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GEOLOGIC CONDITIONS AFFECTING COAL MINE GROUND CONTROL IN THE WESTERN UNITED STATES

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Goodson & Associates, Inc.

BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGIC CONDITIONS AFFECTING COAL MINE GROUND CONTROL IN THE WESTERN UNITED STATES

Developed For:

BUREAU OF MINES

U.S. DEPARTMENT OF THE INTERIOR

Prepared By:

Robert B. Laird, Adolph L. Amundson,
Gary J. Colaizzi, and Lisa M. Bithell

GOODSON AND ASSOCIATES, INC.

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Gary P. Sames
U.S. Bureau of Mines
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R.B. Laird, A.L. Amundson, G.J. Colaizzi, L.M. Bithell

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Lakewood, Colorado 80215

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A comprehensive investigation into geologic features affecting coal mine ground control in western underground coal mines was conducted under contract with the U.S. Bureau of Mines. This study involved a literature search for data on geologic features affecting coal mine ground control, western coal geology associated with specific geologic features, and MSHA roof fall information. Data on mining operations was collected through interviews with mining and research personnel. Selected mines were toured within ten coal fields in Utah and Colorado. This final report summarizes western coal depositional environments and geological structures, and describes mining and geology for the coal fields studied. All observed geologic features and conditions related to coal mine ground control are described in terms of their depositional or structural origin, morphology, diagnostic characteristics, associated adverse mining conditions, and roof control methods. Photographic documentation of these geologic features is included. Adverse geologic features and their locations are correlated with geological environments by coal field, to define their relative impact on mining operations. Recommendations regarding prediction of adverse features, use of the above data in mine development, and further roof control study in the West are provided. Comprehensive bibliographical data and selected MSHA roof fall data are also included.

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FOREWORD

This report was prepared by Goodson & Associates, Inc., Denver, Colorado, under USBM contract number J0145032. The contract was initiated under the Minerals Health and Safety Program. It was administered under the technical direction of the Pittsburgh Mining Research Center with Mr. Gary Sames acting as Technical Project Officer. Mr. Oliver H. Snyder, III was the Contract Administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period October, 1984 to December, 1985. This report was submitted by the authors in December, 1985.

CONTENTS

CONTENTS

CONTENTS

CONTENTS

TABLES

FIGURES

FIGURES

Figure No. Page

PLATES

PLATES

SUMMARY

Coal mine roof failure continues to be the major cause of fatalities and many other mining problems in terms of cleanup, productivity, and unsafe working conditions. For these reasons, the U.S. Bureau of Mines has initiated a research program to assess the geologic conditions affecting underground coal mine ground control in the western United States. The first phase of this research program has been completed with the submittal of this report. This first phase was intended to collect background information on the depositional and structural geology, the mined coal seams, and the coal geology of western coal fields, which have active underground coal mines. This initial phase was also intended to completely describe, utilizing photography, those geologic features and conditions that cause adverse ground control problems in underground coal mines of the western U.S. Subsequent phases of this research program should concentrate on the prediction of adverse geologic features in advance of mining, development of ground control guidelines, and the education of coal mine personnel on the recognition and management of roof control problems caused by hazardous geologic features. This program should significantly benefit the western underground coal mining industry through the development of comprehensive ground control guidelines, which will ultimately lead to increased production in a safer working environment.

An extensive literature search of western coal geology, geologic features that cause ground control problems, and specific information regarding western coal field depositional environments and geologic structures was completed. Interviews with personnel from 51 underground coal mines in Utah, Colorado, Wyoming, and New Mexico were conducted by telephone. These interviews served to develop a complete listing of the types and relative impact of geologic features or conditions in each coal mine. Using this information, and the information obtained from MSHA roof fall data, mines were ranked based on the magnitude and effect of each geologic feature, accessibility, and whether a tour of the mine would be possible. Tours of eleven underground coal mines in Utah and Colorado were made to evaluate, photograph, and describe each of the geologic features and/or conditions observed in the mines. Mine tours were led by geologists or mining engineers who were familiar with geologic features and related adverse roof control problems. The Emery, Wasatch Plateau, Book Cliffs, Grand Mesa, Somerset/Paonia, Carbondale, Yampa, Canon City, Trinidad, and Raton Coal Fields were studied.

Information gathered from the literature search, interviews with coal research geologists and mine personnel, and the photographs and information collected during mine tours was analyzed and organized into a final report. An overview of the depositional and structural history of Rocky Mountain coal fields is presented. The geology, mine location, and mining history of the studied coal fields is discussed.

Geologic features and conditions affecting ground control in western underground coal mines are discussed. They are divided into three groups based on their geologic origin. These groups are depositional features, structural features, and additional conditions consisting of water and in situ stress. Depositional features discussed are sandstone channels, compactional and structural slickensides, lithofacies change, coal rolls, bedding planes,

underclays, and kettlebottoms. Structural features discussed are folding, joints, coal cleat, faults, lineaments, and igneous and sedimentary dikes. The occurrence and location of each feature is discussed. The morphology and diagnostic characteristics, adverse effects on underground coal mine ground control, and methods of roof control used to stabilize the roof in relation to each geologic feature are also discussed.

An additional group of geologic features, which were observed in toured coal mines, and that generally do not create adverse ground control problems, are also presented. These features, which are discussed more out of general interest than as features which cause roof stability problems, include trace fossils, plant fossils, dessication cracks and ripple marks, concretions, and an inferred beach berm.

A section describing roof control methods is presented. This section discusses standard procedures for normal roof control, and those roof control methods utilized in unstable and roof fall-prone areas.

Conclusions concerning geologically induced ground control problems in western underground coal mines are presented. Conclusions correlate geologic features with coal fields, areas of occurrence, and their relative impact to mining in those fields. Recommendations regarding phases of continued study under this research program are presented. These include the analysis and development of predictive methods of use in locating and assessing geologic features in advance of mining, roof control procedures, and the education of underground mining personnel concerning identification and management of adversely affecting geologic features.

An extensive bibliography of publications that deal with geologic features and their effects in underground coal mines, western coal geology, and depositional environments of western coal fields is included.

ACKNOWLEDGEMENTS

The authors are very grateful for the time and cooperation extended by the participating coal mining and operating companies. These companies allowed us to tour their mines for documentation of geologic features that affect ground control.

Appreciation is extended to Mr. John Mercier of Cyprus Coal Company, Mr. Mark Bunnell of Utah Fuel Company, and Mr. Roger Fry of Utah Power and Light for their expertise and valuable input to this project. Appreciation is also extended to Mr. Richard Tifft of Twenty Mile Coal Company and Mr. Laine Adair of Price River Coal Company for their respective mining expertise in geology and mining engineering. We are also grateful to Mr. Douglas Boyd of the Bureau of Mines, Denver Research Center, for making available information concerning reported roof falls in western coal mines and to Dr. Edward Johnson of the U.S. Geological Survey, Coal Branch, Denver, Colorado, for his assistance in evaluation of coal depositional environments in the Rocky Mountain region.

1.0 INTRODUCTION

Roof failure, as a manifestation of ground control problems, continues to be the major cause of fatalities in underground coal mines. Unstable roof conditions also result in continual safety problems, loss of productivity, and increased expense associated with elaborate roof control methods. This report is the result of a study of geologic environments and features that cause unstable roof conditions and other ground control problems in the western United States.

1.1 Objectives

Study of geologic features that affect coal mine ground control in the West, exclusive of studies conducted by coal mine research personnel, has been minimal. The U.S. Bureau of Mines initiated this study to research and document geologic conditions in western coal fields that affect ground control in underground coal mines. Existing information on the geology of coal regions in the West will be utilized with new data gathered directly under this contract. It is intended that this report aid in the location and identification of geologic features causing roof control problems in the coal fields of the Rocky Mountain region, and thoroughly describe these features and their environments in relation to roof control problems. This report will also set forth recommendations for further research under this program that will provide data to be used by mining personnel for the identification, prediction, and control of geologic features and conditions that cause roof control problems.

1.2 Background

The U.S. Bureau of Mines has concentrated previous research on geologic factors contributing to roof control problems in the Northeastern Appalachian Coal Province and the Illinois Coal Basin. Historically, much coal has been mined by underground methods in these two areas and various geologic features related to roof control problems have been encountered. This report initiates a concerted effort by the U.S. Bureau of Mines to evaluate geologic features related to roof control problems in western underground coal mines.

Recent increases in Federal leasing of coal properties in the West has resulted in an increase of underground coal mining, particularly in the Rocky Mountain states of Utah and Colorado. At present, many of these underground coal mines are idle or closed because of poor market conditions. However, due to the low sulfur content of western coal, both surface and underground coal mining is expected to increase in the future.

Differences in age, depositional geology, and structural deformation of coal-bearing formations makes western coal geology significantly different from that of the East and Midwest. The western coal mining industry has had to adapt standard practices and develop new techniques for controlling geologic features that affect underground mines.

Figure 1. shows the coal fields of Utah and Colorado that were investigated during this study, as well as two fields in southeastern Wyoming and one field in northeastern New Mexico. These are the coal fields in the West which contain active underground coal mines.

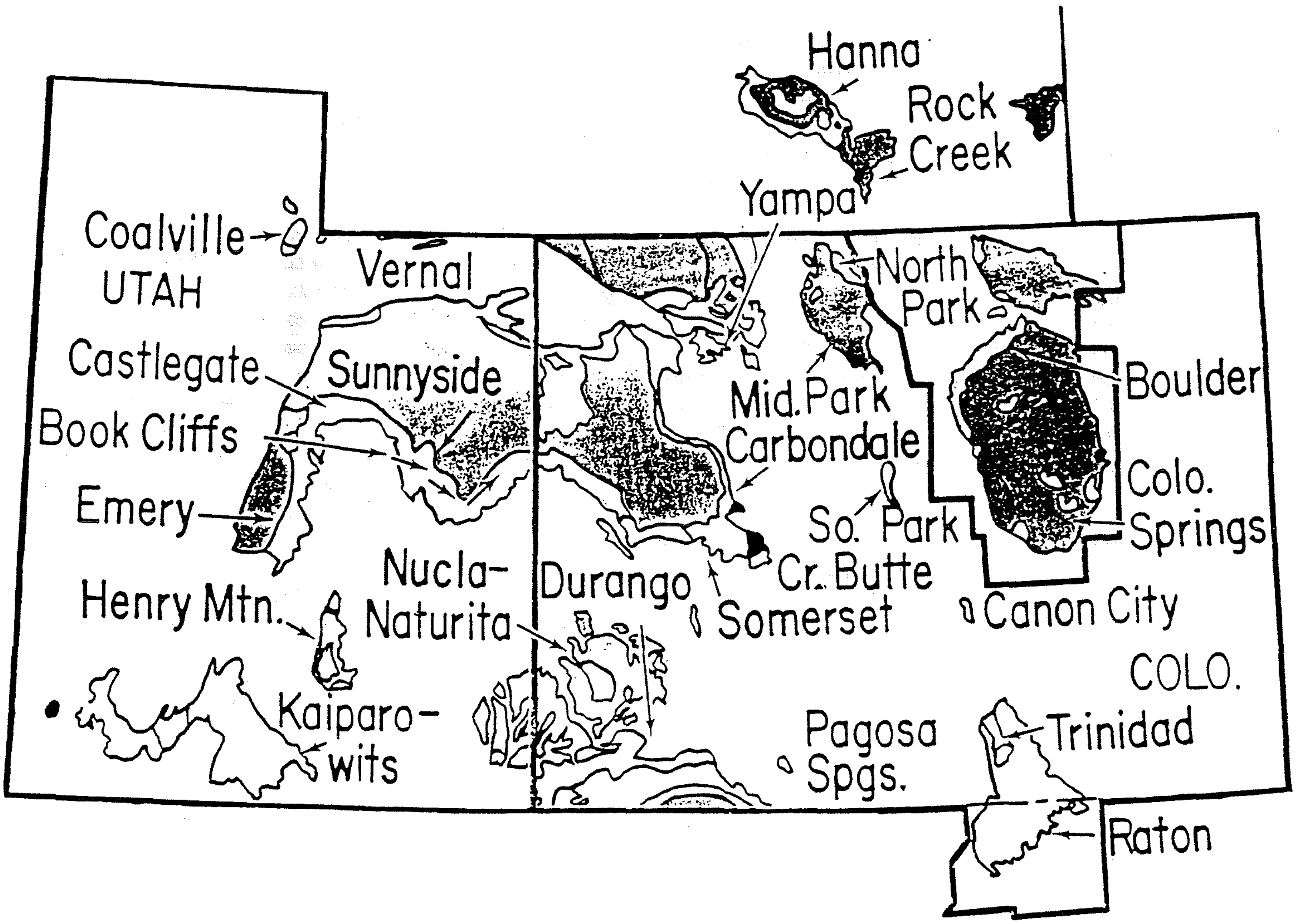

FIGURE 1. - Coal fields of Utah, Colorado, southeast Wyoming, and northeast New Mexico (adapted from 1).[1/]

2.0 METHODOLOGY

2.1 Literature Review

The initial task for this study consisted of a thorough investigation of available literature on geologic features which affect underground coal mine ground control, and general geology of western coal fields. Suggested reports authored by U.S. Bureau of Mines personnel were initially acquired. The first research procedure implemented was a computer search for references. The computer search was performed using a computer information service through the use of a telephone modem. The service utilized key words to locate reference titles. Key words used were "Coal Mine Roof Control," "Kettlebottoms," "Coal Mine Faults," etc. Many useful references were identified through this service, which provided a broad base of published documents from which to continue the literature review.

A search of the U.S. Geological Survey Library in Denver was conducted to acquire references on the geology of western coal fields. This library contains an extensive collection of publications by Federal, State, and county agencies, as well as privately published material. An excellent series of three monographs by Doelling (2) describing Utah's coal fields, mining history, depositional and structural geology, and coal-seam stratigraphy and lithology were thoroughly reviewed. A search was also conducted at the U.S. Bureau of Mines library in Denver for applicable references. Copies of many pertinent Bureau of Mines reports were acquired to familiarize personnel with the various definitions and descriptions of underground geologic features. As contacts were made with coal company geologists and engineers during a later task, additional technical research papers on Rocky Mountain coal geology were acquired that discussed the state-of-the-art of depositional modeling, mine and property geologic mapping, and descriptions and effects of geologic features in western underground coal mines. Key project personnel utilized their familiarity with mine personnel knowledgeable in identification and description of hazardous geological features to obtain accurate, thorough information regarding coal mines and roof control problems in the West.

