstone.	39	135.5	44.1	3.47	0.65-8.90
B. Thin sandstone---	43	33.1	10.7	.77	.20-3.00
C. Mudstone---------	87	112.1	36.5	1.29	.20-4.20
D. Humate-----------	46	26.8	8.7	.58	.10-2.15

B. Relative

Lithologic unit	Relative number	Average thickness (m)	Thickness per relative unit (relative number X average thickness) (m)
A. Thick crossbedded sandstone.	2	3.47	6.94
B. Thin sandstone---	2.20	.77	1.69
C. Mudstone---------	4.20	1.29	5.42
D. Humate-----------	2.36	.58	1.37
Thickness of relative unit------------------			15.42

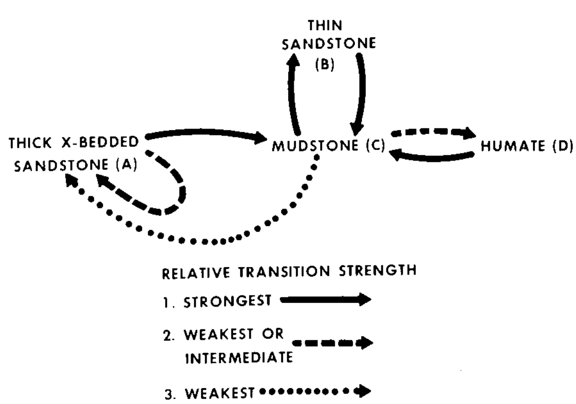


Figure 18.--Transition flow diagram of the lithologic sequence for the non-coal-bearing model of the Menefee Formation.

story sandbody), a relative number of 2 was used for the model sequence (table 5B). The thickness calculated for such a relative unit is 15.42 m, only slightly thinner than the relative unit of the coal-bearing model.

The model lithologic sequence generated for the barren intervals is shown in figure 19. It consists of (1) a basal, 6.5-m-thick, multistory channel sandbody, and (2) an overlying, 8.5-m-thick, repetitive sequence of inactive-channel-fill sediments, flood-plain mudstone, and relatively well drained humate-depositing swamps.

SIGNIFICANCE OF THE APPROACH AND THE MODELS

The simplicity, objectivity, and utility of the modified Markov model technique described above should be obvious. The matrices are extremely simple to complete once the field data have been summarized into the basic "building block" lithologic units of the stratigraphic

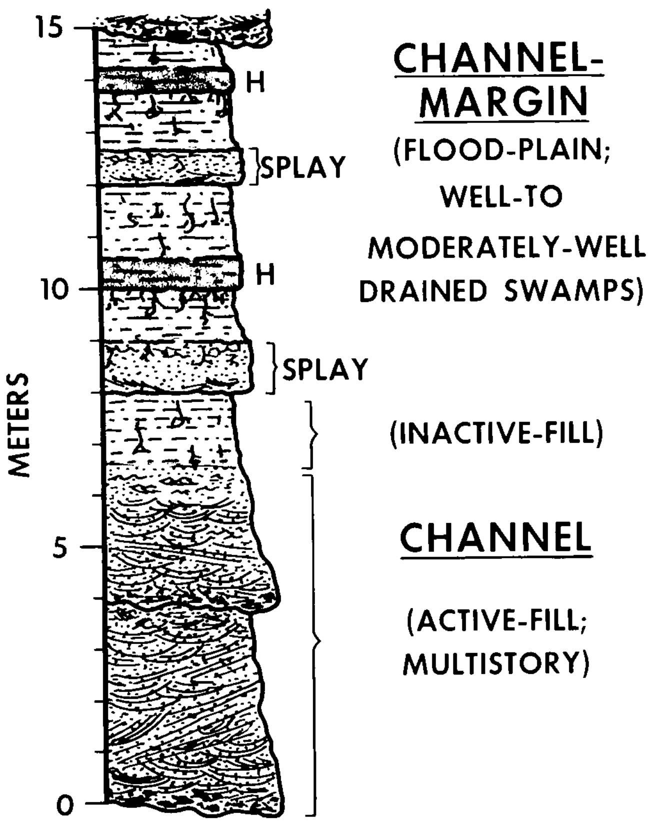


Figure 19.--Model lithologic sequence for the barren interval of the Menefee Formation. Lithologies are sandstone, stippled and bedded patterns; barren mudstone, dashed pattern with roots; humate, sparsely dashed pattern marked by H; and coal, black seams.

sequence. Generation of the transition flow diagram may require sketching several diagrams before arriving at the most logical construction that includes all the positive transitions and emphasizes the strongest transitions. Illustration of the model lithologic sequence requires reference to the transition flow diagram, to the absolute and relative lithologic-unit abundances, and to the basic lithologic features of the lithologic units. Performance of these tasks will undoubtedly create a better understanding of any complex repetitive sequence.

The model lithologic sequences are particularly significant because they are generated directly using field data and are rather specific, inasmuch as absolute and relative lithologic-unit abundance are considered in the model. The statistical significance of the models also can be established. Using the chi-square test, the two models established for the Menefee were found to be statistically representative of sequences having first-order Markov properties (J. H. Doveton and E. A. Beaumont, written and oral communications, April 1977). Second-order Markov properties can also be tested for; neither of the Menefee models was representative of sequences having second-order Markov properties. Testing for Markov properties is explained in detail by Doveton (1971) and Harbaugh and Bonham-Carter (1970).

The model-generation technique obviously is useful for reducing large amounts of stratigraphic data. The models can be used in many different ways. If nothing else, they can provide a summary of a complex sequence. Such a summary might be considered a "norm" for the sequence and could be used to reevaluate the whole stratigraphic sequence to observe how it varies from the "norm." For example, part of the sequence may contain "lithologic sequences" that are much thicker and more complex than the model lithologic sequence, while other parts will contain thinner and simpler "lithologic sequences." Another way of viewing the sequence is to recognize that some parts have "expanded" lithologic sequences while other parts contain "truncated" sequences with respect to the norm. Knowledge of the variability of the sequence will certainly provide a greater understanding of the system. A summary model for a stratigraphic sequence in a particular area also can be used for comparison with the same general stratigraphic sequence in other areas of the same basin, or in other basins of deposition. Such comparisons can become fairly sophisticated, such that the major trends can be detected. The model sequences then provide a framework and guide for making predictions about other unstudied parts of the basin or other basins.

Of special interest is the paleoenvironmental and sedimentological significance of the model lithologic sequences. In that sense, the model sequences can be viewed as "type genetic sequences" or "model depositional sequences." It is hoped that the model lithologic sequences will make sense geologically and sedimentologically. Such models will be far more significant than a model developed subjectively using only models of modern depositional systems or other ancient analogs. They certainly provide the framework for analysis of the general sedimentological processes, which were of importance in the depositional system of the ancient deposits, and for better comparison with other ancient and modern depositional systems.

The model depositional sequences for the Menefee compare well with the generalized model for meandering-stream deposits, summarized by Allen (1970) and discussed by Walker (in Harms and others, 1975, p. 63-79). Such deposits are characterized by the fining-upward, active-channel-fill, lateral-accretion point-bar deposits and the overlying, fine-grained, flood-plain, vertical-accretion deposits. The difference between the coal-bearing and barren Menefee models might be explained in terms of depositional processes in the following way: The barren model system is dominated to a greater extent by transport and deposition of relatively coarse clastic detritus, with relatively less extensive channel-margin areas. The coal-bearing model system received less coarse clastic detritus and is characterized by increased accumulation of organic debris in poorly drained, stagnant swamps, probably as a result of greater subsidence. Such systems mostly likely represent continental fluvial-plain to upper- to middle-delta-plain sedimentation (barren model) versus middle- to lower-delta-plain sedimentation (coal-bearing model). A very significant feature of the Menefee models is that nearshore marine or "lagoonal" deposits are not represented in the Menefee in the study area.

Finally, it must be emphasized that application of this modified Markov chain analytical technique can be done in a great variety of ways. The extreme flexibility of the approach allows for competent, objective analysis of the data as well as for ingenuity in its use. For example, grouping of the stratigraphic intervals to be analyzed is to a great extent controlled by the operator. The Menefee was subdivided in this study on the basis of the presence or absence of coal in the sequence. There are other ways to initially group the data, such as by locality only or by parts of the vertical stratigraphic sequence (for example, upper vs lower vs middle). Also, smaller scale parts of a particular lithologic unit (e.g., thick crossbedded sandstone units) can be modeled using the Markov analytical technique. In general, the technique is extremely valuable for objectively generating ideas about the geological systems and for extracting conceptual information from the data.

ACKNOWLEDGMENTS

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Stratigraphy of the Pierre Shale, Trinidad Sandstone, and Vermejo Formation, Walsenburg Area, Colorado: A Deltaic Model for Sandstone and Coal Deposition

LEE T. BILLINGSLEY[1]

ABSTRACT

The sequence of Pierre Shale, Trinidad Sandstone, and Vermejo Formation of the Raton Basin consists of marine to nonmarine deposits, respectively, that signal the final regression of the Cretaceous seaway in southeastern Colorado. The upper Pierre is highly burrowed, carbonaceous siltstone to very fine grained sandstone that was deposited in a prodelta environment. Transitionally overlying the Pierre, the main body of the Trinidad is clay-filled, burrowed, low-angle cross-stratified, fine-grained sandstone indicative of delta-front deposition. Other evidence supporting a deltaic environment includes penecontemporaneous deformation in the form of ball-and-pillow structures. Also, tongues of the Pierre that extend well into the Trinidad are interpreted as destructional units in the deltaic sequence. The uppermost facies in the Trinidad, which is porous and permeable, is interpreted as a distributary channel on the basis of the lack of burrowing, scour contact, high-angle cross-stratification, and subaqueous shrinkage cracks. This distributary channel facies is the most critical unit in terms of the overall deltaic interpretation.

The overlying Vermejo is composed of coals, claystones, and sandstones deposited on the delta plain. The lack of evidence for faunal activity indicates that freshwater conditions prevailed throughout the Vermejo. The coal accumulated in poorly drained swamps and marshes until an influx of detritus served to raise the level of the swamp and oxidize carbonaceous material. The influx of detritus is represented by light-gray claystone and rippled siltstones to crossbedded sandstones that were deposited as crevasse splays. Light-gray, noncarbonaceous claystone containing root burrows directly overlie the coarser splay deposits. The lack of carbonaceous material is indicative of oxidizing conditions in well-drained swamps. As the channel-margin area continued to subside, reducing conditions were gradually restored, and carbonaceous claystone and coal again began to accumulate. Occasionally the subsidence and low rates of deposition continued, and black claystone was deposited in lakes that overlie the coal swamps. All of the Vermejo deposits appear to be organized in cycles similar to that described above.

According to the depositional model presented here, the geometry of thick Vermejo coal beds is related to the orientation of major fluvial channels. For instance, isopach lines of a coal bed should roughly parallel the channel orientation. However, there are probably numerous interruptions in the coal caused by "splits" from splay deposits. The splits should thicken in a direction toward the channel.

INTRODUCTION

The vertical sequence of Pierre Shale, Trinidad Sandstone, and Vermejo Formation was studied in an area of the Raton Basin that lies between Walsenburg and Aguilar, Colo. (fig. 1). These sediments constitute a fairly complete regressive cycle that was deposited as the Late Cretaceous seaway withdrew from the area. More specifically, these rocks were deposited in a deltaic setting having the following relationship: Pierre--prodelta, Trinidad--delta-front and distributary channel, and Vermejo--delta plain (fig. 2). The relative position of the Pierre, Trinidad, and Vermejo with respect to the overall stratigraphic column is shown in figure 3. This paper will emphasize an interpretation

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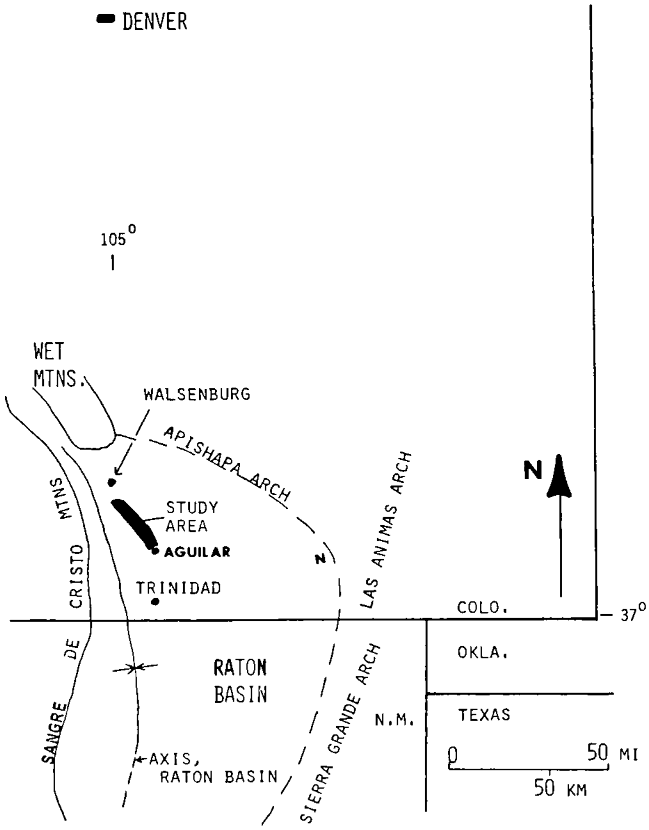

Figure 1.--Location map showing study area and major structural features composing the Raton Basin. (Modified from Johnson and Wood, 1956.)

AGE	LITHOLOGIC UNITS	THICKNESS
Paleocene	Poison Canyon Fm.- conglom., ss.	0-2500'
	Raton Fm.- conglom., ss., silts., coal	0-2075'
Cretaceous	Vermejo Fm.- ss., clay., coal	0-360'
	Trinidad Ss.	0-255'
	Pierre Shale	1300-2900'
	Niobrara Fm. Smoky Hill Marl Mbr. Ft. Hays Ls. Mbr.	900-955'
	Benton Group Carlile Sh. Greenhorn Ls. Graneros Sh.	360-695'
	Dakota Ss.	140-200'
	Purgatoire Fm.-ss., shale	100-150'

Figure 3.--Partial stratigraphic column for Raton Basin, New Mexico and Colorado. (From Ewing and Kues, 1976.)

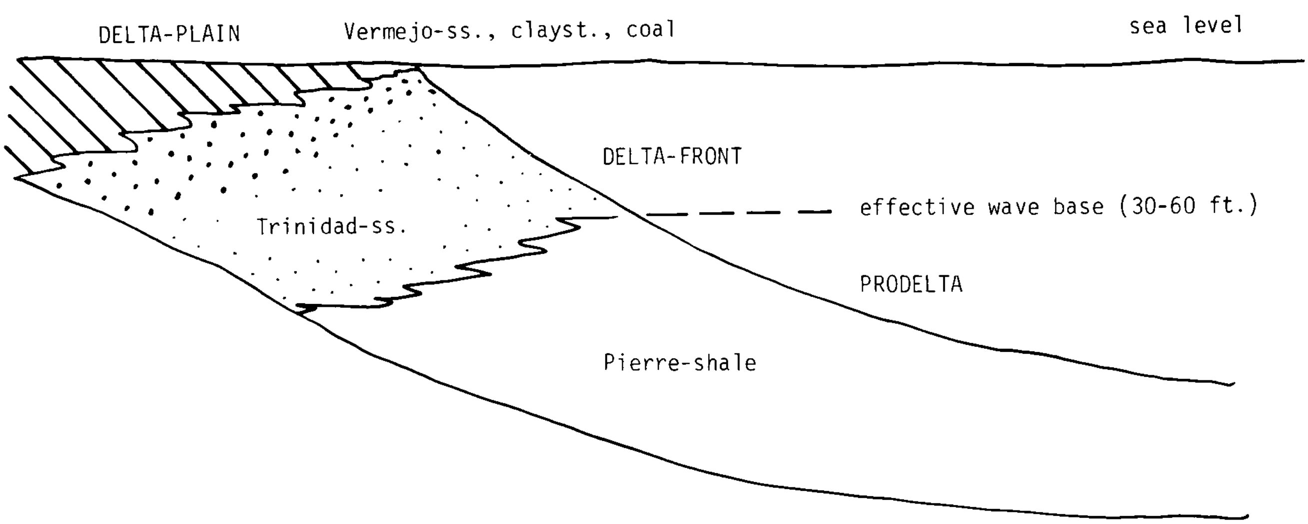

Figure 2.--Diagram showing model of deltaic sedimentation and the corresponding formations and lithologies. (Adapted from Weimer and Land, 1976.)

of the environment of deposition of the Vermejo Formation and the resulting coal-bed geometries. However, data and interpretations of the underlying Pierre and Trinidad are essential for an overall deltaic model and will be presented in a summary manner.

In terms of correlation, the Vermejo in the Raton Basin is slightly younger than the Fruitland Formation, its stratigraphic equivalent in the San Juan Basin. The Vermejo is slightly older than its counterpart in the Denver Basin, the Laramie Formation. These relative ages are based upon faunal ages of underlying sandstones, determined by Cobban (*in* Fassett, 1976) and Obradovich and Cobban (1975).

The stratigraphic interpretations made in this paper are based on data taken from 14 measured sections. The data include outcrop measurements, grain-size and petrographic analysis of samples, and geologic mapping.

ENVIRONMENTS OF DEPOSITION

Prodelta and Delta-Front

The delta-plain environmental interpretation for the coal-bearing Vermejo would appear somewhat tenuous if there was not strong support from underlying deltaic sediments. Such deltaic support extends as much as 200 ft beneath the base of the Vermejo to the upper Pierre Shale.

The main body of the Pierre Shale consists of dark-gray shale deposited in a deep neritic environment. However, the upper 50 ft of Pierre contains thin, bioturbated, carbonaceous, sandy mudstones to argillaceous, very find grained sandstones deposited in a prodelta environment. The coarsening-upward grain size in the Pierre is the first evidence of an approaching delta system. Table 1 contains a summary of the lithology of prodelta and shallow neritic deposits in the study area.

The transitional contact of the Pierre with the overlying Trinidad Sandstone also marks the environmental change from prodelta to delta-front. Delta-front sediments in the Trinidad are tan to gray, burrowed, clay-filled, subparallel to low-angle cross-stratified, very fine grained to fine-grained sandstones. At one location in the study area, delta-front sandstones are in the form of ball-and-pillow, penecontemporaneous deformation structures. These deformation structures confirm a deltaic interpretation because they occur in areas of high rates of sedimentation on oversteepened slopes.

In the study area a tongue of Pierre Shale extends into the delta-front sandstones of the Trinidad. The lithology of the Pierre tongue is not like that of the main body of Pierre Shale. Rather, the tongue is a sequence of black, carbonaceous shale; bioturbated mudstones; and subparallel laminated, very fine grained sandstones.

Table 1.--Summary of Diagnostic Criteria for Prodelta and Neritic (Destructive) Environments, Pierre Shale, Walsenburg Area, Colorado

Diagnostic criteria	Prodelta	Shallow neritic (destructive)
Lithology----	Carbonaceous, argillaceous, very fine grained sandstone to mudstone. Thin sandstone units increase in volume near upper contact.	Very friable, well-sorted, fine-grained sandstones. Argillaceous, silty units, similar to prodelta, may occur near base.
Stratification	Mostly massive owing to bioturbation. Burrowed and nonburrowed, subparallel laminated units alternate near upper contact.	Irregular subparallel bedding to lamination.
Trace fossils-	*Asterosoma* and general bioturbation.	Scattered *Skolithos*. May be highly bioturbated near base.

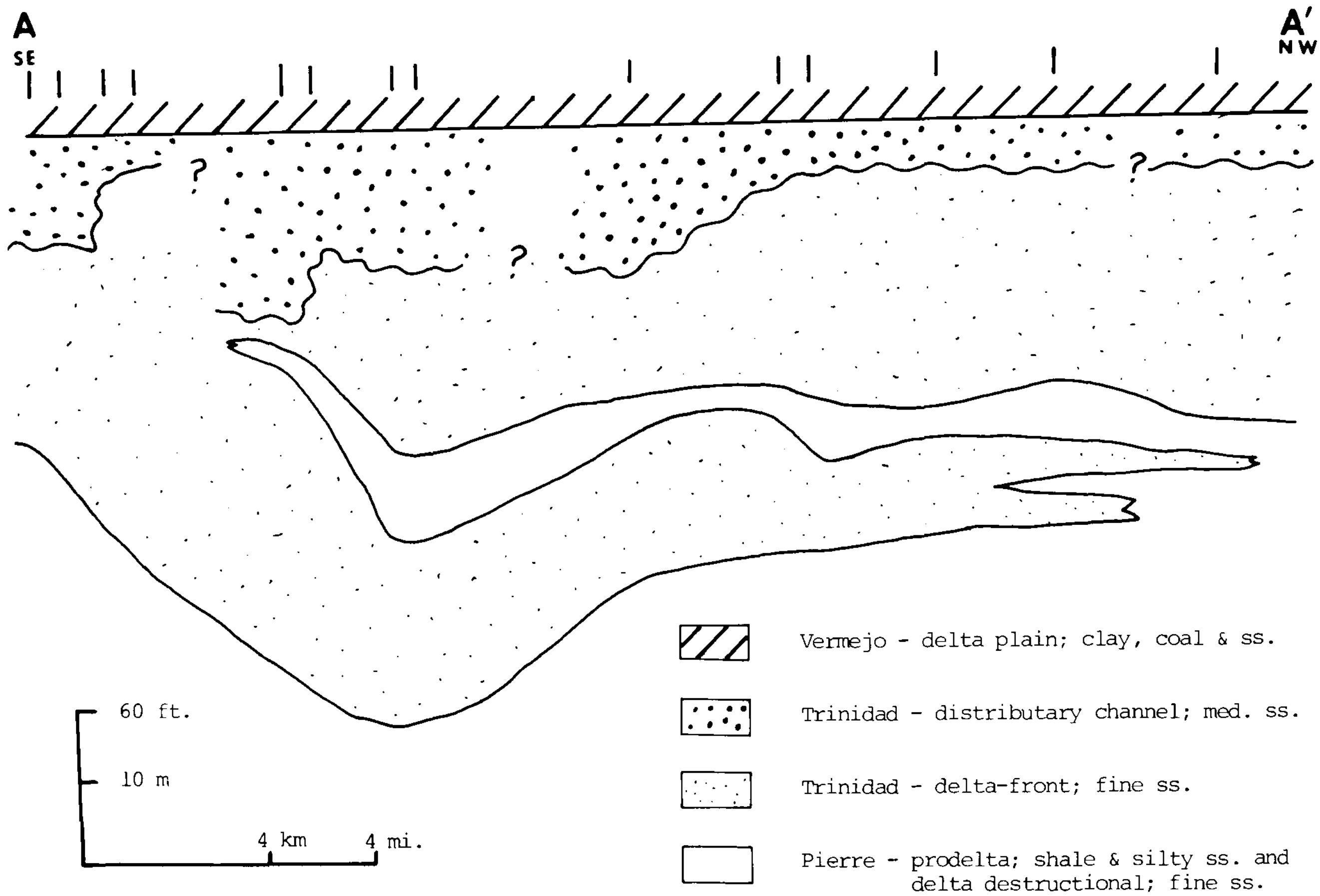

Figure 4.--Cross section (A-A′) of measured sections from Aguilar to Walsenburg. Vertical lines at top of figure show location of measured sections. See figure 11 for location of cross section.

These sediments are probably destructional units that were deposited during abandonment of the delta lobe. A later reshift of the delta caused delta-front sandstones to be deposited on top of the destructional unit (fig. 4). Figure 4 also shows the variation in stratigraphic position of the destructive unit along the outcrop in the study area. This variation occurs because the outcrop and paleoshoreline orientations are not exactly the same. A more complete discussion of the delta-front, prodelta, and destructional-unit interpretation appears in Billingsley (1977a and 1977b).

Distributary Channels

To interpret the environment of deposition of an ancient sedimentary rock sequence such as the Pierre, Trinidad, and Vermejo, the entire section must be considered, because individual units are not always diagnostic of a particular environment. In the case of this deltaic interpretation, the distributary-channel sandstones and associated delta-plain deposits are the most significant units.

Lithologically, the distributary-channel sandstone is a nonburrowed, high-angle cross-stratified, fine- to medium-grained sandstone having a thickness of 5 to 50 ft. Approximately the upper one third of the facies has subparallel to indistinct bedding and a slight decrease in grain size. The basal contact is a sharp scour surface cut into the underlying delta-front sandstone, and five important lithologic changes occur above the contact (table 2 and fig. 5): (1) Grain size is increased 1 1/2 to 2 times. (2) Almost no burrows occur above the contact, whereas they are plentiful beneath it. (3) The cross-stratification changes from low- to high-angle and indicates dominantly unidirectional sediment transport to the southeast. (4) Local lag deposits of nonbored wood imprints, clay

Table 2.--Summary of Diagnostic Criteria for Delta-Front and Distributary Channel Environments, Trinidad Sandstone, Walsenburg Area, Colorado

Diagnostic criteria	Delta-front	Distributary channels
Lithology-----	Very fine grained to fine-grained, clay-filled sandstones with thin black shale interlaminations. Alternating silty units near base. Carbonaceous at base, but decreasing upward.	Relatively porous and permeable, fine- to medium-grained sandstone decreasing in grain size upward. Thin black shale laminations near base. Basal scour contact with local lag deposits of unbored wood, pelecypod casts, or clay clasts.
Stratification	Massive (burrowed) to subparallel (nonburrowed) bedded with some ripple crosslamination. Also ball-and-pillow deformation. Massive to low-angle cross-bedding in upper portion.	High-angle trough and tabular cross-strata near base and subparallel to indistinct bedding upward. Sets of cross-strata are 1 to 3 ft thick and as much as 20 ft along crests. Dominant unidirectional transport to southeast. Syneresis cracks in shale laminations.
Trace Fossils-	Highly bioturbated and *Asterosoma*-burrowed units near base. *Ophiomorpha* increase in size and abundance upward. Scattered *Skolithos* and *Diplocriterion*.	Significantly absent of any evidence of fauna (other than transported pelecypod shells). Roots zones at upper contact.

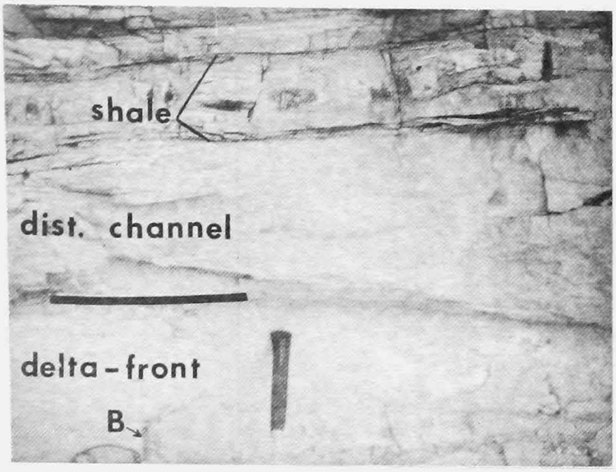

Figure 5.--Low-relief scour contact between Trinidad delta-front and distributary-channel sandstones. Burrows are indicated beneath contact. Shale laminations, which commonly contain syneresis cracks, are also shown. Photograph from outcrop near Rugby, about 6 mi north of Aguilar.

clasts, and pelecypod shells are found within the lower few feet of the channel. (5) Syneresis cracks occur in shale laminations near the base of the channel.

In terms of the environment, the scour contact, grain-size increase, and high-angle cross-stratification all indicate an increase in energy when compared with the underlying sandstone. The abrupt absence of burrowing and presence of nonbored wood are interpreted as having been caused by a freshening of the water. Syneresis cracks in clay were believed by Burst (1965) to have been caused by a change in water salinity. Within the framework of this facies, a saltwater wedge moving up the channel is believed to have been the cause of the subaqueous cracks. The lithologic changes and associated environmental interpretations, when combined, suggest the picture of a freshwater channel entering a marine basin. Thus, this facies is interpreted as a distributary channel.

The distributary channels at several localities show minor variations from the normal lithologies described above. For instance, some measured sections in the northern part of the study area have bimodal transport directions within the channel sandstone. Although the dominant direction of dip of the cross-stratification is southeast, the northwest dip could be the result of sedimentation in a channel that had minor tidal influence. In both modern and ancient examples of estuarine deposits that exhibit strong tidal effects, much burrowing has occurred within the channel sands and adjacent channel-margin clays. Howard and Frey (1973) described burrows of Callianassa sp., a modern decapod that constructs burrows similar to Ophiomorpha, in tidal rivers along the Georgia coast. Also, Land (1972) reported numerous Ophiomorpha, Arenicolites, and Teredo-bored wood in Fox Hills Sandstone (Late Cretaceous) estuary deposits in Wyoming. In an area closer to the study area of this paper, Manzolillo (1976) described burrows similar to those of Land (1972) in Trinidad channels having bimodal transport directions between Aguilar and Trinidad, Colo. He consequently interpreted the channels as tidally influenced.

In contrast, the complete absence of burrowing above the scour base of the channels in this study area is interpreted as an indicator of water conditions that were too fresh to permit inhabitance by marine and brackish-water burrowing organisms. Other evidence for dominantly freshwater conditions exists in the fine detritus of the Vermejo Formation above the channel deposits. These clays and silts were deposited in channel-margin areas, and they are void of any evidence of marine or brackish-water organisms. However, the tidal-channel-margin deposits described by Howard and Frey (1973) and Land (1972) are burrowed and fossiliferous. The lag deposits of pelecypod shells at the base of some of the distributary-channel sandstones are not believed to be inconsistent with a freshwater interpretation. The pelecypod shells were probably present originally in the underlying marine deposits. As the distributary channels scoured downward, the fine-grained marine sands were removed, but the larger shells remained at the base of each channel. The resulting lag deposit is confined to a thin zone about one shell layer thick. Howard (1966) described similar lag deposits at the base of distributary channels in the Panther Sandstone Tongue, Book Cliffs, Utah; and he attributed their occurrence to a similar mechanism.

Other authors have presented alternative interpretations for the uppermost sandstones of the Trinidad. Matuszczak (1969) interpreted the sandstones as beach or barrier bar. However, the scour contact and upward decrease in grain size are negative evidence for a barrier-bar interpretation. Pillmore and Maberry (1976) assigned the high-angle cross-stratified, nonburrowed sandstones to a "beach-and-dune" environment. The subaerial conditions in a "beach-and-dune" would certainly exclude the formation of burrows such as Ophiomorpha. However, the gradual change from high-angle cross-stratification to subparallel laminations in the upper Trinidad is indicative of distributary-channel deposition in the study area.

Channel Margin (Vermejo)

Channel-margin environment is a general term used here to apply to swamps, marshes,

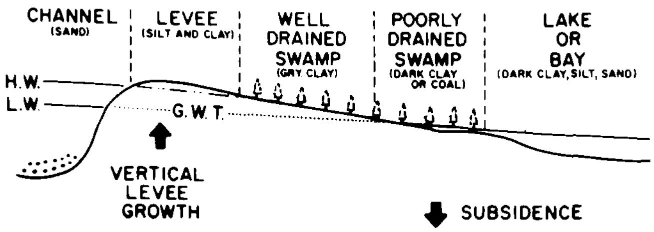

Figure 6.--Channel and channel-margin environments as interpreted for lithologies observed in the Laramie Formation. H.W., flood-stage water level; L.W., normal water level; G.W.T., ground-water table, which fluctuates in response to water level in channel. (From Weimer, 1973.)

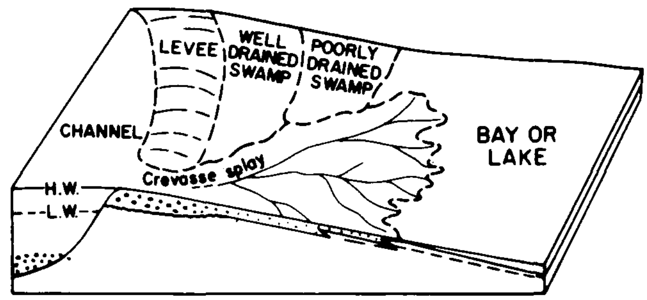

Figure 7.--Relationship of channel-margin environments of figure 6 to crevasse splay deposits of the Laramie Formation. H.W., flood-stage water level; L.W., normal water level. (From Weimer, 1973.)

lakes, and crevasse splays on the delta plain. Figures 6 and 7, taken from Weimer's (1973) paper on the Laramie Formation near Golden, Colo., serve to summarize the specific environments on the Vermejo delta plain. Stratigraphically, the Vermejo channel-margin deposits sharply overlie the distributary-channel sandstones of the Trinidad in the study area.

The lithology of the Vermejo trends toward more carbonaceous material upward within cyclic packages of claystone, siltstone, sandstone, and coal. This trend can be roughly equated with subsidence and sedimentation in the freshwater marshes, swamps, lakes, and splays that occur between channels on the delta plain. Thus, cycles of sediment influx followed by periods of subsidence and reduced influx produce the majority of the Vermejo lithology.

Figure 8 shows the interpreted environment of deposition along with the corresponding lithology in the channel-margin area. The interpretations are based upon the fact that carbonaceous material is preserved only under chemically reducing conditions. Furthermore, reducing conditions are present beneath the upper limit of the water table, and oxidizing conditions, above it. Oxidizing areas are termed well-drained swamps, whereas the reducing ones are poorly drained. In the overall channel-margin environment, the cyclic fluctuations of the level of the water table do not represent changes in sea level. Rather, the fluctuations are due to relative changes between the depositional surface and the water table, which is controlled by the water level in adjacent channels. Relative changes in water level occur because a generally constant rate of subsidence is coupled with a very irregular rate of detrital influx into channel-margin areas.

The above interpretation is supported by the sequence of Vermejo rock units. For instance, black claystone with interlaminated, rippled, gray siltstone units usually overlie coal units. If the claystone-siltstone units become sandy and high-angle cross-stratified upward, they are interpreted as a splay deposit.

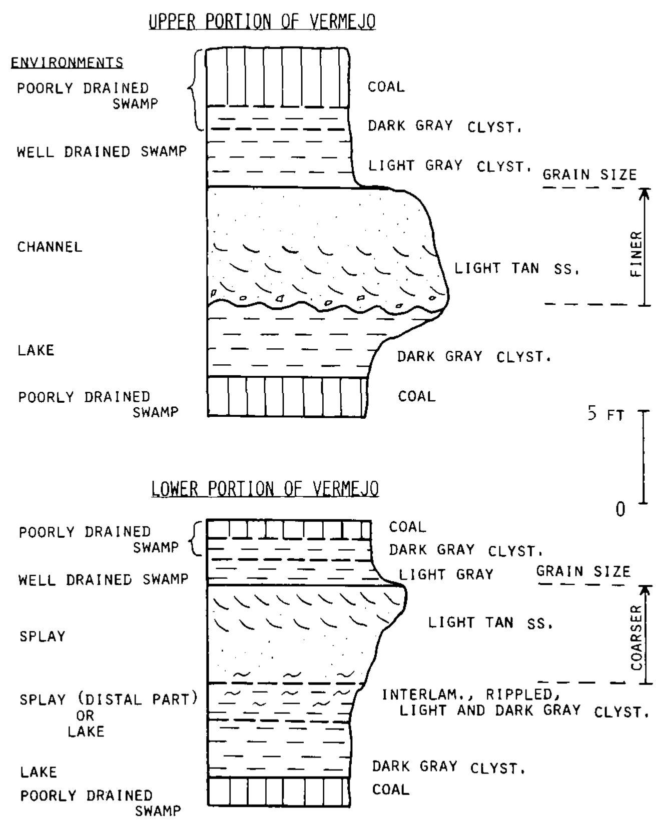

Figure 8.--Generalized lithologic sequence and corresponding environments of deposition of Vermejo Formation.

The splay sequence is best described as a miniature delta. Splays occur when a crevasse breaks through a nearby channel levee and detritus pours into the adjacent channel-margin lowland. A splay sets the limits of an underlying coal bed, because the influx of detritus either dilutes the amount of preserved carbonaceous material or, if of sufficient quantity, it raises the poorly drained swamp above the level of the water table.

Sometime after the splay breaks through the channel levee the crevasse may be healed, at which time the rate of detrital influx into the swamp or marsh is immediately reduced. Healing of the crevasse is represented lithologically by the sharp contact of light-gray, noncarbonaceous claystone overlying cross-stratified, root-burrowed sandstone. As the channel-margin area continues to subside, the rate is slightly greater than that of the buildup of clay-sized detritus, and the transition from a well-drained swamp or marsh to a poorly drained one occurs.

This transition from oxidation to reduction is preserved in the rock record by the gradual increase in carbonaceous material upward. The light-gray, noncarbonaceous claystone may change upward into a black, carbonaceous shale and finally into a coal bed.

Upon deposition of a coal unit, the channel-margin cycle is complete until an influx of detritus begins the cycle anew. Although a complete cycle of lithology and a resulting interpretation has been described here, cycles are not always complete. The cycle of deposition may be interrupted at any stage of its development by an unpredictable detrital influx. Also, splay deposits themselves may not always culminate in the deposition of sand, because the vertical sequence of deposition is dependent upon the distance between the data point and the channel. Thus, in some cases in the record of the channel-margin sequence, only the distal portion of a splay (clay or silt) is observed.

The above relationship between subsidence and deposition occurs because of the positive influence of splay deposits. However, lakes or ponds result if an area continues to subside with very little detrital input. As might be expected, lake deposits frequently overlie coals. Lake deposits consist of black claystones with irregular wavy laminations that might possibly have been caused by algae. Also, light-gray silty laminations are sometimes present, which represent deposition in the distal portion of a splay within the lake.

Fluvial Channels

In addition to lakes, swamps, marshes, and splays, fluvial channels are present within the delta plain. A fluvial-channel environment is attributed to high-angle cross-stratified, coarse- to medium-grained sandstones having scour contacts and clay clasts near their bases. The fluvial-channel deposits show a slight fining-upward in grain size, and they have a lenticular cross-sectional geometry. They are distinguished from splay deposits by their scour rather than gradational basal contact and by the fining--rather than coarsening--upward grain size. Also, fluvial-channel sandstones in the study area are 16 to 40 ft thick, while splay deposits are a few feet to 20 ft thick.

Almost all of the data used for the channel-margin-environment interpretation is from the southern edge of the study area (fig. 9) and is summarized in table 3. None of the exposed units contains any evidence of marine or brackish-water faunal activity. Therefore, the Vermejo, at least in the south, is a sequence of freshwater lakes, swamps, marshes, splays, and small channels that occur in an area marginal to major fluvial channels.

OVERALL DEPOSITIONAL MODEL

In summary, the Pierre Shale, Trinidad Sandstone, and Vermejo Formation in the study area are interpreted as delta deposits for the following reasons: (1) Ball-and-pillow structures, indicative of high rates of deposition on oversteepened slopes, occur in the lower Trinidad. (2) Sediments associated with a destructional phase within the deltaic sequence are present within the lower Trinidad. (3) The upper Trinidad was deposited by dominantly unidirectional, freshwater channels, interpreted as distributaries. (4) Freshwater delta-plain channel-margin deposits in the Vermejo overlie the distributaries. Although the prodelta and many of the delta-front deposits are somewhat similar to deposits from areas of interdeltaic sedimentation (Weimer and Land, 1976), the lack of evidence for marine or brackish-water conditions in overlying strata prohibits an interdeltaic interpretation. Furthermore, the evidence for freshwater conditions in the overlying delta-plain sediments, such as distributary and channel-margin deposits, strongly supports a model of deltaic sedimentation in the study area. Figure 10 is a summary of this depositional model.

The Trinidad delta appears to have been deposited in shallow water, because thickness data are consistent with known shallow water deltas but not with deeper water ones. For example, one cycle of delta-front sediments in the Trinidad averages about 70 ft in thickness, whereas sheet sands of the pre-modern Lafourche delta are about 40 ft thick. However, the mouth bars of deep-water or birdfoot deltas are 200 ft thick. Also, the numerous cycles that occur in birdfoot deltas are not present in the Trinidad. Numerous cycles occur when the rate of deposition is greater than the rate of subsidence. The fact that only two cycles are present in the Trinidad indicates that the rates are nearly equal.

Table 3.--Summary of Diagnostic Criteria for Channel-Margin and Channel Environments, Vermejo Formation, Walsenburg Area, Colorado[1]

Diagnostic criteria	Lithology	Stratification	Fossils
Swamp:			
Well drained	Light-gray claystone containing small iron concretions.	Massive.	Leaf imprints and root burrows.
Poorly drained	Dark-gray to black, carbonaceous shale and coal seams.	Laminated in carbonaceous shale.	Carbonized plant remains and root burrows.
Lacustrine	Dark-gray claystone with minor light-gray siltstone laminations.	Irregular planes of weakness in claystone; micro-cross-lamination in silt.	None observed.
Splay	Tan, very fine grained to fine-grained sandstone with much carbonaceous material along bedding. Transitional base with coarsening-upward texture.	Micro-cross-stratification near base; high-angle trough cross-strata upward.	Root burrows at top.
Channel	Tan, fine- to medium-grained sandstone with clay clasts near scour base. Some thin coaly laminations. Fining-upward texture.	Trough cross-strata near base; indistinct near top.	None observed.

[1]Levee deposits were not recognized in outcrop.

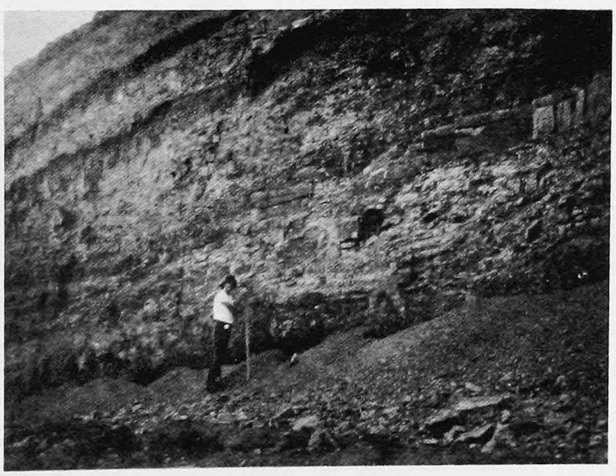

Figure 9.--Coal, sandstone, and claystone of the Vermejo in Jewell mine (about 1.5 mi north of Aguilar). Main coal seam occurs at feet of person in figure. Sandstone unit exhibits variable thickness.

PALEOSHORELINE ORIENTATION AND SEDIMENT-TRANSPORT DIRECTIONS

The interpretation of the orientation of the paleoshoreline is based on geologic mapping in the area (fig. 11) and lateral lithologic changes in the measured sections (fig. 3). The key unit is the destructive deposit, because it is lithologically distinct and serves as a good approximation of a time surface. Northwestward along the outcrop, the destructive event occurs lower in the section until it finally merges with the prodelta deposits of the main body of the Pierre somewhere near Walsenburg. Southwestward the destructive sand unit climbs in the section until it laterally disappears into upper delta-front sandstone of the Trinidad (fig. 3). Thus, if the destructive sand represents a time surface, marine deposition occurred in the north at the same time that nonmarine deposition

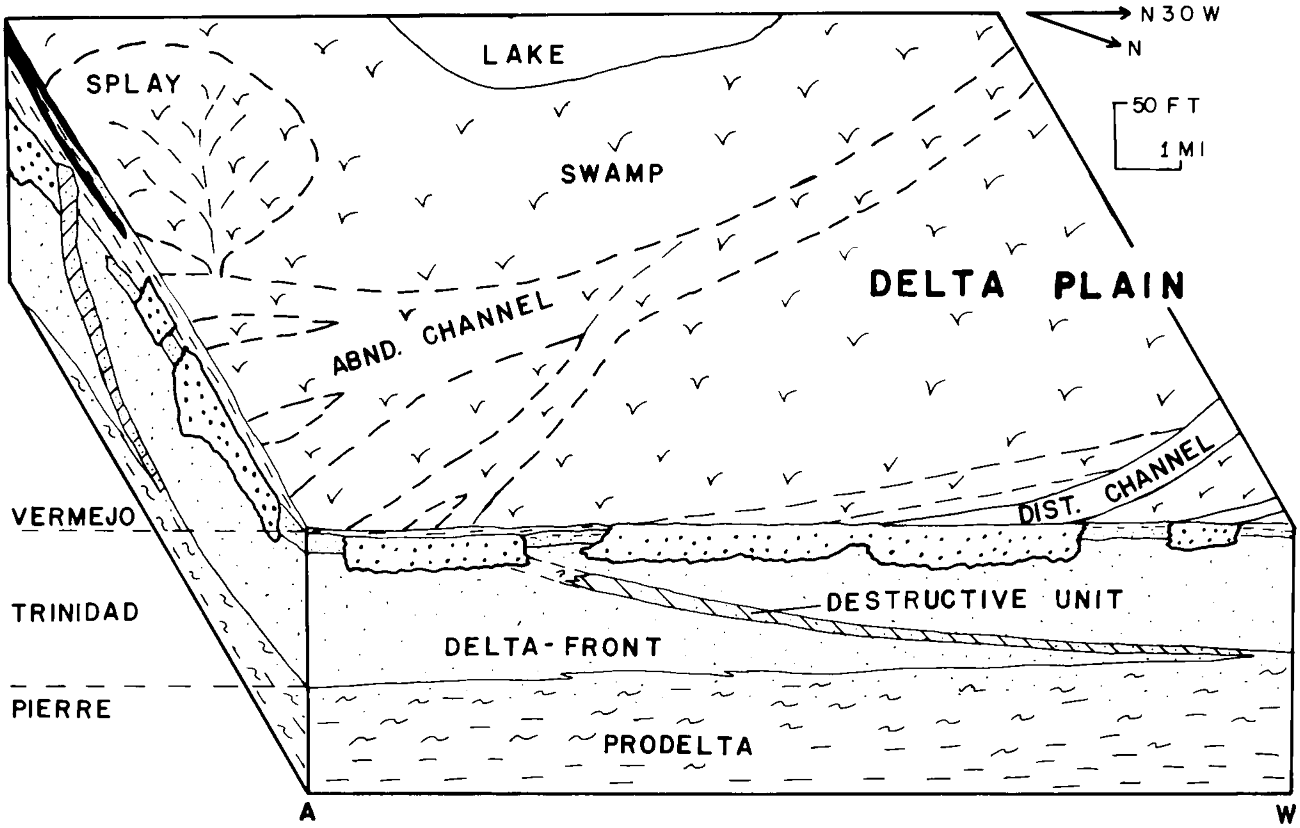

Figure 10.--Depositional model of upper Pierre, Trinidad, and Vermejo, Aguilar-Walsenburg area, Colorado. A-W is along outcrop, oriented approximately N. 30° W.; paleoshoreline trend is approximately N. 45° W. Destructive units are an approximate time surface. Side panel is inferred.

occurred in the south. Since the present outcrops are oriented approximately N. 35° W., the paleoshoreline must have been about N. 45° W. during deposition of the Pierre and most of the Trinidad. Additional data from ripple-crest orientations also tend to support the N. 45° W. orientation. Figure 12 is a map that summarizes paleoshoreline data from Walsenburg to Trinidad.

Sediment transport directions in the distributary channels are approximately parallel to the interpreted paleoshoreline orientation in the central and southern areas. The transport directions, as determined from the dip direction of cross-stratification, are dominantly toward the southeastern quadrant. Although the parallel nature of both channels and shorelines seems odd at first, at least two explanations are possible within the interpreted depositional framework: First, the channel direction may have been strongly influenced by longshore drift toward the southeast. Or, second, although the Pierre-lower Trinidad units appear to be associated with a fairly regular northwest-southeast shoreline, the later distributary channels may have been associated with an irregular shoreline. An irregular-shoreline interpretation is shown in the paleoshoreline map in figure 12. Fisk (1955) reported similar findings in the modern Mississippi River and stated that "depositional patterns and thickness trends of sand bodies in deltaic complexes have been controlled by direction of advance of delta..., and consequently bear no consistent relationship to the regional structure of the gulf basin." Thus, in the study area the prodelta, delta-front, and destructional units were deposited offshore, where marine energy could evenly distribute sediment along the shelf. However, the distributary-channel sands were not as greatly influenced by marine processes and probably were deposited in an irregular growth pattern.

PROBABLE COAL-BED THICKNESS ORIENTATIONS

According to the delta-plain depositional model in the study area, isopachous contours of

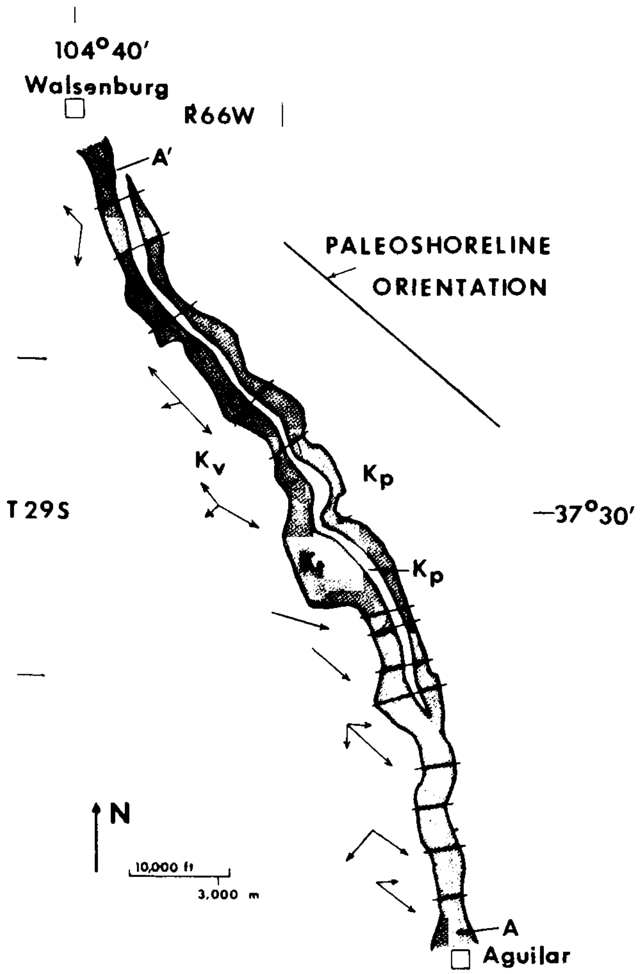

Figure 11.--Geologic map of Trinidad Sandstone and associated formations in study area. Kp, Pierre; Kt, Trinidad; Kv, Vermejo. Arrows indicate directions of sediment transport in distributary channels. Width of Trinidad on maps has been exaggerated 2X. Location of cross section A-A′ (fig. 4) and of measured sections is shown.

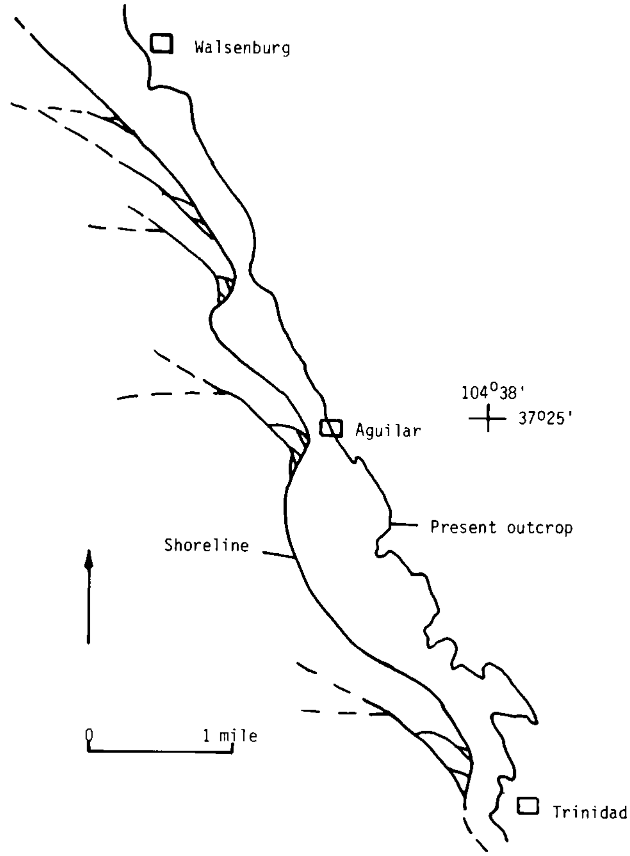

Figure 12.--Interpreted shoreline orientation at time of delta-front deposition in Trinidad Sandstone. Interpretation south of Aguilar based on Manzolillo (1976).

individual coal beds should approximately parallel the sediment transport direction of adjacent fluvial channels. Thus, if the dip direction of cross-stratification in a sandstone of the Vermejo is determined, an interpretation of the general thickness trend of associated Vermejo coal beds could be made. Another reason for determining fluvial-channel orientation is the splay deposits, or "splits," which separate coal beds. A "split" is a wedge of clastic sediment that thickens at the expense of coal in a direction perpendicular to the channel.

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Stratigraphy of the Coalmont Formation near Coalmont, Jackson County, Colorado

MICHAEL L. HENDRICKS[1]

ABSTRACT

The middle and upper members of the Coalmont Formation near Coalmont, Colo., are terrigenous, synorogenic deposits reflecting Laramide crustal movements during late Paleocene and early Eocene time. Palynomorph correlation indicates that the middle member was deposited during late Paleocene and early Eocene time. The upper member is early Eocene in age.

The middle member is a heterogeneous mixture of conglomerate, conglomeratic sandstone, sandstone, mudstone, carbonaceous shale, and sparse coal. The coarser fractions were deposited by bottom-traction transport of braided streams in a rapidly subsiding alluvial basin. The abundance of Precambrian rock fragments in the conglomerates and sandstones indicates an earlier removal of over 8,500 ft (2,600 m) of Paleozoic and Mesozoic sedimentary rocks and the extensive exposure of the Precambrian core of the Park Range during deposition of the middle member.

The carbonaceous shale and coal of the middle member are overbank and swamp deposits not removed by braided-channel migration. The coals of the middle member are composed of humic material. Coal macerals include mostly vitrinite, smaller amounts of resinite, and sparse disseminated fusinite.

Discharge during deposition of the middle member was intermittently high, and the magnitude of some cross sets may indicate locally deep channels. Some of these crossbeds were formed by bar migration within channels.

The upper member is a mixture of sparse conglomerate, sandstone, mudstone, siltstone, carbonaceous shale, and coal. The conglomerates and sandstones were deposited in meandering channels and by crevasse splays. The mudstones and siltstones cap the coarser fractions, and occasionally form levee deposits.

The carbonaceous shales and coals were deposited in swamps affected intermittently by scouring of crevasse splays and lowering of the ground-water table. The coals of the upper member are composed primarily of vitrinite and small amounts of resinite. Sparse disseminated fusinite and very thin, continuous clay laminae are also present. No sapropelic macerals were observed.

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INTRODUCTION

The middle and upper members of the Coalmont Formation near Coalmont, Jackson County, Colo., were studied in order to describe the stratigraphy and reconstruct the environments of deposition of the middle and upper members, to more clearly define biostratigraphic zones and the ages of the middle and upper members, and to petrographically describe selected sandstones and coals of the area.

GEOGRAPHY

North Park, located in north-central Colorado, is a large topographical and structural basin approximately 40 mi (64 km) from north to south and 30 mi (48 km) from east to west.

The northernmost limit of the basin is the Colorado-Wyoming state border, while the Front Range and the Medicine Bow Mountains bound the basin on the east. The Rabbit Ears Range forms the south and southwestern limits of the basin, and the Park Range forms its western limit.

Jackson County, which includes all of North Park, is bordered by Larimer County to the east, Routt County to the west, Grand County to the south, and the Colorado-Wyoming state line to the north.

The Coalmont district is in the southwestern part of the county, and the village of Coalmont is approximately 15 mi (24 km) from

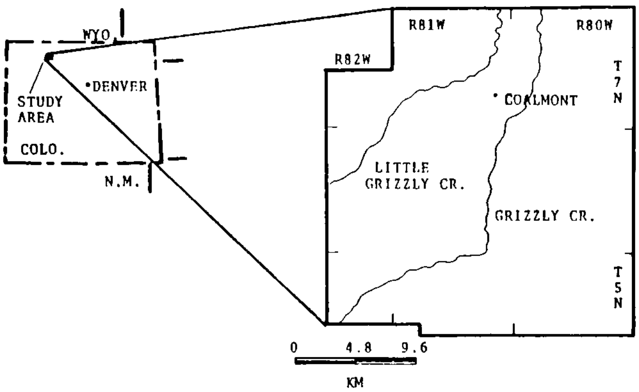

Figure 1.--Location of the Coalmont area, Jackson County, Colo. Study area is roughly bounded by Grizzly and Little Grizzly Creeks.

Walden, the largest town and county seat.

The thesis area is bounded roughly by Grizzly and Little Grizzly Creeks; it includes parts of T. 5, 6, and 7 N. and R. 80, 81, and 82 W. (fig. 1).

Access to the area is relatively easy by two routes from Denver. One access is west on U.S. 40 to Colorado Highway 125, north to Colorado Highway 14, southwest to Hebron, and then approximately 2.5 mi (4 km) southwest to Coalmont. The other access is west on Interstate 70, north on Colorado Highway 9 to Kremmling, northwest on U.S. 40 to Colorado Highway 14, and east to Hebron.

GEOLOGIC SETTING

North Park is in the northernmost central part of the Southern Rocky Mountains Province. The park is an intermontane structural basin within this province (fig. 2), bounded on the east by the Front Range-Medicine Bow anticlinal uplift, on the west by the Park Range anticlinal uplift, on the south and southwest by the Rabbit Ears middle and late Tertiary volcanics, on the north by the Independence Mountain thrust fault, and on the northwest by the Delaney Buttes-Sheep Mountain thrust faults.

The North Park syncline is one of the more conspicuous structural features. The fold is narrow and trends from near the North Platte River to the east-southeast for a distance of about 20 mi (32 km). The North Park syncline is southwest of the Spring Creek fault, which has as much as 4,900 ft (1,500 m) of middle and late Cenozoic displacement (Behrendt and others, 1969).

The stratigraphic section in the southwestern part of the basin includes rocks ranging in age from Permian to Miocene, and also includes Pleistocene and Holocene sediments. Rocks ranging in age from Late Cretaceous to Oligocene(?) crop out in the Coalmont area. Pleistocene and Holocene sediments are widespread in the study area.

Normal faults striking approximately N. 40° W. occur in the area. Displacements along faults do not exceed 500 ft (150 m) and are generally much less (Hail, 1968). Cross faults are confined to the northeastern portion of the study area and have minor displacements.

Several small-scale folds trending northwest occur in the Coalmont area. These folds have subtle surface expressions and are best discerned from aerial photography.

The weathering characteristics of the middle and upper members of the Coalmont Formation, Quaternary cover, and extensive normal faulting hamper lateral stratigraphic correlation. Outcrops are best observed along stream incisements, roadcuts, and surface mines. Faulting is best observed on aerial photographs, and subsurface data expedite stratigraphic and structural interpretations.

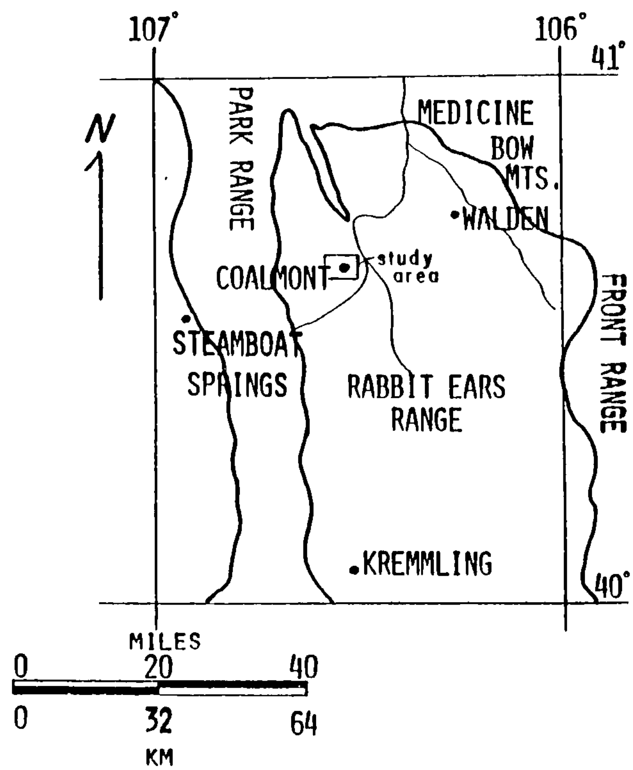

Figure 2.--Physiographic map of North Park, with approximate boundaries of the Coalmont study area.

CENOZOIC STRATIGRAPHY

Tertiary System

The Tertiary System in southwestern North Park includes rocks of Paleocene to late Miocene or Pliocene age (Hail, 1968). Rocks of the Coalmont Formation are the oldest Tertiary rocks exposed near the town of Coalmont.

The Coalmont Formation was named by Beekly (1915, p. 50) in his reconnaissance study of North Park. Beekly named all strata that rest unconformably on the marine Cretaceous and are overlain by the North Park Formation as the Coalmont Formation. According to Beekly, the best exposures of the Coalmont Formation are along the North Platte River north of the Coalmont area.

An informal nomenclature for the Coalmont Formation near Coalmont was used by Hail (1968). His division of the formation into middle and upper members was based on lithologic and paleontological data.

The lower member, or Middle Park Member of the Coalmont Formation, does not crop out in the thesis area, but is described by Hail (1968, p. 42) as consisting of "arkosic sandstone and conglomeratic sandstone, volcanic-pebble conglomerate, sandy claystone or mudstone, and sparse carbonaceous shale." The Middle Park Member is Paleocene in age based on paleontological data (Hail, 1968, p. 48). The Middle Park Member is exposed in the extreme southwestern portion of southwestern North Park.

The middle member of the Coalmont Formation unconformably overlies the Pierre Shale with low structural angularity in the thesis area. The middle member is composed of conglomerate, conglomeratic sandstone, sandstone, siltstone, some carbonaceous shale, and sparse coal (fig. 3). Hail (1968) assigned an age of Paleocene and Eocene to this member on the basis of fossil pollen assemblages.

The lower portion of the upper member is composed of sandstone, mudstone, coal, and extensive carbonaceous shale. To the north and east of the thesis area, the upper member is primarily sandstone and siltstone with local carbonaceous shale.

A possible aggregate thickness of as much as 12,000 ft (3,700 m) for the Coalmont Formation was reported by Hail (1968). Local variations in thicknesses are common; they are probably due to an uneven paleotopography.

The upper member is disconformably overlain by the White River Formation; it has been assigned a late Miocene age using fossil mammals (Hail and Lewis, 1960). The North Park Formation is an ashy limestone, locally conglomeratic, containing granitic and volcanic detritus (Hail, 1968).

The Tertiary igneous rocks in and surrounding the Coalmont area are Oligocene to late Miocene or possibly Pliocene in age (Hail, 1968).

The Rabbit Ears volcanics are directly south and southwest of the Coalmont area. Parts of Mexican Ridge and Pole Mountain are covered by debris from these middle and late Tertiary flows.

Several igneous intrusives which occur in the area are relatively dated as post-Coalmont (Oligocene?) owing to their crosscutting relationships.

Quaternary System

Pleistocene deposits in the Coalmont area include glacial till in the westernmost part of the area, terrace and pediment gravels, stream-deposited alluvium, and landslides. Colluvium partially covering Mexican Ridge and Pole Mountain consists principally of bouldery volcanic debris.

Major stream valleys contain Holocene alluvium, but for this study Holocene deposits were not differentiated from Pleistocene deposits.

ENVIRONMENTS OF DEPOSITION

During late Paleocene time, the middle member of the Coalmont Formation was deposited in a rapidly subsiding alluvial basin by braided streams. The alluvial basin was bounded on the west by the Park Range uplift, which supplied the majority of detrital material to the western portion of the basin. Regional relief was moderate during deposition of the middle member (Leopold and MacGinitie, 1972).

The coarse grain sizes and the crossbedding of the middle member indicate deposition by moderate- to high-velocity currents. Sediment deposition was principally by bottom-traction transport, and the lenticular nature of the conglomerates and sandstones indicates sedimentation by scour and fill of channels. Abandoned channels are often filled by mudstones and shales and, occasionally, by coal. Paleotransport directions are unidirectional to the east-southeast.

Braided streams are marked by successive divisions and rejoinings of the flow around alluvial islands or bars. The development of bars chokes the thalweg, or deepest part of the channel, causing widening of the streambed and channel migration.

Coleman (1969) and others have demonstrated a relation between depth of scour and river width. In narrow channels, scour occurs with increasing flow, and fill, with diminishing flow. In wide channels, fill usually occurs during floods, and scouring may or may not occur during lower flows.

Braided channels occur, therefore, in river systems having relatively steep slopes and an abundance of bedload, or a combination of the two

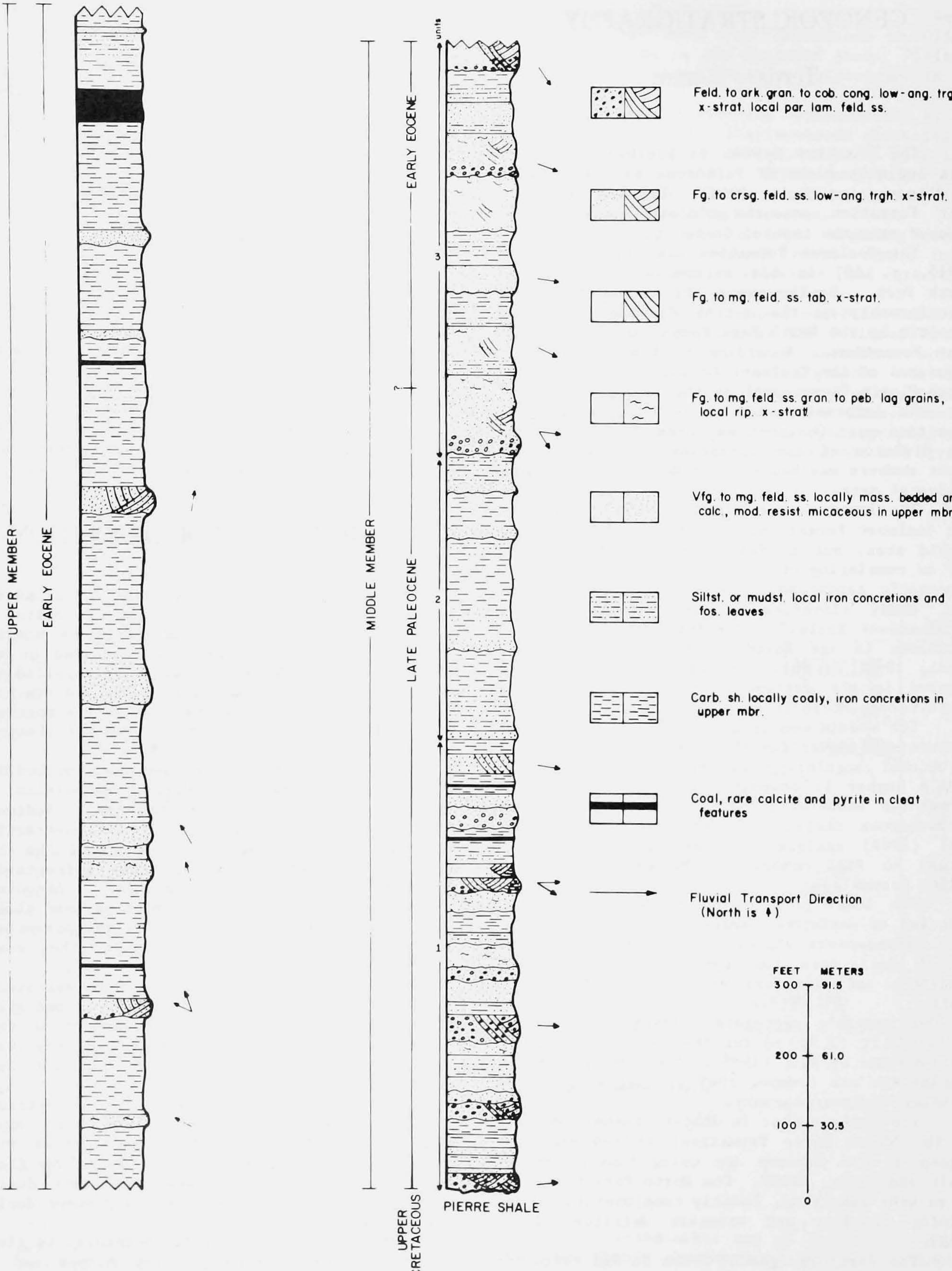

Figure 3.--Generalized composite stratigraphic section of the upper and middle members of the Coalmont Formation near Coalmont, Jackson County, Colo.

(Coleman, 1969).

Many of the 2- to 5-ft (0.6-m to 1.5-m)-thick, upward-fining subunits of the middle member are braided streambeds (table 1). These subunits have sandstone and conglomeratic sandstone bases capped by finer grained sandstones and mudstones. The upper portions of the mudstone capping units are often scoured away, resulting in distinct lenticularity.

The process of bar formation in modern braided-stream environments is not completely understood. One possible explanation for bar development is that a river tends to be wider below narrow or node points. Current velocity diminishes, causing the sediment load to drop out and form bars. Local areas of slack current also develop in channels, causing rapid deposition of bedload and the formation of bars or islands.

In the cobble conglomerate exposed in the roadcut north of Doran Creek, the large conglomeratic rock fragments probably entered the stream channel by downslope movement. The competency of the stream was not sufficient to move the large material, and it remained in the thalweg until channel fill and abandonment.

Granule and finer grained sediment was moved by bottom-traction transport and in suspension during flood stages; during falling water stages, this sediment collected around the immobile granule and larger detritus. As water velocities subsided, fallout sedimentation added a small fraction of silt and clay and filled some of the interstices between the larger detritus.

The abundance of granitic rock fragments in the cobble conglomerate indicates that the Precambrian core of the Park Range was extensively exposed by late Paleocene time. Some of the Precambrian rock fragments could be locally reworked detritus from alluvial fan deposits of the Middle Park Member, the lowest member of the Coalmont Formation.

Sandstone rock fragments, probably from the Dakota Formation (Hail, 1968), indicate reworking of sedimentary deposits and the existence of small ridges or hogbacks in the vicinity.

In the southwestern part of the Coalmont area, along Grizzly Creek and Colorado Highway 14, numerous scour-and-fill sequences are exposed. Trough sets marked by scour bases fine upward and are capped by mudstones, shale, and, rarely, coal. Braided-stream bars in this area are interbedded in the channel scour-and-fill sequences.

The coals of the middle member are thin and discontinuous, grading laterally into carbonaceous shales, and are occasionally truncated by channel scouring. The coals and carbonaceous shales were formed in poorly drained flood basins and swamps between anastomosing channels. Peat formation during deposition was contingent on the stability of channels through space and time. The coals and carbonaceous shales of the middle member represent remains of channel-margin deposits not scoured away by lateral channel migration. Burial of these deposits during floods aided retention in the geologic record.

Approximately 550 ft (170 m) above the base of the Coalmont Formation, a 25-ft (7.6-m) cross set is exposed. The cross set may represent a migrating bar within a channel complex. Similar sedimentary structures have been reported in laterally migrating (accretion) bars. If the cross set is the latter, then a change from a braided system to a meandering system might have taken place during late Paleocene time in the Coalmont area.

Coleman (1969) reported this type of primary sedimentary structure from the modern braided-stream environment of the Brahmaputra River in East Pakistan. Coleman also reported a change from a meandering system to a braided system for the Brahmaputra in the last 200 years (p. 141).

In either case, the height of the cross set suggests a channel as wide as 0.5 mi (0.8 km) having a high seasonal discharge. Maximum depth of the channel might have exceeded 75 ft (23 m) (Coleman, 1969).

Massively bedded sandstone units can be observed in the middle member. These genetic subunits were produced by lower-upper flow-regime velocities moving relatively large amounts of bedload material. Local decreases in velocity, or shoals, produced tabular or trough sets, which laterally and vertically disappear as bedload was subjected to upper flow-regime velocities. This type of depositional environment exists during flood stage, when the balance between stream velocity and bedload becomes critical. Any decrease in stream velocity or increase in bedload changes the planar bed form instantaneously. These types of sedimentary structures can form in channels quickly abandoned after deposition, before reworking of the sediment by lower flow-regime velocities. The sandstones are generally capped by ripple-laminated subunits.

Unit-2 genetic subunits of the middle member are planar-bedded sandstones, mudstones, and shales characteristic of flood-basin and marsh deposits. These subunits are locally scoured by fine- to medium-grained feldspathic channel sandstones. Wood debris and root zones are present, but coal is conspicuously missing. Peat, if deposited, was subjected to dropping ground-water tables and subareal exposure, resulting in oxidation.

The major channel systems during deposition of unit 2 were northeast and southeast of the Coalmont area. Subsurface E-logs in these areas show continuous interbedded sandstones, mudstones, and minor shales similar to those of the lower and upper units of the middle member.

Unit-3 genetic units are similar to the lower portions of the middle member. Numerous 3- to 6-ft (0.9- to 1.8-m)-thick conglomerate trough sets are overlain by ripple-laminated sandstones. Primary sedimentary structures indicate relatively high velocities depositing principally Precambrian detritus by bottom-traction transport. Stream gradients during deposition of unit 3 remained high. Bedload material included rock fragments from the highland to the west,

Table 1.--Environments of Deposition of the Middle Member of the Coalmont Formation

Sedimentary structures	Lithology	Flow regime	Environment	Biogenic activity
Low-angle trough cross stratification.	Arkosic and feldspathic conglomerates, conglomeratic sandstones, and sandstones.	Upper part of the lower flow regime.	Braided channel.	None observed.
Tabular cross-stratification.	Arkosic and feldspathic sandstones.	Lower flow regime.	Braided channel.	Do.
Ripple lamination	Feldspathic sandstones	Lower flow regime.	Braided channel.	Do.
Convolute bedding	Feldspathic sandstones, mudstones, and siltstones.	Lower-upper flow regime.	Braided channel.	Do.
Planar bedding	Feldspathic sandstones, mudstones, and siltstones.	Transition from lower to upper flow regime.	Braided channel.	Do.
Massively bedded (rare horizontal bedding).	Feldspathic sandstones, mudstones, and siltstones.	Transition from lower to upper flow regime.	Braided channel.	Do.
Subparallel lamination.	Sandstones, mudstones, and shale.	Lower flow regime.	Channel, flood plain, and lacustrine.	*Bellamya* and *Lioplacoides* or *Campeloma* snails (freshwater), Hail (1968, p. 48).
Subparallel and horizontal lamination.	Carbonaceous shale, coaly shale, and coal.	Lower flow regime and fallout sedimentation.	Swamp, flood plain, and lacustrine.	None observed.

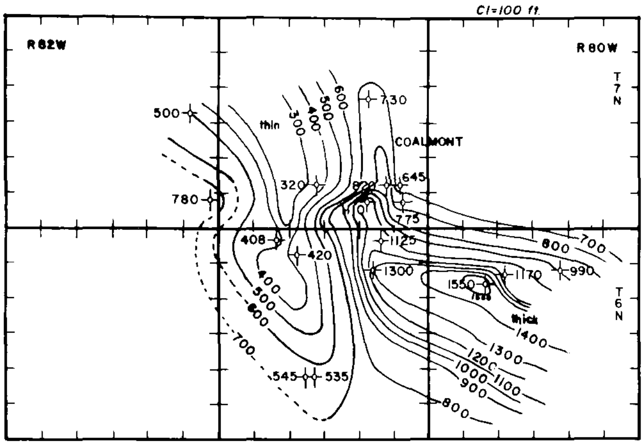

Figure 4.--Thinning and thickening of unit 1 of the middle member produced by deposition along and (or) across penecontemporaneous faults.

materials from band caving, and reworked channel deposits. Paleotransport directions were unidirectional to the east-southeast.

The isopach map of unit 1 (fig. 4) of the middle member shows a definite northwest-southeast thickening. Unit 1 is thickest in the Buffalo Creek test hole and has high thickness values in the Producers and Refiners Hendershot #1 and the L. M. Lockhart Fuller #1 test holes.

This northwest-southeast trend roughly follows the trends of the normal faults in the area. The normal faults are upthrown on their southwest sides, southwest of Pole Mountain. Northwest of Pole Mountain, the faults are upthrown on their northeast sides, creating a grabenlike feature.

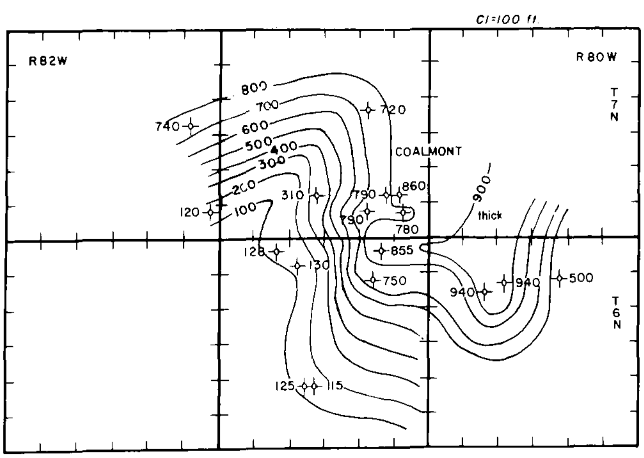

Figure 5.--Thinning and thickening of unit 2 of the middle member produced by deposition along and (or) across penecontemporaneous faults.

Major channels followed this northwest-southeast trend during deposition of unit 1. As deposition exceeded displacement along these faults, the area near Coalmont was partially filled with detritus. Deposition occurred (penecontemporaneously) on the upthrown sides of the faults as well, but at slower rates producing thinner deposits.

These same thickening trends can be observed for units 2 and 3 (figs. 5 and 6). Movement along the faults continued during deposition of these units, resulting in similar thickening trends. As deposition exceeded fault displacement, channel migration deposited bedload material on the upthrown sides of the faults.

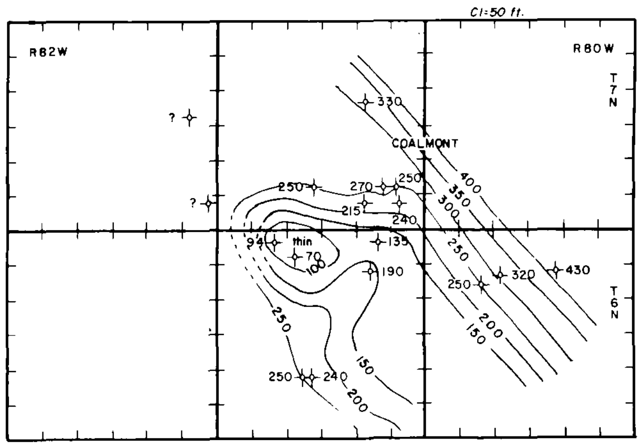

Figure 6.--Thinning and thickening of unit 3 of the middle member produced by deposition along and (or) across penecontemporaneous faults.

The faults operating during deposition of the middle and upper members of the Coalmont Formation were probably normal faults associated with downwarping of the basin. The vertical displacement during deposition was significant, as evidenced by the isopach values for unit 1 (fig. 4).

In the upper member, the thickest coal deposits follow this same structural trend, implying continued movement along the faults during early Eocene time. Channel reworking and poor exposure hamper any recognition of this penecontemporaneous faulting.

Post-Coalmont normal faulting along these same faults has repeated the major coal bed in the Coalmont area, the Riach bed (Erdmann, 1941). Displacement along the faults does not exceed 500 ft (150 m) and is generally much less (Hail, 1968).

The upper member of the Coalmont Formation consists of a heterogeneous mixture of sparse conglomerates, sandstones, mudstones, siltstones, shales, and coal. The sandstones were deposited in moderately sinuous meandering channels and splays.

Meandering rivers are characterized by lateral channel migration on a flood plain. The meandering channel erodes the outer concave bank, scours the riverbed, and deposits sediment on the inner bank, or point bar (Allen, 1965). Paleotransport directions vary, but generally trend in one direction. Meander loops are often abandoned during flood stages, and the water retained in the abandoned channels forms oxbow lakes.

Natural levees form along riverbanks during falling flood stages. The growth or destruction of these levees raises or lowers the ground-water table, affecting the swamp conditions on the flood plain (Weimer, 1973). Splays often break through levees, changing river courses and scouring flood-plain deposits.

Depending on climate and vegetation, swamp conditions may persist, and locally thick lenses of peat may accumulate on the flood plain. The retention of these peat accumulations in the geologic record is partially a function of flood-plain subsidence and the lack of rapid channel migration on the flood plain (Allen, 1965).

Most sediment transportation in meandering rivers is by suspended load. Small amounts of sediment transport by bottom-traction transport may occur during flood stages.

The sandstone subunits of the upper member have fining-upward sequences marked by scour bases. The sandstones are point bars capped by horizontally bedded sandstones and small ripple-bedded sandstones (table 2). These subunits are usually capped by mudstones and shales. Paleotransport directions vary, but generally average northeast.

Shales of the upper member were deposited in poorly drained swamps and flood plains. The shales are generally carbonaceous and locally coaly. The coals of the upper member were deposited in swamps. The peat remained below the ground-water table long enough to produce locally thick coal beds.

Coal maceral studies of the Riach bed indicate an abundance of humic material in the form of vitrinite and resinite. Fusinite and other forms of inertinite were produced by occasional exposure to oxidizing conditions. Alginite or other sapropelic macerals were not observed. The climate was warm at this time, allowing an extensive floral development (Leopold and MacGinitie, 1972).

The thickness of the Riach bed, as much as 65 ft (20 m) (fig. 7), indicates that swamp conditions acceptable to the formation of peat persisted through early Eocene time. These are some of the youngest coals in Colorado. The rank of the coal is subbituminous B.

Lateral thickness variations of the Riach bed represent the influx of detrital overbank material during floods, splays scouring into the swamp, or dropping of the ground-water table and the partial oxidation of the peat.

The mudstones and siltstones of the upper member were deposited in small lakes (oxbows), along levees, and by overbank influxes during flood periods. Some of the mudstones cap point-bar sequences (fig. 8).

The two subsurface cores of rocks stratigraphically above the Riach bed indicate that, in the northwestern portion of the Coalmont area, swamp conditions persisted after deposition of the peat. In the northeastern portion, however, channel processes encroached soon after deposition of the peat, and the thick carbonaceous shales overlying the Riach bed in the northwestern portion of the study area have been replaced by sandstones.

The "Parted Seam," an industry term for the coals and coaly shale in the northwestern subsurface near Coalmont (fig. 9), clearly demonstrate that paludal conditions persisted through space and time after the depositon of the Riach peat.

After reviewing all of the genetic units of the upper member, the existence of a widespread lake during deposition of the upper member is not indicated. Local areas were inundated for short periods of time, but widespread lacustrine conditions, as in Lake Uinta in northeast Utah, did not exist.

Grain sizes are reduced in the upper member, and the persistence of shales and mudstones indicates that very low topographic relief existed in the area during deposition of the upper member. The coarser grained detritus had shifted to the north and northeast of the Coalmont area, where meandering channels containing point-bar deposits continued to fill the basin. These channel processes began to encroach upon the Coalmont area after deposition of the Riach peat; they are represented by the lower section of the upper portion of the upper member. The upper portion of the upper member is a repetitious sequence of sandstones, mudstones, and sparse coal northeast of the town of Coalmont.

CONCLUSION

The middle and upper members of the Coalmont Formation are nonmarine deposits reflecting late Paleocene and early Eocene tectonic uplift, subsidence, and basin fill. During deposition of the middle member, stream gradients were high. Paleotransport directions trended east-southeast through the Coalmont area. The moderately elevated Park Range supplied abundant detritus, which was deposited mainly as bedload in braided streams.

Partial peneplanation of the highland and the filling of the basin reduced stream gradients. The reduction of detrital material changed the depositional environment of the upper member to that of a meandering system.

Table 2.--Environments of Deposition of the Upper Member of the Coalmont Formation

Sedimentary structures	Lithology	Flow regime	Environment	Biogenic activity
Low-angle trough cross stratification.	Arkosic and feldspathic conglomeratic sandstones (rare) and sandstones.	Upper part of the lower flow regime.	Point bars and crevasses.	None observed.
Ripple lamination	Sandstones and mudstones.	Lower flow regime.	Point bars	Do.
Planar bedding (horizontal bedding).	Sandstones, mudstones, and siltstones.	Lower part of the upper flow regime and lower flow regime.	Point bars, levee, and flood plain.	Do.
Subparallel lamination.	Sandstones, mudstones, siltstones, and shale.	Lower flow regime.	Point bars, flood plain, and lacustrine.	Do.
Subparallel and horizontal bedding.	Carbonaceous shale, coaly shale, and coal.	Lower flow regime and fallout sedimentation.	Swamp and flood plain.	Do.

Riach coal core, Mellen Ranch, 350 ft (105 m) from the southwest section corner, sec. 28, T. 7 N., R. 80 W., Jackson County, Colorado

Unit	Description	Thickness Meters	Thickness Feet
18	Gray, fine- to medium-grained, subangular, subrounded, poorly sorted, noncalcareous, slightly micaceous, very friable, feldspathic sandstone....	1.5	5.0
17	Dull-gray, slightly micaceous, very slightly calcareous mudstone.........................	.6	2.0
16	Gray, fine- to medium-grained, subangular, poorly sorted, noncalcareous, slightly micaceous, argillaceous, feldspathic sandstone..........................	1.2	4.0
15	Dull-gray, slightly micaceous, moderately indurated siltstone..	.3	1.0
14	Gray to tan, very fine grained to medium-grained, subangular, subrounded, poorly sorted, noncalcareous, slightly micaceous, very friable, feldspathic sandstone; some dark grains.........	4.6	15.0
13	Dull-gray, slightly micaceous, very slightly calcareous mudstone..........................	1.2	4.0
12	Gray, medium- to coarse-grained, subangular, subrounded, poorly sorted, poorly cemented, micaceous, noncalcareous, quartz sandstone......................	3.4	11.0
11	Dark-brown to black carbonaceous shale. Noncalcareous, moderately fissile.............	.3	1.0
10	Gray to tan, fine- to medium-grained, subangular, subrounded,		

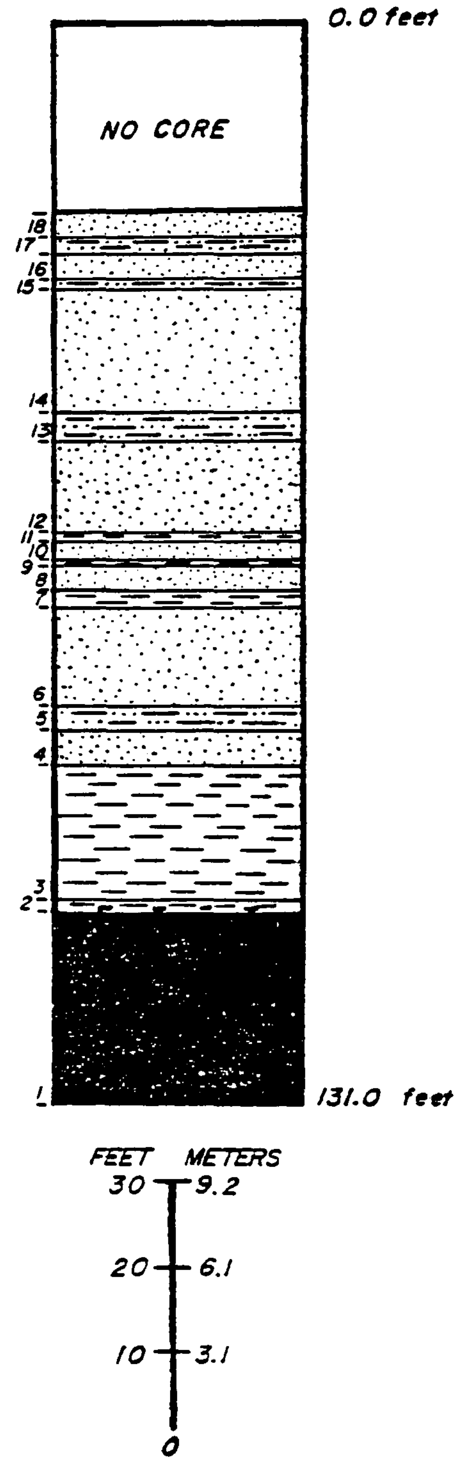

Figure 7.--Zapata coal core, indicating an abundance of sandstone stratigraphically above the Riach coal bed.

	poorly sorted, poorly cemented, slightly micaceous, very slightly argillaceous, felds- pathic sandstone; some dark grains (hornblende)............	.6	2.0
9	Dark-brown to black, very slightly micaceous, carbona- ceous shale.....................	.3	1.1
8	Gray to tan, fine- to medium- grained, subangular, subrounded, poorly sorted, very friable, slightly micaceous, very porous, quartz sandstone................	.9	3.0
7	Dark-brown to black carbona- ceous shale. Noncalcareous, moderately fissile..............	.6	2.0
6	Gray, fine- to coarse-grained, subangular, subrounded, poorly sorted, poorly cemented, mica- ceous, noncalcareous, felds- pathic sandstone; rare inter- bedded shale and coaly flecks...	3.7	12.0
5	Dull-gray to light-brown, slightly micaceous and calcar- eous mudstone..................	.9	3.0
4	Gray, very fine grained to medium-grained, subangular, sub- rounded, poorly sorted, poorly cemented, porous, micaceous, noncalcareous, slightly argilla- ceous, feldspathic sandstone; rare coarse grains; some dark grains (hornblende)............	.6	4.0
3	Black, highly carbonaceous, very slightly silty shale. Occa- sional coal flecks and woody material.......................	3.4	11.0
2	Black coaly shale. Some evi- dence of reworking or transport.	.6	2.0
1	Riach coal bed. No core was observed.......................	7.0	23.0

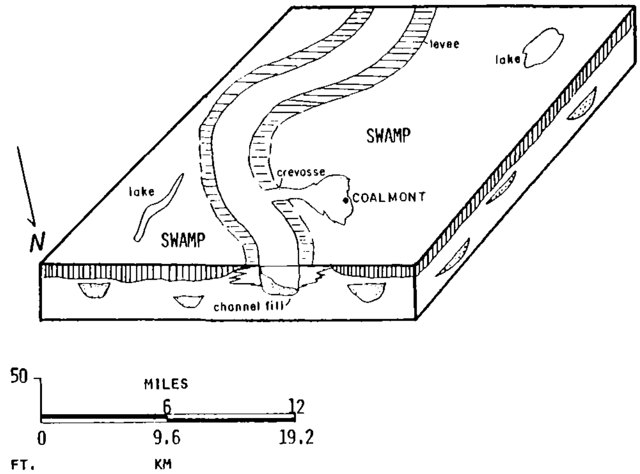

Figure 8.--Depositional environments of the upper member of the Coalmont Formation during deposition of the Riach peat in the Coalmont area.

Basin subsidence continued during deposition of the lower portion of the upper member, allowing thick peat deposits to develop and persist. These deposits were quickly buried as subsidence of the basin continued, resulting in thick coal deposits.

An intimate relationship existed between uplift of the Park Range and gradual subsidence of the basin during deposition of the middle and upper members. As uplift and downwarping ensued, coarser grained detritus was made available. Stream gradients increased and braided-stream environments deposited lenticular conglomerate and sandstone of the middle member.

Periods of tectonic quiescence reduced topography, stream patterns changed to meandering systems, and thick peat deposits developed in channel-margin or flood-basin areas. Renewed tectonic movements increased stream gradients, or the channel systems shifted laterally into the Coalmont area and deposited thicker sands.

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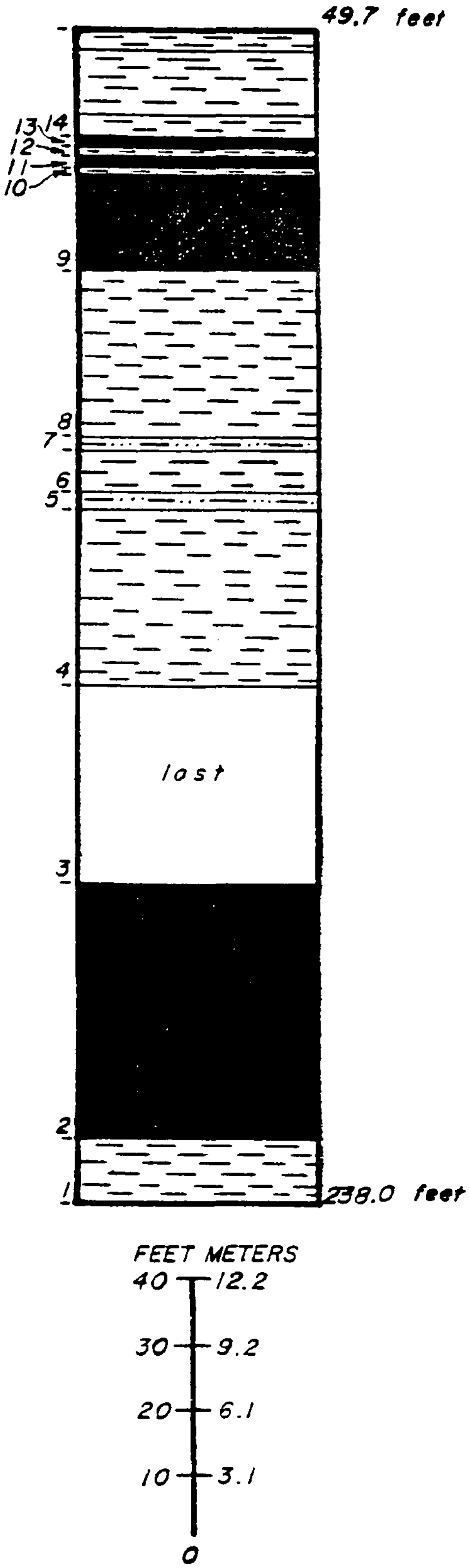

Figure 9.--Zapata coal core, showing the "Parted Seam" interval stratigraphically above the Riach coal bed.