The literature review produced a thorough bibliography of references, including western coal field geologic descriptions, reports describing coal mine geologic features, and many papers describing the depositional environments of western coal fields. The bibliography containing these references is included as Appendix A.

2.2 Telephone Interviews

The second task was to interview, by telephone, personnel from at least 40 active underground coal mines in the West. An active underground coal mine was defined as a mine that was not abandoned, sealed, or only permitted; it was actively operating, on standby, or idle. Active underground coal mines in the West were to be located in the states of North Dakota, Montana, Wyoming, Utah, Colorado, New Mexico, and Arizona. A search was made of both the "Western Mining Directory" (3) and the "Keystone Coal Industry Manual" (1) for underground coal mines in these states that were actively operating, on standby, or idle. Of the 51 mines contacted, 27 were in Colorado, 22 were in Utah, and one each were in New Mexico and Wyoming. There were no active or idle underground coal mines in North Dakota, Montana, or Arizona. Table 1. is a compilation of all mines contacted showing their status at the time of this study. Personnel contacted who had knowledge of roof control problems within the mine were either geologists, mining engineers, superintendents, or mine managers. When possible, geologists were consulted first as they were found to be most knowledgeable about the types of geologic features of concern to this study.

TABLE 1. - Status of mines

Mine name	Mine no.	Status [1]
Apex Mine	1	Active
Apex No. 2 Mine	2	Active
Bear Creek Mine	3	Closed
Bear Mines #1, #2, #3	4	Active
Belina Mines #1, #2	5	#1 Active, #2 Idle
Blue Ribbon Mine	6	Active
Cameo No. 1	7	Idle
Carbon No. 1	8	Active
Coal Basin Mine	9	Active
Co-op Mine	10	Active
Deer Creek Mine	11	Active
Des-Bee-Dove Mines	12	Active
Deserado Mine	13	Active
Dorchester No. 1	14	Active
Dutch Creek Mines #1, #2	15	Active
Eagle Mines #5, #9	16	Active
Emery Mine	17	Idle
Foidel Creek Mine	18	Active
Fruita Mines #1, #2	19	Permitted
Golden Eagle Mine	20	Active
Geneva Coal Mine	21	Closed
Gordon Creek Mines #2, #3, #6	22	Active
Hawks Nest East and West	23	Closed
Helen Mine	24	Idle
Huntington Canyon	25	Active
J. B. King Mine	26	Closed
John Henry Mine	27	Permitted
King Coal Mine	28	Active
King Four Mine	29	Active
King Six Mine	30	Active
L. S. Wood Mine #1, #2	31	Active
Knight Mine	32	Closed
Mt. Gunnison #1	33	Active
Munger Canyon Mine	34	Idle
New Elk Mine	35	Active
Newlin Creek Mine	36	Active
Orchard Valley Mine	37	Active
Pinnacle Mine	38	Active
Price River Mines #3, #5	39	Active

TABLE 1. - Status of mines - Continued

Mine name	Mine no.	Status 1/
Red Canyon Mine	40	Idle
Rienau 2	41	Active
Roadside Mine	42	Active
Skyline Mine No. 3	43	Active
Snowmass Mines #1, #3	44	Idle
Soldier Canyon Mine	45	Active
Somerset Mine	46	Active
Star Point No. 1 and No. 2 . .	47	No. 1 Closed, No. 2 Active
SUFCO Mine	48	Active
Sunnyside Mines #1, #2, #3 . . .	49	#1, #3 Active, #2 Idle
Trail Mountain Mine . . . . . . (2/)	50	Idle
York Canyon Mines #1, Central, Cimarron	51	#1 Closed, Central & Cimarron Active

1/ Status of the mines is described as follows:
Active: The mine is currently operating.
Idle: A small crew is maintaining the mine; ventilating and/or pumping water.
Closed: A watchman is at the mine; no ventilation and/or pumping water.
Permitted: The mine is in the permitting stage only; entrances may have been constructed, but no major development has occurred.

2/ The Wilberg Mine was not contacted due to mine fire conditions that would have precluded a tour.

Before telephone contact was made, the Mine Plan submitted to the Office of Surface Mining by each mine was reviewed, if available. Several mines had not submitted mine plans or were in the submittal process. It was felt that information about seams, coal fields, location, and coal quality could be acquired from the mine plans or the "Keystone Coal Industry Manual" reducing the need to burden mine personnel with background questions.

Upon contact with the geologist or engineer, information acquired from the mine plans or industry manual was verified. In addition, mine personnel were asked questions concerning roof control, geologic features found in the mine, overburden thickness, and hazard perception. Table 2. is a sample questionnaire which was developed for the telephone interviews. In general, most questions were answered at varying levels of completeness or understanding. Initial permission, denial, or identification of the proper authority to obtain permission to tour the mine, was asked of the interviewee. In general, visits to most of the mines were possible.

TABLE 2. - Sample telephone interview questionnaire

OSM Mine plan available? ________ Mine Number ________

OSM Mine Plan No. ________ Tour Ranking ________

Comments ________

TELEPHONE INTERVIEW - GEOLOGIC HAZARDS INVESTIGATION

Mine

1) Name -

2) Company -

3) Location -

4) Coal seam mined -

5) Coalfield -

Geology

1) Group, Formation or Member -

2) Lithology -

3) Depth of cover (range) -

4) Coal seam thickness (range) -

5) Mined Seam thickness (range or avg.) -

TABLE 2. - Sample telephone interview questionnaire - Continued

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Geology (Cont'd)

6) Roof Strata -

7) Floor Strata -

8) Coal rank -

Description of Mine

1) Type of entrance -

2) Mining Methods -

3) Primary and other means of roof support -

4) Active or idle -

Geologic Hazards/Features (accepted terms at the mine used to describe each hazard) -

---

TABLE 2. - Sample telephone interview questionnaire - Continued

Effects of each geologic feature on the mine roof stability?

Interviewers initial assessment of the hazardous features as described?

Would a visit in the future be possible?

Other comments:

Name of person interviewed: ____

____

Interviewer

2.2.1 Western Coal Mine Roof Falls

The following analysis of roof fall data was initially intended to verify the number and severity of roof falls described by mine personnel during telephone interviews. This analysis also provided useful data for assessing the significance of geologic factors related to roof falls.

During the years 1982 through 1984, 258 roof falls of varying magnitudes, locations, and causes were reported to the Mine Safety and Health Administration (MSHA) for coal mines in the studied fields, as shown in Table 3. Appendix B contains a complete listing of data characterizing these falls. The following is a summary and analysis of that data.

TABLE 3. - Roof falls by size and year 1/ 2/

Year	Large	Medium	Small	Other	Total
1982 .	70	24	13	6	113
1983 .	36	33	2	13	84
1984 .	12	23	5	21	61
Total .	118	80	20	40	258

1/ Size estimated from description:

	diameter	height
Large	>10 ft.	>2.5 ft.
Medium	3-10 ft.	1-2.5 ft.
Small	<3 ft.	<1 ft.

2/ Data obtained from MSHA records.

As shown in Figure 2., a significant decline in the number of reported roof falls occurred over this time period. This is inferred to be directly proportional to decreases in underground coal mine production. A significant decline in the number of large roof falls is also evident. This may represent increased perception by mine personnel of the need for mine planning based on geologic factors and the use of fewer mine entries. An obvious decline is not observed for medium and small roof falls.

Tables 4., 5., and 6., show the most commonly reported locations, activities, and geological causes for roof falls, respectively. The relative importance of each location, activity, or geological cause is shown as a percentage of the total number of roof falls for which locational, activity, or geological data was provided. Use of this method may result in exaggeration of the relative importance of observed trends. However, this approach was necessary due to the lack of complete data in MSHA records.

Common locations for roof falls within western coal mines include entries (22%), cross-cuts (20%), faces (15%), and intersections (13%), as shown in Table 4.

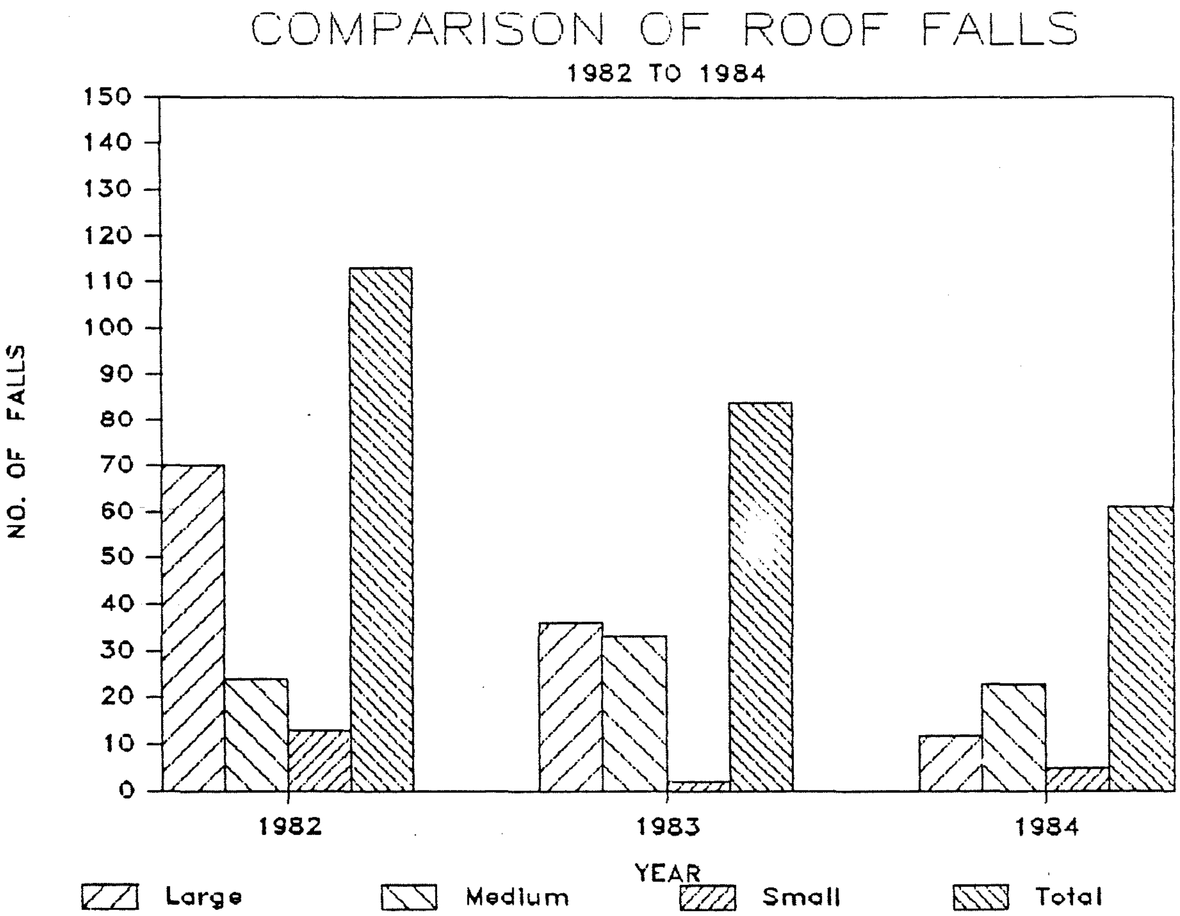

FIGURE 2. - Comparison of western underground coal mine roof falls by size and frequency from 1982 through 1984. Data from MSHA records.

TABLE 4. - Most common roof fall locations 1/ 2/

Location	Number of falls	Percent falls with reported locations
Entry	44	22%
Cross-cut . . .	40	20%
Face	29	15%
Intersection . .	27	13%
Pillar section .	16	8%

1/ 65/258 locations not reported.

2/ Data obtained from MSHA records.

Activities at the time of the reported roof falls were primarily mining advance (31%), idle operations or locations (19%), and mining retreat (9%), as summarized in Table 5.

TABLE 5. - Most common activities during roof fall 1/ 2/

Activity	Number of falls	Percent falls with reported activities
Mining advance .	32	32%
Idle area . . .	19	19%
Mining retreat .	9	9%

1/ 160/258 activities not reported.

2/ Data obtained from MSHA records.

Geological causes for roof falls were only reported for 91 (or 35%) of the 258 falls reported for the 1982-1984 period. Most studied mines do not employ geologists; as a result, geological causes for falls are not well understood or reported. Subjectivity of geologic evaluation by mine personnel for each fall introduces yet another obstacle to evaluation of the major geological causes for the reported roof falls. Most commonly reported geological causes include moisture (23%), fractures and faults (19%), slickensides (10%), and sandstone interbedded with shale (7%). These causes are summarized in Table 6. Changes in geologic conditions from one coal field to another suggest evaluation of reported conditions on a field by field basis, as discussed in Sections 4.0 and 5.0.

TABLE 6. - Most common geological causes reported 1/ 2/

Geological cause	Number of falls	Percent falls with reported causes
Moisture . . .	21	23%
Frac./faults .	18	19%
Slickensides .	10	10%
Ss. interb. sh.	7	7%

1/ 167/258 geological causes not reported.

2/ Data obtained from MSHA records.

2.2.1.1 Review of 1982-1984 Roof Falls by Coal Field

Table 7. summarizes reported roof falls by size and coal field for the 1982-1984 period. Fields are reviewed in order from west to east, following

the major depositional trends observed in the Rocky Mountain region. The Wasatch Field reported the largest number of total falls, followed by the Somerset and Book Cliffs Fields. The Wasatch Field also reported the greatest number of large and medium-sized falls, followed by the Book Cliffs Field. It should be noted that the Wasatch, Somerset, and Book Cliffs Fields currently have the greatest number of large mines in operation, and should be expected to experience a higher number of roof falls.

TABLE 7. - Western coal mine roof falls by field, 1982-1984 1/ 2/

Field	Large	Medium	Small	Other	Total falls
Emery . . .	5	2	1	0	8
Wasatch . .	44	32	5	6	87
Book Cliffs.	20	14	2	2	38
Grand Mesa .	10	2	0	0	12
Somerset . .	6	8	4	27	45
Paonia . . .	3	3	0	2	8
Carbondale .	5	7	3	2	17
Yampa . . .	2	3	1	0	6
Canon City .	8	3	2	1	14
Trinidad . .	12	6	2	0	20
Raton . . .	3	0	0	0	3
Total . . .	118	80	20	40	258

1/ Size estimated by description:

	diameter	height
Large	>10 ft.	>2.5 ft.
Medium	3-10 ft.	1-2.5 ft.
Small	<3 ft.	<1 ft.

2/ Data obtained from MSHA records.

Emery Field

Eight roof falls occurred in the Emery Coal Field mines, with six in 1982, two in 1983, and none in 1984. The decrease in reported roof falls is proportional to decreased mining activity in this field during the reporting period. Falls occurred during both mining and idle periods, most commonly at the working face. Additional falls occurred during pillar extraction operations. Geologic conditions related to roof falls include mud slips and rib bounces.

Wasatch Field

A total of 87 roof falls were reported for the Wasatch Coal Field, leaving the Wasatch Field with the highest total number of roof falls for all western coal fields for this period. The Wasatch Field also reported the greatest number of large and medium-sized falls of the western fields. In 1982, 37 falls were reported, followed by 32 falls in 1983, and 18 falls in

1984. These values are proportional to the number of large, active mines in the field, and also reflect decreased mine production.

Roof falls occurred most commonly at entry, intersection, pillar section, and cross-cut locations, during mining advance and pillar extraction operations. Falls were attributed to failure above bolts, excessive pressure, concurrent mining of seams above fall locations, crib failure, and top coal collapse. Reported geologic causes include igneous dikes, moisture, temperature changes, faulting, floor heave, incompetent roof, mud slips, rock bursts, sandstone channels, shale, slickensides, and strata delamination.

Book Cliffs Field

A total of 38 roof falls occurred in the Book Cliffs Field during the 1982-1984 period. Roof falls decreased from 25 in 1982, to eight in 1983, and five in 1984. This decrease is related to a reduction in mining operations. The majority of falls occurred at cross-cut, pillar section, and entry locations within the Book Cliffs Coal Field mines. Falls commonly occurred during mining advance and roof support operations, and were for the most part due to excessive pressure, and failure above bolts and other roof support. Geologic causes of roof falls include fractured roof, unconsolidated strata, interbedded shale and sandstone, mud slips, and moisture.

Grand Mesa Field

Twelve roof falls, including nine in 1982 and three in 1983, were reported for the Grand Mesa Coal Field mines. As with most Rocky Mountain region coal fields, these values are proportional to production decreases. No roof falls were reported for 1984. Roof falls occurred mainly at entry and cross-cut locations, during idle periods or in idle portions of the mines. Deteriorating roof is the most commonly reported cause of roof failure, suggesting water influx, air slaking, and/or neglect due to idled conditions. Geologic conditions related to falls include moisture, fractures, slickensides, shale roof, and variations in sandstone thickness.

Somerset Field

A total of 45 roof falls occurred in the Somerset Coal Field during the 1982-1984 period. These include 17 falls in 1982, 10 falls in 1983, and 18 falls in 1984, which occurred in face, entry and cross-cut locations. This high number of falls is proportional to the large production rates of several mines in the Somerset Coal Field. Mining advance, pillar extraction, and roof support operations were the primary activities at the time of most roof falls. Roof falls were primarily due to roof support failure above bolts. Geologic causes of roof failure were reported as mud splits, delaminated strata, faulting, moisture, localized rider seams, slickensides, and interbedded sandstone and shale.

Paonia Field

A total of eight roof falls were reported in the Paonia Coal Field during 1982-1984. These included one fall in 1982, six falls in 1983, and one fall in 1984. Falls occurred primarily in entry areas, and were due to failure above bolts. Moisture, fractures, and air slaking were the primary geologic causes of failure.

Carbondale Field

Seventeen roof falls were reported in the Carbondale Field. This total includes four falls in 1982, 10 falls in 1983, and three falls in 1984. These values directly parallel the number of mining operation shutdowns and startups that occurred during this period. The majority of falls occurred at cross-cut, portal, and face locations during support and mining operations. Most roof failures were due to concurrent mining in seams above the fall locations or support failure. Geologic causes of failure are reported as faulting, fracturing, floor heave, and shale/gravel roof conditions.

Yampa Field

Six roof falls occurred in the Yampa Field, including one fall in 1982, two falls in 1983, and three falls in 1984. The Yampa Field is a relatively small field with few underground coal mines. Most mining is in the development stage. Cross-cut areas were the most commonly reported locations for falls, which tended to occur during mining advance operations. Box cutting, roof support failure, and top coal collapse are reported as the major causes of roof falls. Geologic causes include delamination, pinching coal, mud slips, low-angle thrust faults, and moisture.

Canon City Field

Fourteen roof falls were reported for the Canon City Field during the reporting period. Five falls occurred in 1982, followed by seven in 1983, and two in 1984. This decrease is directly attributable to a reduction in mining operations. The majority of these falls occurred at cross-cut and face locations, during both active mining or in idle locations. Most falls were due to failure above bolts or other roof supports, and were attributed to excess moisture.

Trinidad Field

Twenty roof falls were reported for the Trinidad Field during 1982-1984, with six falls in 1982, four falls in 1983, and 10 falls in 1984. The marked increase in roof fall frequency in 1984 is attributed to renewed development and production in Trinidad Coal Field mines. Falls occurred during roof control operations and idle periods, at entry, intersection, and cross-cut locations. Failure above bolts and other roof support are the most commonly reported causes of falls. Geologic causes of failure include kettlebottoms, large mud slips, and moisture.

Raton Field

Three roof falls occurred in the Raton Coal Field during the reporting period, including two falls in 1982 and one fall in 1984. These low values are related to the existence of only one active underground mine in this coal field. These roof falls occurred in entry and cross-cut areas, and were due to failure above bolts.

2.2.1.2 Summary of Roof Fall Data

Careful analysis of both the summary tables and the complete data base (Appendix B) is necessary for evaluation of the reported roof falls. Most injurious or fatal roof falls occurred during roof supporting procedures. This includes "scaling" of loose roof rock, setting timbers and/or cribbing, and bolting. Many large roof falls occurred during pillar robbing operations, such as fender removal. These falls were not usually associated with severe injuries or fatalities. However, mining equipment was often buried and disabled during the roof fall. Most of the large roof falls that occurred during the reporting period occurred either in idle areas of the mine, during vacations, or in idle mines. Most often, these were very large falls with no associated injuries. Mine personnel were not commonly in the roof fall areas of the mines, and thus no documentation of roof conditions prior to the falls was noted. Review of the MSHA Roof Fall data for the studied fields during 1982-1984 indicated that most large and/or injurious roof falls had a direct geologic cause.

2.2.2 Mine Tour Ranking

The telephone interviews involved a procedure to ensure that only mines with sufficiently representative and observable geologic features would be toured. After the telephone interviews had been completed, a list of all pertinent, potentially adverse geologic features that affect western coal mine ground control was developed. A numerical value was assigned to the magnitude of adverse effect of each feature related to mine roof control. Table 8. is a sample form that was used to rank the mines. One form was filled out for each of the 51 mines, to establish a ranking order that was used to determine which mines to tour.

The highest ranking mines, that is, those with numerous and/or adversely impacting features, were listed in order of descending importance. As can be seen on the sample ranking form (Table 8.), space was set aside to include comments which would enhance the ranking to either justify or preclude a tour. Examples of these two situations were:

1) The York Canyon Mine #1 in New Mexico (Mine No. 51) did not rank particularly high in the order, but contained a representative example of a large sandstone channel with associated faulting and was the only underground coal mine in both the Raton Field and New Mexico; these attributes made this mine more desirable to visit.

2) Although the Geneva Coal Mine (Mine No. 21) ranked relatively high and contained pertinent, adversely affecting features, the mine was permanently sealed and could not be entered.

TABLE 8. - Sample mine tour ranking form

Mine Name ______________________________ Mine No. _______________

Does form contain comments ____ yes ____ no Ranking No. _______________

FEATURE	RANKING degree	RANKING number
Kettlebottoms		
Small <2', cave < 2'	low	1
Medium 2'-4', cave 2'-4'	mod	2
Large >4', cave >4'	high	3
Faults		
Small, offset <1' or no gouge and no effect on roof	low	1
Medium, offset 1-10' or some gouge and slight effect on roof	mod	2
Large, >10' offset or much gouge and bad roof	high	3
Mud slips		
Small <1', cave to 8"	low	1
Medium 1'-2', cave 8"-2'	mod	2
Large >2', cave >2'	high	3
Sandstone Channels and Overbank Deposits		
Small, 0'-10' wide, cave >2'	low	1
Medium, 10'-100' wide, cave 4'-8'	mod	2
Large, >100' wide, cave >8'	high	3
Horizontal Stress (horiz. vs. vert. factor)		
Low	low	1
Moderate	mod	2
High	high	3
Jointing		
Few, spaced apart >100'	low	1
Med., spaced apart 10'-100'	mod	2
Many, spaced <10' apart	high	3
Igneous Dikes		
Few or small with little or no effect on roof	low	1
Few to several, moderately affecting roof	mod	2
Several or large and severely affecting roof	high	3

TABLE 8. - Sample mine tour ranking form - Continued

Page 2
Visitation Ranking Form

FEATURE	RANKING degree	RANKING number
Lithofacies Change		
None to slight, slightly affecting roof	low	1
Definite changes, moderately affecting roof	mod	2
Major changes, causing major roof problems	high	3
Water Saturated Roof		
No to little water present, slight roof effect	low	1
Some water present, causing some roof problems	mod	2
Much water saturation, causing major roof problems	high	3
Bumps/Bounces		
None to slight present, causing few roof and rib problems	low	1
Some present, causing some roof and and rib problems	mod	2
Much present, causing major roof and rib problems	high	3
Clastic Dikes		
Few or small with little or no effect on roof	low	1
Few to several, moderately affecting roof	mod	2
Several to many or large causing major roof problems	high	3
Compaction Slickensides		
Few present, causing slight roof problems	low	1
Some present, causing some problems	mod	2
Many present, causing major concern and problems	high	3
Dinosaur Footprints		
Few present, causing minor roof problems or concerns	low	1
Some present, falling out, causing some concern and problems	mod	2
Many present, falling out, causing major problems and concern	high	3
Cover Thickness		
Avg. thickness <500'	low	1
Avg. thickness 500'-1500'	mod	2
Avg. thickness, >1500'	high	3

Comments (possibly unique features that could make this mine stand out to enchance visitation):

The ranking developed from the telephone interviews with mine personnel familiar with roof conditions and geologic features in the mines was based solely on the information obtained. Some personnel contacted felt obliged not to fully discuss the conditions present in the mine. Possible deficiencies in this method suggested that key project personnel use their familiarity with particular coal mines and fields to corroborate or elaborate on the information obtained. Regardless, it was found that mines which ranked the highest were also mines that did contain adverse conditions or sufficient suitable features to warrant a field inspection.

This type of research has not previously been conducted in underground coal mines of the West, with the exception of mine research, exploration, and planning investigations by mining companies. In contrast, many coal mines in the East and Midwest have been studied. Because of the unfamiliarity of mine management with this type of study, two detailed, fully explanatory letters asking permission to tour the mine were sent to the proper authority. One letter was to be signed and returned and the other was to remain with the mine office files.

A logical sequence of tour dates, based on location, was established and permission letters were sent. Fifteen permission letters were mailed to coal or operating companies, and most companies contacted did respond. Eleven companies responded with permission to tour the mines.

2.3 Mine Tours

Mine tours were conducted throughout the major coal fields of the West, in areas where extensive underground mining has occurred. The mines toured contained the best accessible examples of the geologic features that adversely affect coal mine roofs in each important coal field. Eleven (11) mines were visited. These were three in the Wasatch Plateau, one in the Book Cliffs, one in the Trinidad, two in the Carbondale, two in the Somerset/ Paonia, one in the Yampa, and one in the Grand Mesa Coal Field.

Each mine was toured with either a mining engineer or geologist who was knowledgeable about the location, types, and roof control impact of geologic features found in the mine. Three to five hours were spent underground at each mine, depending upon available transportation, distance to each feature, and amount of time spent at each feature. A micro-cassette tape recorder was used to record descriptions of geologic features, general discussion, and the number and description of each photograph taken underground. One to three rolls of 36 exposure, ASA 125, black and white film was used in each mine. Lighting was provided by a regular flash in intake air, and by "painting" with a tripod in return air locations, following MSHA regulations. Both procedures provided excellent photographic results with good contrast and depth of field. Geologic features showing either pertinent, unique, or exemplary characteristics were photographed with the tripod to obtain the best possible results. Most photographs contain a tape, rock hammer, roof bolts, cribbing, or mats for scale.

Mine tours proved to be successful and provided excellent results in the form of photography, descriptions of geologic features, and general discussion with mine personnel regarding the study. Several geologic mine maps were obtained showing roof geology (sandstone channels, crevasse-splay and other overbank deposits, and washouts) and other geologic features such as faults, igneous and clastic dikes, and coal rolls. The observed amount, quality, and diversity of geologic features causing roof control problems were extensive.

3.0 OVERVIEW OF THE DEPOSITIONAL AND STRUCTURAL GEOLOGY OF ROCKY MOUNTAIN COAL FIELDS

3.1 Introduction

The geology of coal in the Rocky Mountain region differs from that of eastern and midwestern coal deposits in several important ways. Western coal deposits are of Cretaceous and Tertiary age, and are thus considerably younger than the Carboniferous coals of eastern and midwestern North America. Associated fossils are therefore different. Lithological and structural characteristics of the coal deposits also differ, largely as a function of depositional environment. Both eastern and western coals are associated with coastal plain depositional environments that were strongly influenced by major transgressive/regressive events. However, Cretaceous Interior Sea transgressive/regressive events were much more erratic and rapid than those observed in the East and Midwest. As a result, western coal seams exhibit much greater lateral and vertical variability. Clastic dikes in the East are primarily composed of clay, as opposed to the sandstone clastic dikes found in the western coal fields. In addition, western coal is more frequently associated with widespread igneous intrusions. These factors combine to create coal mine roof control problems in the Rocky Mountain region that differ from those encountered in midwestern and eastern North America.