Riach coal core, "Parted Seam," 600 ft (180 m) east of the center of sec. 21, T. 7 N., R. 81 W., Jackson County, Colorado

Unit	Description	Thickness Meters	Thickness Feet
14	Dark-brown to black, moderately fissile shale. Discontinuous, laminated, carbonaceous stringers are common	4.9	16.0
13	Black, soft coal and coaly shale. Noncalcareous; no cleat features observed	.2	.8
12	Dark-brown and black, strongly fissile, highly carbonaceous, coaly shale	.1	.4
11	Black, soft coal and coaly shale. Noncalcareous; no clear features observed	.2	.8
10	Dark-brown and black, moderately fissile, highly carbonaceous shale	.1	.2
9	Black, soft coal with coaly shale stringers. Noncalcareous; no cleat features observed	1.8	6.0
8	Dark-brown and black, well-compacted shale; discontinuous, thin-laminated mudstones	3.2	10.4
7	Dull-gray, slightly micaceous, occasionally well-indurated siltstone	.2	.8
6	Dark-brown and black, moderately compacted shale; discontinuous, thin-laminated mudstones	.8	2.6
5	Dull-gray, slightly micaceous, occasionally well-indurated siltstone	.4	1.2
4	Dark-brown and black, moderately fissile, noncalcareous shale	3.4	11.2
3	Lost interval: core lost in hole	3.8	12.4
2	Riach coal bed. No coal was examined	5.0	16.2
1	Dark-brown and black, highly carbonaceous, moderately fissile, well-compacted shale	1.2	4.0

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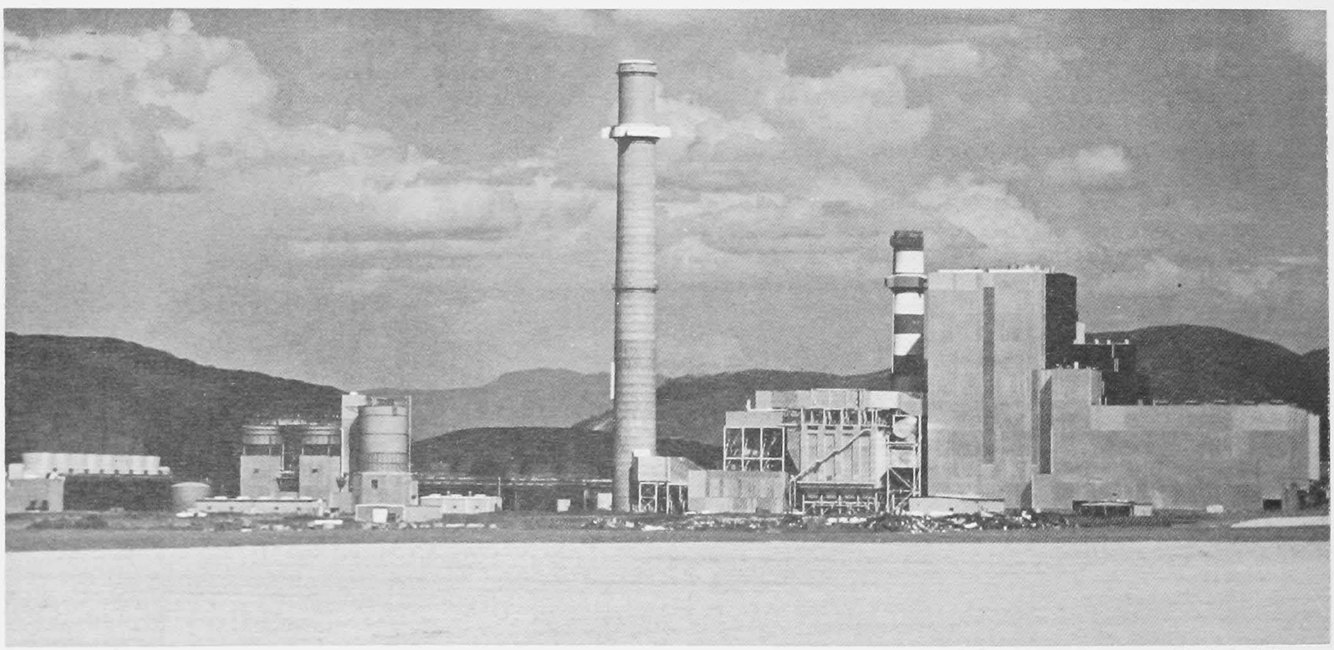
RoMoCoal Field Trip — Photograph by Harold H. Arndt, U.S. Geological Survey

Geologist (Ed Landis of the U.S. Geological Survey) examining the Wadge coal bed in the Williams Fork Formation at the Energy Fuels Corporation pit no. 2.



RoMoCoal Field Trip — Photograph by James M. Soule, Colorado Geological Survey

View of Hayden Power Plant southeast of Hayden, Colo. Locally mined coal from the nearby Seneca mine owned by Peabody Coal Co. is burned in this 450 MW plant.

Basin-Margin Depositional Environments of the Wasatch Formation in the Buffalo-Lake de Smet Area, Johnson County, Wyoming[1]

STAN OBERNYER[2]

ABSTRACT

The Eocene Wasatch Formation along the east flank of the Big Horn Mountains in the Buffalo-Lake de Smet area, Wyoming, contains what is alleged to be the thickest coal bed in the United States. This coal bed--referred to in this paper as the Lake de Smet bed--extends at least 15 mi north-south through the study area, is 1/2-2 mi wide, and is 70 to greater than 250 ft thick. In most areas overburden is less than 100 ft. The coal is marginal lignite-subbituminous C; and many partings of sandstone, siltstone, mudstone, and claystone occur throughout the interval.

The lithologies laterally equivalent to the Lake de Smet bed are characterized by two types of sandstone. They are lithologically and geometrically different and are separated by the thick Lake de Smet coal. Sandstone to the west of Lake de Smet is thin, lenticular, poorly sorted, and conglomeratic. Thick, broad sheets of well-sorted, very fine grained to medium-grained sandstone dominate the stratigraphy east of the coal bed. Five major, mappable, regionally extensive coal beds split from the Lake de Smet bed and extend eastward into the basin. Thin, noneconomic carbonaceous shales and coals split from the coal on the west and rapidly pinch out.

It is suggested that the regional tectonic framework has influenced the location and thickness of the Lake de Smet bed. Active uplift of the Bighorn Mountains to the west resulted in the formation of alluvial-fan and braided-stream deposits along its flanks. The gradually subsiding Powder River Basin to the east created a poorly drained alluvial plain containing vast swamps, meander channels, natural levees, crevasse splays, and lakes. The Lake de Smet bed separates these two environments. The linear orientation of the coal bed axial to the basin may be a facies expression of a basement-controlled basin-margin fault.

ACKNOWLEDGMENTS

I wish to express my appreciation for the generous financial support provided by the U.S. Geological Survey for this study. This paper evolves from work performed for an M. S. thesis at the Colorado School of Mines. Committee members Robert Weimer, Karl Newman, and John Haun provided many helpful suggestions and assistance.

INTRODUCTION

The Lake de Smet bed and accompanying deposits lie along the east flank of the Bighorn Mountains in northern Johnson County, Wyo. (fig. 1). Tectonic activity of the Late Cretaceous and early Tertiary was perhaps more profound in this locality than in any other on and around the periphery of the Powder River Basin. The doubly-plunging synclinal axis of the Powder River Basin, as shown atop the Madison Limestone by Swenson (1974; fig. 2), lies almost directly under Buffalo and Lake de Smet. Structural

[1]As a result of additional work, some material in this paper has been revised since the talk was given in May 1977.

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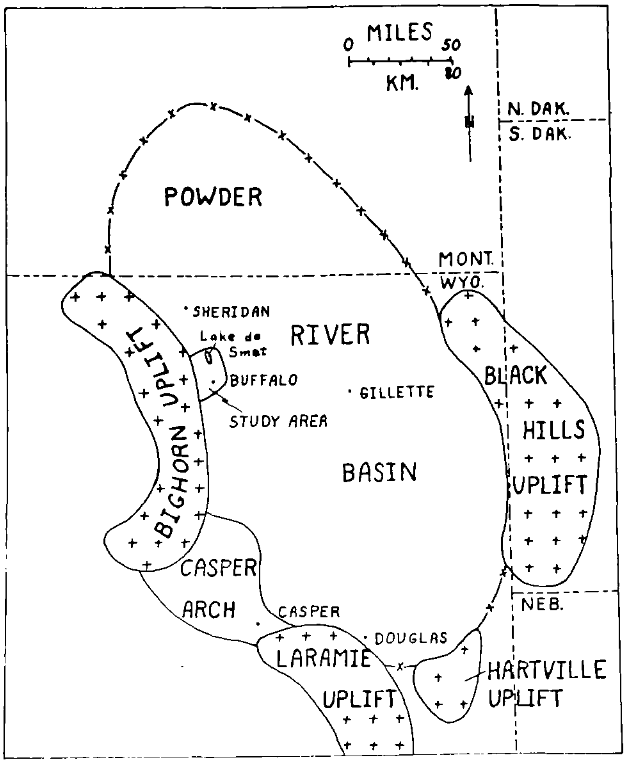

Figure 1.--Index map to Buffalo-Lake de Smet study area, Johnson County, Wyo.

relief from the lowest point in the basin, which lies south of Buffalo, to the top of the Bighorn uplift is in excess of 30,000 ft.

The Paleozoic, Mesozoic, and early Tertiary deposits display relatively broad outcrop patterns and shallow dips along the eastern side of the basin adjacent to the Black Hills uplift, whereas narrow outcrop bands and steep dips prevail along the western margin of the Powder River Basin in the vicinity of Buffalo (fig. 2). However, dips for Wasatch strata covering the study area rapidly flatten out to near-horizontal dips within 4-5 mi of their westernmost occurrence.

DESCRIPTIVE STRATIGRAPHY

Lenticular and interbedded, poorly consolidated conglomeratic sandstone, sandstone, siltstone, mudstone, and thin organic and carbonaceous shale and coal stringers dominate the strata west of the Lake de Smet coal bed. These lithologies interfinger to the west with the conglomerate facies marginal to the Bighorn Mountains and, to the east, with the Lake de Smet coal bed. Figure 3 is a composite section of the fining-upward sequence representative of the Lake de Smet bed. The section is based on limited outcrop exposures and one drill hole in sec. 28, T. 51 N., R. 82 W. This fining-upward sequence is repeated many times and may or may not begin to coarsen again towards the top of each unit. Coal and organic units frequently are not present. Outcrop studies suggest that lateral continuity of any lithology is very limited.

The conglomeratic sandstone is dominantly tan to yellowish-orange with angular to subangular, silty to pebble-conglomeratic, micaceous, arkosic detritus derived from the Bighorn uplift. Abundant carbonaceous grains are found in virtually all of the sandstone. Sorting varies, with finer grained sandstone displaying fair to poor sorting and coarser grained sandstones showing very poor sorting.

The conglomeratic sandstone occurs as

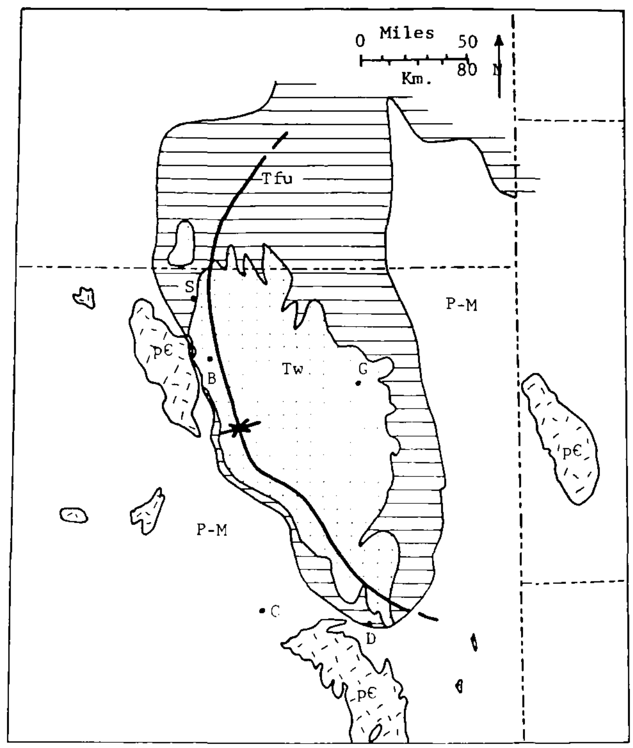

Figure 2.--General geology of the Powder River Basin; structural axis based on the top of the Madison Limestone. Tw, Wasatch Formation; Tfu, Ft. Union Formation; P-M, Paleozoic and Mesozoic; pЄ, Precambrian; S, Sheridan; B, Buffalo; C, Casper, D, Douglas; G, Gillette. Geology modified from Hodson, Pearl, and Druse (1973); Swenson (1974); and Denson and Horn (1975).

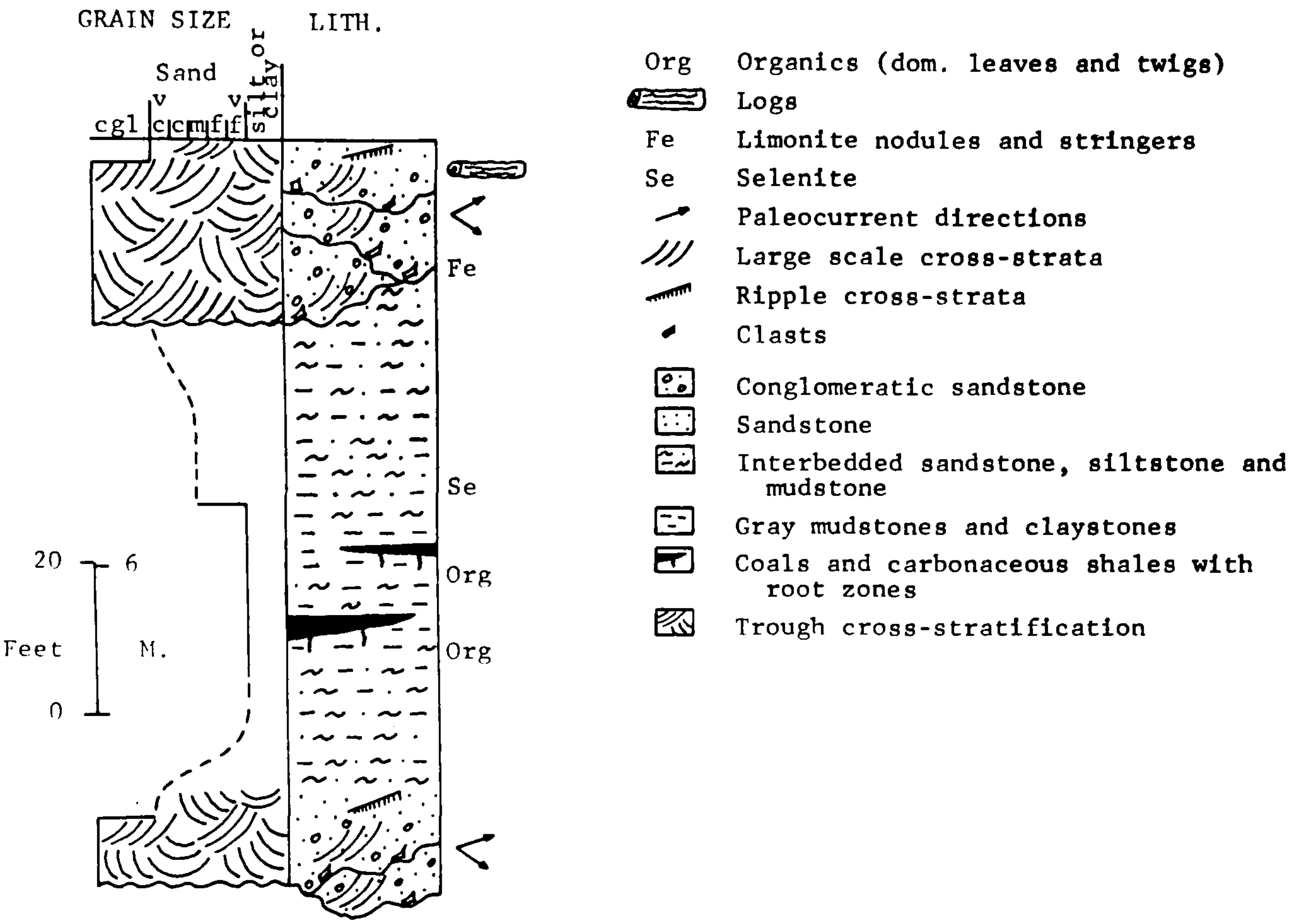

Figure 3.--A composite vertical section showing a representative fining-upward sequence within the coal-bearing strata west of the Lake de Smet bed.

lenses as much as 40 ft thick and greater than 20 ft wide. The scour surfaces at the base of these lenses merge laterally with the interbedded, thin- to thick-bedded, yellowish-orange conglomeratic sandstone and greenish-gray siltstone and mudstone. Additional scour surfaces frequently occur within the sandstone lenses.

Overall, the lenses display a fining-upward trend and a decreasing-upward bedform thickness. A few individual genetic units display coarsening-upward trends. Irregular fluvial energies are reflected in the grain-size distributions, because individual crossbed layers possess much coarser material than adjacent layers. Trough cross-strata as much as 4 ft thick near the base of the lenses are replaced by smaller trough sets, parallel laminations, and ripple cross-stratification. Angular siltstone and mudstone clasts cluster near the base of many trough sets as well as above the scour surfaces of the sandstone lenses.

Sandstone occurring in the interbedded sequences displays little or no scour into the underlying beds. Stratification is generally either disrupted or impossible to discern, although large-scale and ripple cross-strata have been observed. A proportionate decrease in the sandstone volume occurs both laterally and vertically with increasing distance from the sandstone lenses.

The siltstones and mudstones are very organic and carbonaceous. Imprints of twigs and leaves from deciduous trees are common. At two localities (N1/2 sec. 34 and NW1/4 sec. 15, T. 51 N., R. 82 W.), tree trunks 1-2 ft in diameter are buried vertically in a sequence of interbedded sandstones, siltstones, and mudstones. Ripple stratification is sometimes observed in the siltstones, but stratification is absent in the mudstones.

Occasional thin lenses of brown, punky organic shale, carbonaceous shale, and woody coals as much as 5 ft thick occur. Root zones can be observed penetrating underlying clay, silt, and sand. Abundant yellow resins and occasional pyrite crystals can be found within the organic units. Both laterally and vertically adjacent to those organic and carbonaceous lenses, yellowish-orange sandstone is generally absent or is present in minor quantities.

The Lake de Smet Coal Bed

Reputed to be the thickest coal seam in the United States and the second thickest in the world (Texaco press release, 1975), the Lake de Smet bed stretches north-south through the study area for more than 15 mi; it has a thickness ranging from 70 ft to more than 250 ft and a width of approximately 1/2-2 mi (fig. 4). The existence of this thick coal deposit was first reported by Mapel, Schopf, and Gill (1953) after the U.S. Geological Survey and the U.S. Bureau of Reclamation drilled several holes at the northern and southern ends of Lake de Smet. Subsequent drilling by several industrial concerns has vastly extended the length and breadth of the initial reported discovery.

Although hundreds of holes have been drilled in the Buffalo-Lake de Smet area, few holes, aside from those drilled by the Government agencies, are available because of proprietary rights cited by the companies concerned. The drill-hole data are of highly variable quality. Some describe the lithologies only in terms of the presence or absence of coal. Others, such as the hole drilled in Buffalo by the U.S. Geological Survey in 1975, portray very detailed lithologic breakdowns. Few lithologic logs have accompanying geophysical logs. It is questionable whether some of the holes actually penetrated the total thickness of the Lake de Smet bed, as some of the holes either stopped in coal or within a few feet below a coal layer. A basal fossiliferous mudstone, which might be used as a marker bed, has been reported to underlie the Lake de Smet seam at Buffalo and along the northern and western margins of Lake de Smet; however, apparently little effort has been made to verify its existence elsewhere. With these limitations, selected drill holes were assembled to construct north-south and east-west cross sections (figs. 4, 5, 6, and 7) to delineate the extent and thickness of the coal. The thickest coals are north of Lake de Smet and in the vicinity of Buffalo. One drill hole, in sec. 10, T. 51 N., R. 82 W., contained no coal.

Many lenticular, thin partings of very fine grained to medium-grained sandstone, siltstone, mudstone, claystone, and organic shale occur throughout the coal. Sandstone and siltstone partings are more abundant to the west than to the east. The western boundary of the coal is relatively sharp, with the coal rapidly fingering out into thin organic shale, carbonaceous shale, and coal stringers that pinch out to the west. Where these stringers are observable at outcrops, they are directly underlain by pale-yellowish-orange conglomeratic sandstone displaying root zones.

To the east of the Lake de Smet coal seam, the coal beds are generally underlain by dark-gray clays which commonly are conchoidally fractured and possess grooves resembling slickensides. "Clay skins" is the term often applied to such structures. They are the result of roots penetrating and expanding in the clay zones.

Five major mappable coal beds, which merge to form the Lake de Smet bed, can be traced over a regional area both in surface outcrop and in the subsurface (fig. 8). Mapel, Schopf, and Gill (1953) and Mapel (1959) tentatively identified a portion of this thick coal as equivalent to the Healy bed. Subsequent work by Texaco, Inc., and Carter Oil Company has resulted in equating the lowermost coal emanating from the Lake de Smet bed with the Ucross bed. The Walters bed is interpreted to be the uppermost coal identifiable with the Lake de Smet bed. Two pieces of field evidence support this conclusion: The first presence of conglomeratic sandstone east of the Lake de Smet bed is found above the Walters bed. Small channel deposits trending east and northeast were exposed by construction crews in the NE1/4 sec. 28, T. 52 N., R. 82 W. and in the W1/2 sec. 1, T. 51 N., R. 82 W. Also, a coquina mudstone of wide areal extent lies above the Walters bed, but below the conglomeratic sandstone influx, east and south of Lake de Smet (fig. 9). This fossil bed was found to lie above a thick coal sequence, interpreted to be a portion of the Lake de Smet bed, unearthed by construction crews at the southeast corner of Lake de Smet.

Mapel, Schopf, and Gill (1953) reported the coal's rank to be borderline between subbituminous C and lignite (ASTM classification). The coal is a dull black when wet, is brown when dry, and has a strong tendency to break down upon exposure to the air. Metamorphism of the coal has not progressed sufficiently to produce characteristic vitrain. Fusain is thought to represent less than 1 percent of the deposit. Core-hole analyses reveal that woody material makes up 34-39 percent of the coal. Numerous partially coalified tree trunks litter the outcrops of the thin coaly splits along the western margin of the coal bed. Tree stumps as much as 4 ft in diameter are commonly found near or at the base of a coal layer.

Very Fine Grained to Medium-Grained Sandstone Sequence

To the east, the Lake de Smet bed splits into five major coal beds separated by very fine grained to medium-grained sandstone, siltstone, mudstone, claystone, and occasional lenticular, thin organic shale and coal. The intervening clastic intervals range from a few feet thick between the Lower and Upper Cameron beds to

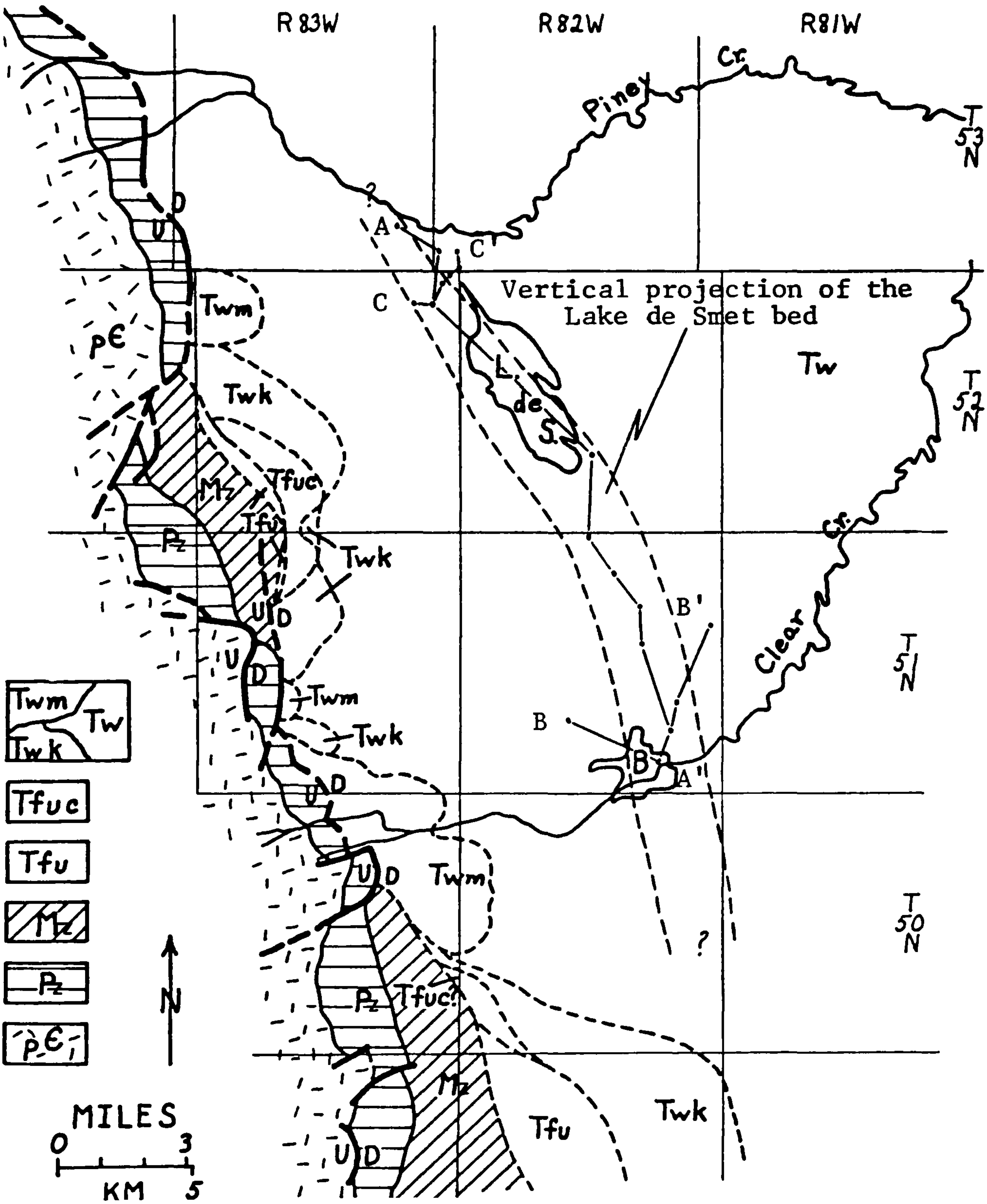

Figure 4.--Vertical projection of the location of the Lake de Smet bed. Cross sections A-A′, B-B′, and C-C′ appear in figures 5, 6, and 7, respectively. pЄ, Precambrian; Pz, Paleozoic units, undivided; Mz, Mesozoic units, undivided; Tfu, Ft. Union Formation; Tfuc, Conglomerate Member of the Ft. Union Formation; Tw, Wasatch Formation; Twk, Kingsbury Conglomerate Member of the Wasatch Formation; Twm, Moncrief Conglomerate Member of the Wasatch Formation. Geology modified from Mapel (1959) and Hose (1955).

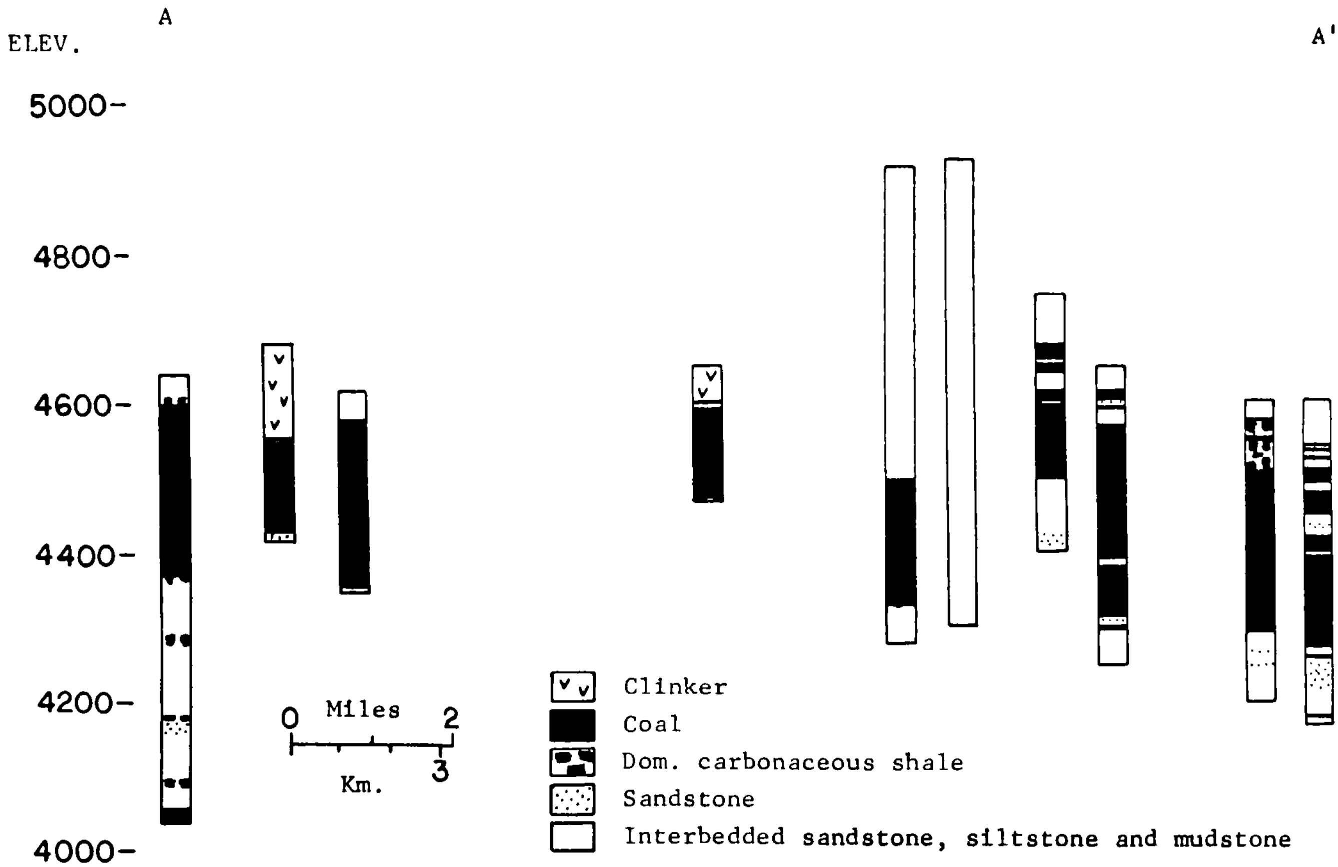

Figure 5.--Cross section A-A′, based on drill-hole lithologic logs.

greater than 200 ft thick between the Healy and Walters beds. From west to east, these clastic intervals develop from 0 ft to average interval thickness in a horizontal distance of 20-500 ft. Figure 10 represents a schematic, typical section of the clastic interval between the Healy and Walters beds. Field work and drill-hole data suggest that this stratigraphic section is representative of the other clastic intervals as well.

The sandstones are gray-tan to pale-yellowish-orange, very fine grained to medium-grained, poorly consolidated, micaceous, and arkosic, with both grain size and bed thickness decreasing upward. The sand grains are angular to subangular and well sorted. Abundant fine- to coarse-grained carbonaceous detritus commonly outlines bedding-plane surfaces. Coarser portions of the sandstone sometimes display calcareous cementation; however, the resulting concretionary aspect of the sandstone displays no continuity with the stratification. Frequently, logs, tree trunks, and tree roots are associated with the concretionary sandstone.

Bed thicknesses range from approximately 5 ft at the base of a sandstone interval to less than 1 in. at the top. Stratification, likewise, reveals a decrease in water energies upward. Trough cross-stratification gives way to tabular ripple cross-stratification and parallel lamination. Asymmetrical, symmetrical, and climbing ripple forms are variously present.

These fining-upward sandstone sequences are repeated anywhere from 1 to 4 times within a single clastic interval between the coals. Each genetic unit has a scour base which is most easily distinguished by the sudden change in thickness of the bed form and the change in stratification. Angular to subrounded claystone, siltstone, and sandstone clasts, as well as lag deposits of pelecypod and gastropod shell fragments, often occur near the scour surface of a sandstone unit.

Current-direction readings vary from southwest to east, but the general flow direction is to the north. However, within each fining-upward unit, the current direction remains fairly constant (figs. 10, 11, and 13).

Petrified logs (replaced largely by silica and calcite), both horizontal and vertical to subvertical to the strata, and imprints of large tree roots are common occurrences. Generally, transported logs lie near the base of a fining-

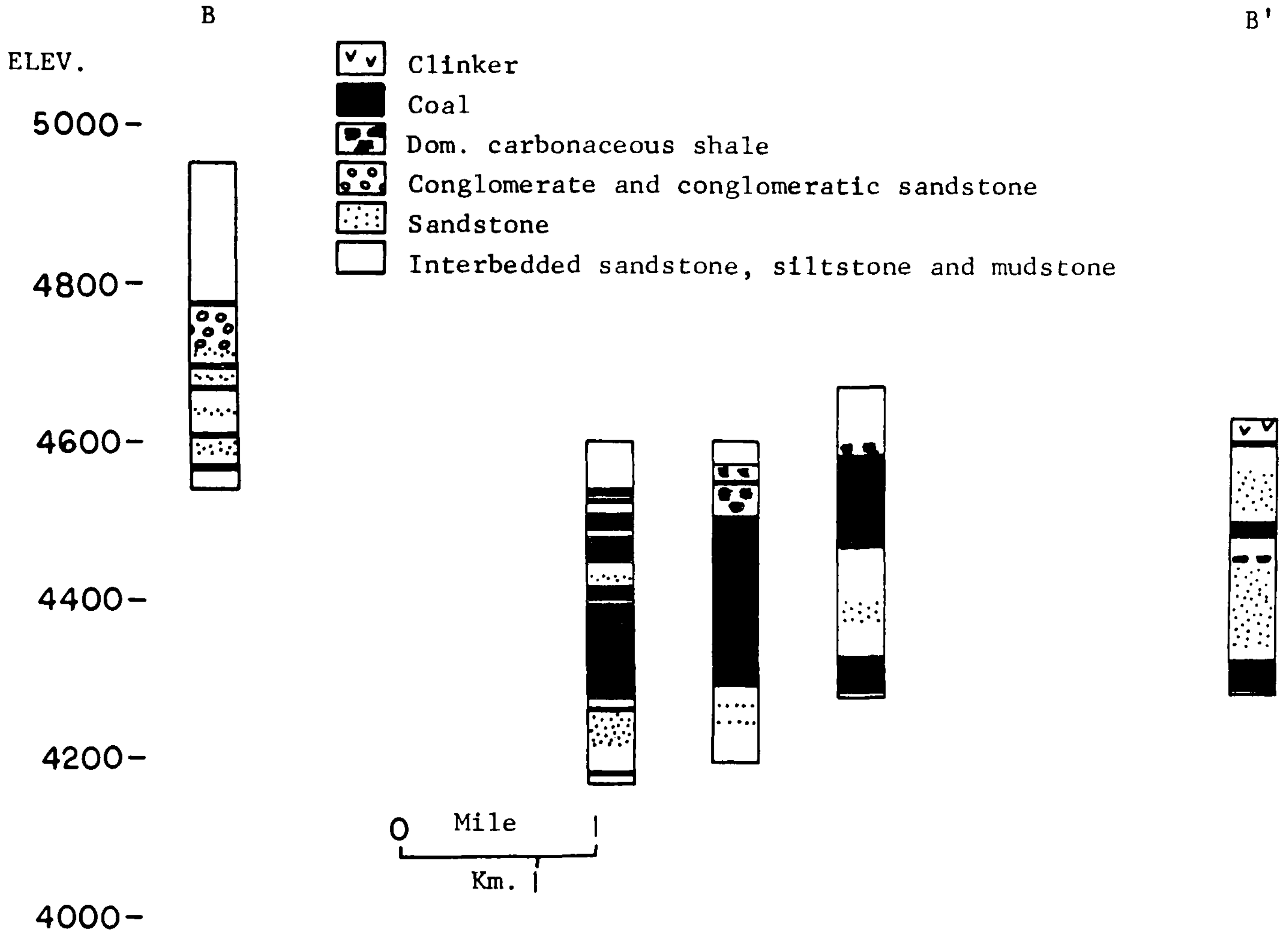

Figure 6.--Cross section B-B′, based on drill-hole lithologic logs.

upward sequence. Vertical logs, in situ buried tree trunks, are usually found in clusters at the outcrop. The best locations for observing such occurrences are in sec. 2, T. 51 N., R. 82 W.; SE1/4, sec. 32, T. 53 N., R. 81 W.; and NW1/4, sec 31, T. 51 N., R. 80 W. Some of these tree trunks are buried primarily by sandstone sequences, while others are buried in interbedded yellowish-orange sandstone and gray siltstone and mudstone sequences.

In a broad sense, these sandstones give the appearance of being broad, regionally extensive sand sheets. Thicknesses range from a few feet to almost 100 ft. The sandstone between the Healy and Walters beds is continuous and extends beyond the boundaries of the study area east of the Lake de Smet bed.

Both above and below the sandstone is found yellowish-orange sandstone interbedded with gray siltstone, mudstone, and claystone. The scour of the basal sandstone makes a sharp contact with the sequence found below the sandstone, whereas the upper interval is a gradational contact. As one approaches the coal from above and below in a typical section, the yellowish-orange cast to the sandstone disappears and the ratio of sandstone to siltstone, mudstone, and claystone decreases.

Organics are abundant in all these units. Twig and leaf imprints and carbonaceous detritus are common in the mudstone and claystone, while carbonaceous material predominates in the sandstone and siltstone. Thin, brown, punky organic shale lenses frequently supplant mudstone units. Occasional mudstone lenses contain abundant pelecypod and gastropod shells. Some fossiliferous beds qualify as coquina units.

The coals invariably display root zones into the underlying clays. Physical characteristics and composition of the coals are similar to those of the Lake de Smet bed, though great variations in thickness, physical character, and quality of these coal beds are encountered

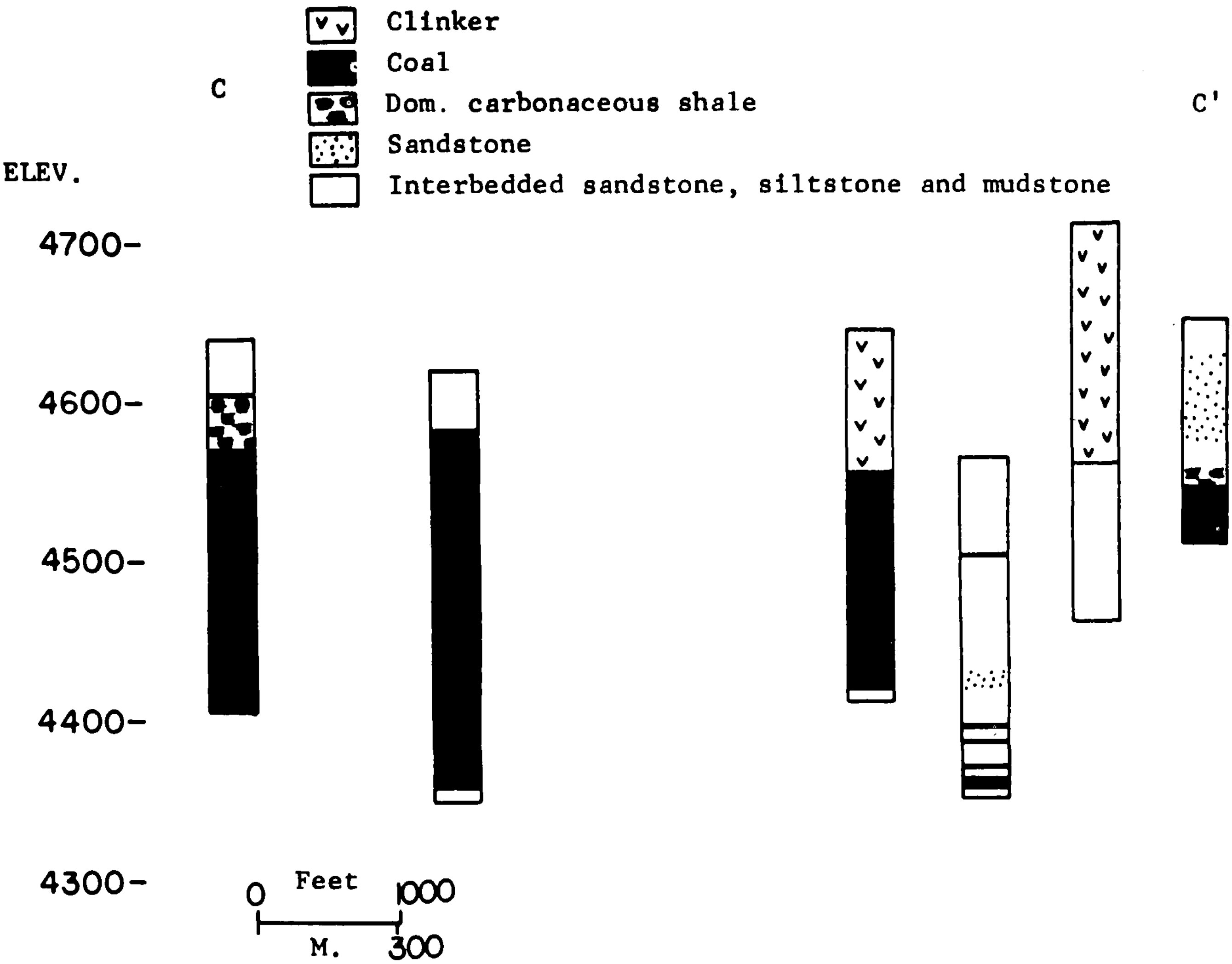

Figure 7.--Cross section C-C′, based on drill-hole lithologic logs.

laterally. Many of the coals burned via the process of spontaneous combustion when the coal was exposed to the atmosphere by the process of erosion (Rogers, 1917). This resulted in baking of the strata overlying the coal seams. The clinker, as the baked strata is called, forms the characteristic resistive reddish-colored butte topography.

Fossil Marker Beds

Three of the fossiliferous mudstone lenses are regional in extent and, as such, serve as excellent marker beds within a formation that is characterized by rapid lateral and vertical lithologic changes. One of the fossiliferous beds lies at the base of the Lake de Smet bed and has already been discussed. In addition to the normal gastropod and pelecypod assemblage, pyritized gar scales and vertebra have been recovered (Texaco, oral communication, 1976).

A second bed is a fossiliferous limestone, a few inches to approximately 2 ft thick, which occurs above the Upper Cameron bed. Mapel (1959) reported its lateral extent to be more than 125 mi^2. Most of its areal extent lies outside the study area; however, where it is observed within the study area, it lies less than 5 ft above the coal bed.

Unlike the fossil horizon above the Upper Cameron bed, the fossiliferous mudstone above the Walters bed lies variously from 3 ft to approximately 50 ft above the coal. This fossiliferous mudstone, which includes gastropods and pelecypods, ranges from less than 1 ft to over 25 ft

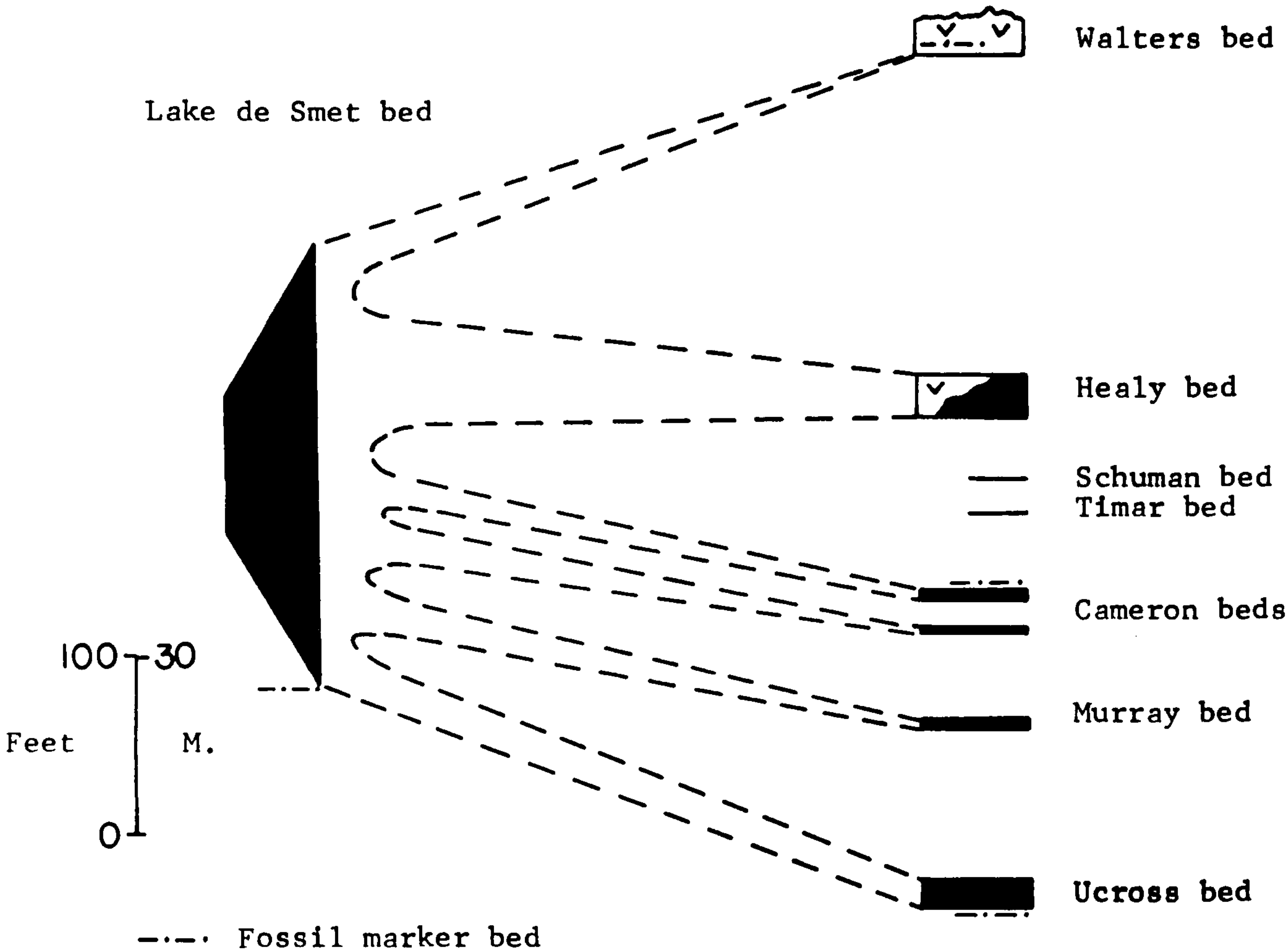

Figure 8.--Schematic diagram showing the relationship of the Lake de Smet bed to the major coal beds to the east, using Mapel's (1959) coal-bed designations.

thick. In a deep, manmade cut at the southeast corner of Lake de Smet, the fossil bed was found to be split into two beds several feet apart. They lie approximately 5 ft above what is interpreted to be the last coal split of the Lake de Smet bed. The wide variance in thickness of the clastic interval between the coal and the fossil bed leads to two conclusions: (1) coals are not necessarily good units for lateral correlation when they cannot be walked out, and (2) the Walters bed may be a series of small discontinuous coal beds rather than a broad extensive coal bed as implied by mapping this horizon as the Walters bed.

ENVIRONMENTS OF DEPOSITION

The strata west of the Lake de Smet bed are interpreted as braided-stream systems emanating from alluvial fans flanking the uplift. These coarse deposits spill onto a broad alluvial plain dominated by meander-channel and related levee and crevasse-splay systems, swamps, and lakes (figs. 12 and 14). The boundary between these two depositional environments is best delineated by the change from a coarse-grained, poorly sorted sandstone to a fine-grained well-sorted sandstone and by a change in the paleocurrent directions from east to north (figs. 11 and 13). The boundary corresponds roughly with the western edge of the Lake de Smet bed.

Braided-Stream Environments

Models and descriptions of braided-stream deposits from recent sediment studies are not easily applied to ancient sediments. Some of the characteristics of the braided-stream deposits in the Buffalo-Lake de Smet area, listed below, have

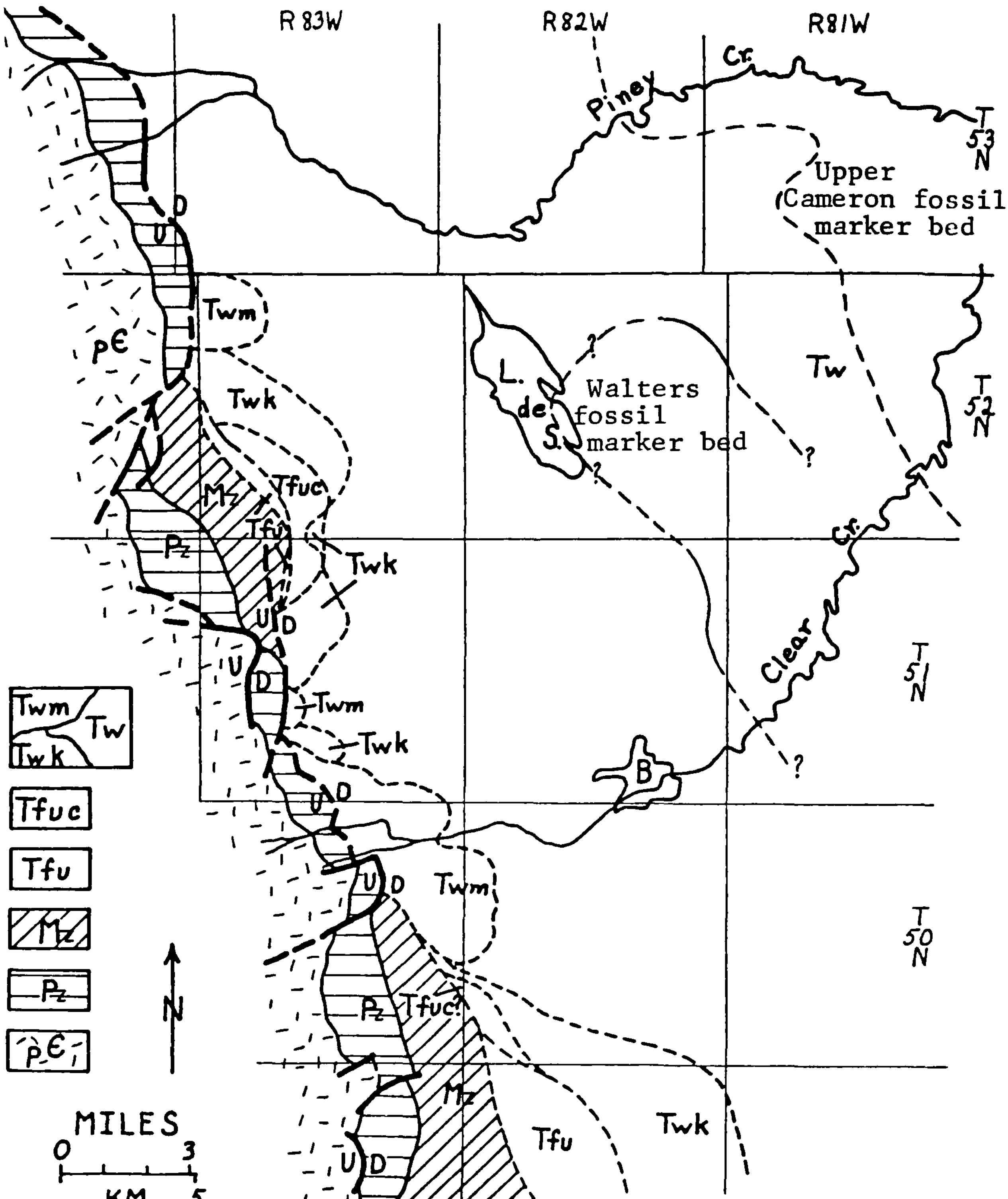

Figure 9.--Areal extent of the fossiliferous marker beds located above the Upper Cameron and Walters beds. pЄ, Precambrian; Pz, Paleozoic units, undivided; Mz, Mesozoic units, undivided; Tfu, Ft. Union Formation; Tfuc, Conglomerate Member of the Ft. Union Formation; Tw, Wasatch Formation; Twk, Kingsbury Conglomerate Member of the Wasatch Formation; Twm, Moncrief Conglomerate Member of the Wasatch Formation. Geology modified from Mapel (1959) and Hose (1955).

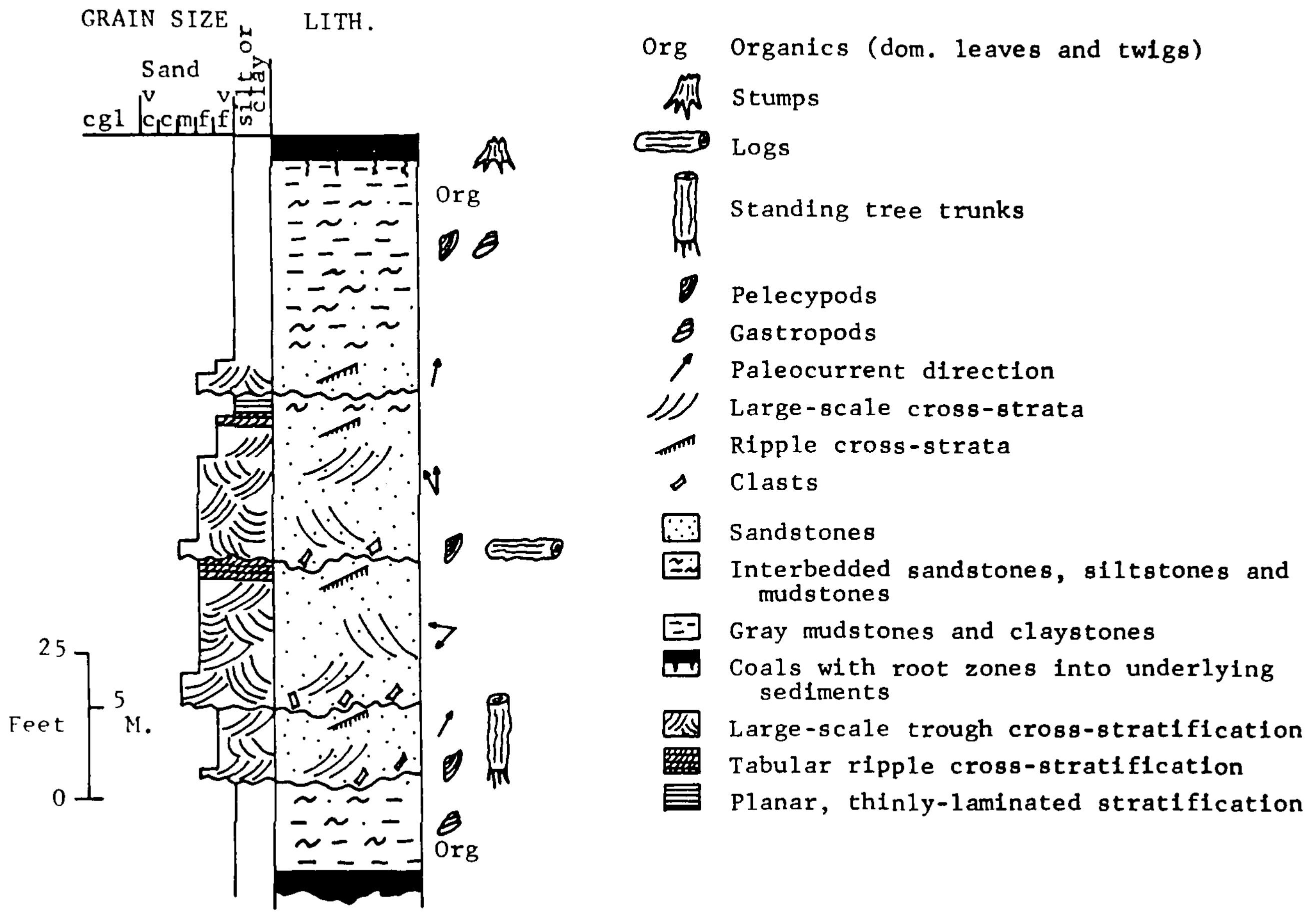

Figure 10.--Schematic vertical section of the clastic interval between the Healy and Walters beds.

been frequently cited, while others have been infrequently observed or reported or are in opposition to generally accepted characteristics of braided-stream deposits.

1. Figure 3 demonstrates repeated sequences of fining-upward units. In some instances, a gradual coarsening of the sands may occur near the top of the unit. Pettijohn (1975) noted a general absence of fining-upward trends in most braided-stream deposits.
2. Irregular scour surfaces occur within the channel deposit as well as at the base.
3. Channel sandstones generally fine upward. A few channel deposits display coarsening-upward trends, while others maintain a constant grain size throughout the sandstone. Weimer and Erickson (1976) observed that each genetic unit within the upper and lower members of the Lyons Formation--interpreted as fluvial braided-channel deposits--is a fining-upward sequence.
4. The sandstones are very poorly sorted. Alternating layers of coarse- and fine-grained detritus in adjacent cross-bed laminations reflect fluctuating water energies.
5. Interbedded yellowish-orange sandstone and greenish-gray siltstone and mudstone sequences observed above, below, and lateral to the channel deposits are interpreted as being levee and crevasse-splay deposits. Coleman (1969) reported significant levee and crevasse-splay deposits in the Brahmaputra River alluvial plain.
6. Significant volumes of siltstone and mudstone and minor concentrations of organic shale and coal are present, contrary to virtually every reported modern or ancient analogue. Smith (1970) and Pettijohn (1975) cited the absence of significant amounts of silt and clay as a criterion for identifying braided-stream environments.

The key to identifying this environment as

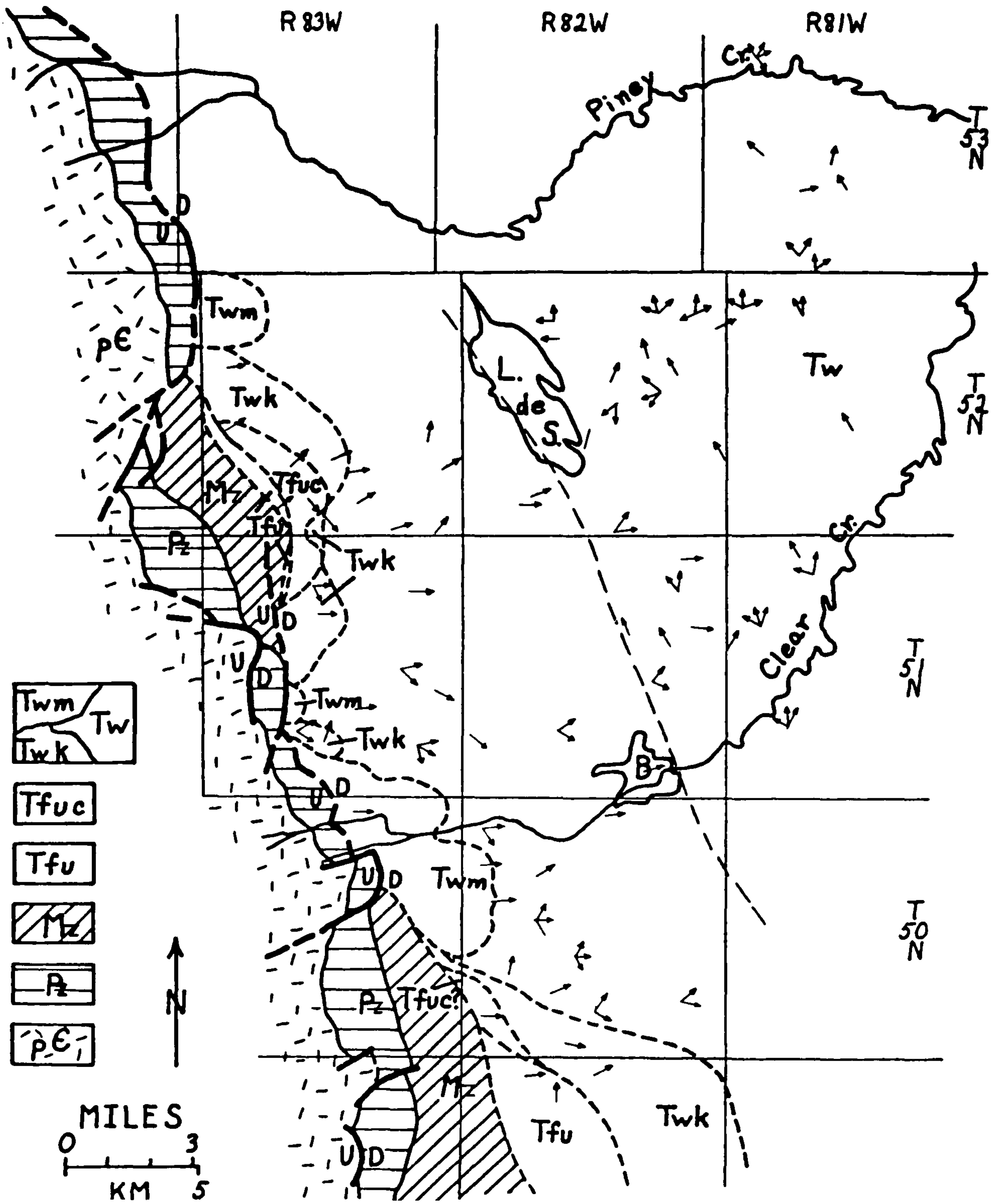

Figure 11.--A representative sampling of paleocurrent-direction readings obtained largely from cross-strata. Readings west of the dashed line show easterly drainage of the alluvial-fan and braided-stream environments. Readings east of the dashed line show a north-northwest drainage pattern for the alluvial-plain environments. pЄ, Precambrian; Pz, Paleozoic units, undivided; Mz, Mesozoic units, undivided; Tfu, Ft. Union Formation; Tfuc, Conglomerate Member of the Ft. Union Formation; Tw, Wasatch Formation; Twk, Kingsbury Conglomerate Member of the Wasatch Formation; Twm, Moncrief Conglomerate Member of the Wasatch Formation. Geology modified from Mapel (1959) and Hose (1955).

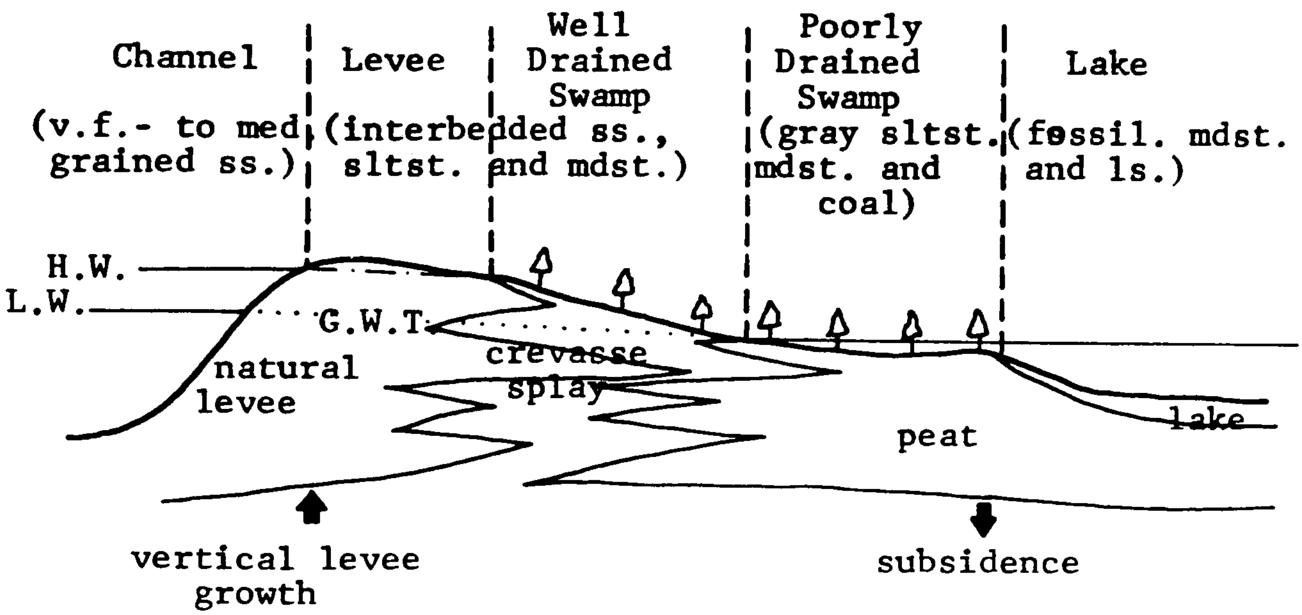

Figure 12.--Environments of deposition interpreted for lithologies of the upper deltaic-alluvial plain facies. H.W., flood-stage water level; L.W., normal water level; G.W.T., groundwater table. Modified from Weimer (1973).

one dominated by braided-stream processes lies with the channel deposits. The poor sorting of the sandstones and the irregular scour surface that cut into the channel and adjacent levee deposits suggest irregular fluvial energies and high sediment transport accompanied by frequent channel shifting. These features are commonly observed in modern braided-stream environments.

As depicted in figure 14, the alluvial fans are interpreted as spilling onto a vast alluvial plain. The braided-stream systems operating in the distal regions of the alluvial fans finger out onto the alluvial plain, where they are rapidly engulfed. Between the stream channels, swamps flourish. The alluvial fan builds upward and outward in a manner resembling that of a delta. The alluvial fan periodically shifts its depocenter to satisfy the dynamics required to transport and deposit its sediment load. These shifts of depocenters, combined with subsidence, help create the fining-upward sequences.

Alluvial-Plain Environment

• Sediments east of and including the Lake de Smet bed consist of meander-channel, levee, crevasse-splay, paludal, and lacustrine deposits (fig. 12). The fining-upward sequence depicted in figure 10, as well as the range of environments, is one commonly attributed to deltaic or alluvial-plain systems in which meandering streams exist. Since Wasatch strata are absent north of the Powder River Basin, considerable uncertainty exists as to the relationship of the basin's Eocene strata with the sea. The Powder River Basin may have been the site of either the upper reaches of a vast deltaic complex or of a partially closed interior basin, which narrowed at the north end before spilling north across an alluvial plain to the sea. Either situation could result in similar depositional environments.

The very fine grained to medium-grained sandstones that show one to four fining-upward repetitions are interpreted as meander-channel complexes. Meandering of the stream resulted in broad scour surfaces at the base of each unit. Current directions vary with each repeated sandstone unit from east to southwest, with the overall drainage pattern trending north-northwest (figs. 10, 11, and 13).

Levee and crevasse-splay deposits form adjacent to the channels (fig. 12). The characteristic lithologies of both environments are interbedded yellowish-orange sandstone and greenish-gray siltstone and mudstone. Allen (1965a, 1965b), Coleman (1969), Jacob (1973), and Weimer (1973), in various ancient and modern sediment and stratigraphic studies, have interpreted similar deposits displaying vertical alternation between coarse and fine sediments to be levee and crevasse-splay deposits. Weimer (1973) reported that crevasse-splay deposits exhibit scour surfaces and generally coarser grained sequences

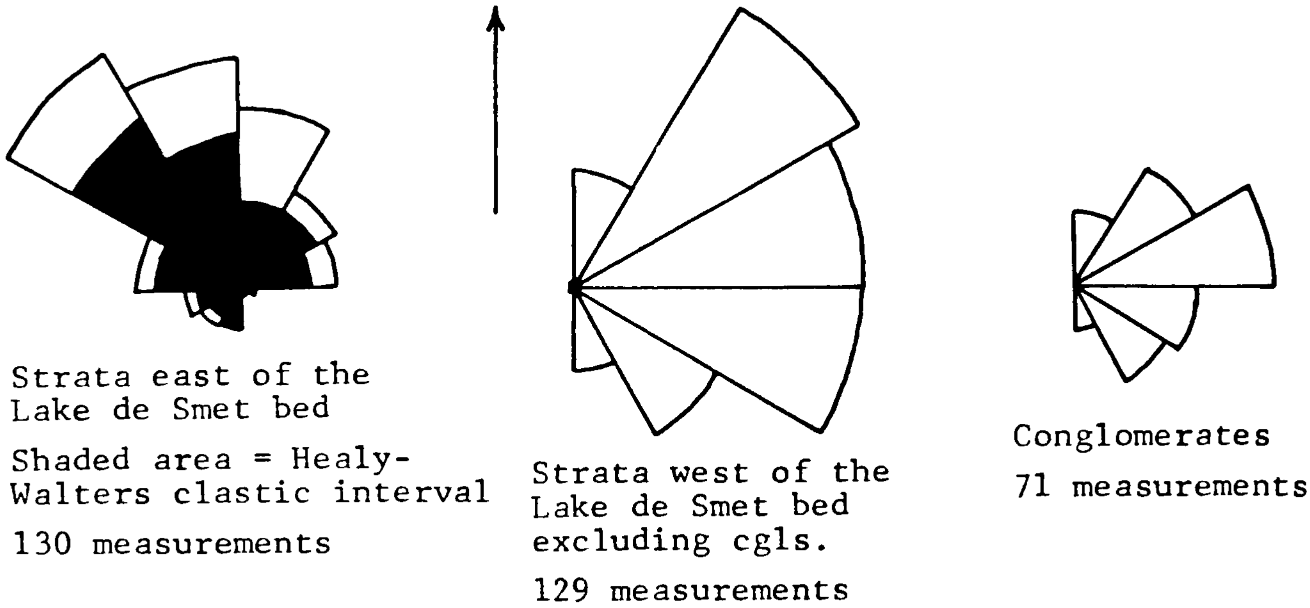

Figure 13.--Rose diagrams for transport directions in the study area.

close to the main channel, while their distal portions merge with levee deposits and are virtually indistinguishable from them. Primarily because of limited outcrop exposures, no sequences close to channel margins could be definitely identified as crevasse-splay channels. Occasional logs found at the base of channels may be indicative of crevasse-splay channel locations.

In comparing levee and crevasse-splay environments, crevasse splays are the sites of a more rapid rate of sediment accumulation. Growth of levees generally keeps pace with the rate of subsidence, whereas crevasse splays build subdelta complexes adjacent to the channels during peak flow periods. Modern studies of crevasse splays in the Mississippi River delta indicate rapid lateral and vertical growth of crevasse-splay deltas (Morgan, 1970). Hence, evidence of rapid accumulation of thick sediment sequences, such as the burial of tree trunks in the growth position, may well indicate sites of crevasse-splay deposits. Jacob (1973) described occurrences of buried tree trunks in interbedded coarse and fine sediments in the Tongue River Formation[1] of western North Dakota, but he attributed burial to rapid vertical growth of the levees. Climbing ripple stratification, another indicator of rapid sedimentation, appears to occur frequently in both environments. Its occurrence can be attributed to a peak flow period which affected both environments. Particularly when the suspension load is high, decrease in flow energy away from a channel produces rapid sedimentation, thus creating an excellent environment for the formation of climbing ripple stratification.

Flanking the levees and crevasse splays are the flood basins whose principal environments are swamps and lakes (fig. 12). Dark-gray clays, carbonaceous shales, and coals were deposited in poorly drained swamps in which the depositional interface was continuously under water. Fossiliferous mudstones and limestones indicate the presence of numerous freshwater lakes. The areal extent of many of these beds indicates that the flood basin between channels often covered hundreds of square miles.

The cyclic repetition of these deltaic-plain deposits indicates shifting of the channel systems into and out of the study area. When the stream channel was diverted to the east, swamps and lakes formed in the region previously abandoned by the channel. The thickness of the coals--in some instances more than 40 ft--suggests that the life of any particular environment in one area was not always a short one.

[1]Jacob noted that the North Dakota Geological Survey considers the Tongue River a formation within the Ft. Union Group, whereas the U.S. Geological Survey assigns member status to the Tongue River and formation status to the Ft. Union.

TECTONICS AND SEDIMENTATION

Coal deposits are very sensitive to sediment and tectonic influences. Weimer (1977) ex-

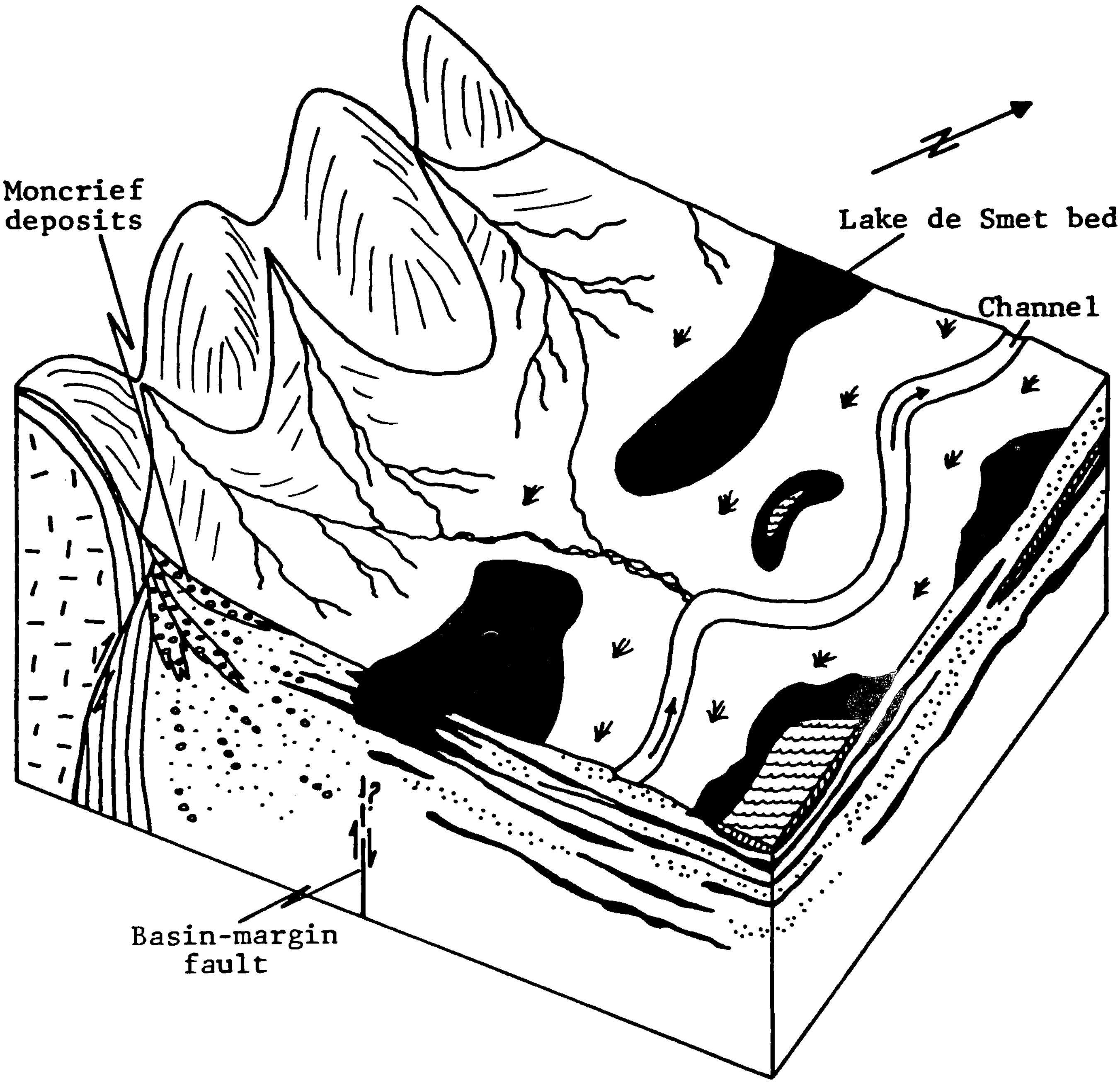

Figure 14.--Schematic block diagram showing the proposed relationships between faulting and sedimentation during early Eocene time.

cellently summarized several geologic factors that control the formation and thickness of coal deposits: (1) fresh, clear, water conditions, with little or no detrital influx; (2) the accumulation of land-derived organics; (3) a balance between the ground-water table and the depositional interface such that the swamp does not dry up, which would permit oxidation of the organics, and such that the water does not become so deep that a lake forms; (4) a favorable climate in which abundant vegetation is produced; and (5) a persistence of these conditions in time and space. The last factor implies that sedimentation must equal subsidence for the swamp to continue to flourish.

Given these constraints, one can then begin to understand some of the problems encountered in interpreting and recreating the depositional environments. The thickness of the Lake de Smet bed suggests an extremely long period of continuous peat deposition. Weimer (1977) suggested a compaction factor of 5 ft of peat to produce 1 ft of bituminous coal. If one assumes 100-200 ft of coal in the Lake de Smet bed, then 500-1,000 ft of peat were deposited. Weimer (1977) cited a study of the Klang-Langat delta of Malaysia by Coleman, Gagliano, and Smith in which the rate of peat accumulation was determined to be 0.33 ft of peat per century. Frazier and Osanki (1969) reported an accumulation of 0.57 ft of peat per century in the Mississippi delta. Assuming 0.5 ft of peat accumulation per century and assuming comparable accumulation rates, the life of the Lake de Smet coal swamp was 100,000 to 200,000 years!

The disposal of the coarse clastics shed from the uplift poses a problem, because no channel has been identified that would have diverted the clastics around or through the swamp forming the Lake de Smet bed. Drill data do indicate one hole--sec. 10, T. 51 N., R. 82 W.--in which no coal was reported (figs. 4 and 5); unfortunately, no lithologic or geophysical logs are available. A channel to the north and south around the swamp may be an alternate explanation.

Structural relationships suggest that the Lake de Smet bed is identifiable with the finer grained sequence immediately below the Moncrief Member of the Wasatch Formation. If one assumes a constant 1-5^{o} dip for the Moncrief and equivalent strata from the mouth of Clear Creek to Buffalo, the base of the Moncrief Member can be projected to the upper portion of the Lake de Smet bed. If this correlation is valid, one can infer that a combination of increased tectonic activity and increased coarse sediment influx combined to kill the Lake de Smet swamp.

A unique feature of the Lake de Smet bed is its generally linear orientation axial to the basin and its proximity to an uplift shedding coarse clastics. One possible explanation establishing its position and length may be the presence of a basin-margin fault at depth, which does not cut the surface and, thus, is not mappable (fig. 14). Foster, Goodwin and Fisher (1969), using seismic data, identified such a fault running the length of the Powder River Basin from Casper to north of Buffalo. They reported that the fault lies 4 to 20 mi out from the mountain front. Near Buffalo it possesses a throw of nearly 4,000 ft. However, its position relative to the Lake de Smet bed is not known. Such a feature, active during the Laramide orogeny, would have affected local depositional patterns.

SUMMARY

1. The Lake de Smet bed lies along the western margin of a poorly drained alluvial plain. To the west are small lenses of conglomeratic sandstone reflecting braided-stream channels emanating from alluvial fans. To the east, thick broad sheets of very fine grained to medium-grained sandstone representing meander channel deposits exist.

2. The alluvial-plain environment is characterized by channel, levee, crevasse-splay, paludal, and lacustrine deposits.

3. The braided-stream deposits are characterized by levee deposits, considerable silt and clay, and minor carbonaceous shale and coal units. Braided-stream deposits are not normally characterized by these fine-sediment sequences. However, an unstable tectonic environment coupled with shifting alluvial-fan depocenters serves to preserve significant silt, clay, and organic sequences.

4. The coals were formed in a back-levee or flood-basin swamp marginal to leveed channels.

5. The Lake de Smet bed divides into five major, mappable, economic coal beds to the east. From oldest to youngest, these coals include the Ucross, Murray, Cameron, Healy and Walters.

6. The thickness of the Lake de Smet bed and its linear orientation axial to the basin may mark the location of a basin-margin fault. A fault at depth is postulated to have been active during Eocene time and to have played a prominent role in the Lake de Smet bed's formation.

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RoMoCoal Field Trip — Photograph by James M. Soule, Colorado Geological Survey

Energy Fuels Corporation's Marion 8050 walking dragline with 55-yard bucket and 325-ft boom length working in pit no. 1. This dragline, whose working weight is 3,100 tons, is capable of moving 2,500 yards per hour, in excess of 12,000,000 yards per year. It is used for removing overburden from the coal.

Sand-Body Geometry and the Occurrence of Lignite in the Eocene of Texas[1]

W. R. KAISER[2], J. E. JOHNSTON[3], and W. H. BACH[4]

ABSTRACT

Lignite occurs in three Eocene stratigraphic units--the Wilcox Group, Yegua Formation, and Jackson Group--that represent three ancient depositional systems--fluvial, deltaic, and strandplain-lagoonal. Sand-body geometry and lignite occurrence in these systems are revealed by regional sand percent, net sand, maximum sand, and lignite isopleth maps made from 3,050 electric and induction logs.

Straight, dendritic, and bifurcating channel geometries are displayed in the Wilcox Group of east-central and east Texas. Lignite at exploitable depths is a component facies of fluvial depositional systems. Sites of accumulation were hardwood swamps located in interchannel basins established by bounding alluvial ridges. Projection updip to the outcrop of coincident subsurface areas of low sand (interchannel basins) and high lignite count intersects many large strippable deposits. The geometries of Wilcox sand dendroids and belts are comparable to those associated with Rocky Mountain Paleocene and Eocene coals.

Lobate sand-body geometry characterizes the Jackson Group of southeast Texas. Lignite is of deltaic origin and represents marsh accumulation in lower delta-plain environments. Commercial lignites are postulated blanket peats which spread across abandoned distributary channels. Projection updip to the outcrop of coincident subsurface areas of high sand (delta lobes) and high lignite count intersects several commercial deposits.

In south Texas, Jackson-Yegua lignite is associated with strike-oriented linear sand bodies and occurs topping strandplain-barrier bar beach sequences. Major occurrences are elongate and landward of the axes of Jackson-Yegua strandplain-barrier bar systems. Projection of this subsurface trend along depositional strike to the outcrop intersects large strippable deposits. Lobate and strike-oriented linear sand bodies of the Jackson Group are comparable to those associated with Rocky Mountain Upper Cretaceous coals.

INTRODUCTION

Objective

Since late 1974 the objective of our geologic work on Texas lignite has been to develop, using available electric and induction logs, an exploration model for lignite under less than 2,000 ft of cover. The relationship between sand-body geometry, two-dimensional map geometry or distribution, and lignite occurrence was expected to be the model's essential element and was meant to serve as a guide for exploratory drilling. Identification of areas of relatively highest potential for reserves was the ultimate goal. Exploratory effort could then be concentrated in those areas.

Approach

Sand-body geometry and lignite occurrence are revealed by regional sand percent, net sand, maximum sand, and lignite isopleth maps made from 3,050 electric induction logs. Sand and lignite are defined in terms of their log responses. Sands containing brackish or saline pore waters are easily recognized by their negative spontaneous potential (SP). Unconsolidated sands charged

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with freshwater are recognized by their high formation resistivity, which is directly related to the resistivity of the interstitial water and to grain size (Alger, 1966). Close agreement was found among total or net sand values determined from either the SP or resistivity curve.

In the absence of porosity logs, such as density or neutron logs, lignite is operationally defined to be those beds having a sharp resistivity spike and baseline SP (Kaiser, 1974, p. 32). Lignite is highly resistive because it is a solid hydrocarbon and lacks appreciable free or gravitational water (Davis, 1977). Baseline SP is a function of the low water content (low chemical activity), high resistivity, bed thickness, and shalyness or dispersed mud content. The operational definition becomes increasingly more difficult to apply as formation water becomes fresher and the SP less and less well defined. Lignites cannot be easily distinguished from thin, freshwater sands. Thus, picking lignites close to the outcrop depends largely on the worker's experience and intuition.

Lignite beds are best picked on electric logs. Opposite a lignite seam the long lateral curve (18-ft 8-inch spacing) has a resistivity kick of extreme peakedness. This curve will identify lignites as thin as 1 ft. The long normal curve (64-inch spacing) displays a reversal back toward the baseline in beds thinner than 64 in. (fig. 1, well Q-30). A sequence of thin, closely spaced lignite beds complicates the interpretation because of bed-boundary and interference effects. The induction log is not well suited to the identification of lignite beds less than 4 ft thick. Thicker beds can be picked reasonably well on curve peakedness. Figure 1 (well Q-48) illustrates the response to lignites on an induction log.

STRATIGRAPHY

Cyclic deposition is the fundamental style of sedimentation in the Texas Eocene (Fisher, 1964). The motif is an alternation of regressive fluvial-deltaic units and transgressive marine units (fig. 2). Thick lignite-bearing, fluvial-deltaic units--the Wilcox Group is the best example--are separated by thin, richly fossiliferous glauconitic sands, muds, and marls of marine origin--the Weches Formation is an excellent example.

Commercial lignite occurs in three Eocene stratigraphic units, the Wilcox Group, Jackson Group, and Yegua Formation. The stratigraphic section shown in figure 2 is most representative of the Eocene between the Trinity and Colorado Rivers (fig. 3). North and south of these rivers, respectively, the Wilcox is undivided because the Simsboro Sand is lost as a mappable unit and thus the Wilcox strata are no longer divisible. South of the Colorado River, lignite occurs in the lower part of the Jackson and upper part of the Yegua in strandplain-lagoonal facies, genetically and lithically dissimilar from those shown in figure 2 (Fisher and others, 1970).

Lignite is a component facies of ancient fluvial, deltaic, and strandplain-lagoonal depositional systems (Fisher, 1969; Fisher and McGowen, 1967; Fisher and others, 1970; Kaiser, 1974; Kaiser, 1976; Kaiser, in press). North of the Colorado River at exploitable depths, either by surface mining or in situ gasification, Wilcox and Yegua lignite are fluvial in origin, whereas Jackson lignite is of deltaic origin. Strandplain-lagoonal lignite occurs south of the Colorado River in all stratigraphic units, but primarily in the lower part of the Jackson Group. Presented in this paper are examples of four types of lignite occurrence: (1) Calvert Bluff Formation (Wilcox) of east-central Texas, (2) undivided Wilcox Group of east Texas, (3) Jackson Group of southeast Texas, and (4) Jackson-Yegua of south Texas (fig. 3). Represented among these examples is the full range of ancient lignite depositional environments in Texas.

CALVERT BLUFF FORMATION

Stratigraphy

In east-central Texas, between the Colorado and Trinity Rivers, the Wilcox Group is 1,200 to 3,500 ft thick and has been divided by Barnes (1970, 1974) into three formations, the Calvert Bluff, Simsboro, and Hooper (fig. 4). The Calvert Bluff, 500 to 2,000 ft of sand and mud, contains the only significant lignite; it conformably overlies the fluvial Simsboro Sand and is recognized on electric logs by its finer grain size, as reflected in reduced resistivity on normal curves, and by the first occurrence of lignite above the Simsboro (fig. 4). Resting unconformably on the Calvert Bluff is the Carrizo Sand, a massive fluvial sand displaying high electrical resistivity similar to that of the Simsboro. Mapping extended into the subsurface until the Simsboro fluvial facies became unrecognizable. At this point the Calvert Bluff Formation could no longer be differentiated.

Sand-Body Geometry

In the Calvert Bluff Formation, dendroids and belts (Pettijohn and others, 1972, p. 440-442) of dip-oriented sand merge downdip with thick deltoid depocenters of sand flaring basinward (compare 400- and 600- vs. 800- and 1000-ft isoliths, fig. 5). A straight or slightly dendritic channel geometry updip merges downdip near the limit of mapping with a bifurcating channel geometry (fig. 6). Four major areas of sand input are indicated by the

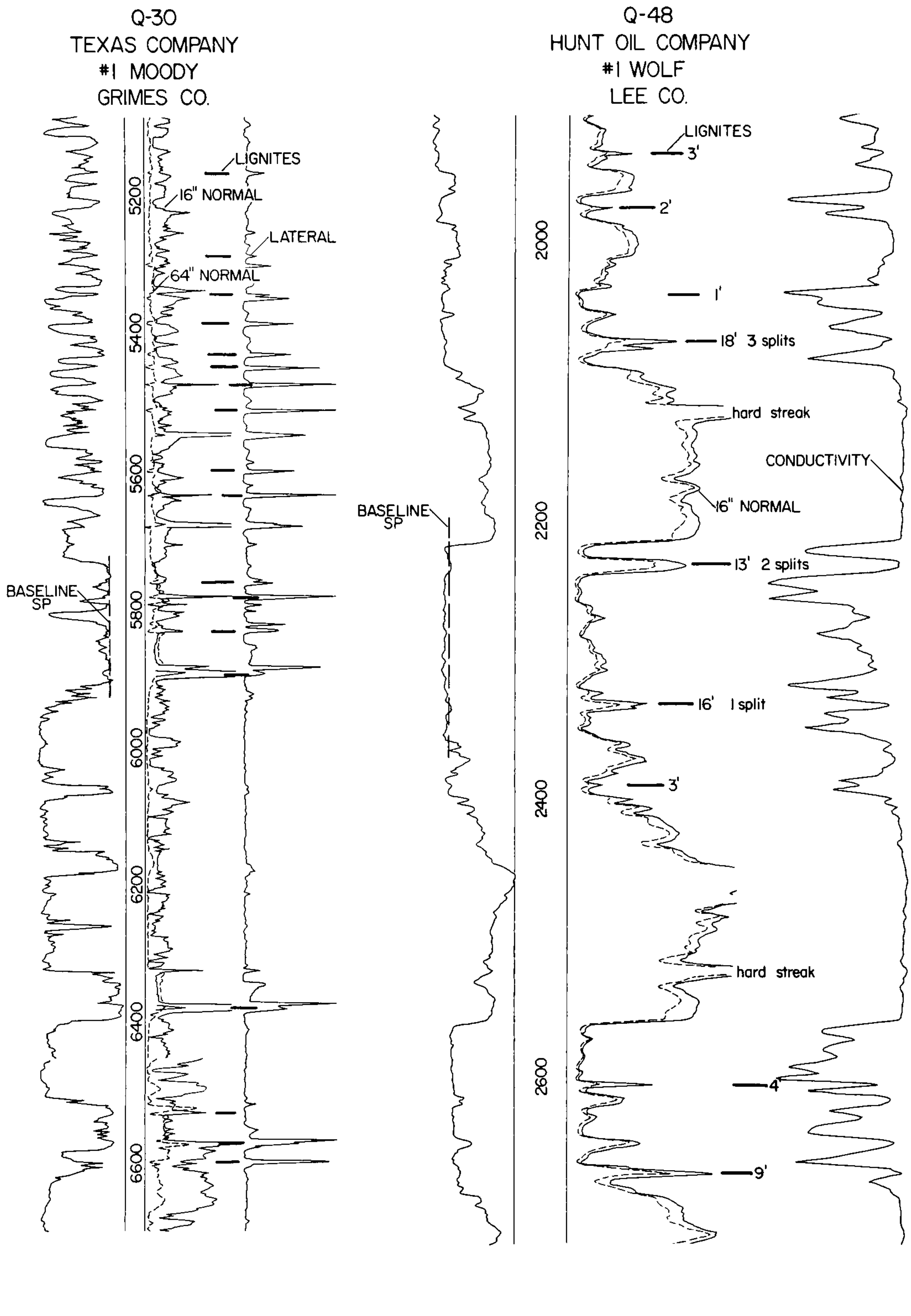

Figure 1.--Lignite response on an electric log (Q-30) and on an induction log (Q-48). Lignites on Q-48 identified from a companion neutron log. See figure 6 for location of logs.

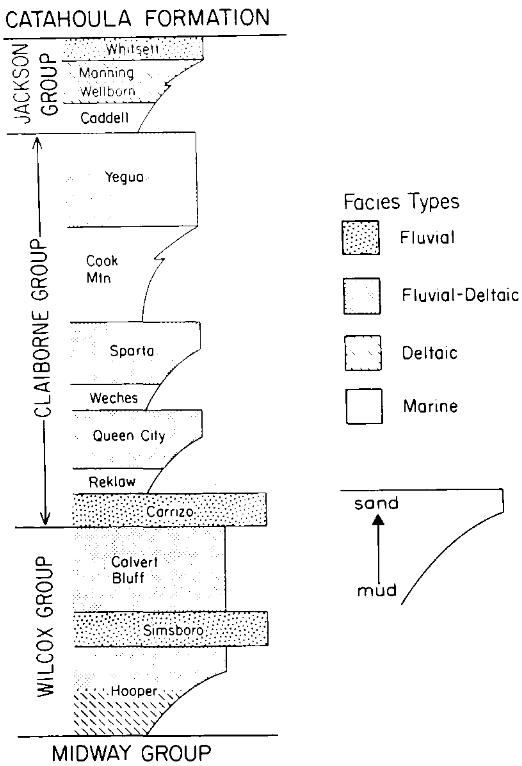

Figure 2.--Cyclic deposition in the Texas Eocene. Terminology from Barnes, 1974.

400- and 600-ft sand isoliths that extend to the outcrop (fig. 5). Major river systems flowed east-southeastward, except to the north in Anderson County where they flowed southward (figs. 5 and 6).

Fisher and McGowen (1967), in establishing the regional framework of Wilcox deposition, defined updip fluvial channel facies merging downdip with high-constructive or fluvially dominated deltas. Clearly, the Calvert Bluff is a complex channel network having sand bodies characteristic of fluvial and delta systems. The straight or slightly dendritic channel geometry of the Calvert Bluff, on the basis of analogy with modern deltas, was located at the transition between the dendritic fluvial channel facies of the high alluvial plain and the bifurcating distributary channel facies of the lower delta plain. At this physiographic position on modern deltas, active and abandoned alluvial belts of major river courses diverge little and are subparallel (Smith, 1966). The ancient transition zone between the lower alluvial plain and the upper delta plain is exposed at the outcrop of the Calvert Bluff Formation and extends into the shallow subsurface. Major sand bodies are composed of multistory and multilateral, fine- to coarse-grained meanderbelt deposits as much as 200 ft thick. Downdip, in the deep subsurface, the bifurcating distributary channel network of the lower delta plain (fig. 6) is coincident with deltoid depocenters of figure 5.

Lignite Occurrence

Stratigraphically, lignite occurs regularly in a zone in the lower part of the Calvert Bluff Formation just above the Simsboro Sand throughout the area and irregularly in the upper part of the Calvert Bluff. Lignite deposits in the lower part of the Calvert Bluff are the most commercially significant. Seams are typically 5 to 10 ft thick and range from 2 to 25 ft thick; some have been traced by shallow drilling for as much as 14 mi. Areally, lignite occurs in elongate concentrations roughly parallel to paleoslope or perpendicular to the outcrop (fig. 7). Areas of low lignite occurrence (<2 lignites) correlate well with high sand-percent areas (>55 percent), especially in Milam and Freestone Counties. In central Milam County, very high sand-percent values and low lignite counts coincide almost exactly (figs. 6 and 7). The number of lignite beds decreases into this and other areas of high sand content. Consequently, lignite is most abundant in interchannel areas defined by relatively low sand percent. For example, low sand-percent interchannel areas occur just downdip from Alcoa and Fairfield, sites of large deposits well in excess of 200 million short tons.