The following geologic description of coal-bearing formations is intended to provide a general overview of the depositional environments and associated geologic structures of the Rocky Mountain coal fields. More specific lithological, depositional, and structural information for each of the studied fields is provided in Section 4.0.

3.2 Depositional and Structural Geology

The majority of Rocky Mountain coal was deposited during Upper Cretaceous and Lower Tertiary time, from 95 to 50 million years before present. Minor coal seams of the Dakota Group, found in sediments derived from the Siouxia Arch in South Dakota and Northern Nebraska, were deposited in latest Lower Cretaceous (Aptian) time (4). However, Lower Cretaceous coal does not represent significant underground mining deposits in the Rocky Mountain region, and are not further discussed in this study.

Coal rank, thickness, and lateral extent of coal-bearing lithologies is controlled by a complex group of tectonic and depositional factors. The character of roof rock is similarly controlled. Upper Cretaceous coal differs from Tertiary coal, in that Upper Cretaceous deposition occurred in a coastal plain environment. Tertiary coals were deposited in association with terrestrial fluvial systems within structural basins formed during the Laramide Orogeny.

3.2.1 Upper Cretaceous Sedimentary Deposits

Upper Cretaceous Rocky Mountain coal was deposited from late Albian through Maestrichtian time. A Cretaceous time scale is provided as Figure 3. Coal was deposited along the western shoreline of the Cretaceous Interior Sea, a north-south trending epicontinental seaway that extended from western Utah

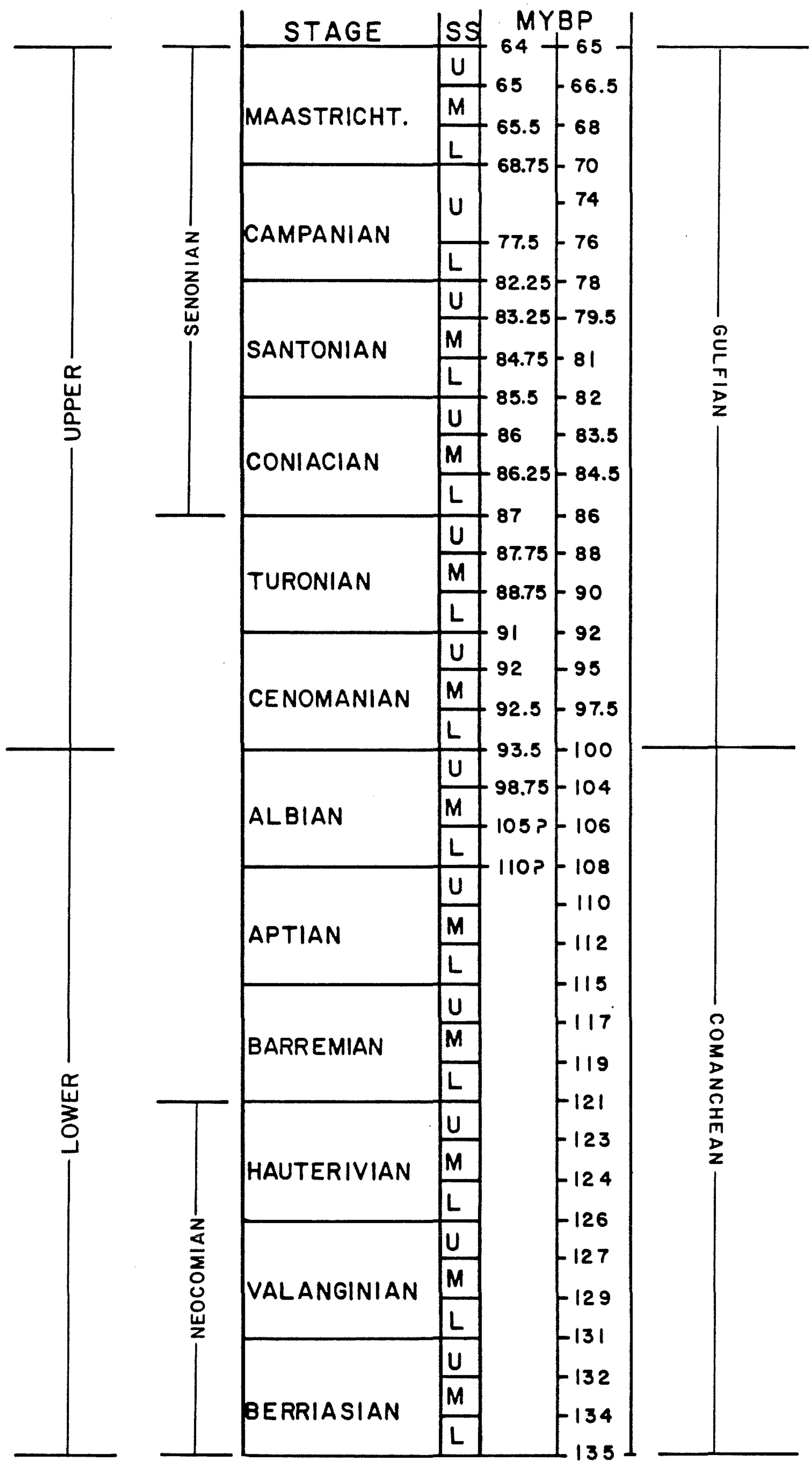

FIGURE 3. - Geologic time scale of the Cretaceous Period.

through the midwest of North America to the present day location of the Mississippi River, and from the Arctic Ocean to the Gulf of Mexico. The Sevier Orogenic Belt, an orogenic highland that was located in present day western Utah and extended from Arizona to Idaho, shed sediments eastward into an assymmetrically subsiding basin oriented along a north-south axis located in central Utah. The Sevier Orogenic Belt supplied all sediment to the basin during the Upper Cretaceous, as basin subsidence at the close of the Lower Cretaceous eliminated clastic supply from the eastern Siouxia Arch. The Cretaceous Interior Sea and the Sevier Orogenic Belt are shown in Figure 4.

A subtropical to tropical climate promoted high rates of vegetative growth, and thus permitted the deposition of large volumes of organic matter. Coal swamps formed on coastal plains between the Sevier Highland to the west, and the marine basin to the east. Rivers discharging into the marine basin formed large deltas, with associated peat swamps (5). The linear clastic shoreline of the Cretaceous Interior Sea was thus characterized by coastal swamps, littoral, barrier and strandline sands, and wave-dominated deltas. Peat deposits were later buried by marine and continental sediments in transgressive/regressive events that were erratic in rate and lateral extent.

Upper Cretaceous stratigraphy throughout the Rocky Mountain region is very complex. Deposition occurred in nonmarine, shoreline, and marine environments simultaneously. Migration of the shoreline, in response to a general regression from west to east throughout the Upper Cretaceous, which was interrupted by no fewer than four major transgressive/regressive cycles, produced large wedges of sediment that interfinger laterally and are vertically interbedded (5).

Three major sedimentary facies have been documented in the Rocky Mountain region. From west to east, these are the coal-bearing facies, the sandstone facies, and the shale facies (6, 7). Respectively, these facies represent nonmarine coastal plain, shoreline, and marine depositional environments, as shown in Figure 5.

3.2.1.1 The Coal-Bearing Facies

The coal-bearing facies is composed of nonmarine shale and lenticular sandstone interbedded with conglomerate lenses and locally thick coal seams (7). Sediments exhibit prominent channelling and cross-bedding. Volcanic ash and volcaniclastic fragments are interbedded with sandstone and conglomerate. Grain size generally diminishes to the east, grading into medium and fine cross-bedded sands with channeled bases and interbedded shales. Shale is often carbonaceous (6). Deposition of these sediments occurred in broad, open coastal swamps, delta plains, strand plains, littoral beach environments, and lagoonal and fluvial interchannel swamps (8). At least three large delta complexes have been identified, the largest of which extended from Moffat County, Colorado to Rawlins, Wyoming with dimensions of up to 150 miles in width and 250 miles in length (9). Many smaller deltaic complexes have also been identified, which were wave-dominated and are thus found in association with strandline and littoral sand deposits (10).

The coal-bearing facies is over 1,000 ft. thick in the western basin, where clastic input to the piedmont was episodically high in response to

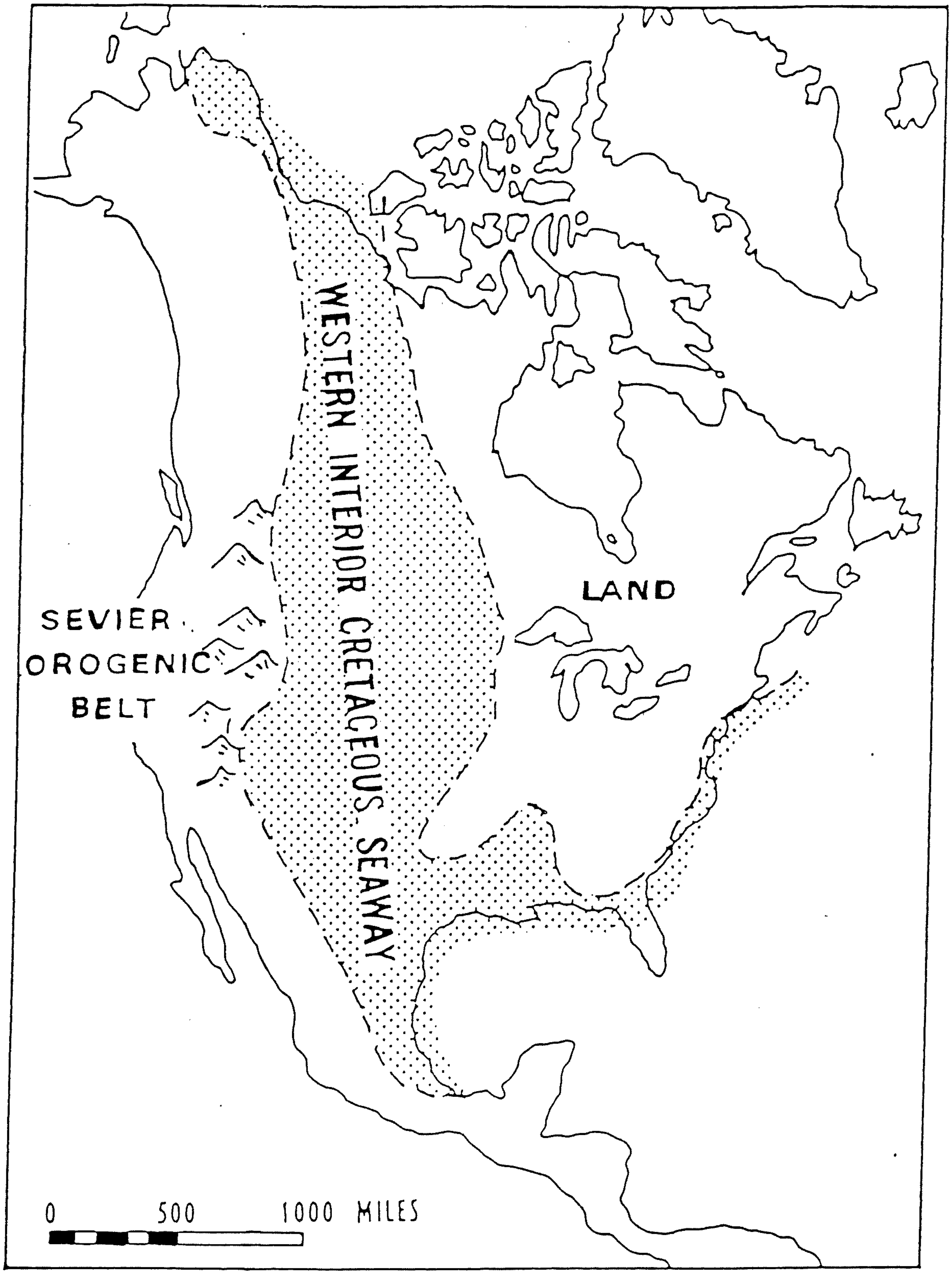

FIGURE 4. - Generalized map of the Western Interior Basin showing its extent at maximum transgression and location of the Sevier Orogenic Belt along its western margin (10). 2/

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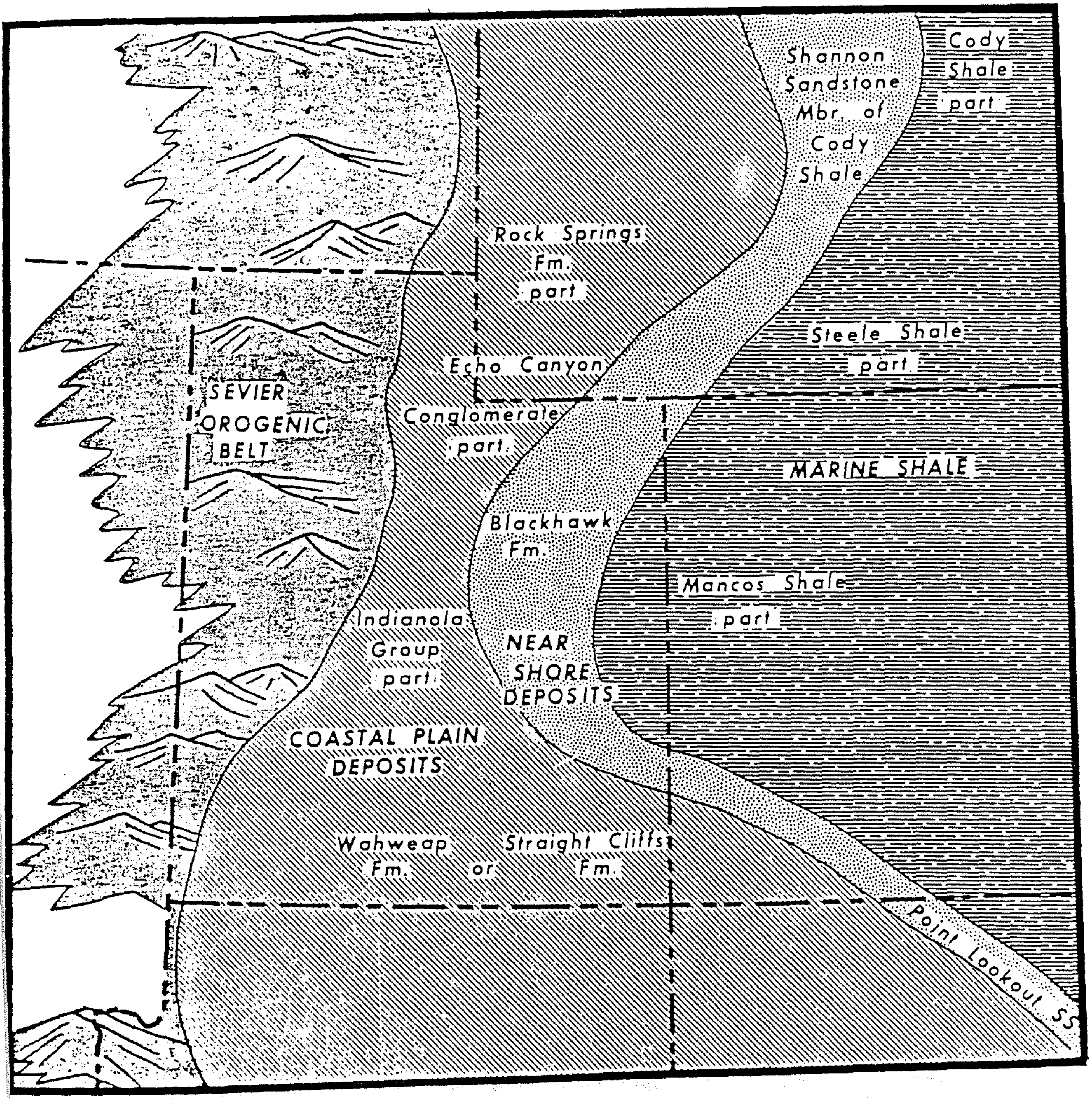

FIGURE 5. - Generalized paleoenvironments developed during the Campanian Stage when the near-shore facies Blackhawk Formation was deposited simultaneously with the coastal plain and marine facies, as shown. Lithogenetic equivalent and partially equivalent formations for each of the facies are noted in the figure (10). 3/

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erosion of the Sevier Orogenic Belt. The facies thins to the east, and splits into a number of easterly thinning tongues that interfinger with sandstone and, locally, marine shale.

The complexity of the Upper Cretaceous strata and depositional environments makes correlation of lithogenetic facies with specific formations difficult. Formations in western North America were defined prior to understanding of their depositional environments. For this reason, one formation or group may represent one or more facies. The coal-bearing units generally include, among others, the Mesaverde Group of Colorado and New Mexico, the Lance Formation, and parts of the Almond and Judith River Formations of Wyoming and Montana. Excellent studies by Weimer (7, 11, 5), Kauffman (12), and others on correlation of lithologic formations with lithogenetic units and depositional environments should be referred to for more specific information.

3.2.1.2 The Sandstone Facies

Thin to massive sands were deposited in sheet and shoestring geometries that clearly separate the coal-bearing facies in the western basin from the shale facies to the east. Sandstone beds are locally thick, up to 100 ft., and can be traced for considerable distances both along, and perpendicular to, the paleoshoreline. In Colorado and New Mexico, sheet sandstones contain locally thickened benches that are laterally persistent along the paleoshoreline for tens of miles (6). These sheet sandstones are representative of strandline sands. Isolated sand lenses, with north-south trending shoestring geometries, are interbedded with shale to the east of the main sand development, and are inferred to represent offshore barrier or shoal sands. The Eagle Sandstone is an example of this type of deposit. Examples of the sandstone facies are the Trout Creek Sandstone, Fox Hills Formation, the lower Judith River Formation of Wyoming and Montana, and the Cliff House and Point Lookout Formations of southwestern Colorado.

3.2.1.3 The Shale Facies

The shale facies is composed of extremely thick, marine, fossiliferous shale deposits that are frequently laminated and carbonaceous. Shale is associated with thin beds of limestone, siltstone, and sandstone. The thick deposits of limestone that are found throughout the midwest of North America, which indicate moderately deep, quiet-water environments with low clastic input, are not found in the Rocky Mountain region. The marine depositional environment in the Rocky Mountain region is therefore inferred to be shallow, open water. Traced to the western edge of the basin, the shale facies thins and splits into a number of tongues that interfinger with the sandstone facies deposits. Contacts are gradational with a siltstone sequence separating the shales from the very-fine silty sands of the sandstone facies. In some locations, shale directly overlies the coal-bearing facies. The shale facies group includes the Lewis, Mancos, Bearpaw, and Pierre Shale Formations.

The complex interbedding and lateral variation observed in the Upper Cretaceous sediments, as shown in Figure 6., makes generalization regarding the geological characteristics of coal field roof rocks difficult. In many

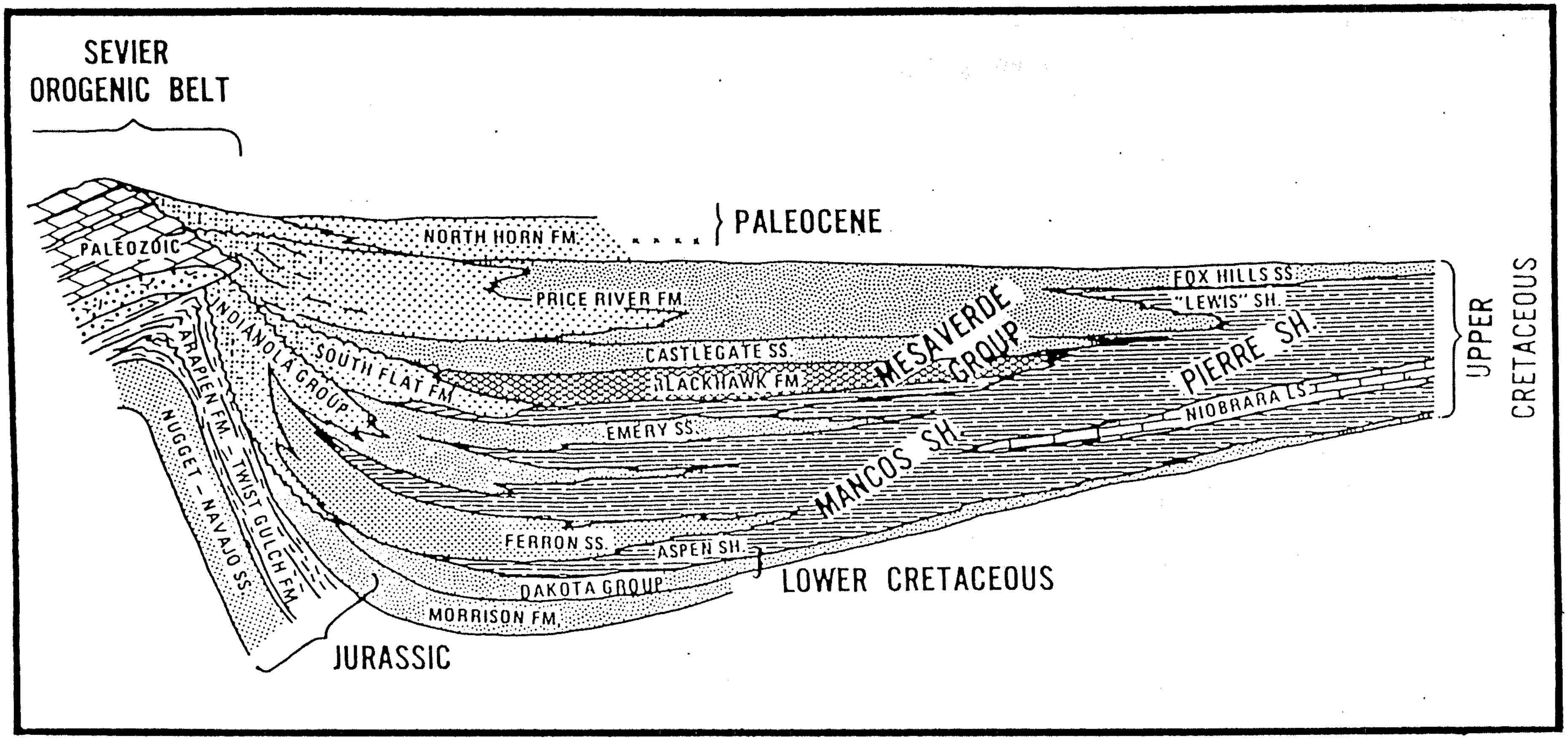


FIGURE 6. - Generalized cross-section through the Western Interior Cretaceous Basin in central Utah showing the complex interbedding and interfingering of formations and lithogenetic facies in relation to the location of the Sevier Orogenic Belt (10). 4/

places, coal is overlain by beach sands deposited during shoreline transgression. In other locations, coal is immediately overlain by marine shale deposited during periods of rapid transgression and low clastic input. Coal is also overlain by fluvial or delta plain sediments that were deposited during shoreline regression and progradation of coastal plain alluvial and deltaic systems. More detailed study would require careful stratigraphic correlation of depositional environments and transgressive/regressive events on a local scale.

3.2.1.4 Migration of the Paleoshoreline

The Cretaceous Interior Sea shoreline transgressed and regressed repeatedly in response to large scale eustatic, tectonic, sedimentologic, and climatic changes (12). Several models are found in the literature, but certainly no fewer than four major cycles occurred. Weimer (5) presents an excellent model indicating that an overall regressive trend within the basin, from west to east throughout the Cretaceous, was interrupted by four transgressive/regressive cycles, as shown in Figures 7. and 8. Weimer dates these events, which are numbered from 1-4, and are shown in Table 9. Figure 7.

TABLE 9. - Transgressive/regressive events in the Cretaceous Interior Basin

Event 1/	Time
R4	Maestrichtian Stage
T4	Upper-Campanian Stage
R3	Mid-Campanian Stage
T3	Lower Mid-Campanian Stage
R2	Lower-Campanian Stage
T2	Mid-Coniacian Stage
R1	Late-Turonian Stage
T1	Mid-Turonian Stage

1/ R is regression and T is transgression.

indicates the location of the paleoshoreline at the point of maximum regression of each cycle, and illustrates the potential for widespread migration of the sedimentary facies noted above. The paleoshoreline migrated from within 100 miles of the Sevier Orogenic Belt in Cycle R1, to a distance of over 300 miles from the highland in Cycle R4. Figure 8. clearly illustrates the resulting lateral intertonguing and vertical interbedding of sediments in response to the four events.

Another excellent model is presented by Kauffman (12). Five transgressive/regressive cycles are identified and correlated with specific lithologic sequences. These are shown in Figure 9.

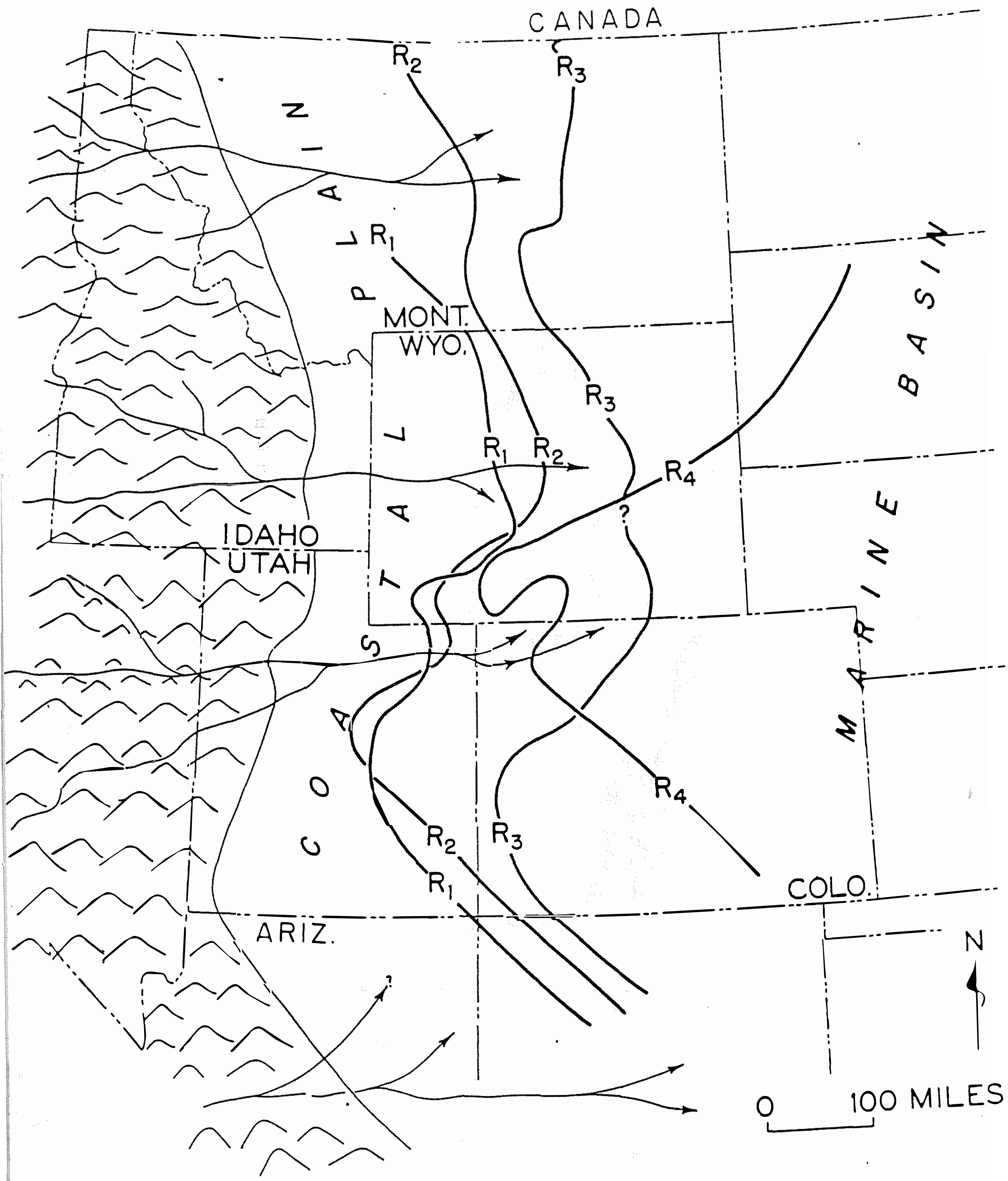


FIGURE 7. - Position of shorelines during major regressive cycles in Upper Cretaceous of Rocky Mountain region. R_1 is oldest (5).