Modern Analogue

Modern analogues for Calvert Bluff lignite depositional environments are found on the Mississippi delta system, a Holocene high-constructive or fluvially dominated system (Fisher, 1969). The relationship of swamps and marshes to channels on the Mississippi delta is similar to that exhibited by the Calvert Bluff lignite and channel facies (figs. 6 and 7 vs. fig. 8). In interchannel basins, developed between alluvial ridges formed by modern and ancient Mississippi river courses, freshwater swamps and marshes are the sites of greatest organic accumulation. Analogues of Calvert Bluff interchannel basins are the Des Allemands-Barataria and Atchafalaya basins (fig. 8) (Kaiser, 1976; Lentz, 1975). Towards the Gulf of Mexico, these interchannel basins diminish in size and increase in number as trunk streams bifurcate into distributary networks which enclose smaller and smaller interdistributary basins (Frazier and others, in press).

Peat is best developed far from the contaminating influence of sediment from active channels and inland from the destructive effects of the Gulf, at the junction of the delta and

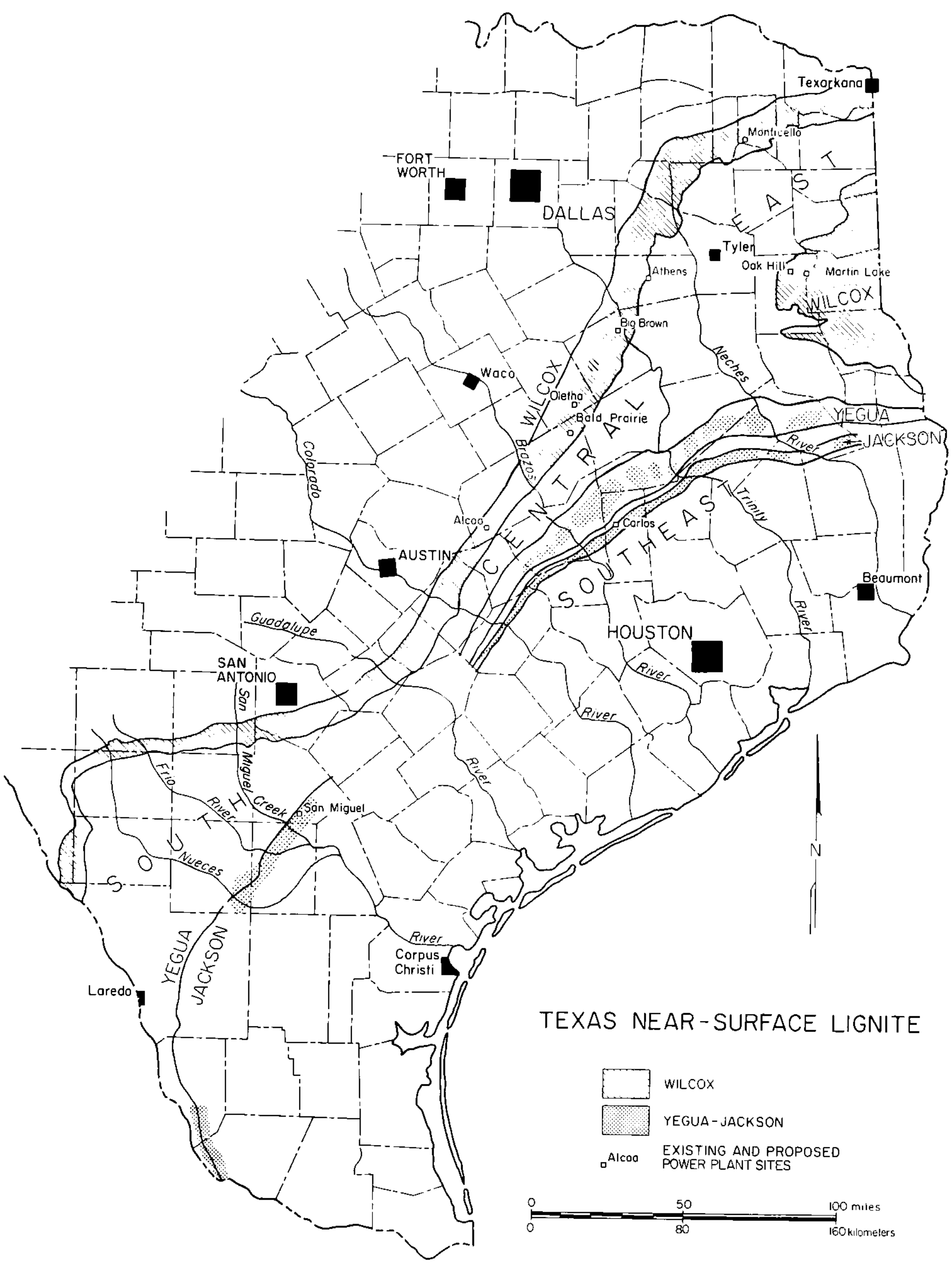

Figure 3.--Distribution of near-surface lignite in Texas.

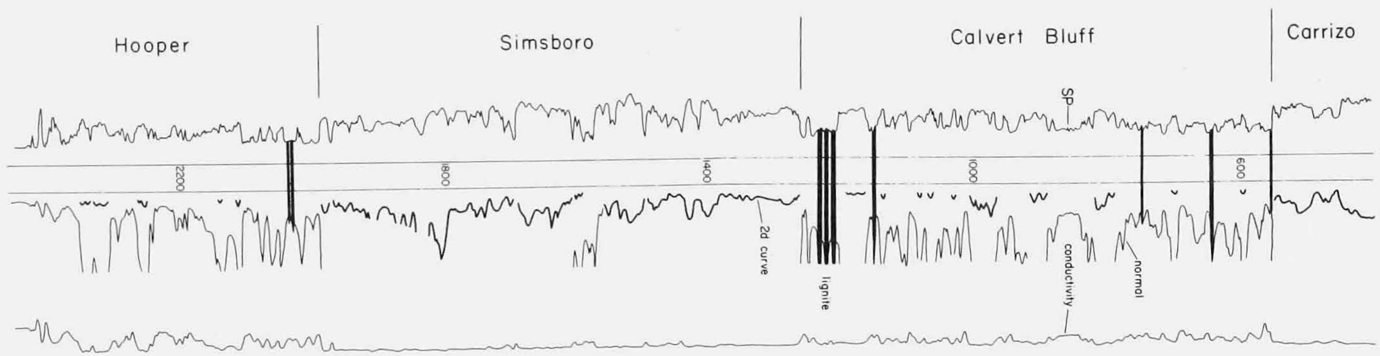

Figure 4.--Wilcox stratigraphy of east-central Texas and the occurrence of lignite. See figure 6 for location of electric log.

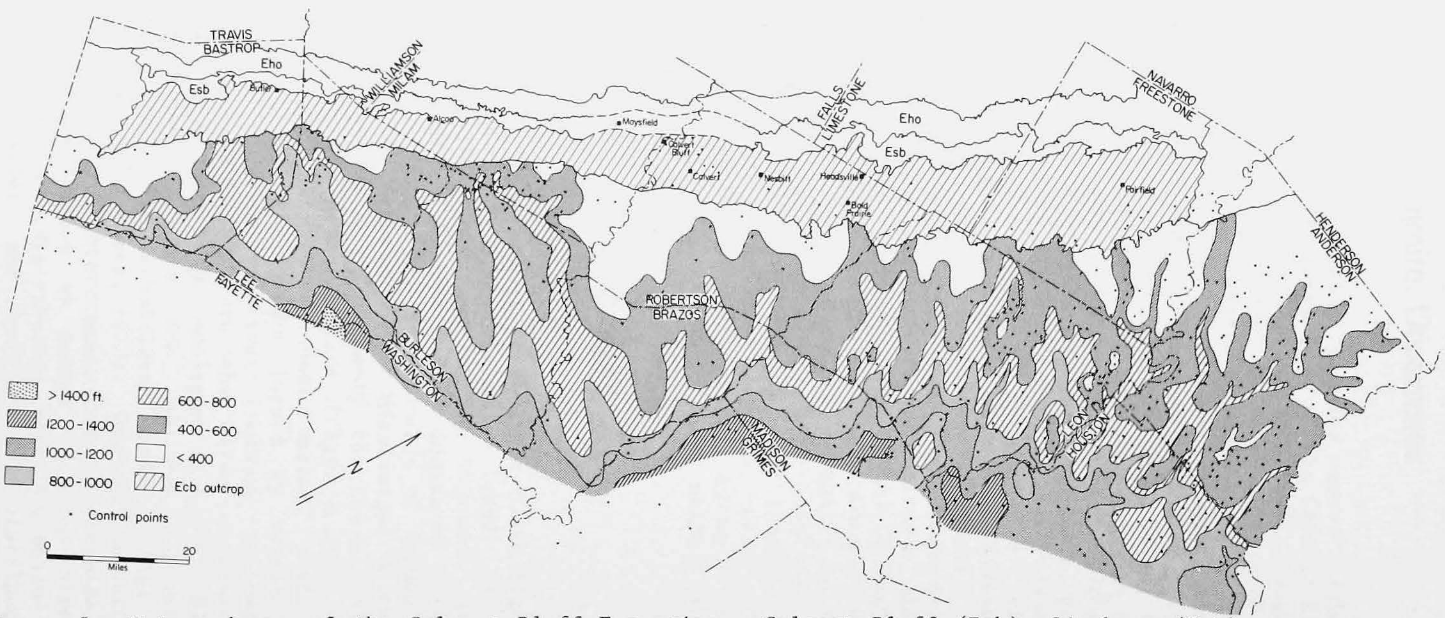

Figure 5.--Net-sand map of the Calvert Bluff Formation. Calvert Bluff (Ecb), Simsboro (Esb), and Hooper (Eho) outcrop from Barnes (1970, 1974).

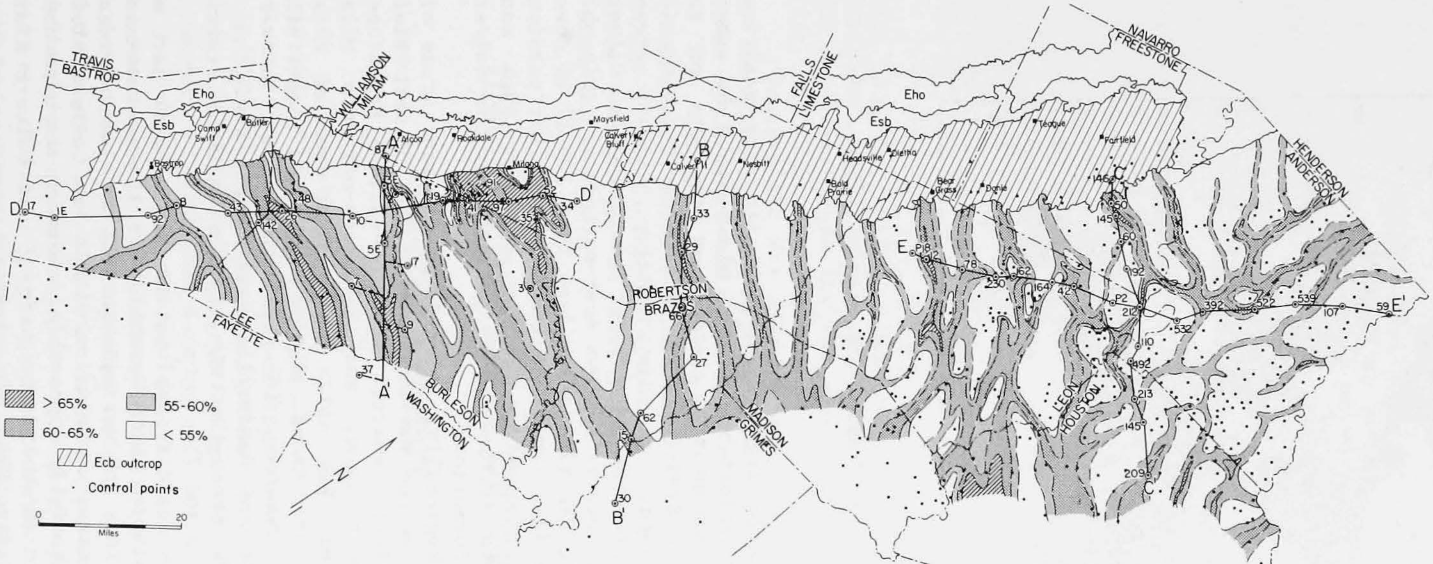

Figure 6. Sand-percent map of the Calvert Bluff Formation.

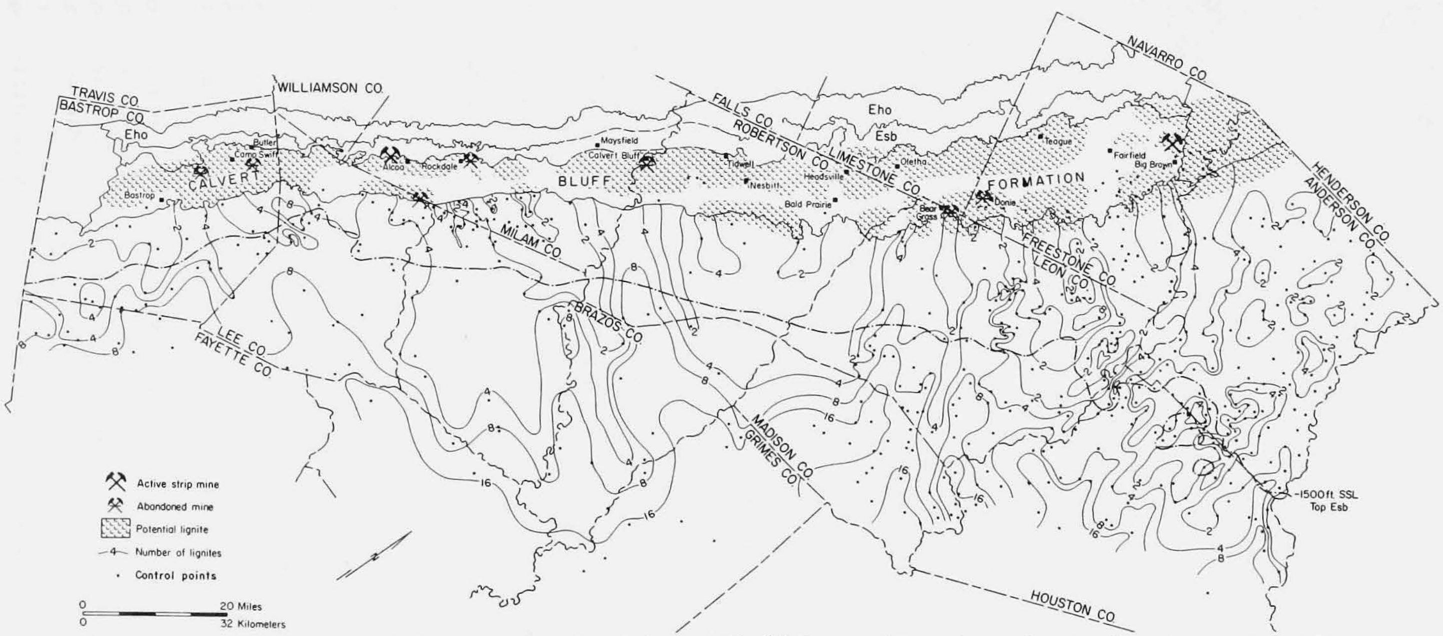

Figure 7.--Occurrence of lignite in the Calvert Bluff Formation. Deep-basin lignite, identified from electric logs, shown by isopleths (number of lignite beds).

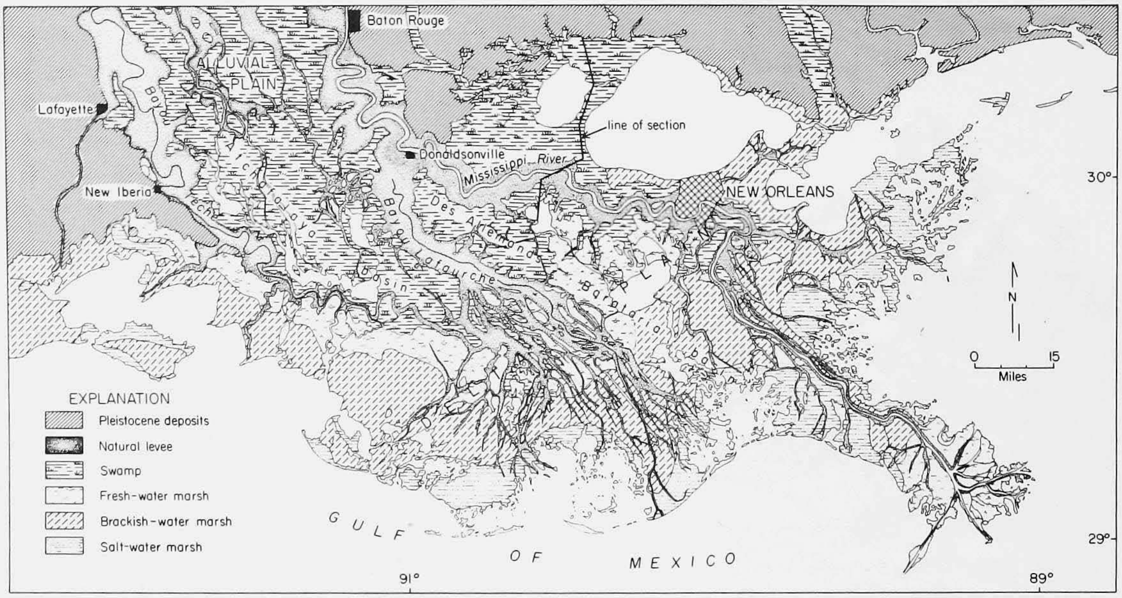

Figure 8.--Mississippi-delta physiography. From Frazier and Osanik, 1969.

alluvial plain. Peat beds of the upper delta plain and inland interchannel areas are thicker and more widespread than coastal-marsh peats (Frazier and Osanik, 1969; Gagliano and van Beek, 1970; Frazier and others, in press). The thickest peats are encountered in inland swamps flanking distal levees composed of cypress-gum vegetation (Frazier and Osanki, 1969). Palynology of Calvert Bluff lignites supports an interpretation of dominantly ancient hardwood swamp environments; that is, inland swamp areas and only occasional marsh environments during accumulation (Elsik, in press).

Exploration Model

On the Mississippi delta system, the Calvert Bluff's modern analogue, the thickest and most extensive peats occur inland at the junction of the alluvial and delta plains. All the Calvert Bluff outcrop and shallow subsurface is inferred to be of similar environmental setting. Only in extreme southern Bastrop County, where Calvert Bluff equivalents were deposited off the ancient delta system, is the Wilcox nonprospective (fig. 7).

Exploration for Calvert Bluff lignite will be most productive in low sand areas (low sand percent, low net sand, thin maximum sands) coincident with areas of high lignite count. Good positive correlation exists in the subsurface of areas having less than 55 percent sand and greater than four lignites (figs. 6 and 7). Deep-basin lignite is, using in situ gasification, exploitable to the minus 1,500 ft subsea level structural contour on the top of the Simsboro Sand (fig. 7). When projected updip (up paleoslope) to the outcrop, these areas, especially of the lower part of the Calvert Bluff, intersect known near-surface or strippable lignite deposits under less than 200 ft of cover (table 1). Central Milam County is not particularly prospective because of very high sand percents (values to 73 percent) in the Calvert Bluff Formation.

Regionally, three large low-sand areas are shown on the net-sand map of the Calvert Bluff Formation: western Anderson-eastern Freestone, northwest Leon, and Robertson-northern Milam Counties (fig. 5). Updip from each of these areas are known lignite deposits; especially large reserves in Robertson County between Nesbitt and Headsville will supply fuel for a 1500-MW steam-electric station at Bald Prairie (figs. 3 and 7).

A guide to exploration in the upper part of the Calvert Bluff Formation is the maximum-sand map. This map was made instead of a sand-percent map because correlation within the Calvert Bluff is essentially impossible. Between the uppermost lignite of the lower part of the Calvert Bluff and Carrizo Sand, the single thickest or maximum-sand unit was picked and mapped (isoplethed) irrespective of stratigraphic position. The map reveals a dip-oriented channel system with a trend very similar to that of the sand-percent map of the total formation. Major channel belts, as shown by the distribution of sands greater

Table 1.--Exploration for Calvert Bluff lignite deposits

Coincident subsurface areas, by county (<55 percent sand and >4 lignites)	updip projection	Intersected outcrop areas (near-surface deposits)
Western Anderson-eastern Freestone		Trinity River alluvial plain, Big Brown
South-central Freestone-----------		Donie northeast, Teague
Northwest Leon--------------------		Bear Grass
Southwest Robertson---------------		Calvert Bluff, Tidwell
Northwest Milam-------------------		Maysfield-Calvert Bluff
Southwest Milam-------------------		Alcoa
Lee-northern Bastrop--------------		Butler northeast
Northern Bastrop------------------		Bastrop-Camp Swift

than 75 ft thick, closely approximate the positions occupied by the highest sand-percent and net-sand values for the formation as a whole (fig. 9).

Exploration for lignite in the upper part of the Calvert Bluff will be most productive in those areas where the maximum sands are less than 50 ft thick. Promising areas appear to be McDade, Blue, Milano, Owensville, Turlington, and Cayuga (fig. 9). Upper Calvert Bluff lignite was mined underground in the past at Hicks, Bear Grass, and Donie.

UNDIVIDED WILCOX GROUP

Sand-Body Geometry

In east Texas, north of the Trinity River, the Wilcox Group is composed of 400 to 1,400 ft of undivided sand, mud, and lignite with sand-body geometries and vertical sequences characteristic of fluvial systems (fig. 10). Two prominent north-south-oriented channel-sand belts, a western and an eastern belt, merge southward and lose their separate identities in Anderson and Cherokee Counties (figs. 11 and 12). Between the two belts is an interchannel area defined by considerably lower net-sand and sand-percent values. An excellent dendritic or tributary channel geometry is developed and is characteristic of the high alluvial plain. Fisher and McGowen (1967) assigned the name Mt. Pleasant fluvial system to this dendritic system. Additional mapping by the writers confirms Fisher and McGowen's interpretation and adds sufficient detail to better define the Mt. Pleasant System.

Modern Analogue

The high alluvial plain of the Mississippi River upstream from Baton Rouge (fig. 8) is not a modern analogue for east Texas Wilcox depositional environments. Though swamps are present, peat is not accumulating between the dendritic stream networks (Fisk, 1944). Possible modern analogues may occur in tropical and temperate regions. In Borneo extensive peats are accumulating today between dendritic fluvial networks (Anderson, 1964). In view of the Wilcox subtropical, humid paleoclimate (Berry, 1916, 1930), we postulate that peat swamps were able to establish themselves high on the ancient alluvial plain. In east Texas peat-containing marshes, 1 to 4 mi wide, flank the upland Trinity River; smaller marshes flank other rivers (Fisher, 1965, p. 5). Individual peat bogs cover 10 acres or less and are about 10 ft thick (Plummer, 1941, 1945). Little is known about the extent of peat beyond present stream courses. The writers prefer the tropical model, whereas Fisher and McGowen (1967) proposed the temperate model.

Lignite Occurrence

Lignite commonly occurs in the upper two-thirds of the Wilcox Group (fig. 10); it accumulated in hardwood swamps (Nichols and Traverse, 1971; Elsik, in press) established between alluvial ridges. Commercial deposits range widely in size--from 25 to 400 million tons in seams 2 to 13 ft thick. Lignite is abundant in the sand-poor interchannel facies between major channel belts. High lignite counts were recorded between western and eastern channel belts in

Upshur and Smith Counties and between tributaries feeding western belts in Wood, Van Zandt, and Henderson Counties (figs. 12 and 13). Sizable deposits occur on the northwest flank of the Sabine Uplift in a large interchannel area east of the eastern channel belt. Southward in Anderson and Cherokee Counties, lignite occurrences show little positive correlation with sand facies because of the merging of major channel-sand belts (figs. 11, 12, and 13).

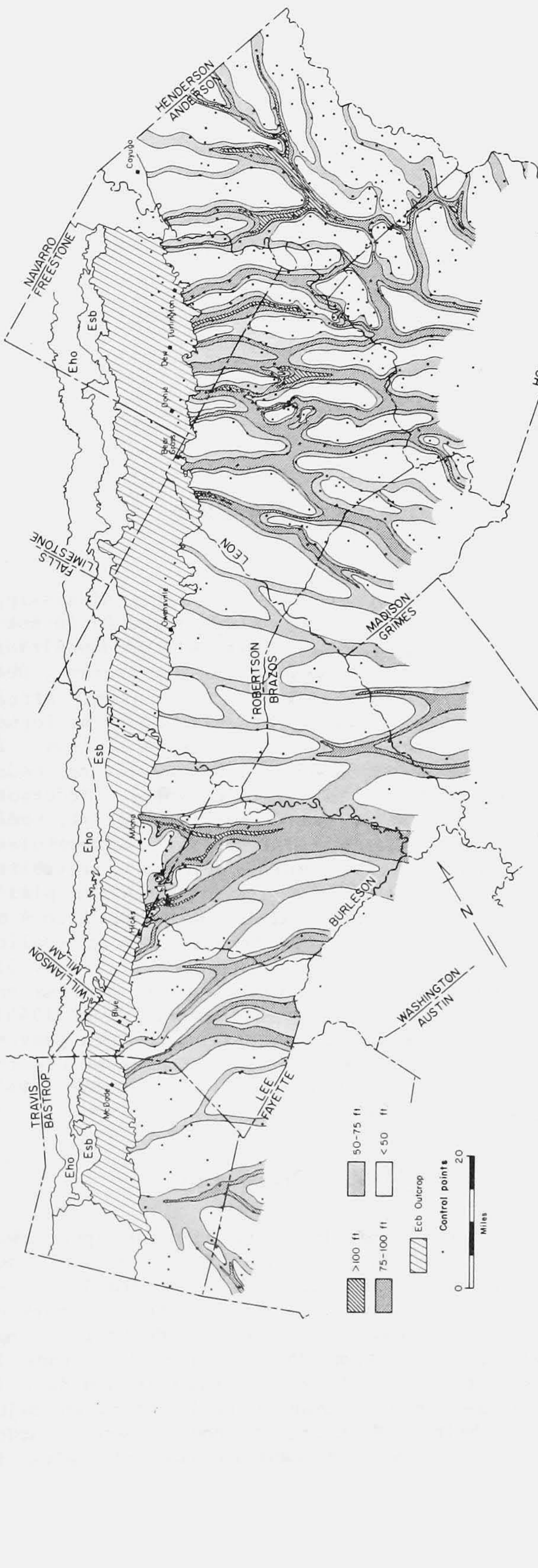

Figure 9.--Maximum-sand map of the upper part of the Calvert Bluff Formation.

Exploration Model

A positive correlation exists between low-sand or interchannel areas and the occurrence of lignite. The correlation of areas having less than 50-percent sand and high lignite count is good (figs. 12 and 13). For example, there is good alinement of low sand-percent areas, occurrence of deep lignite, and old mining districts such as Malakoff, Canton, Edgewood, Alba, and Como. Deposits at Athens, Martin Springs, Winfield, Darco, and Beckville, sites of current or future mines, are similarly located (fig. 13).

Deep-basin lignite is prospective to the zero structural contour on the top of the Wilcox and deeper for lignite in the upper part of the Wilcox (fig. 13). Gentle dip (0.2^{o}) on the northwest flank of the Sabine Uplift and a structural arch along an axis from Martin Lake to Monticello means that strippable lignite is present well downdip beyond the Wilcox outcrop.

JACKSON GROUP

Stratigraphy

In southeast Texas, between the Colorado and Neches Rivers, the Jackson Group includes about 1,000 ft (ranges from 600 to 1,200 ft) of mud, sand, and lignite extending from the top of the Yegua Formation to a correlative point at or near the base of the Catahoula Formation updip and the Vicksburg Formation downdip (fig. 14). The Jackson Group has been divided into four formations; from the base upward they are the Caddell, Wellborn, Manning, and Whitsett (Renick, 1936). Lignite occurs in the upper part of the Wellborn and Manning Formations at the outcrop (Russell, 1955, 1960) and in subsurface equivalents. Fisher and others (1970) recognized the Manning to be the most important lignitiferous Jackson unit. To focus more narrowly on lignite, the interval from the top of the Yegua to the base of the Whitsett Formation was studied for this paper.

Sand-Body Geometry

The sand-percent map of the Jackson Group,

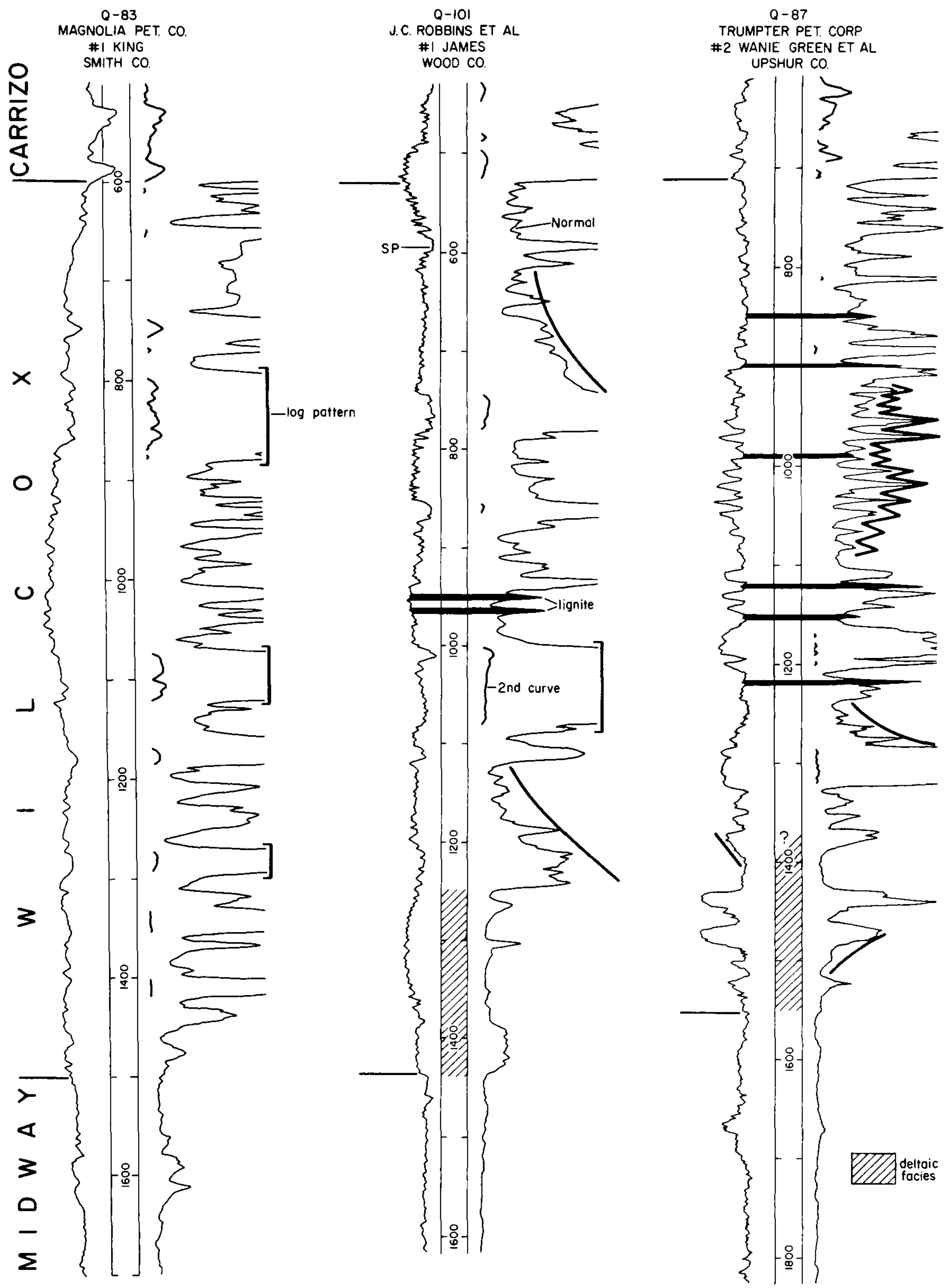

Figure 10.--Wilcox stratigraphy of east Texas and the occurrence of lignite. See figure 12 for location of electric logs.

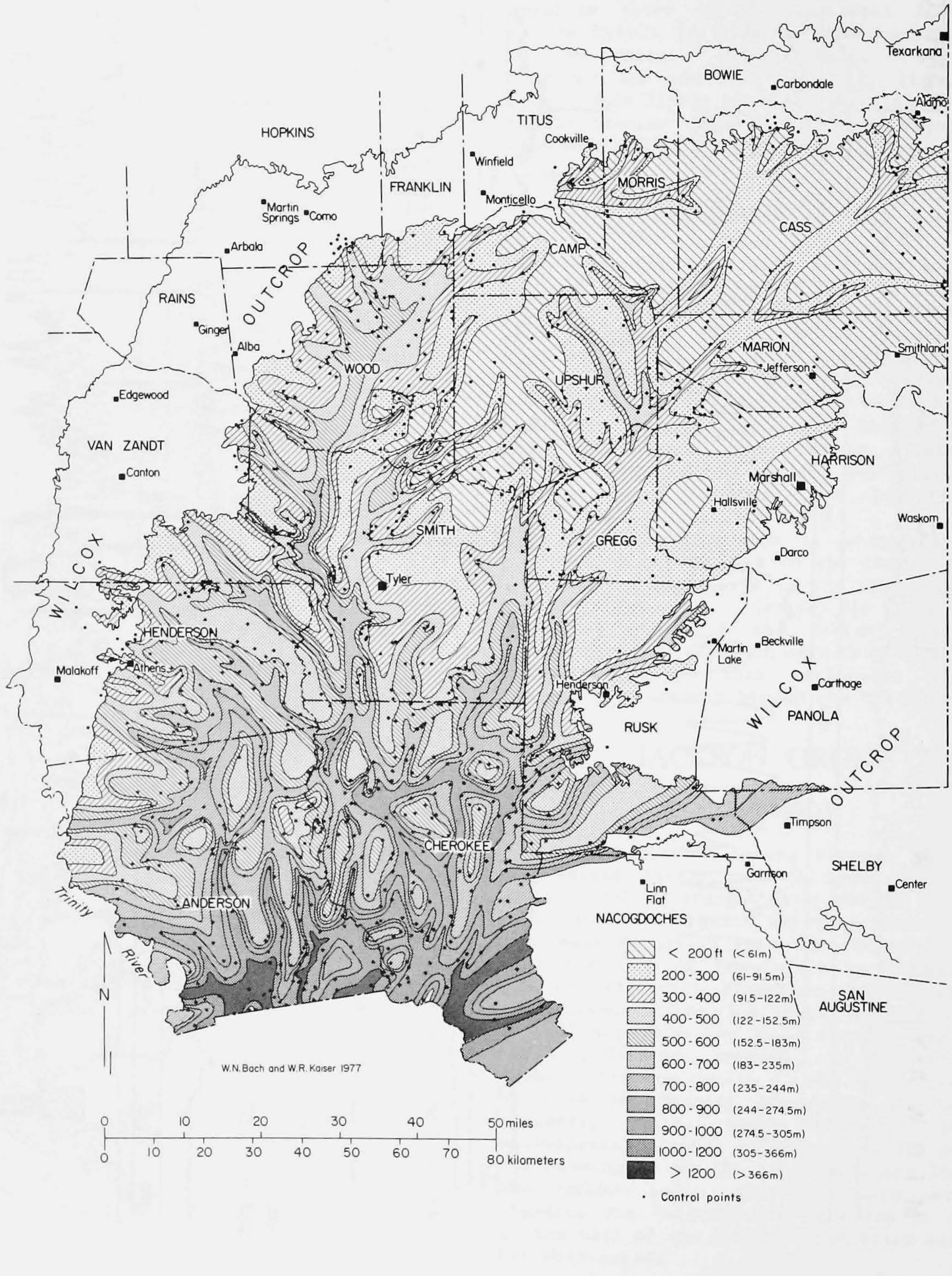

Figure 11.--Net-sand map of the undivided Wilcox Group. Wilcox outcrop from Barnes (1965, 1966, 1967).

Figure 12.--Sand-percent map of the undivided Wilcox Group.

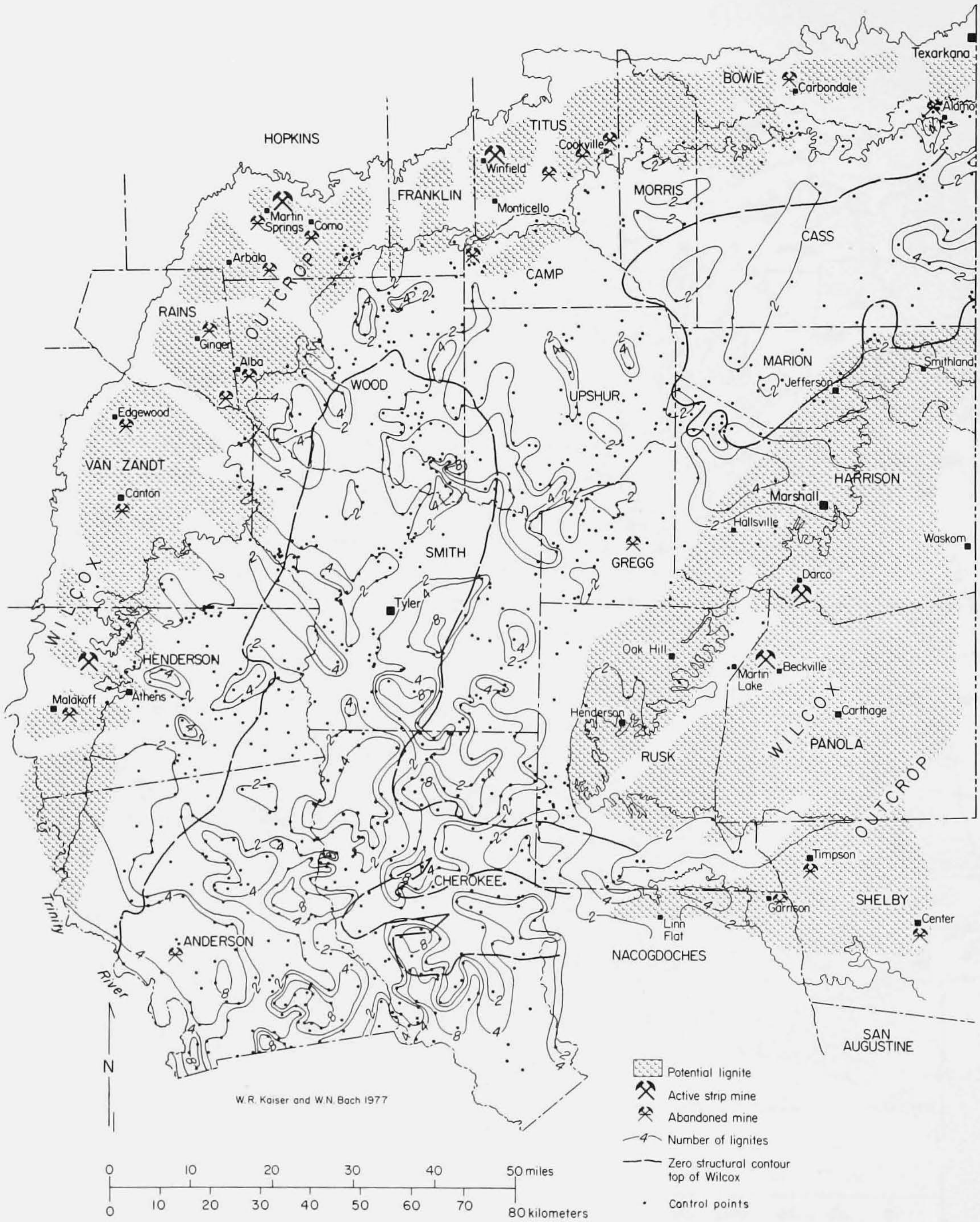

Figure 13.--Occurrence of lignite in the undivided Wilcox Group.

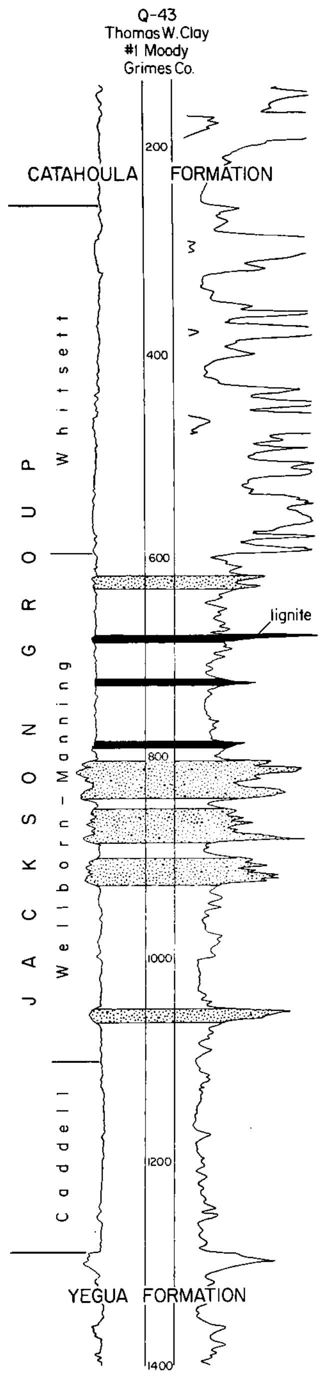

Figure 14.--Jackson stratigraphy of southeast Texas and the occurrence of lignite. See figure 15 for location of electric log.

exclusive of the Whitsett Formation, reveals a lobate sand-body geometry that becomes digitate downdip to the south and southeast. Within individual lobes a bifurcating or distributive geometry is displayed or suggested (fig. 15, eastern Washington County). Sand percent decreases downdip into the subsurface and overall is much lower than anything observed in the Wilcox Group at comparable depths. The maximum-sand map also displays an overall lobate geometry, but a definite linear, strike-oriented element that reflects the geometry of individual sands is now evident (fig. 16). Lithofacies mapping terminates downdip at the limit of sand occurrence.

An ancient Jackson delta system is clearly indicated; it was named the Fayette delta system and compared to the Holocene Mississippi delta system by Fisher and others (1970). This study confirms their interpretation and adds detail allowing identification of specific associated facies such as barrier islands and lagoons. Nine fluvially dominated delta lobes can be recognized (fig. 15). These lobes were supplied sediment by a fluvial system preserved in the Whitsett Formation that marks the culmination of the Jackson progradational or regressive cycle (figs. 2 and 14) (Fisher and others, 1970).

Maximum sands greater than 40 ft thick are believed to mark successively more seaward positions of prograding delta lobes (fig. 15). Individual sands are probably individual delta-front or delta-destructional sands (strike-oriented) that are more texturally mature and hence are prominently defined on electric logs. Less mature distributary channel-fill sands (dip-oriented) are less well defined on logs. Isolated sand pods downdip from the delta front are inferred to be relict islands formed during delta destruction (fig. 16). A possible modern analogue is the Chandeleur Islands of the Mississippi delta system, forming by destruction of the St. Bernard delta.

Bay and lagoon facies flank and front Fayette delta lobes. Between individual lobes are deep interdeltaic embayments such as in Grimes and Walker Counties (fig. 15). Lagoons, defined by low sand-percent or thin maximum-sand areas behind and landward of linear, strike-oriented sand bodies of probable barrier-island origin, are particularly well developed along the delta front in Austin, Montgomery, Walker, San Jacinto, and Polk Counties (figs. 15 and 16). A possible bayhead delta and associated barrier island were mapped in northeastern Montgomery County (fig. 15). The Guadalupe delta behind Matagorda Island on the Texas Gulf coast is a possible modern analogue.

Lignite Occurrence

Jackson lignites are numerous at the outcrop; however, most are commercially insignificant (less than 3 ft thick). At Somerville 18

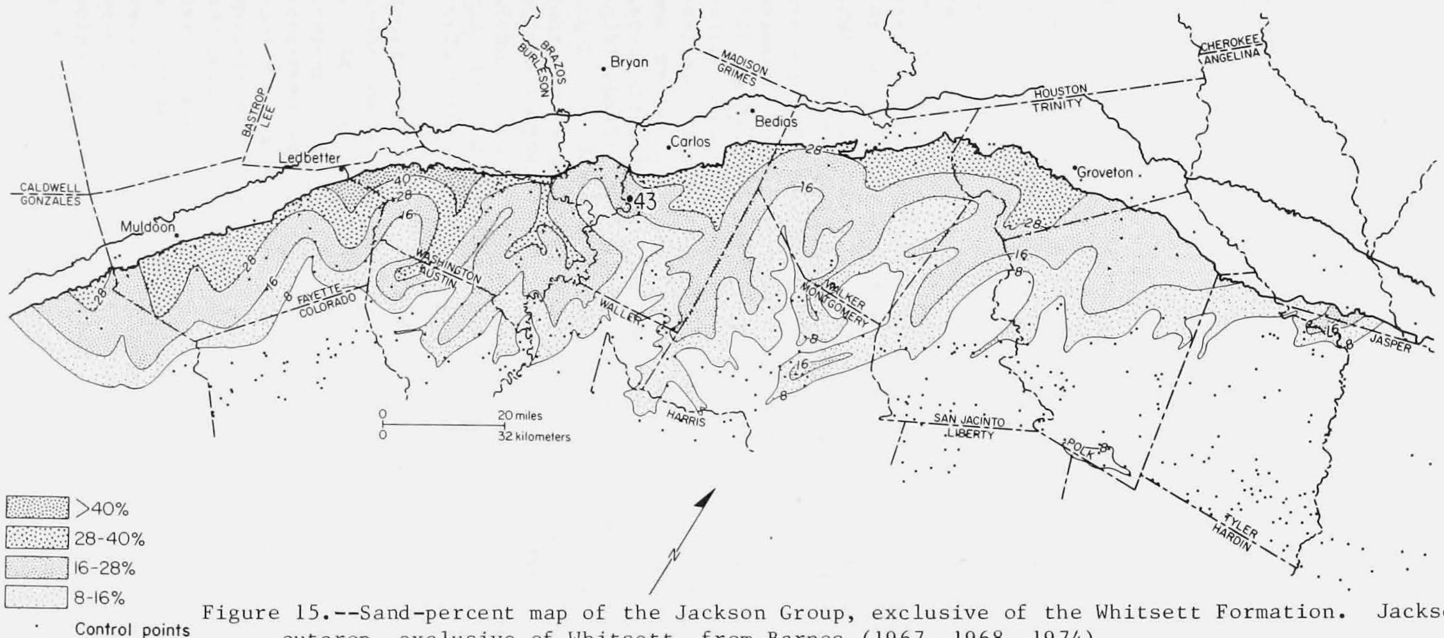

Figure 15.--Sand-percent map of the Jackson Group, exclusive of the Whitsett Formation. Jackson outcrop, exclusive of Whitsett, from Barnes (1967, 1968, 1974).

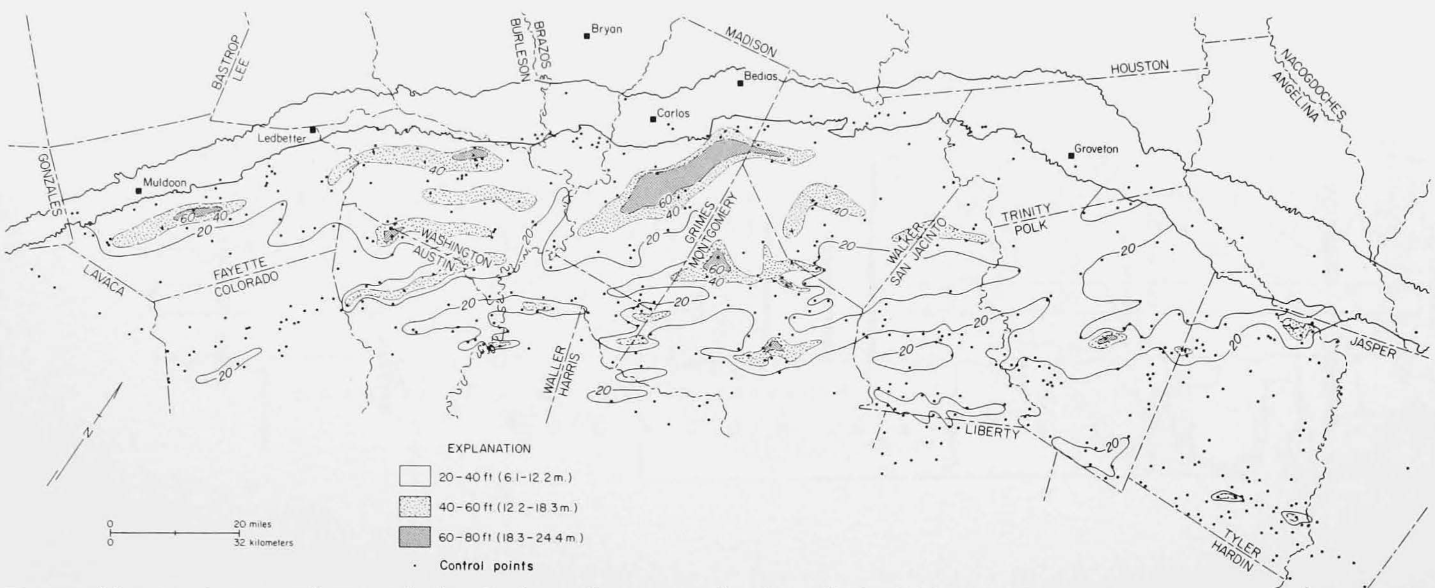

Figure 16.--Maximum-sand map of the Jackson Group, exclusive of the Whitsett Formation.

lignites are present in 200 ft of section, but only 4 exceed 3 ft thick. The lignite-occurrence map (fig. 17) reveals a lobate distribution in the subsurface that mirrors the sand-percent map (fig. 15). In fact lignite and relatively high sand percent coincide almost exactly (figs. 15 and 17). The correlation is directly contrary to that found in the Wilcox, where high lignite count correlates with relatively low sand percent.

Palynology (Elsik, in press) and digitate and bifurcating sand-body geometries suggest that marshes on the lower delta plain were sites of organic accumulation. Thicker, laterally extensive lignites are inferred to be blanket marsh peats that accumulated on foundering delta lobes extending across abandoned distributary channels (fig. 18). Commercial seams are typically 4 to 8 ft thick, tabular to lenticular, and continuous for as much as 20 mi. Areally restricted lignites probably accumulated in interdistributary basins during active deltation. Small isolated pods of lignite at the delta front may represent salt marshes on the backside of barrier and destructional islands (fig. 17).

Exploration Model

The most prospective areas for lignite are those in which high sand percent and high lignite count coincide. Projection of these subsurface areas updip (up paleoslope) to the outcrop intersects several known deposits. The best known is at Carlos, Tex., where approximately 2.7 million tons per year will be mined beginning in 1980. Other commercial deposits of 100 to 200 million tons coincide with projections in Washington, Burleson, and Walker Counties (fig. 17). Jackson lignite in an 8- to 10-mi-wide belt immediately downdip from the outcrop is exploitable using in situ gasification.

The flanks of the Jackson delta system and interdeltaic embayments, as expected, are less prospective or nonprospective. Projection of prominent embayments and associated interdeltaic facies identified in the subsurface in Grimes and Walker Counties extends to the outcrop in areas of poorer grade lignite in Brazos and eastern Walker Counties, respectively (figs. 15 and 16). Finally, strike-oriented sands may be identified in outcrop as linear topographic ridges and are an aid to exploration. Exploratory drilling in the strike valleys between ridges will be most productive.

JACKSON GROUP-YEGUA FORMATION

In south Texas, south of the Colorado River (fig. 3), Jackson-Yegua lignite deposits occur in the lower part of the Jackson Group and upper part of the Yegua Formation near the transitional

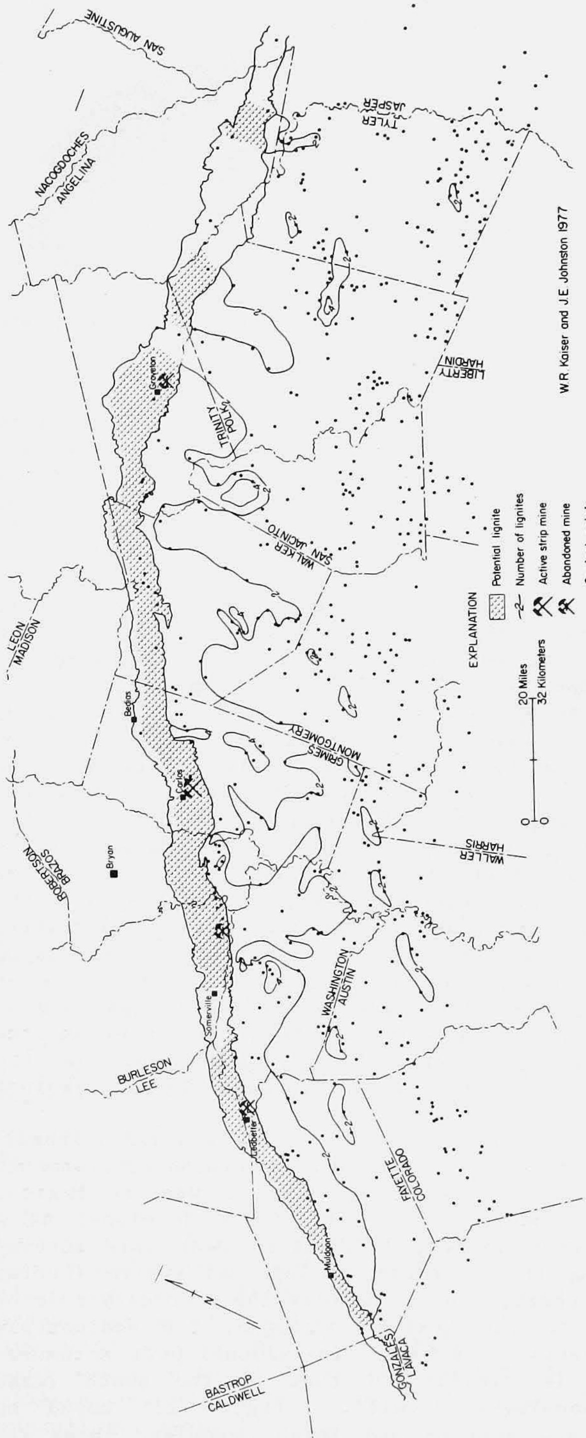

Figure 17.--Occurrence of lignite in the Jackson Group (Manning-Wellborn Formations). Manning-Wellborn outcrop from Barnes (1967, 1968, 1974).

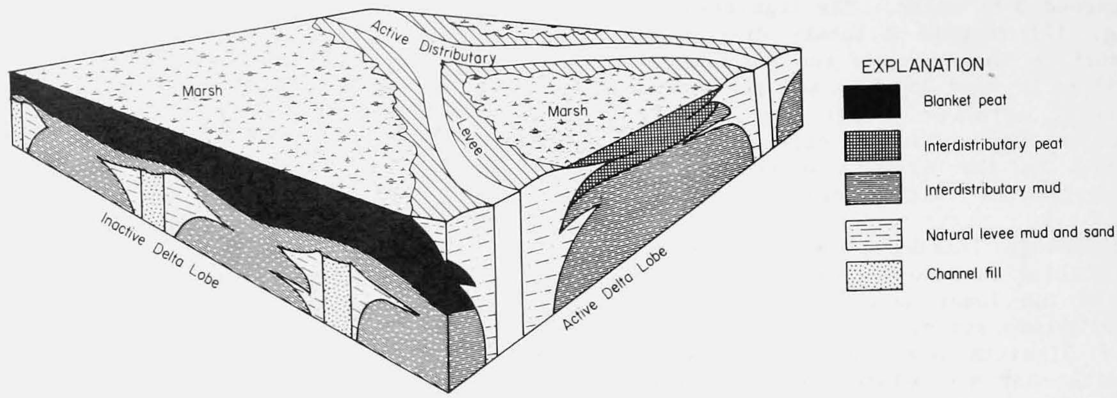

Figure 18.--Modern deltaic peats, blanket vs interdistributary origin.

Jackson-Yegua boundary (fig. 19). No distinctive rock-stratigraphic marker separates the two stratigraphic units. Downdip, a marine-mud section at the base of the Jackson Group separates it from the underlying Yegua Formation. Updip, at the position of lignite occurrence, the two units are transitional.

Deep-basin lignite occurs in a linear, well-defined, north-northeast-trending, narrow band located updip (landward or lagoonward) of the axes of Jackson-Yegua strandplain-barrier bar systems (Fisher and others, 1970; Fisher, 1969; Kaiser, 1974). Projection of the lignite trend north along depositional strike intersects the outcrop in north-central McMullen and Atascosa Counties, an area of commercial lignite currently being developed to fuel the San Miguel steam-electric station. Similarly, projection of the trend south intersects strippable deposits in the Rio Grande valley in southern Zapata and western Starr Counties (fig. 20). Deposits in excess of 200 million tons are present in south Texas in seams 2 to 13 ft thick extending for as much as 13.5 mi. Surface mapping places most of the strippable lignite in the lower part of the Jackson Group (fig. 20, San Miguel) (Barnes 1976).

Holocene analogues of Jackson-Yegua linear, regressive shorelines and associated environments occur on the Nayarit coast of western Mexico. Though peat is not extensively developed as a component facies, thin marsh peats are accumulating in a strandplain-lagoonal system (Curray and others, 1969). Despite the secondary role of peat in the Mexican analogue, the sedimentary framework of strandplain-lagoonal peat accumulation is similar to that of the south Texas Jackson-Yegua lignite. Figure 21, based on Holocene Mexican and Texan examples, shows the component facies of a progradational, strand-plain-barrier bar sequence. The resulting coarsening-upward sequence capped by peat-bearing marsh-strandplain or marsh-lagoonal sediments is closely analogous to sequences recognized in the

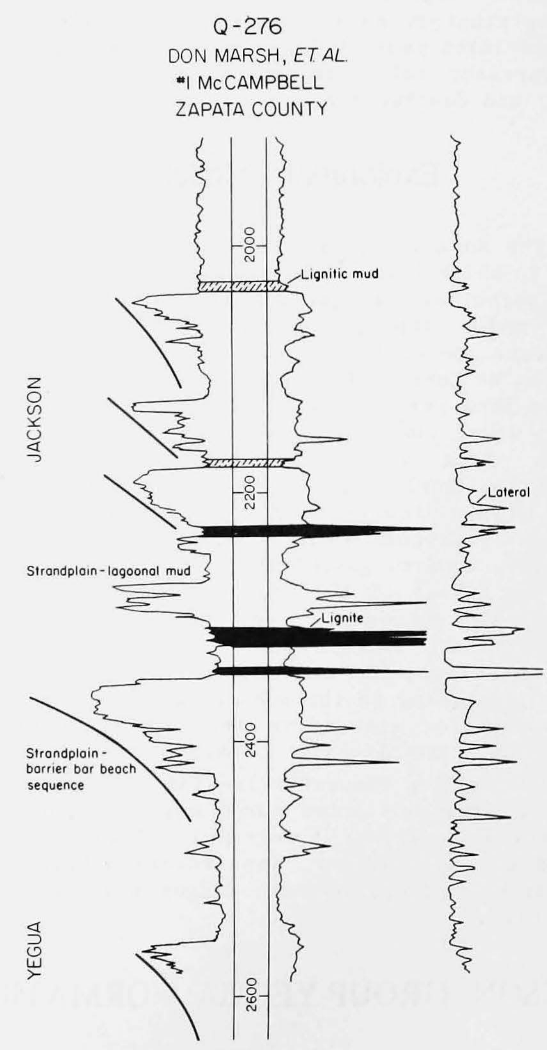

Figure 19.--Jackson-Yegua stratigraphy of south Texas and the occurrence of lignite. See figure 20 for location of electric log.

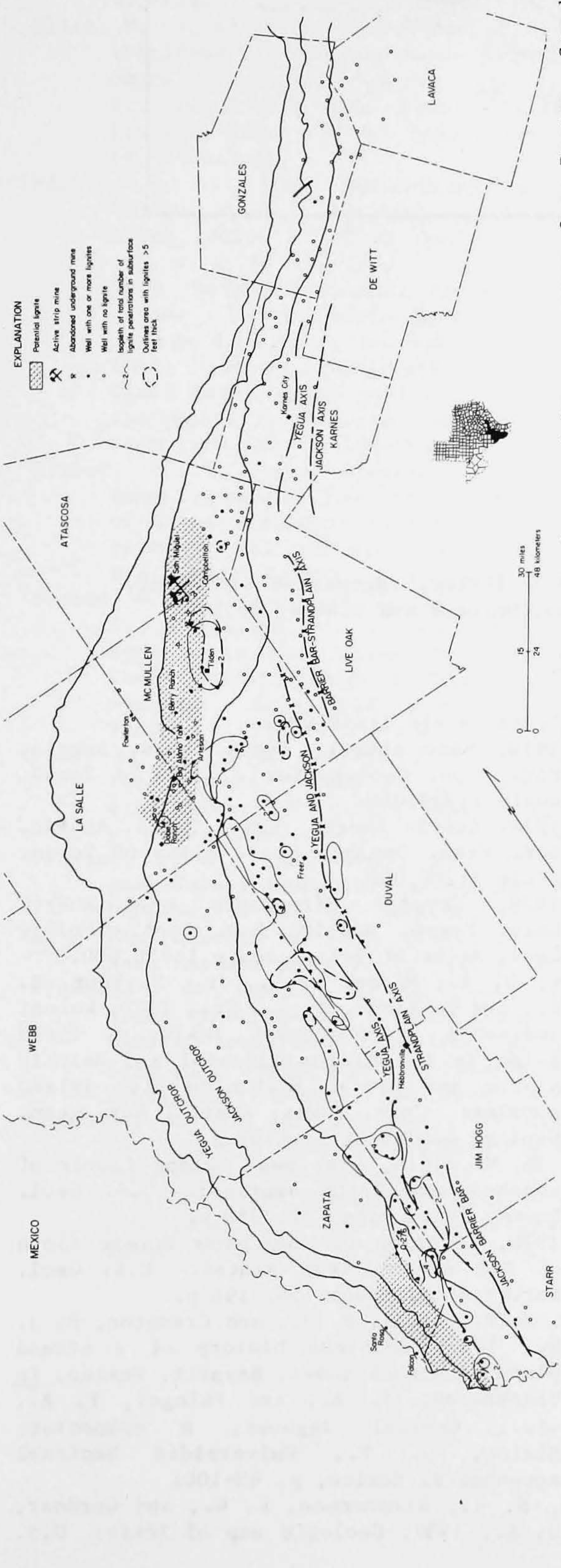

Figure 20.--Occurrence of lignite in the Jackson Group-Yegua Formation. Jackson and Yegua outcrop from Darton, Stephenson, and Gardner, 1937; Barnes, 1976. Jackson-Yegua strandplain-barrier bar axes from Fisher and others, 1970; Fisher (Bur. Econ. Geology work maps).

Jackson-Yegua strata, inferred strandplain-barrier bar sequences separated by strandplain-lagoonal mud and lignite (fig. 19).

CONCLUSIONS

1. Using an operational definition of high resistivity and baseline SP, lignite beds can be identified on electric and induction logs without use of density or neutron logs. Lignites are best picked on electric logs. Those beds greater than 4 ft thick can be recogized on induction logs.

2. The sand-percent map, which minimizes the effect of downdip stratigraphic thickening on map patterns, provides the best correlation between mapped sand-body geometry and lignite occurrence. There is a poorer correlation between sand-body geometry determined from net-sand mapping and lignite occurrence. The maximum-sand map, which can be quickly made, provides a useful exploration tool that should be prepared routinely.

3. The proposed exploration model is facies-dependent. In fluvial-facies tracts, low-sand areas and high lignite count are coincident, whereas in deltaic-facies tracts, high-sand areas and high lignite count are coincident. Almost all major near-surface strippable deposits could have been discovered using this model. Significantly, this study was done using old logs commonly found in the files of almost every exploration company and without logs specifically run for lignite exploration (density logs).

4. Sand dendroids and belts and associated lignite of the Wilcox Group of Texas are most like Paleocene and Eocene coal strata of the Rocky Mountain region; for example, the Fort Union and Wasatch Formations of the Powder River Basin, Wyo., and the Hanna Formation, Hanna Basin, Wyo. Lobate and strike-oriented linear sand bodies and associated lignite of the Jackson Group of Texas are most like Upper Cretaceous coal strata of the Rocky Mountain region; for example, the Mesaverde Group of northwestern Colorado and the Fruitland Formation, San Juan Basin.

5. Correct interpretation of coal depositional environments cannot be made without knowledge of sand-body geometry. To assign a fluvial, deltaic (lobate shoreline), or strand-plain-lagoonal (linear shoreline) origin to a deposit requires demonstration of sand dendroids and belts oriented parallel to paleoslope, lobate sand bodies with internal bifurcation, and sand ribbons and sheets oriented parallel to relict shorelines, respectively.

ACKNOWLEDGMENTS

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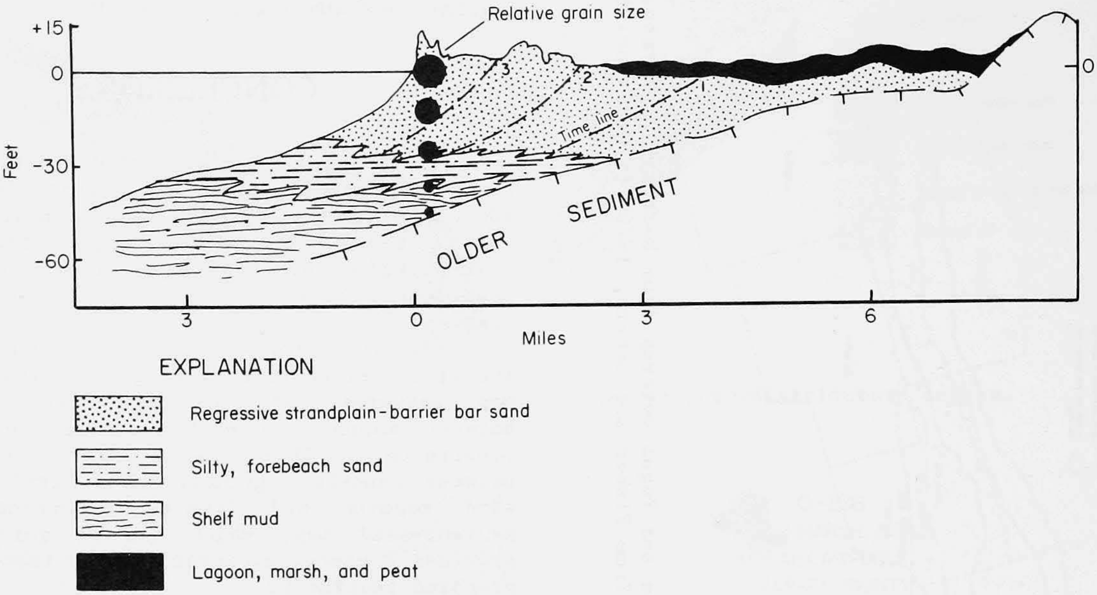

Figure 21.--Vertical sequence produced by a Holocene linear, regressive shoreline. Adapted from Curray, Emmel, and Crampton,1969; Bernard and others, 1970.

Illustrations were drafted by the Bureau of Economic Geology cartographic staff under the direction of J. W. Macon. L. F. Brown, Jr., reviewed the manuscript; his editorial comments tightened the presentation. Discussions with W. E. Galloway, W. L. Fisher, and J. H. McGowen illuminated aspects of Eocene sedimentation.

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RoMoCoal Field Trip — Photograph by Harold H. Arndt, U.S. Geological Survey

Field trip participants watching the Energy Fuels Marion 8050 dragline dumping overburden material from its 55-yard bucket at Energy Fuels Corporation pit no. 1.

Splay Deposits as an Economic Factor in Coal Mining

JOHN C. HORNE, DAVID J. HOWELL, BRUCE P. BAGANZ, and JOHN C. FERM[1]

ABSTRACT

Splay deposits are an important component of lower delta-plain sequences in the Carboniferous coal measures of the eastern United States. They are elongate linear or lobate in shape and range in thickness from 5 to 40 ft (1.5 to 12 m); long-dimension diameters are 200 ft to 4 mi (60 m to 6.5 km). These features directly affect the economic parameters (thickness, quality, roof conditions, and sulfur content) of coals formed in this depositional setting.

Splays that cause splits in coal seams may reduce coal thickness below minable mimimums and increase the percentage of reject material above tolerable limits. Where splay deposits occur directly over a minable coal, are less than 20 ft (6 m) thick, and have a rider coal or extensively rooted zone (fireclay) over the top of the splay, severe roof problems may be encountered during mining.

In general, when overlain by marine to brackish-water roof rocks, coals formed in a lower delta-plain setting tend to be high in sulfur as a result of sulfur-reducing bacteria in the marine to brackish waters. However, if splay deposits are introduced early and are of sufficient thickness, they shield the coal from the bacteria, and the sulfur content remains low.

Because of their effect on these economic parameters, splay deposits must be considered during the coal exploration phase with respect to corehole spacing in order to delineate these features and with respect to the number of sample analyses to determine the variations in coal quality. In addition, these deposits must be taken into account during mine planning and development because of the roof problems they may cause.

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INTRODUCTION

In the past, the role of geology in coal exploration, mine planning, and mine development has been relatively insignificant. Primarily responsible for this has been the simplicity of geologic concepts necessary to conduct these operations. Today, however, in many areas, the easily mined, high-quality coals are now nearing exhaustion, and the increased demand for clean, nonpolluting, safe energy is quickly bringing a need for new techniques for exploration and mining that will make development of formerly unminable seams a profitable venture. Hence, the coal explorationist must now consider such matters as roof and floor control, methane problems, and sulfur and trace-element distributions along with problems of continuity and thickness of coal seams. Because most practical applications occur in relatively small areas (approximately 15,000 acres or less), all these matters require a high level of precision. Research in the Carboniferous coal measures of the Appalachian region has shown that one of the most critical determinants of seam character that can be used in a precise investigation is the depositional environment of the coal. Studies indicate that the surface upon which the coal swamp developed played a major role in controlling its thickness and extent, whereas the environment of deposition of the sediments that covered the peat strongly influenced roof conditions in mines as well as many aspects of coal quality.

The principal objective of this paper is to illustrate how a single component of the lower delta-plain depositional environment--splay deposits--can directly influence the thickness, extent, quality, and potential minability of coal seams.

CHARACTERISTICS OF MODERN SPLAY DEPOSITS

The principal criteria for the identification of splay deposits in the Carboniferous coal

Figure 1.--Distributary channels in the lower delta plain of the Mississippi Delta. Observe the numerous breaches in the poorly developed levees of the distributary channels. (Photo courtesy of R. S. Saxena.)

are small and are easily breached with slight rises of water level in the distributary channels (Saxena and Ferm, 1976) (fig. 1). Farther upstream where the levees are better developed, breaches occur only at times of major floods and are plugged quickly as the floodwaters recede.

The size and areal extent of crevasse splay deposits are highly variable and depend on the time interval over which the crevasse system remained active. Generally, splay sedimentation is an episodic, short-term process, and deposits have an areal extent of less than 1 to 3 mi (1.6 to 5 km) and are less than 10 ft (3 m) thick (fig. 2). However, crevasse subdeltas with areal extents of more than 10 mi (16 km) and thicknesses greater than 40 ft (12 m) are not uncommon (Saxena, 1976).

Laterally, grain size of the splay sediments decreases away from the breach in the levee (Welder, 1959) (fig. 3). Over a scoured base in the proximal portion of the splays, the grain size of the deposits either decreases upward or remains constant, whereas, in the distal portion, the grain size coarsens upward over a gradational lower contact. Internally, splay deposits exhibit small-scale cross-stratification with some graded beds in the distal portion (Coleman and Gagliano, 1964). Where exposed, the sediments are extensively rooted; and, where covered by bay waters, they are burrowed.

CHARACTERISTICS OF CARBONIFEROUS SPLAY DEPOSITS

Carboniferous crevasse splay deposits display all the characteristics of coarsening-upward mini-deltas (Baganz and others, 1975). They become gradationally finer grained away from the breached levee until they grade laterally into interdistributary bayfill sequences. Frequently, they contain abandoned channel-fill sequences which formed as a result of the plugging of crevasses in the levees. Carboniferous splay deposits are elongate-linear or lobate in shape and vary in size, with thicknesses to as much as 40 ft (12 m) and horizontal extents ranging from 100 ft (30 m) to 5 mi (8 km).

Excellent highway exposures in the Carboniferous coal measures of eastern Kentucky permit a detailed three-dimensional study of a splay deposit (fig. 4). These exposures show relationships that can only be inferred from geomorphic features and core data in modern depositional systems.

Near the crevasse that breached the levee of the distributary channel, the splay deposit consists of a single lobe (30 ft (10 m) thick) of sediment. This sediment, deposited over a scour

Figure 2.--Crevasse splay deposit in the lower delta plain of the Mississippi Delta. (Photo courtesy of R. S. Saxena.)

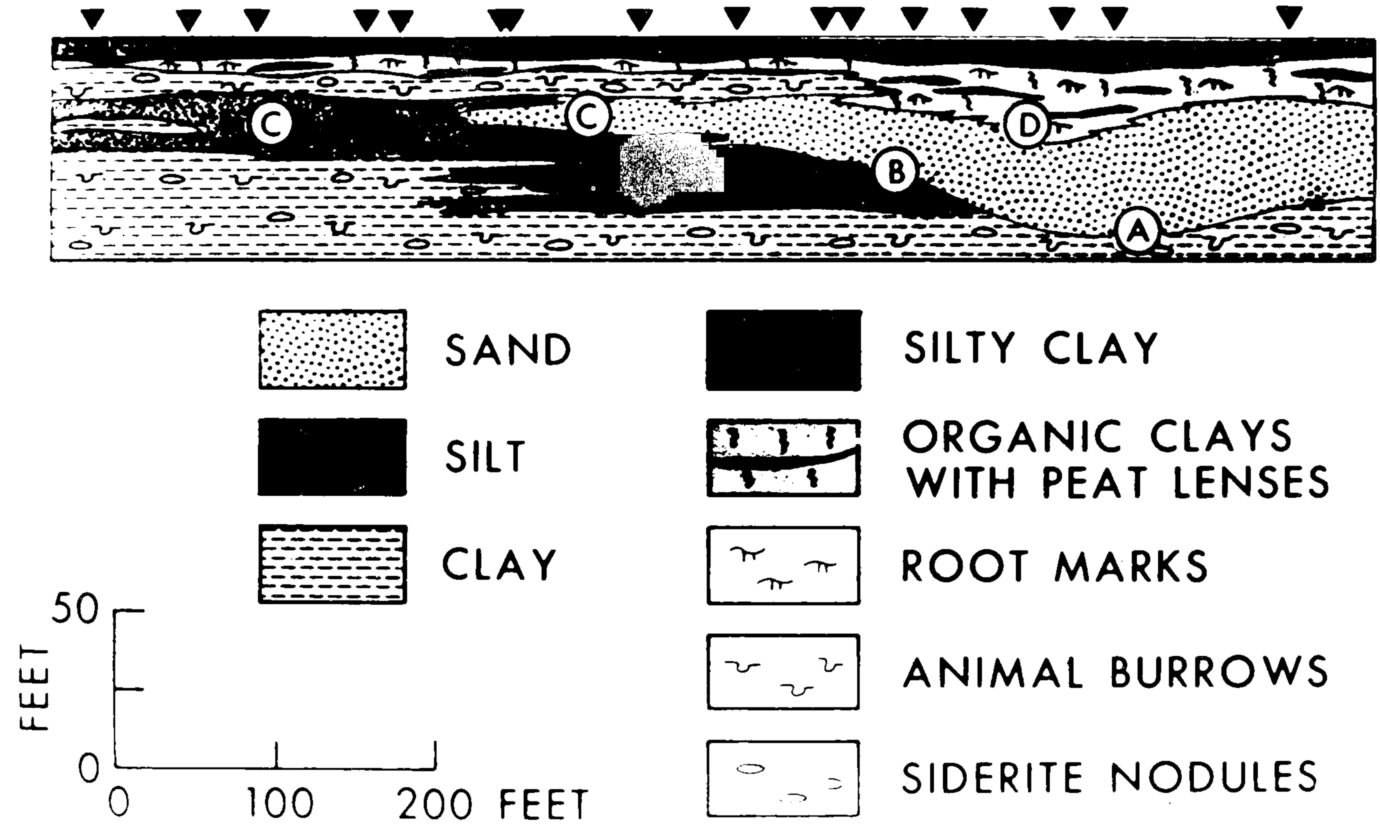

Figure 3.--Cross section of modern splay deposit in the lower delta plain of the Mississippi Delta. A and B, scour at base of sand in proximal portion of splay deposit; C, coarsening-upward silts and sands in distal portion of splay deposit; D, levee deposits that plugged crevasse.

surface, is composed of fine- to medium-grained sandstone (fig. 5). The sandstone is trough crossbedded and contains numerous examples of type-A and type-B ripple drift (Jopling and Walker, 1968), indicating rapid sedimentation and waning currents (fig. 6). Numerous channels, some with active (sandstone) fill and others with abandoned (shale and siltstone) fill, scour the upper portion of the splay deposit. Also, capping the splay sequence at this locality are irregularly interbedded siltstones and sandstones from the levee deposits of the associated distributary, which plugged the crevasse.

At location II (fig. 4), the splay deposit has bifurcated into two lobes (fig. 7). The lobes are still about 30 ft (10 m) thick; however, the sediment is finer grained and coarsens upward from dark-gray, organic-rich shales at the base to interbedded siltstones and fine-grained sandstones at the top. The fine-grained sandstones contain climbing ripples, further indicating decreasing current velocities and rapid sedimentation. Scouring through the upper portion of these two lobes are small channels containing fine-grained (shale and siltstone) fill (fig. 8).

At location III (fig. 4), near the distal margin of the splay, the splay deposit still consists of two lobes (fig. 9). However, the maximum thickness of the lobes is 15 ft (4.5 m) and widths are 200 to 300 ft (60 to 90 m). The sediment in these lobes constitutes a coarsening-upward sequence consisting of a dark-gray, organic-rich shale in the lower portion, which grades upward into thin (0.5 in. (1 cm) thick), graded, bedded sideritic siltstones (fig. 10) containing abundant plant debris on bedding planes (fig. 11). This plant debris was transported to the site of deposition during periods of high water (floods) when the levee was breached.

APPLICATION OF SPLAY MODELS

The delineation of splay sequences is an excellent academic exercise but is of no use to

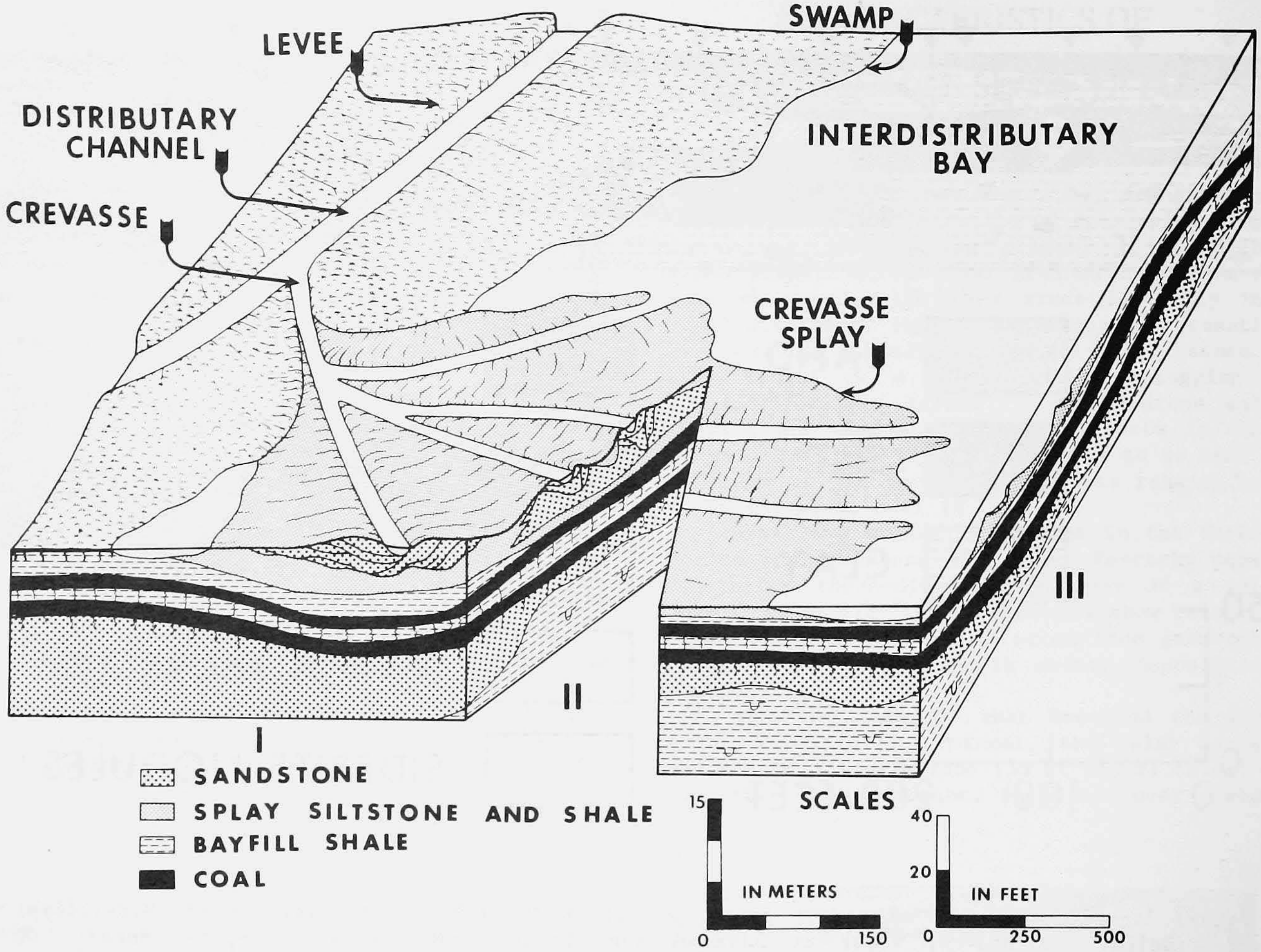

Figure 4.--Crevasse splay deposits exposed in the interval above the Upper Elkhorn No. 1, 2 coals along U.S. Highway 23 near Betsy Layne, Ky. Side panels of the block diagram based on greater than 80 percent exposure (Baganz and others, 1975). I, II, and III are locations referred to in the subsequent illustrations and in the text.

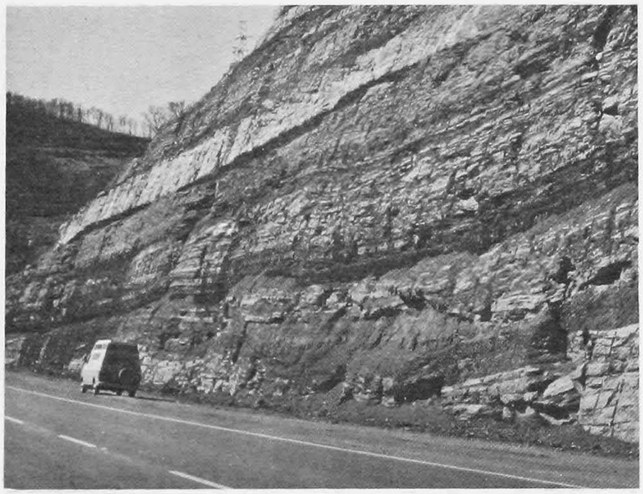

Figure 5.--Proximal portion of crevasse splay (location I, fig. 4) overlain by levee deposits in lower part of photo (Horne and Ferm, 1976).

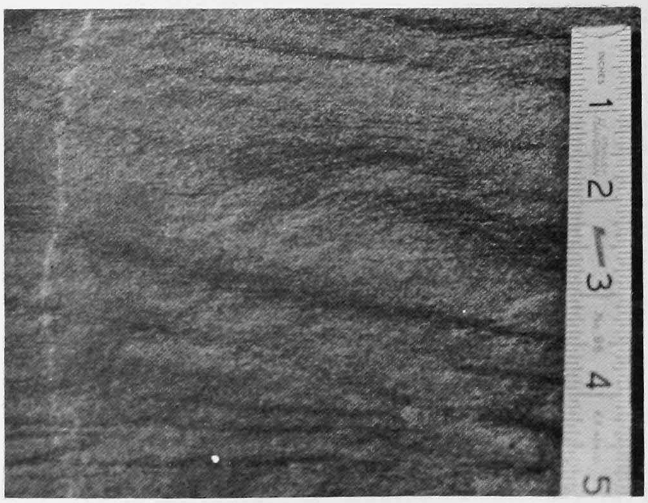

Figure 6.--Ripple-drift cross-laminations at location I (fig. 4), indicating rapid sedimentation and waning currents (Horne and Ferm, 1976).

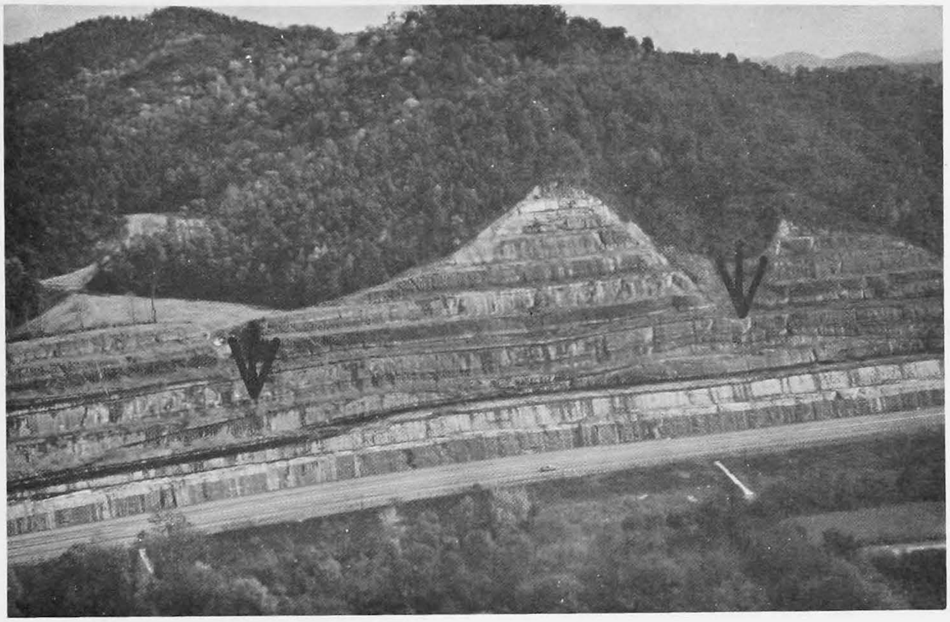

Figure 7.--Airphoto of the two lobes of the crevasse splay deposit at location II (fig. 4) (Horne and Ferm, 1976).

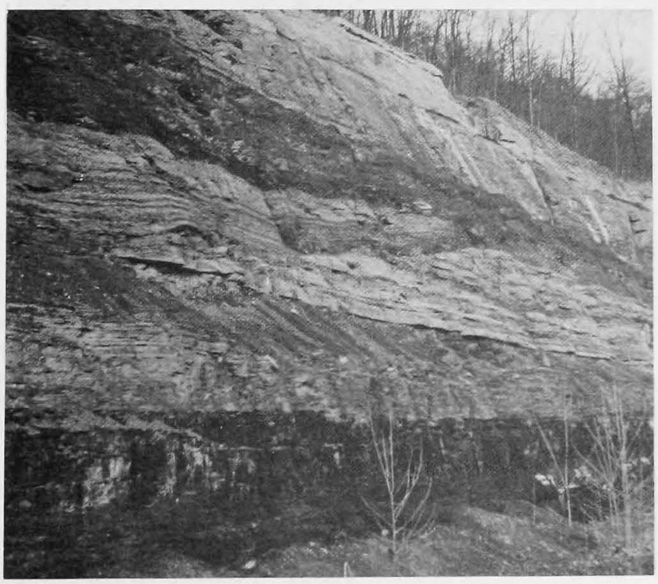

Figure 8.--Abandoned channel fill in splay deposit formed as the result of the closing of the crevasse in the levee (Horne and Ferm, 1976).

the coal industry unless it can be applied to produce predictive models that are of economic significance in coal exploration and mine planning. The rest of this paper will be devoted to the manner in which splay deposits influence the quality and potential minability of coal seams.

COAL QUALITY

Sulfur Problems

Iron disulfides (FS_2) are present in coals either as marcasite or pyrite. They occur as euhedral grains, coarse-grained masses (greater than 25 μm) that replace original plant material, coarse-grained platy masses (cleats) occupying joints in the strata, and framboidal pyrite (fig. 12) (Caruccio and others, 1977). The latter is found as clusters of spherical agglomerates comprising 0.25-μm grains of iron disulfides, which are finely disseminated throughout the coal and associated strata. Of these four basic types, only the framboidal form decomposes rapidly enough to produce severe acid-mine drainage (Caruccio, 1970) in the absence of carbonate and is so disseminated throughout the coal that it cannot be removed in the 1.50-density sink fraction of washability tests.

Research by Love (1957), Love and Amstutz (1966), Cohen (1968), Rickard (1970), Berner (1971), and Javor and Mountjoy (1976) suggests

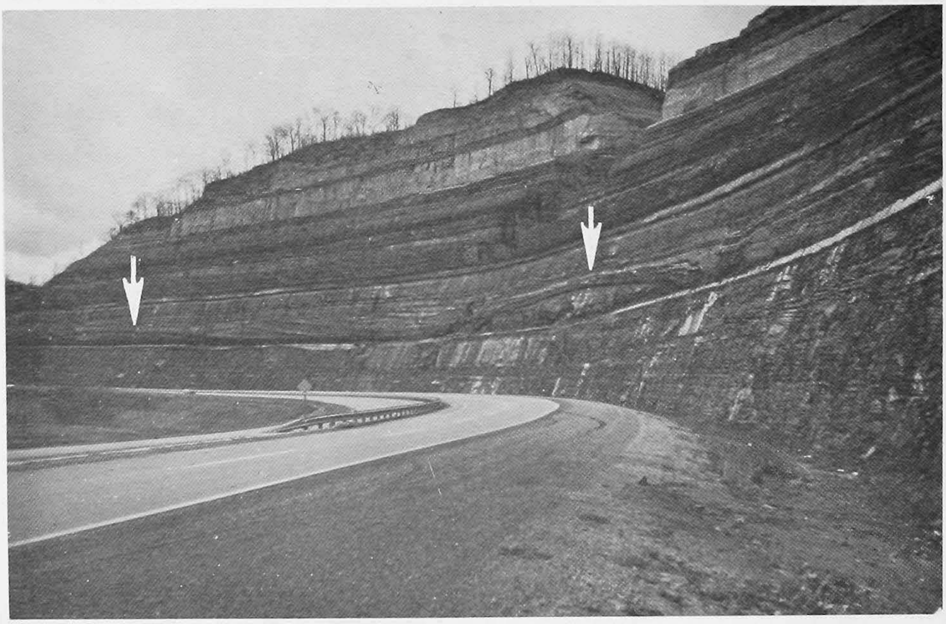

Figure 9.--Two lobes at the distal margin of the splay deposit at location III (fig. 4) (Horne and Ferm, 1976).

Figure 10.--Graded bedding in sideritic siltstones at the distal margin of the splay deposit (location III, fig. 4) (Horne and Ferm, 1976).

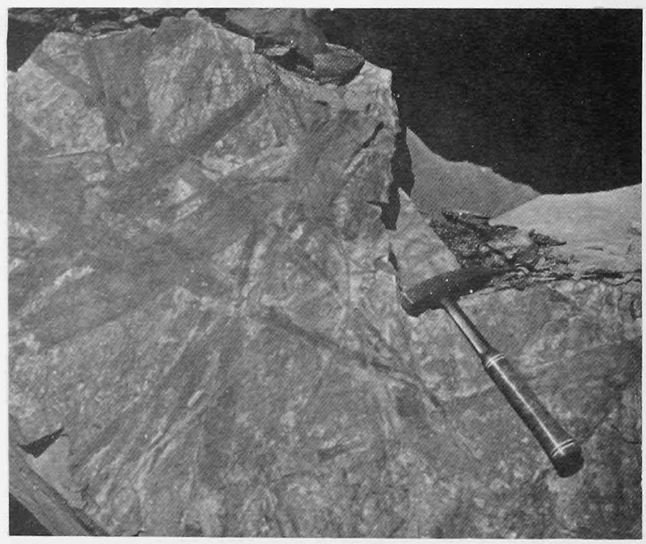

Figure 11.--Abundant plant debris on bedding surface at the distal margin of the splay deposit (location III, fig. 4) (Horne and Ferm, 1976).

that the framboidal form of pyritic sulfur is produced by sulfur-reducing microbial organisms that are found in marine to brackish waters but not in freshwater. Ferm and others (1976) and Caruccio and others (1977), on the basis of research in the Carboniferous of eastern Kentucky and southern West Virginia, have established that it is sulfur present in the framboidal form of

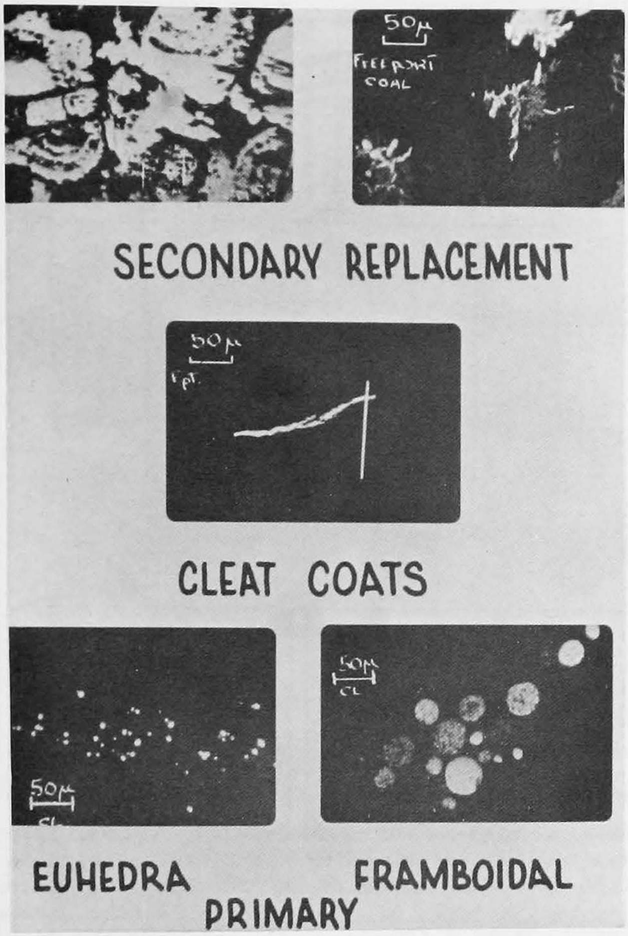

Figure 12.--Forms of pyrite that occur in coals. (Caruccio and others, 1977).

iron disulfide that is most strongly associated with roof rock deposited in marine to brackish-water environments. The only exception to this occurs where a sufficient thickness of sediment is introduced early enough to shield the peat from the marine to brackish waters.