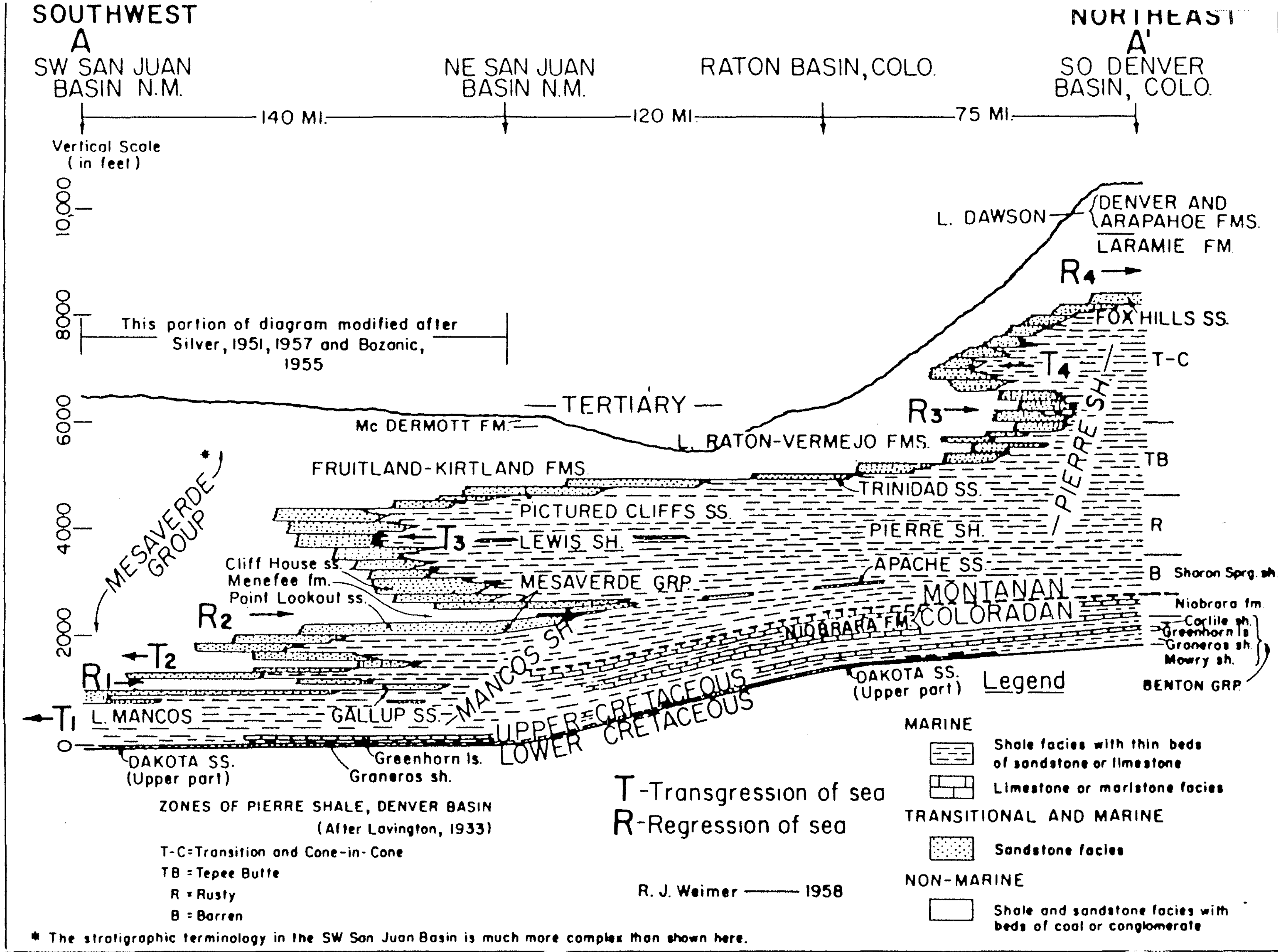
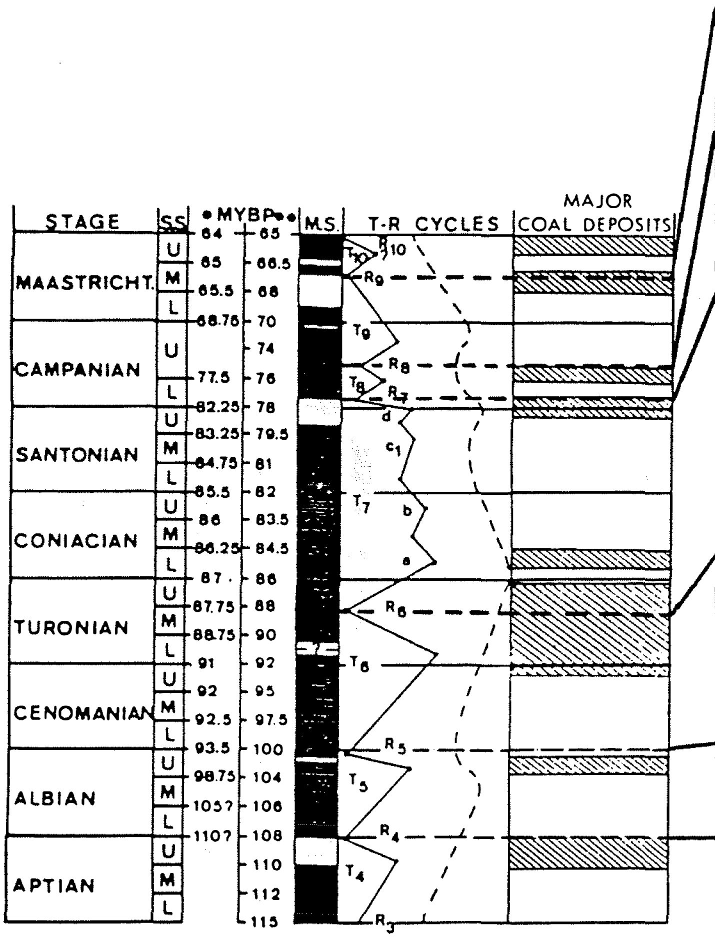


FIGURE 8. - Restored stratigraphic section across the western portion of the Cretaceous Interior Basin, showing stratigraphic distribution of lithogenetic facies in response to four major transgressive/regressive events (5).



Cyclothem	Associated Strata
Bearpaw	Cliff House Ss, Lewis Sh, Pictured Cliffs Ss, Fruitland-Kirtland sequence of New Mexico.
Claggett	Point Lookout Ss, Menefee Fm, lower Cliff House Ss sequence New Mexico, upper Emery Ss, Sh basal Mesaverde sequence of Utah.
Niobrara	Juana Lopez and Sage Brears Members of Carlisle Sh, Niobrara Group, through Apache Creek Ss member, Pierre Sh, upper part Ferron Ss, Blue Gate Sh, and lower Emery Ss member of Mancos Sh in Utah.
Greenhorn	Upper Dakota Group. Mowry and Graneros Sh, Greenhorn Fm and Carlisle Sh or equivalents through sands of Codell, Turner and Ferron members.
Kiowa Skull-Creek	Upper Dakota Group

FIGURE 9. - Generalized diagram showing five major transgressive/regressive sequences during the Upper Cretaceous and their asssociated lithologic sequences (adapted from 12).

Kauffman also targets the geologic factors controlling the observed transgressive/regressive events (8). Accelerated tectonic activity along orogenic belts worldwide has been correlated with the major transgressive events observed for the Cretaceous Interior Sea. These transgressive events are thus thought to be due to global sea-level rise in response to changes in sea-floor topography. In the Cretaceous Interior Sea, transgressive events are associated with increased clastic input from the west, probably due to increased rates of uplift and erosion during Sevier Belt orogenic activity. Periods of tectonic quiescence are correlated with regressive events and periods of lower clastic input, which provided wide, wet coastal plains suitable for thick coal accumulation. The thicker and higher quality western coal deposits can be stratigraphically correlated with periods of regression, while coals associated with transgressive episodes are characteristically higher in clastic content and thinner in extent (12).

3.2.2 Geologic Structures Associated with Upper Cretaceous Sedimentary Deposits

Upper Cretaceous sediments were influenced by several types of geologic structures. Progradational deltaic deposits are commonly offset by listric-normal growth faults, which were created by slumping along the delta front under excessive sediment loading. These faults are locally steep (60 degrees) and shallow with depth, terminating along bedding planes lower in the stratigraphic sequence. Sediments deposited in latest Cretaceous time are also influenced by normal faulting activity, related to the Laramide Orogeny, along reactivated basement faults.

Not only are sediments offset by these structures, but latest Cretaceous deposition was locally controlled as well. Larger accumulations are observed on the downfaulted blocks, resulting in variation of seam thickness. The Laramie Formation of the Colorado Front Range is an excellent example of this phenomena (5, 11). Early Laramide orogenic activity also resulted in the formation of several structural arches, which controlled facies changes in latest Cretaceous sediments. These arches include the Apishapa Uplift between the Denver and Raton Basins, and the Sawatch Range, Axial Basin, and Uinta Mountain structural trend between the Sand Wash and Piceance Basins of northwestern Colorado (7).

The close of the Cretaceous is marked by complete regression of the Cretaceous Interior Sea, and by the beginning of the Laramide Orogeny. Structural deformation throughout the Rocky Mountains at this time produced both a series of thrust-fault structures, and a number of graben features in which Cretaceous and older sediments were lowered relative to uplifted blocks of Precambrian, Paleozoic, and Mesozoic rocks. These graben structures define the intermontane basins, or "parks", where Cretaceous coal seams are located. Cretaceous sediments overlying the Laramide Orogenic Belt that were not downfaulted into protected basins were eroded, supplying the clastic material for Tertiary sedimentation.

3.2.3 Tertiary Sedimentary Deposits

Coal deposition during Tertiary time occurred within the structurally defined intermontane basins described in Section 3.2.2. Coal deposition occurred in lacustrine floodplain areas adjacent to channels, which transported large quantities of sediments shed from Laramide orogenic highlands. Fluvial channel facies were deposited in isolated interchannel flood basins that formed poorly drained, freshwater swamps. These basins were protected by levees from frequent incursions of floodwaters, allowing stable, long-term areas of peat generation. These areas were occasionally disrupted by shifts in channels and local overbank crevasse-splay sedimentation. Important coal-bearing Tertiary formations include the Raton, Fort Union, and Coalmont Formations (13).

3.2.4 Geologic Structures Associated with Tertiary Sedimentary Deposits

Intraformational structures, due to differential compaction, truncate sand lenses and related coal seams within the Raton Formation of early Tertiary age. Fluvial scouring is noted along these intraformational structures (14). Additional structural deformation of Tertiary sediments is noted along Laramide structures, as described in Section 3.2.2.

4.0 LOCATION, MINING HISTORY AND GEOLOGY OF STUDIED ROCKY MOUNTAIN COAL FIELDS

4.1 Introduction

The significant lateral and vertical lithological variation produced by the localized depositional environments that existed during deposition of Rocky Mountain coal suggests a review of geological parameters on a more local scale. The following section provides a review of the location, mining history, mining locations and geology, depositional environments, and structural geology of each studied field. Only fields with accessible, active underground coal mining operations were studied.

Coal fields are presented in rough order from west to east, following the major depositional trends described in Section 3.0. Three fields are reviewed in Utah. From west to east, and roughly south to north, these are the Emery, Wasatch Plateau, and Book Cliffs Coal Fields. The locations of these fields are shown in Figure 10. Figure 11. indicates the eight major coal regions and 21 coal fields of Colorado. The six Colorado coal fields reviewed in this report are the Grand Mesa, Somerset/Paonia, Carbondale, Yampa, Canon City, and Trinidad Coal Fields. The Raton Coal Field of New Mexico is also reviewed.

4.2 Emery Coal Field

4.2.1 Location

The Emery Coal Field is located in eastern Sevier County and western Emery County, Utah, as shown in Figure 12. The field is 4 to 8 miles in width and 35 miles long, and is approximately 210 miles in area. The Emery Field parallels the Wasatch Plateau escarpment to the south and west, along a northeasterly trend. Figure 13. is an east-west cross-section showing the structural relationship of the Emery Coal Field to the Wasatch Plateau Coal Field. The Emery Field is located 35 miles east of Salina, and 70 miles south of Price, Utah.

4.2.2 Mining History

Mining in this field began in 1881, but was sporadic until 1930. By 1912, 6,000 short tons had been produced from six mines (2, 15). Over 5.7 million short tons were produced from the field through 1981, with recent annual production averaging between 500,000 and 800,000 short tons. Remaining coal resources are estimated at 471 million short tons (15). At the time of this study, three coal mines were operating in the field with one closed, one idle, and one active.

4.2.3 Mining and Geology

All coal mined in the Emery Field is from the early Upper Cretaceous, Turonian Stage, Ferron Sandstone Member of the Mancos Shale. Figure 14. is a generalized stratigraphic section through the Emery and Wasatch Plateau Coal Fields, showing the position of major coal producing horizons. The Ferron

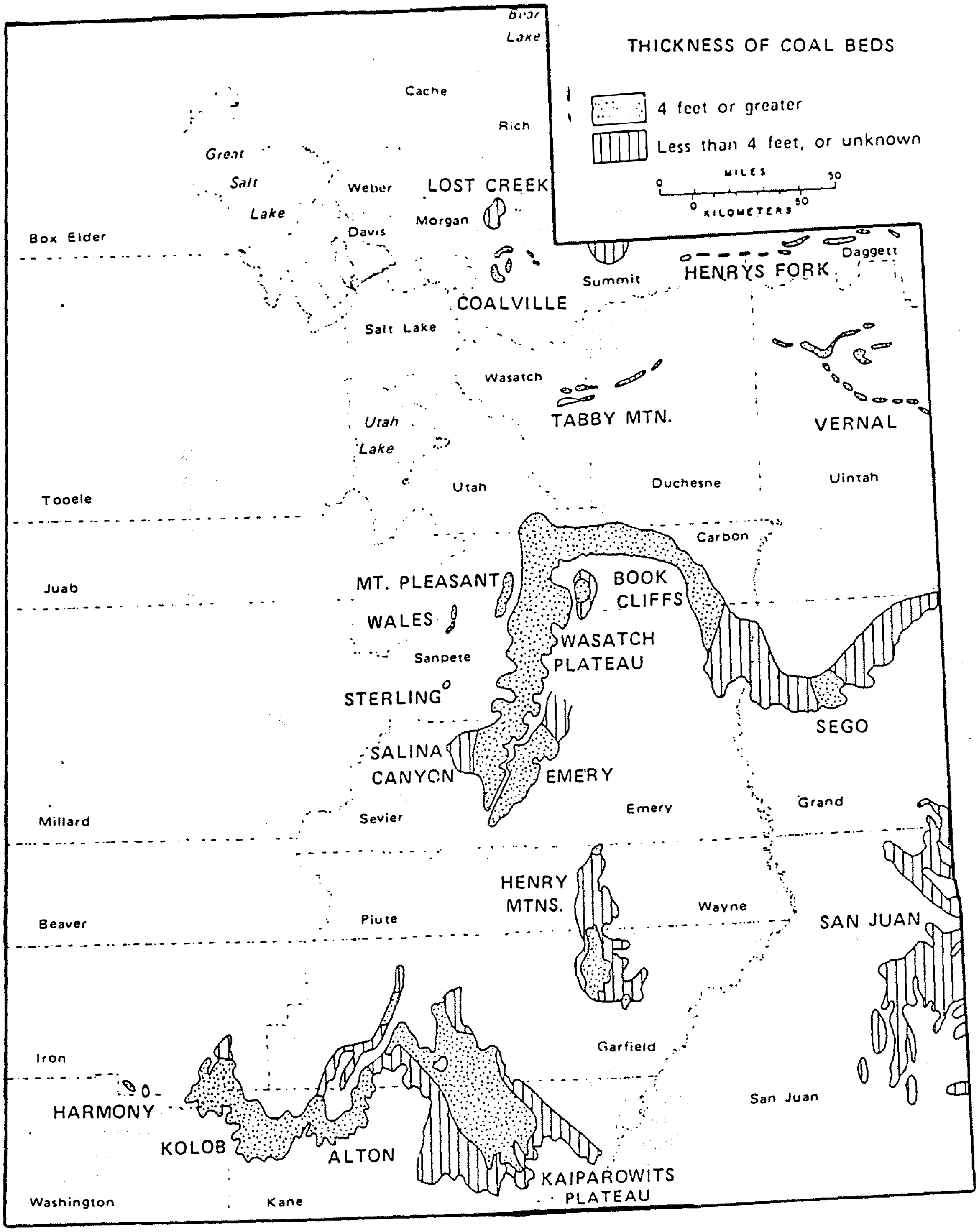
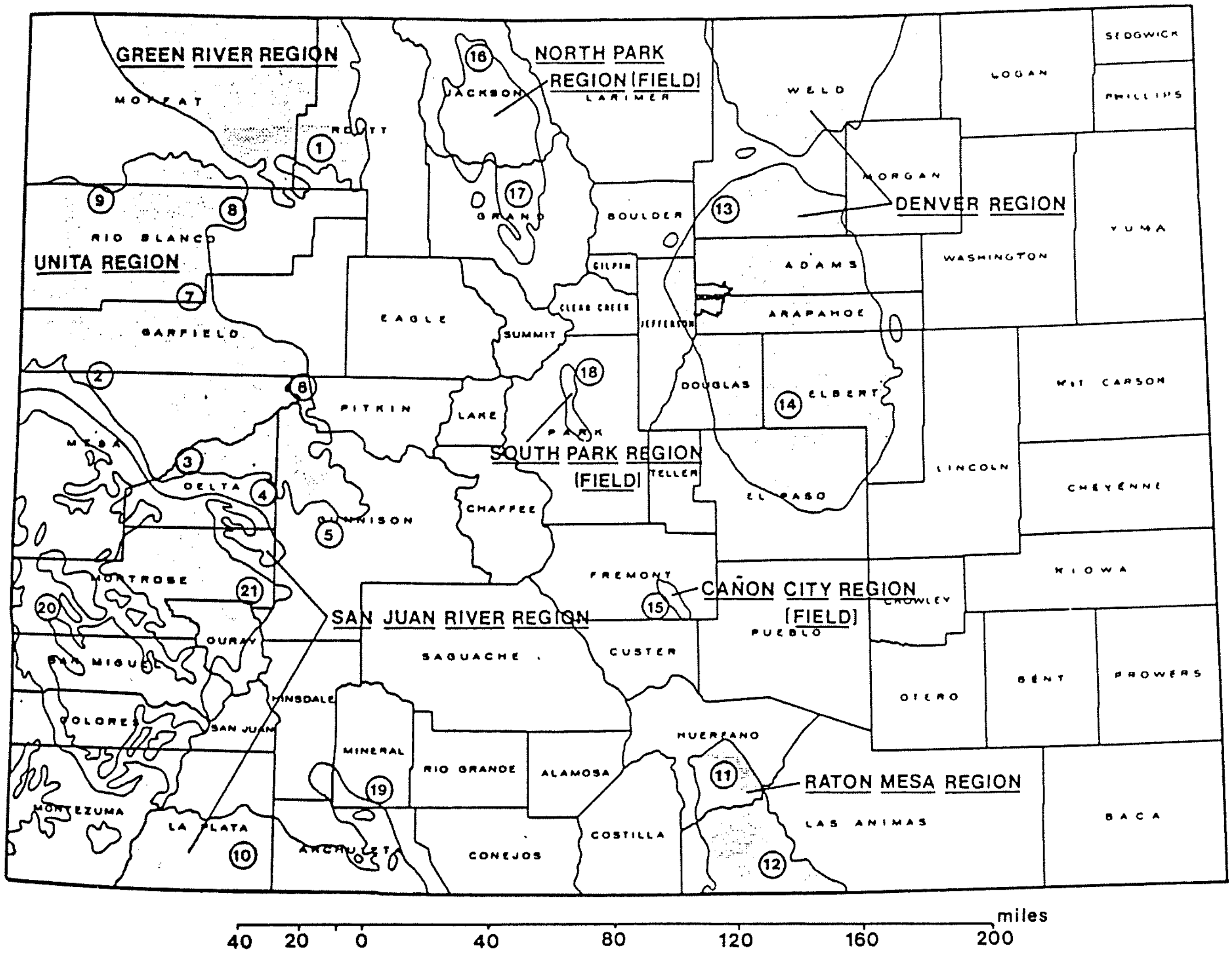


FIGURE 10. - Map showing the locations of Utah Coal Fields (15).



1. Yampa
2. Book Cliffs
3. Grand Mesa
4. Somerset
5. Crested Butte
6. Carbondale
7. Grand Hogback
8. Danforth Hills
9. Lower White River
10. Durango
11. Walsenburg
12. Trinidad
13. Boulder-Weld
14. Colorado Springs
15. Canon City
16. North Park
17. Middle Park
18. South Park
19. Pagosa Springs
20. Nucla-Naturita
21. Tongue Mesa

FIGURE 11. - Map of Colorado Coal Regions and Coal Fields (1). 5/

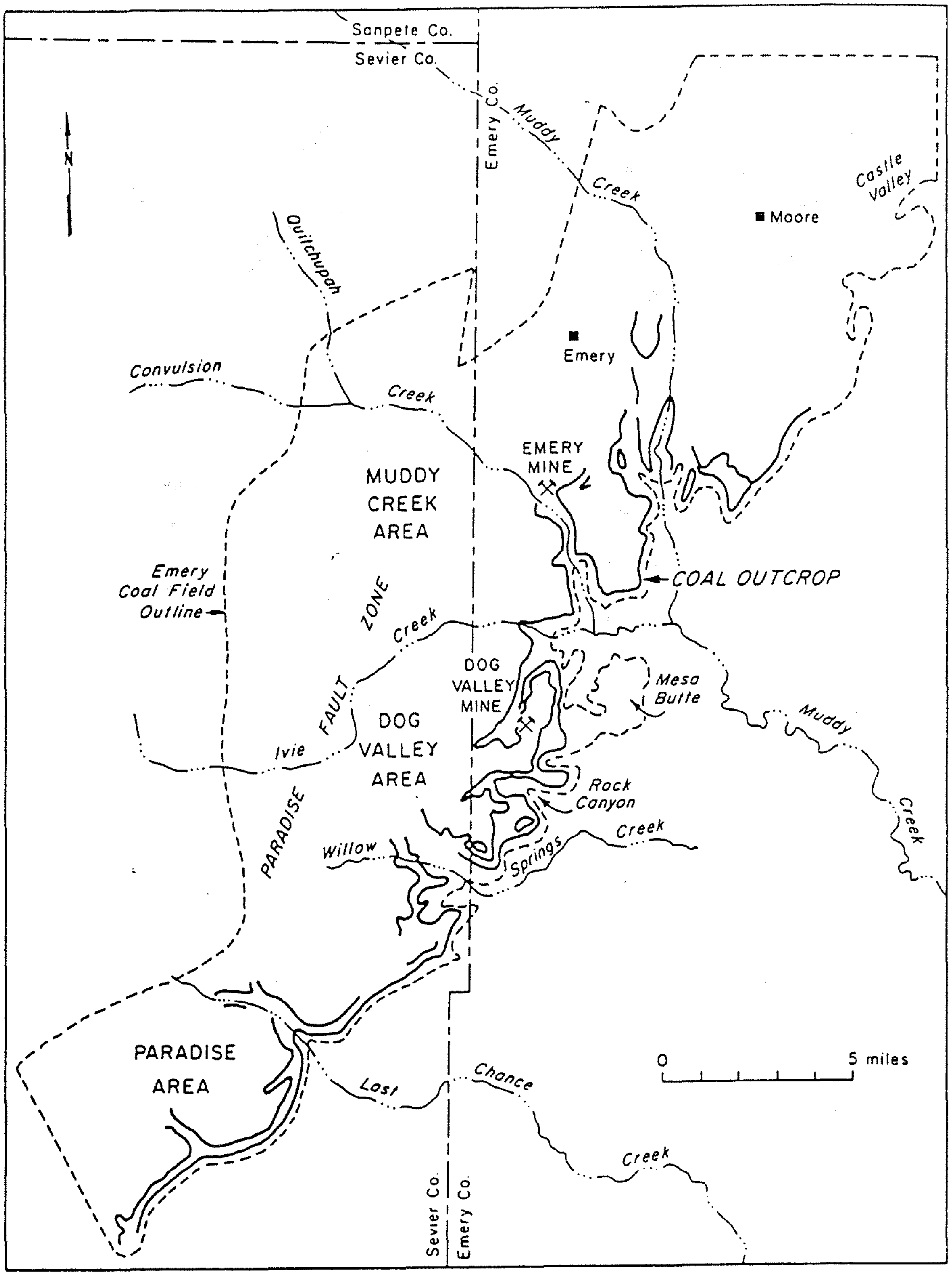


FIGURE 12. - Map of the Emery Coal Field, showing mining and coal outcrop locations (15).

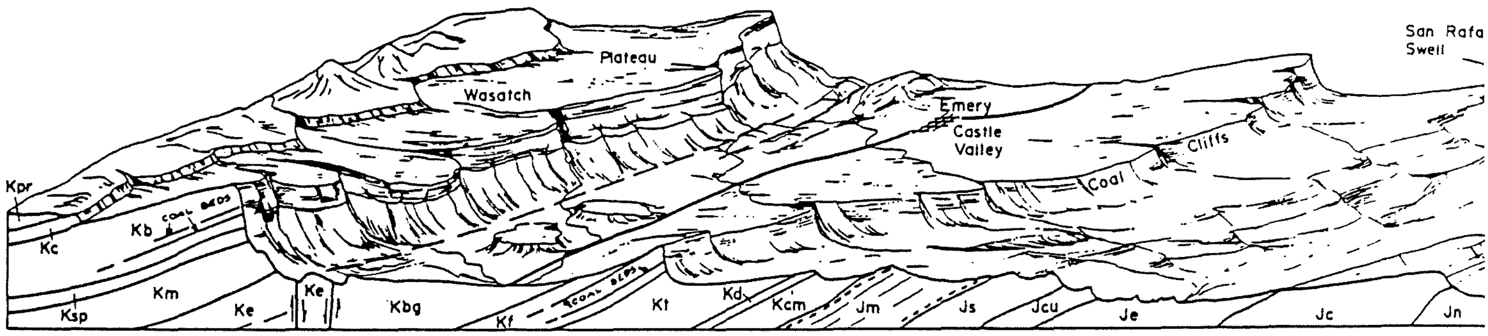


FIGURE 13. - East-west structural cross-section and physiographic diagram of the Emery and Wasatch Plateau Coal Fields (2).

Sandstone lies conformably and gradationally above the Tununk Shale, with 50 ft. to 60 ft. of thinly bedded sandstone and shale separating the two units. The lower Ferron Sandstone is a gray, fine-grained calcareous marine sandstone with two concretion zones and a uniform thickness of approximately 60 ft.

The upper Ferron Sandstone is composed of floodplain and lagoonal deposits that range in thickness up to 800 ft. The upper Ferron Sandstone beds are primarily yellow-gray and medium-grained, with sandy shale and siltstone interbeds. Shale can be clayey, silty, or carbonaceous. Coal seams are associated with the upper Ferron Sandstone shale beds, and occur within the upper two-thirds of the unit. Coal seams are lenticular in shape, and average 4 ft. to 6 ft. in thickness. Thirteen coal seams occur in three distinct groups that are seperated by barren sections. Coal seams have been assigned letter designations A through M. The lower coal group consists of seams A through E, and lies 75 ft. to 150 ft. below the middle group of seams, F and G. A second barren section separates the middle group from the upper coal group and are capped by lagoonal sediments containing the M seam. At the time of this study, two mines operated in the I seam, and one mine operated in the C seam (1).

Coal seams are laterally discontinuous and variable in quality. Many coal seams contain ash bands, splits, and other discontinuities; some are high in sulfur content (15). The coal is rated high volatile C bituminous to the north, but degrades locally to sub-bituminous in the south. Coals range from 7,800 to 12,970 in BTU value.

4.2.4 Depositional Environment

The Ferron Sandstone Member of the Mancos Shale Formation was deposited by a progradational delta that developed to the northeast onto the shelf of the Cretaceous Interior Sea (16). Lower Ferron Sandstone sands were deposited from the southwest as the basin filled with sediment. Upper Ferron Sandstone sands represent deposition of clastic material supplied by highlands to the northwest and west.