Thus, the environments of deposition of the sediment that overlies the coal are more important to the distribution of type and amount of sulfur in the coal than the environments of deposition of the sediment on which the coal developed. Because of this, coals that accumulated in areas under marine influence, such as lower delta-plain environments, are likely to be overlain by marine to brackish-water sediments and have high amounts of disseminated pyritic sulfur present in the reactive framboidal form.

At the lease-tract level, an understanding of the controls that depositional settings exert on the distribution of the amount of sulfur and the type of pyrite can permit the exploration for low sulfur coals in areas where the sulfur content is usually high. This can be illustrated by an example from the Carboniferous of the eastern United States. In this example, on the basis of 450 coreholes in a 200-mi^2 (500-km^2) area, the coal accumulated in a lower delta-plain environment. When overlain by marine to brackish-water roof rock, coals formed in this depositional setting commonly have a propensity to be high (greater than two percent) in sulfur, with a majority of the sulfur (greater than 75 percent) occurring in the form of framboidal pyrite (Caruccio and others, 1977). However, when splay deposits are introduced early and are of sufficient thickness, they shield the coal from the sulfur-reducing bacteria and the sulfur content remains low (less than 1 percent) (Horne and others, 1976).

An east-west cross section (fig. 13) through the exploration area shows a fossiliferous limestone and black shale that rest directly on coal X in the eastern portion of the cross section. However, the limestone and black shale rise off the coal to the west, being separated by an intervening wedge of terrigenous clastic sediment. The distribution and thickness of this detrital wedge, as well as the area where the limestone and black shale immediately overlie the coal, are shown in figure 14. That the detrital sediment was introduced early and shielded the coal from the marine to brackish waters is evidenced by the fact that the deposits of these waters (the limestone and black shale) rise over the terrigenous clastics. This indicates that the detrital influx occurred before or during marine inundation.

Figure 15 is a reconstruction of the depositional setting immediately after the formation of coal X. It is based on data related to lithologic and sediment-thickness variations. These data suggest that the levees of a distributary channel in the southwestern portion of the area were breached several times, forming large splay deposits to the north and east over the coal and into the intervening interdistributary bay. In areas removed from this detrital influx, fossiliferous limestone and black shale were deposited from the marine to brackish waters of the bay.

Figure 16 illustrates the distribution of the sulfur in coal X that cannot be removed in the 1.50-density sink fraction of washability tests. As might be expected, the coal in the eastern portion of the area where it is overlain by roof rock of marine to brackish-water origin is high (greater than 2 percent) in sulfur, with most of the pyritic sulfur occurring in the form of disseminated framboids. To the west and south where the coal is overlain by the wedge of terrigenous clastic sediment, the sulfur content decreases to less than 1 percent.

This example demonstrates the importance of splay deposits in the occurrence of pockets of low-sulfur coal of sufficient areal extent to be economic in the lower delta-plain setting, nor-

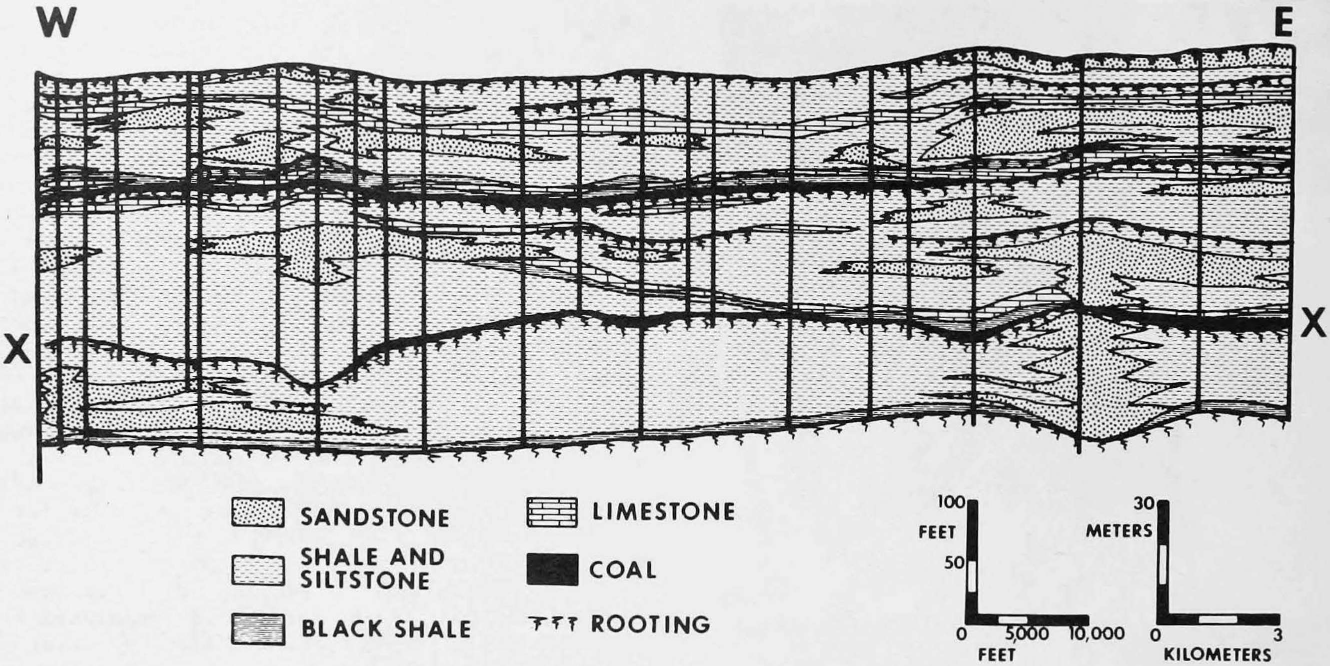

Figure 13.--Cross section showing the distribution of lithologies overlying coal X. Location of cross section shown on figure 14.

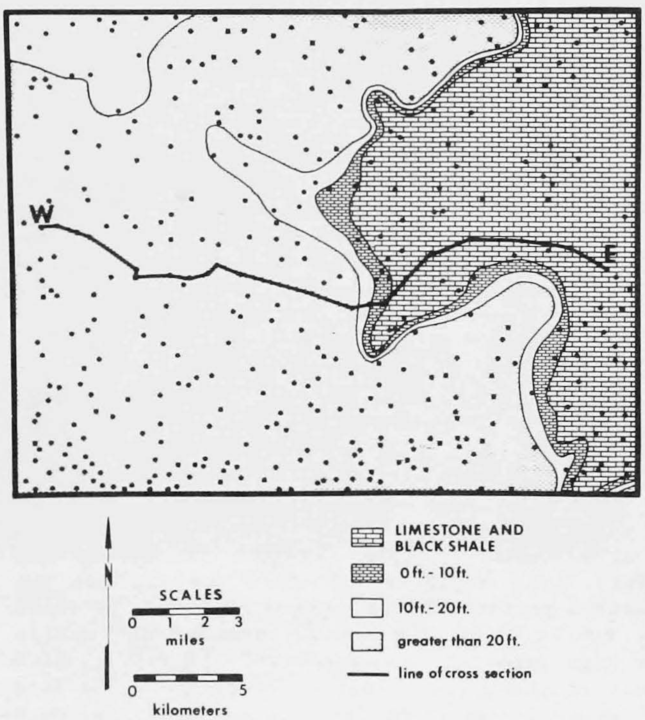

Figure 14.--Thickness of terrigenous clastic wedge of sediment between coal X and overlying marine limestone and black shale. Location of cross section in figure 13 shown by heavy line.

mally a high-sulfur coal realm. Since splay deposits form adjacent to the distributary channels in this depositional setting, drilling programs should be devised to define these features. In this manner, the areas of the lower delta plain having the greatest potential for low-sulfur coal can be delineated. The relationships shown in this example illustrate the close parallel between the distribution of coals containing disseminated pyritic sulfur and of roof rock of marine to brackish-water origin. Moreover, when terrigenous clastic sediment is introduced early and is of sufficient thickness, the sulfur content in the underlying coal remains low. With the knowledge of these characteristics and an understanding of the depositional setting, exploration programs can be designed to outline areas of low-sulfur coal in what is most commonly a high-sulfur coal province.

ROOF PROBLEMS ASSOCIATED WITH SPLAY DEPOSITS

Some of the most severe roof problems arise in areas where rider coals have formed within 20 ft (6 m) over the main seam and where the intervening rock type is dominantly fine-grained material such as shale or siltstone (Ferm and Melton, 1975). Since the rider coals and underlying root-penetrated clays have little strength, they provide zones of weakness along

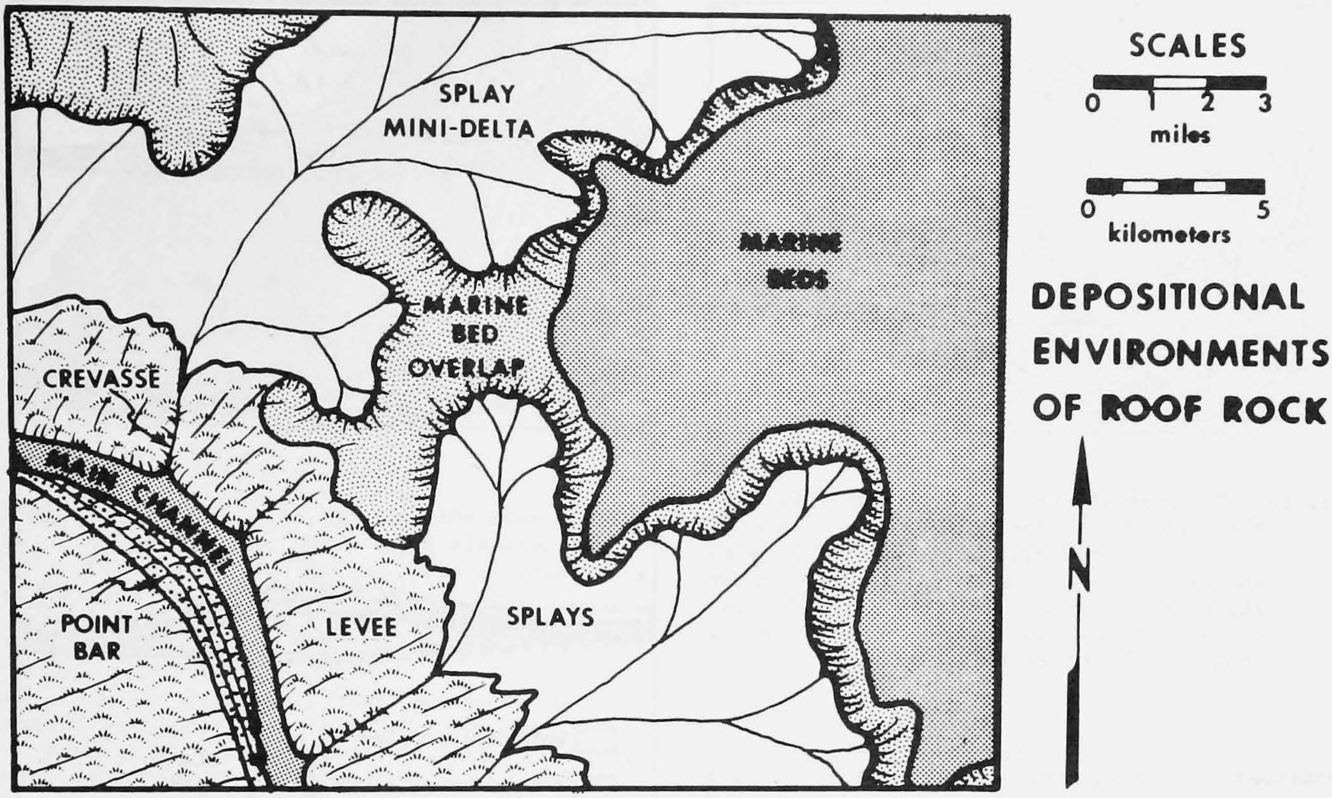

Figure 15.--Reconstruction of the depositional setting immediately after the formation of coal X. The diagram is based on data related to lithologic and sediment-thickness variations.

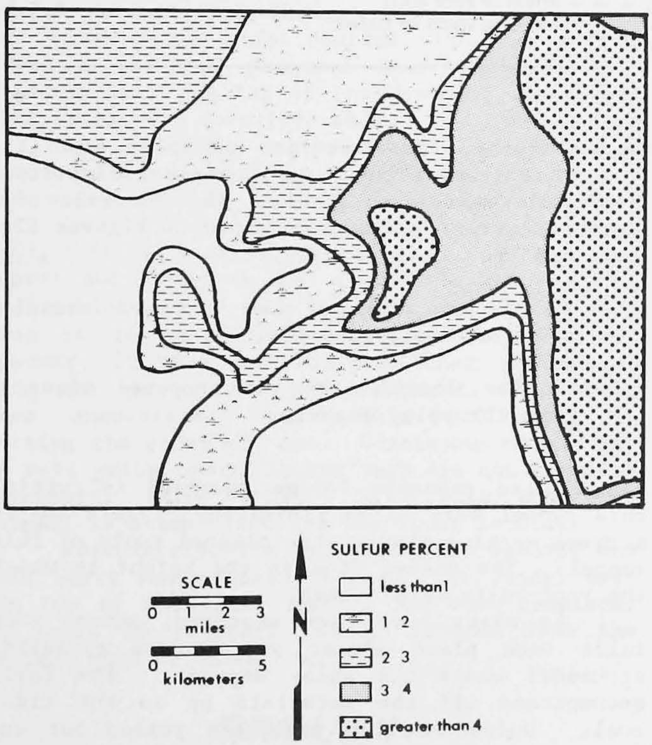

Figure 16.--The distribution of sulfur in coal X that cannot be removed in the 1.50-density sink fraction of washability tests.

which separations can take place. When these separations develop, severe roof falls evolve, encompassing all the material up to the rider seam. Thus, these areas should be circumvented whenever possible.

These rider seams developed in areas where the levees of sediment-laden channels were crevassed and detritus splayed over the adjoining coal swamps. After the floodwaters subsided, the swamps re-established themselves; and peat, from which the rider coals formed, accumulated. This situation is common in any of the delta-plain environments but is most common in the lower delta plain.

To demonstrate how splay deposits can affect roof conditions in underground mines, a case history of a roof problem will be illustrated for a mine in the Cedar Grove coal of southern West Virginia. Regional exploration data indicated that the depositional setting in which the Cedar Grove coal formed was the lower delta plain (fig. 17). In this area, peat (coal) accumulation was interrupted at many localities by terrigenous clastic sediment that splayed over the coal swamp. The sediment of these splays originated from the waters of the distributary channel located in the northern portion of the area. After the period of splaying, the swamp re-established itself and a thin rider coal developed over the splay deposits (fig. 18A).

Between the splays, peat accumulation

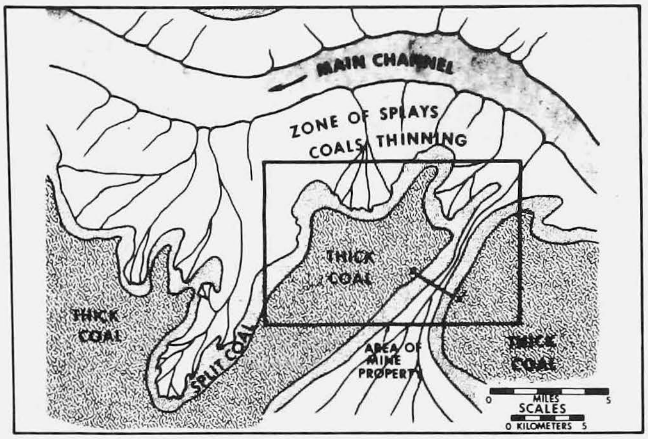

Figure 17.--Transitional lower delta-plain setting in which the Cedar Grove coal of southern West Virginia accumulated. Area enclosed in heavy lines is the location of the mine property shown in figure 19. The cross-section location in figure 18 is shown by the heavy line X-X'.

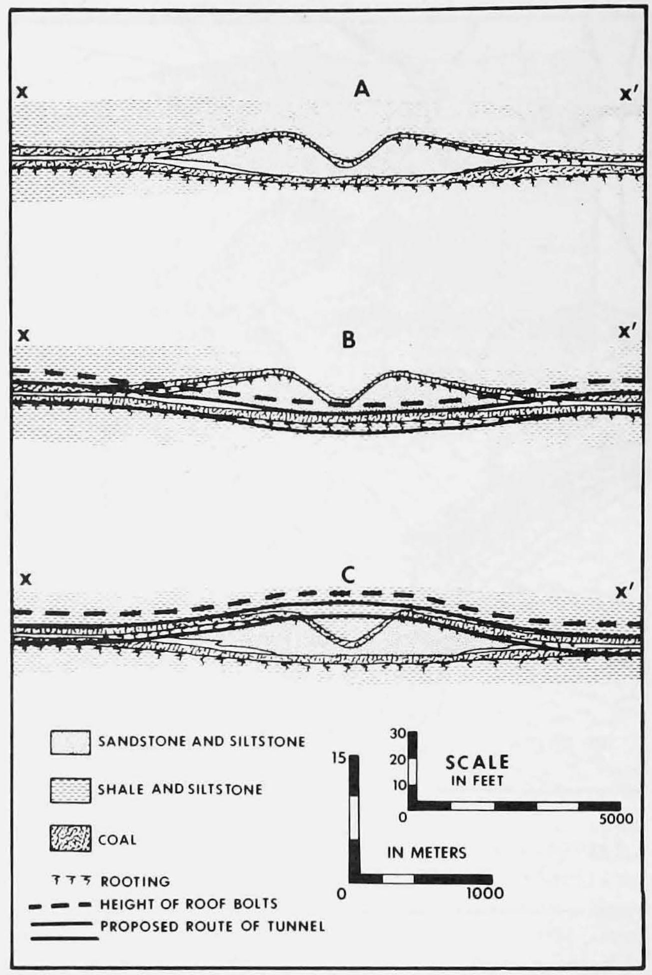

Figure 18.--A, Cross section of splay deposit that crosses the mine property and splits the Cedar Grove coal. The location of this cross section is shown on figures 17 and 19.

B, The location of the proposed tunnel under the splay deposit.

C, The location of the proposed tunnel over the splay deposit.

continued uninterrupted, and economically thick bodies of coal were amassed. In the area of exploration, there were two bodies of thick coal. Separating these two bodies was a zone in which the coal had been split into two thinner seams by a splay deposit (fig. 18A). On the basis of detailed exploratory drilling, a company developed a mine in the western pocket of thick coal. The location of this mine within the depositional setting is shown by the area enclosed in heavy lines on figure 17. In addition, the company's property encompassed a sizable portion of the eastern body of thick coal; and, ultimately, they planned to extend their mine into that area.

With the continued removal of coal from the western pocket of thick coal, the mine eventually began to impinge upon the edge of the splay deposit (fig. 19). This splay deposit divided the coal into two benches, with the interval of sediment between the benches increasing toward the center of the splay deposit (fig. 18A). For this reason, as mining proceeded into the splay deposit, the percentage of rejects increased until it became uneconomical to continue mining both benches of coal.

Initially, the company tried to circumvent the splay deposit by going around its southern terminus. Unfortunately, they ran out of property before they ran out of the splay deposit. Then, they decided to extend the mine to the eastern body of thick coal by driving a tunnel through the splay deposit. As neither bench of the coal was of economic thickness by itself, the company chose to have the tunnel follow the thicker of the two benches (the lower seam) so they could continue to mine some coal. In this manner, the economic losses incurred in cutting this tunnel were to be minimized. Figure 18B is a cross section showing the planned route of this tunnel. The dashed line is the height to which the roof bolts were driven.

As might have been expected, severe roof falls took place almost as soon as tunneling proceeded under the splay deposit. The falls encompassed all the materials up to the rider coal. Undaunted, the engineers pulled out and tried again, and then, a third time. Each time severe roof falls occurred.

Finally, after a sizable economic expense

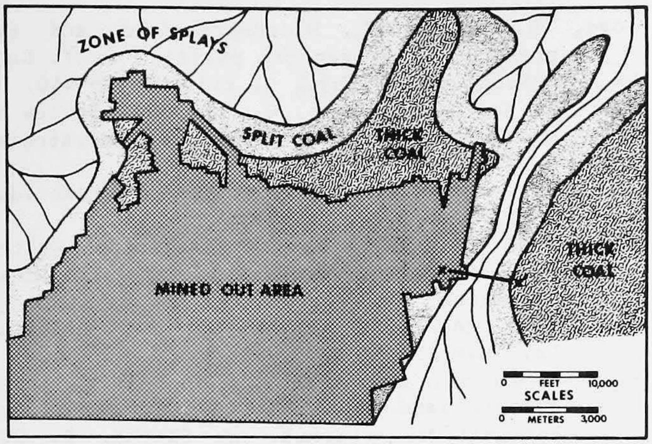

Figure 19.--Detailed diagram of the mine property showing the location of mined-out Cedar Grove coal and the position of cross section X-X'.

and loss of equipment, the engineers for the company were convinced that this was not the way to reach the eastern body of coal. At this point, a study of roof conditions as related to depositional setting was commissioned. From this study, a revised plan for reaching the eastern pocket of coal was proposed. This plan took into account the geologic patterns imposed by the depositional setting. Thus, rather than go under the splay deposit and contend with severe roof problems, it was proposed that the tunnel go directly over the top of the deposit, where roof conditions were more favorable.

The company engineers and miners were cautioned strongly to go straight over the top of the splay deposit and not to follow the rider coal down into the central gut of the splay (fig. 18C). It is a difficult thing to convince mine owners and operators that it will be economically profitable in the long term to mine rock, even when it is just for a short period of time. However, if they had followed that rider coal into the gut of the splay deposit, they would have encountered considerable difficulty in getting the machinery out. Continuous miners may do well going downhill, but they are not terribly successful going uphill, especially when the channel is steep-sided and the floor is clay.

Fortunately, the warnings were heeded, and this story has a happy ending. The tunnel over the top of the splay deposit has been completed and coal is presently being removed from the eastern body of thick coal.

SUMMARY

In summary, splay deposits can be described best as good news and bad news. From the standpoint of coal quality and sulfur distribution, splay deposits can be good news in that they may shield the coal from the marine to brackish waters containing sulfur-reducing bacteria. This permits the formation of low-sulfur coals in what is normally a high-sulfur coal province. However, splay deposits may be bad news from the standpoint of roof conditions in underground mines, in that severe roof problems occur when rider coal seams form on splay deposits (less than 20 ft (6 m) thick) that are deposited over minable seams.

Because of their effect on economic parameters, splay deposits must be considered during the coal exploration phase with respect to core-hole spacing in order to delineate these features and with respect to the number of sample analyses necessary to determine the variations in coal quality. In addition, these deposits must be taken into account during mine planning and development because of the roof problems they may cause.

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The Role of the Geologist in Coal Mining

CHARLES M. McCULLOCH[1]

ABSTRACT

The geologist has an important role to play in the design and layout of coal mines and in the choice of mining extraction techniques. His expertise was rarely used in the past, other than for coal exploration and reserve estimation. Today, there is an increasing need to combine and integrate the education and experience of the mining engineer and the geologist to create safe and economically successful mining operations. To accomplish this goal, the author proposes the use of a "risk-reduction" system, which involves a continuous appraisal of the mining situation from the time of reserve estimation through the production operations.

Prior to commencement of mining, the geologist should identify the potential geologic problems that could affect operations. These would include investigation of cleat orientation with a view to determining its effect on strata control, minability, and water and gas flows; structure and its relationship to mine design and layout; adjacent strata and their effects on mining layouts and techniques; and the environment of deposition of the seam.

During mining, the geologist should play an active role, mapping geologic features and abnormalities in addition to "trouble-shooting" problems that may have geologic solutions. By performing these tasks, the geologist can complement the mining engineer, and together they can form a team capable of achieving optimum results from any given mining situation.

INTRODUCTION

The importance of geology in coal exploration and reserve evaluation is now reasonably well known and recognized. Mine planning and development, on the other hand, are in most cases entirely the province of the mining engineer. Without doubt, mining engineers are important to a successful operation, but so are geologists.

Today a majority of the coal that can be easily mined has been mined, and any new operations are being forced to go deeper and mine coal under tougher geologic and mining conditions. Coal mining is not normally undertaken as a nonprofit operation; the cost of going deeper and mining under worse conditions has to be offset by an increase in production, something that in many cases is almost impossible to achieve because of limitations of the mining system being used.

Strangely enough, the recent technical innovations involving continuous and long-wall systems have generally increased the significance of certain geologic features, so that many areas of coal once included in a mine's reserves are now thought to be economically unworkable. Because of these new developments in mining methods and a greater degree of mechanization, the careful selection of mining areas, using the most advanced engineering and geologic techniques, is imperative.

There are many methods by which risks can be reduced, depending on the geologic environment of the seams and the rate of change of the factors to which each mining project is most sensitive (Siddall, 1968). Obviously this would involve core borings, seam sampling, geophysical investigations, and the systematic detailed recording of geologic mine data, something that is rarely done today.

Modification of Reserve Evaluation

An example of an area where change is needed is in our reserve classification. In the United States, reserves are classified in three categories: inferred, indicated, and measured. This system is based mainly on the distance between the data points as well as on a minable thickness. Such things as quality, market value, and method of extraction are not considered at this stage.

In Europe, the easily mined coal was mined out a number of years ago. Europeans are now forced to mine deeper coal in tectonically disturbed areas that dip as much as 60 degrees. Because of this, they have been forced to use a

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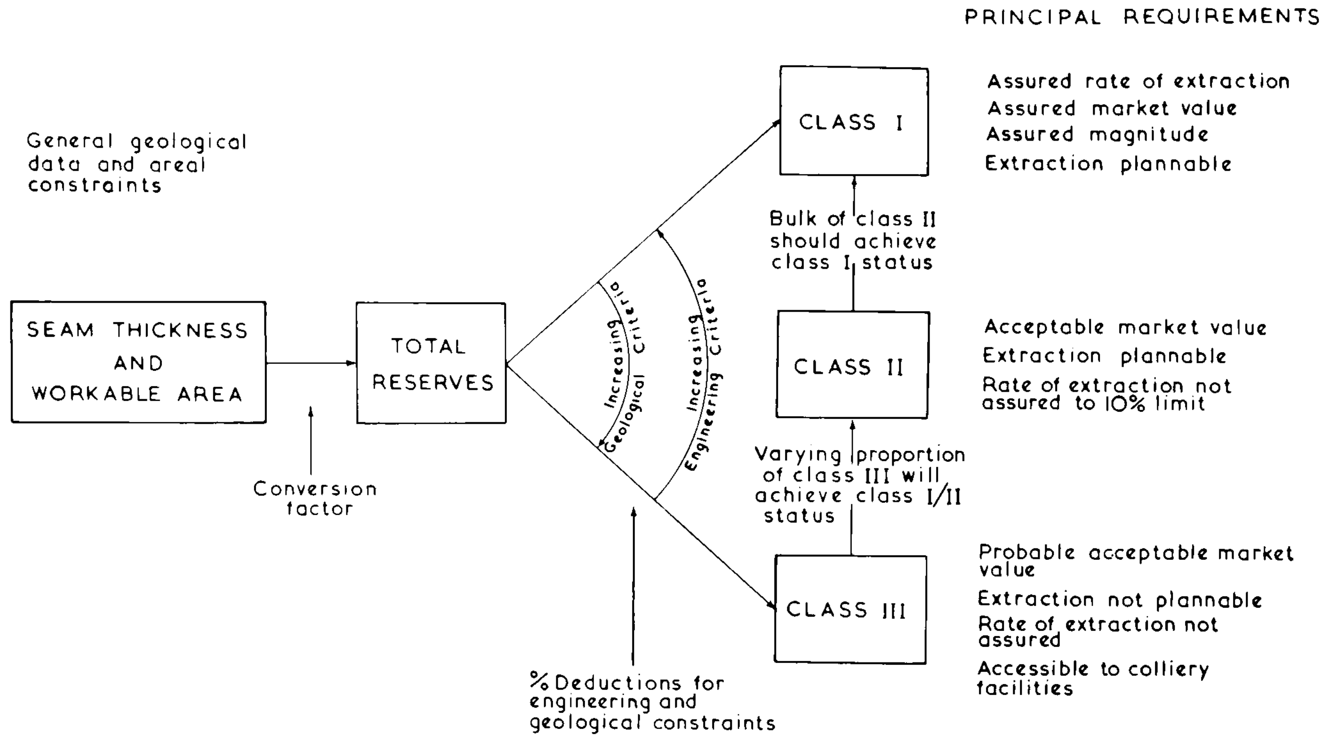

Figure 1.--European method of classifying reserves. From Siddall, 1968.

more detailed criteria for the investigation of the seam, as seen in figure 1 (Siddall, 1968). Not only do they have the assured magnitude used in the United States, but their Class I, which would be equivalent to the United States' measured reserve, also includes the assured rate of extraction, assured market value, and plannable extraction. Classes II and III are greater risk areas, but each can possibly be upgraded with more data.

It is also interesting to note that the geologic and engineering criteria increase in opposite directions. The reason for this is that the coal mining geologist works "from the outside inwards." He should know, from his experience in the coal field, the range of geologic "things" that can happen in the unknown portion of the coal field being investigated. The mining engineer, on the other hand, works from the inside outward. He starts from a given spot in a coal and works toward the unknown (Mills, 1972).

Approaches to Coal Mine Planning

In the past, the planning of coal mining ventures has taken one of two typical approaches: The first is (1) "Taking one thing at a time and crossing each bridge when you come to it." This system breaks the problems down into a time sequence. The geologist does his study (including exploration) first and presents it to the mining engineer, who builds on it and presents it to the accountant, who figures if the company can mine enough coal (and sell it for enough) to make money. The second approach is (2) "All other things being equal." Here each department is responsible for its own problems. The geologist again does his study, but it is done at the same time the mining engineer is doing his, and without knowledge of the type of mining that is being planned. Because all the coal geologist or mining engineer has is the data each is working on, each states that the coal can be successfully mined "all other things being equal" (Clarke, 1966).

Obviously the major problem in both of these methods is a lack of communication. In the first, the geologist does the initial work but probably is never asked to contribute or review the plans after that. In the second method, the geologist's role is much the same, although no one really knows what anyone else is doing. Neither procedure employs any formal method of development and weighting to select significant elements at an early state of planning. What is needed is an interaction between geological facts, mining facts, and their financial implications.

RISK-REDUCTION PROGRAM

To accomplish this interaction, a "risk-reduction" program similar to the one used in Europe is needed (Elliott, 1974). A loop or cycle is set up (fig. 2). For example, the additional geologic data from the drilling program contribute to the "Assessment and Classification of Reserves." Other potential problems can also be identified, leading to the "Risk Reduction Program." Here the flow separates, either back to the "Risk-Reduction Action" and more drilling or investigations until the risks are reduced, or to the "Mining Simulation Program." If time and money permit, it would probably be better to go through the "Mining Simulation Program" before going to "Planning," in order to test the mining strategy against the probable geology. From there the flow is into the "Action Planning," or actually taking the mine from the drawing board to reality. The flow then is into the actual "Mine Operations," but the flow does not stop there. It should continue back to the "Assessment" step where the cycle begins again; the mine plan should be continually updated using the available information and should therefore cut down the potential risk involved.

The geologist should be involved in all phases of this system. In the past, he has been involved in only one or two areas, but this was in error. He should be involved in the

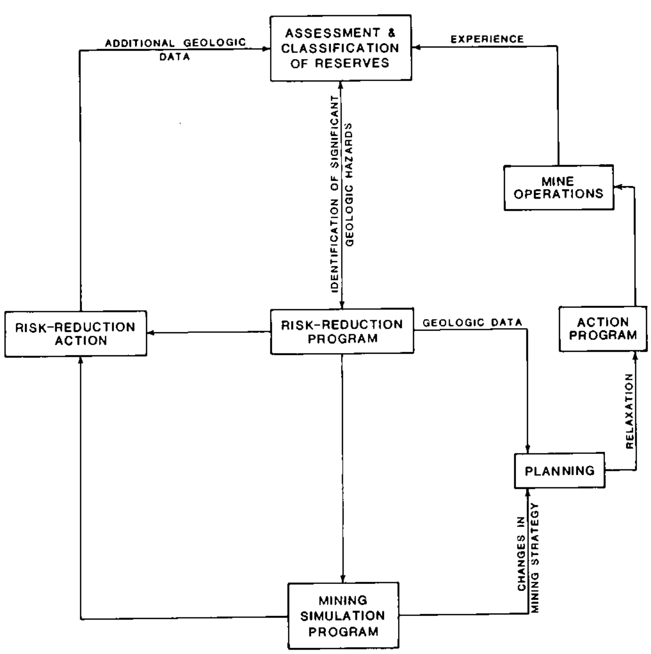

Figure 2.--Risk-reduction program. From Elliott, 1974.

"Planning," "Action Program," and "Mine Operations," as well as in the "Assessment and Classification of Reserves."

The key to successful "risk reduction" lies in following a formal procedure which asks what could go wrong with the plan, with what degree of threat; what the likely causes are; what action can be taken to solve the problem; which action is worthwhile financially; and how its implementation can be brought into being. If these questions can be answered, then the chances for improving both productivity and safety are enhanced.

Geologic Factors That Can Affect Mining

A number of geologic factors can affect the mining of coal. Obviously the list can be fairly long (table 1).

Because the topic of environment of deposition is covered in other papers (Horne, this volume; Kaiser, this volume), it is not discussed here; however, it does play a major role in mine design and layout.

The most serious hazard of a geologic nature today is a roof fall, which is the cause of the largest number of fatalities in mines (table 2). The majority of these falls are due to either geologic conditions, poor mining practices, inadequate support, or carelessness on the miners' behalf. Because geologic factors are the main concern of this paper, the geologic conditions that are related to roof falls will be examined, and possible methods of prediction and possible solutions will be discussed.

Washouts

A washout causes problems not only because the coal is thin or missing but also with mine roofs. The following examples indicate how the existence of these abnormalities can be foreseen if attention is given to geologic detail and analysis. Figure 3 is a compilation of the major problems that can be associated with a washout; in this case, sandstone has cut out the coal (MESA, 1977). One of the first problems usually encountered when approaching such a channel is water. Abnormal amounts dripping from the roof bolts are a cause for alarm. Also the roof rock tends to become more fractured as the washout is approached, and numerous slickensides are in evidence. These problems lead to very dangerous roof conditions. Another unique feature that has been noted in a number of mines is a tendency for the sulfur content to increase (sometimes more than double) as the channel is approached. Figure 4 is an example of a channel approaching and occasionally cutting the coal. Not only does it affect the coal quantity, but also the quality. In this mine in the Pittsburgh coal, on

Table 1.--Geologic Factors That May Cause Mining Problems

1. Washout and channel cuts	7. Environment of deposition
2. Faults	8. Partings or splits
3. Structure	9. Gas content
4. Nature of roof and floor strata	10. Joint and cleat patterns
5. Slickensides, horsebacks, and kettle bottoms	11. Proximity of water-bearing formations
6. Differential compaction	12. Pyrite inclusions

the shale side of the channel the sulfur content is less than 2 percent, but on the sandstone side, it ranges between 2 and 3 percent.

When a sandstone channel or washout is approached, the coal sometimes will become abnormally thick and the number of partings will increase. Figure 5 is a drawing of a sandstone channel and its relationship to a split in the Freeport coal (McCulloch, Jeran, and Sullivan, 1975). The split can greatly affect the reserve estimates, as well as roof conditions, owing to differential compaction. The roof tends to be much poorer and more prone to falls above the sand-shale contact zone than elsewhere in the mine. Another example of a split related to a sandstone channel can be seen in figure 6. In this case the Bechley coal of West Virginia splits and quickly reaches unminable thickness. Another important fact to be observed here is that if this had occurred underground and this coal was being mined, the roof bolts normally used would not have been long enough to bolt through the sandstone unit up to a competent strata.

In the Pittsburgh coal bed, the thickness of coal has gone from 7 to 12 ft within 150 ft horizontally, and then to 6 in. within another 50 ft when approaching a washout. The cutoff by the sand or shale of the washout can be abrupt. This abrupt change is one major way to tell the difference between a washout and an area of nondeposition. Figure 7 shows a channel cutting into the B seam in Colorado. This channel did not cut completely through the coal but still would have caused mining problems if it had occurred underground. Figure 8 shows another example of the same thing, this time in the Pittsburgh coal (McCulloch, Diamond, and others, 1975). TH1 was the "normal" coal hole. Observations revealed no major problems, but TH2

Table 2.--Number of Fatalities in Underground U.S. Coal Mines, by Cause, in 1973, 1974, and 1975

Cause	Fatalities		
	1973	1974	1975
Falls of roof	39	45	47
Falls of face, side, rib, or pillar.	5	4	6
Pressure bumps/bursts	0	1	2
Inrush of water	0	0	0
Haulage	31	15	19
Ignition	2	0	0
Explosives	1	0	0
Electricity	5	5	8
Machinery	15	15	16
Mine fires	0	0	0
All other	0	5	0
Total	98	90	98

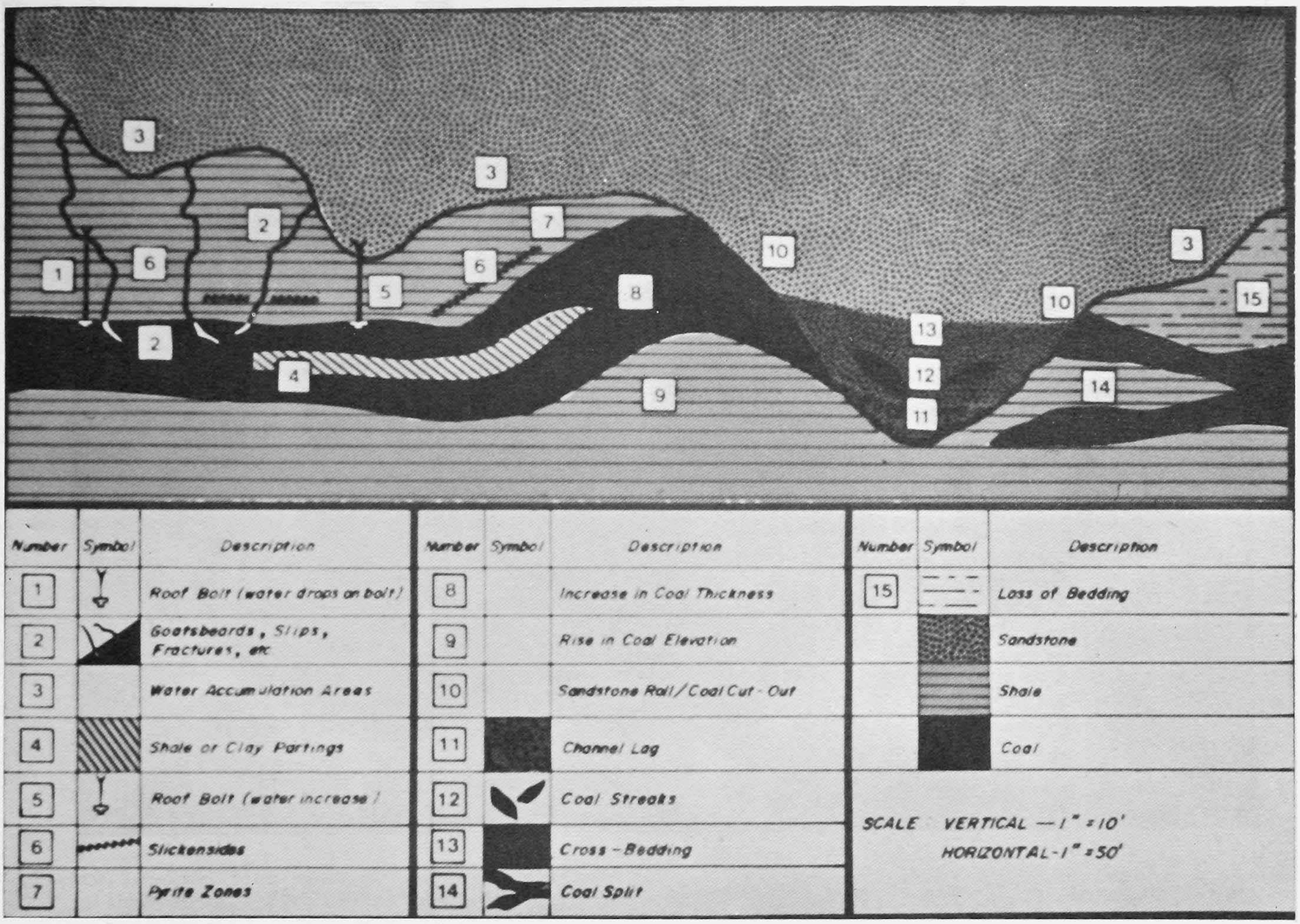

Figure 3.--Features associated with channel washouts. Modified from MESA, 1977.

was drilled at the insistence of the geologist because of washout problems in an adjacent mine. In TH2, the sandstone had cut within 8 ft of the coal; and later, when mining reached the area within 75 ft of TH2, the coal was completely absent. Hence, because of knowledge of this washout on the adjacent property, the location of an area of risk and the problem zone were defined.

Once a washout or channel has been encountered, the important thing is to determine where it is going. The washout presents a problem for any type of mining, but especially for longwall units as a washout cutting through a panel can force the entire panel to be abandoned.

An example of mapping one of these features can be seen in figure 9. A panel or fence diagram was made from core-hole data to cover part of the property in the Pittsburgh coal (McCulloch, Diamond, and others, 1975). The areas where the sand was found to be directly on the coal were marked as potential washouts. Obviously a number of areas in the northern portion of the property were outlined as possible problem areas. Figure 10 shows the actual situation encountered during mining in this and the adjacent mine. Note how many of the washout or sandstone channels are in areas that were predicted as possible problems areas.

Similar results have been found on a property being explored in Utah, where a large washout was encountered. Because of some additional drilling to delineate the body, geologists were able to map the extent and assist in planning the mine around it.

Faults

Faults are another discontinuity that disrupt mining and can affect the roof. Figure 11 shows where a number of strike-slip faults were predicted and later encountered in six mines in the Pocahontas No. 3 coal, and shows their relationship to poor roof conditions in these

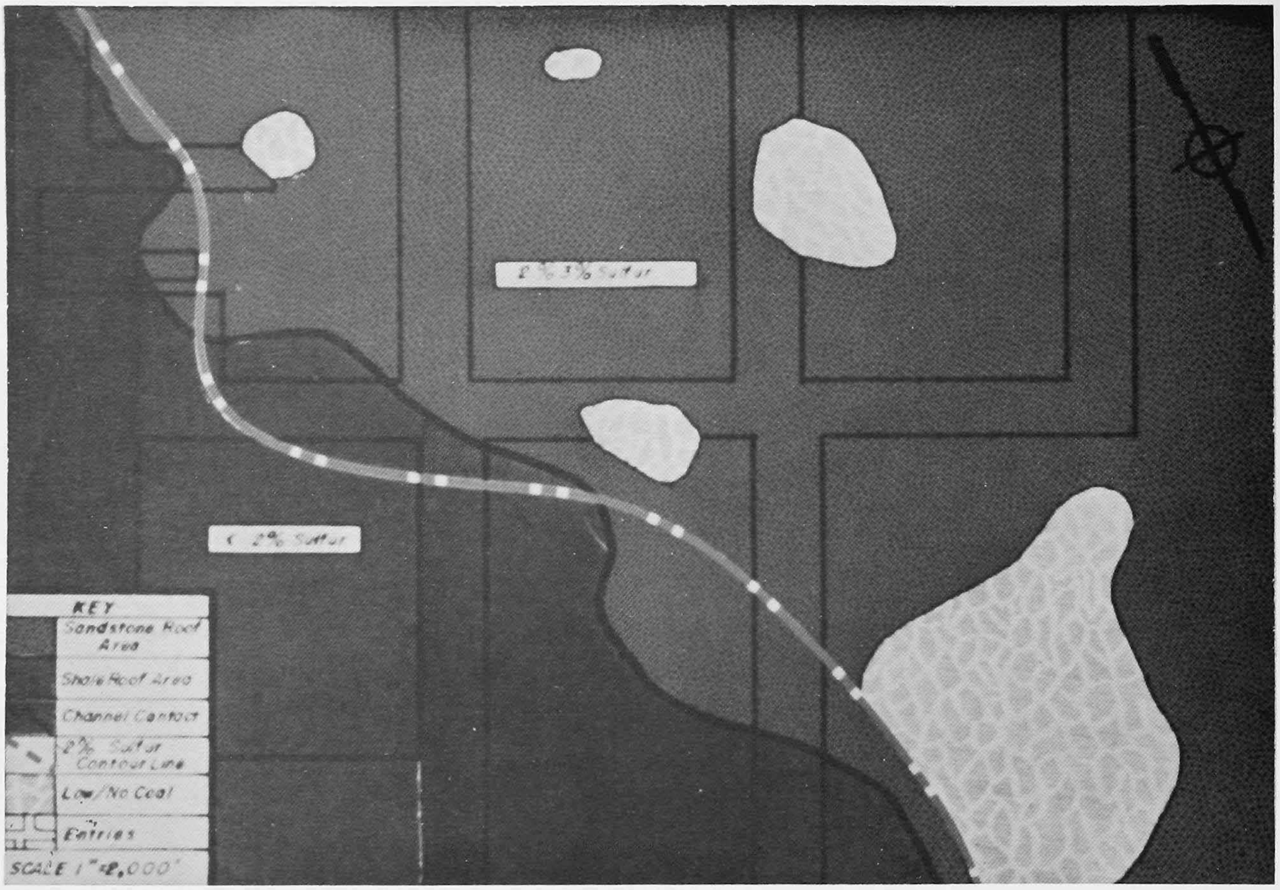

Figure 4.--Mine "X"--Map showing relationship between sulfur content and channel washout.

mines. A surface exposure of the Keen Mountain fault was found in a strip mine (fig. 12) and had a vertical displacement of less than 2 ft. The faulting was originally detected using SLAR (Side-Looking Airshore Radar), but for awhile it could not be located underground. By measuring the cleat direction underground, it was possible to locate the fault (fig. 13) before many entries had intersected it (McCulloch and others, 1974b). For 100 ft on the east side of the fault the zone was badly broken; and, after mining, the roof rapidly disintegrated. Once this fault was located and its orientation plotted, then either a zone was left to allow for the gouge area or the zone was reinforced if mined through; consequently the hazard decreased and, hence, the risk involved.

Low-angle thrust faults present a different problem. As encountered in a mine in the Upper Freeport coal in Pennsylvania, the fault allowed abnormal water and methane emissions into the mine (fig. 14) (McCulloch, Jeran, and Sullivan, 1975). Again, the actual fault did not greatly displace the coal, but it did cause considerable mining problems as the roof had to be cribbed extensively and a great deal of water flowed from the fault plane into the mine, causing haulage problems. In an examination of some SLAR photos of the area, a series of distinct linears was seen on the surface approximately 1,000 ft to the west of the mine. This is roughly where the fault would be expected to intersect the surface. Another pair of sets of linears were observed on approximately 5,000-ft centers past the zone mined, suggesting a high probability of more faults being encountered when mining reached this area. A surface investigation was made, but no evidence of either proposed fault could be found. This original study was done in 1972. Last year the company mined through another series of faults having the same orientation as those originally encountered and in the area where their occurrence had been predicted.

In western coal fields, faults occur that have enough vertical displacement to actually stop mining. In one western mine (Dunrud and Barnes, 1972; Dunrud, 1976) a number of faults were encountered. Because of these faults, a great deal of reserves were lost; also dangerous mining conditions were encountered. The faults did seem to be oriented en echelon and appeared to be at right angles to the strike of the coal

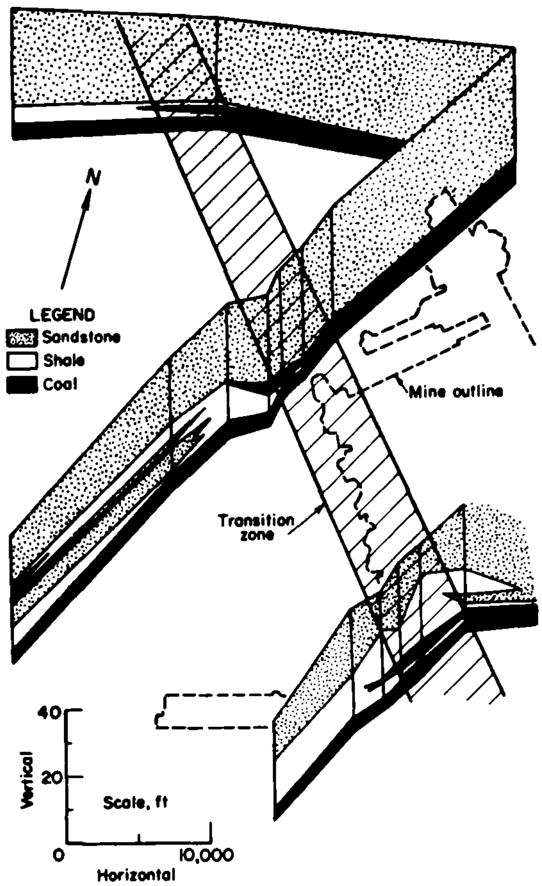

Figure 5.--Sandstone channel and its relationship to a split in the Freeport coal in Pennsylvania. From McCulloch, Jeran, and Sullivan, 1975.

in one part of the mine. Subsidence cracks were also noted; the majority of these appeared to be parallel to the strike or principal joint direction--hence, the greatest zone of weakness. In this mine, it is apparent that a mining system such as longwall panels would be difficult to lay out except in an east-west direction or between the fault zones. Because of the cost involved in longwall, this degree of risk would probably be prohibitive. In a case like this, exploration drilling and surface exploration would not reveal all of these faults, but exploration entries would be beneficial to use in encountering the faults and mapping their orientation as long as adequate ventilation could be maintained.

A number of mines in Colorado and Utah have similar problems, and mapping of the faults through the use of linears observed from photographs is coming into more frequent use and is starting to gain acceptance. Geologists from MESA (Mine Environmental Safety Administration) in Denver, as well as from other groups, are using SLAR, Landsat, and Skylab imagery to locate linears, many of which are turning out to be faults. Much of this type of photography is becoming available to the public; once a geologist gains experience, the recognition of linears is relatively easy (Rinkenberger, 1977).

An example of this is a mine in the west that is over 1,000 ft deep and has a number of faults that have been mapped by the U.S. Geological Survey. Linear features seen on NASA (National Aeronautics and Space Administration) color-infrared photographs at a scale of 1:120,000 closely matched the location and orientation of the mapped faults. From the photographs it was also possible to extend the surface linear expression of these faults for almost 2 mi beyond the mined area. Other linear features crossed the faults, forming intersection anomalies. In talking to mine officials, the MESA geologists found that numerous roof falls occurred at these locations. Several other anomalies were located in virgin coal; hence, these are areas that merit special watching as mining progresses toward them.

Studies by Dunrud (1976) of Skylab 2 color-infrared imagery of parts of Colorado indicate that most lineaments (fig. 15) occur along streaks which in turn occur along linear, profusely jointed or faulted zones. Indeed all but one of the major trends of these lineaments parallel the dominant trends of the faults and joints that span the district.

Joints and Fractures

In another study in Pennsylvania, linears were mapped from infrared photographs. These were compared with the surface rock joints and the coal cleat orientation measured underground in a mine (McCulloch and Deul, 1973). Figure 16 shows the results of this study; it is noticeable that the coal face cleat, the systematic (or principal) rock joints, and one of the three regional linears are oriented in the same direction. Hence, linears can be used not only to predict faults, but also the principal rock and coal cleat orientations. These features can also be related to roof conditions; studies have shown that the poorest roof conditions occur when the linears are parallel to the entries. In a mine where a number of falls have occurred along an entry that was parallel to the principal joint orientations in the roof (and the linear orientation, if photos are available), it was found that by turning the mine layout 45 degrees, the problem was greatly reduced. The falls that occur because of the mine layout not only cause an inconvenience, clean-up problems, and problems with methane emission, but may also cause serious inuries. Figure 17 is an example of a fall that occurred in the Pittsburgh coal (Moebs and Curth, 1976). Note that, within the caved area, other coals were encountered. When the falls occurred, large emissions of gas from the other coals, shales, and mudstones entered the mine, causing

Figure 6.--Sandstone split in the Bechley coal in West Virginia.

the section to be shut down until the ventilation could reduce the methane concentration to within an acceptable limit. Similar results were found in other mines. In one, little gas was encountered during advance mining of the outlining of pillars, but upon retreat, when the pillars were extracted, the roof rock fractured and the methane emissions forced constant shutdowns and critical emission problems.

Cleat

Cleat, or the vertical fracture in coal, also plays an important role in coal mining. In the past, mining was usually done parallel or perpendicular to the cleat because the coal broke away from the face more easily, but today that is no longer the case. With the advent of continuous and longwall systems, coal can be mined as rapidly in one direction as another, but cleat is still important in mine layout and design because it affects the flow of water and gas into the mine.

A number of studies have been done recently to determine if it would be possible to predict the coal cleat orientation before mining in order to anticipate water- and gas-flow problems (McCulloch and others, 1974b; McCulloch and others, 1976). In Alabama (fig. 18), a new mine was operating a couple of hundred feet below a seam which was to be abandoned. An unmined seam at the surface was also examined. By measuring the cleat orientation of all three, it was found that the cleat orientations were very close (fig. 19). The face cleats were particularly well lined up.

Figure 7.--Channel cutting the B seam in Colorado.

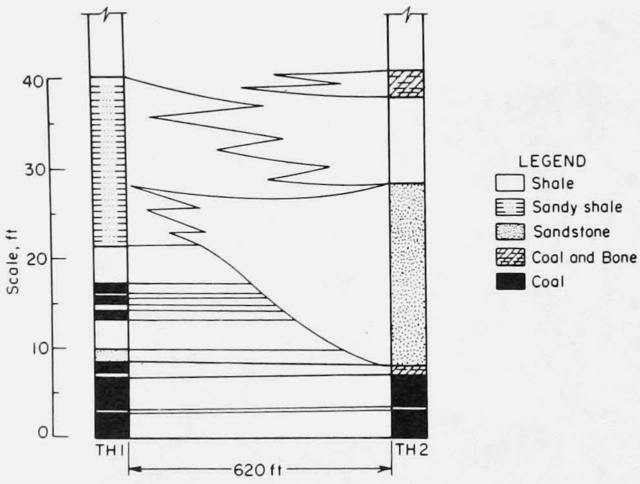

Figure 8.--Sandstone channel cutting into the Pittsburgh seam in Pennsylvania. From McCulloch, Diamond, and others, 1975.

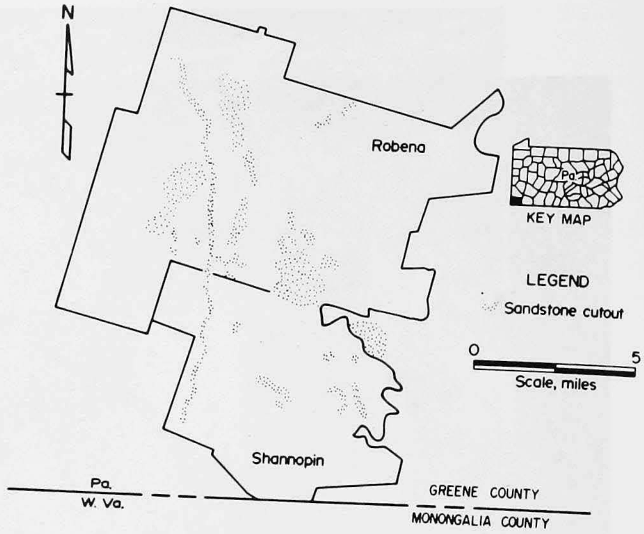

Figure 10.--Sandstone channel washouts encountered during mining of the property in the Pittsburgh coal. From McCulloch, Diamond, and others, 1975.

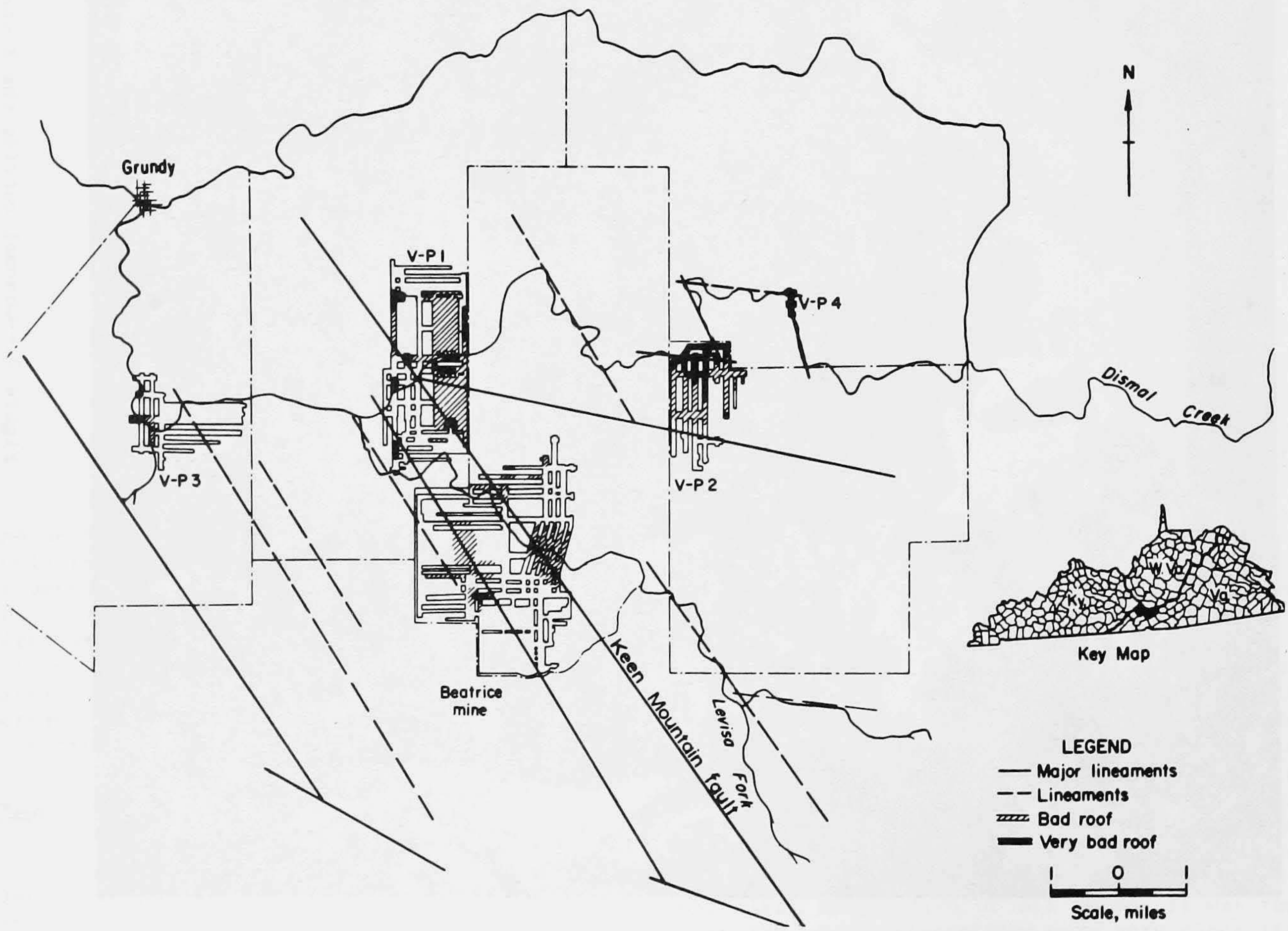

Figure 11.--Strike-slip faults observed from SLAR (Side-Looking Airshore Radar). From McCulloch, Jeran, and Sullivan, 1975.

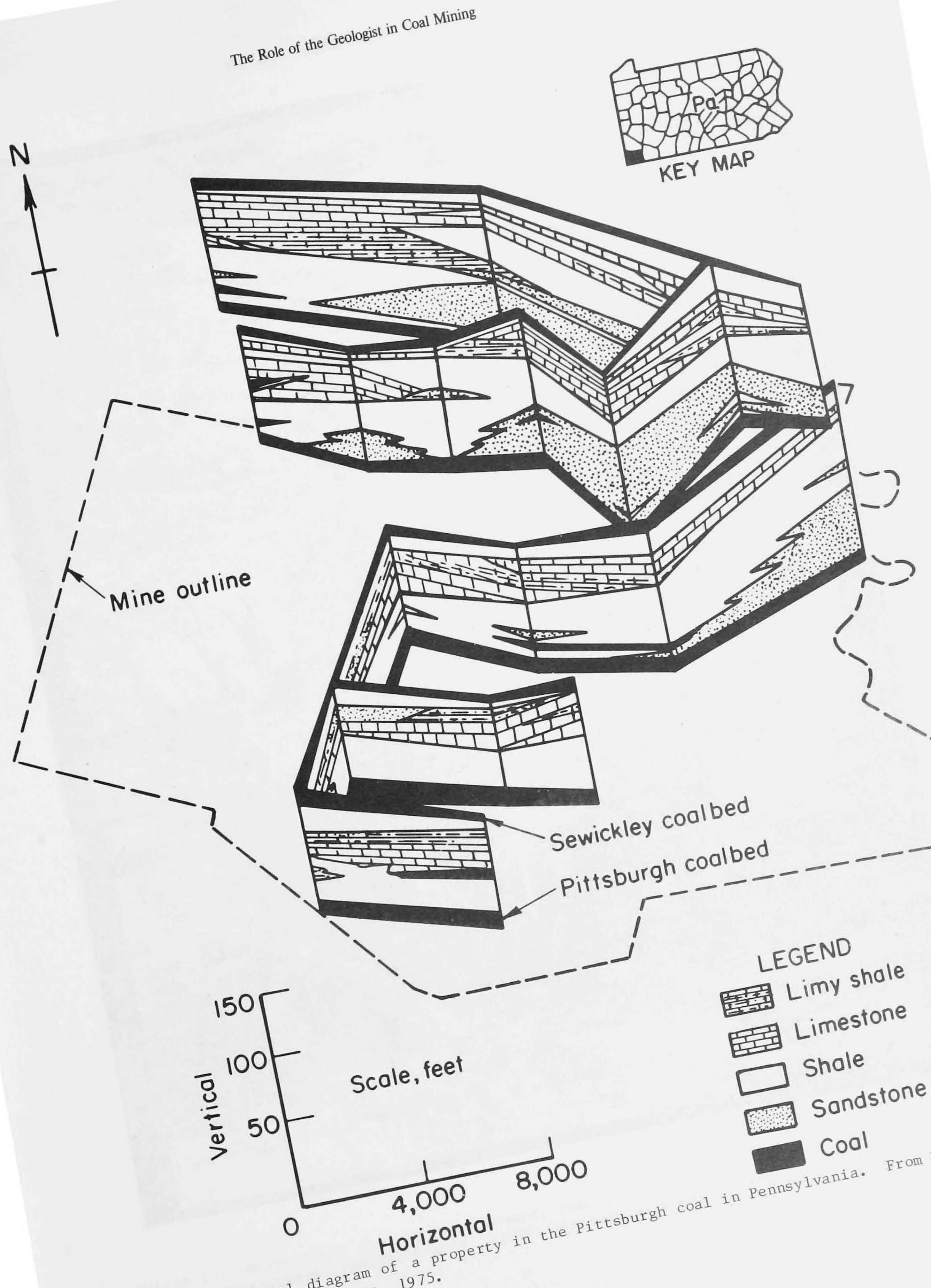

Figure 9.--Panel diagram of a property in the Pittsburgh coal in Pennsylvania. From McCulloch, Diamond, and others, 1975.

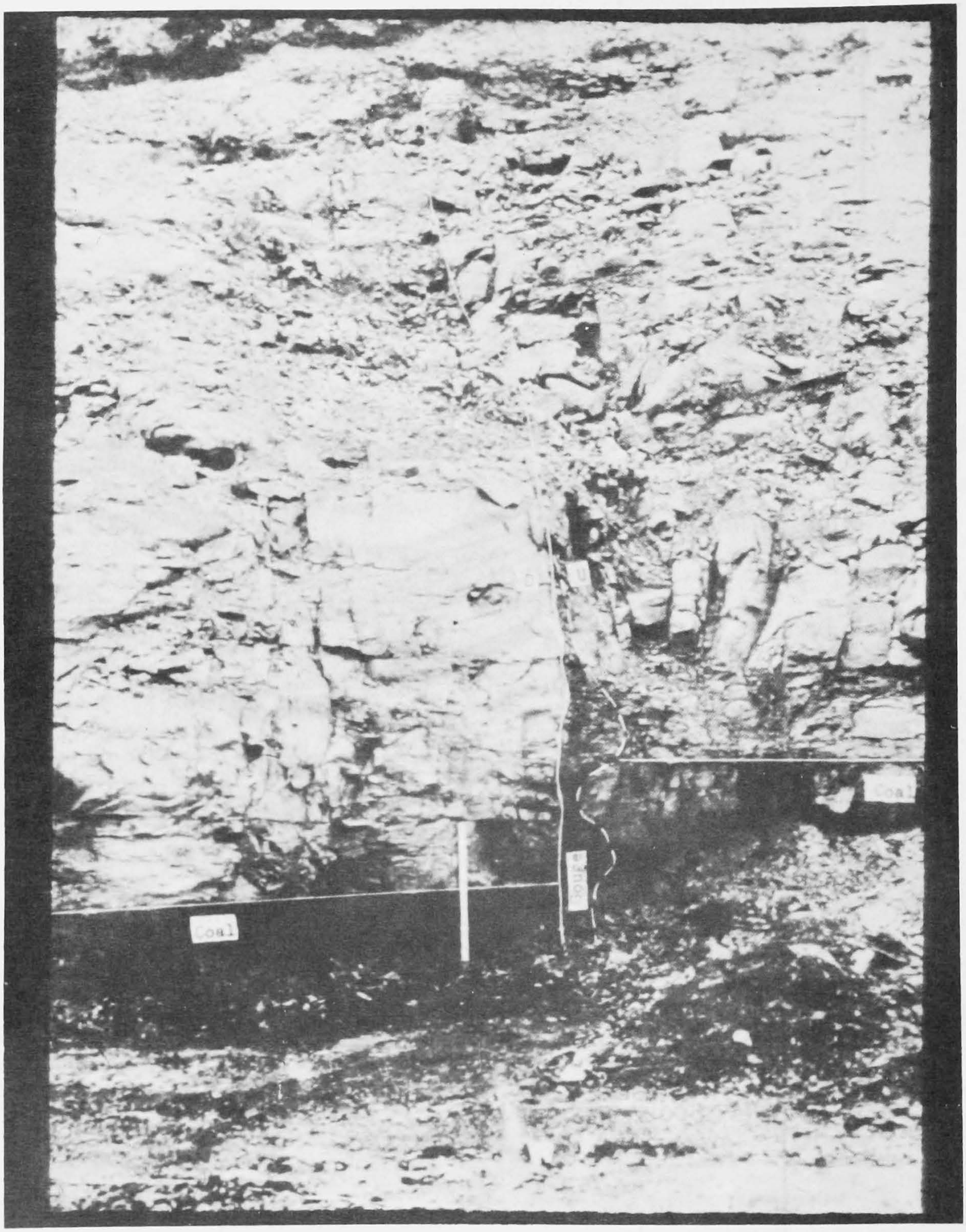

Figure 12.--Surface expression of the Keen Mountain fault. From McCulloch, Jeran, and Sullivan, 1975.

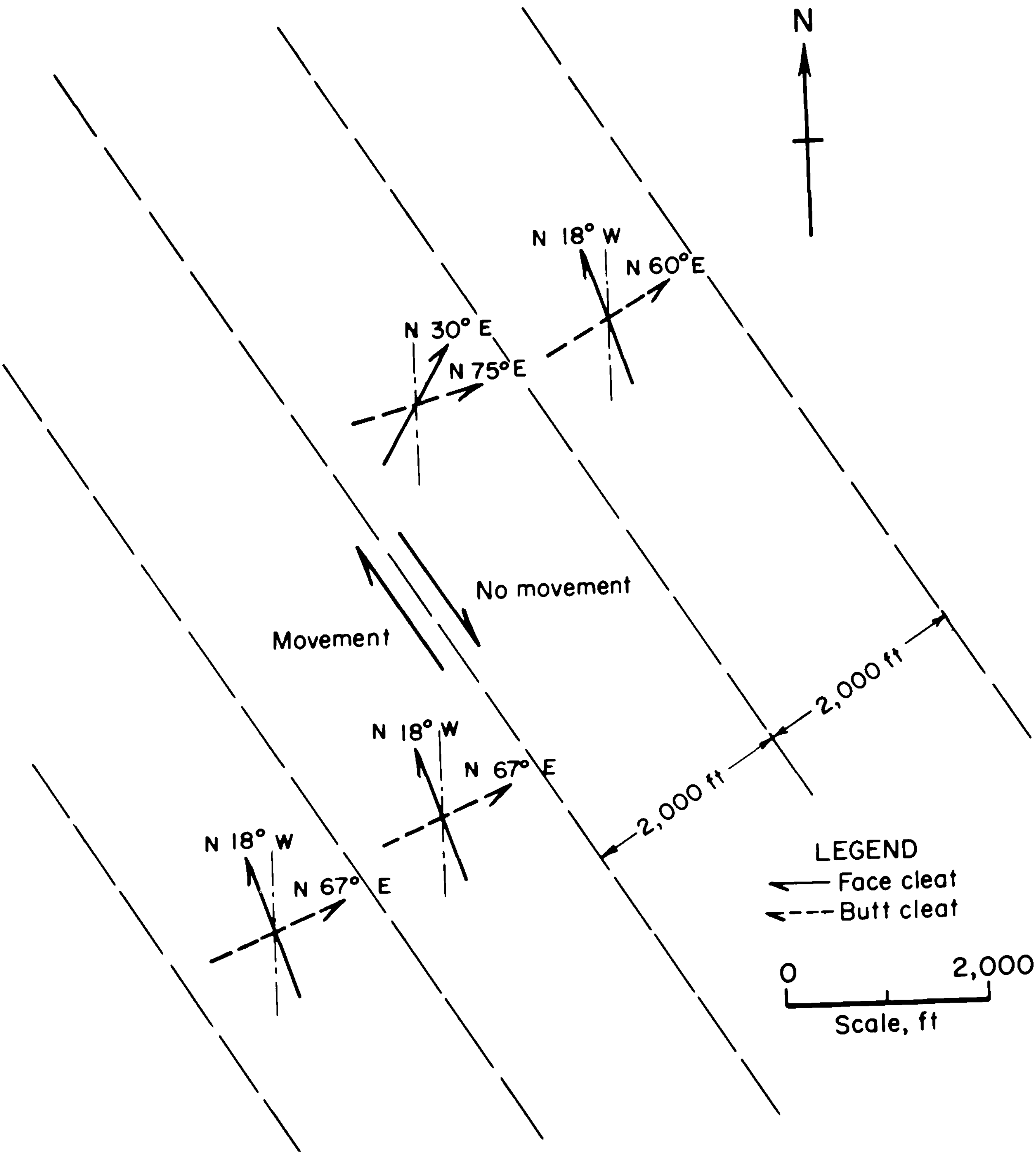

Figure 13.--Measurement of cleat underground, used in locating strike of fault. From McCulloch, Deul, and Jeran, 1974b.

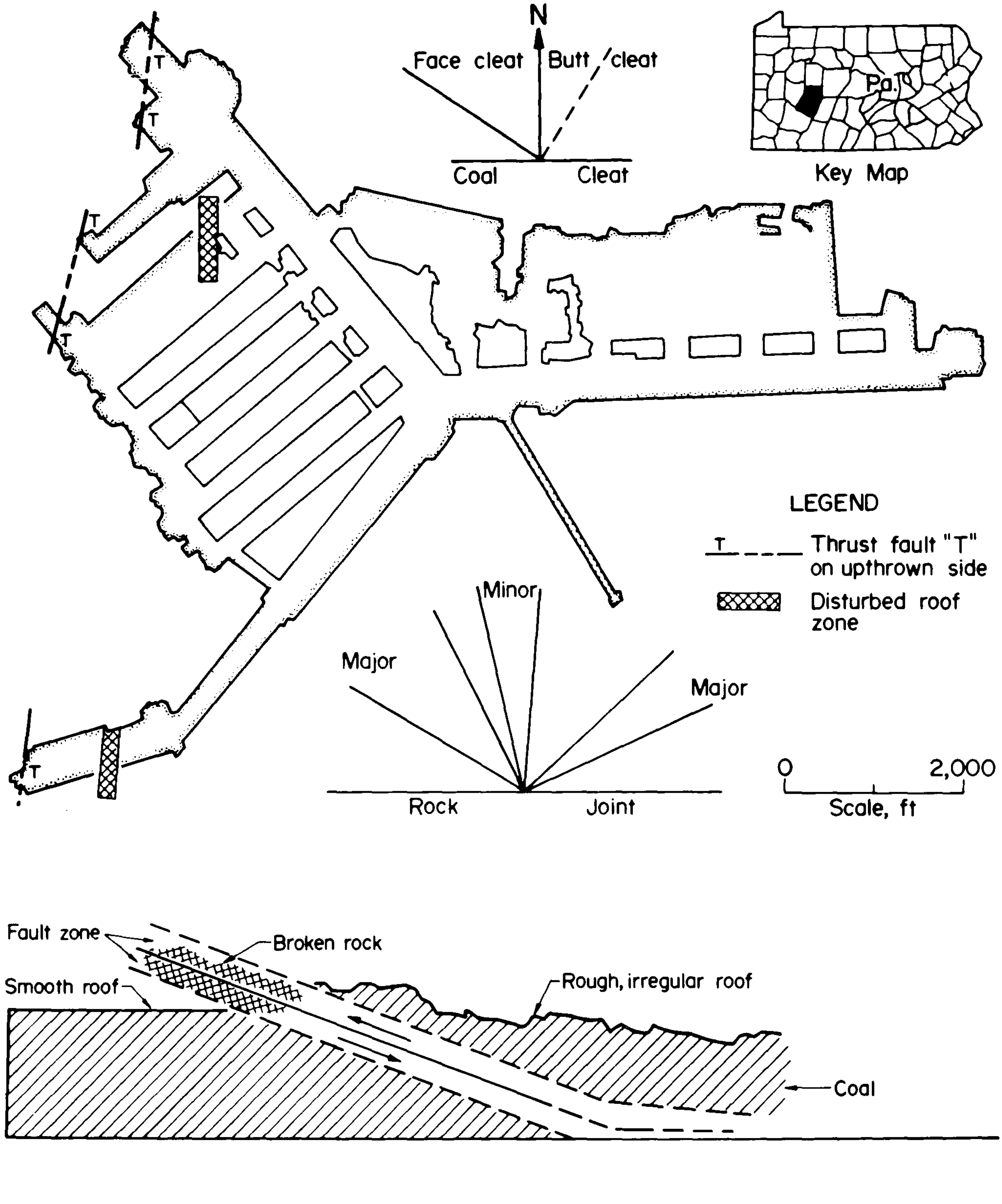

Figure 14.--Low-angle thrust fault in the Upper Freeport coal of Pennsylvania. From McCulloch, Jeran, and Sullivan, 1975.

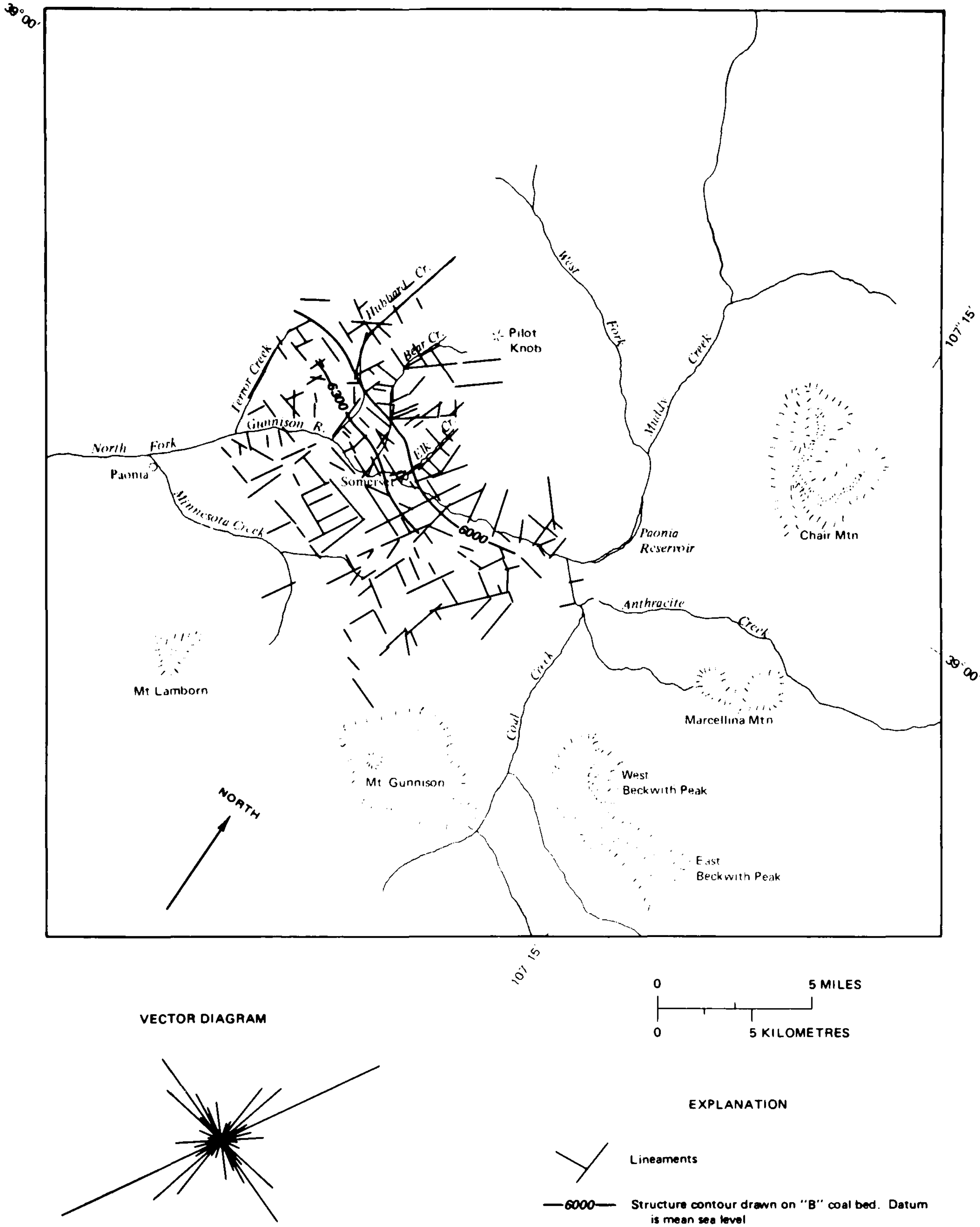

Figure 15.--Lineaments related to stream patterns. Modified from Dunrud, 1976.

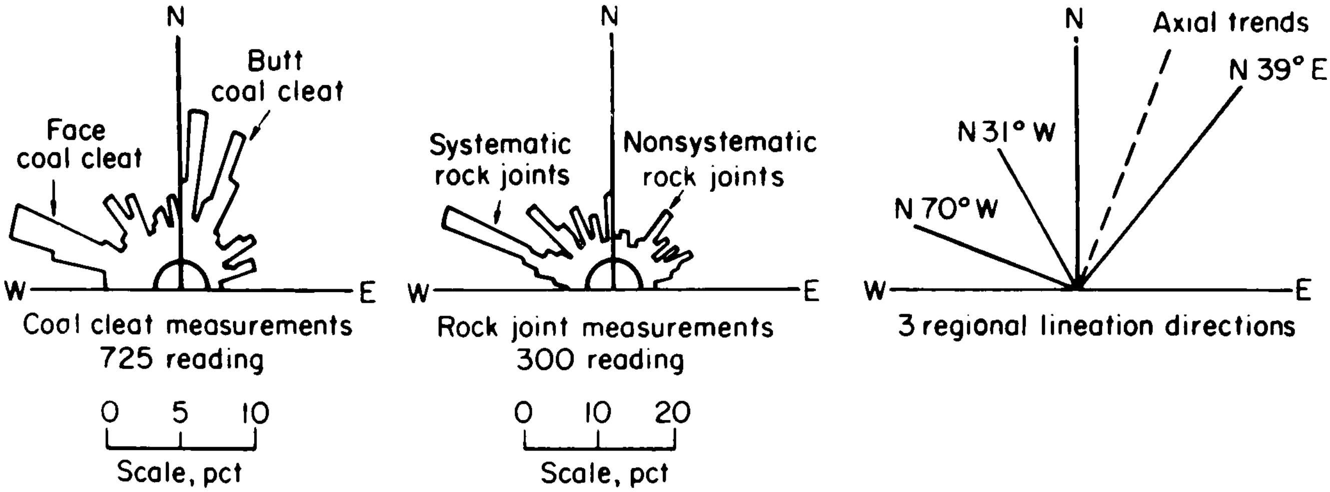

Figure 16.--Relationship between coal cleat, surface joints, and regional linears. From McCulloch and Deul, 1973.

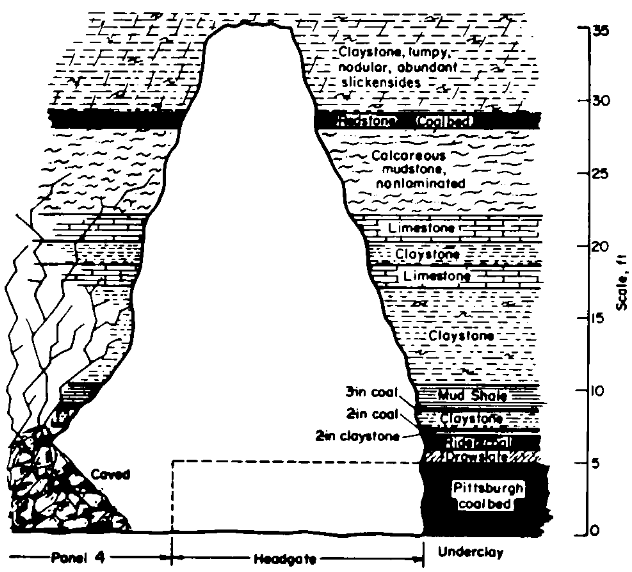

Figure 17.--Example of roof fall in the Pittsburgh coal in Ohio. From Moebs and Curth, 1976.

A similar study in West Virginia was done to substantiate these results. Here six coals were being stripped on a mountainside over 350 ft vertical section (fig. 20). Again, the face-cleat directions lined up well. On the basis of these data and a number of other studies, it was determined that coal cleat orientation could be predicted before mining.

As mentioned earlier, the principal cleat orientations are important because of the directional permeability in coal beds. This permeability is directly related to the two main cleat directions. This can be important in the mine design if the seam is considered to be gassy. Tests in the past, in which horizontal holes parallel and perpendicular to the face cleat have been drilled in the coal, have shown that a hole drilled into the coal bed perpendicular to the face cleat can be expected to yield a much higher gas flow (up to a factor of 10) than a hole perpendicular to the butt cleat. The reason for this is that the face cleat is a longer, more continuous joint surface. It crosses bedding planes in the coal and can extend for a distance of many feet. The butt cleat, on the other hand, is short, is often curved, and is a discontinuous feature that frequently terminates against the face cleat.

Figure 21 shows how a hole drilled horizontally and parallel to the butt cleat (perpendicular to the face cleats) would intersect the more permeable face cleats and therefore drain a greater area. In contrast, a hole drilled horizontally and parallel to the face cleat (perpendicular to the butt cleat) would intersect the butt cleats, which are shorter in length and less frequent (McCulloch and others, 1974b).

One test in which this theory was examined was conducted in a mine in the Lower Kittanning coal. Two holes were drilled horizontally into the coal bed parallel to the cleat directions at N. 65° W. and N. 25° E. directions. The gas pressure, after the hole was sealed along the N. 65° W. direction, was 12 psi, whereas the pressure measured along the N. 25° E. direction was 30 psi. This test was repeated in two other

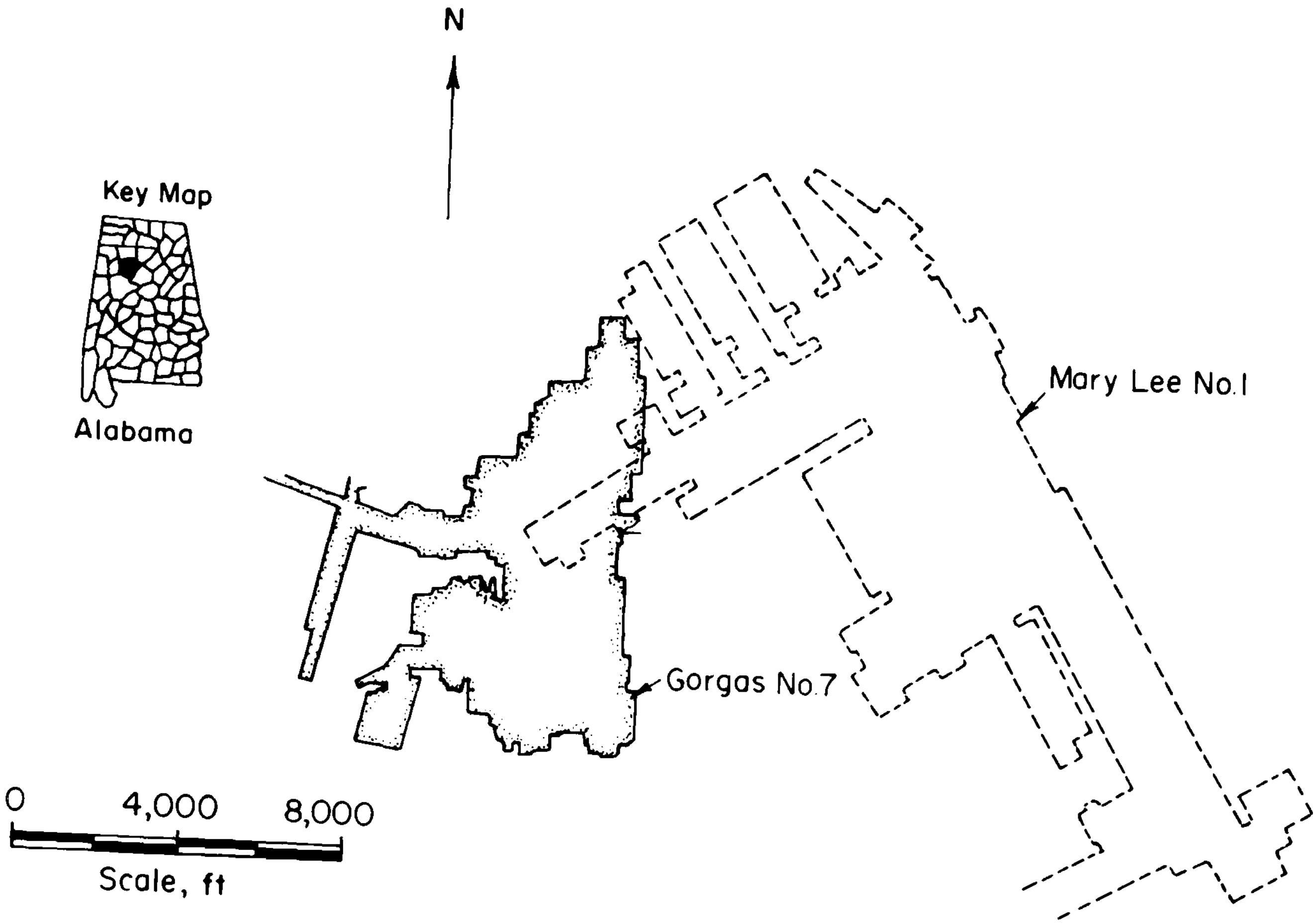

Figure 18.--A mine operating over another mine in Alabama. From McCulloch, Lambert, and White, 1976.

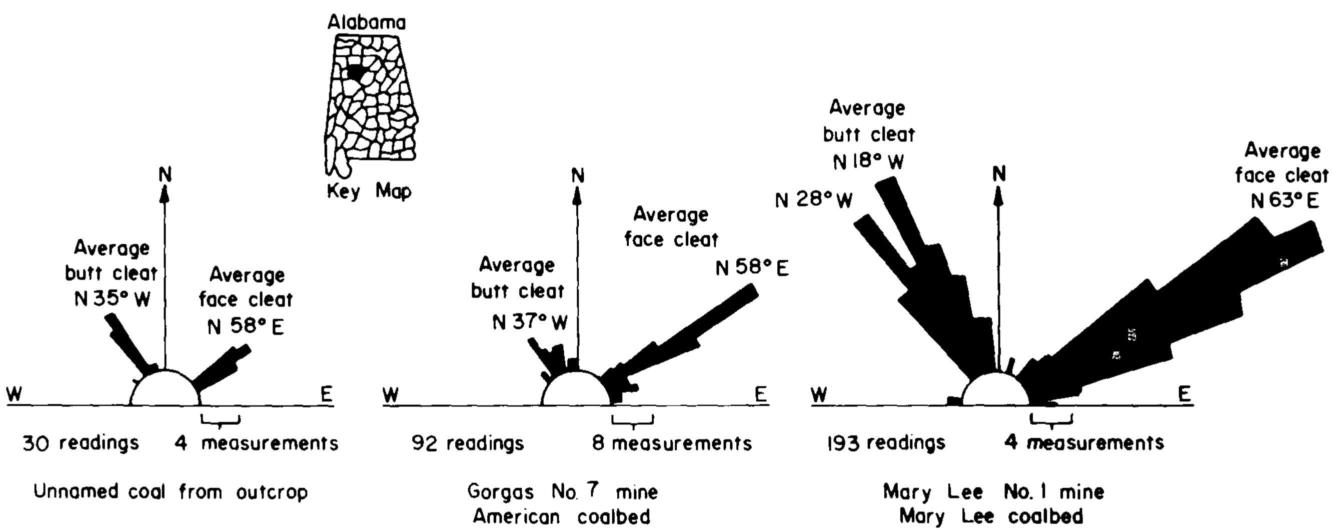

Figure 19.--Cleat orientations in surface coal outcrop and two underground mines. From McCulloch, Lambert, and White, 1976.

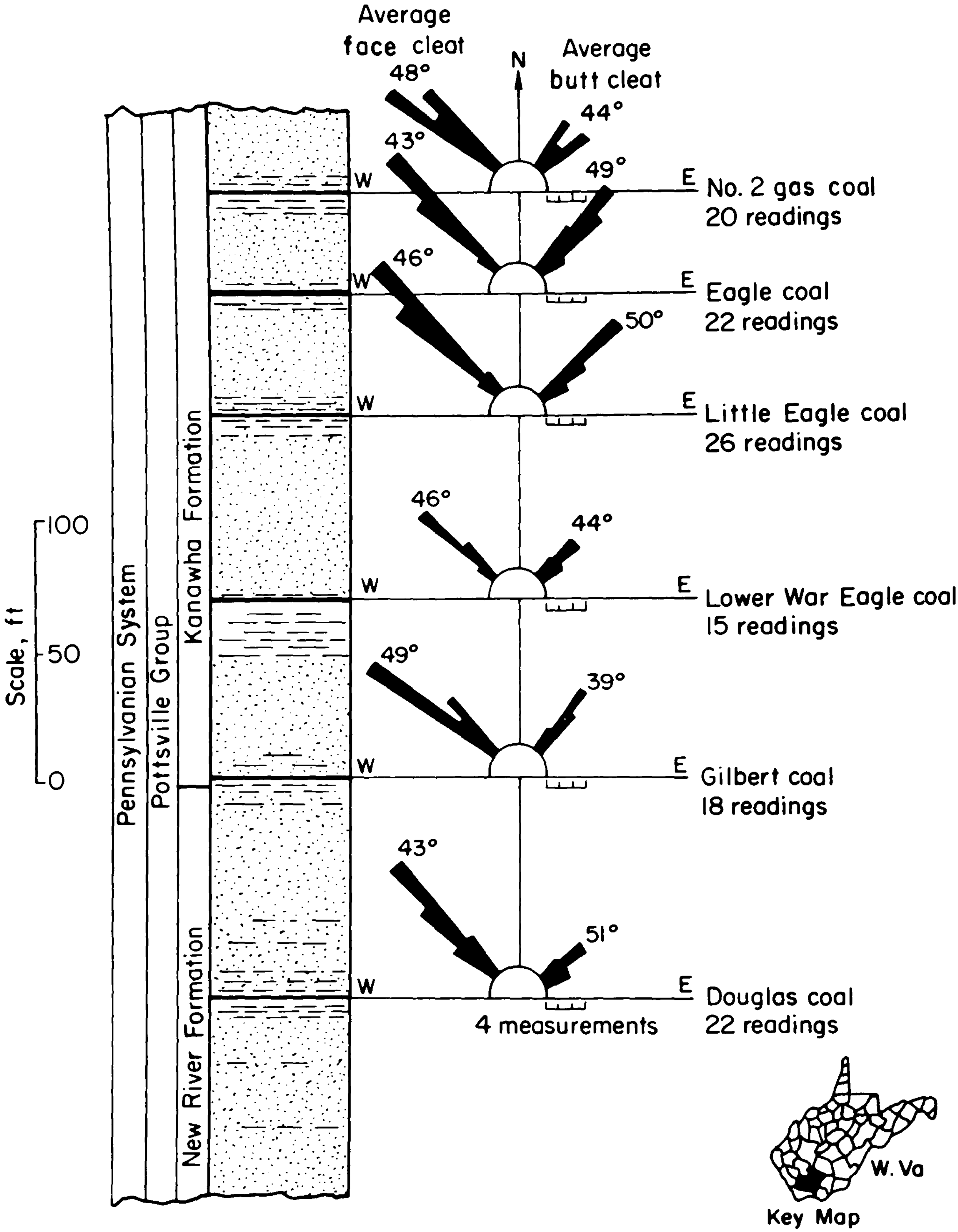

Figure 20.--Cleat orientations in six coals being stripped in West Virginia. From McCulloch, Lambert, and White, 1976.

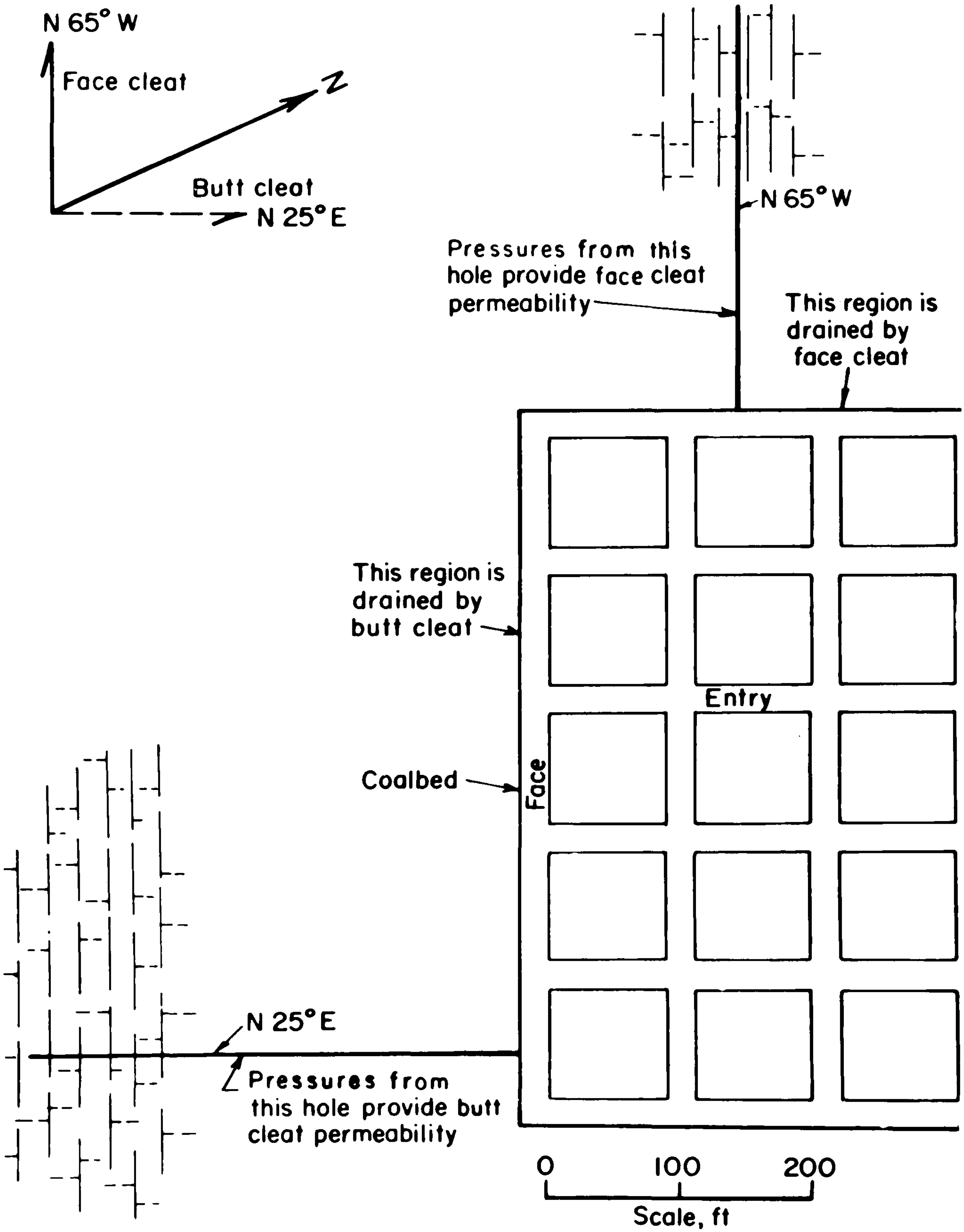

Figure 21.--Two holes drilled horizontally into coal to determine relationship of cleat orientations to gas pressure. From McCulloch, Deul, and Jeran, 1974b.

coal beds and similar results were found; hence, the cleat would be important in a gassy coal in that it could be used to control the location of the higher gas emission--on the main entries or crosscuts.

Structure

Another important geologic factor that is recognized but not always fully utilized is the structure of the coal. During exploration the structure of the coal and, occasionally, of other key marker zones is mapped. The generally simple structure of most U.S. coals allows simple mine designs and layouts. However, when the structure is complicated by folds and faults, more elaborate mining layouts are required. These involve extensive development before the seams can be entered. Structure is used by the mining engineers in the layout of a mine; for example, to lay out longwall panels. Usually these are laid out parallel to the strike of the coal such that the coal may be conveyed downdip on the face, assisted by gravity.

Structure should be considered in the location of the mine shafts as well. In a number of documented cases, the mine shafts were located at the center of the property, regardless of other factors. This was normally done because the haulage distance was the shortest from all parts of the property. The idea looks good on paper, but underground, before a property is mined out, another shaft is normally sunk to cut down on haulage. Hence, the location of the original shaft in the center of the property is not always necessary.

In one case in West Virginia, a mine was planned and the shafts were located in the center of the property. This also happened to be the axis of a syncline in a very wet coal seam. A study was done in this mine shortly after it opened and the water was as much as 2 ft deep in the 10 rooms outlined, with over 35 ft of water in the coal bin. It took over a year to get the water problem under control. The mine also had trouble with gas emission, as both water and gas were flowing downhill. Figure 22 shows the gas bubbling from the center of the floor of the mine. Because of the water and gas problems, the production was less than one third of that anticipated for the first year. If the shafts had been moved onto one of the flanks of the syncline, the water problem could probably have been controlled without affecting production.

Structure can also affect coal deposition. In a study performed in the Pittsburgh coal, many of the thin coal deposits (less than 4 ft thick) were found to be on the axis of anticlines, whereas many of the thick deposits (greater than 8 ft thick) were in the troughs of synclines (fig. 23).

When structure and its relationship to mining are discussed, the cleat orientations should also be considered because studies have shown a relationship between these two (McCulloch and others, 1974a). The cleat in bituminous coal beds was probably formed by local structural forces rather than by internal forces within the coal, such as resulted during diagenesis and compaction. The face cleats tend to be perpendicular to the axial trends of the folds and probably formed as extension fractures. The butt cleats tend to be parallel to the axial trends and formed after the compressive forces were released. Figure 24 shows the structural axis of the folds in the Pittsburgh coal in relationship to mines in which the cleat orientations were mapped. Note that, in the majority of cases, the butt cleat is parallel to the axial trends, whereas the face cleat is perpendicular to it.

In tectonically disturbed areas, there are places where this relationship does not hold true, but in the large majority of areas, this relationship can be used, before any other information is available, as a quick estimate of the orientation that the structural axes will take.

Nature of Roof and Floor Strata

Another feature that has received increasing attention recently is the nature of the strata above and below the coal to be mined. A great deal of data can be determined from coal logs, but even more can be collected as advancing entries are driven. Mapping of the strata that make up roof falls is important, as this is one of the only opportunities to record the type of strata that are within the fall zone. Figure 25 shows a coal with the roof bolts anchored, for the most part, in an incompetent claystone. If the roof bolts had been only a foot or two longer, they would have been anchored in a competent limestone. As it was, a fall occurred and caused a great deal of trouble.

To take this a step further, if one unit is known to fail or a great many falls occur in it, then there are two possible solutions: The first is to take that unit down, or at least reduce its thickness. The second choice is to design a different support system. Obviously the choice is not this simple--the thickness of the incompetent unit, its extent, and its location in the mine are all important--but something has to be done.

Knowing the vertical and lateral extent of an incompetent unit can greatly assist in planning a mine. An example of this can be seen in figure 26. Here a draw slate unit above the coal caused a number of problems, mainly roof falls. The unit ranged from 0 to 10 ft thick. When the unit was less than 4 ft thick, little inconvenience to mining was normally encountered; but when it was thicker than 4 ft, some precautions needed to be taken. By knowing this, the company was able to redesign its bolting lengths and patterns, and falls were decreased by

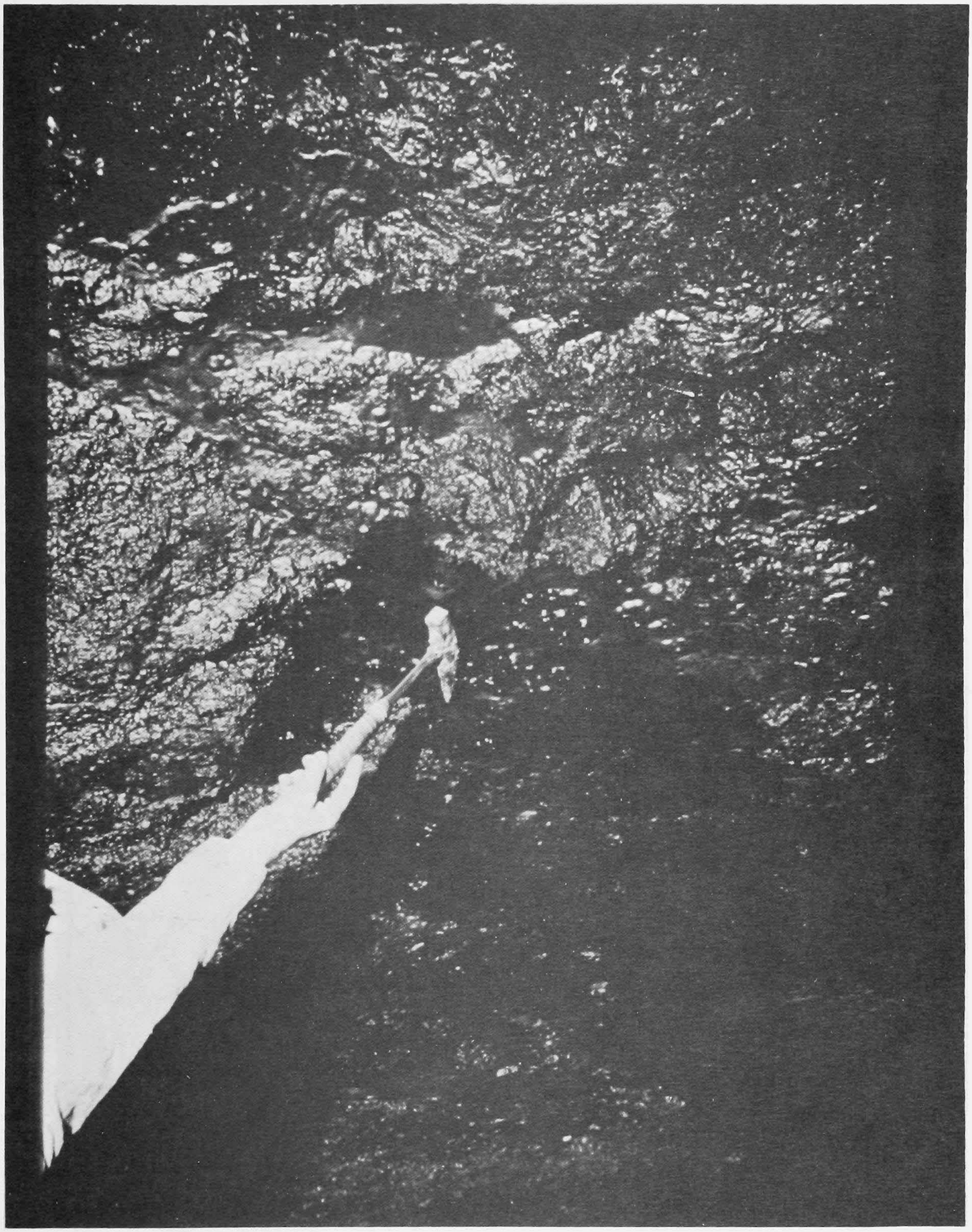

Figure 22.--Gas bubbling from the floor in the Bechley coal.

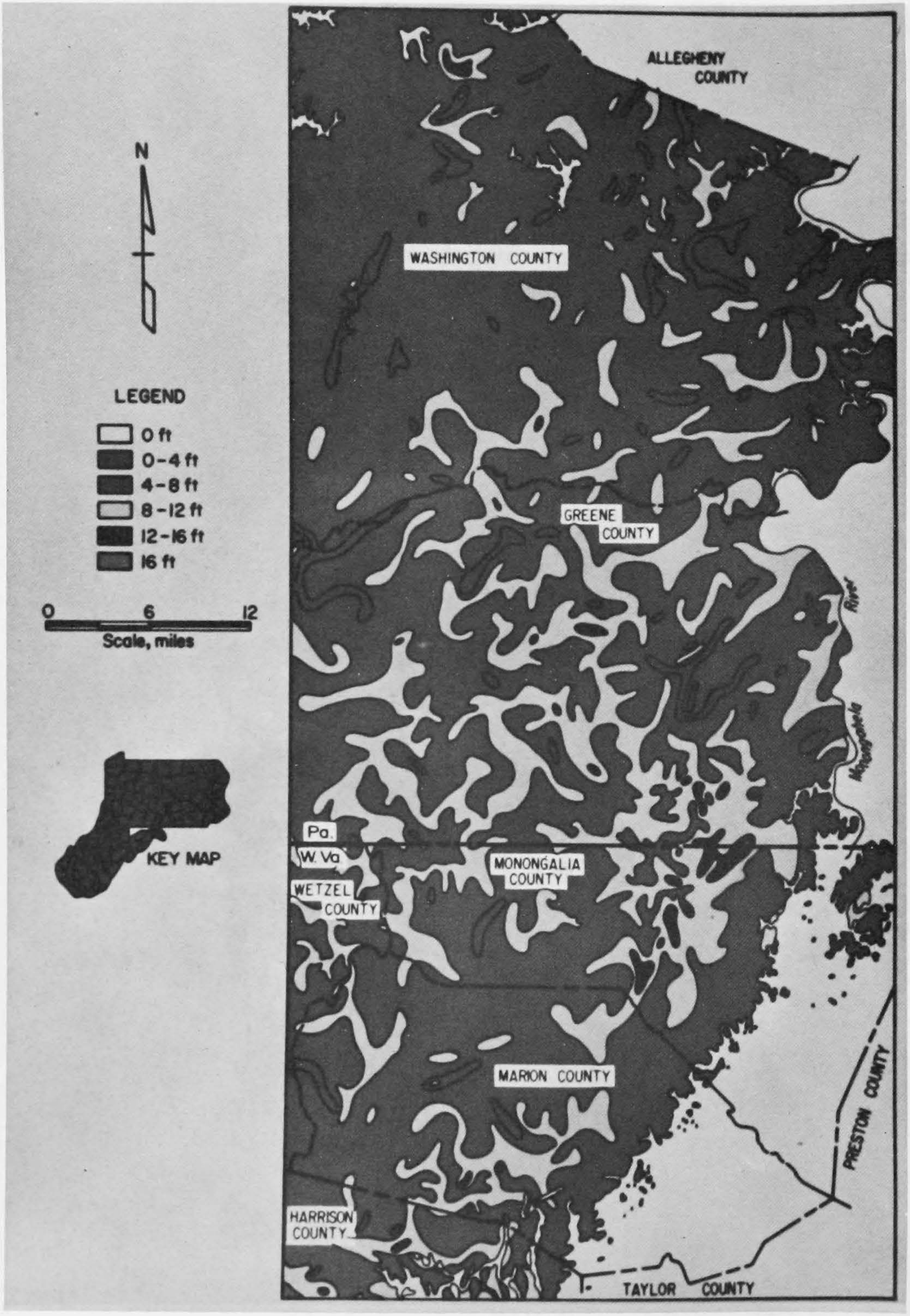

Figure 23.--Isopach of Pittsburgh coal. Modified from McCulloch, Diamond, and others, 1975.

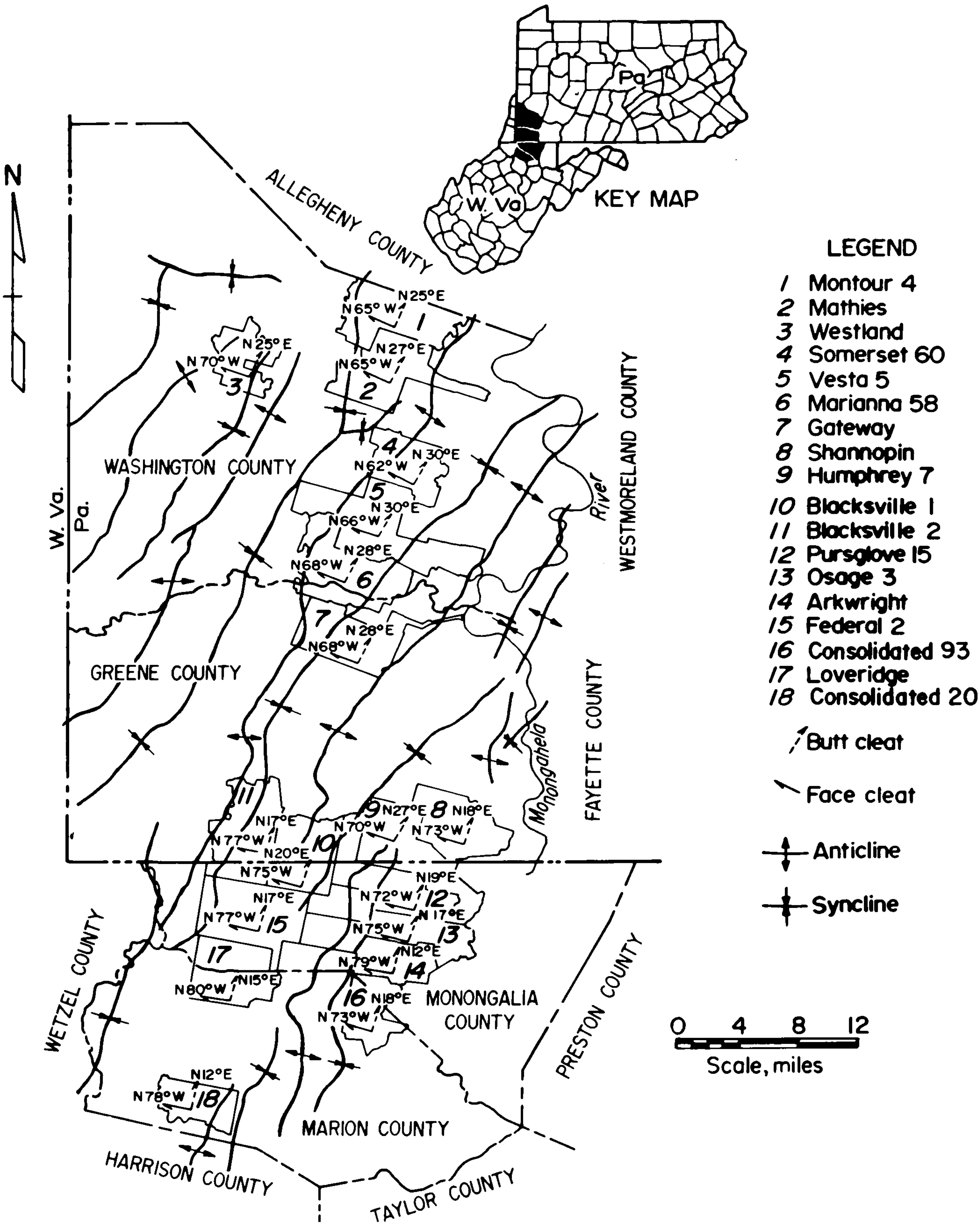

Figure 24.--Structural axes of folds in Pittsburgh coal and their relationship to the cleat orientation. Modified from McCulloch, Deul, and Jeran, 1974a.

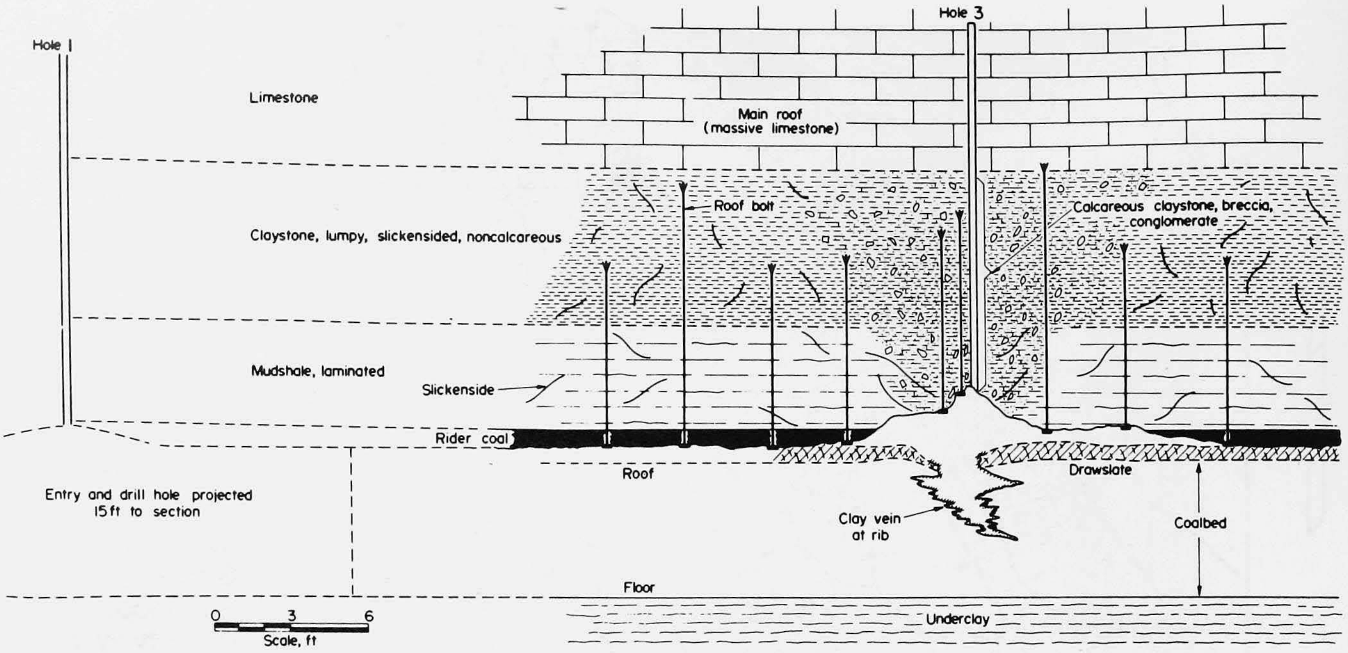

Figure 25.--Roof bolts anchored in incompetent strata. Modified from Moebs and Curth, 1976.

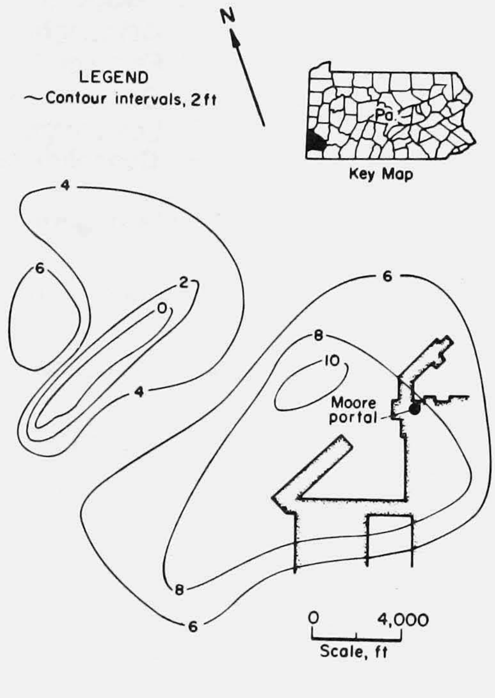

Figure 26.--Isopach of incompetent strata in the roof of a mine. From McCulloch, Diamond, and others, 1975.

approximately 50 percent in this mine.

Knowing the thickness of an incompetent unit is not always enough. When slickensides are found, even though the bolts may go through the incompetent strata into a competent one, falls can occur between the bolts (fig. 27) or a bolt may hold for a while and then fall at any time (Moebs and Curth, 1976).

Another problem that is occasionally encountered, especially in longwall operations, is a roof rock that is too competent. The idea behind the longwall system is that the roof will fall behind the chocks, thereby relieving the pressure and allowing the subsidence to be gradual. However, in Virginia in a mine in the Pocahontas No. 3 coal, this did not happen. Here the roof above the coal being mined was an orthoquartzitic sandstone (fig. 28). On one panel they had advanced over 300 ft and the roof had not fallen. This then became an extremely dangerous situation because when this roof did fall, a large amount of air was displaced. Fortunately no explosion occurred when the roof fell, but some rather large machinery was moved around. In other words, roofs can be too good as well as too poor. In this case, a geologic analysis and mining appraisal of the problem should have been made and a redesigned support system used.

The floor strata also play a major role in any successful mining venture, as is evident when one looks at core data. Normally, the strata are cored through the coal zone, but very little floor rock is cored, so knowledge of this strata is limited. If the floor rock is soft, it can allow pillars to sink. In the case of longwalls, premature failure of the roof may be caused by the sinking of the jacks in the soft floor.

Because the floor generally consists of clays, knowledge of mineralogy of the floor rock

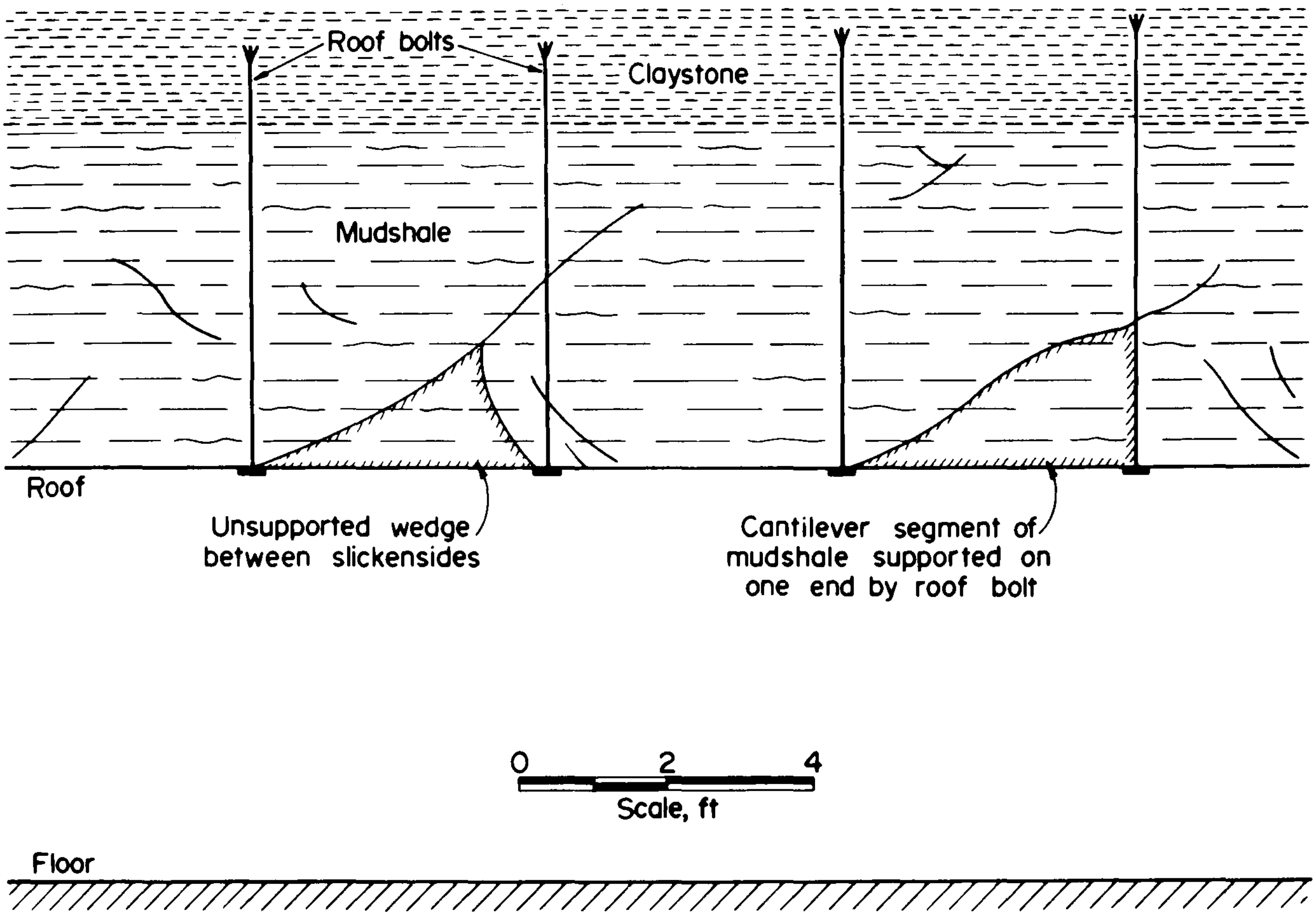

Figure 27.--Mine roof exhibiting slickenside structures. Modified from Moebs and Curth, 1976.

can assist in determining the ripping horizons and the effect that water can have on the floor rock. This information can even dictate the type of transportation needed. For example, if the floor rock contained a large percentage of expansive clay and had a low slaking index, then it probably would not be suitable for track mining. This type of floor would also be affected by the water used in dust suppression, and soft floor can heave several inches, requiring extensive regrading and road work (Kalia, 1976).

SUMMARY

A number of geologic features, such as washouts, faults, joints, cleats, slickensides, and the nature of the roof and floor rock, can affect and hinder mining. Today methods are available to anticipate the potential problems that these or other features may cause and also to determine some possible solutions. The important thing is that these potential problems be recognized earlier in the planning state, not after the mine has begun operation.

It is evident that the geologist has an important role in the mining industry and not just in the exploration phase if a "risk-reduction" program is to be successful. As companies are forced to mine coal under more difficult conditions, the geologist and his interaction with the mining engineer may make the difference between a successful operation and a failure.

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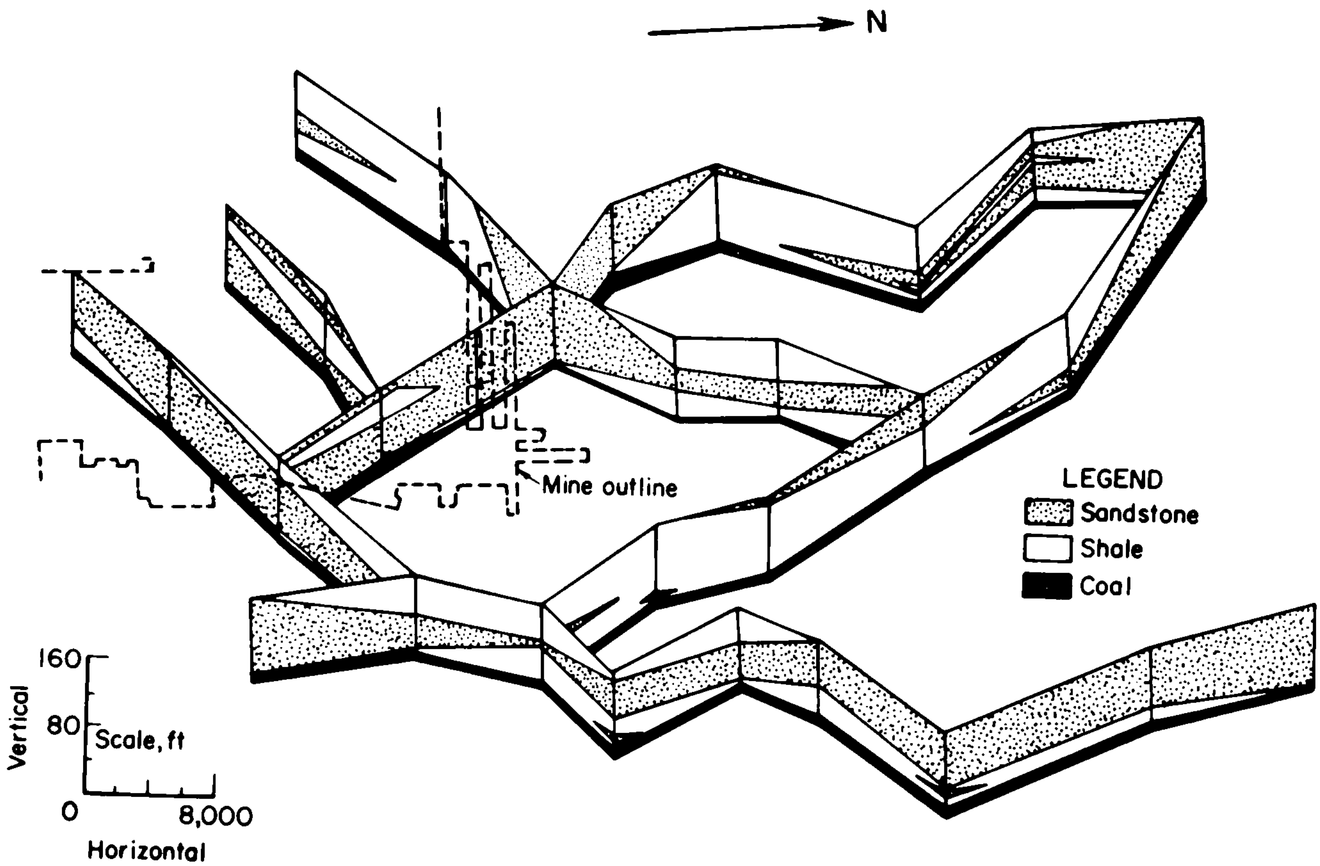

Figure 28.--Orthoquartzitic sandstone roof in the Pocahontas No. 3 coal. From McCulloch, Jeran, and Sullivan, 1975.

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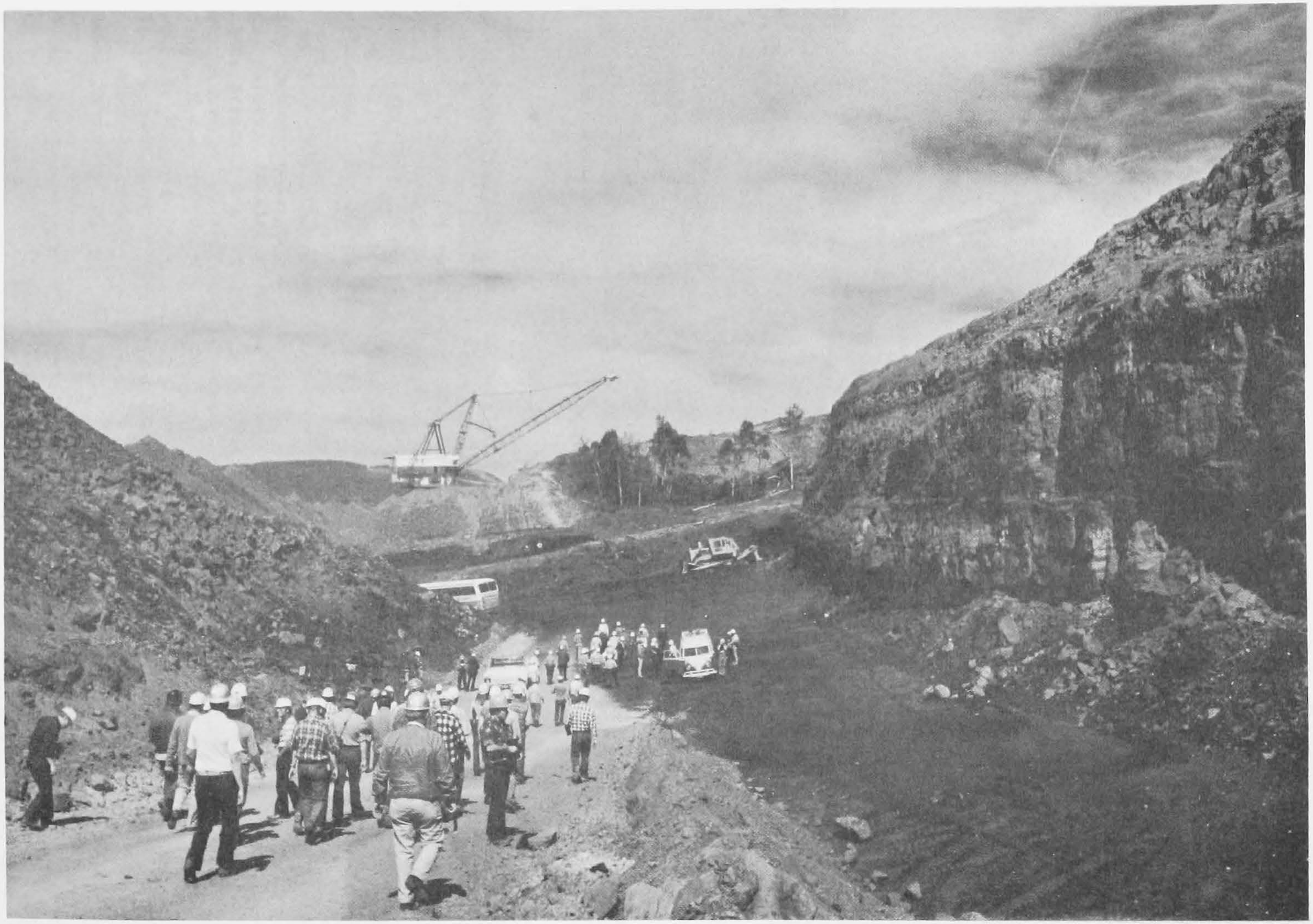

RoMoCoal Field Trip

Photograph by Harold H. Arndt, U.S. Geological Survey

Participants returning to buses after examining the Wadge coal bed and the strip-mining operation at Energy Fuels Corporation pit no. 1-A. The Bucyrus Erie 770 dragline is shown in the background.

Cleat Orientation in Some Subbituminous Coals of the Powder River and Hanna Basins, Wyoming

WILLIAM R. HENKLE, JR., JAMES R. MUHM, and MARC H. F. DeBUYL[1]

ABSTRACT

Cleating, or jointing, in coals has historically influenced coal mine orientation. Because cleats (or joints) in coal beds often parallel joints in the surrounding strata, mine orientation and stability are often interrelated. When joints in surrounding strata parallel cleats (or joints) in a coal bed, roof and floor stability in underground mines and highwall stability in surface mines can often be related to cleating.

Explanation of cleat origin has always been controversial, being divided between endogenetic and exogenetic theories. Both theories are discussed, with examples of the veracity of each cited from coal fields in the British Isles and the United States.

Cleat orientations were determined at two coal properties in Wyoming: one in the Powder River Basin, the other in the Hanna Basin. Standard structural geologic techniques useful in determining joint orientations over large areas, coupled with oriented coring of selected coal seams, were used to determine major joint orientations over both properties.

Excellent correlations between cleat orientations of coal seams and joint orientations of overburden were noticed at both properties. Two conjugate joint sets were also found at both properties.

At the Powder River Basin property, the conjugate joint sets are similar to joints intruded by Precambrian dikes in basement rocks throughout the middle Rocky Mountains and to joints that predate Laramide intrusives in the Black Hills. An exogenetic theory of cleat and joint origin, related to basement control, is proposed and discussed.

At the Hanna Basin property, the conjugate joint sets are subparallel to major fold and fault geometries. An exogenetic theory of cleat and joint origin, related to stresses induced by folding and faulting, is proposed and discussed.

INTRODUCTION

Importance of Cleat in Coal Mining

Cleat planes form one of the major planes of weakness in a coal bed; the other is formed by bedding. The term "cleat," which originated in the British coal fields, refers to vertical or nearly vertical sets of fractures in coal beds.

The cleats generally occur in conjugate pairs. The more pronounced or systematic cleat is called the "face cleat"; the less pronounced or nonsystematic cleat is called the "butt cleat." Cleat planes and bedding planes are responsible for the tendency of most coals to have blocky fracture. Cleats are analogous to joints in other sedimentary rock types; cleat orientations, however, do not always coincide with joint orientations in surrounding strata.

Underground Mining

In the early days of mining, when coals was won with hand-got methods, it was natural for the miner to align his mine with the cleat directions. Work was thus easier and productivity higher than with other orientations.

Although mining underground parallel to the cleat does make the coal easier to break out, it is not always advantageous. Roof joints often reflect cleat orientations; and, just as cleats are planes of weakness in the coal, joints are planes of weakness in the roof strata. Underground mine openings parallel to planes of weakness in the coal bed and the surrounding strata can result in increased incidence of roof falls.

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Some mining machines, such as the longwall plow, are designed to take advantage of the planes of weakness along the cleats. Plows are generally most efficiently operated parallel to or at a small angle to the cleat of the coal bed. Other mining machines, such as continuous miners and longwall shearers, can cut coal at any angle to the cleat and are not constrained to mining in any single direction.

The modern mine designer is no longer required to orient his mine parallel to the cleat of the coal. Problems of strata control, seam-breakage characteristics, and haulage considerations can be balanced, thus arriving at an optimum orientation for the mine.

Surface Mining

As coal miners begin to develop deeper reserves using surface mining methods, slope-stability problems similar to those encountered in open pit mining of other minerals will have to be faced. Knowledge of joint orientation is a major factor in open-pit slope design. Unfavorably oriented joints are often the cause of slope failures.

Because cleat orientations in coal often reflect joint orientations in overburden strata, investigators can use coal beds as targets for oriented core testing. Orientations of joints (or cleats) at depth can thus be obtained readily, because coals are closely jointed (or cleated). Knowledge of discontinuities caused by jointing in the overburden aids in optimum slope design.

Permeability Considerations

Cleat orientation is also related to the permeability of a coal bed. Studies by the U.S. Bureau of Mines (McCulloch and others, 1974) and by Lawrence Livermore Laboratories (Stone and Snoeberger, 1976) have shown that fracture permeabilities in coals are from two to ten times greater along the face cleat than they are along the butt cleat. In addition to water-inflow considerations, the determination of the permeability characteristics of a coal bed is essential for projects involving degasification of coal before mining or in situ gasification.

Controversy as to Cleat Origin

Explanations as to why cleat exists in coal beds are controversial, being divided between endogenetic and exogenetic theories. Adherents to endogenetic theories believe that cleats are formed by contraction induced by compaction, dessication, recrystallization, and coalification of the original peat bed. Adherents to exogenetic theories believe that cleats are formed in response to tectonic pressures induced by folding and faulting of the strata of which the coal bed is a member.

Evidence abounds as to the correctness of either theory; often separate interpretations are used to explain cleat origin from two separate coal fields fairly near to each other. For example, in the English coal fields, the strike of the cleat is parallel throughout a vertical succession of coal beds and also parallels formation fissures in the region (Kaiser, 1908). However, in the Scottish coal fields, cleat trends may even vary between upper and lower seams in the same colliery (Dran, 1925). Of the two reports cited, the first favors an exogenetic origin for cleating, while the second favors an endogenetic origin.

In the United States, at least two coal fields are known to the writers in which a simple exogenetic theory of cleat origin may not apply. In the Raton Basin of Colorado and New Mexico, coals have been reported to have a unique fracture system that is distinctly different from overburden joint patterns (C. L. Pillmore, oral communication, 1977). In the Paonia-Somerset coal field of Colorado, cleat orientations in the "F" seam at the proposed Mt. Gunnison No. 1 mine of ARCO are reportedly unrelated to overburden joint orientations (Atlantic Richfield Company, 1976). In the same coal field, at Colorado Westmoreland Incorporated's Orchard Valley mine, cleat orientations in the "D" seam are reported to be rotated 30° clockwise from the orientations reported at the Mt. Gunnison property (Colorado Westmoreland Incorporated, 1976).

In the Powder River Basin and Hanna Basin study areas discussed in this report, a definite association exists between coal cleat and overburden joint orientations and regional structural trends. In the Appalachian Coal Region, McCulloch, Deul, and Jeran (1974) and Ver Steeg (1942) also reported definite associations between cleating, jointing, and regional structure. In this paper, we assume cleats to be the same as joints and the two terms are used synonymously.

POWDER RIVER BASIN STUDY AREA

Location and Geologic Setting

Highwall-stability and hydrogeologic investigations were conducted for a proposed surface mine to be situated in the northeastern Powder River Basin. The location of the proposed mine is shown on figure 1, a map of the central Rocky Mountain region.

The proposed mine is situated in a region characterized by low dips and absence of major faulting. Surface outcrops strike about N. 35° W. and dip 1°-2° SW. No faults are known on the

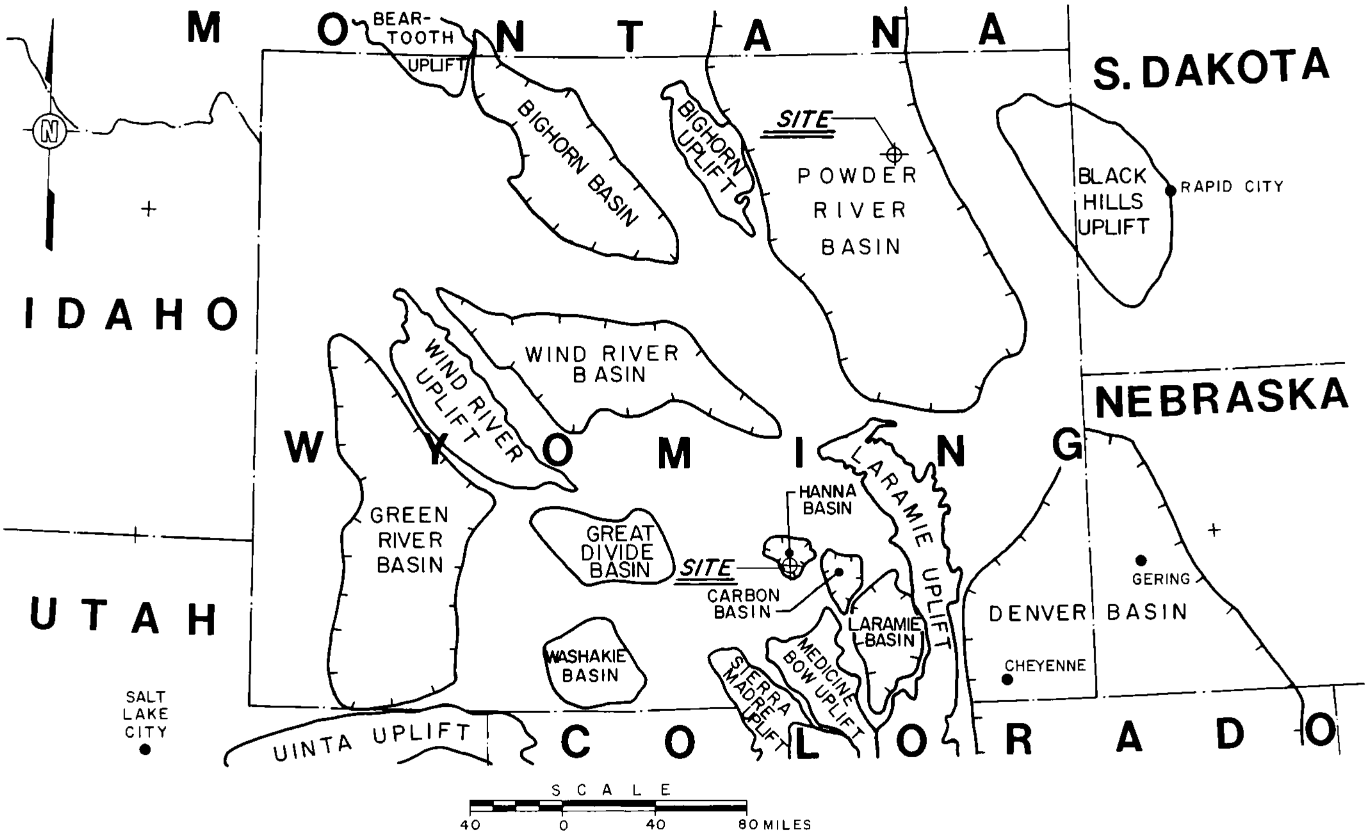

Figure 1.--Central Rocky Mountain region, showing location of Powder River and Hanna Basin study areas.

property investigated; several northeast-trending faults have been mapped several miles north of the property, however (Kent, 1976).

The coals of interest at this site occur near the contact of the Eocene Wasatch Formation with the underlying Fort Union Formation of Paleocene age. The coal is of subbituminous C rank; individual beds range in thickness from 3 ft to more than 35 ft. In places, beds merge to form coal seams 60-80 ft thick, with only minor clay or shale partings.

Methods of Investigation

The investigation of this study site was conducted to determine geologic features in the section to be mined that might adversely affect highwall stability. A major part of this investigation involved determination of overburden joint and coal-seam cleat attitudes.

The surface investigation began with photogeologic mapping of the study area. In addition to formational contacts and strikes and dips of bedding and faults, fracture traces observed on aerial photographs were also mapped. Stream lineations showing evidence of joint control were also plotted on the geologic base map.

During field checking of the map, joint orientations were measured at coal-seam outcrops and in overburden strata that exhibited well-developed jointing. The Roland coal seam (terminology of Glass, 1975) is the only seam cropping out over most of the property. Cleat orientations were measured in this seam by digging into the outcrop until a fresh coal face was exposed. The stationing method was used to obtain representative overburden joint orientations; between 20 and 50 joints were measured at each station. Results of the surface mapping program are shown on figure 2, a geologic and fracture-trace orientation map of the area.

The subsurface investigation included drilling and extensive coring of nine boreholes over the property; instrumentation was installed and extensive geophysical testing was performed in the boreholes. Oriented cores were taken of the Roland and Smith coals (terminology of Glass, 1975) from a borehole located at a critical highwall-stability point. Cleat directions in oriented cores were compared with outcrop data to determine failure-plane orientations in the strata planned for mining.

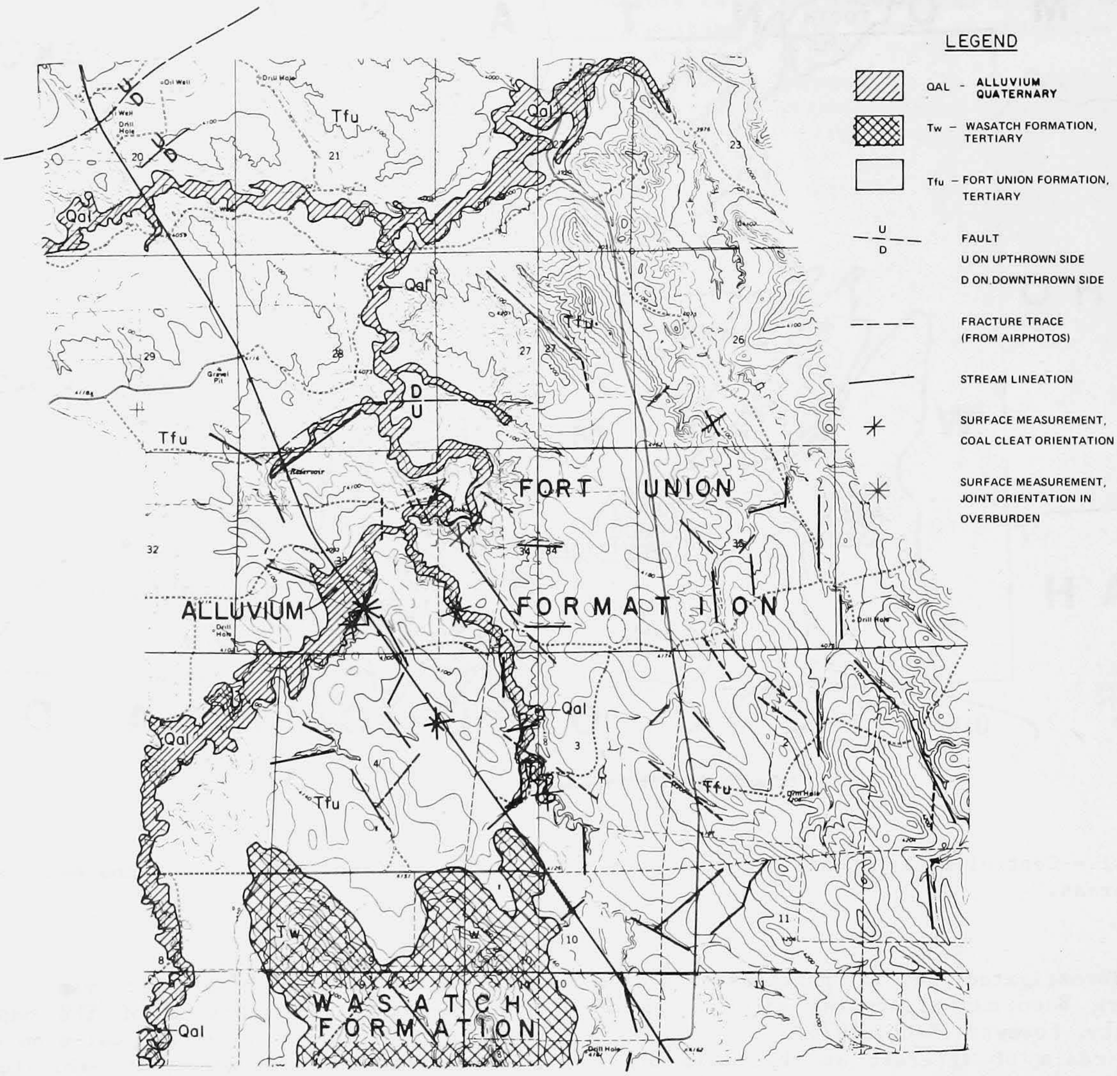

Figure 2.--Geologic map showing stream lineations and fracture traces, northeast Powder River Basin study area. Modified from Kent (1976).

Data Analysis and Results

Rose diagrams were prepared of individual data sets such as oriented core of the Roland coal, stream lineations, and fracture-trace orientations. The rose-diagram format was used because all joints (or cleats) observed during the investigation are vertical or nearly so. Rose diagrams of the major data sets used in the analysis are shown in figure 3. Fracture-trace orientations across and in the vicinity of the study area show a definite peak from N. 30°-70° W., which centers on N. 50° W. A minor peak centered on 0°, or north-south, is also apparent. Stream-lineation directions across and in the vicinity of the property show a major peak from N. 5° W. to N. 5° E. and two nearly equal peaks from N. 35°-45° W. and from N. 45°-55° E.

Oriented cores of the Roland coal seam show that cleat (or joint) orientations have two equal major peaks at N. 75°-85° W. and N. 35°-45° W. and a minor peak at N. 25°-35° E. Oriented cores of the Smith coal seam show equal peaks at N. 80°-90° W. and N. 5°-15° E. A minor peak from N. 5°-15° W. is also present in the Smith coal seam cores.

Excellent correlation was noted between cleat orientations in coal outcrops and joint orientations in overburden strata measured at or near the same location. This correlation, which can be seen on figure 2, leads us to believe that a definite relationship exists between cleating in coal beds and jointing in overburden strata in the study area.

In order to further define the relationship

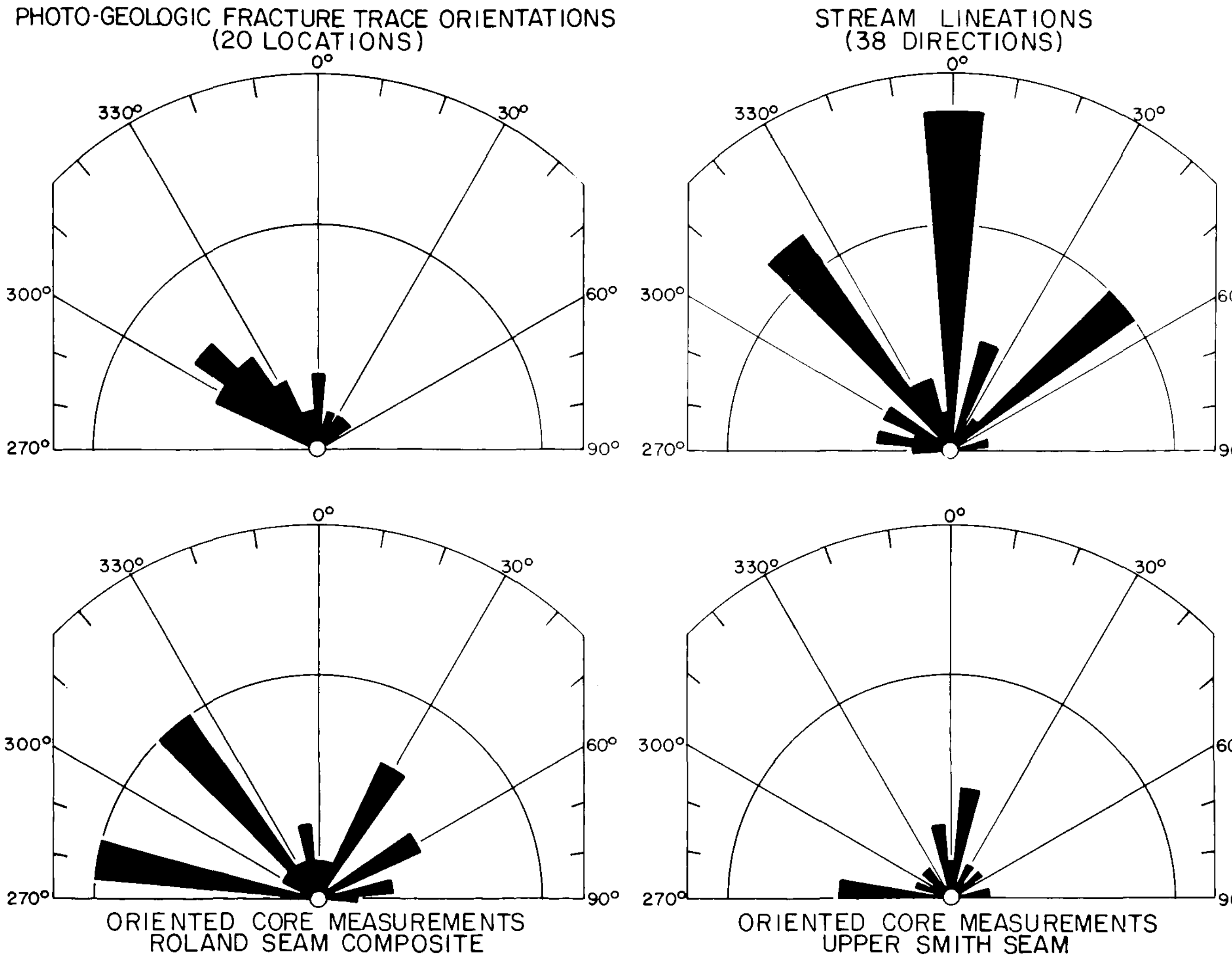

Figure 3.--Rose diagrams of fracture traces, stream lineations, and coal cleats in the northeast Powder River Basin study area.

between the various fractures, a percentage frequency plot of all lineations, joints, and cleats measured in the investigation versus azimuth was prepared. This plot, which is shown at the top of figure 4, shows four definite peaks. The dominant peak (21 percent) is centered on the N. 5° W.-N. 5° E. azimuth. The second most dominant peak (16 percent) is centered on the N. 35°-45° W. azimuth. Two minor peaks (11 percent) at N. 75° E.-S. 85° E. and (8 percent) at N. 45°-55° E. are also apparent. The peaks centered at N. 35°-45° W. and N. 45°-55° E. represent orientations that are subparallel to the regional strike and dip of the eastern flank of the Powder River Basin. The peak centered at N. 5° W.-N. 5° E. is subparallel to the valley of the Powder River, which flows nearly north-south for about 80 mi in the Gillette area.

Results of Other Studies

Several other studies relate to joint orientations in the Powder River Basin and surrounding regions. Using oriented cores, Stone and Snoeberger (1976) determined fracture (or cleat) orientations in the Felix coal about 20 mi southwest of Gillette. Glass (1975) measured joint (or cleat) orientations at the locations of measured sections in all operating coal mines in the Powder River Basin. Lee, Smith, and Savage (1976) determined joint orientations in coals and overburden strata in the Sheridan-Decker coal field in the northwestern part of the basin.

Osterwald (1959), Hodgson (1965), and Wise (1964) examined joint orientations in uplifted basement rocks of the Bighorn Mountains to the

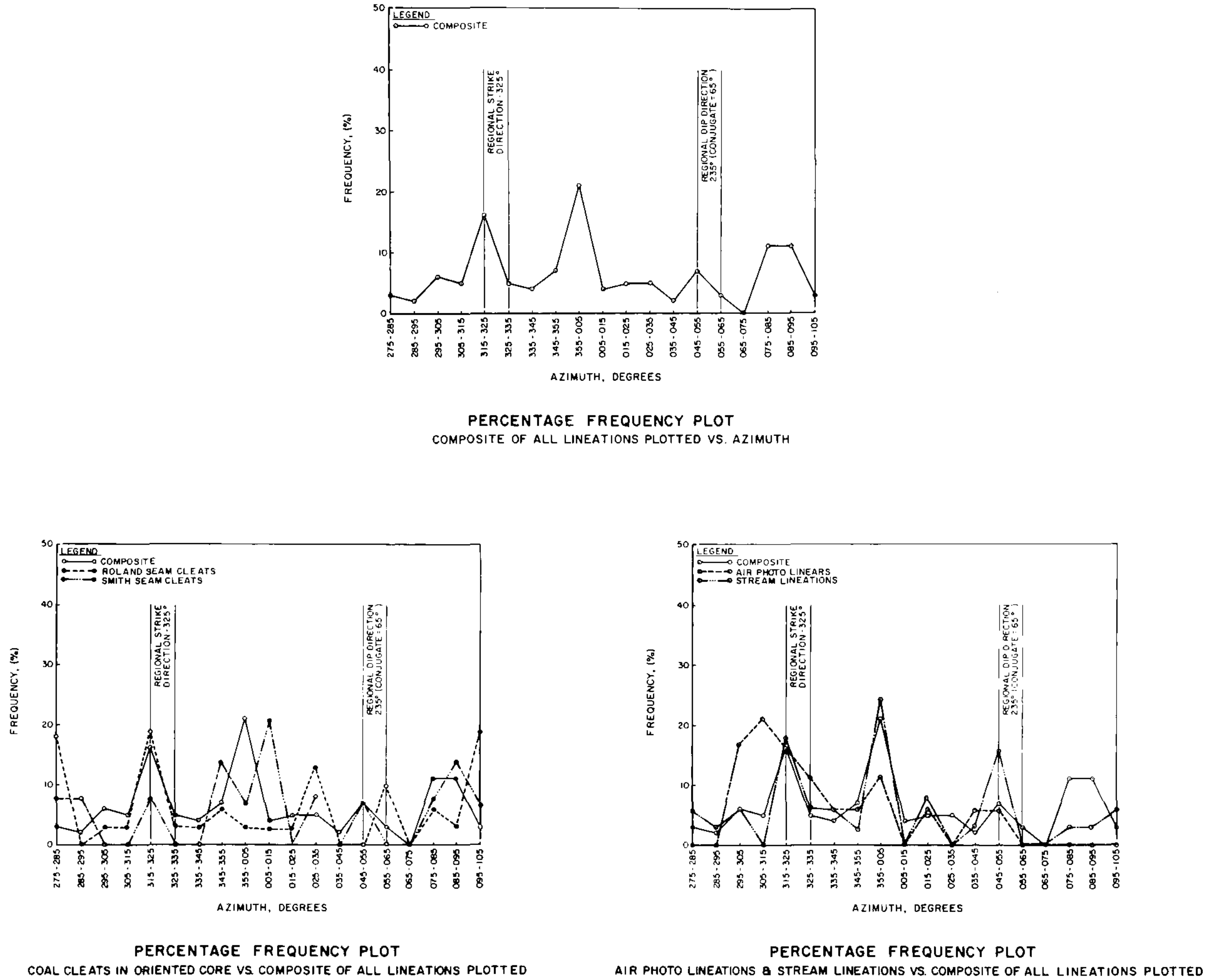

Figure 4.--Percentage frequency plots of stream and airphoto lineations and of coal cleats from oriented cores.

west of the study area. Shapiro and Gries (1970) examined joint orientations and their relationship to orebodies in Cambrian rocks in the Black Hills, to the east of the study area. Hoppin (1961) studied relationships between structures in Precambrian rocks and Laramide structures along the western edge of the Powder River Basin, near Buffalo, Wyo.

The results of the work of these researchers and the work of the writers are shown in a generalized form on figure 5. Joint orientations were plotted using "Tectonic Map of the United States exclusive of Alaska and Hawaii" as a base (U.S. Geological Survey and American Association of Petroleum Geologists, 1961), in order to show the relationship between major joint patterns and other geologic structures in the region.

Joint Studies in Coal-Bearing Strata

Stone and Snoeberger (1976) reported fracture orientations in the Felix coal that are subparallel to regional strike and dip. The fracture (or cleat) set that subparallels regional dip was reported by these workers to be twice as permeable as the fracture (or cleat) set that subparallels the regional strike. McCulloch, Deul, and Jeran (1974) reported that the more permeable face cleat is subparallel to regional dip in other coal fields. Glass (1975) reported joint (or cleat) orientations in the Anderson-Canyon coal in the Gillette area that are very similar to the directions the writers found in the study area. These directions consist of two conjugate pairs: one oriented nearly north-south

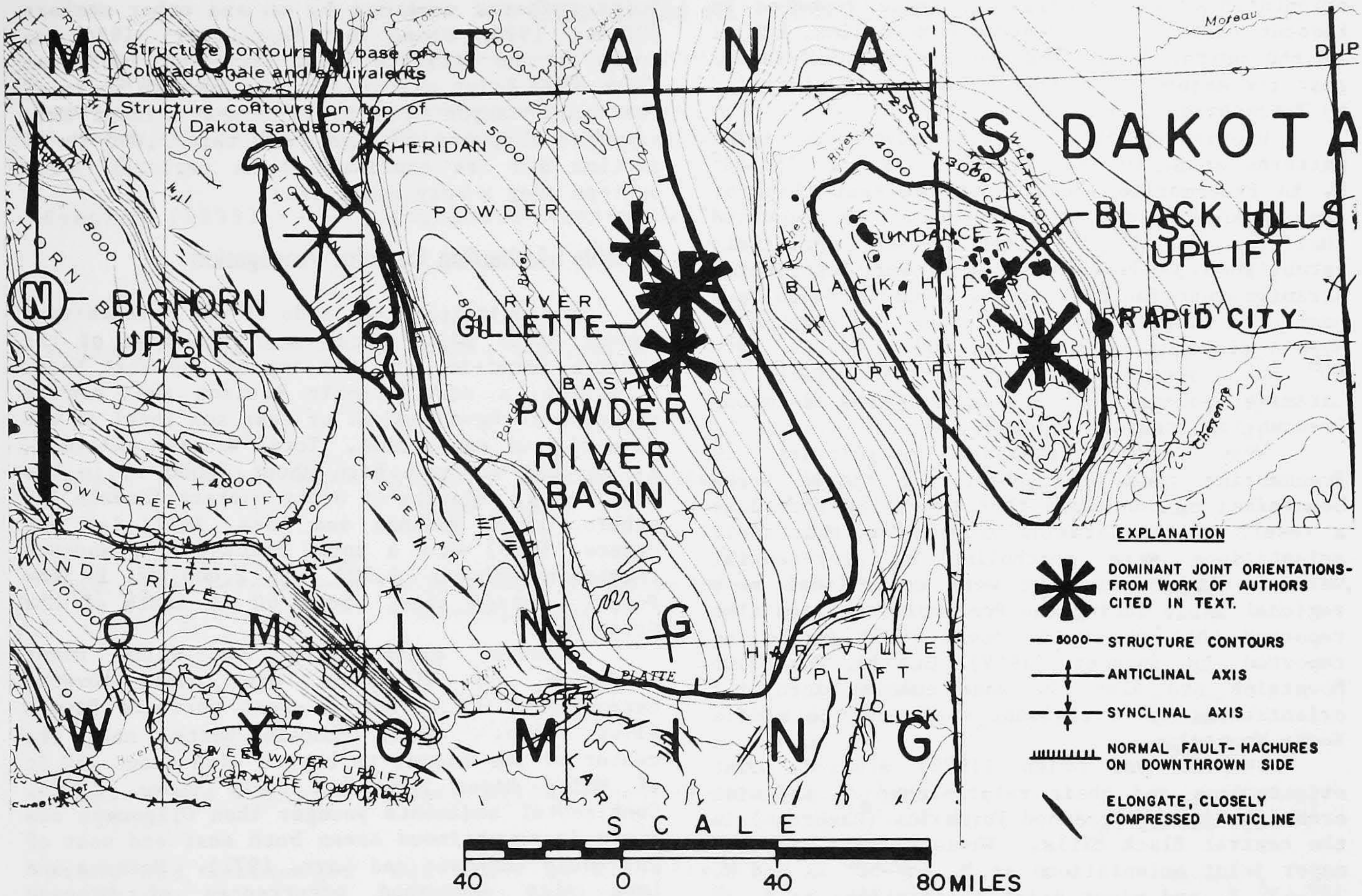

Figure 5.--Dominant joint orientations in coal beds and basement rocks, northeast Powder River Basin and adjacent areas. Modified from U.S. Geological Survey and American Association of Petroleum Geologists (1961).

and east-west, the other oriented northwest and northeast. The northwest and northeast pair is subparallel to regional strike and dip on the eastern flank of the Powder River Basin. Glass (1975) also reported joint orientations from the Badger and School coals in the southern Powder River Basin that subparallel regional strike and dip.

Lee, Smith, and Savage (1976) reported three major joint orientations in the Tongue River Member of the Fort Union Formation in the Sheridan-Decker coal field. These directions are N. 45° W., N. 37°E., and N. 13° E.; the N. 45° W. direction is reported as the dominant direction. The Sheridan-Decker area is situated on the northwest side of the Powder River Basin, where the geology is more complex than in the Gillette area; numerous northwest-trending faults of large displacement occur in that region. The northwest-northeast conjugate joint set reported by Lee, Smith, and Savage (1976) is subparallel to regional strike and dip. The joint orientations which these workers measured are similar to those reported by Osterwald (1959) in Precambrian rocks in the Tongue River area of the Bighorn Mountains.

Joint Studies in Older Rocks

Numerous studies have been conducted in the Bighorn Mountains to determine relationships between structures in basement rocks and overlying sediments. Osterwald (1959) reported two major, steeply dipping joint sets which strike north-northeast and northwest in the Tongue River area of the Bighorn Mountains. An additional, less-well-developed set striking northeast and dipping vertically was also mentioned in that report.

Hodgson (1965) reported major sets of joints striking N. 5°-10° E., N. 30°-35° W., N. 40°-50° E., and N. 85° E.-N. 85° W. for an area of approximately 1,100 mi^2 in the Precambrian rocks of the Bighorn Mountains. In the same report, the author showed that these joint orientations were similar to those reported by Spencer (1959) in the Beartooth Mountains, 100 mi to the north. Both Hodgson and Spencer showed that the major joints they observed were intruded by Precambrian dikes.

Hoppin (1961) reported dominant joint patterns of N. 10° E., N. 45° E., and N. 75°-80° W. in Precambrian rocks along the east flank of the Bighorns, near Buffalo, Wyo. He reported that the N. 10° E. direction was definitely established in Precambrian time and interpreted Laramide tear faulting in the study area to have been controlled by this plane of weakness. Hoppin also reported that N. 45° E. and N. 75°-80° W. directions appear to be related to Laramide movement that was reactivated along Precambrian fracture systems.

Wise (1964) examined microjoints in Precambrian rocks throughout the middle Rocky Mountains; he concluded that they were formed as a result of the Laramide orogeny but that their orientations were controlled by preferential weakness directions that were established on a regional basis during the Precambrian. Wise also reported that the most common joint directions reported by Spencer (1959) in the Beartooth Mountains are also the most common microjoint orientations on a regional scale in the middle Rocky Mountains.

Shapiro and Gries (1970) studied joint orientations and their relationship to Laramide orebodies in the Deadwood Formation (Cambrian) in the central Black Hills. These workers reported major joint orientations at N. 45°-50° W. and N. 35°-45° E. and minor joint orientations at N. 5° E.-N. 5° W, and N. 80°-90° E. These orientations reportedly predate Laramide intrusives in the study area (J. P. Gries, oral communication, 1977).

Possible Origin of Cleat and Joint Orientations

The foregoing studies in the Powder River Basin and adjoining areas have reported strikingly similar joint orientations for this region. The results of these studies are presented in tabular form in table 1.

The authors of these reports either concluded or deduced that Laramide structural deformation in the middle Rocky Mountains occurred along planes of weakness established during Precambrian time. Other workers, notably Closs and Closs (1934) and Chamberlain (1945), espoused the same ideas though on a much more philosophical basis.

The writers believe that joint and cleat orientations in Tertiary rocks in the northeastern Powder River Basin were inherited from joint patterns in Precambrian basement rocks. Joint patterns measured by Hodgson (1965) and by Shapiro and Gries (1970) in uplifted areas on either side of the study area are similar to joint patterns measured by us and other workers (Glass, 1975; Stone and Snoeberger, 1976) in coals in the Gillette area. Hodgson (1965) has shown that joint patterns in Precambrian rocks of the Grand Canyon area of Utah and Arizona have propagated upward through more than 5,000 ft of section and are expressed as a regional joint pattern over a very large area.

Possible Mechanism for Joint Propagation

The principal coal beds of the northeastern Powder River Basin occur near the base of the Wasatch Formation and the top of the Fort Union Formation, a stratigraphic horizon that can be presumed to have been at or near sea level at the time of coal deposition. Total Wasatch thickness is assumed to have been about 2,000 ft in the study area. Reports of other workers (Hodson and others, 1973; McKenna and Love, 1972; Lee and others, 1976) show a total thickness of Wasatch Formation between 1,500 and 2,000 ft in the Pumpkin Buttes area, about 60 mi south of the study area.

Evidence exists that the White River Formation of Oligocene age once covered essentially all of the present northern Powder River Basin. North Pumpkin Butte, near the center of the basin, is capped with about 250 ft of White River Formation rocks (Love, 1952). Continental sediments younger than Oligocene are known in mountainous areas both east and west of the basin (McKenna and Love, 1972). McKenna and Love also described occurrences of Miocene mammals in isolated sediments found at elevations above 9,000 ft in the Bighorn Mountains. The fossil mammal assemblage of this locality is similar to that of the plains of western Nebraska. Additional thin post-Oligocene sediments, probably Ogallala Formation, exist in the northwestern Black Hills. The suggestion is strong, then, that extensive deposits of Cenozoic continental sediments at one time covered the northern Powder River Basin.

Direct evidence for the maximum depth of burial of the northern Powder River Basin is lacking, but a total thickness of 1,000 ft above the Wasatch would not seem unreasonable in the study area. Lee, Smith, and Savage (1976) arrived at a similar conclusion with respect to post-Wasatch deposition in the Sheridan-Decker area, in the northwestern Powder River Basin. This combined thickness (2,000 ft Wasatch and 1,000 ft post-Wasatch) results in an approximate gravitational load of about 3,000 psi on the coal.

The exact depths to which the coal beds were depressed below sea level is unknown. However, stratigraphic evidence indicates that a depth of about 1,000 ft below sea level is reasonable. Since they now occur at roughly 4,000 ft above sea level, we can assume that they have been uplifted at least 5,000 ft, probably more. The uplift was accompanied by erosional

Table 1.--Comparison of Joint Directions

Author	Study area	Major sets	Minor sets
Osterwald (1959)----	Tongue River--Bighorns--	N. 49°-56° W. N.-S.-N. 18° E.	N. 50°-55° E. ------
Spencer (1959)------	Beartooth Mountains-----	N. 15° W. N. 45° W. N. 45° W. N. 65° W.	N. 15°-20° E. N.-S.-N. 5° E. N. 55°-60° E. N. 85° E.-E.-W.
Hodgson (1965)------	Bighorn Mountains-------	N. 5° W.-10° E. N. 30°-35° W. N. 45°-50° E. N. 85° E.-N. 85° W.	N. 10°-15° W. N. 45° W. N. 25°-30° E. N. 65°-70° W.
Hoppin (1961)-------	Bighorn Mountains--Buffalo area.	N. 10° E. N. 45° E. N. 75°-80° W.	------ ------ ------
Wise (1964)---------	Middle Rocky Mountains--microjoints.	N. 70° W. N. 45° W. N. 10° W N. 10° E. N. 25° E. N. 65° E. N. 85° E.	------ ------ ------ ------ ------ ------ ------
Shapiro and Gries--(1965).	Black Hills-------------	N. 45°-50° W. N. 35°-45° E.	N. 5° W.-N. 5° E. N. 80°-90° E.
Stone and Snoeberger (1976).	Southwest of Gillette---(Felix coal).	N. 24° W. N. 78° E.	------ ------
Glass (1975)--------	Gillette area (Anderson-Canyon coal).	N. 10° W.-N. 5° E. N. 85° E.-S. 88° E. N. 56°-70° E. N. 26°-38° E. N. 30° W. N. 70°-82° W. N. 50°-60° W.	------ ------ ------ ------ ------ ------ ------
Lee, Smith and------ Savage (1976).	Sheridan-Decker coal-field.	N. 45° W. N. 37° E. N. 13° E.	------ ------ ------
This study----------	15 mi northwest of------Gillette.	N. 35°-45° W. N. 45°-55° E. N. 5° W.-N. 5° E. N. 75° E.-S. 85° E.	------ ------ ------ ------

release of about 3,000 psi of overburden pressure.

Lee, Smith, and Savage (1976) followed the same line of reasoning to explain the uplift history of the Sheridan-Decker area. They used this hypothesis to explain time-dependent highwall failures that they had observed in active surface mines, and felt that tensile strains generated by lateral expansion of overconsolidated rocks in an excavation could cause fresh fractures to appear that might eventually lead to slope failures.

Price (1966) showed that large-scale uplifts such as this one of the northern Powder River Basin result in a lateral extension of the uplifted strata. He also showed that a practical relationship exists between extensional stresses developed during uplift and the gravitational load causing the initial vertical compression. He stated that the tensile stresses which tend to develop owing to the horizontal extension of the beds during uplift are equal to approximately half the change in the gravitational load. Thus, a release of 3,000 psi of overburden pressure will cause an extensional stress of 1,500 psi to the rocks near the ground surface. Assuming that lateral stresses which develop as a result of the vertical compressive stresses remain as residual compressive stresses, he suggested that the subsequent tensile stresses will result in jointing along pre-existing planes of weakness in the rock mass.

We feel that such lateral extension in the northern Powder River Basin occurred along planes of weakness inherited from basement rocks. The planes of weakness are thought to have acted as stress concentrators along which fractures were propagated upward into overlying sediments as a continuing process. We feel that this process is responsible for the similarity between joint orientations in the Gillette area and in the adjacent Bighorn Mountains and Black Hills.

HANNA BASIN STUDY AREA

Location and Geologic Setting

Roof- and floor-stability and hydrogeologic investigations were conducted for a proposed underground mine to be located near the center of the Hanna Basin. The location of the proposed mine is shown on figure 1.

The Hanna Basin may be a northward extension of the Rio Grande Rift system; it is a tension-induced downward fold at the surface and near-subsurface which has been attributed to basement faulting (Dobbin and others, 1929). Coals of economic interest over the property occur in the Hanna Formation, which contains more than 30 coal beds greater than 3 ft in thickness. The Hanna Formation, Paleocene and Eocene in age, is about 13,500 ft thick at this location and consists of interbedded sandstones, conglomerates, shales, and coal beds. Three coal beds of subbituminous A rank were investigated at this property to determine their suitability for various types of underground mining.

Site-Specific Structural Geology

The proposed mine complex is located near the axis of the Hanna syncline (fig. 6) in the deepest part of the Hanna Basin. Dip of the coals and associated strata ranges from about 5 degrees near the synclinal axis to 15-20 degrees 2 mi from the proposed mining complex. The axial trace of the Hanna syncline strikes about N. 15° E. and plunges about 5 degrees. Numerous northwest-trending normal faults having displacements of as much as 100 ft are present just west of the mining area. As shown on figure 6, three major faults have been mapped on the property.

Fault A is a northwestward-striking reverse fault having 25-30 ft of displacement. The fault can be seen in the pit highwall of a surface mine adjacent to the property, and may have been produced by soft-sediment deformation during folding.

Fault B, the major fault occurring on the property, is a north-northwest- to north-striking normal fault which is downthrown to the east. Vertical displacement of about 70 ft was measured; subsurface data indicate that this may be a growth fault. This fault becomes difficult to trace and may merge with other structures as it approaches the synclinal axis in the south-central part of the property.

Fault C is a northeastward-striking normal fault downthrown about 40 ft to the west. This fault is difficult to trace over the mine property, but does coincide with a northeastward-striking fault mapped by Dobbin, Bowen, and Hoots (1929).

Methods of Investigation

The methods of investigation used to determine cleat orientations at the Hanna Basin property were similar to those used at the Powder River Basin property. However, owing to the more complex nature of the geologic structure at the Hanna Basin property, considerably more geologic field work was required.

The field investigation at the Hanna Basin property was a combined coal exploration and geotechnical investigation. The photogeologic portion of the investigation involved mapping of lineations and faults on Landsat imagery and conventional aerial photographs. All lineations mapped during this phase of the investigation were walked out on the ground. Displacements of bedding planes were measured where possible. Outcrops of coal seams of economic interest were mapped on the ground. Cleat and joint measurements were made at outcrops and in strip-mine pits throughout the property.

The subsurface investigations for this project consisted of normal exploration drilling and coring, coupled with additional coring of floor and roof rock in selected drill holes. Oriented cores were taken from coal seams of economic interest in four drill holes. Additional testing and geophysical logging were conducted in all holes drilled during the project.

In addition to the field investigation, various Government agencies having information on past and present mines in the basin were visited. Files of these agencies were searched, and various reports and maps of existing and abandoned mines were studied.

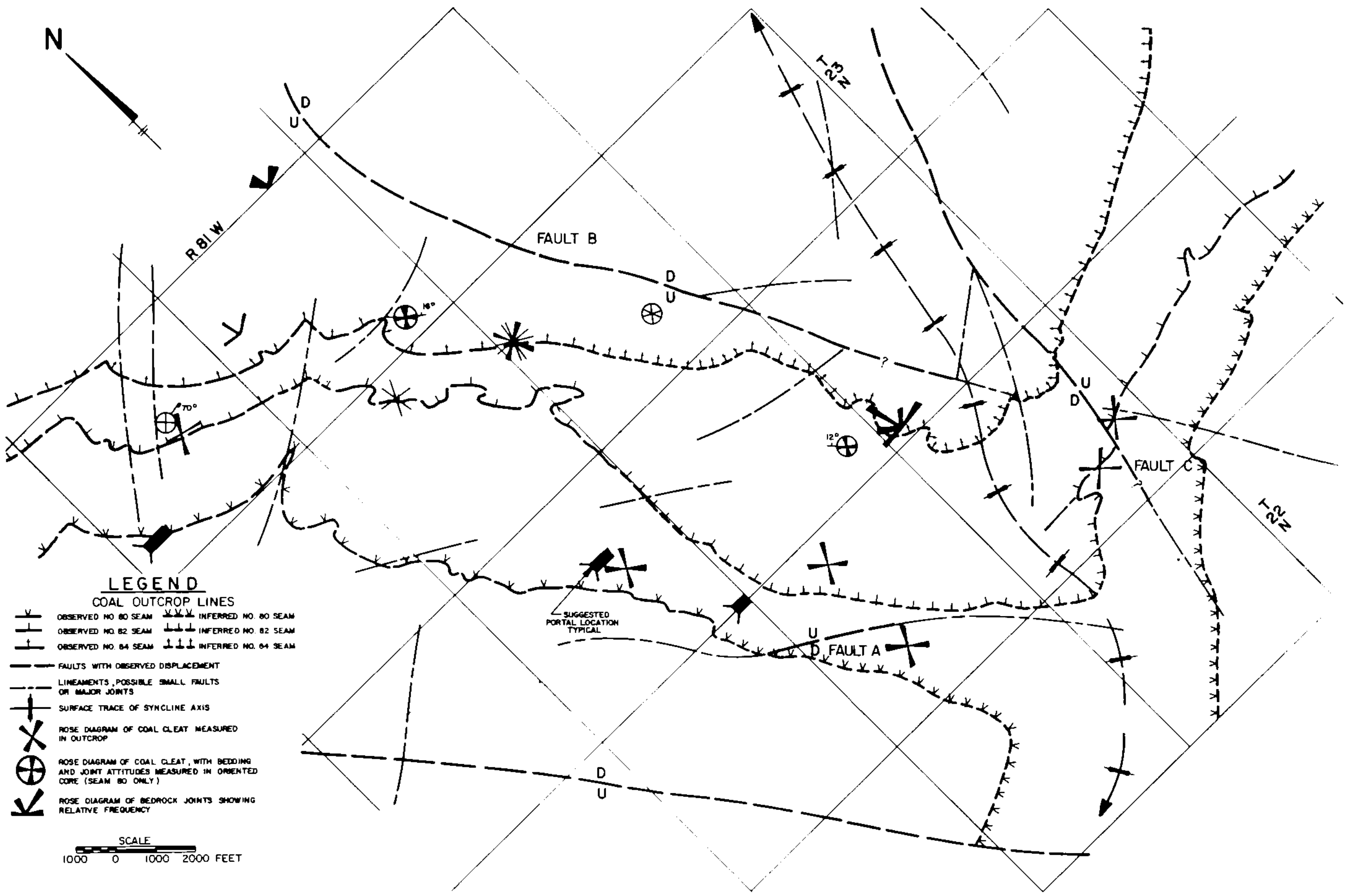

Figure 6.--Structural geologic map, Hanna Basin study area.

Data Analysis and Results

In the northwest part of the property, jointing is subparallel to dip direction and may represent extension fractures formed during folding. During field mapping, joint spacing was found to be at 5- to 10-ft intervals in areas remote from topographic lineations and faults. Spacing at 2- to 5-ft intervals is present in areas within about 0.25 mi of faults and major topographic lineations. Most of the joints are closed; however, they are open slightly in those areas within 0.25 mi of faults and major topographic lineations. Most of the joints have clean planes, but joints in carbonaceous shales and cleats (or joints) in the coals have calcite filling. Cleat spacing is on the order of 1/8 to 1/16 in. for secondary cleats and 1-2 ft for master cleats exposed on pit floors in the surface mine; distinction between face and butt cleat is difficult. Cleats in coals and joints in overburden are subparallel to the strike and dip of bedding in those areas that are more than 0.25 mi from major faults and major topographic lineations and away from the nose of the Hanna syncline.

In those areas of the property that are structurally complex, both cleats in coals and joints in overburden are very well developed. Along fault B, a conjugate joint and cleat set subparallel to the trace of the fault is predominant. This conjugate set is superimposed and dominant over the conjugate set thought to be produced by folding. The cleat element parallel to the fault trace is the dominant cleat at most locations. Near the nose of the Hanna syncline, cleat orientation is subparallel to fault B.

Possible Origin of Joint and Cleat Orientations

Our observations indicate that folding induced by faulting produced a conjugate cleat and joint set subparallel to strike and dip of the syncline. This orientation appears to predominate throughout the northwest portion of the Hanna syncline, where the strata are only moderately disturbed. We believe that growth faulting produced by further development of the syncline then superimposed a locally dominant conjugate cleat and joint set over that produced by folding.

The local dominance of the fault-produced cleat over the fold-produced cleat appears to extend for about 0.25 mi on either side of fault B. Reports from mines that formerly operated in the Hanna Basin show that splinter faults have been encountered in workings that approach major faults. These splinter faults are subparallel to the trace of the larger faults. This zone of influence of splinter faulting is about 500-750 ft on either side of the major fault; the zone of influence over joint and cleat orientations is about 1,000-1,500 ft wide.

CONCLUSIONS

In conclusion, we feel that basement control of coal cleat and overburden joint orientation exists in the northeast portion of the Powder River Basin where a large, simple fold occurs. On the northeast flank of this large fold, joint and cleat orientations are subparallel to the traces of strike and dip of underlying strata. An additional joint and cleat orientation is also present and sometimes locally dominant over the strike and dip orientations. This system in the northeast Powder River Basin has a north-south, east-west orientation and also appears to be inherited from the basement.

In the Hanna Basin, an area of smaller, more intense folding, a local dominance of conjugate sets of coal cleats and overburden joints subparallel to the trace of major faults was found. This zone of influence at the Hanna site was about 0.25 mi on either side of the fault. Splinter faults of lesser displacement, subparallel to the trace of major faults, are thought to exist within 750 ft of major faults in the Hanna Basin.

Other intermontane basins in the Rocky Mountain region, which also contain major coal fields, were produced by tectonic forces similar to the forces that produced the Powder River and the Hanna Basins. Similar relationships between coal cleat and overburden joint orientations and folding and faulting may also exist in these basins.

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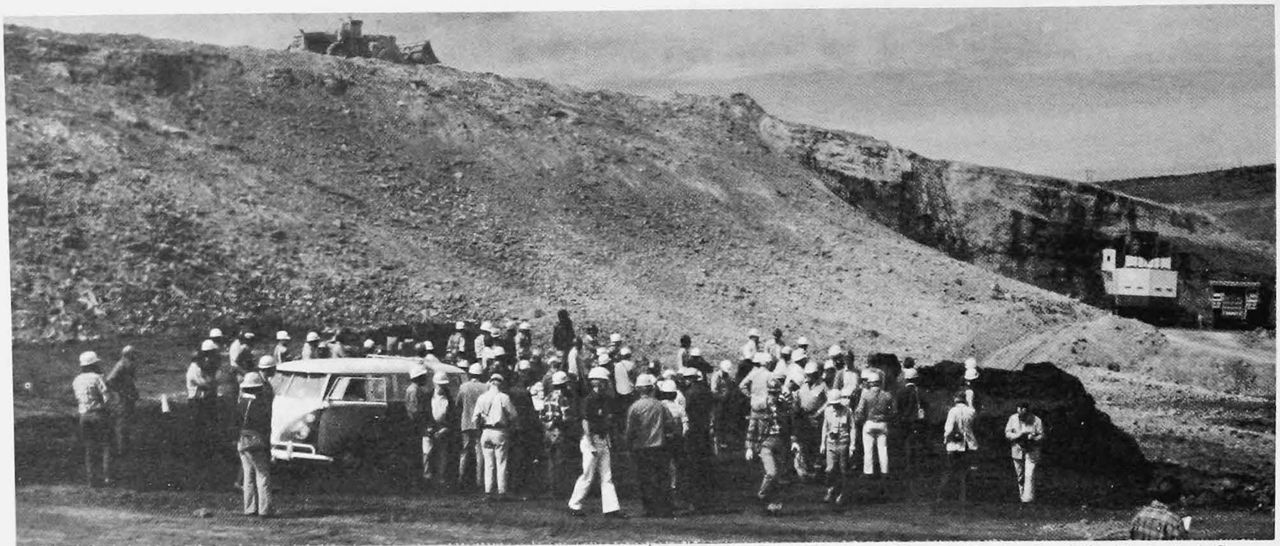

RoMoCoal Field Trip — Photograph by Harold H. Arndt, U.S. Geological Survey

Participants of the RoMoCoal field trip assembled around the sound truck to hear Ira McKeever discuss reclamation and plans for mining multiple coal seams during visit to ColoWyo mine.

RoMoCoal Field Trip — Photograph by Harold H. Arndt, U.S. Geological Survey

Scene at the ColoWyo mine showing a 191-m power shovel emptying overburden material into an Electra-haul 120-ton truck.

A Core Logging Technique for Standardizing Descriptions and Simplifying Computerization of Data

One of the major problems concerning field logging of cores is the difficulty of obtaining consistency in core descriptions written by various individuals in different places and at different times. One technique that achieves success in standardizing descriptions involves the use of core photographs that represent rock types found in a particular area of interest. The technique can be set up for easy computerization, thus simplifying the handling of the large amounts of data generated in the process of core drilling.

The following three papers were presented as a single workshop. The first paper discusses development and application of a core logging technique and computerization of results by the Carolina Coal Group in the Department of Geology at the University of South Carolina. The second discusses the development and application of a modified version of that technique by the coal exploration group of Atlantic Richfield Company, and the third discusses Atlantic Richfield Company's program for computerization and retrieval of data for coal-property evaluation and planning.

Following the formal presentation, cores and core-photo books were available at the workshop for attendees to use in testing the logging technique. Also the use of a teletype and a graphics terminal was demonstrated, and lithologic plots were on display.

Photo-Book Construction and Computer-Assisted Procedures for Assimilation and Preparation of Core Data

ROBERT A. MELTON and JOHN C. FERM[1]

ABSTRACT

Because many of the easily mined, continuous, thick coal seams in the Appalachian Region have been exhausted, new exploration and mining are being directed toward less continuous seams that are under more cover and are more difficult to mine. The direct results of this are that more money, time, expertise, and data are needed to plan and open new coal mines. Furthermore, the old methods of assimilating and preparing information needed for mine planning are inadequate to meet the needs of today's mining engineer, especially in the areas of data gathering, storage, retrieval, preparation, and interpretation.

Procedures described here show (1) construction of a photo-book for core logging, (2) its use in the field, (3) procedures for inputting data into an IBM 370/168 computer, (4) assimilation of data, and (5) graphic display of data.

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INTRODUCTION

In the early days of coal mining in the Appalachian Region, relatively little sophistication in mine planning or exploration was needed, and little (or less) was applied. Some widely spaced holes were drilled to determine seam continuity in a general way, and projections were laid out irrespective of seam or roof conditions. Such procedures were adequate and workable when seams were thick, continuous, and high in quality. More recently, however, as the better seams have been exhausted, attention has been focused on coals that are erratically distributed with respect to both thickness and quality. Because of increased emphasis on mine safety, greater attention is being directed to potentially troublesome roof rock, which may inhibit or even prohibit mining of a seam. Hence, greater emphasis is being placed on careful drilling of coal properties and on mine planning based on results of drilling.

One of the major problems in coal-property drilling is consistency and accuracy of collected data. A practical solution to this problem is the use of a photo-book for logging core.

The Carolina Coal Group at U.S.C. (the University of South Carolina) constructed a book of 64 color photographs illustrating common rock types found in the coal-bearing strata in a portion of the Appalachian Plateau. Use of this book as a standard for logging rock core substantially reduces the amount of information now lost in core logging by eliminating difficulties in communication between persons who describe core. A color photograph of rock core provides a standard to which all loggers--drillers, engineers, and geologists--can refer, thereby eliminating differences arising from confusion in terminology or misidentification of rock types.

Another major problem is the input and preparation of data gathered using a photo-book, as well as preparation and graphic display of data already on hand. A practical solution to this problem is the use of modern digital computers. The system described here allows assimilation of old and new core data in a relatively quick, accurate, and efficient manner. The procedures consist of the following four basic steps: (1) use of the photo-book for data collection; (2) computer input, storage, and graphic preparation; (3) geologic-profile correlation and establishment of seam continuity; and (4) computerized data posting of important seam parameters.

PHOTO—BOOK CONSTRUCTION

The area for which the Carolina Coal Group's photo-book was designed is the geographic-geologic province known as the Pocahontas Basin, a major coal-producing area located in southern West Virginia, eastern Kentucky, western Virginia, and northern Tennessee (fig. 1).

In order to obtain representative samples of commonly occurring rock types in this region, eight complete cores were sampled in a systematic fashion. Several geologists, experienced in the Pocahontas Basin, gathered 6- to 8-in. core samples at every visually apparent lithological change throughout the length of each core hole sampled. In this fashion, about 5,000 pieces of core were collected. These samples were returned to U.S.C. and sorted into groups primarily on the basis of grain-size, color, and sedimentary structures. Methods for distinguishing these attributes were those used in the field; namely, visual appearance, toughness, hardness, and fracture. After considerable sorting by several

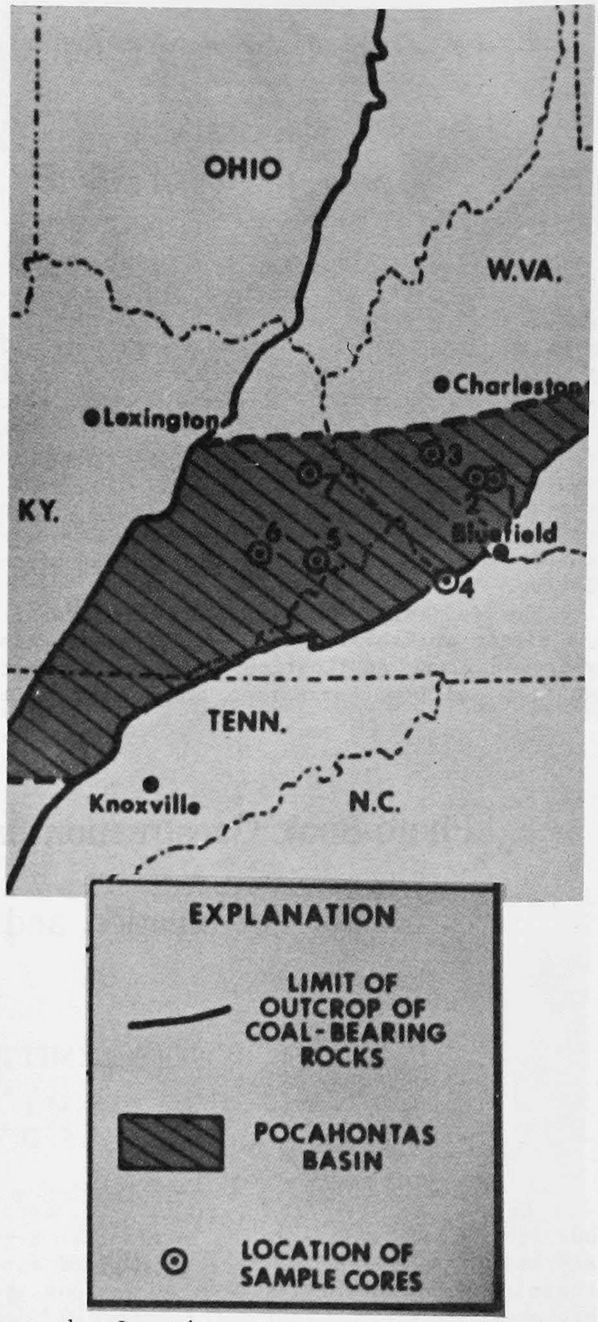

Figure 1.--Location of the Pocahontas Basin in the Appalachian coal field. Also shown are the locations of cores from which the rock classification was generated (table 1).

persons, 35 groups of common rock types emerged.

Photographs of representative samples for each group were taken at a one-to-one scale. A Sinar-F 4x5 view camera was used to photograph each sample. Two 3200 K tungsten lights were used as a light source, directed obliquely down the length of each sample.

A preliminary photo-book was assembled and field tested; several groups were reorganized and a few were added, resulting in 42 groups of different rock types common to the Pocahontas Basin. These were assembled into a final photo-book, and a list of the rock types used is given in table 1.

Names that have been applied to rock groups are a combination of the drillers' and geologists' terms but, in every case, the drillers' term is used if at all feasible. Some geologists object to this practice; however, the most important factor is the photograph, which constitutes a basic method for communication and a base from which more detailed description can proceed. For example, specific information concerning grain size, mineral composition, physical strength, etc., can be readily appended to the basic rock type that is readily and consistently recognized.

Each rock name has a three-digit-code number. The use of numbers rather than written words is an efficient method for recording data. Moreover, it simplifies the question of terminology and permits ready manipulation of the data by modern computers.

TECHNIQUES FOR LOGGING

The first steps in describing a core are washing and alignment. The latter step is merely a matter of convenience, as misaligned core creates difficulties in measurement. Washing and wetting are only necessary with dark-colored sandy shales in which distinctive features can be readily masked by drill marks or a thin film of mud. Most sandstones need not be thoroughly cleaned as they tend to be sufficiently uniform or to have features so large as to be visible even if the core surface is partially obscured.

The photo-book does not have to be held next to the core in order to compare the core with a photograph, because the eye readily makes adjustment for distance; most observations can be made at distances to as much as 5 ft. Some care may be necessary in comparing colors shown in photographs with those found under field conditions. Rock samples are generally photographed with ideal lighting against a neutral background and, hence, are the closest approximation to true color. Cores compared to the photographs under any other conditions may not match perfectly. Clothing, ground color, foliage, sky color, and temperature will affect the color of the rock and photograph. Consequently, it may be difficult in some cases to match colors exactly. However, such differences are generally so small that they are unnoticed or negligible in terms of identifying rock types.

Actual handling of the core is usually necessary only to distinguish different subtypes within major rock classes; for example, subtypes of sandstones, sandy shales, and shales. Touching many fine-grained rocks is a good test for the relative degree of grittiness. Scratching the core with a knife blade is especially important in distinguishing coals, bones, and black shales. Dilute hydrochloric acid is useful in detecting the presence of calcium carbonate but, in many cases, these rocks can be equally well recognized by their hardness and density.

Procedures for measurement of rock thickness vary widely. Drillers usually employ a combination of direct thickness measurement and known depth of hole. Engineers and geologists generally measure thicknesses found in the core pile and use them in combination with depths marked on the core by the driller. The Carolina Coal Group has developed a system of measuring cumulative thicknesses of rock units in the core pile, which are transformed into individual thicknesses during computer treatment of core data.

This procedure is done using a 50-ft steel tape, a photo-book, and special data forms. The tape is stretched along the core as it is laid out by the driller. Using the photo-book and data forms, the geologist or engineer matches the rock types found in the core with photographs in the photo-book, posting the codes on the data form. (See fig. 2 for an example.) Footages are posted cumulatively in core-barrel-length increments until the entire core is completed. (Interactive computer programs subtract out individual thicknesses during processing.) The completed log is given a cover sheet showing location and identification information. The log is then ready to be submitted to computer personnel for computer input.

DATA INPUT

Logs prepared using the Carolina photo-book technique as well as conventional drillers' logs are typed into the computer via IBM 2741 teletypewriter terminals. An interactive language, APL, accepts the data in an easily typed form. Once in the computer, it is checked carefully for errors by computer editing programs and input personnel. Batch jobs process the data into a keyed master disc file, where it is checked again in printout form for correct lithologic thickness and description.

GRAPHIC DATA PREPARATION

In order to produce graphic logs from drillers' and geologists' data, logs are retrieved from the master file and passed on to a coding program. Coded data are transferred to a plotting program, which translates the codes to graphic symbols of the appropriate thickness and plots them in their proper sequence.

The program for plotting graphic logs was designed for use with both older drillers' logs and Carolina Coal Group logs that use a numeric coded system of recording data. An example of rock patterns and other relevant data as they appear on a log strip is shown in figure 3. Heading information, listed in a 3-in. x 2-1/2-in. box at the top of the log, includes quadran-

Table 1.--List of commonly occurring rocks in the Pocahontas Basin

Name	Carolina Coal code number
Pebbly sandstones and conglomerates	
Gray shale and (or) ironstone pebble conglomerate (undifferentiated)	741
Gray shale pebble conglomerate	742
Gray ironstone pebble conglomerate	743
Gray rock pebble conglomerate	745
Gray sandstone with coal bands	748
Gray sandstone with coal spars	749
Crystallized quartz pebble conglomerate	754
Sandstones	
Crossbedded gray sandstone	541
Gray sandstone with shale streaks (undifferentiated)	543
Gray sandstone with shale streaks, rippled	543 RIP
Gray sandstone with shale streaks, flat	543 FLT
Massive gray sandstone	544
Churned gray sandstone (if roots or burrows cannot be differentiated)	546
Rooted gray sandstone	547
Burrowed gray sandstone	548
Crossbedded crystallized sandstone	551
Crystallized sandstone with shale streaks, rippled	553 RIP
Massive crystallized sandstone	554
Crossbedded hard sandstone	561
Massive hard sandstone	564
Carbonate-cemented sandstone, siderite	644 $FeCO_3$
Sandy shales	
Black shale with sandstone streaks	313
Dark-gray, interbedded sandstone and shale (undifferentiated)	322
Dark-gray, interbedded sandstone and shale, flat	322 FLT
Dark-gray, interbedded sandstone and shale, rippled and streaked	322 RIP & STRKD
Dark-gray, interbedded sandstone and shale, rippled	322 RIP
Dark-gray shale with sandstone streaks	323
Dark-gray, massive sandy shale	324
Dark-gray, massive, churned sandy shale	325
Dark-gray, sandy fire clay	327
Dark-gray, burrowed sandy shale	328
Shales and fire clays	
Black shale with coal streaks	113
Black shale	114
Dark-gray shale	124
Dark-gray fire clay	127

Table 1.--(continued)

Name	Carolina Coal code number
Limestones and ironstones	
Massive, fine-grained limestone	044
Massive, fine-grained limestone with fossil shells	054
Massive ironstone	074
Nodular ironstone	076
Coal and bone	
Coal (undifferentiated)	020
Impure coal (undifferentiated)	030
Slumps and mudflows	
Slump or mudflow (undifferentiated)	011
Slump deposits	012
Slumped shale	013
Slumped sandy shale	014
Mudflow deposits (undifferentiated)	016
Sandy shale mudflow	018
Sandstone mudflow	019
Rocks with fossil shells other than limestone	
Black shale with fossil shells	119
No rock recovered	
Open space or crevice	002

gle name, identification number, top hole elevation, vertical scale, and company number. Beneath the heading box are symbols representing the sequence of lithologies found in any given log. The contact between each two rock units is indicated by a diagonal tick mark on the right margin of the column. The vertical scale for this column is 1 in. = 10 ft. Cumulative thickness downward is printed at 10-ft intervals and, at the bottom of the column, the total cumulative thickness of the hole is indicated. The program prints symbols for most rock units as thin as 1 ft and for coals having thicknesses as small as 1 in. The thicknesses of all units, even when too thin to show symbolically, are indicated by diagonal ticks on the column margin.

After all logs for a particular property are entered into the computer, a computer-plotted base map is prepared showing the Carolina Coal Group and Company ID numbers. These maps are plotted at a scale of 1,000 ft = 1 in. and 2,000 ft = 1 in. Maps plotted at the scale of 2,000 ft = 1 in. can be directly overlain by 7-1/2-minute base maps to check the accuracy of U.T.M. X-Y coordinates. If errors are found, they are corrected and submitted to computer personnel to be entered on the master file. New maps are then made and rechecked.

ESTABLISHMENT OF SEAM CONTINUITY AND DATA POSTING

Once the geologist has obtained accurate base maps and accompanying log-strips, the correlation process begins. The geologist follows a best-fit procedure of matching all rock-type sequences between all logs in a pair-wise fashion, building a network of correlated logs.

Once correlations are complete, a print-out of the logs is obtained, and the top or bottom of each seam on each log is labeled with a six-digit alpha-numeric code enclosed in parentheses; for example, (Pocy 3). This label is input to the computer master file.

Once the seams are computer-labeled, quadrangle maps or quadrangle maps with property lines, at a scale of 2,000 ft or 1,000 ft = 1 in., are computer-generated. Several types of maps can be made: (1) elevation of the coal seam, (2) rock types at various levels above the coal seam, (3) coal thickness, (4) seam thickness, (5) reject thickness, and (6) percent rejects. These data can be contoured using any number of existing contouring programs.

In practice, however, it is not advisable to use computer contouring programs unless data points are evenly distributed throughout the map area. Clustering of data can ofter cause errors in contouring programs. To avoid this hazard, it is often quicker to hand contour when data is unevenly distributed.

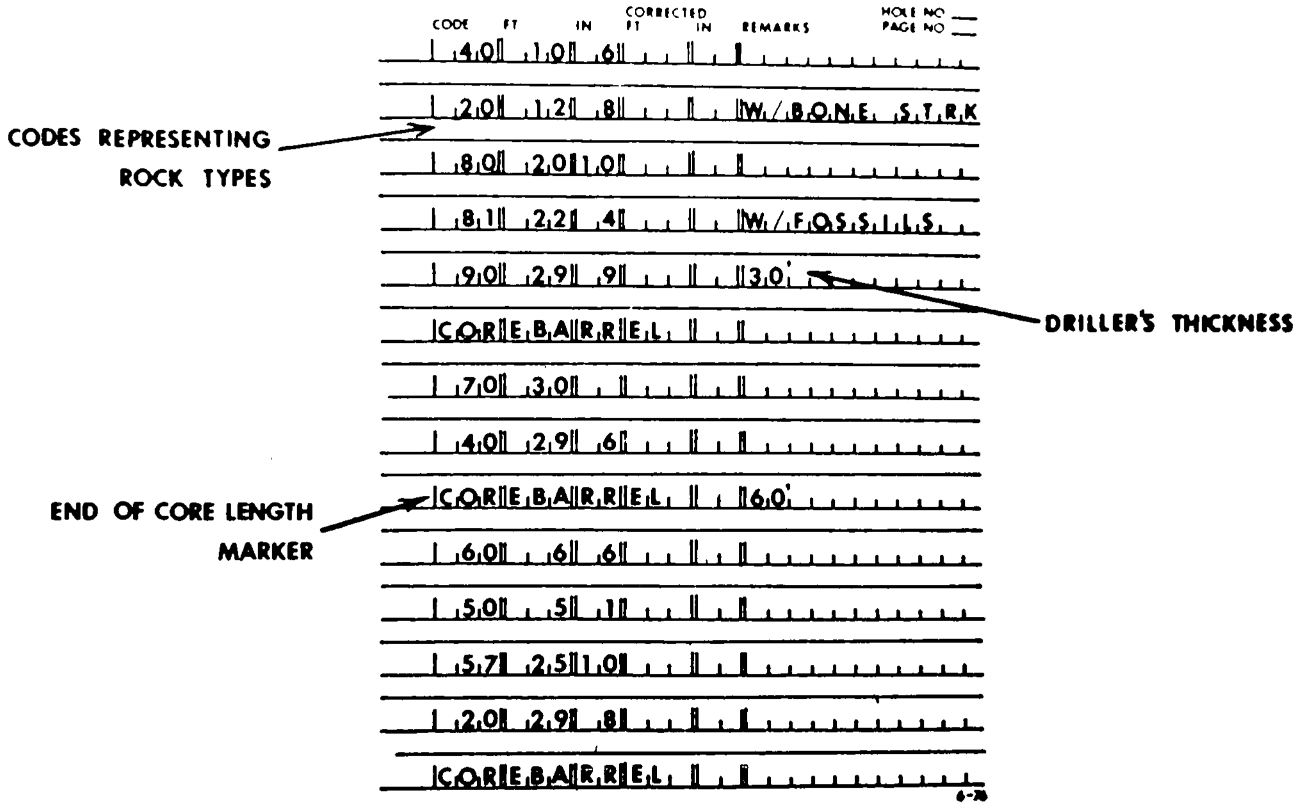

Figure 2.--Special data form and example of data input. Following data are entered: rock-type code, thickness cumulatively in feet and inches by corebarrel, and logger's comments. The end of each core length is denoted in the form as "COREBARREL."

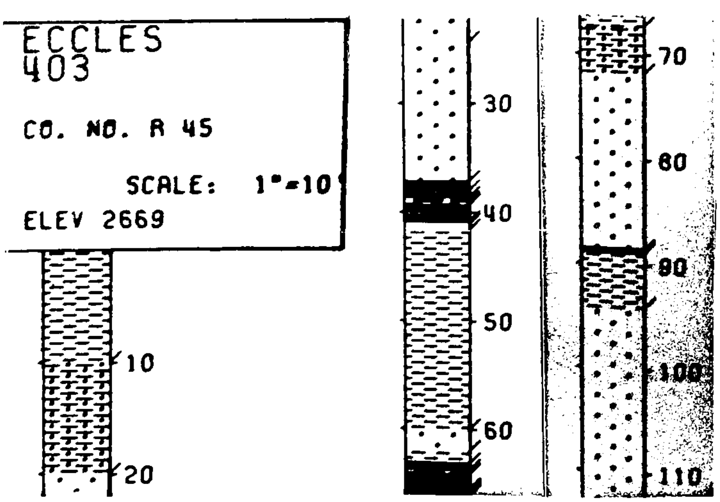

Figure 3.--Example of output of graphic plotting program "LOGPLOT" (shown at reduced scale).

Application of a Core Logging Technique for Standardizing Descriptions and Simplifying Computerization of Data

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INTRODUCTION

The exploration group of Atlantic Richfield Company uses, with modifications, the University of South Carolina core logging technique discussed by Robert Melton in the previous paper. We had two basic reasons for wanting to try this technique: One was the need to standardize our core descriptions, and the other was to make the best use of core data and that included simplying computerization. The technique is conducive to, but independent of, computerization; and we feel it is valid whether or not the data is ever computerized. We have been using the technique for a little over a year in the Illinois Basin and are in the process of implementing it in the western Cretaceous coal fields. We have not yet realized all its potential or identified all its weaknesses.

ILLINOIS BASIN COAL FIELDS

Photography

We chose the Illinois Basin for a test area because we hold a lot of acreage there, have done much coring, and plan to do a lot more. We also have many cores available for photographing in our Denver warehouse. We used 3-in. cores for photo samples since we are now cutting 3-in. cores on all of our Illinois projects. We used a professional photographer and the work was done at the studio. The Illinois cores were photographed using a 35-mm camera. (The Cretaceous cores were photographed using a 2-1/4-in. x 2-1/4-in. camera.) We photographed end views as well as side views of most of the cores in order to better show the rock texture (fig. 1). All cores were photographed in color and both wet and dry. We did not attempt to photograph coal cores, most of which do not photograph very well. The cores are printed full scale, and so we ended up with a rather large field book (9 in. x 12 in.).

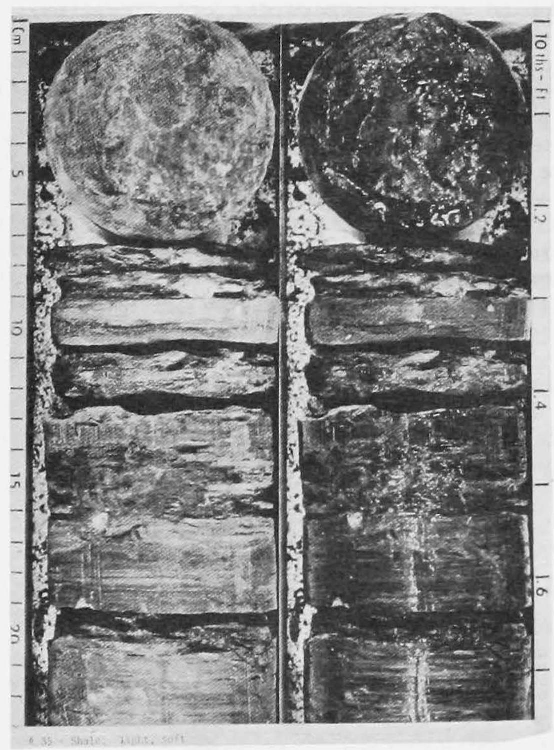

Figure 1.--Example of page from core photo-book. (Actual photo is full-scale 3-in. core in color.)

Rock Types

We selected rock types using the method that Melton outlined in the preceding paper. The next step was to identify rock types. We have identified 35 basic types so far, 29 of which were suitable for making colored photographs. It is important that the basic lithologic descriptions

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be kept elementary and not too specific, or the system does not work very efficiently. Variations from the basic lithologic types are handled as remarks, allowing for flexibility in the system. Admittedly, this method allows for subjectivity and some inconsistencies, so there is somewhat of a trade-off.

Coding

One of the things that we have struggled with most is the rock-coding system; and, in fact, we are planning to make some changes in our system after a year's use in the field. We set up a numbering system exclusively for Illinois, and we had planned to set up others for other regions. Now we feel that we will probably group the rock types into one universal numbering system, but keep the photo-books separated on a regional basis. (Since this paper was first presented, we have set up a universal coal-field classification system, which we are currently testing in the field in conjunction with a western Cretaceous core photo-book. So far the results have been very encouraging.) We are adopting a universal numbering system, because we are seeing many of the same rock types in different coal regions. They differ mainly in frequency of occurrence. Our present system for Illinois uses numbers in the 0 to 99 range, leaving gaps for later additions (fig. 2). We have tried to group lithologies within certain number sequences, so that the numbers can be more easily related to the rocks.

Drill-site Procedures

We log the cores in the field, relating the cores to the photographs for identification. We have set up a form for rapid recording at the drill site and also for ease of extracting data for geological evaluation, whether it be by hand or with computer assistance (fig. 3). Key punching may be done directly from the form.

Logging cuttings can also be lithologically identified using the rock-coding technique, although obviously no photographs are involved. We usually make an interpretive log with the aid of our electric logs and code the lithologic units as closely as we can to the rock types. Within each lithologic grouping in our classification system, we have one undifferentiated type. This is a "catch-all" for all lithologic information that cannot readily be classified into a more specific type. Usually it is necessary to use the undifferentiated types to classify cuttings.

Retrieval of Data

We have put the computer to work for us and have been retrieving useful data from our drilling efforts in Illinois. Thus far, these data include computer-typed field notes, detailed lithologic plots, certain geologic maps that can be constructed without geologic interpretation, and reserve calculations. If field notes are normally typed, this method saves a lot of secretarial time

ILLINOIS TYPE ROCKS

Type #	Description and Comments
00	Lost
01	Surficial Material:. (Sand, gravel, etc in remarks.)
05	Pyrite (NP)
06	Pyrite with shale and coal (NP)
10	Coal: undifferentiated (NP)
11	Coal: bright, blocky, with calcite cleat fill, (NP)
12	Coal: dull to medium bright, blocky, with calcite cleat fill (NP)
13	Coal: shaly or bony (NP)
14	Bone (NP)
20	Claystone: undifferentiated (NP)
21	Claystone: dark, medium hard, few slickensides
22	Claystone: light, medium hard, few slickensides
23	Claystone: dark, soft, few slickensides
24	Claystone: light, soft, few slickensides
25	Claystone: dark, soft, abundant slickensides, broken
26	Claystone: light, soft, abundant slickensides,broken
27	Claystone: with limestone inclusions
29	Clay: very soft (NP)
30	Shale: undifferentiated (NP)
31	Shale: carbonaceous, black, hard
32	Shale: dark, hard
33	Shale: light, hard
34	Shale: dark, soft
35	Shale: light, soft
36	Shale: dark, with siderite, hard
37	Shale: fossiliferous, limy, dark, hard, (grades to type #92)
38	Shale: with coal, dark to black, medium hard, (may also be claystone)
50	Shale: with sandstone, undifferentiated (NP)
51	Shale: medium-dark gray, with few thin sandstone interbeds (<25% sandstone
52	Shale: medium-dark gray, with siderite and with few thin sandstone interbeds
53	Shale: medium-dark gray, with abundant thin sandstone interbeds (25%-50% sandstone)

NP = No Photo

Illinois Type Rocks
Page -2-

Type #	Description and Comments
60	Siltstone: undifferentiated (NP)
61	Siltstone: medium gray, massive, hard
70	Sandstone: undifferentiated (NP)
71	Sandstone: light gray, medium-grained massive (may be cross-bedded)
72	Sandstone: light gray, very fine-grained, - fine grained, massive (may be cross-bedded)
73	Sandstone: light gray, fine - medium grained, with coal inclusions
74	Sandstone: with abundant carbonaceous trash, light gray, very fine-grained - fine grained, massive (may or may not have banded appearance, generally massive)
80	Sandstone: with shale undifferentiated (NP)
81	Sandstone: light gray, with few thin, dark shale interbeds (<25% shale)
82	Sandstone: light gray, with abundant dark interbeds (25-50% shale)
90	Limestone: undifferentiated (NP)
91	Limestone: light, dense, very hard (may be argillaceous)
92	Limestone: very fossilferous, very dark, very hard (grades to type #37, may be argillaceous)
93	Limestone: with calcite fracture fill, very hard (may be light or dark, may be argillaceous).
94	Limestone: brecciated, light, clayey matrix, hard
99	Siderite: (NP)

NP = No Photo

Figure 2.--Rock-coding system for Illinois rocks.

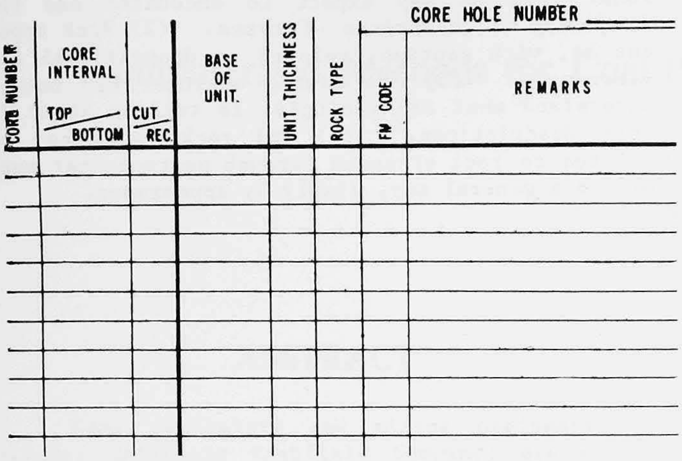


Figure 3.--Field form for core-drill logging.

ATLANTIC RICHFIELD COAL EXPLORATION GROUP - U.S. RESOURCES - SCHD -- COMPANY CONFIDENTIAL --
FIELD LITHOLOGY DESCRIPTION PAGE 124
ALBION DATE 77/04/12

HOLE AB 32

CORE NO.	INTERVAL TOP	INTERVAL BOTTOM	CUT	REC.	BASE OF UNIT	UNIT THICK.	ROCK TYPE	FORM CODE	ROCK	DESCRIPTIONS/COMMENTS
0					896.00	2.00	10	17M	COAL	UNDIFFERENTIATED
0					908.00	12.00	90		LIMESTONE	UNDIFFERENTIATED POSSIBLY BANKSTON FORK LS
0					932.00	24.00	60		SILTSTONE	UNDIFFERENTIATED W/ SS INTBDS
1	932.00	952.00	20.00	20.00	934.20	2.20	81	EN	SANDSTONE	LIGHT GRAY, WITH FEW THIN, DARK SHALE INTERBEDS (LESS THAN 25% SHALE) DIST BEDDING
1					936.70	2.50	82	EN	SANDSTONE	LIGHT GRAY, WITH ABUNDANT DARK INTERBEDS (25-50% SHALE) DIST BEDDING, TR SID NODS
1					938.90	2.20	60	EN	SILTSTONE	UNDIFFERENTIATED DIST BEDDING
1					940.10	1.20	51	EN	SHALE	MEDIUM-DARK GRAY, WITH FEW THIN SANDSTONE INTERBEDS (LESS THAN 25% SANDSTONE) SILTY, MOD SID BANDS
1					943.10	3.00	81	EN	SANDSTONE	LIGHT GRAY, WITH FEW THIN, DARK SHALE INTERBEDS (LESS THAN 25% SHALE) LIMY
1					944.60	1.50	60	EN	SILTSTONE	UNDIFFERENTIATED DIST BEDDING
1					945.40	.80	82	EN	SANDSTONE	LIGHT GRAY, WITH ABUNDANT DARK INTERBEDS (25-50% SHALE)
1					952.00	6.60	33	EN	SHALE	LIGHT, HARD SILTY, TR SS, TR SID BANDS, TR DISS PYR
2	952.00	968.00	16.00	16.00	961.30	9.30	51	EN	SHALE	MEDIUM-DARK GRAY, WITH FEW THIN SANDSTONE INTERBEDS (LESS THAN 25% SANDSTONE) SILTY, TR SID BANDS, TR DISS PYR
2					962.90	1.60	53	EN	SHALE	MEDIUM-DARK GRAY, WITH ABUNDANT THIN SANDSTONE INTERBEDS (25-50% SANDSTONE) TR DISS PYR
2					964.20	1.30	81	EN	SANDSTONE	LIGHT GRAY, WITH FEW THIN, DARK SHALE INTERBEDS (LESS THAN 25% SHALE)
2					967.10	2.90	72	EN	SANDSTONE	LIGHT GRAY, VERY FINE-GRAINED, - FINE GRAINED, MASSIVE TR CARB TRASH
2					967.70	.60	81	EN	SANDSTONE	LIGHT GRAY, WITH FEW THIN, DARK SHALE INTERBEDS (LESS THAN 25% SHALE)
2					968.00	.30	72	EN	SANDSTONE	LIGHT GRAY, VERY FINE-GRAINED, - FINE GRAINED, MASSIVE

CORE HOLE SUMMARY SHEET

COAL DATA

FORMATION	TOP	BOTTOM	THICKNESS
17M	894.00	896.00	2.00
16M	1012.90	1016.90	4.00
15M	1038.20	1042.20	4.00

PROJECT/ ALBION
COUNTY AND STATE/ EDWARDS,ILL
HOLE NO/ AB-32
LOCATION/ 752FT FNL 770FT FEL SEC 10
SW NE NE SEC 10 T1S R13W
COORDINATES x = 4591320
y = 3261591
SPUDDING DATE 07/22/76
COMPLETION DATE 08/08/76
ELEVATION/ 540FT
TOTAL DEPTH/ 1065FT
CORE SIZE/ 3IN
CASING DEPTH/ 113.7FT
DRILLING MEDIUM/ WATER
WATER ENCOUNTERED/
GEOPHYSICAL/ GAMMA-RAY,DENSITY,RESISTIVITY
PLUGGING RECORD/ PLUGGED WITH CEMENT FROM SURFACE TO TOTAL DEPTH.
COMMENTS/ #7 COAL DRILLED; 80.9FT ROOF ROCK CORED, ENERGY SHALE 106FT THICK.

Figure 4.--Core-hole summary sheet and lithologic-field-description document.

(fig. 4). The computerized lithologic plot saves much geologic and drafting time and allows the flexibility of plotting logs on different scales (fig. 5). The computer symbols that we use are a combination of those borrowed from the University of South Carolina and some that we have created ourselves. In some cases we have chosen to combine two or more rock types under one lithologic symbol. The person using these data in the office may not have been involved with them in the field, but he still has a reasonable idea of what the geologist was thinking if he is familiar with rock types. The following paper, by L. Y. Bajwa, further discusses computer applications and the potential of retrieving data.

CONCLUSIONS

Like any other, this core logging technique has certain weaknesses: (1) You must have access to many cores in your area of interest. (2) Not all rocks fit nicely into a rock-type system, and so, as in any other system, a certain amount of subjectivity is involved. (3) This system is not conducive to detailed lithologic descriptions if that is your intent. (4) The system must be very carefully set up, and it takes a lot of field testing before it can be successfully used.

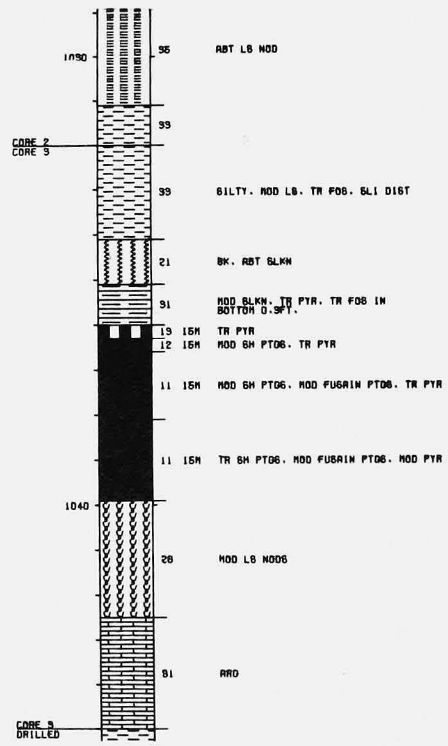


Figure 5.--Computer-plotted columnar section. Core-drill intervals and depths to left; rock-description codes, seam codes, and remarks to right.

On the positive side, I have already mentioned the standardization of descriptions and the ease of computerization. But, in addition, some other important things should be considered: (1) We have found that this sytem gives everyone involved a better feel for the rocks--in a way, it is like being able to look at the rocks in the office. The classification of rock types gives the geologist an indication of the variation of rock types he may expect to encounter and the frequency of occurrence of types. (2) Rock types can be, with caution, related to depositional environments. (3) The mining engineer can better understand what the geologist is talking about in core descriptions. (4) And rock types can be related to rock strength through geotechnical work or, in a general way, simply by appearance.

Computerized Methods for Coal-Property Planning and Evaluation

L. Y. BAJWA[1]

ABSTRACT

Coal geologists and mining engineers at A.R.Co. (Atlantic Richfield Company) are using software systems to assist in mine-planning and evaluation activities. A.R.Co.'s technical systems include programs to report lithologic and quality data, to plot columnar sections and generate quality or structure[2]-contour maps, to compute and report reserve and overburden estimates, and to aid in determining the environmental effects of a mining operation.

INTRODUCTION

More than two years ago, members of the Technical Systems Group of the Synthetic Crude and Minerals Division at A.R.Co. began developing an interrelated system of software programs to aid in coal-property evaluation. This system, fostered by the needs of geologists and mining engineers alike, grew to include many diverse features. The resulting CAS (Coal Analysis System) has weathered field testing and has been accepted in-house as an effective geological and mining engineering tool.

COAL DATA BASE

Vital to all programs within the CAS is a large, computerized data base that includes direct-core and drilling measurements, electric- and geologic-log data, survey coordinates, and information from laboratory quality reports. Items are entered on-line via a time-sharing terminal and are appended to either a coal quality-structure file or a lithology file. Entries are free-format; all data entry and editing procedures are easily handled by a trained clerk, and the system includes programs to check the primary files for errors in order to flag obvious problems. Once a data base has been assembled for a property, various production requests may be made. However, all systems within the CAS are user-interactive; and, by answering a series of simple questions at a terminal, a geologist or engineer may exercise the programs directly.

LITHOLOGY SYSTEM

Primary lithologic data consist of drill-core intervals, amounts cut and (or) recovered, interval thicknesses, rock-description codes, and comments. The rock-description codes (numeric) are based on the photo-book identification procedure developed by geologists at the University of South Carolina and later adapted for use by exploration geologists at A.R.Co. (See Melton, this volume; Lehmann, this volume.) Each code is keyed to a standard rock description from a predetermined list.

The first program in the lithology system reorganizes the primary data, supplies actual rock descriptions in place of codes, and prints out a <u>field description document</u> which provides a convenient reference for geological investigations. The same information may also be reproduced in the form of <u>plotted columnar sections</u>. These strip charts are useful in correlating geologic units and in determining underground-mine roof- and floor-support requirements. (See figs. 4 and 5 of Lehmann, this volume.)

QUALITY-STRUCTURE SYSTEM

Coal-quality information enters the system via official laboratory data sheets, as in figure 1. Proximate analyses are most often performed; but a particular sample may be analyzed for various items, including ash, fusion temperature, sulfur forms, and trace elements. These data, in addition to Lambert coordinates, collar elevations, hole total depths, and composite and (or) interval thicknesses are assembled in the quality-structure primary file. A typical core-hole data set is displayed in figure 2.

<u>Quality reports</u> are generally the first

---

[1]Atlantic Richfield Company
1500 Security Life Building
1616 Glenarm Place
Denver, CO 80202

[2]Please note that 'structure' as used herein refers to all types of spatial measurements, including coordinates, seam thickness, elevations, etc.

CT&E Co.

A DIVISION OF COMMERCIAL TESTING & ENGINEERING CO.

GENERAL OFFICES 228 NORTH LA SALLE STREET, CHICAGO ILLINOIS 60601 • AREA CODE 312 726-8434

July 9, 1971

MAIL ADDRESS
2180 EAST 40TH AVENUE
DENVER COLORADO 80205
PHONE 303 255-3377

ATLANTIC RICHFIELD COMPANY
1500 Security Life Bldg.
Denver, Colorado 80205

Sample identification by ARCO

Kind of sample reported to us: Coal

Sample taken at: XXXXX

Sample taken by: ARCO

Date sampled: XXXXX

Drill Hole No. BT-34
Samples 1 thru 7
Composite of Lab Nos.
72-7305 thru 72-7311
113' - 178'7"
Full Seam Analysis Composite on footage basis

Analysis report no. 72-7312

PROXIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	28.47	XXXXX
% Ash	5.79	8.09
% Volatile	33.40	46.70
% Fixed Carbon	32.34	45.21
	100.00	100.00
Btu	8516	11905
% Sulfur	0.43	0.60

ULTIMATE ANALYSIS

	As Received	Dry Basis
% Moisture	28.47	XXXXX
% Carbon	50.57	70.70
% Hydrogen	3.23	4.51
% Nitrogen	0.58	0.81
% Chlorine	0.01	0.02
% Sulfur	0.43	0.60
% Ash	5.79	8.09
% Oxygen (diff.)	10.92	15.27
	100.00	100.00

% EQUILIBRIUM MOISTURE = 26.67
HARDGROVE GRINDABILITY INDEX = 60.3

Respectfully submitted,
CT&E Co.
L.W. TAYLOR, District Manager

LWT/ps

Charter Member

CHICAGO, ILLINOIS • CHARLESTON, W. VA. • CLARKSBURG, W. VA. • CLEVELAND, OHIO • NORFOLK, VA. • TERRE HAUTE, IND. • TOLEDO, OHIO • DENVER, COLO. • BIRMINGHAM, ALA.

Figure 1.--Example of coal-quality laboratory data sheet.

items generated from the quality-structure file of a new coal property. These reports show quality information in either a hole-by-hole (fig. 3) or all-hole-summary (fig. 4) format. The statistical distribution of values for a given coal quality may also be computed and printed out (fig. 5).

As property evaluation proceeds, the relative structures of minable seams must be studied and potential problem areas must be identified--regions of high sulfur content, for example. Both tasks are made easier through the use of a CRT terminal with plotting capabilities.

In the former task, property core-hole locations are displayed at the terminal, and the user defines desired cross sections (fig. 6) by moving the terminal cursor to each end point of a strip. The resulting cross-section plots (fig. 7) are immediately available at the terminal and may be either hard-copied or transmitted to a regular plotter.

The latter task calls for contour maps of selected coal qualities and structures. Raw data points (X, Y, Z, with Z being a quality-structure

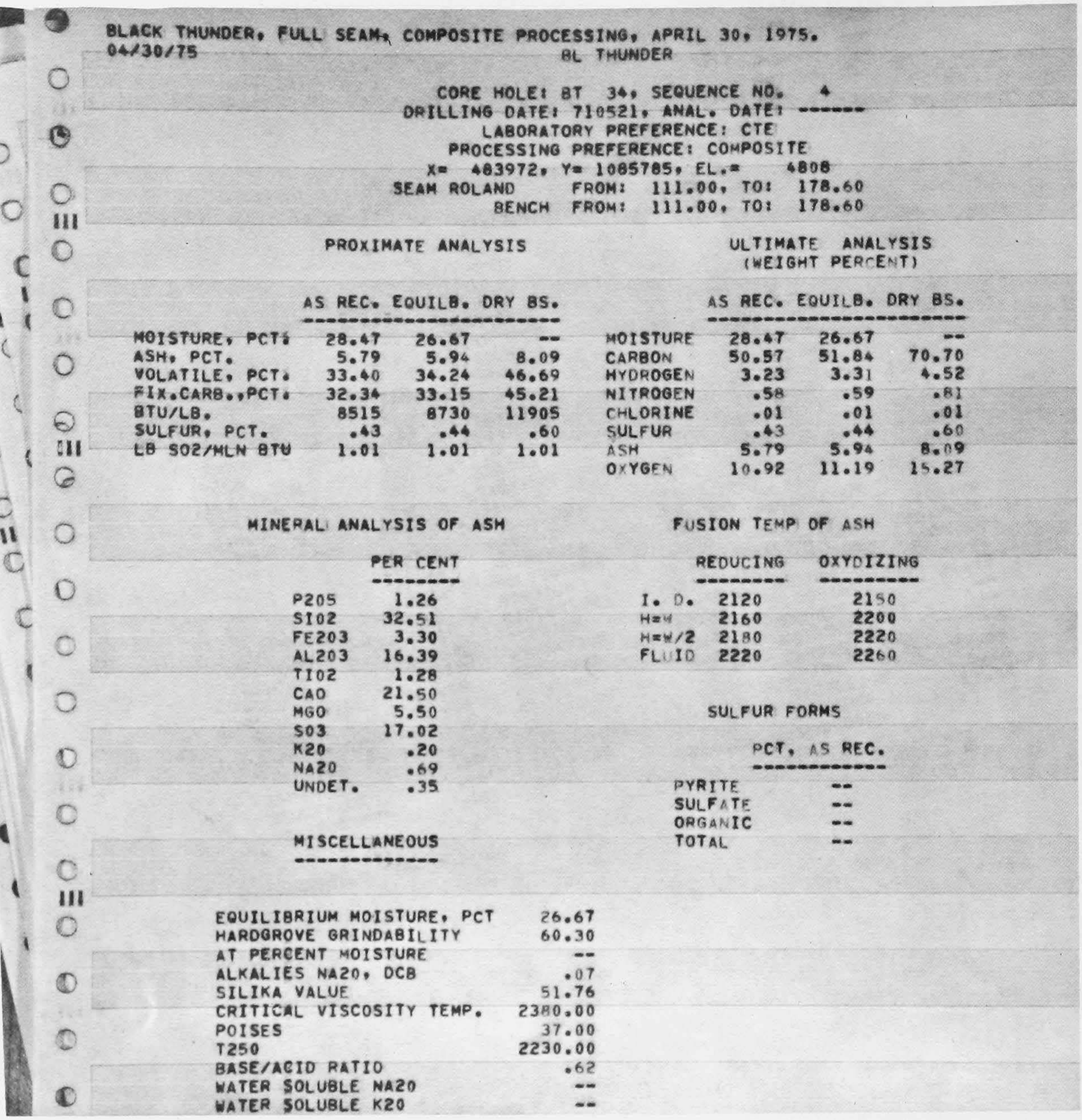
```
01180  CTF 196 208 PROX 27.65 7.98 -1 -1 8308 .64
01200  CTF 208 215.5 PROX 32.45 4.7 -1 -1 8192 .36
01220  CTF 215.5 216 PROX -1 -1 -1 -1 -1 -1
01240  CTF 216 219 PROX 32.45 4.7 -1 -1 8192 .36
01260  CTF 219 226 PROX -1
01280  CTF 226 236 PROX 30.46 4.03 -1 -1 8379 .24
01300  CTF 236 246 PROX 27.59 4.53 -1 -1 8769 .26
01320  CTF 246 249.3 PROX 30.12 5.05 -1 -1 9555 .26
01340  CTF 249.3 250 PROX -1 -1 -1 -1 -1 -1
01360  CTF 250 256 PROX 30.12 5.05 -1 -1 9555 .26
01380  CTF 256 266 PROX 28.89 5.28 -1 -1 8574 .35
01400 HOLE RT 34 710521 E483972 N1085785 S2 R70W T42N EL4808
01420  1 TOTAL ROLAND 0 111 178.6
01440  KOMPOSITE ROLAND 0 111 113
01460  CTF C PROX -1
01480  KOMPOSITE ROLAND 0 113 178.6
01500  CTF C PROX 28.47 5.79 33.4 32.34 8516 .43
01520  CTF C ULT 28.47 50.57 3.23 .58 .01 .43 5.79 10.92
01540  CTF C ASH 1.26 32.51 3.3 16.39 1.28 21.5 5.5 17.02 .2 .69 .35
01560  CTF C RETA 2120 2160 2180 2220
01580  CTE C OFTA 2150 2200 2220 2260
01600  CTF C MISC 26.67 60.3 -1 .07 51.76 2380 37 2230 .622 -1 -1
01620  ACCU C T 1 .13 .1 0 .26 0 .16 0 0 0 0
01640  ACCU C T 2 0 .1 1.8 1.5 .1 .1 .1 .1 .1 .1
01660  ACCU C T 3 .1 .1 .1 .1 .9 .15 .5 .39 27 .03
01680  ACCU C T 4 .15 .1 .27 .04 -1 .01 .020 0 0
01700  ACCU C T 5 0 .75 .6 3.2 .41 40 .31 1.3 .1 .3
01720  ACCU C T 6 .02 .1 220 4.3 .21 2.5 390 2.3 7.2
01740  ACCU C T 7 5.6 190 .52 570 830 72 1300 180 4000 9000
01760  ACCU C T 8 1000 3100 36 -1 -1 -1 22 3.2 13 -1
01780  INTERVAL ROLAND 0
01800  CTF 111 119 PROX -1
01820  CTF 119 123 PROX -1
01840  CTE 123 133 PROX 28.44 4.83 -1 -1 8524 .47
01860  CTF 133 136 PROX 28.1 4.02 -1 -1 8803 .31
01880  CTF 136 137 PROX -1 -1 -1 -1 -1 -1
01900  CTF 137 143 PROX 28.1 4.02 -1 -1 8803 .31
01920  CTF 143 153 PROX 29.58 4.64 -1 -1 8500 .37
01940  CTF 153 163 PROX 28.03 5.19 -1 -1 8585 .31
01960  CTF 163 173 PROX 30.14 4.23 -1 -1 8477 .34
01980  CTF 173 178.6 PROX 29.27 8.33 -1 -1 7986 .47
02000 HOLE RT 35 710603 E472772 N1087738 S33 R70W T43N EL4776
02020  1 TOTAL ROLAND 0 187 260.5
02040  KOMPOSITE ROLAND 0 187 190
02060  CTF C PROX -1
02080  KOMPOSITE ROLAND 0 190 260.5
02100  CTF C PROX 30.49 5.44 31.41 32.66 8236 .26
02120  CTF C ULT 30.49 48.22 3.54 .51 0 .26 5.44 11.54
```

Figure 2.--Quality-structure primary-file layout. The data within the square pertain to one core hole.

value) are selected from the quality-structure file; these data are gridded and contoured. The resulting maps are previewed at a plotting terminal to insure that costly plotting charges are avoided in the event that the plots are unacceptable (fig. 8); at times even hard copy of the terminal plots is sufficient for a particular study. At any rate the terminal plots are quickly available to the user, for whatever purpose. That can rarely be said of system plots, no matter how sophisticated the computer facility.

RESERVES AND OVERBURDEN SYSTEM

As evaluation fades into mine planning, timely methods for coal-reserve estimates become important. The economics of a particular mine plan must include information on the quantity and quality of the coal to be mined. In times past, even minor mine-plan revisions resulted in months of painstaking calculations and endless sessions



```
BLACK THUNDER, FULL SEAM, COMPOSITE PROCESSING, APRIL 30, 1975.
04/30/75                                   BL THUNDER

                        CORE HOLE: BT  34, SEQUENCE NO.   4
                      DRILLING DATE: 710521, ANAL. DATE: ------
                           LABORATORY PREFERENCE: CTE
                        PROCESSING PREFERENCE: COMPOSITE
                        X=  483972, Y= 1085785, EL.=    4808
                    SEAM ROLAND      FROM:  111.00, TO:  178.60
                              BENCH  FROM:  111.00, TO:  178.60

              PROXIMATE ANALYSIS                        ULTIMATE  ANALYSIS
                                                        (WEIGHT PERCENT)

                    AS REC. EQUILB. DRY BS.             AS REC. EQUILB. DRY BS.
                    -----------------------             -----------------------
MOISTURE, PCT.       28.47    26.67      --   MOISTURE   28.47    26.67      --
ASH, PCT.             5.79     5.94    8.09   CARBON     50.57    51.84   70.70
VOLATILE, PCT.       33.40    34.24   46.69   HYDROGEN    3.23     3.31    4.52
FIX.CARB.,PCT.       32.34    33.15   45.21   NITROGEN     .58      .59     .81
BTU/LB.               8515     8730   11905   CHLORINE     .01      .01     .01
SULFUR, PCT.           .43      .44     .60   SULFUR       .43      .44     .60
LB SO2/MLN BTU        1.01     1.01    1.01   ASH         5.79     5.94    8.09
                                              OXYGEN     10.92    11.19   15.27

           MINERAL ANALYSIS OF ASH                   FUSION TEMP OF ASH

                   PER CENT                        REDUCING   OXYDIZING
                   --------                        --------   ---------
           P205      1.26                  I. D.   2120         2150
           SI02     32.51                  H=W     2160         2200
           FE203     3.30                  H=W/2   2180         2220
           AL203    16.39                  FLUID   2220         2260
           TI02      1.28
           CAO      21.50
           MGO       5.50                           SULFUR FORMS
           SO3      17.02
           K20        .20                           PCT, AS REC.
           NA20       .69                           ------------
           UNDET.     .35                  PYRITE        --
                                           SULFATE       --
                                           ORGANIC       --
           MISCELLANEOUS                   TOTAL         --
           -------------

   EQUILIBRIUM MOISTURE, PCT      26.67
   HARDGROVE GRINDABILITY         60.30
   AT PERCENT MOISTURE               --
   ALKALIES NA20, DCB               .07
   SILIKA VALUE                   51.76
   CRITICAL VISCOSITY TEMP.     2380.00
   POISES                         37.00
   T250                         2230.00
   BASE/ACID RATIO                  .62
   WATER SOLUBLE NA20                --
   WATER SOLUBLE K20                 --
```

Figure 3.--Hole-by-hole coal-quality report.

with a drafting board and planimeter. Now such tasks are carried out quickly and accurately using a digitizer[1] in combination with a plotting terminal and programs that calculate areas and volumes for point-defined polygonal figures.

[1] A digitizer is a magnetized tablet that relates magnetic-field intensity at a given point to the digitizer's coordinate field of reference.

Briefly, the procedure for a surface mining operation is as follows: The mine plan is drawn and corner points for each mining year, for example, are digitized. The resulting coordinates are translated via software to the "real world" Lambert values. These points, connected by straight lines, are displayed at a plotting terminal and visually checked for errors (fig. 9). They are in turn input to the Reserves and Overburden System and define the boundaries of the various mining blocks. Gridded seam-thickness and quality data complete the informa-

BLACK THUNDER, FULL SEAM, COMPOSITE PROCESSING, APRIL 30, 1975.

PROXIMATE ANALYSIS
AS RECEIVED

CORE	MOISTURE	ASH	VOLATILE	FIX CARBO	BTU/LB
220	28.51	4.74	32.66	34.09	8589.00
222	33.42	3.97	29.74	32.87	8013.00
224	26.84	4.67	32.89	35.60	8625.00
226	29.69	4.33	30.24	35.75	8505.00
234	23.40	5.01	33.80	37.79	9083.00
236	27.88	4.65	32.48	34.99	8708.00
238	28.18	4.23	32.17	35.42	8651.00
240	25.35	4.83	33.20	36.62	8959.00
242	30.58	4.39	29.89	35.14	8334.00
249	29.13	4.54	31.89	34.44	8497.00
251	24.75	5.16	33.60	36.49	9096.00
253	29.68	5.08	30.99	34.25	8391.00
270	28.15	4.96	31.17	35.72	8623.79
273	27.08	5.30	33.08	34.54	8598.92
274	32.34	5.59	30.50	31.57	8056.20
280	31.42	4.98	30.09	33.51	8119.00
281	29.39	4.63	34.53	39.30	8466.56
283	27.35	4.34	32.95	35.36	8888.00
284	31.67	4.30	29.93	34.10	8174.00
286	28.52	4.53	31.98	34.97	8672.00
289	30.07	4.46	30.74	34.73	8436.00
290	25.78	4.42	-1.00	-1.00	8942.00
291	26.39	4.48	-1.00	-1.00	8855.00
292	27.60	4.24	33.68	34.48	8834.00
293	26.55	4.88	31.83	36.74	8843.00
299	28.69	4.59	32.50	34.22	8609.00
301	25.82	4.52	32.45	37.21	9020.00
302	26.84	4.57	32.78	35.81	8916.00
303	27.18	4.68	31.88	36.26	8799.00
MEAN	28.27	4.74	32.00	35.00	8603.51
MAX	34.52	8.79	38.04	40.02	9203.00
MIN	22.59	3.69	27.39	30.96	7765.00
NUM	140	140	138	138	140

Figure 4.--All-hole coal-quality summary report.

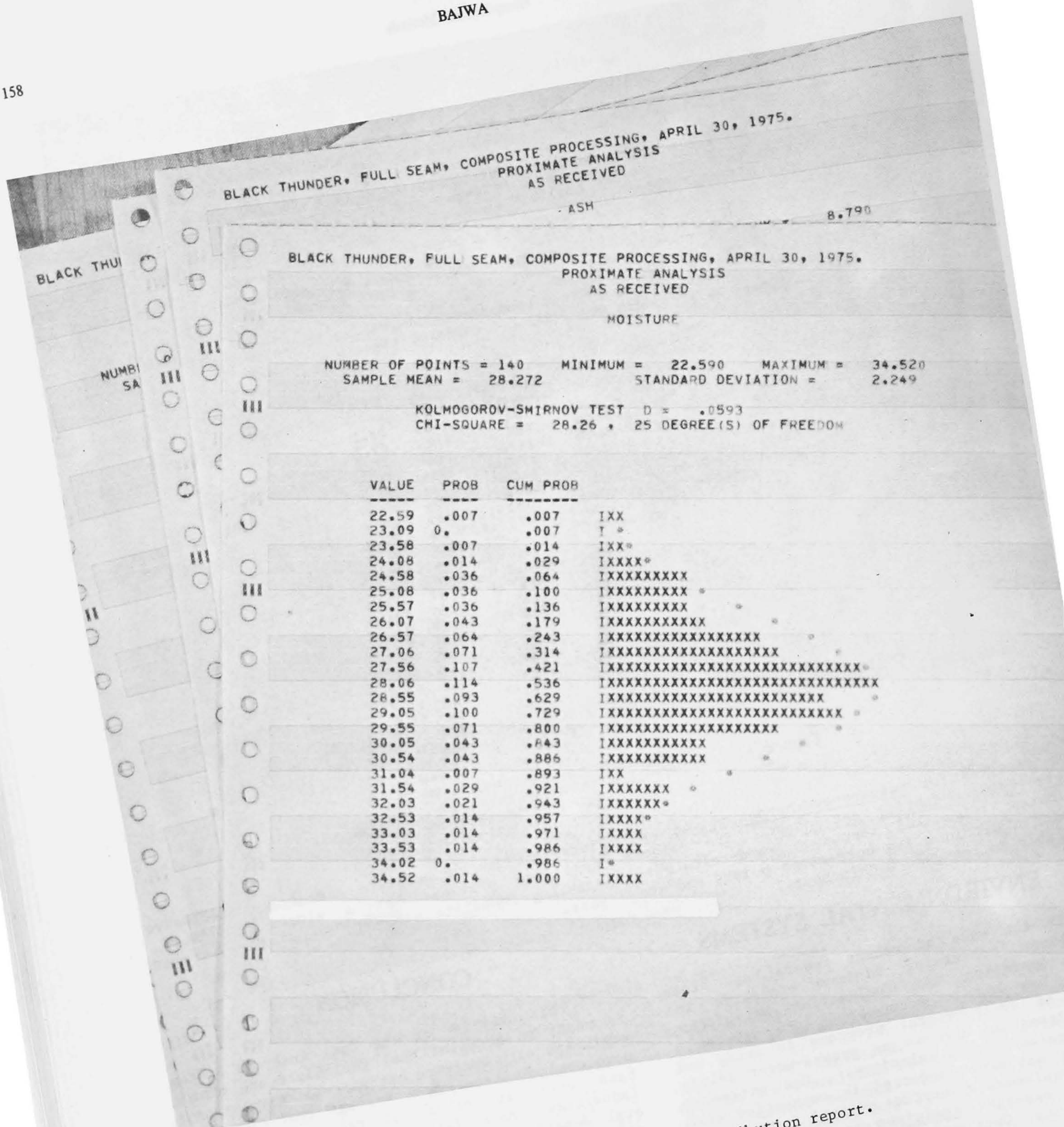
tion required for reserve-overburden volume and weight-averaged-quality estimates. The volume estimates (fig. 10) reproduce hand-calculated values to within a few percentage points and are available to the user within hours.

ENVIRONMENTAL SYSTEMS

In the wake of recent federal and state regulations concerning minimum standards for mining operation and reclamation activities, A.R.Co. has had to secure and (or) develop a variety of environmental programs to study and report items as diverse as ground-water levels and kangaroo rat populations. One extremely important activity conducted in connection with permit requirements (surface mining) is to determine the eventual reclaimed topography of the mining area. Once more the digitizer and plotting terminal are key elements in the system, as overburden and coal volumes are juggled iteratively via the digitizer to produce an acceptable landscape having adequate drainage. Successive maps are previewed at a plotting terminal, enabling immediate planned "fixes" for the next pass.

CONCLUSION

This overview of the Coal Analysis System is meant to acquaint coal geologists and mining engineers with emerging hardware-software systems developed for coal from systems that have long been used in other mineral and petroleum industries. As we face increased public and federal demands for coal development, we must use all available tools to reduce the lag time from coal lease acquisition to first coal delivery. Computerized methods have been found to contribute meaningfully to this revolution and must take their rightful place within this industry if we are to cope with the growing demand for our product.



BLACK THUNDER, FULL SEAM, COMPOSITE PROCESSING, APRIL 30, 1975.
PROXIMATE ANALYSIS
AS RECEIVED

MOISTURE

NUMBER OF POINTS = 140 MINIMUM = 22.590 MAXIMUM = 34.520
SAMPLE MEAN = 28.272 STANDARD DEVIATION = 2.249

KOLMOGOROV-SMIRNOV TEST D = .0593
CHI-SQUARE = 28.26 , 25 DEGREE(S) OF FREEDOM

VALUE	PROB	CUM PROB	
22.59	.007	.007	IXX
23.09	0.	.007	I *
23.58	.007	.014	IXX*
24.08	.014	.029	IXXXX*
24.58	.036	.064	IXXXXXXXXX
25.08	.036	.100	IXXXXXXXXX *
25.57	.036	.136	IXXXXXXXXX *
26.07	.043	.179	IXXXXXXXXXXX *
26.57	.064	.243	IXXXXXXXXXXXXXXXXX *
27.06	.071	.314	IXXXXXXXXXXXXXXXXXXX *
27.56	.107	.421	IXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*
28.06	.114	.536	IXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
28.55	.093	.629	IXXXXXXXXXXXXXXXXXXXXXXXXX *
29.05	.100	.729	IXXXXXXXXXXXXXXXXXXXXXXXXXX *
29.55	.071	.800	IXXXXXXXXXXXXXXXXXXX *
30.05	.043	.843	IXXXXXXXXXXX *
30.54	.043	.886	IXXXXXXXXXXX *
31.04	.007	.893	IXX *
31.54	.029	.921	IXXXXXXX *
32.03	.021	.943	IXXXXXX*
32.53	.014	.957	IXXXX*
33.03	.014	.971	IXXXX
33.53	.014	.986	IXXXX
34.02	0.	.986	I*
34.52	.014	1.000	IXXXX

Figure 5.--Coal-quality distribution report.

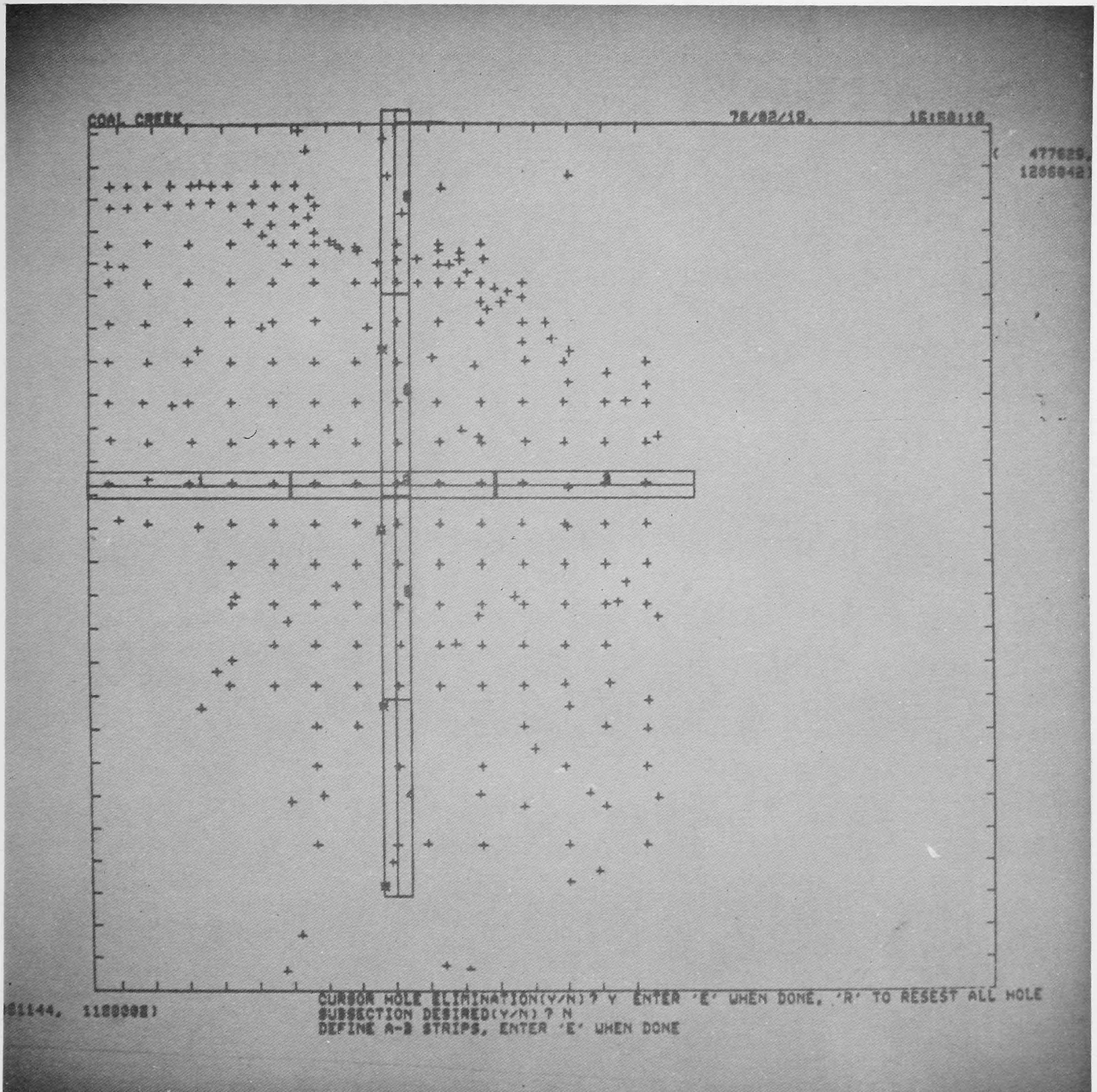


Figure 6.--Defining cross-section strips using a plotting terminal (bird's eye view). Crosses show hole locations; beginning and terminal points of each strip are indicated with terminal's moving crosshairs, not shown.

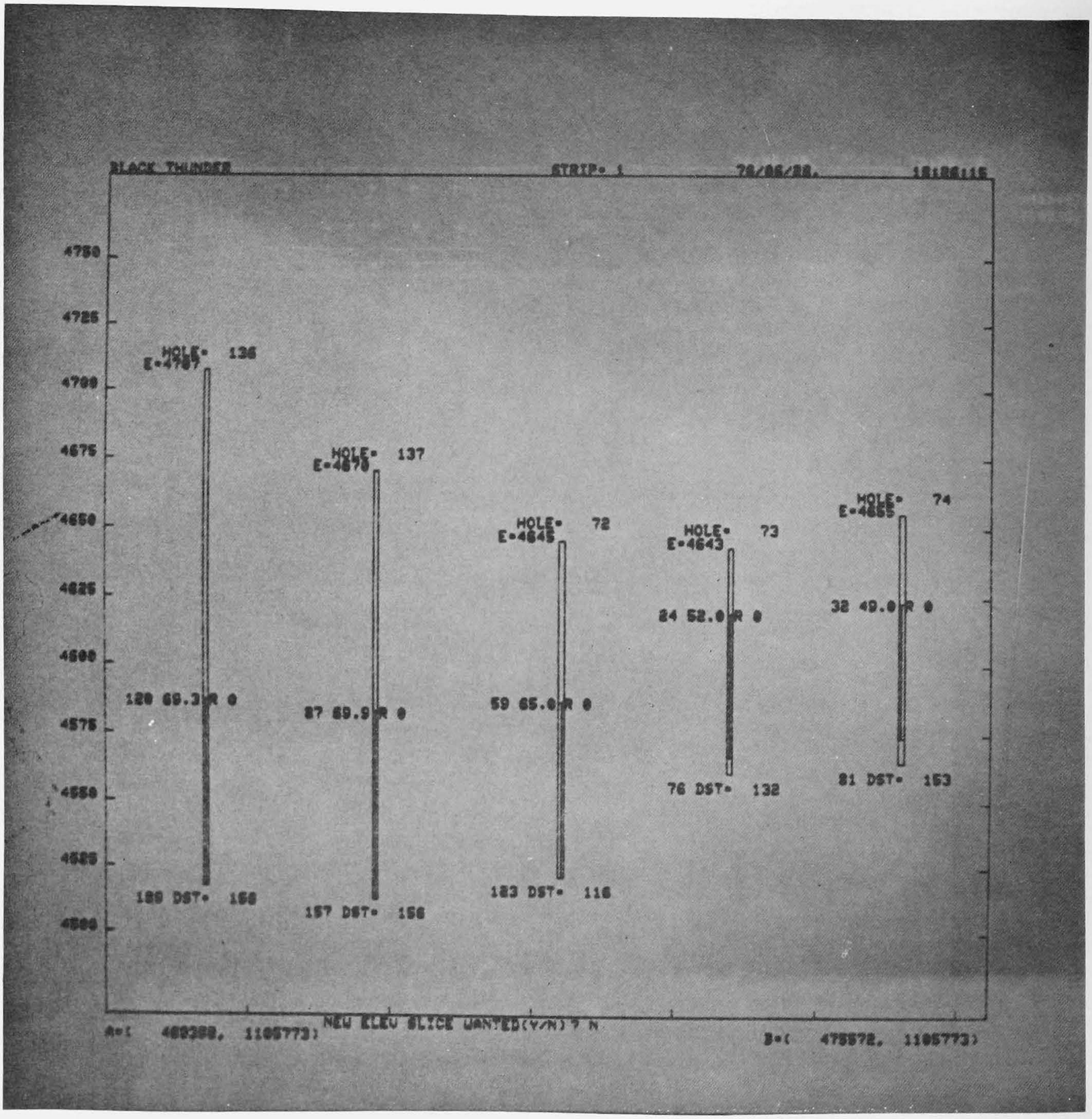


Figure 7.--Cross-section preview plot (worm's eye view). Coal seams are darkened.

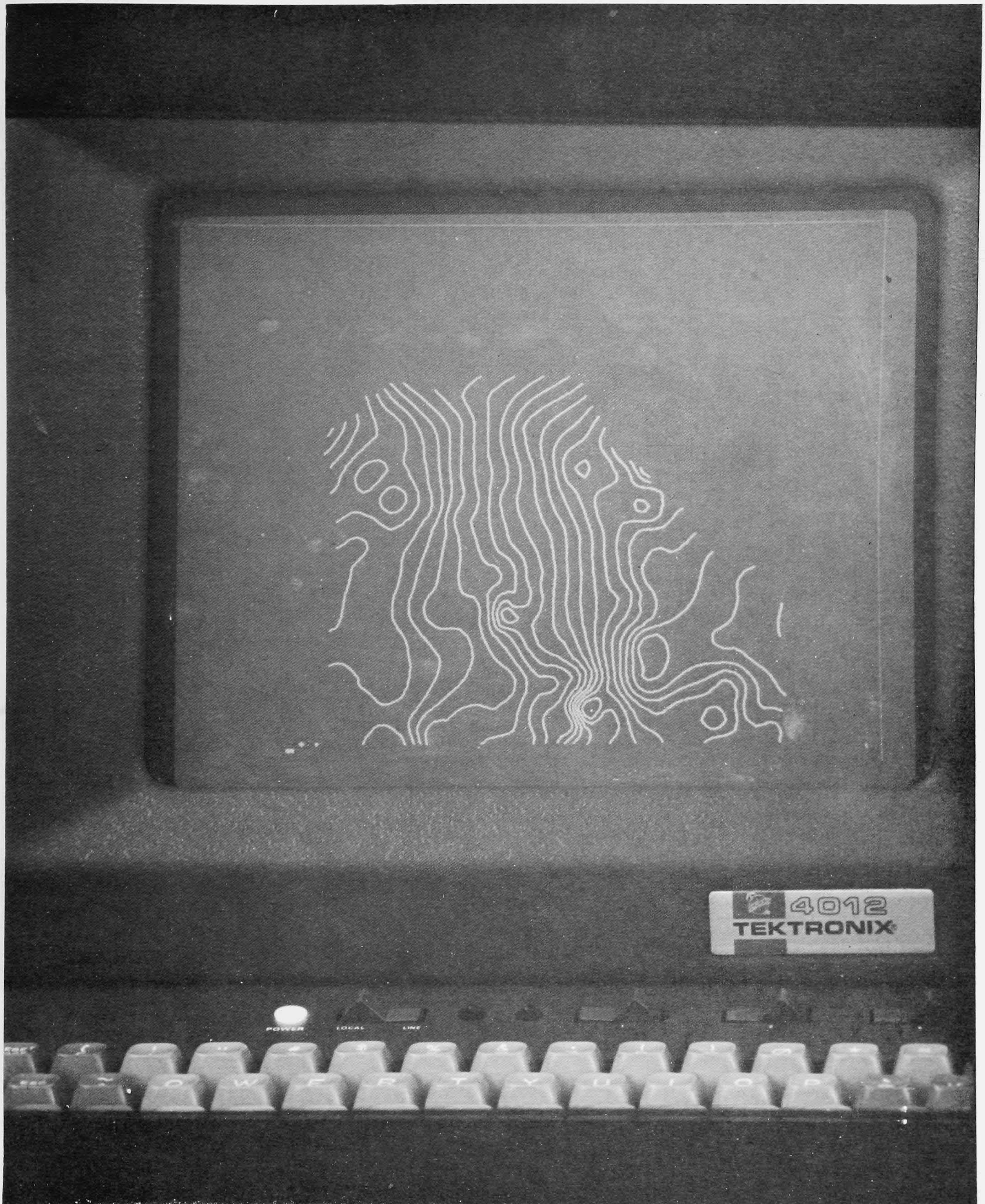


Figure 8.--Example of contoured coal-quality preview plot.

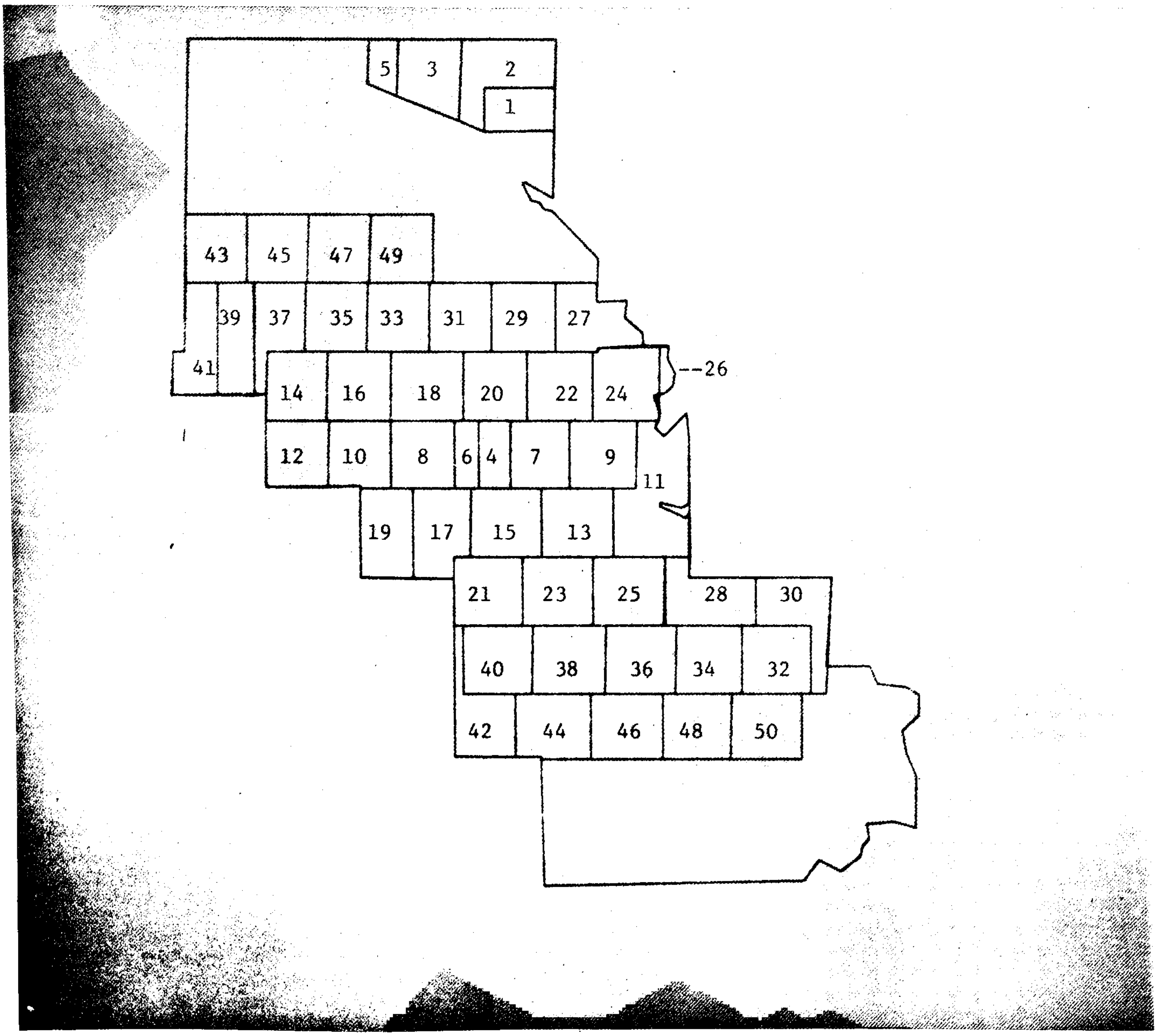


Figure 9.--Digitized mining blocks and property boundaries. Numbers were added for reference.

K THUNDER. RESERVES. PROX. AS REC.. MINING BLOCK [redacted] 04/20/76

LOOP NUMBER	S-AREA T-AREA	VOLUME (CUBIC YARDS)	T.F. (T/Y3)	TONNAGE (TONS)	THICKNESS (FEET)	MOISTURE	ASH	BTU	SULFUR
1.	59.84	5525694.91	1.08	5967750.51	57.24	[redacted]	[redacted]	[redacted]	[redacted]
1.	59.84								
2.	110.09	11385202.62	1.08	12296018.83	64.10	[redacted]	[redacted]	[redacted]	[redacted]
2.	110.09								
3.	86.42	9371088.22	1.08	10120775.27	67.21	[redacted]	[redacted]	[redacted]	[redacted]
3.	86.42								
4.	40.50	4547146.06	1.08	4910917.74	69.60	[redacted]	[redacted]	[redacted]	[redacted]
4.	40.50								
5.	29.86	3210708.15	1.08	3467564.80	56.66	[redacted]	[redacted]	[redacted]	[redacted]
5.	29.86								
6.	32.16	3479379.21	1.08	3757729.55	67.05	[redacted]	[redacted]	[redacted]	[redacted]
6.	32.16								
7.	76.56	8632404.50	1.08	9322995.86	69.89	[redacted]	[redacted]	[redacted]	[redacted]
7.	76.56								
8.	82.99	8718549.57	1.08	9416033.53	65.12	[redacted]	[redacted]	[redacted]	[redacted]
8.	82.99								
9.	86.78	9481780.03	1.08	10240322.44	67.73	[redacted]	[redacted]	[redacted]	[redacted]
9.	86.78								
10.	78.95	8165589.51	1.08	8818836.67	64.11	[redacted]	[redacted]	[redacted]	[redacted]
10.	78.95								
11.	167.44	12514072.15	1.08	13515197.92	46.32	[redacted]	[redacted]	[redacted]	[redacted]
11.	167.44								
12.	77.84	8435944.80	1.08	9110820.39	67.18	[redacted]	[redacted]	[redacted]	[redacted]
12.	77.84								
13.	91.83	10360661.68	1.08	11189514.61	69.93	[redacted]	[redacted]	[redacted]	[redacted]
13.	91.83								
14.	78.67	9084954.06	1.08	9811750.39	71.58	[redacted]	[redacted]	[redacted]	[redacted]
14.	78.67								
15.	91.94	9298765.28	1.08	10042666.50	62.69	[redacted]	[redacted]	[redacted]	[redacted]
15.	91.94								
16.	81.68	9229407.96	1.08	9967760.60	70.04	[redacted]	[redacted]	[redacted]	[redacted]
16.	81.68								
17.	91.37	9751319.43	1.08	10531425.41	66.15	[redacted]	[redacted]	[redacted]	[redacted]
17.	91.37								
18.	94.28	10626556.35	1.08	11476680.66	69.86	[redacted]	[redacted]	[redacted]	[redacted]
18.	94.28								
19.	89.30	9979931.86	1.08	10778326.41	69.27	[redacted]	[redacted]	[redacted]	[redacted]
19.	89.30								
20.	83.75	9270766.76	1.08	10012428.11	68.62	[redacted]	[redacted]	[redacted]	[redacted]
20.	83.75								
21.	89.53	9953016.98	1.08	10749258.34	68.91	[redacted]	[redacted]	[redacted]	[redacted]
21.	89.53								
22.	84.02	9433604.78	1.08	10188293.16	69.59	[redacted]	[redacted]	[redacted]	[redacted]
22.	84.02								
23.	91.14	10050585.59	1.08	10854632.44	68.35	[redacted]	[redacted]	[redacted]	[redacted]
23.	91.14								
24.	91.38	9949806.63	1.08	10745791.37	67.49	[redacted]	[redacted]	[redacted]	[redacted]
24.	91.38								
25.	94.01	10379105.59	1.08	11209434.03	68.43	[redacted]	[redacted]	[redacted]	[redacted]
25.	94.01								
26.	10.06	1082726.14	1.08	1169344.23	66.74	[redacted]	[redacted]	[redacted]	[redacted]
26.	10.06								
27.	86.02	9690528.36	1.08	10465770.63	69.83	[redacted]	[redacted]	[redacted]	[redacted]
27.	86.02								

Figure 10.--Sample reserve report. Quality values have been intentionally deleted.

RoMoCoal Field Trip Photograph by Harold H. Arndt, U.S. Geological Survey

Glen Izett of the U.S. Geological Survey pointing out thin tonstein bed in thick "X" coal seam at the ColoWyo mine. Tonsteins are considered by some geologists to be altered volcanic ash beds and useful for correlation of coal beds.

Core and Wire-Line Log Analysis of a Coal-Bearing Sequence: Lower Part of the Upper Cretaceous Menefee Formation (Mesaverde Group), Northwestern New Mexico

CHARLES T. SIEMERS[1]

ABSTRACT

In a workshop held during the 1977 Rocky Mountain Coal Symposium, a continuous 185-ft core and corresponding wire-line log from the Menefee Formation of northwestern New Mexico (San Juan Basin) was on display. The core is illustrated photographically herein. Emphasis is on (1) basic core handling and detailed lithologic description, (2) lithologic calibration of the wire-line log using the core analysis, and (3) paleoenvironmental interpretation of the lithologic sequence using a depositional model developed from the study of nearby outcrops.

INTRODUCTION

On display during the 1977 Rocky Mountain Coal Symposium were a core and corresponding wire-line log of the lower part of the Upper Cretaceous Menefee Formation of northwestern New Mexico (fig. 1). The core is illustrated photographically herein. The purpose of this paper is to emphasize several aspects of core analysis: (1) basic core handling and lithologic description, (2) lithologic calibration of the wire-line logs, and (3) paleoenvironmental interpretation of the lithologic sequence using the core and logs.

GENERAL STRATIGRAPHIC FRAMEWORK

The Menefee Formation of the San Juan Basin area (fig. 1) is the middle, nonmarine, coal-bearing unit of the tripartite Mesaverde Group. It is underlain by nearshore marine sandstones of the Point Lookout Sandstone (Siemers and others, 1975) and overlain by the destructional delta-front and nearshore marine sandstones and shales of the Cliff House Sandstone and Lewis Shale (Mannhard, 1976). The general stratigraphic relationships of the Menefee Formation and other Cretaceous and Tertiary units of the San Juan Basin area are shown in figure 2. Details of Menefee Formation stratigraphy and lithology are discussed by Mannhard (1976), Siemers and Wadell (1977), and Siemers (this volume). In general the Menefee Formation represents nonmarine alluvial-plain, deltaic, and coastal-plain

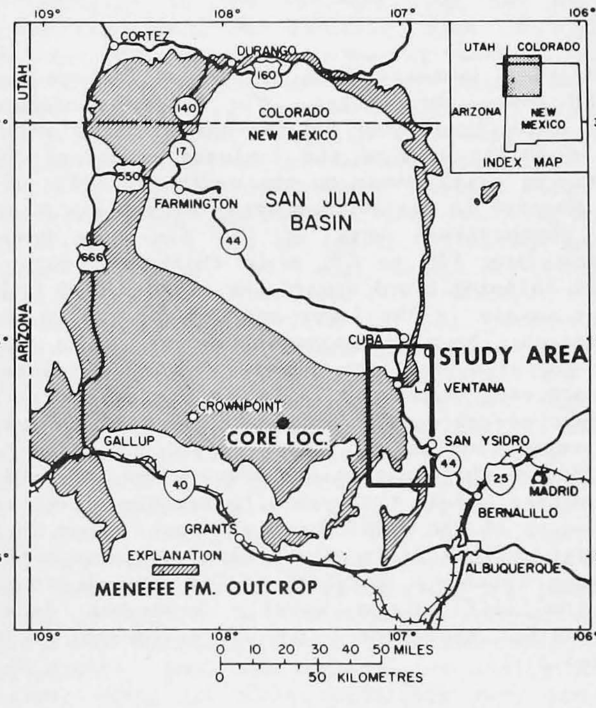


Figure 1.--Locality map of northwestern New Mexico showing outcrop study area and approximate locality of core P-25 of the lower part of the Menefee Formation. The cross-ruled area represents the approximate area of outcrop of the Menefee Formation and Mesaverde Group. Map modified from Shomaker and Hiss (1974).

[1]Cities Service Company
Energy Resources Group
Exploration and Production Research
Tulsa, Oklahoma

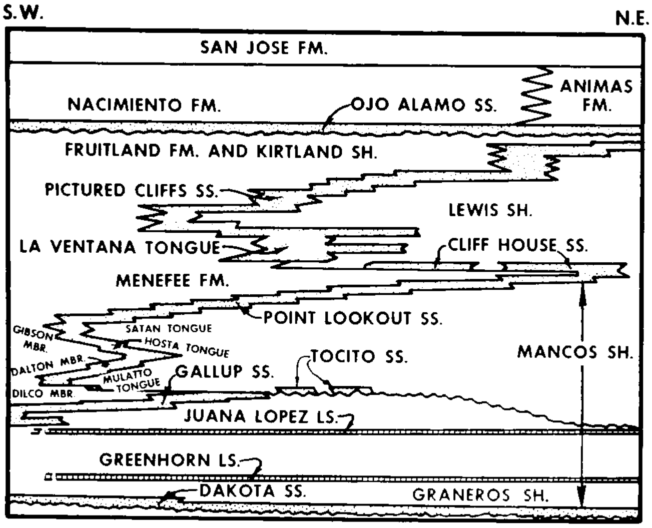


Figure 2.--Diagrammatic stratigraphic cross section of Cretaceous and Tertiary rocks of the San Juan Basin, northwestern New Mexico; vertical exaggeration is about X150. Cross section modified from illustration by Fassett (1974, fig. 1).

deposition landward from the Point Lookout and Cliff House shorelines. The Menefee thickens from a pinchout edge on the northeast to about 610 m in the area of the landward extent of the overlying Cliff House to the southwest (fig. 2). The Menefee in the outcrop study area (fig. 1) in the southeastern part of the San Juan Basin ranges from 128 to 251 m in thickness, with a rapid thinning trend toward the north. Coal beds occur mainly in the lower and upper parts of the formation; the middle portion commonly lacks coal but contains abundant humate (brownish-colored carbonaceous mudstone). In an overall stratigraphic sequence, the Menefee represents a maximum regression of the Upper Cretaceous sea from the Mancos Shale and Point Lookout Sandstone sedimentation below; the overlying marine-influenced sediments of the Cliff House and Lewis occur in a transgressive stratigraphic relationship with the Menefee (although marginal-marine sand buildups of the Cliff House usually represent local prograding shorelines, in a sedimentological sense).

CORE HANDLING AND DESCRIPTION

Cores are relatively expensive to obtain and analyze. Therefore, considerable care should be taken in order to obtain, inasmuch as possible, a complete, continuous, undisturbed core. Concern and common sense are primary requirements for obtaining and maintaining good cores. Proper handling and labeling at the well site are absolutely necessary; considerable information can be lost through inconsistent labeling and lack of concern over obtaining a complete core with all pieces in the proper orientation and order. Complete geological analysis of a core requires virtually a complete core in the proper orientation. If the core is to be sampled for engineering or other analysis, care should be taken not to unduly destroy parts of the core critical for geological study (for example, lithologic contacts, or all of one lithology).

Most cores are merely described at the well site, with descriptions being made by observing only the exterior and core chips. Much can be gained by taking the time to slab the core and, if sufficiently consolidated, to lap the core to remove mud and saw marks. Sedimentary structures and lithologic unit contacts, which are of considerable importance in paleoenvironmental interpretation, can be best observed on a slabbed and lapped core. A photographic record of the core, such as that included in this paper, is of considerable value.

A detailed lithologic description of the core is highly desirable. Many approaches and techniques are available for lithologic description, and individual operators or groups should devise that which best suits their purpose; however, it is important not to sacrifice detail in observation and description. Emphasis should be placed on (1) primary textural and compositional features and variations of such features in the vertical sequence, (2) types and distribution of physical and biogenic sedimentary structures, (3) contact relationships between vertically adjacent lithologic units, and (4) secondary (diagenetic) features. A detailed sketch (such as that in fig. 3) should be prepared as a permanent record.

Menefee Core

The cored interval of the lower part of the Menefee Formation in the South Hospah area is illustrated by the core photographs (following the text of this paper) and the lithologic sketch in figure 3. The major lithologic types present in the Menefee part of the core and their general characteristics are as follows:

1. Sandstone: medium- to light-gray; fine- to very fine grained, generally decreasing in grain size upward within "genetic units"; moderately sorted; quartzose; pebble- to cobble-size, rounded to subrounded mudstone clasts commonly occurring in considerable abundance within 0.5- to 1.0-ft intervals throughout sandstone units; sparse to moderately abundant black carbonaceous debris along bedding surfaces throughout; low to moderate angle (4^{o}-10^{o}) cross-stratification; friable with abundant clay

matrix and (or) cement; occasional soft-sediment deformation structures in units containing finer sand to coarse silt; sharp lower sandstone unit contacts, commonly displaying scour, and sharp to gradational upper contacts with mudstone units.

2. Mudstone: light-gray to brownish-gray; silty claystone to clayey siltstone; may decrease or increase in grain size vertically; soft to moderate induration; finely laminated to "massive"; characteristically blocky fabric with absence of fissility; may contain in situ root structures with carbonaceous matter; units carbonaceous in part; soft-sediment deformation structures present where very silty; contacts gradational to sharp with vertically adjacent lithologic units.
3. Coal: brownish-black to black; dull to moderately brilliant luster; good cleat; abundant resin; may contain abundant pyrite on fracture faces; hard to soft; may contain thin sandstone and mudstone interlayers; contacts generally slightly transitional with sandstone or mudstone above and below; main coal bed in core interval removed for analysis and not available for description or photography.
4. Siderite: nodular, septarian in part, clayey, calcitic, brownish-gray to reddish-brown; dense, massive; generally less than 1 ft thick; occurs in both sandstone and mudstone units.

NOTE: The lower, light-gray, fine-grained sandstone unit of the core is of the marginal-marine Point Lookout Sandstone; the sandstone is rather massive-appearing but displays a few burrows; vertical in situ roots are abundant in the upper part of the sandstone.

LITHOLOGIC CALIBRATION OF WIRE-LINE LOG

All drill holes are not generally cored owing to the expense of such an operation; however, wire-line electronic and radioactive logs are usually run and can serve as excellent lithologic guides, provided that such logs are carefully calibrated by detailed comparison with core lithologies. The first step is to establish the core-to-log depth correction at several distinct lithologic boundaries.

The wire-line logs obtained in this study include a combination density and resistance log. The logs and their correlation with the core are shown in figure 3. The density log is obtained using a tool with a focused gamma-ray source, cobalt-60 in this case, which emits gamma rays into the strata. These gamma rays interact with the electrons in the material opposite the focused source. The intensity of the back-scattered gammas rays is measured in the gamma-ray detectors located above the source. The measured gamma-ray intensity is a function of the electron density of the strata. As the electron density (proportional to the bulk density) increases, the probability of more collisions of the induced gamma rays in a fixed distance increases, leading to a greater loss of energy and a higher probability of capture or absorption. In effect, the greater the electron density (and in general the bulk density) of a lithologic unit, the less the counting rate of the detectors. In figure 3 the density tool response is in gamma-ray counts per second, with 10 divisions on the log representing 2500 counts per second. An absolute scale has not been developed for this log. The zero point on the log is an arbitrary point, and the response (more gamma-ray counts/second) increases to the left. The exact relationship between tool response and absolute density of the strata has not been established; however, increased tool response represents decreased density. (For example, coal, with the lowest density of all lithologies in the sequence, has the highest gamma-ray count; and siderite, with the highest density, has the lowest gamma-ray count.) Resistance, measured in ohms, is the right-hand log shown in figure 3. Borehole fluid was relatively fresh ground water mixed in a holding pit with the various clays of the surface soil.

Using the Gamma-Gamma Density Log and Resistance Log combination, the following major lithologic uits can be easily delineated on the wire-line logs: (1) coal beds, (2) siderite nodules, (3) sandstone, and (4) mudstone. Easily recognized are intervals of (5) carbonaceous sandstone and (6) carbonaceous mudstone, and (7) sandy mudstone and (8) clayey sandstone and (or) (9) sandstone with abundant reworked mudstone clasts; also (10) sandy or muddy coal is recognizable on the wire-line logs.

Figure 4 illustrates the general "cross-plot" character of the wire-line logs as they delineate lithologies. The plot has been generated using the absolute resistance (in ohms) as indicated on this particular log and the relative density as indicated by back-scattered gamma-ray intensity, with zero intensity being arbitrary. Coal and siderite are easily delineated, owing to their relatively very low and very high densities, respectively. Mudstone and sandstone also can be delineated rather well, and several fining-upward sequences in the sandstones (as reflected by increased silt and clay in the sand) have been delineated using the wire-line logs alone. It is noteworthy that even mudstone-clast accumulations in the sandstones can be identified on the logs.

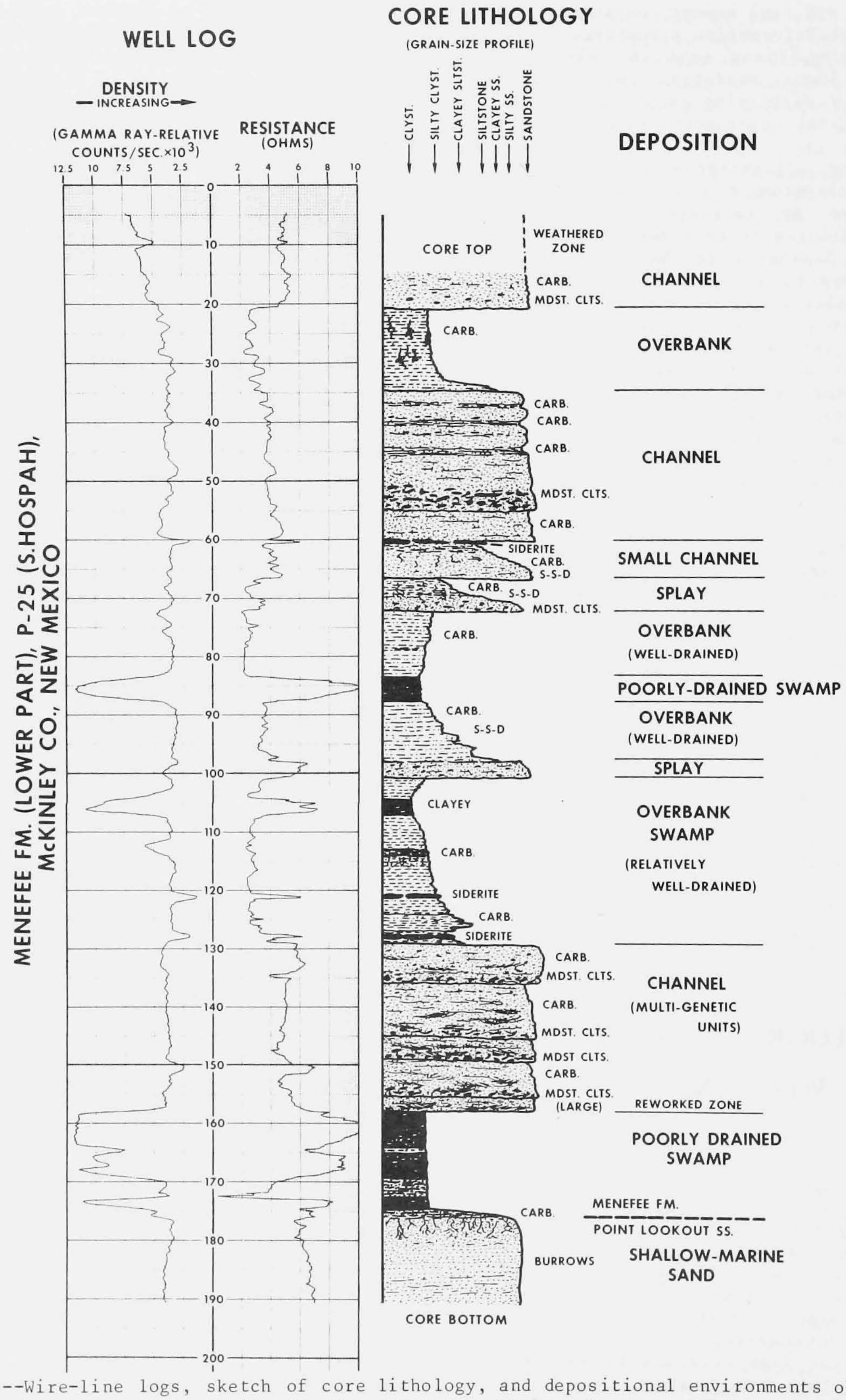


Figure 3.--Wire-line logs, sketch of core lithology, and depositional environments of core from the lower part of the Menefee Formation, South Hospah area, McKinley County, N. Mex. Depth on the log is in feet below ground surface. Profile of lithologic sketch reflects grain size.

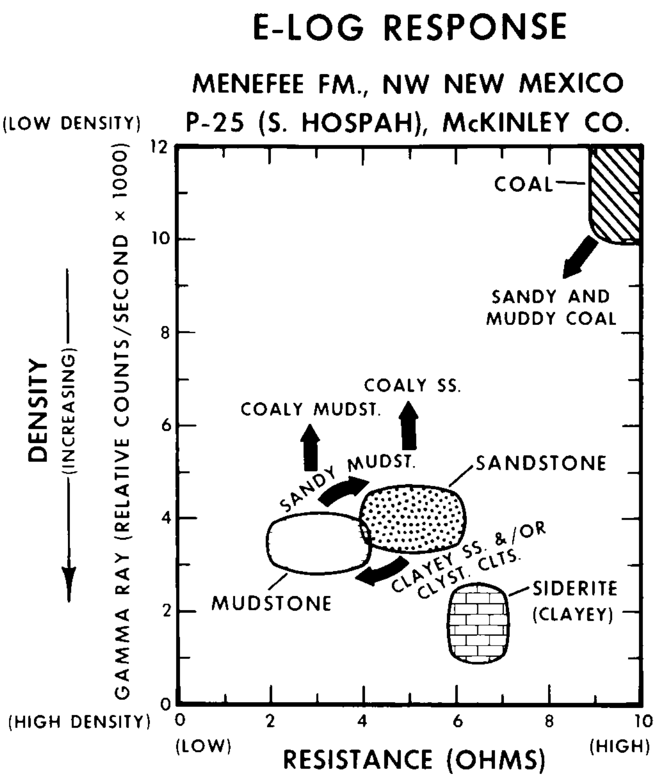


Figure 4.--General "cross-plot" relationships of Gamma-Gamma Density and Resistance logs for the lower part of the Menefee Formation in McKinley County, N. Mex.

DEPOSITIONAL ENVIRONMENTS

From a detailed analysis of nearby outcrops (fig. 1), a model lithologic sequence has been generated for the coal-bearing intervals of the Menefee Formation within that study area. The procedure for the generation of the model lithologic sequence shown in figure 5 is the main topic of Siemers (this volume). In summary, the coal-bearing model consists of (1) a lower, 3-m-thick, fining-upward, active-channel-fill sandbody having a scour base, and (2) an overlying, 12-m-thick repetitive sequence of inactive-channel-fill mudstone, channel-margin levee and flood-plain mudstone and splay sandstone, and well to poorly drained humate- and coal-depositing swamps. Generally, two thin (0.3- to 0.5-m-thick) coal beds occur in the model sequence, and coal represents an "end-member" of the sequence, commonly being overlain by another channel sand. Three or four thin (0.4- to 0.8-m-thick) humate beds and three 0.7- to 1.5-m-thick splay sandstone beds occur interbedded with the six to seven 0.5- to 2.0-m-thick mudstone units and the coal seams. This is basically a model of fluvial-deltaic sedimentation with meander-channel sedimentation and channel-margin areas ranging from well-drained flood plain to poorly drained swamps.

In comparison, the core lithologic sequence contains several interesting characteristics: (1) The crossbedded sandstones containing abundant mudstone clasts and carbonaceous debris are active-channel-fill deposits and are overlain by inactive-channel-fill and overbank flood-plain mudstone and coaly sediments. A few, thin, probably splay-type sandstone layers are also represented. (2) Channel sandstones observed in the core are much thicker, multistory channel-complex sequences than would be predicted by the model. (3) Non-channel units tend to be more

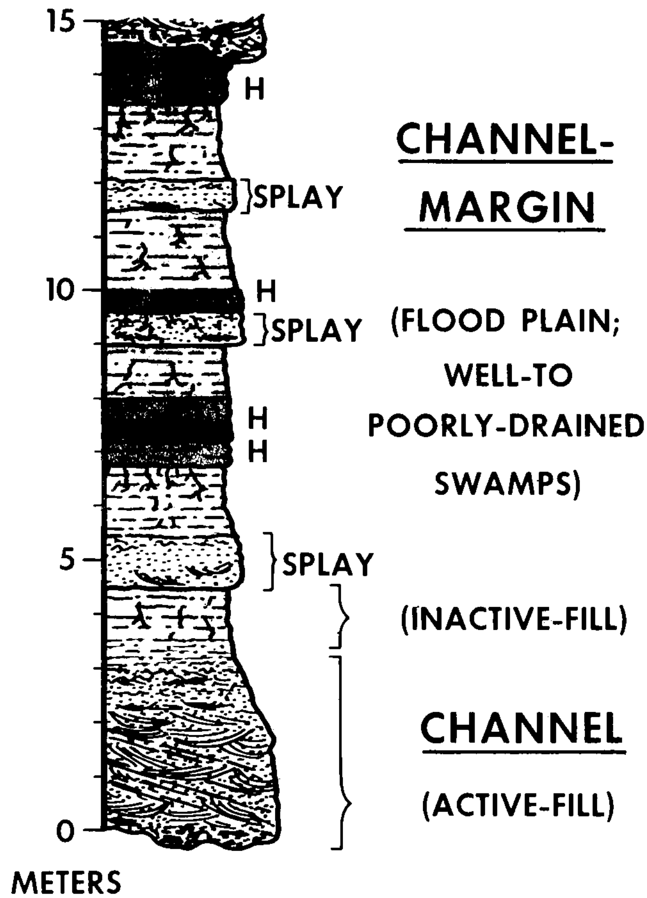


Figure 5.--Model depositional sequence for the coal-bearing intervals of the Menefee Formation. Lithologies are sandstone, stippled and bedded patterns; barren mudstone, dashed pattern with roots; humate, sparsely dashed pattern marked by H; coal, black. From Siemers (this volume).

typical, as predicted by the model, although some intervals are shorter, or more truncated, than would be expected. (4) The thickest coal in the lower part of the core may be related more to the interaction between marginal-marine processes associated with Point Lookout sedimentation and fluvial-deltaic processes of Menefee deposition than to just the fluvial-deltaic processes responsible for deposition of most of the Menefee in the area.

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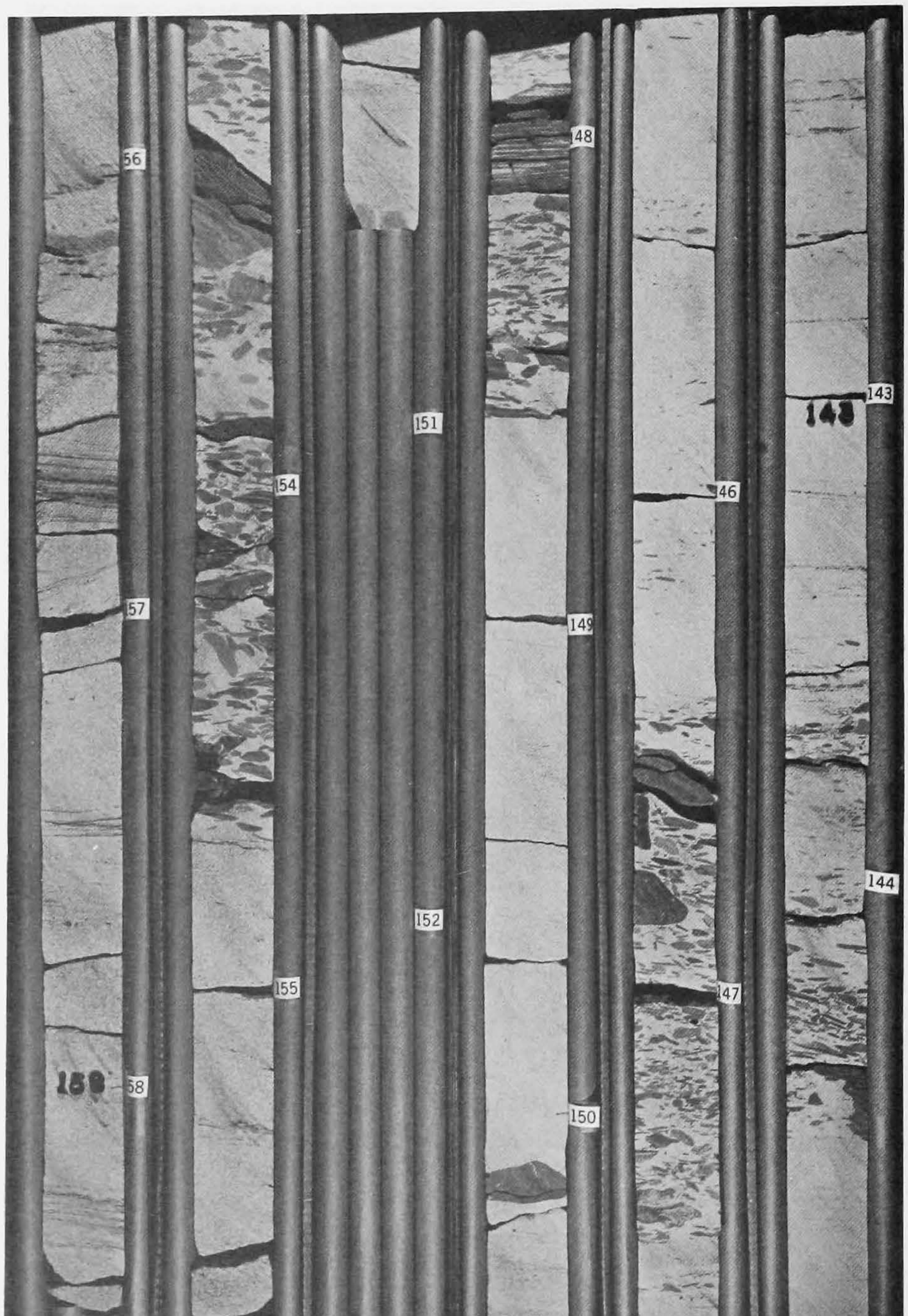
MENEFEE FORMATION (LOWER PART),
P-25 (SOUTH HOSPAH AREA),
MCKINLEY COUNTY, N. MEX.

MENEFEE FORMATION (LOWER PART),
P-25 (SOUTH HOSPAH AREA),
MCKINLEY COUNTY, N. MEX.



MENEFEE FORMATION (LOWER PART),
P-25 (SOUTH HOSPAH AREA),
MCKINLEY COUNTY, N. MEX.

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P-25 (SOUTH HOSPAH AREA),
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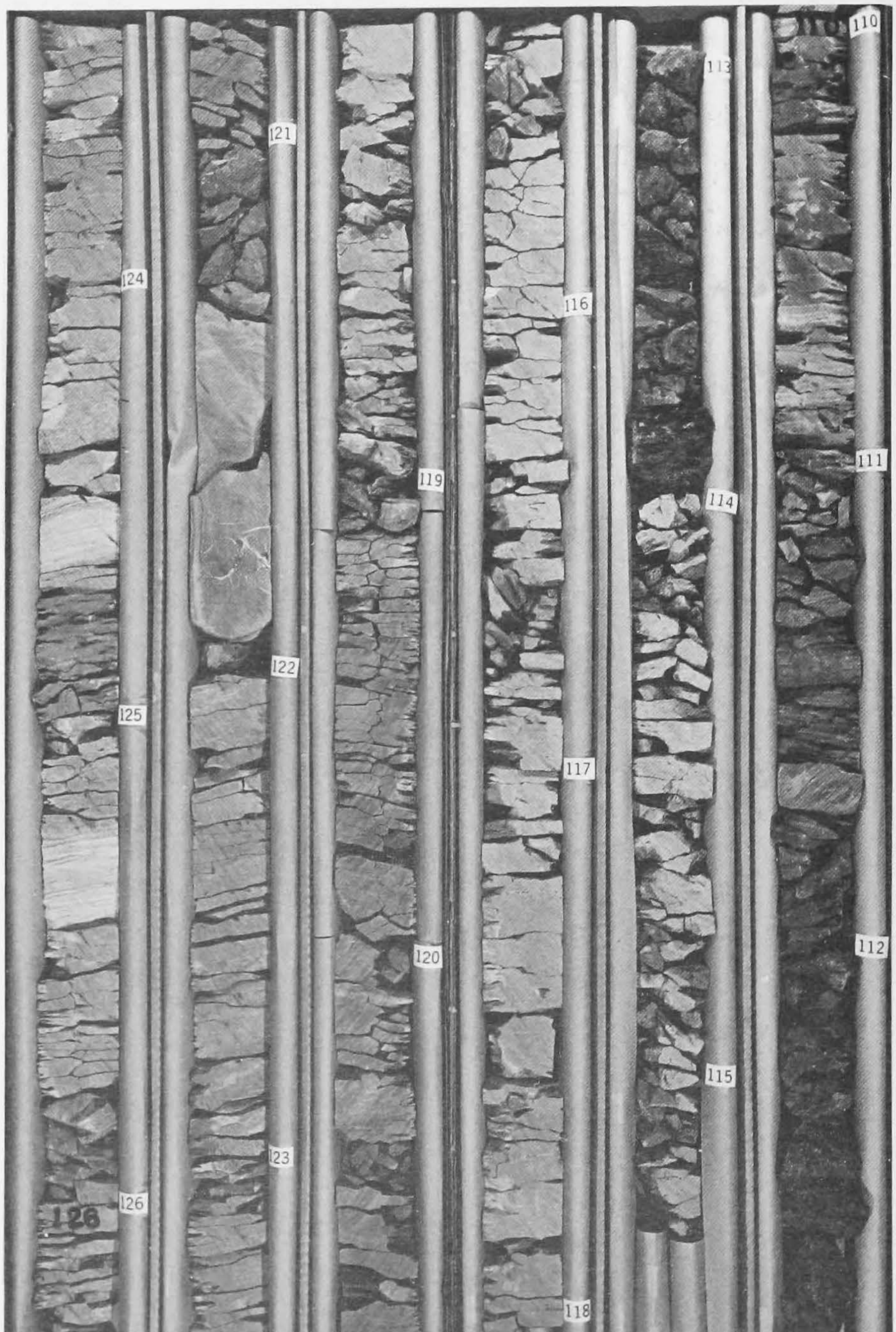
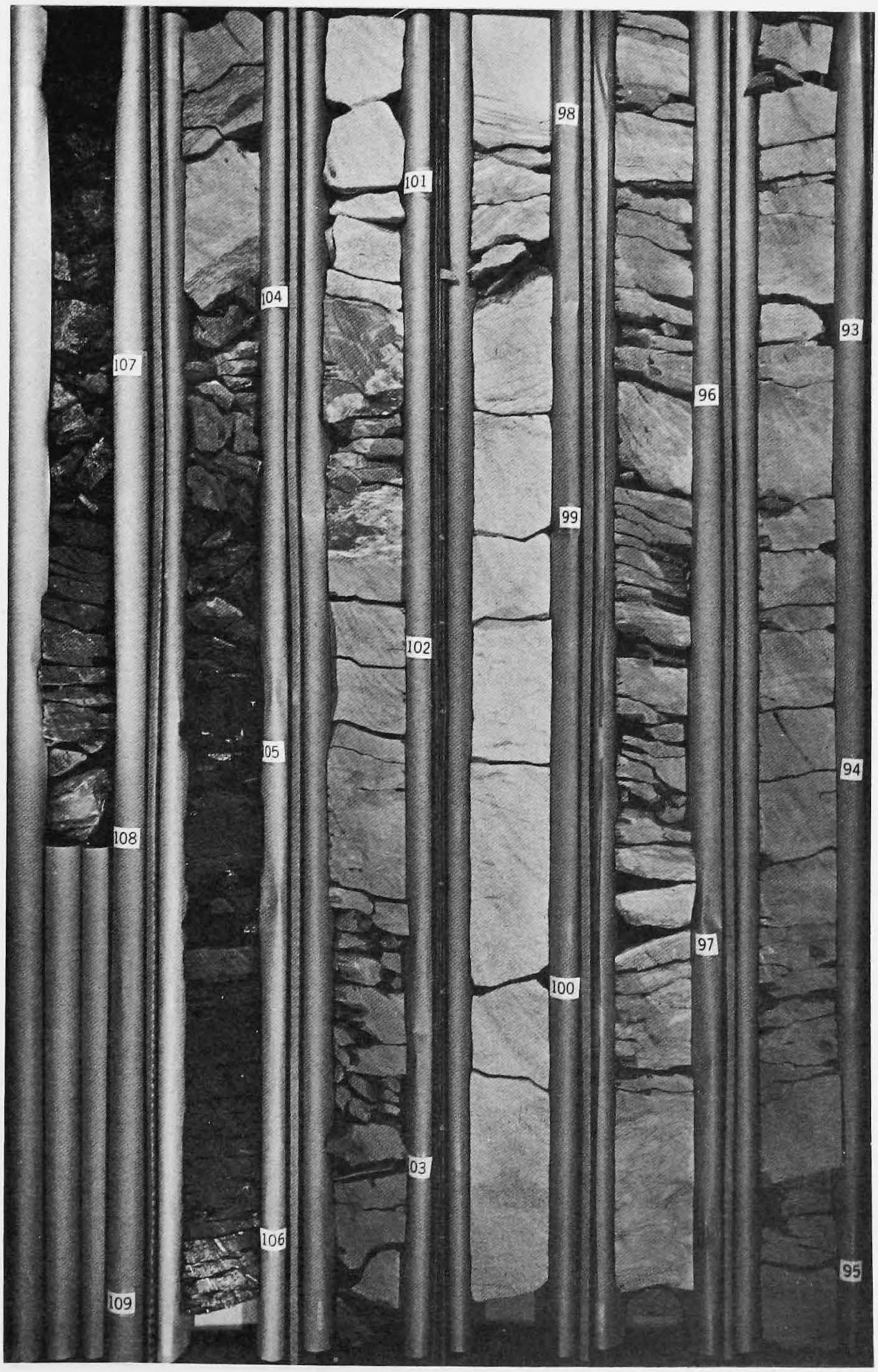


MENEFEE FORMATION (LOWER PART), P-25 (SOUTH HOSPAH AREA), MCKINLEY COUNTY, N. MEX.



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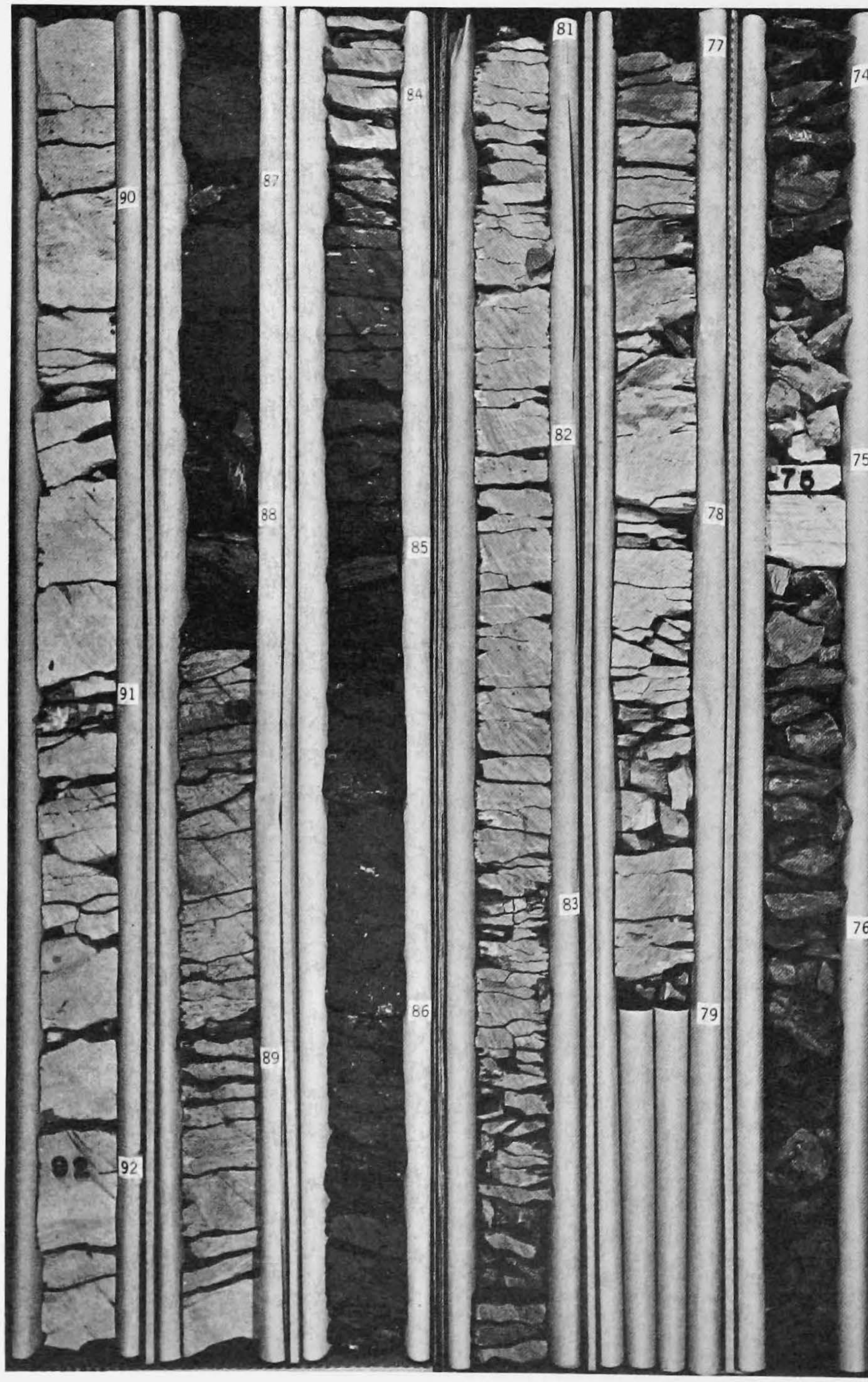

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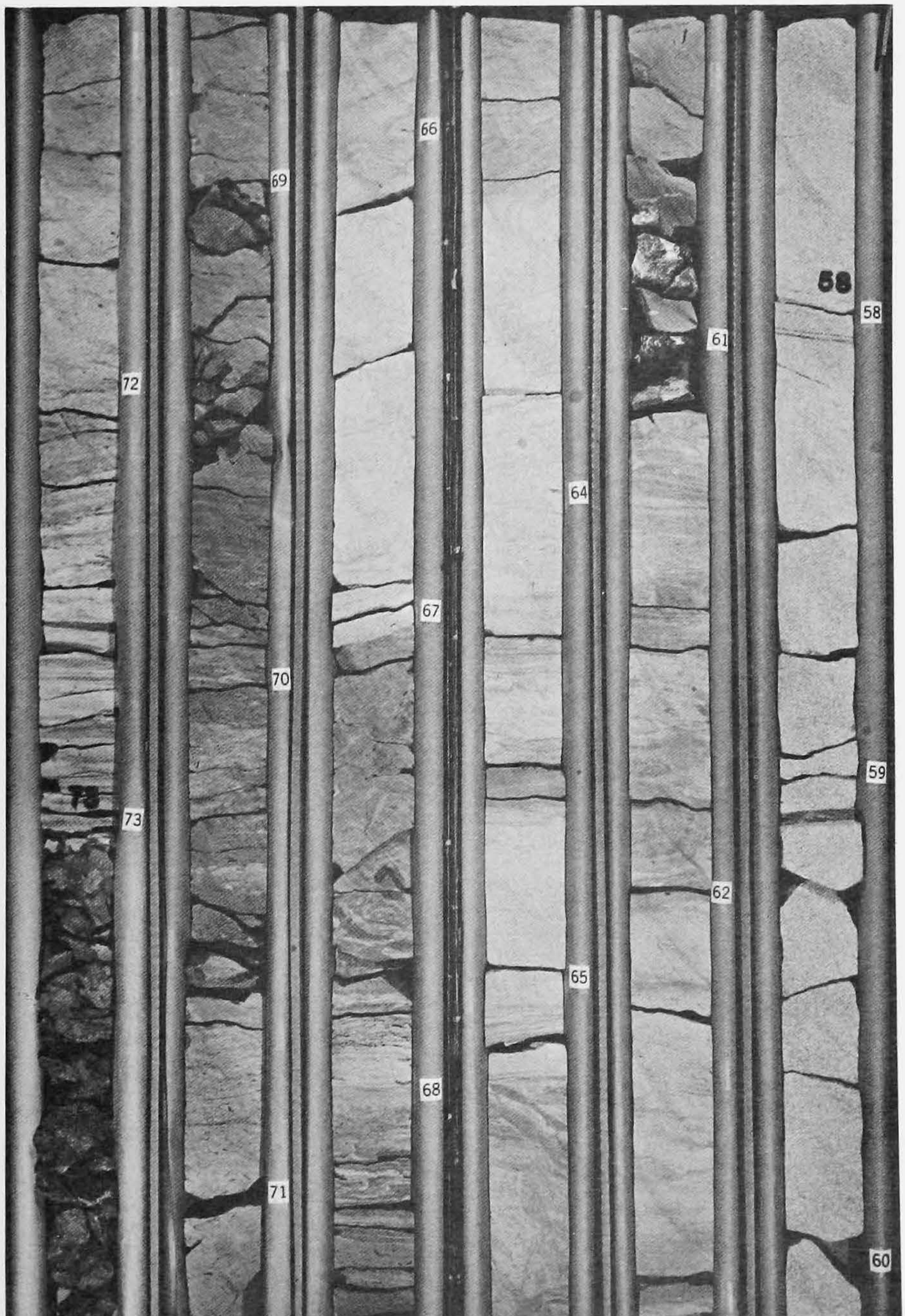

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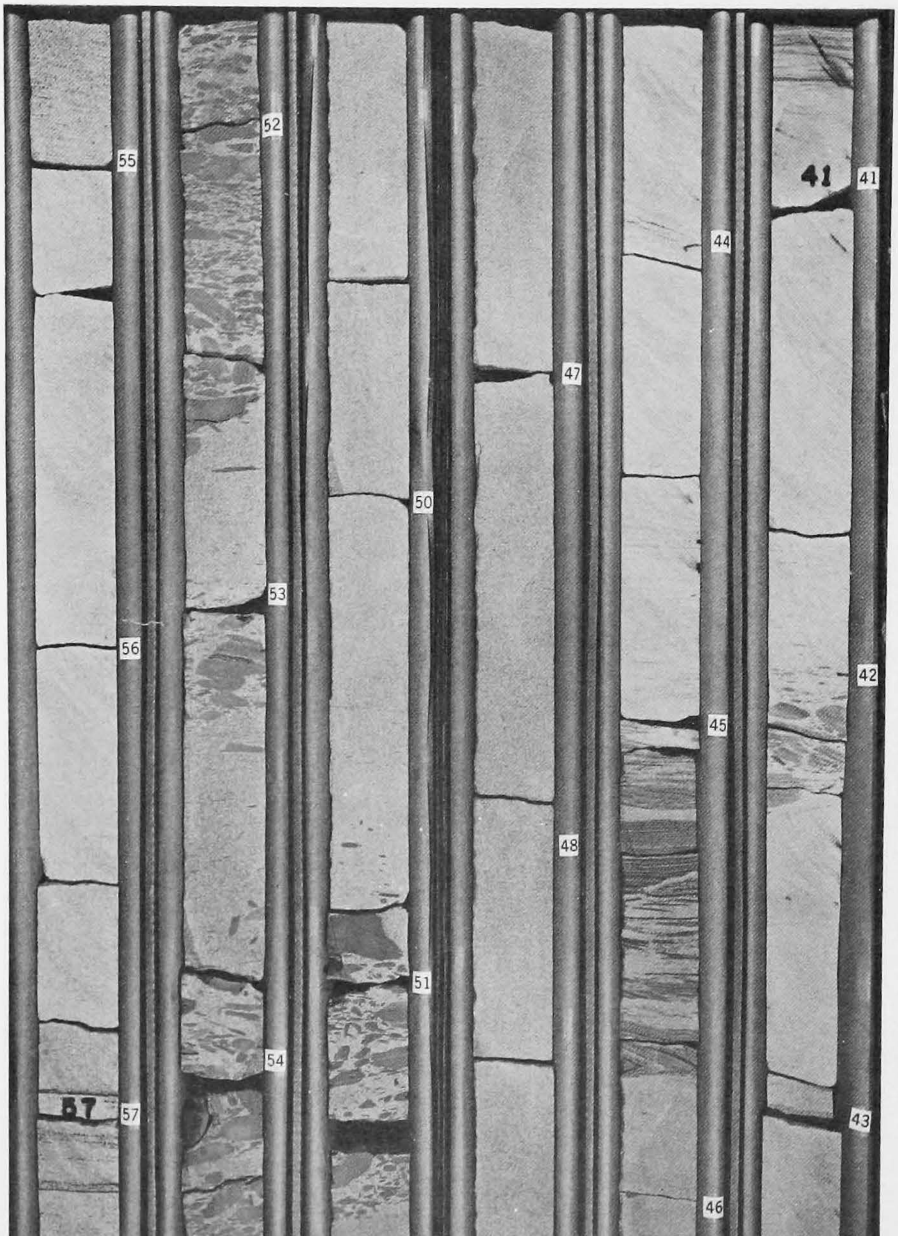

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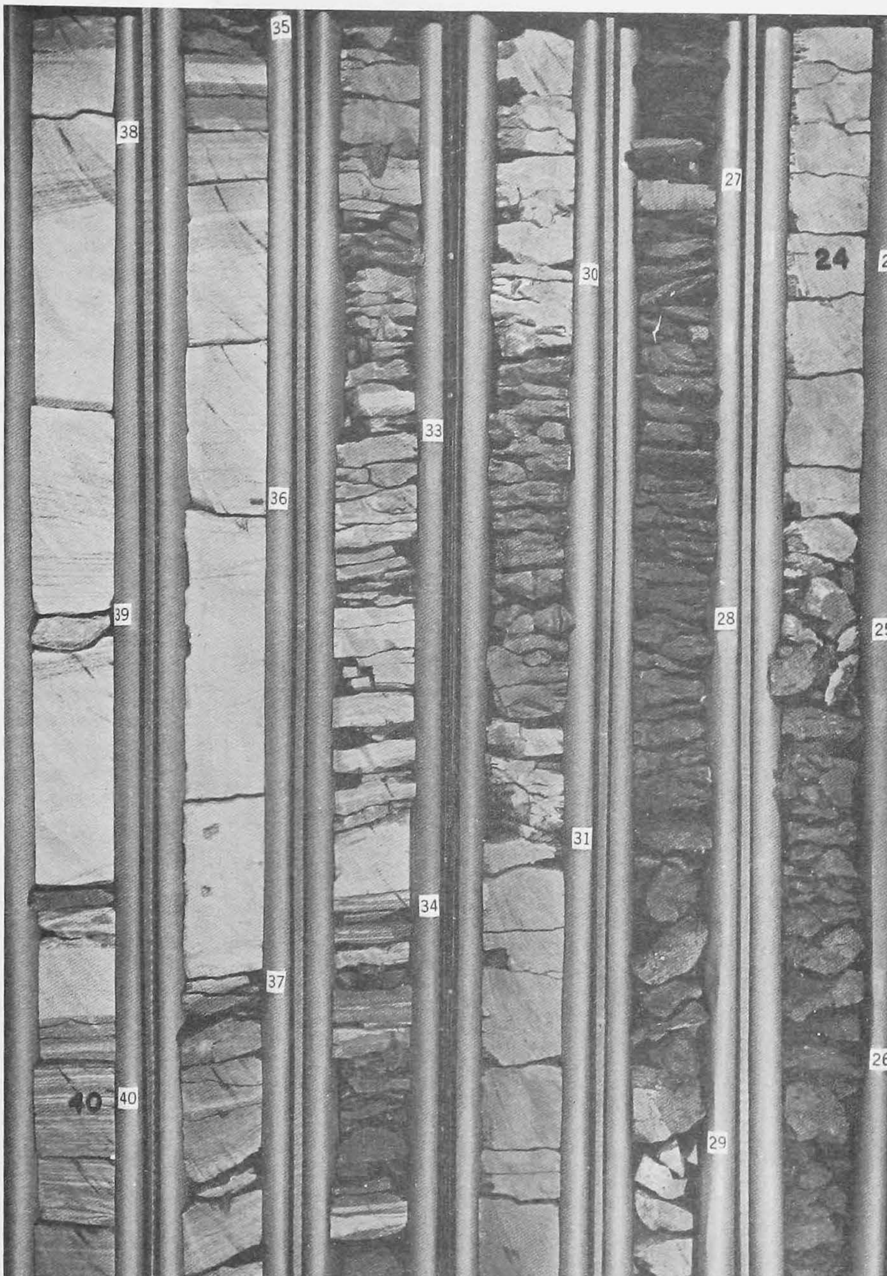

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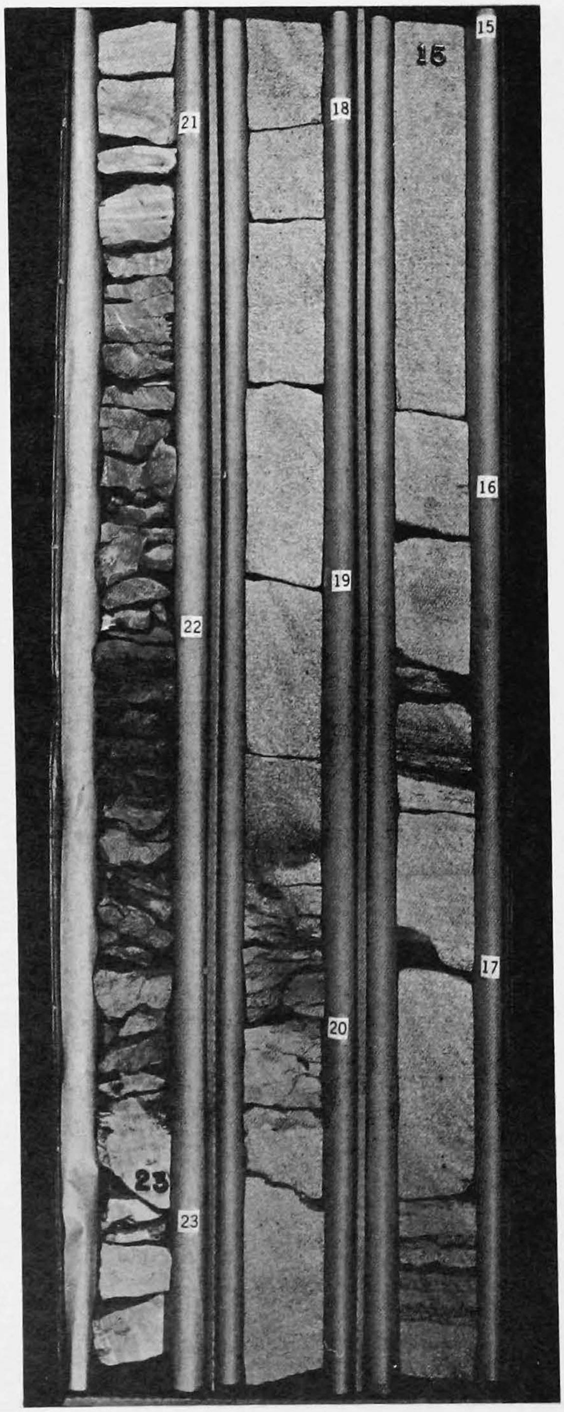

The Petrography of Western Coals

G. J. JANSEN[1]

ABSTRACT

A correlation exists between maceral composition, vitrinite reflectance, and technological behavior of a coal in coking, gasification/liquefaction, and combustion processes. Recently quantified procedures permit estimation of strength of coke produced with good accuracy and liquefaction yields with fair accuracy. Of the four western coals examined, three were considered good candidates for liquefaction. Two of the coals merited further investigation as candidates for coking coals.

INTRODUCTION

The objectives of the workshop on the Petrography of Western Coal were (1) an introduction to the theory and procedures of coal petrography, (2) an exposition of the technological significance of coal-petrography data, and (3) a brief discussion of some petrographic features of four western coals.

Coal is an organic sediment. Its technological properties depend upon its composition and its degree of metamorphism. The composition of coal can conveniently be expressed in terms of the microscopically distinguishable organic constituents or macerals. The degree of metamorphism, or rank, can be measured by determining the reflectance of vitrinite, the principal maceral of the coal.

The maceral composition and reflectance of a coal can be used to determine the probable behavior of coal in coking, yields in gasification and (or) liquefaction, and, to some degree, behavior in combustion.

Macerals

An explanation of macerals can best begin with an examination of a photomicrograph of a polished surface of coal; figure 1 was taken at 500 diameters. The variety of macerals and the inhomogeneity are typical of coal. The darkest constituent that can be seen is exinite, the coalified remains of spore exines, leaf coatings, and other material of vegetable origin. Note the convoluted, lenticular shape, which is typical of exinites. Less dark than exinite are the structureless, even gray bands of vitrinite. Vitrinite includes those substances derived primarily from woody materials in the coal-forming environment. Scattered throughout the vitrinite are fine, iridescent particles of mineral matter. Occupying most of the upper right-hand corner of the micrograph is a light-gray material showing some relief. This maceral is fusinite, which represents almost completely carbonized plant remains. Fusinite frequently shows a distinct cellular structure. Directly below the fusinite on the right-hand edge of the photomicrograph is a wedge-shaped band of a darker gray maceral that has a texture of apparently crushed and broken cellular fragments. This maceral is semifusinite, which is coalified material transitional in texture and rank between fusinite and vitrinite. The light- to dark-gray, scattered, irregular fragments seen in the section are micrinite, which is almost completely carbonized organic debris.

Degree of Metamorphism

The degree of metamorphism, or rank, of the coal has a direct, approximately linear relationship to the reflectance of the vitrinite in the coal. The higher the reflectance of the vitrinite, the higher the rank of the coal.

PETROGRAPHIC PROCEDURES

Obtaining the Basic Data

Sample Preparation

Coal petrographic work in reflected light begins with sample preparation. From 15 to 30 g of coal are mixed with an epoxy resin and formed into a cylindrical specimen in a pressurized mold. The specimen is brought to a mirror polish on a flat end by grinding and polishing with successively finer abrasives.

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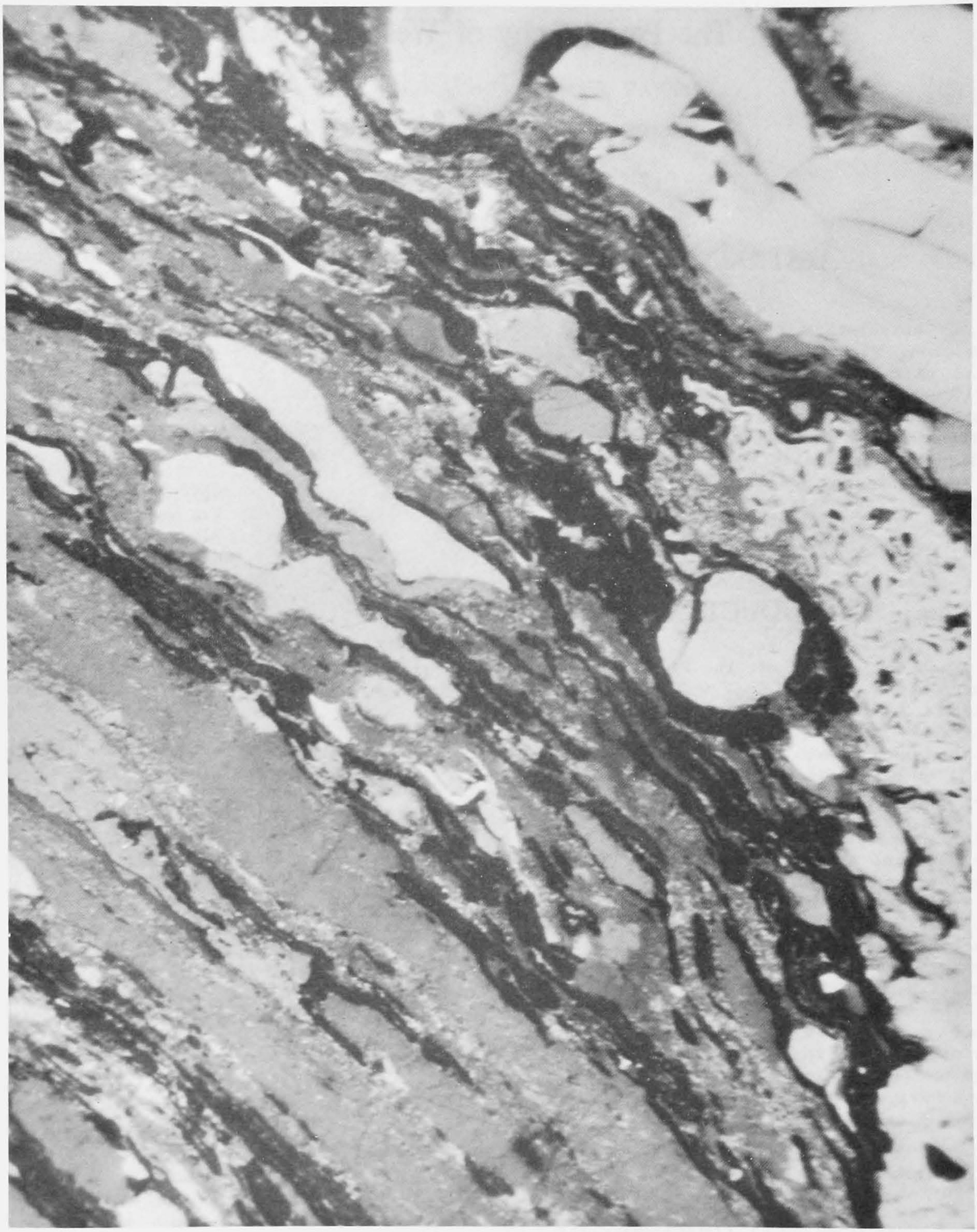

Figure 1.--Photomicrograph of a portion of polished microsection of a high-volatile bituminous coal.

Maceral Analysis

To obtain the maceral analysis, the polished specimen is examined at magnification of at least 400 diameters using an oil-immersion lens. A point-counting scheme is used which involves inspection at the intersections of a rectangular grid superimposed on the specimen. After the maceral at one intersection has been identified and recorded, the petrographer moves to the next intersection and repeats this procedure until 500 points have been counted. It is common practice to point-count two specimens per sample for a total of 1,000 maceral determinations.

Reflectance Determination

For the determination of vitrinite reflectance, a sensitive photometric device, a stabilized light source, and a group of standards of known reflectance are required. A reflectance standard that is close in value to the coal to be examined is used to calibrate the apparatus. Following this calibration, not more than 25 vitrinites are measured, after which the reflectance standard is measured again. If the standard checks out to 0.02 reflectance units or less, the 25 readings are accepted and 25 more vitrinites are measured. It is common practice to determine 50 vitrinite reflectances on each of two specimens for a total of 100 reflectances per sample.

SIGNIFICANCE OF PETROGRAPHIC DATA

Although researchers as far back as the 19th century had appreciated the importance of maceral composition to the behavior of coal, relationships have only recently been quantified. At Pennsylvania State University, hot-stage microscope work (Dutcher, 1960) established that some macerals react readily to heating by fusing and swelling. Other macerals tend to be inert or nearly so upon heating. Still others are intermediate in behavior between reactive and inert. Other research (Spackman and others, 1960) suggested that the ideal coal for coking should contain an optimum amount of inerts to act as a matrix about which the reactive constituents could coalesce.

Basing their work on the research of the Penn State group and on the work of Ammosov and others (1957) in the USSR, Schapiro, Gray, and Eusner at U.S. Steel (1961) quantified the relationship between microscopic composition, rank, and the strength of coke produced from the coal. By careful correlation of pilot-scale coking tests with microscopic work, Schapiro and his associates established two parameters, the composition-balance index and the strength index. The composition-balance index is a mathematical measure of whether or not the inert-to-reactive ratio in a coal is "ideal" or not. The ideal ratio for any coal is 1.0. A composition-balance index of 2.0 indicates that the coal has twice the optimum inerts for balance. The composition-balance index is a function of the maceral composition of the coal and varies with variation in rank. The strength index is a function of the rank of the coal, expressing mathematically the fact that reactivity also depends on rank; that is, the higher the rank, the higher the reactivity of the reactive constituents and the higher the strength of the resulting coke.

The influence of composition and rank can be appreciated by examining figure 2. The horizontal scale in the chart is the composition-balance index. The vertical scale is the strength index. The curves are iso-stability lines, a measure of the strength of coke to be expected from a coal whose petrographic parameters are plotted.

As an illustration, note that a coal having a composition-balance index of 1.0 and a strength index of 2.8 will produce a coke with a stability factor of 30. However, a coal with the same strength index (2.8) but a composition-balance index of 0.5 will produce a coke with a stability of approximately 21.

Readers interested in further information on stability calculations should consult Harrison, Jackman, and Simon (1964), who gave full details and included a sample calculation.

Gasification/Liquefaction

To some degree, those coal macerals that are reactive in the coking process will be susceptible to liquefaction and those that are inert will be resistant to liquefaction. Fisher and others (1942), at the U.S. Bureau of Mines, did the original work that established the correlations between petrographic composition and liquefaction yields. Davis, Spackman, and Gwens (1976), in a series of experimental liquefaction studies done in conjunction with petrographic work, found correlations between petrographic composition and rank of coals and the yields in liquefaction. They gave reflectance maceral ranges for optimum yield.

Combustion Problems

Nandi, Brown, and Lee (1977) reported on problems involving incomplete combustion of a Western Canadian coal in a power plant. The authors found a positive correlation between rank, percentage of inerts, and unburned fuel in

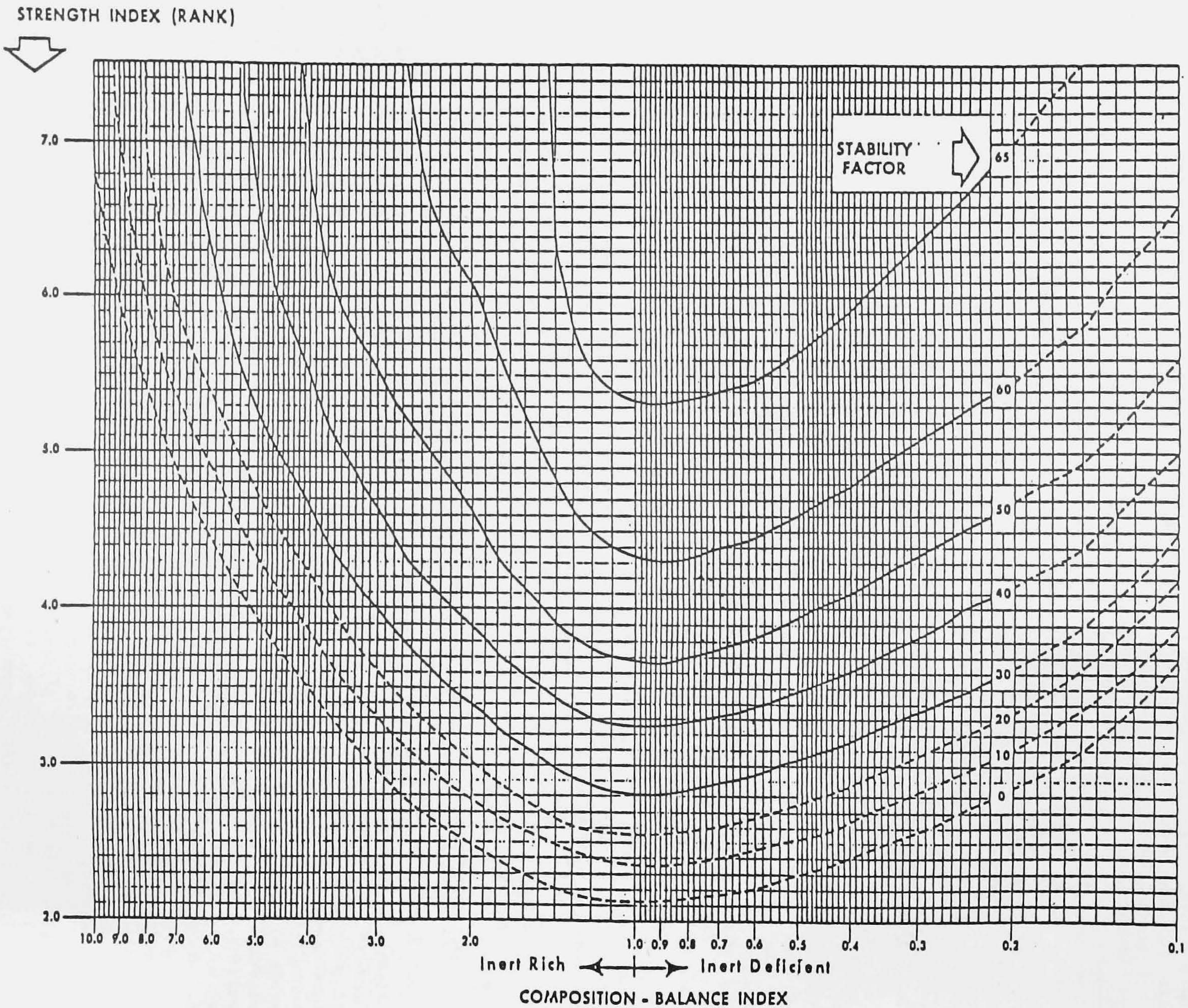

Figure 2.--Diagram used to predict coke stability from petrographic data.

Table 1.--Petrographic Data on Western Coals

[R_o, mean maximum reflectance]

Coal	Percent vitrinite	Percent exinite	Percent resinite	Percent semi-fusinite	Percent fusinite	Percent micrinite	Percent mineral matter	Percent R_o
School Bed Glen Rock, Wyo.	83.1	8.4	0.5	0.7	0.5	1.5	5.3	0.40
Marr Strip Mine North Park, Colo.	85.3	6.2	2.4	.7	.7	1.8	2.8	.53
Deep Creek Routt County, Colo.	68.8	8.7	1.9	5.4	3.3	5.4	6.5	.60
Denson Strip Mine Routt County, Colo.	73.6	6.0	2.6	4.2	3.5	4.7	5.4	.63

the fly ash. The more inert macerals were not being ignited in the combustion chamber. A redesign of the combustion chamber solved the problem.

Other Applications

Techniques similar to those used in coal petrography are finding increasing application in the study of hydrocarbon maturation as an aid in the search for oil. Readers interested in this area of research should consult Geological Society of America Special Paper 153 (Dutcher and others, 1974).

PETROGRAPHIC FEATURES OF FOUR WESTERN COALS

Results and Discussion

Table 1 shows the results of the maceral and reflectance analyses performed on the School Bed, Marr Strip, Deep Creek, and Denton Strip coals. From the point of view of coking coal, both the School Bed and Marr Strip coals are too low in rank to be of much interest. The rank of the Deep Creek and of the Denton Strip coals approach the interesting range, and the reactives-to-inerts ratios will provide far better composition-balance indexes than would the Marr Strip and School Bed coals. Both the Deep Creek and Denton properties would merit further exploration for coking coals, in my opinion.

From the point of view of gasification and liquefaction, the Marr Strip, the Deep Creek, and the Denton strip coals all meet the criteria of Davis, Spackman, and Gwens (1976) for the optimum range for liquefaction. All four coals are apt to liquify easily, but the Deep Creek and Denton Strip coals may give the best yields.

Western Coals in General

Western coals are generally lower in rank than eastern coals. All western coals are younger in age and are usually lower in sulfur than those in the east.

Because western coals are younger and generally of lower rank than eastern coals, they are apt to be richer in resinous materials and in fungal remains. The general course of metamorphism, higher in eastern coals, tends to transform resinites and fungal remains into other substances.

ACKNOWLEDGMENTS

I am grateful to my employer, Commercial Testing and Engineering Co., for permission to do this work and to publish the results; to Dr. Karl Newman of the Colorado School of Mines for the western coal specimens; and to D. Keith Murray of the Colorado Geological Survey for providing chemical analyses for sulfur and ash on the coals.

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Geophysical Techniques for Coal Exploration and Development

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ABSTRACT

The coal geophysicist, working as part of the exploration and development team, approaches solutions to coal-related problems by adapting and using the tools and techniques of oil, mining, engineering, and borehole geophysics. Coal geophysics is applicable to regional, coal-field, tract-evaluation, mine-development, and post-mining studies. Because of the large contrasts in physical properties between coals and the surrounding rocks, and because of the relatively simple geometry of many coal deposits, coals are excellent geophysical targets--almost every known geophysical device shows a response to either their presence or abrupt lateral termination.

Of immediate need in the exploration and development of Western coals are rapid and economic methods to supplement drilling in order to define want areas, to determine thickness variations of strippable-depth coals, to map clinkered areas, and to establish the continuity of coal beds. Field results show that high-precision gravity surveys are capable of delineating coal basins and locating cutouts of thick coals at shallow depth; magnetic methods work extremely well in mapping clinker; and shallow seismic-reflection methods coupled with seam-wave certification techniques appear to be the methods of choice for tracing the continuity of coal beds.

INTRODUCTION

This paper discusses the uses of modern coal geophysics and gives examples of how coal geophysics has been used in delimiting want areas, determining thickness variations of strippable-depth coals, mapping clinker facies, and establishing the continuity of coal beds--all problems of immediate concern in the development of the coals of the Western States. The function of this paper is to introduce coal geophysics to coal explorationists and developers. We hope that, upon reading this paper and the references it contains, those people who are faced with the challenging task of extracting coals will become more aware of the existence of classes of coal exploration and development problems whose solutions may be more readily and economically approached if geophysical procedures are integrated with those of geologists and engineers.

Let us begin by discussing what coal geophysics is and why it should work well, and then give a brief review of its history, followed by a few words on its present status.

Coal geophysics is the application of geophysical engineering principles and methods to coal-related problems, problems that range from delineation of coaliferous basins and exploration for coals within established provinces, to planning and development of coal mines and determination of the location and effects of mines long after they have been abandoned.

Of all commodities sought geophysically, coals present perhaps the best targets. Not only do coals exhibit marked contrasts in their physical properties relative to those of the neighboring materials, but also coal deposits have a layered geometry well suited for geophysical study. Within the coaliferous areas of the Western United States, the coals are less dense than their neighbors--density contrasts of -1.0 g per cm^3 are common; the coals are higher in electrical resistivity--in some areas, they are higher by a factor of 10; the deeper coals often are lower in seismic velocity--velocity differences of 40 to 50 percent have been observed; and the coals generally exhibit less natural radioactivity--a lignite on a gamma-ray log may show a count rate of 20 counts per second in contrast to a count rate of 100 counts per second for the surrounding rocks. In addition, secondary effects associated with coals may also serve as guides to exploration, a good example

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being the change in magnetization of overlying rocks after they have been baked by coal fires. D. E. Watson (U.S. Geological Survey, oral commun., 1976) has observed a 6000-fold increase in magnetization in the overlying sediments when he has duplicated these natural baking and cooling processes in his laboratory.

Thus, when one scans the list of major geophysical methods (gravity, electrical, seismic, radioactivity, and magnetic), it is not surprising that all of them appear to have application to some aspect of coal exploration and development. However, the above statement is not to be interpreted as suggesting that all geophysical methods will be effective on all coal problems. The task of the coal geophysicist is to select that particular method, or set of methods, best suited to the problems at hand, put those methods into practice, and then arrive at an interpretation which most reasonably satisfies the geological constraints.

Geophysical studies of coal deposits are not new. Heiland (1934, p. 572-573) listed 30 publications on the application of geophysics to coal problems, the earliest being a report of a torsion-balance (an ancient and honorable, albeit very demanding and time-consuming, gravity-type instrument no longer used commercially) survey run in 1919 to find faults delimiting a lignite deposit in Austria. Kelley (1936, p. 480) reported that, in 1935, de la Peña and Sineriz, working with Government geologists in Spain, conducted a coordinated electrical, magnetic, gravity, and seismic geophysical program to map a faulted area adjacent to known coal production. In the stepout area, 17 holes had previously failed to reveal any coal. However, after the faults were mapped geophysically and the relative displacements of the blocks were ascertained, the first hole, on the basis of the recommendations of these geophysicists, encountered five coal seams at minable depths. Estimated reserve in one of the undisturbed blocks was placed at 45 million tonnes. The work in Spain is an illustration of the use of indirect geophysical prospecting; that is, using geophysics to map a structural or stratigraphic environment favorable to the occurrence of a commodity and thereby increase the probability of locating this commodity with the use of the smallest number of drill holes. Most oil geophysics uses the indirect approach. In coal work, however, because of the large differences in physical properties of coals and their neighbors, direct methods of prospecting can sometimes be used. Here one searches for the material itself rather than for an associated effect. An outstandingly successful example of direct prospecting was reported by Ewing and others (1936), who employed a fixed-spacing electrical resistivity method to locate anthracite subcrops in Pennsylvania. In one of the areas studied, exploration drilling had been abandoned because of the large number of barren holes. After this area was mapped geoelectrically, only three non-coal holes were drilled, and the stripping area was extended 200 m. Another use of coal geophysics is to locate geologic disturbances that can make mining unprofitable. Malamphy (1934, p. 323-325) employed geophysics in this manner when he ran a series of magnetic profiles in order to find igneous dikes that had cut and coked the coals in and near the São Jeronymo mine in Brazil.

Despite these early demonstrations of the applicability of coal geophysics, and despite the rapid development of geophysical technology since the 1930's, only a handful of additional citations appeared in the coal-geophysics literature until the early 1970's. Notable among these interim papers were those by Thyer (1963) showing the use of gravity surveys to outline coal deposits, by Tixier and Alger (1967) describing the continuing work done by the Schlumberger organization on borehole logging of coals, and by Krey (1963) discussing his pioneering studies on developing the concepts and demonstrating the utilization of seismic seam waves. If papers of this quality had been addressed to oil exploration, they would have created a flurry of activity. But this did not happen in the coal business. The conclusion is inescapable: though the work was excellent, there was no market for it. Today, however, it is evident that the long period of quasi-dormancy in the development of coal geophysics has ended. In England last year, Dunn and Clarke (1976) reported that 800 km of high-resolution seismic line had been run; in Germany, Great Britain, France, and the Netherlands more than 250 seam-wave studies have been made since 1967 (Krey, 1976); in the U.S.S.R., for the last 10 years, coal geophysics has been used before any major mine was started (Terentyev, 1976, and oral commun., 1976); and in the United States, an active coal geophysics program is underway (Hasbrouck and Hadsell, 1974 and 1976; Lepper and Ruskey, 1976).

APPLICABILITY OF COAL GEOPHYSICS

The areas to be discussed are ones either in which geophysical surveys have been made or for which results of current research strongly suggest that geophysical studies might be useful. No attempt has been made to assess specific cost effectiveness, mainly because economic conditions can vary so widely. As an example of this variability, consider drill costs--the usual standard against which the cost of a geophysical program is compared. In certain easy-access, shallow-coal-depth areas, stratigraphic drilling on a long-term contract has been obtained for $3 per m; in another area in which coring is required, drilling cost may be $60 per

m. At one deep-drilling (300 m) site in central Utah, we have heard of coal exploration holes costing $60,000. Economic evaluation also has to balance money spent against value of data received. We freely concede that no geophysical interpretation can produce information as definitive as that obtainable from a good string of cores taken from a series of closely spaced holes, but, on the other hand, no one could afford drilling at the 2.5-m lateral subsurface sample distance commonly obtained in some high-resolution seismic-reflection surveys.

Regional Studies

Regional geophysical studies extend over areas comparable in size to major coal basins. (See Averitt, 1975, p. 5, 35.) In the conterminous United States, coal provinces and regions are well established; but in Alaska and along the continental margins, outlines of coal regions have not as yet been drawn (E. R. Landis, U.S. Geological Survey, oral commun., 1976). Also, in other parts of the world, it is unlikely that all possible coaliferous basins have been fully explored.

The task of the geophysicist engaged in regional studies is to assist the geologist in delimiting hypothetical-resource and speculative-resource areas. Terminology used for coal resources classification in this paper is the one jointly developed by the U.S. Bureau of Mines and the U.S. Geological Survey (U.S. Geological Survey, 1976). For a geophysical technique to be useful in regional studies, it must be one that can examine large areas quickly, effectively, and economically. Remote sensing (from aircraft and from satellites), regional gravimetry, and airborne magnetometry are geophysical methods with this capability.

Large-scale geologic problems and various types of regional geophysical methods that might be used to help solve them are as follows:

1. Determination of regional tectonic framework--remote sensing methods using Landsat images and images from high-flying aircraft equipped with multispectral scanners, side-looking airborne radar and other microwave methods, regional gravity surveys with helicopter support to speed field operations in areas of poor accessibility, and airborne or truck-mounted magnetometry.
2. Determination of basement configuration within the basin--regional gravimetric and magnetometric surveys.
3. Determination of structure within the basin--use of results from borehole logging and geophysical surveys previously made as part of oil exploration programs.

Let us discuss this last point more fully. In the Western United States there are many regions, the Powder River Basin of Wyoming being one example, where coal as well as oil and gas occur within the same basin, and where geophysical prospecting for oil and gas has been going on for many years. In order to reduce exploration budgets, many companies today will sell oil-geophysics data to a broker who in turn offers these data on the open market at a price far less than their original acquisition costs. Station gravity values, for example, which might cost $15 per station to obtain at current field-work prices, can be purchased for $2 per station from a broker. Companies that supply these data and organizations that offer data-interpretation services are listed in the Geophysical Directory, an annual publication. Although the coal exploration dollar can be stretched considerably by purchasing gravity, magnetic, seismic, and borehole data from a broker, it should be remembered that the field procedures used to acquire these data were focused on an oil and gas target. Therefore, it is possible that the shallow horizons, which are of most interest to the coal geologist, may have been ignored. For example, surface casing might have been set before the well logs were run and thus electric logs would not have been taken near the surface; gamma-ray and density logs (logs of great value in coal studies) might not have been considered in probing for oil and gas; and seismic recordings might have been made with the earliest arrivals suppressed--some older seismograms available from brokers do not show reflection events at times less than 300 milliseconds, equivalent to a depth of about 500 m.

Coal-Field Studies

Coal fields, as we are using the term, are those subdivisions of coal regions for which the coal resource is classified as either an inferred or an indicated resource; that is, the distance from known coal occurrences in mines, trenches, outcrops, or drill holes ranges from 0.8 to 9.6 km (U.S. Geological Survey, 1976). No universal agreement exists as to the difference between a coal field and a coal area, the terms often being used interchangeably. For the sake of semantics, we distinguish between the two on the nature of their boundaries: if the boundary is set by the geology, we call it a coal field; if the boundary is cadastral, we think of it as a coal area. For example, the Gillette area of Wyoming (Denson and others, 1973) is called an area because it is bounded by township lines; whereas the Gillette coal field is geologically delimited on the east by a subcrop line and on the west by an arbitrary depth line, say 1000 m, on some selected coal measure that dips toward the center of the Powder River Basin. But whether coal field or area, the amount of land covered is large (1000 to 4000 km^2), coals are known to occur, and the objective of the study is the same: to obtain sufficient geologic information upon which to base tract selections.

Because more detail is needed for a coal-field study than for a regional study, closer spacing of observation points and finer interpretation of data are required. It is almost axiomatic that if greater detail is needed, then the cost will be increased. This rule applies to airborne as well as ground-based surveys. Not only must flight lines be more closely spaced, but also more data processing will be needed to reduce and interpret the increased volume of data. Meeting the need for greater station densities in a land-based geophysical survey also forces one to face the ever-growing, costly and vexatious problem of land access. For regional surveys, the network of public roads is usually sufficiently dense to allow establishment of enough gravity and magnetic stations; but for coal-field surveys, entry to areas between roads must be made in order to gather data at the required smaller station intervals, usually 400 m. One advantage of satellite and high-altitude geophysical surveys is that, as yet, no one has devised a way to charge for or to restrict these flights.

Types of problems encountered in the preparation of coal-field maps and geophysical techniques that could be useful in providing information for these maps are listed below:

1. Determination of surface geology, basin boundaries, and coal-bed subcrop lines--remote sensing to supplement photogeology, airborne magnetometry (from low-flying aircraft) to map general outline of clinker facies, and borehole geophysical logging in shallow holes.
2. Determination of subsurface geology--borehole geophysics to supplement sample and core data, gravity and magnetic methods to determine basement configuration and major structural trends, and seismic exploration to study structure within the sedimentary basin.
3. Determination of trends and extensions of large ancient stream channels and other want areas--gravity surveys, microwave and thermal-inertia methods, and seismic methods including use of velocity profiling.
4. Determination of geologic settings unfavorable for coal deposition, for example, thick marine sections; igneous, metamorphic, and volcanic sequences; and massive salt intrusions --geophysical well logging and magnetic, gravity, and seismic methods.

Because of economic and governmental restraints, the parcels of land that a company might be considering for future development may be only a small portion of a coal field. The question therefore can be raised as to the commercial value of a reconnaissance coal geophysical survey if only relatively small acreage is of interest. The answer is twofold: first, although a large number of possible future properties may exist, the company naturally wants to select only the best of these; and second, the key to gaining understanding of the probable geologic conditions within a given portion of land may lie outside of it--determination of the tectonic framework, for instance.

To reduce the costs of acquiring large-scale geophysical data, one can either go through a broker or, if seismic data are needed, one can consider participating in what is called a "group shoot." The way a group shoot works is that a seismic firm will contact a group of companies known to be interested in a given prospect. Upon agreement to participate, these companies then share the cost of the survey and each receives a copy of the processed, but not interpreted, data. The thinking is that it is not the data themselves, but what you do with them that gives you the competitive edge. Though we know of no group data-gathering operations in the coal business similar to those employed in the oil and gas business, we fully expect to see this type of shared-cost effort being adopted in the future, particularly after high-resolution seismic methods are perfected.

One application of a group shoot would be to establish reasonable correlations of the deeper coals in the unmapped regions between widely spaced drill holes. If the seismic surveys showed that major coal beds maintain their continuity along several profiles, then this would be a more favorable economic sign than if seismic mapping indicated that the coal beds either were highly discontinuous or were subject to severe and variable parting. High-resolution seismic surveys, as the experience in Great Britain indicates, also appear capable of determining the distribution and amount of faulting in an area--a factor of great economic importance in all mining methods.

For Government agencies charged with the responsibility of determining the identified resources of a coal field in which beds to depths of 1800 m are to be included (U.S. Geological Survey, 1976, p. B4-B5), the application of reconnaissance coal geophysics would appear to be worthy of consideration. Only in those coal fields that have been intensively explored and drilled for oil and gas is one likely to obtain geologic information on the deeper beds relatively inexpensively. In all other areas, the choice is between drilling and logging many deep and costly exploration holes or conducting geophysical surveys to link results obtained in far fewer holes.

At the conclusion of a coal-field study, the company geologist has to be prepared to supply geologic input to assist management in its decision as to what tracts are to be bid and at what cost. In 1970, leases for 25-km strip mines on Federal lands near Gillette, Wyo., were bid at from two to three million dollars. It seems only reasonable to us that when so much money is required for lease acquisition an increase in the exploration budget, in order to more fully evaluate the coal potential of a nominated area, would be a wise expenditure.

Tract-Evaluation Studies

The size of a tract is determined by the bounding dimensions of the prospective mine, and these in turn are functions of the amount of recoverable coal reserves necessary to meet long-term coal-sale contractual requirements. In order to give an idea of the amount of land in a tract, consider a strip mining operation at a moderately sized mine for which the contract calls for delivery of five million tonnes of subbituminous coal per year for 20 years. Production of 100 million tonnes of coal from a set of undisturbed seams whose thickness sums to 10 m would require a 9.6-km^2 tract, assuming a recoverability of 80 percent.

Because a major strip mine, one with an anticipated yearly peak output of 10 million tonnes, may require a capital investment of 40 to 60 million dollars and may take 5 to 8 years after tract acquisition to reach full productivity (1976 figures from R. G. Hobbs, U.S. Geological Survey, oral commun., 1976), it is not surprising that extensive development drilling programs are undertaken. In one area near Gillette, Wyo., we observed test holes drilled on 50-m spacings--if topped with flags, the steel fence posts used to mark the drill-site locations would have given this area the appearance of a pitch-and-putt golf course.

The purpose of a coal-tract geophysical survey is to reduce the number of drill holes required to evaluate a given tract. The number of drill holes can be considerable, as can their cost. For example, if drilled out on a spacing of 125 m, a 20-km^2 tract for a major mine would require 1353 holes; at an average depth of 75 m and at a cost of $6 per m, the cost would be $608,850, and it would take three drills averaging 300 m per day approximately 22 five-day weeks to do the job. But coal geophysics isn't free, either. Thus, the problem of selecting the optimum combinations of methods to produce the most information at the lowest possible costs takes on the look of an operations research task. One of the objectives of this paper is to create awareness that geophysics offers other exploration and development methods besides surface and geological mapping, drilling, and borehole logging.

From past and current experience, geophysicists hold little doubt that their methods are applicable in tract evaluation. Some of the problems in tract studies and the types of geophysical techniques that are of demonstrated and potential use in approaching solutions to these problems are as follows:

1. Determination of the surface and subsurface extent of clinkered zones--magnetic and seismic methods, coal-quality borehole logging, and electrical soundings.
2. Determination of position of an active burn front--geothermal, magnetic, seismic, and electrical methods. (Current research in monitoring the in situ gasification process will very likely lead to rapid development in this application of coal geophysics.)
3. Determination of subcrops, ancient shorelines, and channel sands--seismic of several types, high-precision gravity, and electrical methods.
4. Mapping of lenticular coal deposits--seismic methods and, if the deposits are shallow, electrical techniques.
5. Determination of the continuity of coal beds between known points--seismic high-resolution reflection and seam-wave certification methods, electrical methods, and high-precision gravity surveys.
6. Determination of the kind, distribution, and amount of faulting--dominantly seismic methods, but also electrical and gravity methods.
7. Location of igneous dikes cutting coal beds--magnetic and seismic methods.
8. Determination of coal quantity and quality in place--advanced borehole logging methods.
9. Delineation of old mine workings (old mines not only are want areas but also may constitute a hazard to the miner at the working face and may be sources of flooding and polluting mine waters)--seismic, gravity, electrical, borehole-radar, and microwave methods.
10. Location of very old, and now well-hidden, mine shafts--geochemical methods using helium and sulfur hexafluoride tracers.
11. Determination of nature of coal beds beneath the present mine-plan depths; that is, coals which upon improvement in technology or rise in price may become economically attractive--seismic and borehole procedures.
12. Investigation of water resources--almost all geophysical methods. (See manual written by Zohdy and others, 1974.)
13. Determination of overburden, roof, and floor strengths prior to mining--borehole and hole-to-hole (also called crosshole) seismic methods.
14. Determination of overburden rippability, foundation-site competence, and principal stress directions--seismic and strain-seismology techniques.
15. Detection of the presence of other economic materials such as gravels and uranium-bearing rocks--borehole logging and radioactive methods.

At the conclusion of the initial phase of a tract study, not only should enough general information have been gathered to establish the indicated reserve over the entire tract and to set the design criteria for that mine equipment requiring the most lead time for aquisition, but also sufficient specific data should have been taken and analyzed to block out the measured reserve in the area for which the first five-year mining plan is to be developed. Once the reserve base has been determined, then the latter phases of the tract studies begin. This work entails completing the measured reserve estimate for the remainder of the tract and making engineering geophysics studies. Good coal geophysics programs, like good mine plans, take considerable effort to formulate; and like good mine plans, they can contribute to the profitability of the mining venture.

Mine-Development Studies

Mine-development studies begin immediately after completion of the first phase of tract studies, and they continue well after the final tract work is done and mining is in progress. Whereas tract studies are dominantly exploration efforts directed toward establishing reserves, mine-development studies are oriented more toward geological engineering and mining engineering problems.

The following is an annotated list of types of problems that fall into the mine-development-study category:

1. Selection of mine-shaft locations--in England, at one of the National Coal Board's new mines (details withheld on request), the entire cost of the high-resolution seismic survey was repaid because that survey showed that the proposed location of the main shaft was in a highly faulted region which very probably would have suffered severe flooding. Results from the same survey were used to select a new site for the main shaft, at which, to date, no flooding problems have occurred.
2. Blocking out panels prior to longwall mining--in Germany, seismic seam-wave technology has been very successful (better than 90 percent) in predicting coal-bed behavior ahead of the advancing longwall.
3. Determination of roof and floor strengths ahead of mining--research continues on this problem, but brochures from several well logging companies exhibit borehole logs on which variations of elastic parameters with depth are displayed, and high-frequency, hole-to-hole seismic studies show great promise.
4. Determination in place of clinker strength--using magnetic methods, Carter H. Miller (U.S. Geological Survey, oral commun., 1976) has drawn a correlation between amplitude variations on magnetic profiles across clinker quarries and strengths of the different varieties of clinker within these quarries.
5. Evaluation of open-pit slope stabilities and design of underground mine openings--for years the U.S. Bureau of Mines has been using geophysical data in these studies.
6. Monitoring and prediction of subsidence as mining proceeds--introduction of a new generation of monitoring equipment (tiltmeters, strain meters, and electronic surveying devices), coupled with recent developments in the field of strain seismology stemming from research in earthquake prediction, volcanic-eruption prediction, and underground-nuclear-explosion detection, presages development of radically new approaches to early detection and more accurate prediction of subsidence resulting from underground coal mining.
7. Location of trapped miners--a seismic approach to this problem has been under investigation since 1969 by the U.S. Bureau of Mines and the Mining Enforcement and Safety Administration (C.M. Lepper, U.S. Bureau of Mines, oral commun., 1976). The reasoning is that though a trapped miner may be cut off from an electronic signaling device he will usually have something with or near him that can be used to beat on the rocks and thus create a seismic signal. Triangulation back to this source requires not only a sensitive seismic system but also a set of observation stations distributed throughout and above the mine, such that, at each of these stations, the nature of the seismic arrivals from all parts of the mine is established as mining proceeds.

Other Applications

Other problems for which the methods of coal geophysics appear to be applicable are as follows:

1. Location of coal-mine fires--the geophysical techniques used are essentially those developed for monitoring in situ coal gasification processes and delineating the boundaries of coal consumed in those processes.
2. Determination of the pattern and magnitude of subsidence following cessation of mining--quick-response subsidence of about 2 m across the ground surface overlying the break line of longwall removal of 3-m-thick coal at a depth of 60 m does not need elegant instrumentation for its detection; however, under particular geologic conditions and with certain mining practices, incipient subsidence may be subtle (Adler and Sun, 1968) and final subsidence may be delayed for decades. For these cases, periodic tiltmeter observations over an established grid could provide early indications of eventual subsidence (M. W. Major, Colorado School of Mines, oral commun., 1976).
3. Determination of subsidence associated with in situ coal gasification processes--a different set of ground-control problems may

very likely develop when coals are taken by burning rather than by mechanical means. Using borehole and seismic methods to determine the elastic properties of rocks above the retort volume before and after gasification, and using tiltmeters to monitor subsidence as the burn front migrates to and beyond the sensor array, the characteristic behavior of subsidence associated with the in situ gasification process for a given area may be developed.

4. Selection of shotpoints for seismic investigation of deeper coals and for oil prospecting in a clinker area--experience in the Powder River Basin shows that detonation of seismic shots in the clinker produces extremely poor seismograms; thus, shotpoints in clinker areas are to be avoided. The magnetic method can be used to certify that clinker is not present near the surface.

5. Contributions to technology transfer--in its beginnings, coal geophysics took its techniques from those previously developed in oil, mining, and engineering geophysics. Thus, technology transfer was in one direction only. Now, however, coal geophysics has started to repay its technological debt. Consider, for example, the high-resolution seismic systems that have been developed for coal studies. These methods have recently been used in West Texas to map near-surface velocity structures, ones whose effects must be removed from the seismic sections obtained in the search for oil and gas. Shallow seismic methods also appear to be useful in site studies for nuclear power plants. As another example, results of theoretical investigations on the propagation of seismic seam waves (bounded or trapped waves) and studies of hole-to-hole seismic transmissions will undoubtedly be incorporated into the crosshole technology employed in the evaluation of dam sites.

From the foregoing it indeed appears that coal geophysics is applicable to a wide range of coal-related problems. And from the lessons taught us by the history of technological growth in the fields of mining and oil geophysics, increased usage of coal geophysics very likely will spawn new ideas and techniques which will in turn greatly expand the list of applications.

Let us now look at some results representative of those that have been obtained using the methods of coal geophysics.

EXAMPLES OF THE APPLICABILITY OF COAL GEOPHYSICS

When we were starting our studies several years ago, we asked coal exploration and development people for their help in deciding which direction our research might take in order for it to be most beneficial to them. Almost all said that their immediate requirement was for some means, besides closely spaced drilling, by which to determine what happened to the coal seams in the areas between logged holes. In particular, they stated a need for methods by which to locate want areas, determine thickness variations and bed undulations of strippable-depth coals, map the contact between burned and unburned coal in the subsurface, and establish the continuity of coal beds. The examples are addressed to these problems.

Gravity Methods

Density of coal is almost always considerably lower than the densities of the surrounding rocks; therefore, gravity methods offer a simple, straightforward means of locating the abrupt edges of cutouts of thick coals at strippable depth. Once the lateral variation and magnitude of the densities of the sediments within a given region have been determined to a reasonable accuracy, gravity surveys can usefully be extended from those areas of known geology into neighboring ones of meager drill-hole control. Approximations of the required densities can be obtained from cores, samples, and density logs and by computational procedures--density profiling and iterative-interpretation schemes, for example.

An elliptically shaped cutout in sec. 17, T. 51 N., R. 72 W., Campbell County, Wyo. (Denson and Keefer, 1975) was selected for a feasibility study of cutout-edge detection by the gravity method. Coals in this area are approximately 30 m thick and 60 m deep, and density logs from comparable sections indicate that a density contrast of -1.0 g per cm^3 is to be expected. Under these conditions, the anticipated maximum gravity anomaly would be 1.3 milligals, with quarter-anomaly points about 75 m to either side of the inflection point on the maximum-gradient gravity profile.

Results of our initial gravity survey are shown in figure 1. The station spacing was 30.48 m along all traverse lines, and the readings were taken using a high-sensitivity gravity meter whose scale constant was 0.0755 milligals per scale division. Differences in terrain effects along each profile were insignificant relative to the size of anomalies measured. By accepting only those station readings whose sample standard deviations did not exceed 0.1 scale divisions, and by maintaining a closure error in station elevation of less than 0.12 m, the combined maximum instrumental and data-reduction error would have the effect of shifting the plotted contours of figure 1 by no more than one-half a contour, a shift that would not change the gravity map appreciably.

The maximum gravity anomaly observed was within 0.1 milligals of what was predicted,

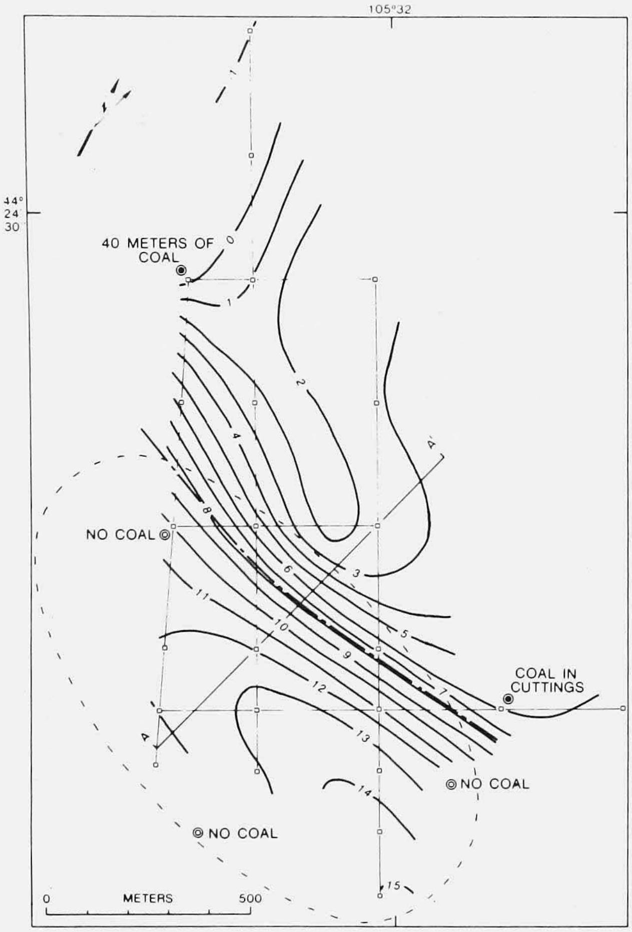

Figure 1.--Results of a gravity survey covering the northeasterly edge (outlined by the dashed line) of a suspected elliptical cut-out. Station spacing along each traverse was 30.48 m, and base stations were positioned at the locations shown by squares. Contour interval = 1 gravity unit (gu) = 0.1 mgal. The dot-dash line that roughly parallels the 8-gu contour indicates the boundary of a possible channel as interpreted from the gravity data.

suggesting that the assumed density contrasts, depth to top of the seam, and seam thickness were realistic.

From visual inspection of the gravity map of figure 1, the boundary between the coal and no-coal regions appears to roughly parallel the 8-gravity unit (0.8 milligal) contour. Decrease in the slope of gravity values along the west border of the area could have been produced either by thickening of overburden or by loss of abruptness of the coal's leading edge. Regardless of the cause of the diminution in slope values, the alignment of inflection points exhibits a definite trend on the west and southeast edge of the area suggestive of a channel edge.

The results of this first study allow several statements to be made: (1) gravity mapping (at least in this area) appears capable of delimiting the edge of a thick-seam cutout, (2) the edge of a seam one-third the thickness of the existing seam would have been only marginally detectable by a standard high-precision gravity survey, (3) the gravity map could have been used as a guide for optimizing subsequent drilling programs, and (4) a station spacing of 60 m would have been sufficient to reveal the gravity anomaly.

In computing the coal resources in the Beulah-Zap KRCRA (Known Recoverable Coal Resource Area) of North Dakota, lignite cut-outs produced by glacial outwash streams must be delineated. Because the meandering glacial channels in this area may be a kilometer wide, a hundred meters deep, and more than 10 km long, their occurrence can reduce the coal resource markedly, as well as present mining problems. Present-day drainage may follow in the path of its progenitors, but it does not always. Sometimes, the oscillatory movement of the leading edge of a great continental ice sheet caused earlier channels to be filled and then later covered by drift as the glacier retreated. Water wells and exploratory drilling in this area have encountered ancient channels under almost featureless terrain.

Prior to making field observations, we reasoned that because the glacial channels were filled with debris carried down from the Canadian Shield by the ice sheets and because this igneous material should be more dense than the sediments (particularly the coal) along the channel borders, we should obtain a gravity maximum over the glacial channel. The gravity profile of figure 2 shows that the supposition was not correct. But the profile does show a well-developed anomaly and, after all, it is more important that the surveys produce usable results than that they agree with our preconceived notions. Initial interpretation of this anomaly indicates that the channel edges are at a traverse distance of 600 to 1450 m from the west end of the profile. The larger data scatter on the left side of the profile (from 0 to 500 m) reflects temporal variations of the gravitational acceleration produced by a far-distant earthquake.

Although we have run only one traverse in this KRCRA, this single profile tells us a great deal; namely: (1) a gravity anomaly is associated with this channel; (2) a reconnaissance gravity survey with a station spacing of 300 m (10 times more than was used on the test run) would have detected the presence of the channel; (3) though the area is covered by glacial drift containing large erratics and thus the gravity data are expected to be noisy, spatial noise

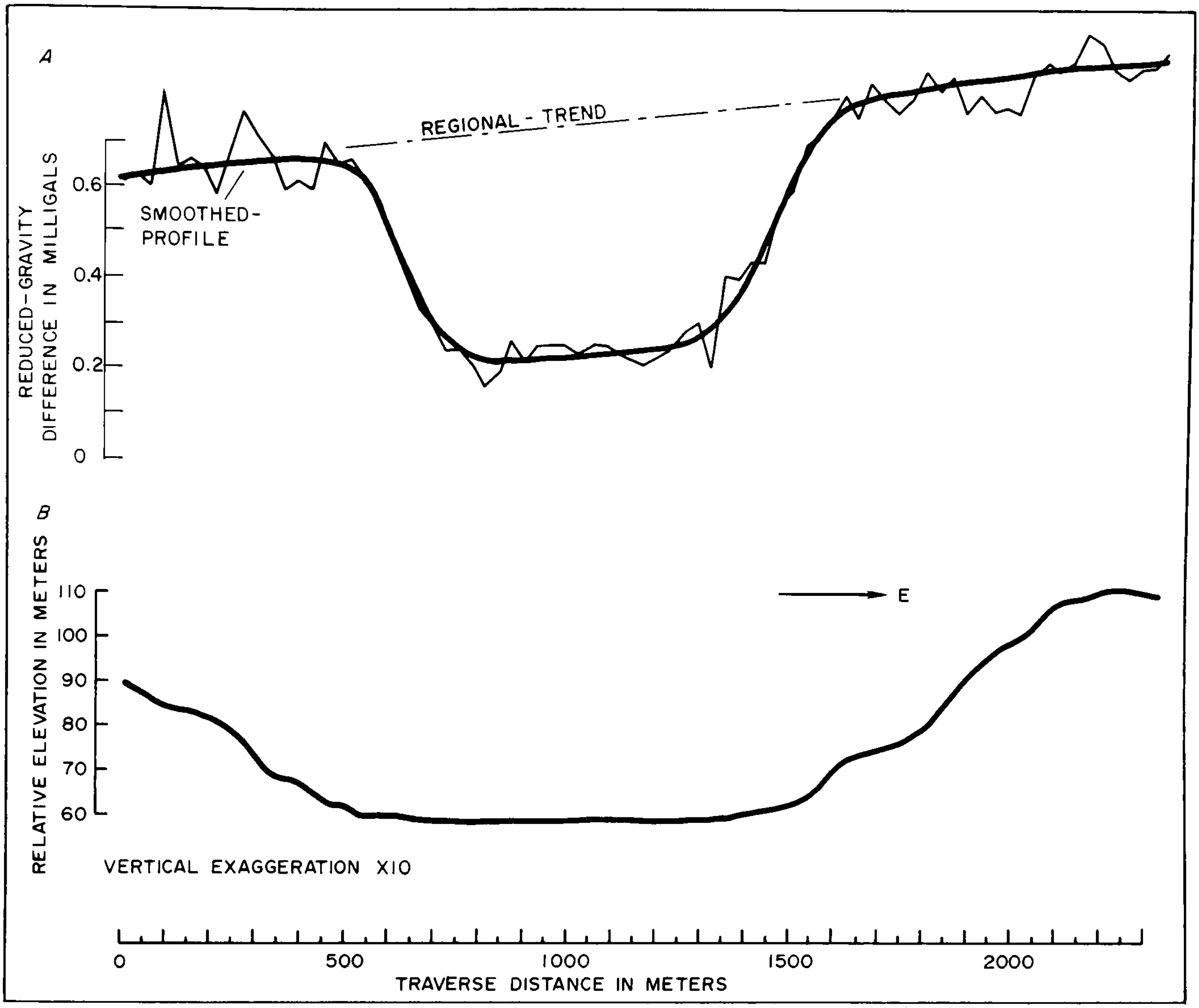

Figure 2.--A, Gravity profile across an ancient glacial channel in the Beulah-Zap KRCRA, North Dakota. Jagged line connects the reduced-gravity values. Smoothed-profile and regional-trend lines were drawn subjectively. Station spacing was 30 m, and base-station separation was 300 m. B, Elevation profile. Note that, with an assumed surface density of 1.9 m per cm^3, the reduced-gravity profile exhibits little elevation effect.

does not mask the channel anomaly; and (4) results from this initial profile are sufficiently encouraging to warrant recommendation of an extensive gravity-field study in this area.

Figure 3 shows one of the residual gravity profiles obtained over a shallow lignite deposit near Watkins, Colo. The objective of this survey was to see if thickness changes in the lignites and if locations of near-surface faults and slumps could be determined gravimetrically. Sample and geophysical logs (Sanchez, 1976) indicate that the lignite zone varies in thickness from 4 to 8 m; is composed of a series of lignite beds intercalated with sandstones, mudstones, and siltstones; and contains only one lignite bed capable of being easily correlated across the entire profile. Thus, the average density of the lignite zone is not expected to be uniform from one end of the profile to the other. Faults and slumps are anticipated, because the core taken at location 9-1, the only hole cored, showed a few slickensides; because the dip between holes 6-1 and 7-1 differs from that observed between other holes along the profile;

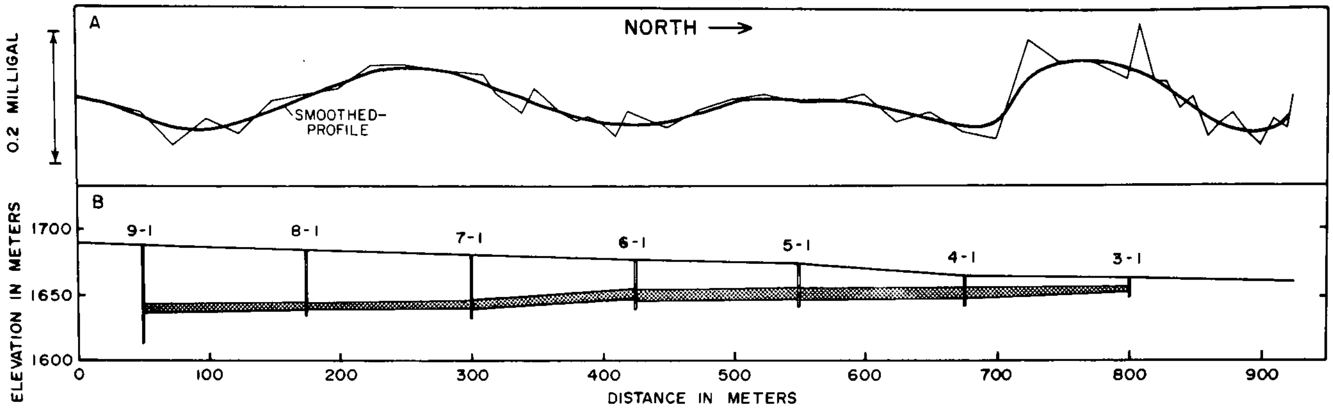

Figure 3.--A, Residual gravity profile across a highly parted lignite zone near Watkins, Colo. Jagged line connects residual gravity values, and smoothed-profile line represents a subjective estimate of the error-free residual anomaly. Station separations were 10 and 25 m. The regional gravity was assumed to follow the best straight line through the Bouguer gravity values. B, Data for the section extending from drill hole 9-1 north to drill hole 3-1 were obtained from sample and geophysical logs. Note steepening of dip of the lignite zone between holes 6-1 and 7-1, and change in lignite-zone thickness between holes 4-1 and 3-1.

and because slumps are common in this area (R. G. Hobbs, U.S. Geological Survey, oral commun., 1977). Recently, the U.S. Bureau of Mines (Frank Ruskey, oral commun., 1977) ran a preliminary high-resolution seismic-reflection experiment along this profile, and its interpretation indicated probable faults or slumps between locations 6-1 and 7-1 and near 8-1.

Crude interpretation of the gravity data displayed on figure 3 suggests that faults or slumps may be present at traverse distances of 25, 150, 350, 460, 710, and 820 m. Upon integration of the gravity data with those obtained from the logs and from the seismic survey, the interpretation of possible faults or slumps south of hole 8-1 and between holes 7-1 and 6-1 is strengthened. On figure 3, the change in thickness of the lignites between holes 4-1 and 3-1 is shown as stratigraphic thinning because the hole data are all we had to work with. However, on the gravity profile, note that north of hole 4-1 at a traverse distance of 710 m the gravitational field shows a sharp increase. This may well be an indication that, instead of a gradual decrease in thickness of the lignite zone, the lignites have abruptly thinned just north of location 4-1. The north end of the profile terminates in a drainage depression, and we suspect that the low values of gravity observed on this end of the traverse are produced either by low-density material within the alluvium or by weathered lignite and rock.

One would expect that as the low-density lignites and the topography converge the gravitational attraction would become gradually less. That this does not appear to happen on figure 3 is due, we suspect, to our poor choice of the regional gravity used in calculation of the residual gravity. Using an assumed surface density of 2.0 g per cm^3, the variation in Bouguer gravity from one end of the traverse to the other was 0.54 milligals, more than five times greater than the residual anomaly across location 8-1. Regional gravity gradients of 0.6 milligal per km are common along the east flank of the Denver Basin. Our initial objective in the gravity survey near Watkins was to determine if anything could be seen using gravity. The results shown on figure 3 indicate some potential. They also tell us that we must have a better grasp of the regional variations if the longer wavelength anomalies are to be interpreted.

Although only a few lines of gravity have been run in the Watkins area, they are sufficient to tell us the following:

1. Gravity surveys may be useful in determining thickness variations of lignite zones at strippable depths and for locating minor faults or slumps in these areas.
2. Areal, rather than line, coverage will be required not only to trace fault patterns but also to establish the regional gravity needed for making better residual gravity maps.
3. High-precision observations and surveys are an absolute necessity.

In 1931, 45 years before our work at Watkins, Miller (1940, p. 191-192) made a series of torsion-balance observations at 100-m intervals along a 6-km traverse across the Onakawana lignites of Ontario, Canada. The results of his excellent work are shown (with minor redrafting) on figure 4.

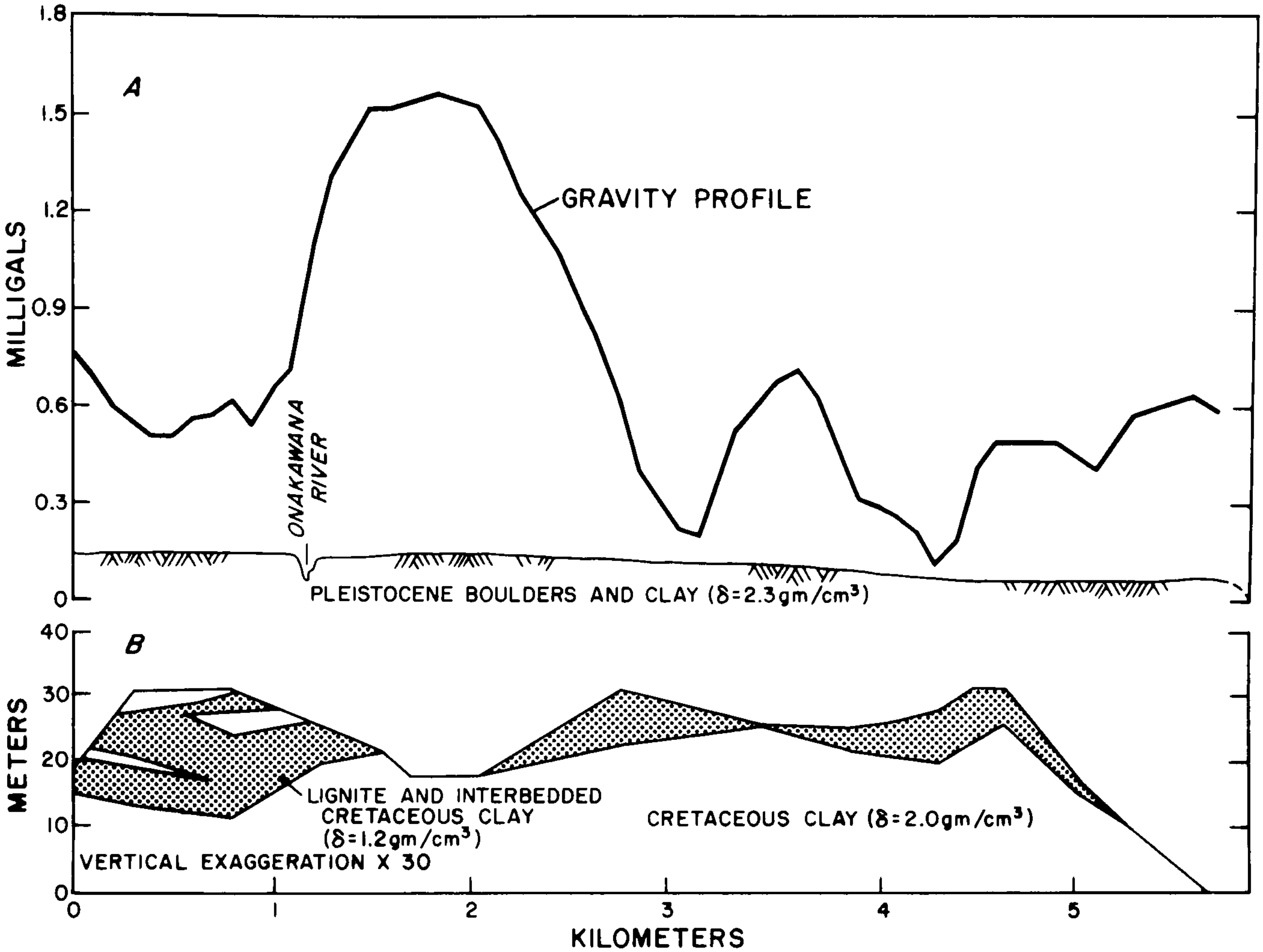

Figure 4.--A, Gravity profile from torsion-balance data taken in 1931 at 100-m intervals across the Onākawana lignite deposits of Ontario, Canada. Modified from A. H. Miller (1940, fig. 11). B, Interpreted configuration of lignites based on drill data from 15 holes, only 6 of which were within the plane of the section.

For the two outer lignite bodies, the gravity profile clearly shows an inverse correlation between gravitational attraction and lignite thickness--thicker lignites, less gravity. However, for the central deposit, the gravity low is displaced 400 m to the right of the indicated thickest part of the lignite accumulation. This mismatch is no cause for alarm because, at this location, the spacing between drill holes is seven times greater than the spacing between gravity stations and because the schematic cross-sectional representation of the central lignite deposit does not necessarily reflect its actual shape accurately. For example, the left vertex of this triangular body could be just a small lignite stringer, and the right vertex may be only the left edge of the far-right deposit. Drilled and logged holes at 350 m to either side of the central hole would have resolved these questions.

Since the time of Miller's survey, gravity meters capable of making observations in a few minutes (instead of the several hours required for the torsion balance) and electronic topographic surveying equipment have been developed. Using these devices, data for a complete gravity map of this area could now be obtained in less time than it took Miller to record readings along a single profile. Also, advances in computer science have added powerful tools, allowing the interpreter to attain a refinement in interpretation with a speed unimagined in the 1930's. Thus, in today's world, it would be faster and cheaper to do the gravity work first and then use these results to set the drill program, rather than to use gravity solely to provide fill-in data between drill-hole locations.

From the preceding four examples it appears that if thick, shallow-depth coals are the target, then the use of gravity methods should be considered.

Let us now look at some examples which show how another natural-source geophysical method, the magnetic method, may contribute to the coal exploration and development effort.

Magnetic Methods

The examples which follow illustrate the use of the magnetic method to delineate areas of clinker, rocks baked by coal fires.

Figure 5 shows the results of our first magnetic survey across a clinker area (Hasbrouck and Hadsell, 1974). The traverse started from the edge of a clinker quarry and extended northward into an area where drilling showed that clinker was not present. The left side of the magnetic profile is clearly different from its right side. From the traverse origin to a distance of 125 m, the soil has the reddish cast characteristic of clinkered areas. Between 125 and 250 m (open arrowhead to filled arrowhead positions on fig. 5) no reddening of the ground can be seen; however, something within that interval produced the ragged appearance of the magnetic-field profile. What more reasonable interpretation could there be than placing the buried edge of the clinker farther north than its surface signs would indicate?

The 125-m difference between the magnetic and color-change interpretation of the edge of the burn facies may not seem like much until one realizes that a 125-m-wide section of 20-m-thick coal along an outcrop distance of 300 m represents a withdrawal of about 1 million tonnes from the reserve.

In the area where the data for figure 5 were obtained, the usual spacing between holes drilled to block out the coal is about 40 m. Rather than holding to a fixed pattern of drill holes on 40-m centers to establish the edge of the clinker, a better procedure would be to use the magnetic results to guide the selection of the drill sites. For example (with reference to fig. 5), holes at traverse distances of 240 and 260 m could be expected to span the edge of the burned zone. Experience gained by working back and forth between magnetic and drill data should build confidence to the point that perhaps only one drill hole per profile would be required to verify the position of the burn facies. A representative of one company operating in the Powder River Basin has told us that, with use of the magnetic method, he estimates that his firm should be able to reduce its exploration drilling cost in defining clinker boundaries by more than half. Another group now instructs their geologist to run a magnetic survey at each tentative drill site in order to certify the absence of clinker.

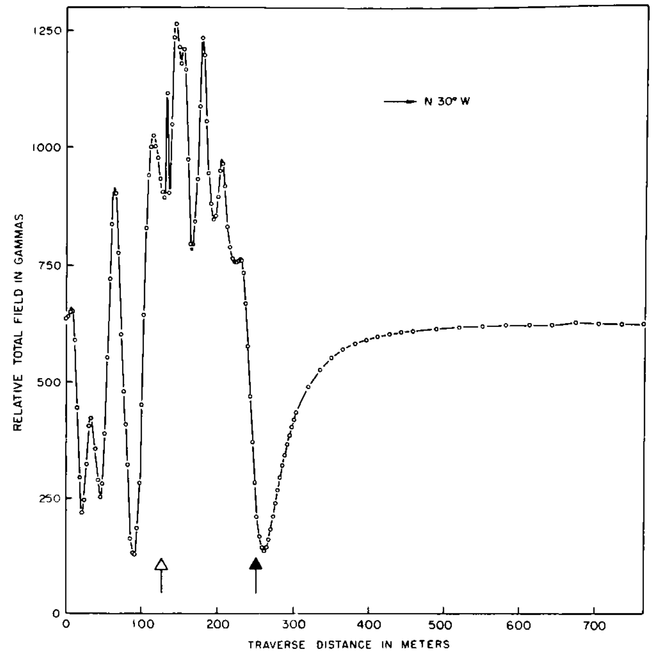

Figure 5.--Magnetic profile across edge of a clinkered area near Gillette, Wyo. Station locations, shown by the circles, are separated by 7.6, 15.2, and 30.5 m. Open arrowhead points to the position of the color-change boundary between the red-colored ground to the left (near the edge of a clinker quarry) and the buff-brown color of the ground in an unbaked area. Solid arrowhead indicates the edge of the clinkered area as interpreted from the magnetic data. Observe the difference between the roughness of the anomaly over the burned area and the smoothness of the anomaly over the unburned area, the difference in slope of the anomaly to the left of the edge of the clinkered area in contrast to the slope to the right of the boundary, and the recovery of the anomaly from a low value just beyond the border of the burned area. These three anomaly-shape characteristics (difference in smoothness, variation in slope, and asymptotic recovery from a bounding low value) are commonly observable in magnetic traverses that cross the edge of a clinkered zone. See figures 6, 7, 10, and 11.

Figure 6 illustrates results from another magnetic survey which show that the edge positions of the burn facies as interpreted from soil-color change and from magnetics may differ. Because this is a west-east profile, the magnetic anomaly is not as sharply defined as it would be along a north-south traverse. Nevertheless, the coal has clearly been burned farther into the hillside than the soil-color boundary would indicate. Note that the magnitude of the leading edge of the magnetic anomaly along this profile is about one-third of what it was on figure 5. This loss in amplitude may be due to a thinner clinker zone or to a greater depth of the baked zone.

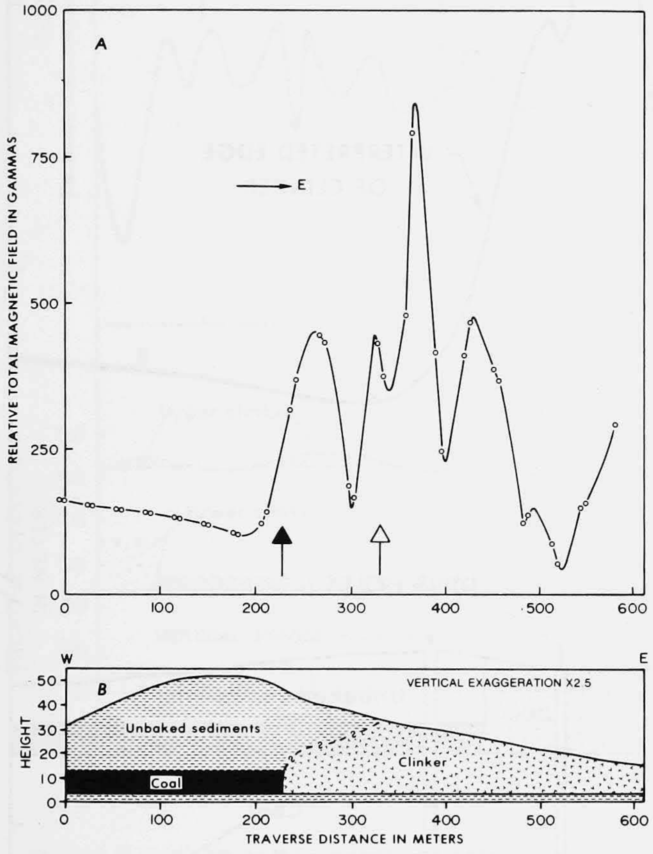

Figure 6.--A, Magnetic profile across edge of a clinkered area near Recluse, Wyo. Pairs of readings at 6.1-m separations were taken at 30.5-m intervals at station locations shown by the circles. Open arrowhead points to the position of the color-change boundary; solid arrowhead indicates the edge of the clinkered area as interpreted from the magnetic data. B, Inferred section underlying the magnetic profile. No drill data are available in the immediate area; however, the coal beds outcrop in a gulley 150 m west of the west edge of the profile, and differences in soil color are apparent.

Figure 7 shows a magnetic profile across a multiple-seam area (Juliana Waring, U.S. Geological Survey, oral commun., 1976). Before this magnetic survey was run, the east edge of the clinker was tentatively placed at the position of the color boundary, traverse distance equal to 25 m. In this area, high grasses made detection of changes in soil color difficult. Drilling at a traverse distance of 175 m encountered no clinker. Thus, the clinker edge could probably lie anywhere along the 150 m of traverse from a distance of 25 to 175 m. After the magnetic data were taken, plotted, and interpreted (about a 30-minute process), this uncertainty was reduced from 150 to 20 m. Subsequently, a hole was drilled at a traverse distance of 145 m. It pierced clinker--just as the magnetics indicated it would.

From the results displayed on figure 7 we can draw several conclusions:

1. Soil-color boundary does not always reveal the true edge of the clinkered zone.
2. The magnetic technique can apparently be used to effectively and economically map the clinker in this area.
3. The burn zone very likely extends from the origin of the traverse to a distance of about 160 m;, that is, the clinker found in the drill cuttings from the hole at 145 m is not from an isolated tongue.
4. Presence of clinker on the surface does not imply that all the seams at strippable depth have been burned.

This last point raises the question as to whether magnetic methods can be used to determine if beds beneath the uppermost seam of a series of coal beds also have been burned. As of now, we don't know the answer to that question. But we do know that magnetic determination of the extent of burning within a lower seam will be a challenging task.

Figure 8 shows a magnetic profile and the inferred cross section in a known multiple-burn (M. L. Botsford and James Goolsby, U.S. Geological Survey, oral commun., 1976). Unfortunately, because no drill data exist along this traverse, the speculated distribution of the clinker produced by burning of the lower seam has not been verified.

The examples shown in figures 5, 6, and 7 illustrate the use of magnetic methods to locate the edge of a single clinker zone. Their interpretation was relatively straightforward: if the magnetic profile was smooth, then no clinker existed; if the magnetic profile was highly irregular, then clinker was nearby. However, before attempting a qualitative interpretation either of a multiple-burn problem or of a partial-burn case, it is necessary to gain additional understanding of the behavior of magnetic-field variations across clinker zones.

Figure 9 shows magnetic data taken by D. E.

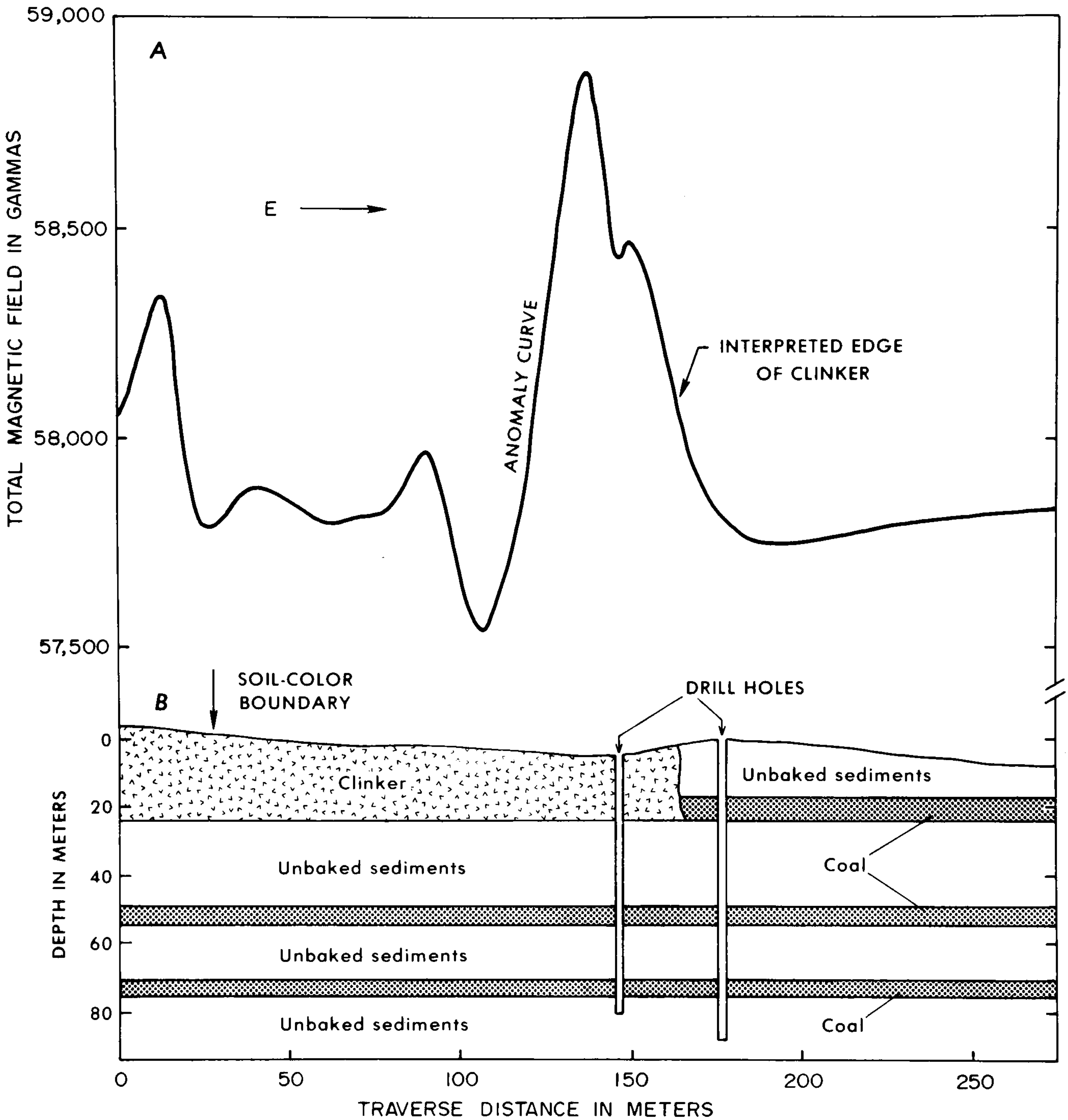

Figure 7.--A, Magnetic profile across a clinkered area near Decker, Mont. Station spacing was 7.6 m. Edge of the burned area is interpreted as lying beneath the inflection point of the anomaly curve at a traverse distance of 160 m. B, Section of multiple-seam area showing the presence of three coal beds, only the upper one of which was burned. Samples from the two exploratory drill holes (traverse distances of 145 and 175 m) show that the interpretation of the edge of the clinkered area from the magnetic data is reasonably correct.

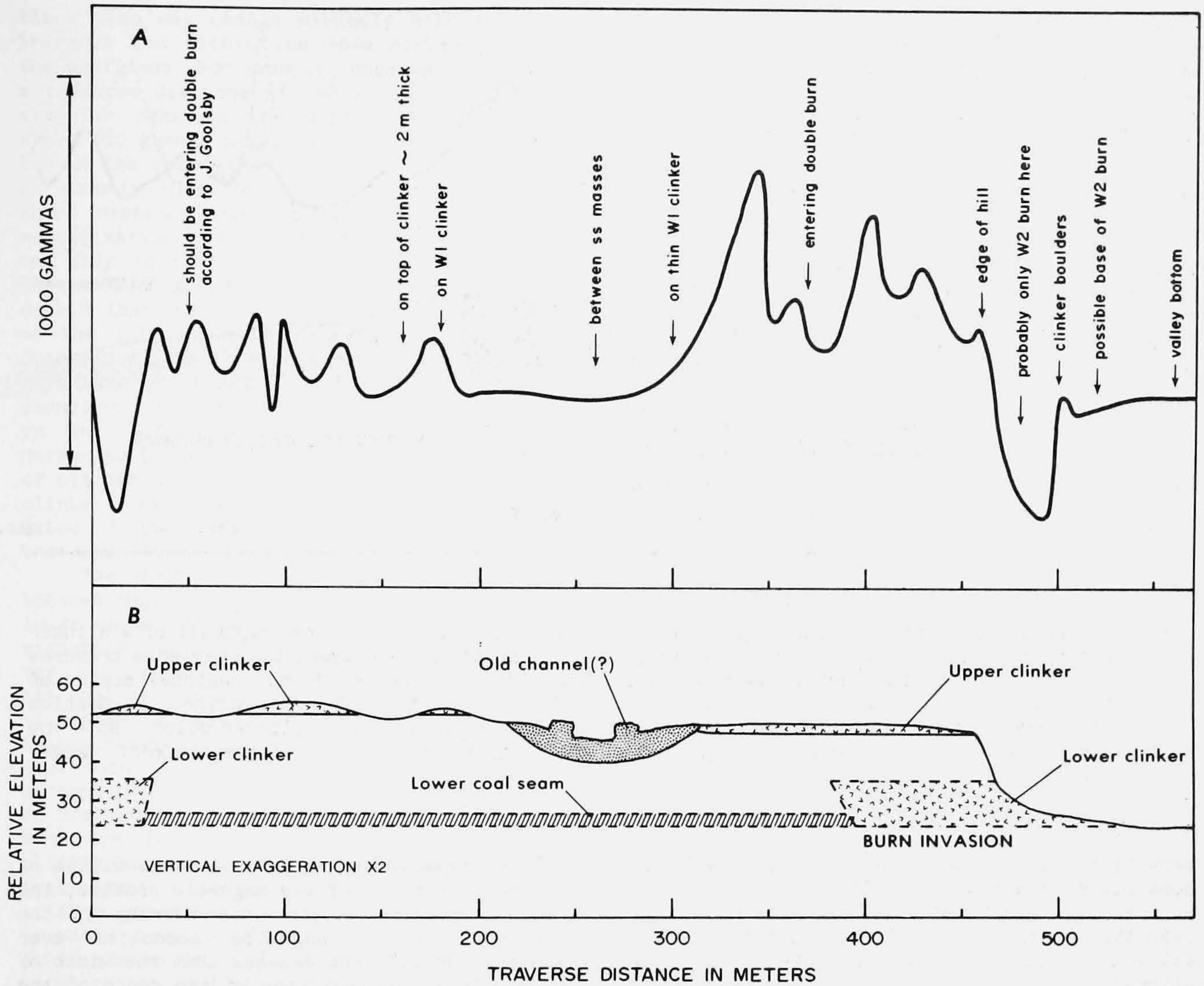

Figure 8.--A, Magnetic profile across a multiple-burn area located along the southeasterly border of the Powder River Basin, Wyo. Geologists's notes, taken at the time the survey was run, are shown across the top of the magnetic profile. B, Interpreted section showing two distinct clinker zones and a partially burned lower coal seam. The upper clinker zone and the colluvium derived from it cover the upper surface of the hill, except in the central section where a remnant of a postulated channel exists. The lower clinker zone is visible at the base of the hill, and is clearly separate from the upper clinker zone. The depicted distance of burn invasion of the lower zone is speculative.

Watson and M. L. Botsford (U.S. Geological Survey, oral commun., 1976) along two parallel profiles (10 m apart) run on the top and near the edge of a clinker quarry. The cross section, shown with a vertical exaggeration of 1.5, was drawn from sketches made of the highwall of the quarry. Regional strike of the unbaked sediments in this area is approximately perpendicular to the traverse direction.

We would like you to observe the following from figure 9:

1. Magnetic anomalies range in magnitude from tens to hundreds of gammas.
2. Spatial wavelengths, here defined as the traverse distance from peak to peak of the anomalies, vary from tens to hundreds of meters.
3. Although the two magnetic profiles are

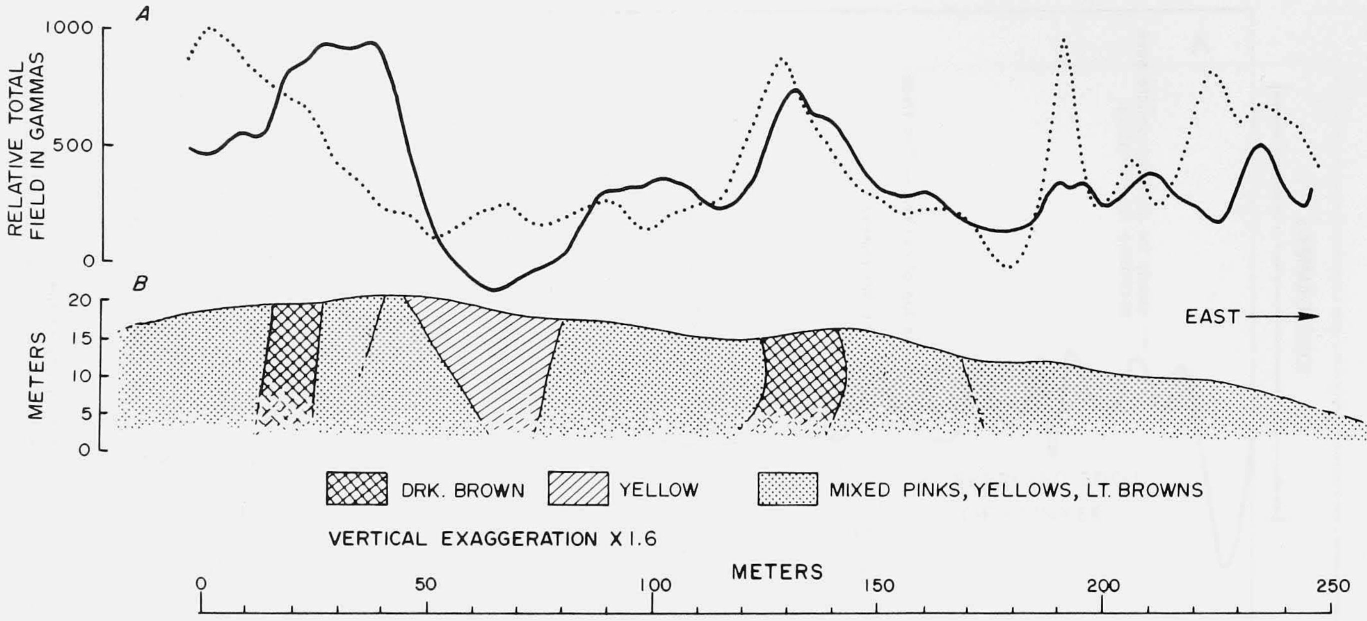

Figure 9.--A, Two parallel magnetic profiles across and near the edge of the highwall of a clinker quarry near Wyodak, Wyo. Station spacing is 5 m, and distance between the near-edge traverse (solid line) and the back-from-the-edge traverse (dotted line) is 10 m. Regional strike of the unburned sediments is approximately perpendicular to the profile direction. B, Section of clinker quarry exposed on the highwall showing gross variations in clinker color. Note the general correlation between the magnitude of the anomaly and the color of the clinker: larger anomaly, darker clinker.

separated only by 10 m, they correlate well in some places and poorly in others.

4. Greatest magnetic anomalies occur over the darker colored clinker, and the smallest anomaly is found over the lighter colored clinker.

These are significant observations. The first one tells us that the magnetization within the large mass of clinker is not uniform. If the magnetization were uniform, there would be no magnetic anomalies of the kind observed. Comparison of the magnetic anomalies and the cross section across the quarry indicates that the clinker mass appears to be composed of individual bodies, each with its own magnetization. Magnetic studies of cores taken along the traverse of figure 9 (D. E. Watson, U.S. Geological Survey, oral commun., 1976) revealed that the magnetization within different parts of the clinkered mass varied greatly in magnitude, but maintained approximately the same direction of magnetization as the present-day magnetic field.

Because of the nonuniformity of the magnetization within a clinker deposit, the configuration and depth of a concealed clinker mass cannot be interpreted using the same mathematical procedures usually applied in magnetic prospecting for mineral deposits.

The observation on the variable widths of different segments of the magnetic profile, the second observation, also has bearing on the interpretation of magnetic anomalies over clinker. Usually one assumes that the width of an anomaly is an indicator of the depth of the body which produced it--deeper body, wider anomaly. The profiles of figure 9, however, show that the anomaly widths across a clinker deposit are controlled as much by the lateral extent of individual bodies within the clinker as by their depth. Therefore, one cannot view a set of wider anomalies and assert that they probably have been produced by a clinker bed at greater depth.

The third observation, the correlation between the two profiles of figure 9, indicates that the pattern of heat distribution during burning of the underlying coals is erratic. The edge of the burned zone certainly does not follow the regional strike of the unburned rocks; if it did, the two profiles either would have been almost congruent or they would have displayed a constant phase shift--they do neither. Note that the peaks on the two profiles at a traverse distance of about 130 m almost align, but that the peaks near the beginning of the traverse are offset from one another by about 40 m.

Magnitude of the anomaly within a given

block also may change markedly both along the traverse and within the 10-m distance between the profiles. For example, observe the peaks at a traverse distance of 190 m and note that the singular peak on the dotted-line profile is about 600 gammas bigger than its doublet neighbor on the solid-line profile. Drastic changes in anomaly shape and size within a relatively short distance imply that large variations in magnetization have occurred over a short span, and this in turn indicates that the magnetization mechanism also must have differed radically within that same short distance. Visual study of the intra-clinker structure exposed on the quarry's highwall reveals the presence of chimneys near which the clinker exhibits both flow structure (similar in appearance to what is seen on the roof of a lava tube) and presence of darker purplish-red clinker. Because this type of clinker has the largest magnetization of all clinker rocks tested, the occurrence of an isolated, high-value peak on a magnetic map may indicate that a clinker chimney is close by.

The observation of an apparent correlation between magnetic anomaly size and clinker color leads to an interesting application of clinker magnetics. C. H. Miller (U.S. Geological Survey, oral commun., 1976) pointed out to us that his engineering-geology studies on the behavior of clinker reveal that the dark-purplish-brown (clayappearing) clinker makes the most durable road metal and that the yellow clinker is the easiest to strip. Evidence of this is also seen in the erosional record--the purple-brown nubbins are left standing after other types of clinker have been removed. Thus, Miller reasons that magnetic surveys can be used over concealed clinker deposits not only to locate the most probable areas in which to find the better road metal (areas of high-value anomalies) but also to chart the easiest path for cutting strip-mine haulage roads through the clinker (areas of low-value anomalies). Because the magnetic anomalies over clinker deposits are highly irregular, a variation of form-line contouring is required to construct magnetic maps of clinkered areas. In this procedure, one uses judgment to separate moderately low and high value areas, and then draws bounding lines (usually not of equal value) delimiting these regions. Very high value, short wavelength anomalies (at a traverse distance of 190 m on the dotted traverse of fig. 9, for example), which probably indicate chimneys, are shown by special coding.

Keeping the anticipated behavior of magnetic field variations in mind, let us return to figure 8 and see if we can tell from its data where the edges of the lower seam burn are located. The first thing we notice is that the magnetic profile can be divided into three zones: a clinker zone from the origin to a traverse distance of about 190 m, a clinker-free zone from 190 to 310 m, and a clinker zone from 310 to 510 m. Assuming that the perturbations on the magnetic profile at a distance from 160 to 190 m are due to the small mound of clinker between these distances, then the edge of the left-side lower burn lies somewhere within the interval from 10 to 160 m. The edge of the right-side lower burn occurs between traverse distances of 310 and 460 m. Comparing magnetic responses over the two clinkered areas, the right zone appears to have a higher average value and the left zone to contain more short-wavelength anomalies. One could contend that because there are no long-wavelength anomalies in the left zone comparable to those in the right zone, the left zone is not underlain by a deeper bed burn. On the other hand, the right zone exhibits a mixture of longer and shorter wavelength anomalies, which might possibly be indicative of the presence of a deeper burn zone beneath it. The higher average value of the right-zone anomaly could have resulted from the additional magnetic effect produced by magnetic material associated with the burning of the lower bed. Also, note that the base of the top clinker in the right zone is about 3 m lower in elevation than the base of the clinker in the left zone. This drop in elevation might reflect subsidence of the right zone following removal of the lower seam by burning, or it may be only a reflection of bed undulation.

Geologic inference places the edge of the right-zone burn facies at a traverse distance of about 385 m; but geophysical interpretation of the magnetic results does not negate the possibility of a fire in the lower seam invading to a traverse distance of 320 m. The speculated position of the edge of the left burn from geological extrapolation and from geophysical interpretation are in agreement--but that does not, we hasten to add, assure that the position of the lower burn is necessarily correct as drawn, because (1) every map we have made shows that clinker terminates along an irregular line (thus, geological extrapolation between outcrops would be risky), and (2) magnetic variations along the traverse of figure 8 could have been produced solely by lateral changes in magnetization within a single burned zone (as was seen in the quarry studies, fig. 9).

Consider now the problem of determining magnetically whether burning has taken all or part of a seam divided by a thin, non-coal bed. Figure 10 shows a magnetic profile obtained across a coal seam which exhibits a parting approximately 2 m thick at a nearby outcrop (M. L. Botsford and James Goolsby, U.S. Geological Survey, oral commun., 1976). Partings of this size commonly can block downward, but not upward, burning. Field evidence from this area indicates that if the fire had begun in the lower coal bed, then both this seam and the one above the parting would have been consumed (as appears to have happened to the seams on the right, traverse distance of 500 m eastward); but if only the bed above the parting was exposed

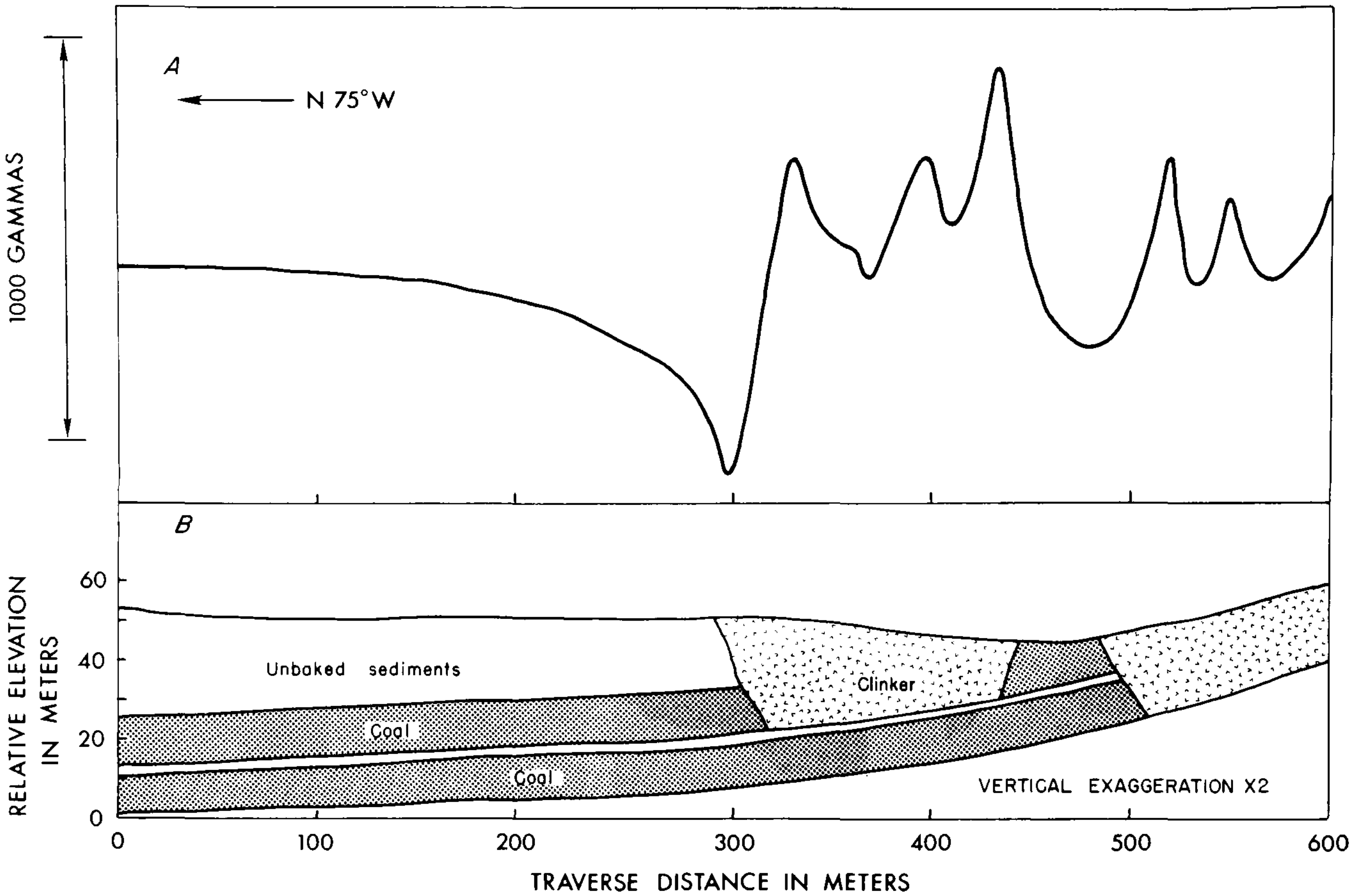

Figure 10.--A, Magnetic profile across a parted coal seam near Tekla, Wyo. Station separation is 10 m. Viewing from left to right, observe the smoothness of the profile over the unbaked sediments, the slow and regular decrease in the anomaly as the bounding low value is approached, the sharper rise in the anomaly soon after the edge of the clinkered area is crossed, the irregular appearance of the anomaly over the clinkered area, the subtle change in the distance between anomaly peaks when the profile data are taken across the unburned coal at a traverse distance of 440 to 490 m, and finally the return of the irregular-anomaly pattern when the clinkered area to the far right is traversed. B, Interpreted section based on drill-hole and outcrop data from outside the plane of the section. Soil-color boundary at 300-m traverse distance is indistinct.

when the fire started on its outcrop, then only it would have been burned (as indicated on the section from a traverse distance of 300 to 440 m). Coal beneath thin colluvium was found in the shallow valley between traverse distances of 440 to 490 m.

The magnetic profile of figure 10 clearly shows the demarcation between the unbaked and baked sediments at a traverse distance of 310 m, the inflection point of the magnetic anomaly curve being used to set its position. Presence of a non-burned area from 440 to 500 m is apparent once the geologist in the field has found coal and marked its position within this interval on the cross section; but it is not as easy to detect if one has only the magnetic profile with which to work. Because the width of this surface exposure of coal is relatively narrow, 60 m, the magnetic anomalies from the clinker to the left and right of the unburned area have combined their effects to produce a partial cancellation of the normally expected deep lows in the profile (such as the one at 300 m, for example). Note that the swale-shaped anomaly centered over the section of exposed coal has a different appearance than its neighbors to either side. Not only is its crest-to-crest distance greater, but also it is smoother--more like an anomaly over unburned material. Be careful, though, in attaching too much reliance to subtle changes in the character of the anomaly, because their significance can be evaluated only after experience has been gained with the magnetic method in any given area.

The question as to whether magnetics can ascertain if all coal in a parted seam has been burned is not readily answerable from the data presented on the single profile of figure 10. Observe that both the average values and the spatial wavelengths of the anomalies are about the same over the fully and partially burned seam segments; thus, these interpretation guides offer no clue. However, this sameness is to be expected because the thicknesses of the burned facies at a traverse distance of 300 m and at 500 m are approximately equal, even though at 300 m only the coal above the parting was burned, whereas at 500 m the total seam was consumed. Our recommendation on the use of magnetics in this area is to use it to locate edges of the burn facies (traverse distances of 310, 440, and 500 m) and then select drill sites on the basis of an intelligent combination of both magnetic and geologic interpretations. Magnetics, like any other exploration tool, has its limits--the problem displayed on figure 10 may be one of them.

Having gone through several examples that show some of the more challenging applications of magnetic mapping in clinkered areas, it is easy to lose sight of what the magnetic method can do in the vast majority of cases. To regain some of our confidence (lost at the expense of increased awareness--always a good trade), let us finish this section by looking at an example that illustrates a typical usage of clinker mapping in magnetics.

Figure 11 shows three magnetic profiles obtained by Juliana Waring (U.S. Geological Survey, oral commun., 1976) in an area for which early maps indicated complete clinker cover. Clearly from what we have seen and learned from the preceding examples, the entire area has not been baked by coal fires.

Profile 1, figure 11, was taken across an area covered with clinker colluvium, but mapped as burn facies. That the reddish-colored soil traversed by profile 1 covers a clinkered zone can be quickly discounted by comparing amplitudes of the magnetic-field changes along profile 1 (about 10 gammas) with those across the clinkered areas traversed by profiles 2 and 3 (several hundred gammas). It is highly unlikely that the surficial clinker along profile 1 is a thin autochtonous layer, because field observations commonly show clinker knobs remaining long after the other rocks of the burn facies have been erosionally removed. If clinker nubbins were concealed within a 50-m-wide swath to either side of the first traverse, their presence would have been readily detected magnetically. On profiles 2 and 3, figure 11, the traverses were intentionally bent to skirt exposed clinker knobs; yet the magnetic readings near these erosional remnants were so large they exceeded the limits of the profile plots. Anomalies of this magnitude (and possibly of greater width, as the buried anomaly-producing body is deeper) would have been detected.

The value of magnetics as a guide to selecting drill sites is well demonstrated by the results displayed on figure 11. Note that no more than a single 100-m-long traverse, at a spacing between observation points of 20 m, would have been required to determine if a site was underlain by a clinkered section. Once the magnetometer is taken from its carrying case and assembled (about 5 minutes), it requires about 6 minutes to make and plot the observations--a small investment in time considering that it usually cost three times more to drill a hole through clinker than through an unbaked section.

Experience of seismograph crews in the Powder River Basin has repeatedly shown that shots detonated in clinker produce poor quality seismograms consisting mostly of low-frequency and unpatterned seismic arrivals (Junger, 1951, fig. 1, p. 500). Advanced seismic data-acquisition and -processing methods appear capable of mitigating clinker-associated noise. Although the results produced by these costly procedures may meet the requirements of oil prospecting, they are inadequate for mapping minable-depth coal beds. Seismic exploration for coal requires higher resolution (Farr, 1976a, b), and this can be obtained only with seismic data that are initially rich in the higher seismic frequencies--those seemingly suppressed when shots are fired in clinker. The simplistic solution to this problem is to select seismic traverses such that, whenever possible, the shotholes are not located in clinker. Thus, a reconnaissance map like the one in the upper right-hand corner of figure 11 could be used to advantage when the seismic program is being developed.

The last set of examples in this paper is directed toward the problem of determining the continuity of coal beds. In our opinion, seismic techniques have great potential for mapping coals at shallow depths--they have already demonstrated their ability to map deeper coals in Europe.

Seismic Methods

For seismic methods to be effective, the target must possess a good acoustic mismatch between itself and the surrounding rocks, and it must have a reasonably simple geometry. Deeper coal beds (those below usual stripping depth) meet both requirements. Commonly, their seismic velocities and densities are markedly lower than those in the neighboring beds; and although coals may undergo changes in their bed and interburden thicknesses, these vertical variations are usually small in comparison to the

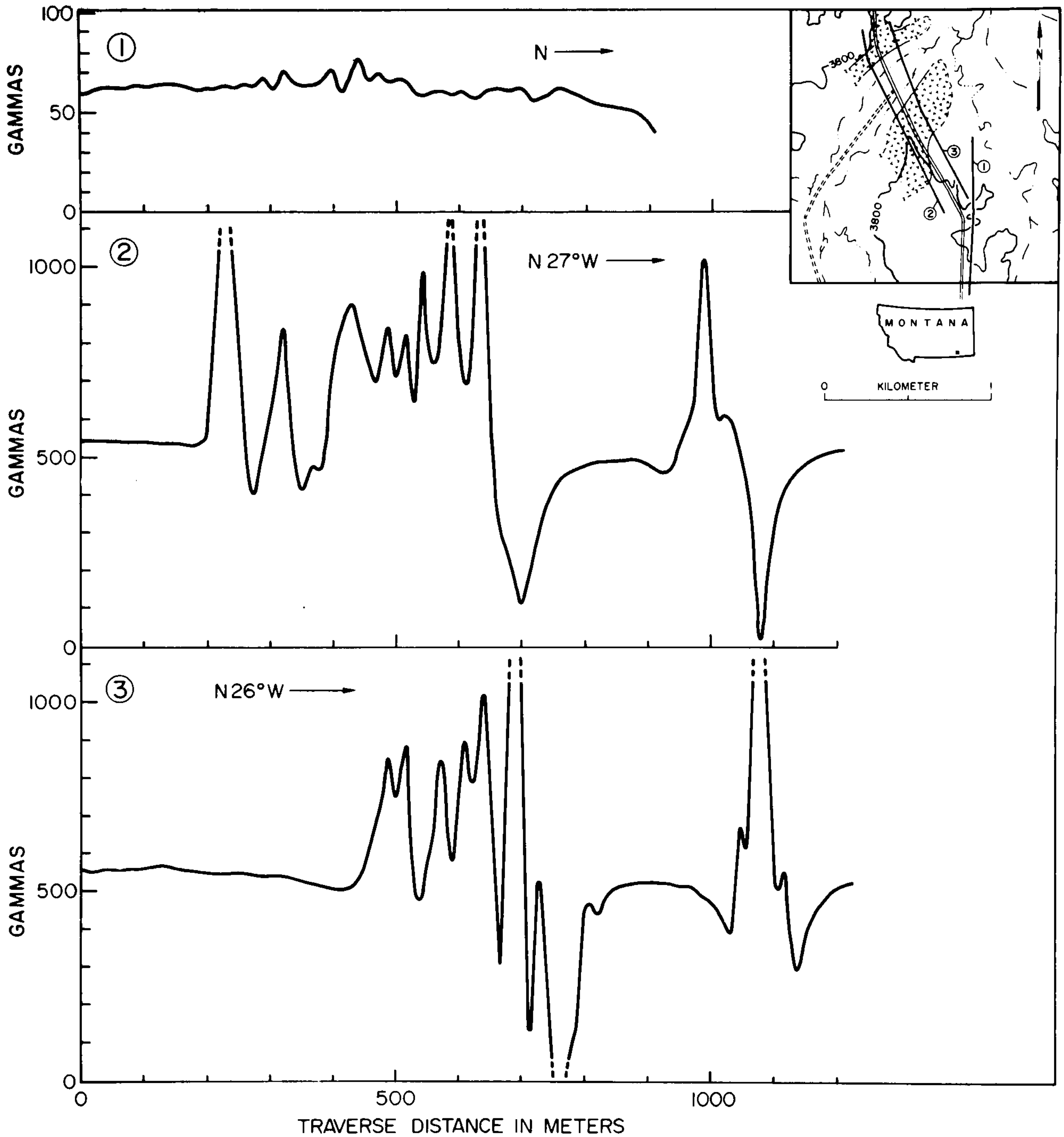

Figure 11.--Three magnetic profiles at station spacings of 15 m obtained in an area near Sayle, Mont., previously mapped as being almost completely underlain by clinker. Index map shows reinterpretation of extent of clinkered areas after magnetic surveys were conducted and surface geology was re-examined (Juliana Waring, U.S. Geological Survey, oral commun., 1976). Note the difference in gamma scale on profile 1 in contrast to scales on profiles 2 and 3.

horizontal distances over which they occur. Thus, except where coal beds are abruptly terminated (at faults, subcrops, edges of ancient stream channels, and so on), coal seams appear to the impinging seismic-wave fronts as well behaved layers.

Almost every procedure known to exploration, theoretical, and engineering seismologists appears to be adaptable for coal exploration and development. For example, in coal seismology one sees the standard seismic-reflection method of oil geophysics modified so as to increase its resolution (Farr, 1976a, b) in order to examine the thinner and shallower targets; the mathematical treatment of the low-velocity channel of earthquake seismology extended so as to study another low-velocity wave guide, the coal seam; and the cross-hole (hole-to-hole), hole-to-surface, and single-hole methods of engineering geophysics utilized to determine both the physical properties and the structure of roof and floor rocks between closely spaced locations.

The emphasis in Great Britain in coal seismology is on the use of high-resolution reflection methods; special attention is being given to the interpretative significance of diffraction patterns and wave shapes (the so-called "character" of the seismic arrivals) in the recognition of faults. The basic objective of the seismic studies in the United Kingdom is the identification of tectonically disturbed areas within coaliferous regions so that these troublesome sectors can be isolated and then avoided when the longwall mining plan is drafted.

Two chapters in a recently published book (Muir, 1976) describe the extensive seismic work being done in England: Chapter 6 by A. M. Clarke of the NCB (National Coal Board) of the United Kingdom discusses the philosophic and economic aspects as well as the technical accomplishments of the NCB effort; Chapter 7 by T. E. Daly and R. F. Hagemann presents a highly readable treatment of seismic-reflection methods as they are applied in the delineation of coal deposits. Both articles contain numerous examples, one of which is shown in figure 12.

Figure 12 depicts a seismic cross section processed from high-resolution seismic-reflection data taken near the center of NCB's Selby coal field (Clarke, 1976, fig. 7, p. 185). Here the coal beds appear to be relatively undisturbed. Seismic data for this section were sampled at 1-millisec intervals, 0.45-kg shots were detonated in 3-m-deep holes, seismometer separation was about 8 m (thus, horizontal distance between subsurface seismic data points was approximately 4 m), filters were set to pass information between 50 and 160 Hz, and 12-fold stacking was employed. Only after extensive tests of various coal-seismic field and processing methods were evaluated was it decided that the above combination of procedures produced the optimum results for this particular site. A seismic cross section through a more disturbed part of the Selby coal field is shown by Dunn and Clarke (1976, fig. 2, p. 31).

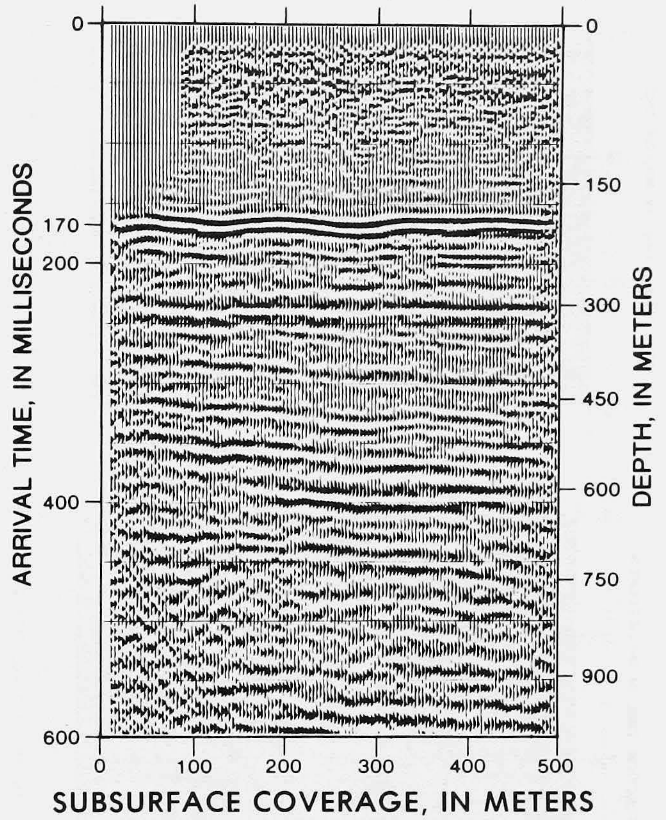

Figure 12.--High-resolution seismic cross section obtained near the center of the Selby coal field, England. Seismometer separation was approximately 8 m, and data were sampled at 1-millisec intervals. Events at an arrival time of about 170 millisec are seismic reflections from a coal seam. Reprinted from Clarke (1976, fig. 7).

Though no coal beds exist in the area from which the data displayed on figure 13 were obtained, the power of high-resolution seismic-reflection methods to reveal shallow stratigraphic and structural variations is well illustrated. These data are from selected portions of seismic cross sections taken near Houston, Tex. (Farr, 1976a). The upper part of figure 13 dramatically shows the termination of a seismic-reflection horizon at the edge of an ancient stream channel (300-m section distance and 212-m depth). If this seismic horizon were a coal bed, one could easily determine its lateral extent to within 10 m. The sets of events which plunge semicircularly downward to the left of this reflection represent a diffraction arrival. The lower part of figure 13 shows diffraction

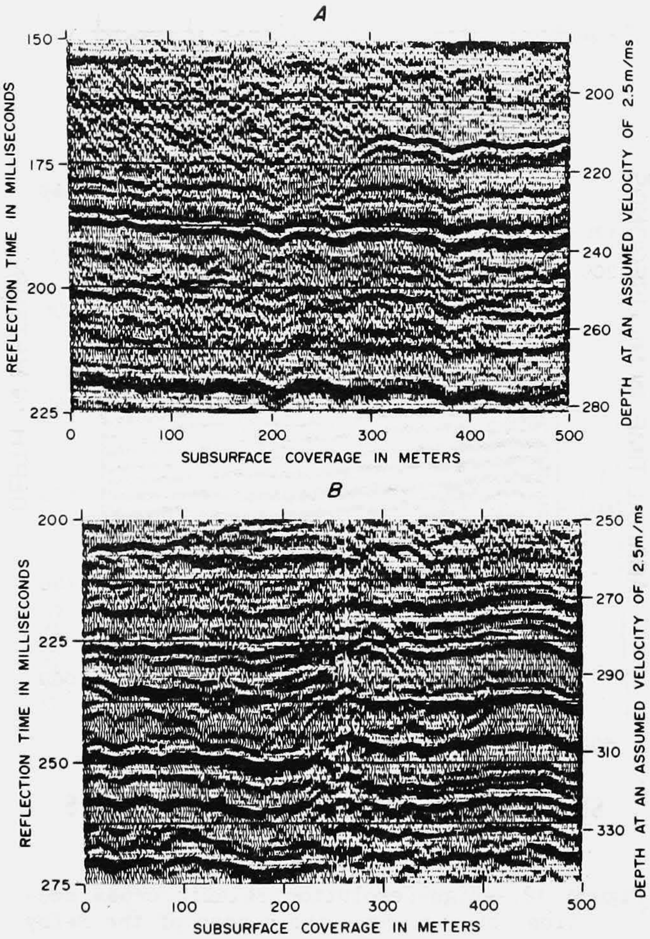

Figure 13.--Portions of a high-resolution seismic section processed from data taken near Houston, Tex. Seismometer separation was 5 m, and data were sampled at ¼-millisec intervals. Modified from Farr (1976b, fig. 24). A, Note the abrupt termination of seismic reflections and the associated diffraction arrivals--the downward-heading, almost-circular pattern of seismic events--at a section distance of 300 m and an arrival time of about 170 millisec. This position on the seismic section is the location of the edge of an ancient stream channel. B, Note the breaks in the continuity of reflection arrivals and the set of diffraction patterns distributed vertically through the central part of the section. A growth fault is known to occur through this part of the section.

patterns and bed displacements associated with growth faults. Using this newly developed high-resolution seismic system, Farr (1976a, b) has been able to map sediments at 40-m depths and he has been able to trace growth faults downward from the surface. In the Boulder-Weld coal field of Colorado, Prof. Robert Weimer of the Colorado School of Mines (oral commun., 1976) believes that the thickest coal deposits are found in grabens between growth faults; thus, it would be very useful to have an exploration tool--such as the high-resolution seismograph--that could effectively and quickly detect the bounding faults and their relative displacements.

Lepper and Ruskey (1976) discussed the use of high-resolution seismic-reflection techniques for mapping coal seams from the surface, with particular emphasis being given to locating channel sands in southern Ohio and growth faults in the Boulder-Weld field of Colorado. The seismic cross sections displayed in their paper indicate that their initial research efforts were successful. M. G. Scherba (oral commun., 1977) has conducted high-resolution seismic-reflection surveys in the Hanna Basin of Wyoming. When his shotpoints were below the water table, coal seams approximately 2, 3, and 6 m thick at depths of 80, 200, and 300 m, respectively, could be traced seismically; and faults with throws as small as 6 m could be discerned.

As in England, determination of coal-panel continuity ahead of the advancing longwall face is the prime objective of the work being done by German geophysicists. However, rather than utilizing high-resolution seismic-reflection methods, the Germans prefer to stress the seismic seam-wave techniques pioneered and developed by Krey (1963) of Prakla-Seismos GmbH, Hannover, West Germany.

Seismic seam waves, also known as guided or channel waves, are seismic waves confined within a low-velocity, low-density layer. A coal bed can constitute such a trapping layer (Evison, 1955). Utilizing seam-wave methods, solutions to problems beyond the reach of current methods of seismic-reflection prospecting can be approached. For example, finding a fault displacement of 2 m (a disruption sufficient to make a longwall operation unprofitable) across a 2-m-thick coal panel at a depth of 1 km cannot be accomplished with any surface-to-surface, high-resolution seismic-reflection system of which we are aware; however, seam-wave methods appear quite capable of detecting this complete break in coal-bed continuity. Model studies by Su (1976) showed that a seam displaced by a vertical fault having a displacement equal to one-third the coal-bed thickness will contain both partially reflected and transmitted seam waves, the amplitude of the transmitted seam wave being approximately half of what it would have been if the bed had not been faulted.

Seismic seam-wave techniques operate in two modes: transmission and reflection. In a seam-wave transmission survey, the seismic source and receivers are deployed on opposite sides of a longwall panel. If a seam wave of the correct form and amplitude is obtained, then the seismic waveguide must be intact between the source and observation points, and thus the coal panel must be continuous. In a seam-wave reflection survey, the seismic source and detectors are positioned on the same face of a longwall panel. If the coal panel is faulted beyond the drift, the seam wave will reflect from this fault. The position of the fault ahead of the face is indicated by the amount of time necessary for the seam wave to travel to and from the fault and by the angle at which the returning wave sweeps across the line of seismometers embedded in the face. Krey and Arnetzl (1971) reported that when several small faults (throws of 20 to 50 percent of the seam thickness) are present, individual reflection arrivals from these minor faults can be detected; but if the throw of a fault is greater than half the coal-bed thickness, no seismic reflections indicative of faults lying behind that fault can be seen. Because the waves must travel out and back from the seam break when a seam-wave reflection survey is used, the probing distance of a reflection survey is approximately half that of a transmission survey. With use of their present equipment, Krey (1976, p. 247) reported that transmitted seam waves were reliably detected 2 km from the source, but the maximum distance that reflected seam waves were observed from a fault was 300 m. However, research on improvement of signal-to-noise ratio and on pattern recognition lead Krey (1976, p. 251) to believe that within the near future the range of reflection seam-wave methods would be increased to 600 m, and perhaps beyond. The current practice in the underground mines of Europe is to run transmission and reflection seam-wave surveys in combination.

Figure 14 shows an example of a transmission-survey recording obtained in the Ruhr area, West Germany (Arnetzl, 1971, fig. 6, p. 138). The seismometers were emplaced within a drift at a depth of approximately 750 m, and the shots were detonated in an entry about 1100 m deep. Both source and detectors were in the same seam. Distance between the shots and detectors varied from 1081 to 1486 m, and thickness of the same was 1.7 m. The first arrivals, labeled N_L on figure 14, are refractions from the higher speed roof and floor; the events labeled with an F (for Flozwellen) are called seam waves by Arnetzl. It appears to us, however, that those events could equally well be interpreted as refractions with vertically polarized shear-wave propagation through the roof and floor and with multiple bounces within the coal seam. Subsequent mining showed the longwall panel between the shot and receiver positions to be fault free (Krey, 1976, p. 242). Experiments also were conducted at this same site (Krey, 1976, fig. 13, p. 244) to see if a shot in a borehole could be used as a source of seismic seam waves. A seam wave of usable quality was obtained, but it was not as noise free as the entry-to-entry result.

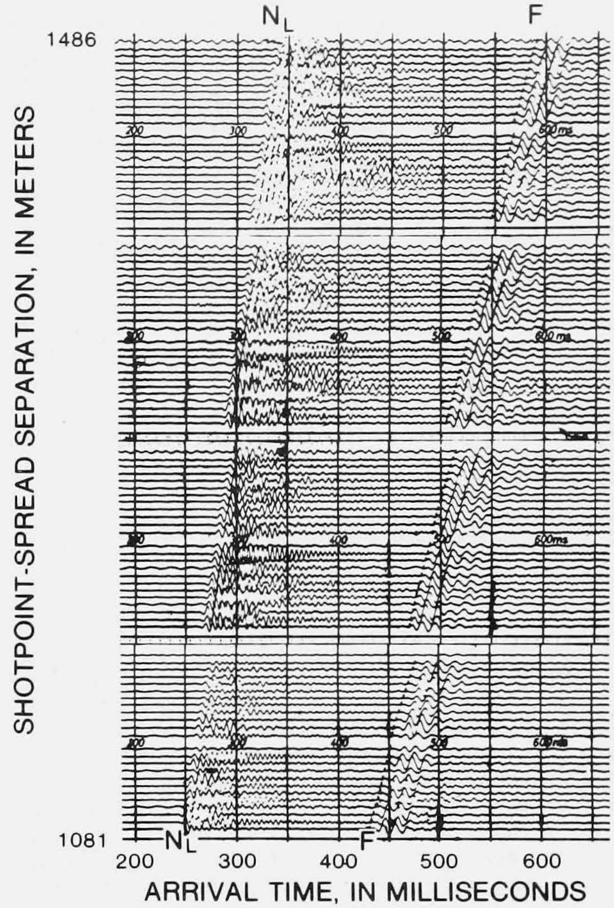

Figure 14.--Field data recorded during a transmission seam-wave study in the Ruhr area of West Germany. Arrivals labeled N_L are refraction arrivals from the higher velocity beds bounding the lower velocity coal seams; arrivals labeled F are identified by Arnetzl as seismic seam waves trapped within a 1.7-m-thick coal seam. Distances from the seismic source to the nearest and farthest detectors are 1081 and 1486 m, respectively. Reprinted from Arnetzl (1971, fig. 6).

Figure 15, taken from Krey's original work (Krey, 1963, fig. 15, p. 711), shows a reflected seam wave generated by an explosive source and recorded with seismometers attached to the coal face in such a way as to emphasize Love-type wave arrivals. Reflected seam waves also were obtained using a hammer seismic source; however, these arrivals were very much weaker (Krey, 1963, fig. 14, p. 710). Since Krey did his first work, a near revolution in seismic instrumentation has occurred. One wonders if digital-recording, signal-enhancement seismographs now

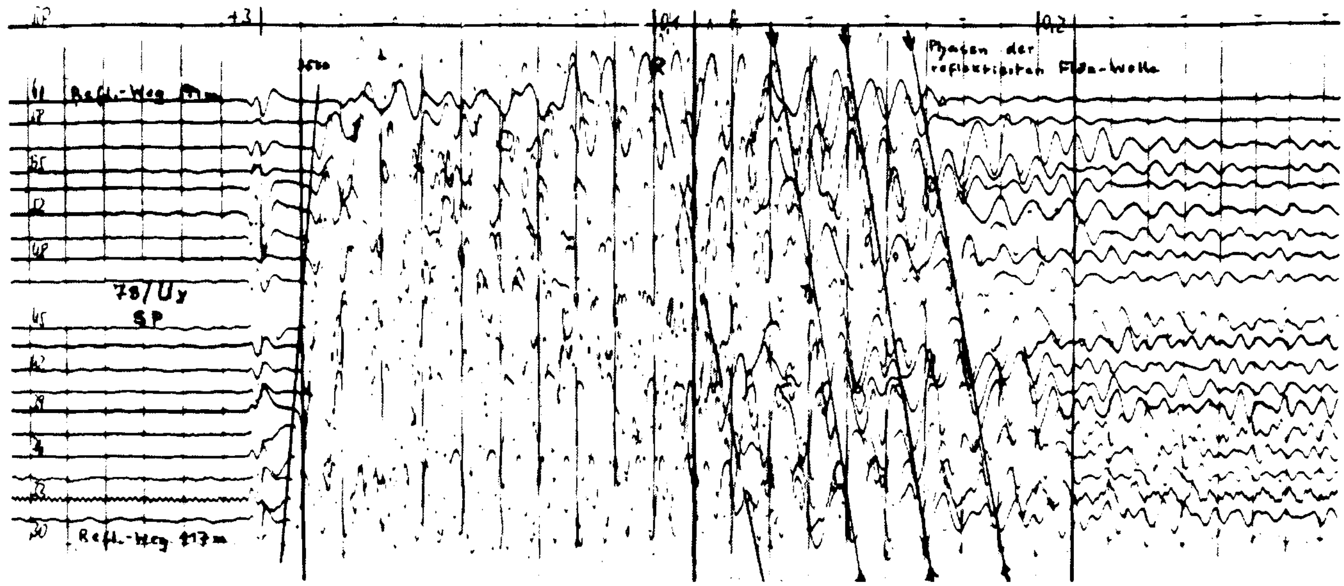

Figure 15.--Copy of Krey's original and history-making seismogram showing the first (as far as we know) recording of a reflected seam wave. The reflected seam waves are that bundle of events having an onset time of 105 millisec (labeled R) and continuing across the seismogram and parallel to the arrowhead-topped lines sloping downward to the right. The fault from which these seam waves were reflected is located beyond the end of the upper trace of the detector spread, and the orientation of the fault is almost perpendicular to the line of detectors. Thus, whereas the direct arrivals from the shotpoint to the detectors strike the lower trace detectors first, the seam-wave arrivals that bounce back from the fault are detected first by the seismometers positioned closer to the fault, the upper-trace detectors. Copied from Krey (1963, fig. 15, p. 711).

available will not be able (through use of internal stacking) to build up the weaker signals generated by hammer blows.

Intensive research and development programs in seam-wave technology are now underway. The thrusts of these programs are in three directions: (1) development of analytical and physical models in order to gain a fuller understanding of seam-wave propagation (Freystätter, 1974; Darken, 1974; Guu, 1975; Lagasse and Mason, 1975; Dressen and Freystätter, 1976; and Su, 1976); (2) design and test of new seam-wave sources and receivers (Krey, 1976; Hasbrouck and Hadsell, 1976); and (3) improvement of data processing and interpretation methods (David Buchanan, National Coal Board, oral commun., 1976).

An indication of the ability of computer modeling systems to produce results which look very much like field data is shown on figure 16. On the left side of figure 16 are tracings of the field data obtained by Krey (1963, figs. 10, 12, p. 709); on the right side of the figure are model results redrawn from those produced using a digital computer (Guu, 1975, figs. 12, 13, p. 35, 36). Aside from selecting model parameters to approximately match the observed velocities and densities, no other attempts were made to duplicate the conditions of Krey's experiments. For example, instrument responses, source conditions, and attenuation factors were not introduced into the digital-computer model. Also, the distances from the shot to the detector arrays, the spacing between seismometers, and the coal-seam thickness are not the same in the model as they were in the experiment. Even so, the two sets of results are strikingly similar:

1. Center traces of each record made with vertical-component seismometers exhibit a reduction in amplitude produced by partial cancellation of wave forms of opposite polarity.

2. In contrast, traces near the center of the horizontal-component records have amplitudes greater than those nearer the edges of the coal seam.

3. Amplitude of seam-wave arrivals is considerably larger than amplitude of longitudinal and shear-wave arrivals, these body waves being barely perceptible when gain of the recorders is set to contain the full excursion of the seam-wave arrivals.

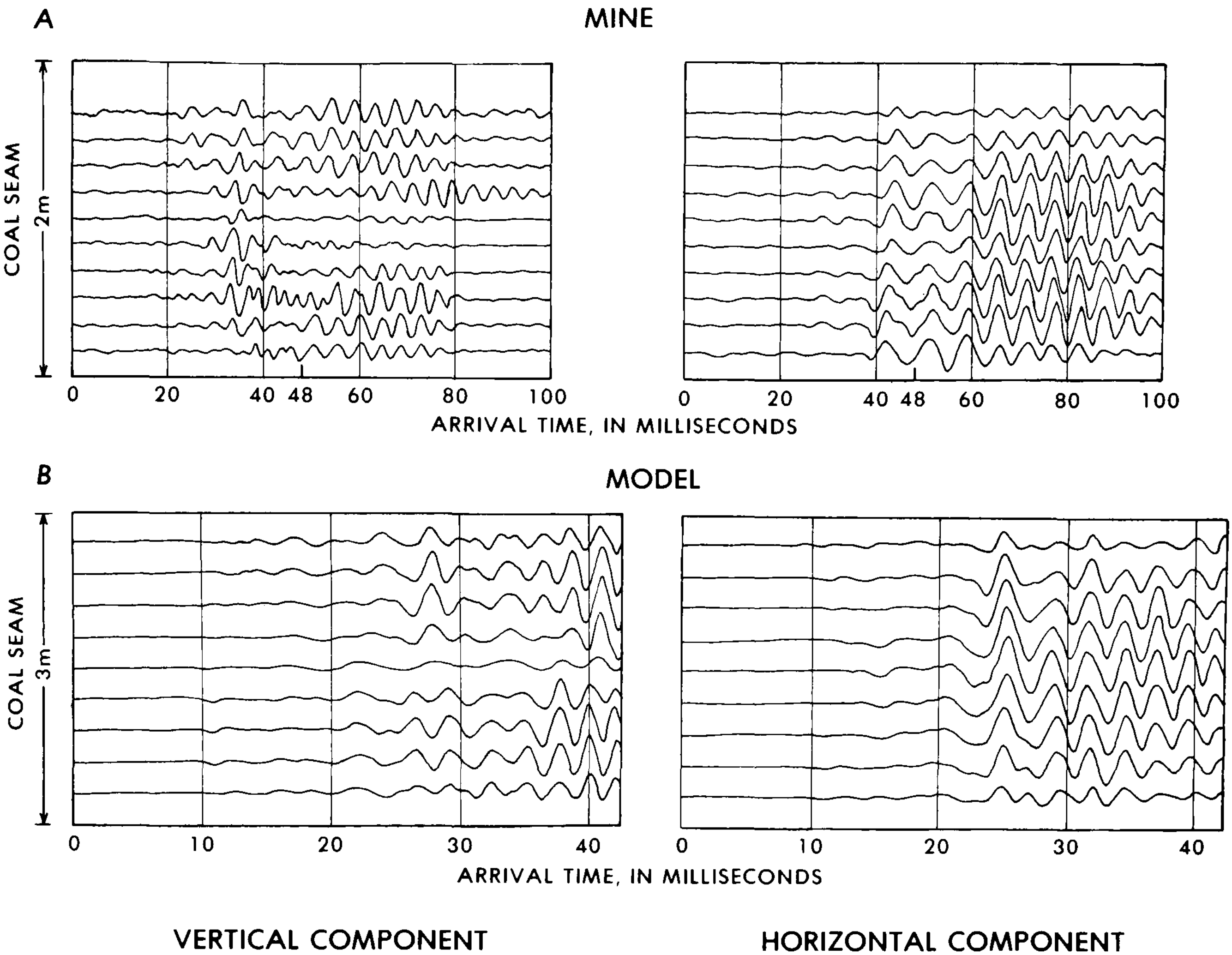

Figure 16.--A, Seam-wave data taken along the mine face of a coal seam, modified from Krey (1962, figs. 10, 12), contrasted to B, seam-wave results generated using a digital-computer model, modified from Guu (1975, figs. 12, 13). Thickness of the coal seam is 2 m and 3 m respectively; distance from the seismic source to the vertical array of horizontal- and vertical-component seismometers is 48 m in the mine and 20 m in the model. Onset of bundles of seam waves has an arrival time of approximately 46 millisec on the field recording and about 20 millisec on the computer-derived recording. Although the model parameters and the field conditions differ, note the general similarity in appearance of the mine and model results.

One dimension of seam-wave recognizability not revealed in the field data of figures 14, 15, and 16, all of which were taken with in-seam detectors, is the marked drop in amplitude detected by seismometers positioned outside the coal seam. Is it unreasonable to expect the amplitudes to be greater inside the seam, where the seismic waves are trapped, than outside the seam? The ratio of interior to exterior amplitudes is a measure of the efficiency of the seismic waveguide. Su (1976), as part of his model investigations of seam-wave propagation, varied the ratio of longitudinal and shear velocities of the coals and the bounding rocks. When Krey's and Guu's velocity parameters were used, the ratio of maximum amplitude inside the seam to that just outside the seam was 19. This ratio was 5 when the shear velocity of the shale was less than the longitudinal velocity of the coal; and it was 8 when the longitudinal, but not the shear, velocities of the coal and the neighboring rock were equal. Thus, even when model parameters are widely varied, Su's results indicate that seam-wave phenomena are robust; that is, their existence is not dependent on a highly specialized and restrictive set of conditions which may or may not be found in nature. Our field tests (M. W. Major, Colorado School of Mines, oral commun., 1976) indicate that, although the longitudinal velocities of shallower coals may vary only slightly from those of the rocks to either side, their shear velocities may be considerably different. Thus, Su's work gives us hope that seam-wave technology can be applied in hole-to-hole tests of coal-bed continuity, even for those seams at strippable depth.

The emphasis of our theoretical, model, and field studies in seam-wave technology is toward developing hole-to-hole methods, techniques of direct applicability in making resource and reserve estimates. Special equipment developed for field investigations and results of computer modeling are discussed by Hasbrouck and Hadsell (1976, p. 266-284). Figure 17 schematically illustrates the basic ideas of hole-to-hole seismic seam-wave certification. The problem here is to determine if the coal seam encountered in hole A extends unbroken to hole B. To accomplish this task, a seismic source is lowered to seam depth (previously determined by borehole logging) in one hole, and a string of seismic detectors is emplaced so as to bracket the seam in the other hole. If (upper part of fig. 17) the seam is continuous, seismic waves trapped within the coal seam will travel within it and will be recorded as they pass the vertical array of seismometers. Under field conditions which match those of Guu's model (1975, p. 25), a set of seismic records similar to those shown on the right side of figure 16 very likely would be obtained. If, on the other hand, the seam is not continuous (lower part of fig. 17), then no seam waves would be detected in hole B. Krey and Arnetzl (1971, fig. 5, p. 5) often have observed that when a Ruhr-type coal bed is cut by a roadway, seam-wave transmission is effectively stopped. Could hole-to-hole seam-wave methods then be used to determine the extent of underground workings whose locations from old (or purposely incomplete) mine maps are either suspect or not adequately known?

For strippable-depth seams that have been faulted, Su (1976) showed that diffraction events (wave-type 4 on fig. 17) could be anticipated, their detection requiring a spread of seismometers along the surface. This finding opens the interesting possibility that, with use of a down-hole seismic source capable of repeatedly emitting the same signal, areal arrays of surface detectors might be used to map the fault trace. For this scheme to be effective, a pattern-recognition procedure would have to be applied.

One question that bothered us was whether a seam wave initiated in one seam of a multiseam group of beds would transfer a sufficient portion of its energy to a nearby seam to make certification of seam continuity unreliable. Guu (1975, figs. 21, 22, p. 49-54) set up a computer model to look at this problem. His redrafted results are displayed on figure 18. Clearly, the seam waves recorded by either the vertical or the radial seismometers are dominantly within the upper seam, the one containing the source. Note also that, on the radial-component recording, not only are the same waves better displayed but also the body-wave events appear to be more suppressed.

Of particular interest in coal-resource evaluation are Krey's studies (Krey, 1976, fig. 13, p. 244) in which he detonated an in-seam shot at a depth of 1100 m and recorded seam waves with a group of seismometers embedded in a 750-m-deep working face 1.2 km away. Subsequent mining showed the 2-m-thick longwall panel between the source and receivers to be fault free. On entry-to-entry tests, Krey's group has been able to detect seam waves that traveled 2 km. These results strongly suggest that hole-to-hole seismic seam-wave certification tests run between holes on a 2-km-grid spacing may be a highly practical way to economically evaluate the continuity of coal beds lying at depths of a kilometer or more, depths at which closely spaced exploratory drilling would be prohibitively expensive. Within the Western States, some deep coals of the velocity and density contrasts found in the Ruhr are mined. And from core and borehole logging data, coals are known to occur at depths well below those reached in normal mining operations. If these deeper coals are to be utilized at some future time, perhaps by in situ gasification, it is imperative that their continuity be reliably established. Although, to our knowledge, no hole-to-hole tools specifically designed for seam-wave studies at these depths now exist, their development is certainly within the capability of modern technology.

At the Coal Exploration Symposium held in London in the spring of 1976, Krey (1976) described the fundamentals, field procedures, equipment, and problems of in-seam seismic methods; and he summarized the results of 250 seam-wave studies conducted since 1967 by Prakla-Seismos in French, British, and German coal mines. According to H. Arnetzl (written commun., 1976), Professor Krey's co-worker in many of these investigations, seam-wave predictions of coal-bed continuity have been more than 90 percent right, and detection of faulting by use of seam-wave methods has been correct approximately two out of every three times. As of February 1975, seam-wave methods also had been successfully tested and employed for the preceding 4 years in Czechoslovakian coal mines using methods developed at the Scientific Coal Research Institute at Ostrava-Radvancie (Jiri Gabriel, Polyteckna, Prague, Czechoslovakia,

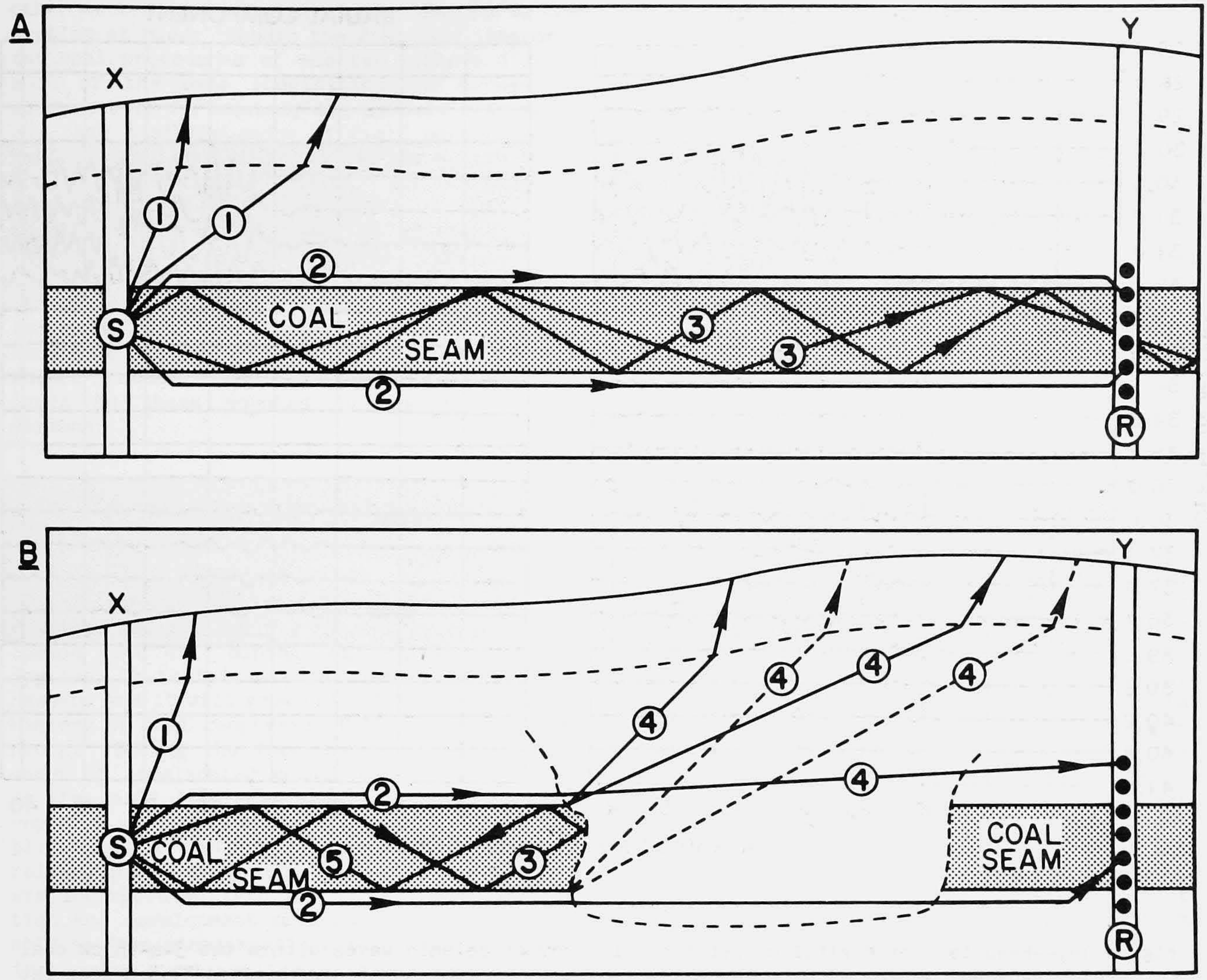

Figure 17.--Schematic representation of basic ideas of hole-to-hole seismic seam-wave certification, in A, undisturbed coal seam and B, disrupted coal seam. Circled S represents a seismic source embedded in a coal seam pierced by borehole X; circled R is an array of seismometers that span the coal seam and is rigidly held to the walls of the borehole Y. Dashed line roughly paralleling the topography is the low-velocity layer. Five types of ray paths are shown: type 1 is a direct ray, type 2 is a ray refracted along the higher velocity layers that bound the coal seam, type 3 are multiply reflected rays trapped with the seam, type 4 is a diffracted ray originating at the top and bottom of the disrupted coal seam, and type 5 is a ray that is reflected at the seam discontinuity and then channeled back toward the source. If, as shown in A, the seam is continuous, then both refracted waves (type 2) and seam waves (type 3) will be recorded; if the seam is broken by a fairly wide channel, B, no seam-wave arrivals (type 3) are likely to be seen.

written commun., 1976).

From the foregoing material, seam-wave methods appear to be almost ideal. Not only have there been many instances in which theory has been confirmed by experiments, but also (and perhaps of more importance to the pragmatists among us) results with a high success ratio--9 out of 10 times for transmitted seam-wave methods--have been obtained in more than 300 cases in Europe. Are there, then, no limitations on the methods? Of course there are. As Krey pointed out (1976, p. 245-247):

1. An uncertainty of perhaps 25 m exists

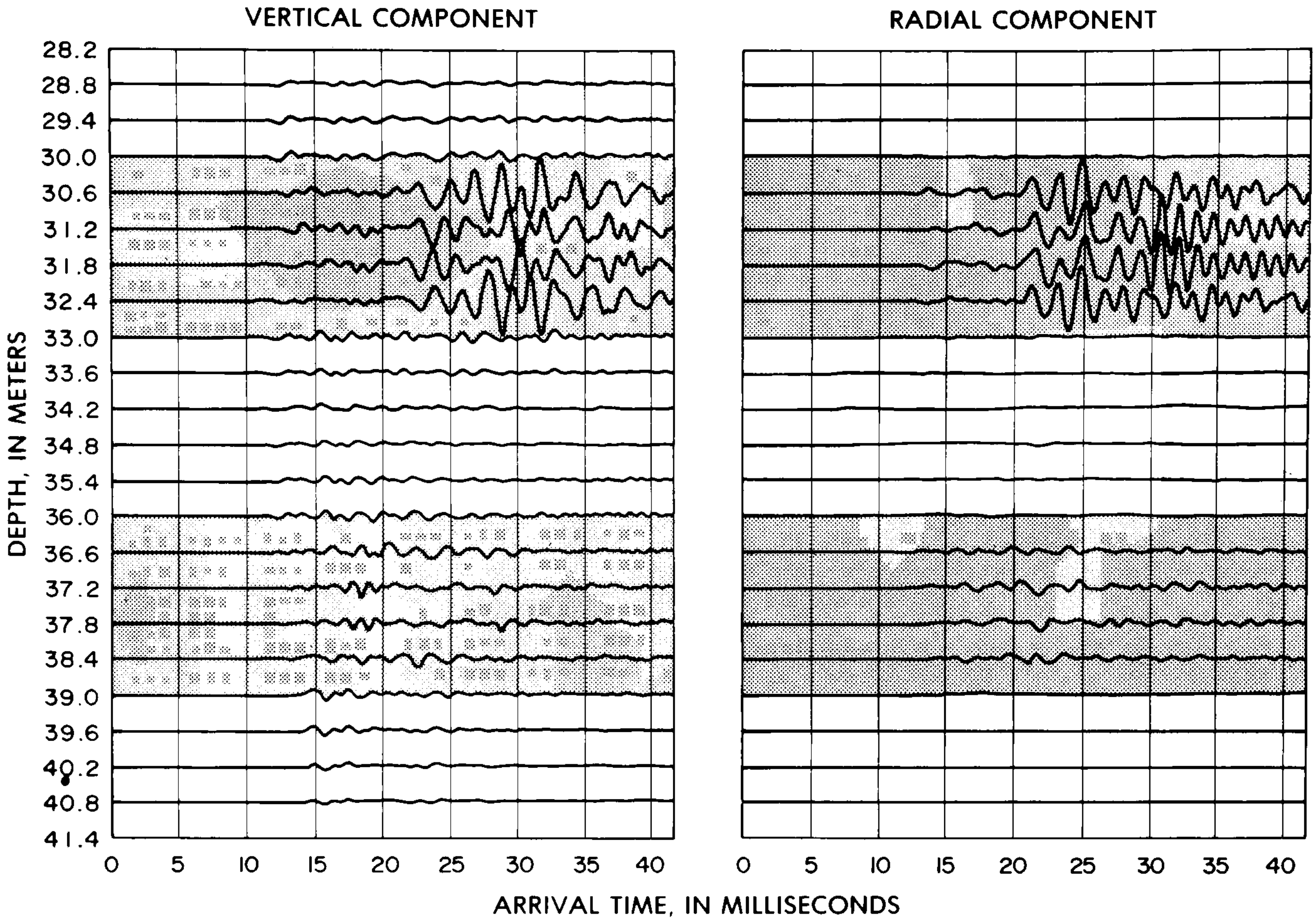

Figure 18.--Results from digital-computer model study of seismic waves within two 3-m-thick coal seams (shaded) separated by a 3-m-thick parting. Seismic source was located 31.5 m deep (at the center of the upper seam) and 20 m from the vertical array of vertical-and radial-component seismometers. Body-wave arrivals are at about 12 millisec; seam waves arrive some 10 millisec later. Note that the lower seam, the one that does not contain the source, has no seam-wave arrivals.

in locating discontinuities by horizontal probing with reflected seam waves.

2. The greatest distance that a fault can be detected with present-day equipment is 300 m--industry would like to see this range extended to 1200 m.

3. Because seam-wave methods employed in an underground coal mine must be explosion proof and be certified so by MESA, it may take years before newly developed equipment is certified safe for use in a gaseous environment. The biggest problem, however, is the general unpredictability inherent in all geological-type problems--the earth is never as simple as our mathematical models indicate it to be. In our studies at Kemmerer, Wyo., for example, the underclay and the coal seam appear to combine to produce a single waveguide in which lower frequency seam waves are transmitted. Also, computer studies now being done by Steven Peterson (oral commun., 1977) at the Colorado School of Mines indicate that seam waves within shallow seams (ones whose seam thickness-to-depth ratio is less than 10) would require special data processing to separate them from the guided and boundary waves associated with the air-ground, or free, surface.

Seismic seam-wave techniques and high-resolution reflection methods are complementary; that is, what one might not do, the other might. The most reasonable approach, therefore, is to use both seismic methods, letting the emphasis on usage shift from one method to the other according to the particular demands of the problem at hand. Though the field and interpretational procedures of the two methods differ; much of the data acquisition and processing equipment is fortunately the same in both methods, and a single cadre of field personnel can handle both tasks. The NCB of the United Kingdom recognizes this duality of utilization. Since the early 1970's, the NCB, in addition to shooting approximately 1600 km of high-quality seismic-reflection lines (Clarke, 1976, p. 187), has concomitantly supported an intensive research effort in seam-wave technology (D. Buchanan, NCB, oral commun., 1976). To our knowledge, as yet no operational programs in the United States are comparable in sustained excellence to those mounted by the British and Germans.

CONCLUDING REMARKS

To work in applied geophysics one must be a realist, and the reality in coal geophysics (in common with oil, mining, and engineering geophysics) is that it will be used only if it is needed, and it will grow only if it is used. The history of coal geophysics fully supports these dicta. During the four decades preceding the onset of accelerated growth of coal geophysics in the early 1970's, a small group of articles reported work that clearly demonstrated the applicability of geophysics to a variety of coal-related problems. Yet, none of these methods was incorporated into industrial coal exploration and development programs, and understandably so from management's point of view. "Why," they asked, and still ask, "should we take on something new when we already have something that does the job well enough for us?" But conditions changed. Suddenly, but predictably to those with the acuity of hindsight, demand for coal began to increase, reaching a clamor in November 1973. What was good enough before no longer sufficed.

The solution to meeting increased demands for coal is easy to state with what we call an "all you've got to do is" statement. For example, one could say, "All you've got to do to put a man on the moon is build a powerful rocket and train some people to launch, run, and retrieve it," or, "All you've got to do to solve the energy crisis is use less and find more." Similarly, all you've got to do in coal is acquire more properties so as to replace those older ones which now, under increased demand, will be more quickly depleted, and then mechanize the new mines so as to increase their productivity per man hour. But it isn't that easy--it never is. The number of coal properties is limited, and their availability may be hampered by legal and environmental constraints. And mechanization requires more than buying additional ventilation and extraction machines and then pushing their start buttons. Whereas the flexibility of the older methods of underground mining permitted mine plans to be altered almost as mining proceeded, with increased mechanization and automation, the geologic state of the coal panel has to be known well in advance of the emplacement of this new and costly equipment. With longwall mining, for example, minor faulting does not constitute a minor problem--it can make the difference between profit and loss, or even life and death.

Coal geophysics is used in Britain and on the Continent not because Europeans have some grand passion for fostering the scientific well-being of coal geophysics, but rather because they can make more money with it than without it. But is the European experience transferable? We think it is. But we also believe that, because coals in the Americas vary so greatly in rank and mode of occurrence, coal geophysics on this side of the Atlantic will necessarily be more diverse. Consider, for example, the mapping of burn facies. This problem does not occur in England and, therefore, it is of no economic interest to the English. But if we can reduce the exploration drilling costs in clinkered areas by half (as has been done in the Powder River Basin of Wyoming and Montana by one company that used the magnetic method), then this geophysical technique is of great interest.

The following list illustrates the diversity of coal-related problems to which coal geophysicists (working in full partnership with coal geologists and mining engineers) either have applied their methods or have strong indications leading them to believe that their techniques will be successful:

1. Determination of regional tectonic framework.
2. Study of basement configuration, subsurface geology, and boundaries of coaliferous basins.
3. Identification of intra-basin regions whose geologic settings are unfavorable for coal occurrence.
4. Location of trends and extensions of major want areas, including glacially cut channels, within coaliferous areas.
5. Mapping of burn facies, positions of active burn fronts, and boundaries of in-situ gasification retorts.
6. Detailed investigation of subcrops, ancient shorelines, and channel sands within a particular tract.
7. Discovery and delimiting of lenticular coal deposits.
8. Tracing continuity of sets of coal seams between drilled, sampled, and logged locations.
9. Identification and mapping of distribution, type, and amount of faulting within a tract.

10. Location of igneous dikes that have cut coal beds.

11. Delineation of old mine workings and location of long-abandoned mine shafts.

12. Blocking out of coal panels prior to the installation of longwall mining equipment, especially advancing longwall.

13. Determination of coal resources beneath those beds now being mined.

14. Assaying quality of coal in place, thus reducing number of cores required.

15. Investigation of water resources.

16. Determination of overburden rippability, foundation competence, and direction of principal stresses.

17. Determination of roof and floor strengths in advance of mining.

18. Exploration and mapping of other economic materials, such as gravel, road metal, and uranium-bearing rocks, within the mine area.

19. Prediction and monitoring of mine-related subsidence.

20. Evaluation of slope stabilities and design of mine openings.

And this list is only the beginning, for the history of geophysics has repeatedly demonstrated that the more the methods are used, the more uses are discovered.

The examples given in this paper were selected to show the capabilities and potential of coal geophysics to approach solutions to four problems of immediate concern in the exploration and development of coals of the Western States: delineation of want areas, determination of thickness variations of strippable-depth coals, mapping of clinker areas, and establishment of seam continuity. Being so limited, we only touched on what can be accomplished using modern coal-geophysics technology. Remote-sensing methods, electrical and electromagnetic techniques (airborne, ground, and borehole), and geochemical-tracing procedures were given short shrift--hardly equitable considering their present and future value. Geophysical logging of coal was not discussed because it has been described elsewhere (David, 1977).

The examples in this paper, besides illustrating what geophysics can do, also show that we have a long way to go and a lot to learn. But this is the same conclusion that we read in, or read into, every article we have seen. Krey and Arnetzl (1971, p. 9) expressed this same thought when they said, "But in spite of all these demands for development we should not forget what has so far been researched, for in normal exploration seismic too, practical surveys were carried out very successfully in early times when equipment, theory, and interpretation were still far from being perfect."

ACKNOWLEDGMENTS

We wish to express our gratitude to the many friends in the coal exploration and development business who, through long and patient conversations, helped us strike the balance between what is geophysically interesting and what is industrially needed--the two not necessarily being mutually exclusive. In particular, we want to thank Prof. Dr. Krey of Prakla-Seismos for opening the door, and helping us through, in seam-wave technology; and Mr. A. M. Clarke of the National Coal Board for strengthening (by word and action) our conviction that coal geophysics can be used profitably.

Manton L. Botsford and Robert G. Hobbs (U.S. Geological Survey) were especially helpful in planning and executing experiments. We are much appreciative of the useful suggestions freely given by graduate students and members of the Department of Geophysics at the Colorado School of Mines, in particular Prof. Maurice W. Major, our partner in many of these studies.

We also want to thank the Mintech Corporation (Denver, Colorado) for their kind permission in allowing us to establish an outdoor coal-geophysics laboratory on their properties near Watkins, Colo.

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Depositional Environments and Coal-Seam Discontinuities—Rocky Mountain Cretaceous Coals

COOPER B. LAND[1] and ROBERT J. WEIMER[2]

ABSTRACT

Extensive coal deposits in Cretaceous rocks in the Rocky Mountain region accumulated mostly in back-levee and flood-basin environments marginal to lower alluvial-valley and delta-plain channels. Less extensive and generally thinner coals were deposited in coastal swamps and marshes. Some thin, discontinuous coals were deposited in swamps that formed as fills of abandoned channels.

Elements critical to the formation of thick commercial coals include fresh, clear water; accumulation of freshwater plant debris; a favorable climate; and maintenance of the proper balance between the ground-water table and the depositional interface. A basinwide or local tectonic influence on sedimentation is necessary for the above conditions to persist over large areas for the long periods of time required for thick peats to accumulate.

Many discontinuities in Cretaceous coal seams can be related to sedimentary processes. The most important of these are crevasse splay splits, sand- or clay-filled channel wants, and penecontemporaneous (growth) faults. Post-depositonal faults and in situ burning also account for discontinuities. The recognition of penecontemporaneous faulting in coal-bearing strata is important, because these faults may have influenced swamp environments and controlled peat thicknesses. Along the west margin of the Denver Basin, in the Boulder-Weld coal field, growth faulting was a primary control on sedimentation in the Laramie Formation and, consequently, it controlled the thickness of coal deposits. The lateral continuity of coals in the Laramie is interrupted by these faults, and most of the minable thicknesses of coal occurs in graben structures.

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Deltaic Origin of the Sunnyside Coal, Western Book Cliffs, Utah

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ABSTRACT

The Sunnyside coal, the major source of high-volatile coking coal in Utah, occurs in the Blackhawk Formation of Late Cretaceous age. The coal is interpreted as having accumulated on a wave-dominated delta that prograded southeastward from the western margin of the interior seaway. The sheet sandstone of the delta, as much as 150 ft thick, overlies the Mancos Shale and consists of an imbricate sequence of sandstone bodies representing separate cycles or episodes of delta progradation. Each cycle was followed by minor or major transgression and subsequent seaward accretion of foreshore and shoreface deposits. In the Columbia area, foreshore and shoreface facies have been partially to completely replaced by river-mouth bar sediments.

The Sunnyside coal commonly overlies beach sandstone and, rarely, washover deposits. The coal is autochthonous and continuous along the outcrop for a minimum of 30 mi. A coniferous origin is indicated by branches of Araucaria and Sequoia preserved in seat rocks and partings, and by coniferous material in coal thin sections.

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