System	Series	Group	Stratigraphic Unit	Thickness (feet)	Description
TERTIARY	Eocene		Green River Formation	-	Chiefly greenish lacustrine shale and siltstone.
TERTIARY		Wasatch Group	Colton Formation	300-1,500	Varicolored shale with sandstone and limestone lenses, thickest to the north.
TERTIARY	Paleocene	Wasatch Group	Flagstaff Limestone	200-1,500	Dark yellow gray to cream limestone, evenly bedded with minor amounts of sandstone, shale and volcanic ash, ledge former.
TERTIARY / CRETACEOUS	?	Wasatch Group	North Horn Formation (Lower Wasatch)	500-2,500	Variegated shales with subordinate sandstone, conglomerate and freshwater limestone, thickens to north, slope former.
CRETACEOUS	Maestrichtian	Mesaverde Group	Price River Formation	600-1,000	Gray to white gritty sandstone interbedded with subordinate shale and conglomerate, ledge and slope former.
CRETACEOUS		Mesaverde Group	Castlegate Sandstone	150- 500	White to gray, coarse-grained often conglomeratic sandstone, cliff former, weathers to shades of brown.
CRETACEOUS		Mesaverde Group	Blackhawk Formation *MAJOR COAL SEAMS*	700-1,000	Yellow to gray, fine- to medium-grained sandstone, interbedded with subordinate gray and carbonaceous shale, several thick *coal* seams.
CRETACEOUS	Campanian	Mesaverde Group	Star Point Sandstone	90- 500	Yellow-gray, massive cliff-forming sandstone, often in several tongues separated by Masuk Shale, thickens westward.
CRETACEOUS	Santonian	Mancos Shale	Masuk Shale	300-1,000	Yellow to blue-gray sandy shale, slope former, thick in north and central plateau area, thins southward.
CRETACEOUS		Mancos Shale	Emery Sandstone *COAL (?)*	500-1,000?	Yellow-gray friable sandstone tongue or tongues, cliff former, may contain *coal* (?) in south part of plateau if mapping is correct, thickens to west and south. *Coal* may be present in subsurface to west.
CRETACEOUS	Coniacian	Mancos Shale	Blue Gate Member	1,500-2,000	Pale blue-gray, nodular and irregularly bedded marine mudstone and siltstone with several arenaceous beds, weathers into low rolling hills and badlands, thickens northerly.
CRETACEOUS	Turonian	Mancos Shale	Ferron Sandstone Member *MAJOR COAL SEAMS*	300- 800	Alternating yellow-gray sandstone, sandy shale and gray shale with important *coal* beds of Emery coal field, resistant cliff former, thickens to the south.
CRETACEOUS	Cenomanian	Mancos Shale	Tununk Shale Member	500- 800	Blue-gray to black sandy marine slope forming mudstone.
CRETACEOUS	Albian		Dakota Sandstone *MINOR COAL*	185- 300	Variable assemblages of yellow-gray sandstone, conglomerate shale and *coal*. Beds lenticular and discontinuous.
CRETACEOUS	Aptian		Cedar Mountain Formation	230- 300	Light lavender and gray shales with subordinate conglomerate and shale.
JURASSIC	Upper		Morrison Formation	150- 425	Varicolored mudstone, sandstone and conglomerate, forms slopes and conglomerate portions contain large amounts of agate and jasper.
JURASSIC			Summerville Formation	260- 275	Brown to reddish brown siltstone and sandstone, thin-bedded, semiresistant.
JURASSIC			Curtis Formation	175- 240	Tan-gray to greenish gray sandstone, siltstone and occasional conglomerate, cliffy, and softer units, occasionally glauconitic.
JURASSIC			Entrada Sandstone	600- 800	Reddish brown sandstone, fine-grained and silty, partly earthy weathering and partly smooth weathering, thin-bedded to massive, weathers into cliffs and monuments.
JURASSIC			Carmel Formation	800±	Varicolored shale, sandstone, siltstone, limestone and gypsum, limestone more prevalent in lower half and more resistant than other beds.
JURASSIC	Lower		Navajo Sandstone	500±	Orange and yellow sandstone, medium-grained cross-bedded and massive, resistant, but weathers into picturesque buttes, knolls and deep gorges.

FIGURE 14. - Generalized stratigraphic section for the Emery and Wasatch Plateau Coal Fields (2).

4.2.5 Structural Geology

Several small domes and anticlines exist within the Emery Coal Field. All units dip to the west under the regional control of the San Rafael Swell upwarp. The Joes Valley-Paradise Fault Zone, a major fault system trending N20E, essentially marks the west boundary of the field. Less significant faults also exist within the field.

4.3 Wasatch Plateau Coal Field

4.3.1 Location

The Wasatch Plateau Coal Field is the largest field, in areal extent, in the State of Utah. Figure 10. shows the location of the Wasatch Plateau Coal Field. The field trends north-south, encompasses 1,100 square miles, and is characterized by rugged topography consisting of plateaus and deeply incised canyons. Figure 13. shows the structure and physiography of the Wasatch Plateau. It is within the indicated canyons that underground coal mines are developed westward into the Wasatch Plateau.

4.3.2 Mining History

Mining began in 1875 in the Wasatch Plateau Coal Field with the opening of the Fairview Coal and Coke Company mine in Huntington Canyon. By 1877, seven mines owned by the Utah Coal Mining and Coke Company were operating in the field. In 1900, over one million tons of coal were produced by the Utah Fuel Company. Production increased with the demand for coal to power locomotives, resulting in construction of many spur lines. By 1969, 100 million tons of coal had been produced from this field. At the time of this study, 12 underground coal mines were operating in the field, with another possibly reopening in the near future.

4.3.3 Mining and Geology

Mined coal seams of the Wasatch Plateau occur only in the Blackhawk Formation of the Upper Cretaceous Mesa Verde Group. The Blackhawk Formation is a heterogenous unit of littoral, lagoonal, and fluvial sediments (15).

Sandstone is yellow-gray to white-gray, and commonly forms cliffs. Three types of shales are found within this formation. These include a soft, gray to green clay shale, a brown and black carbonaceous shale, and a gray shale which is closely associated with the coal seams. The Hiawatha and the Castlegate "A" seams are the two important mined seams. They are lenticular in geometry, and range in thickness from 4 ft. to 16 ft. Other important mined seams are the Ivie, Blind Canyon, and Wattis. Figure 15. is a map of the Wasatch Plateau Coal Field showing mines and coal outcrops. Figure 16. shows coal mining areas and coal seam extent and development within the Wasatch Plateau Coal field. The coal is ranked as a high volatile B coal with an average of 12,600 BTU's per pound.

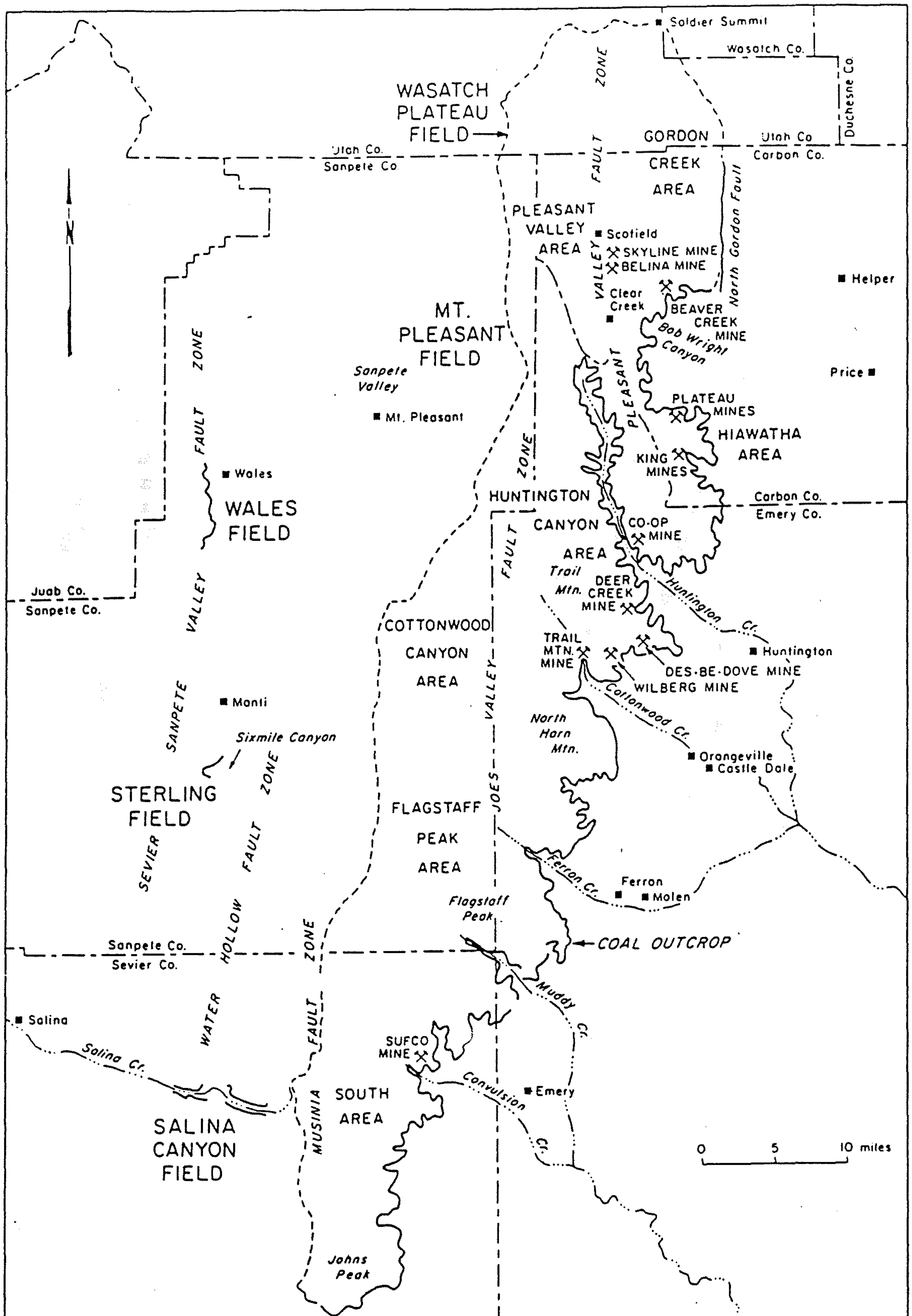


FIGURE 15. - Map of the Wasatch Plateau Coal Field, showing mining and coal outcrop locations (15).

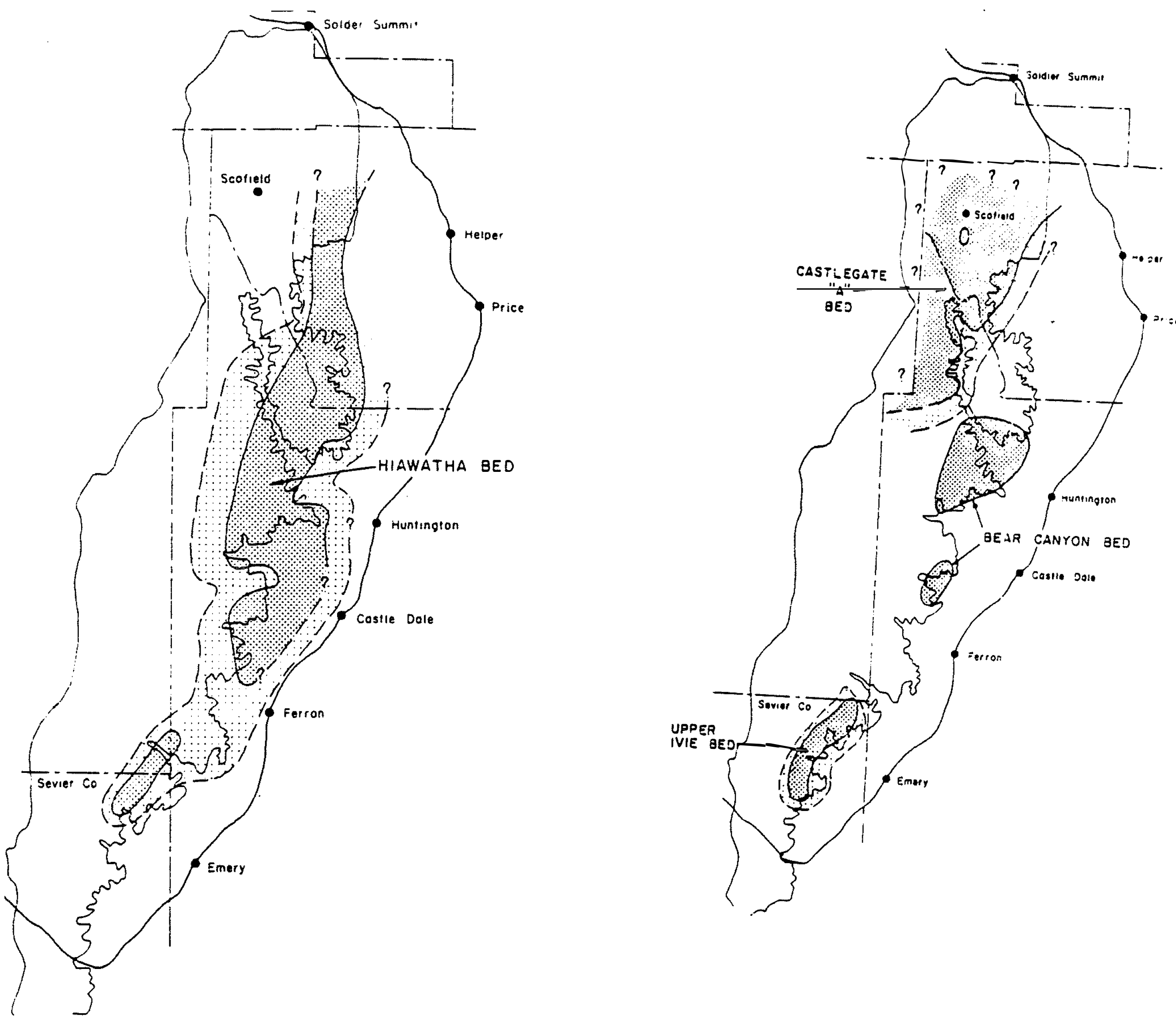
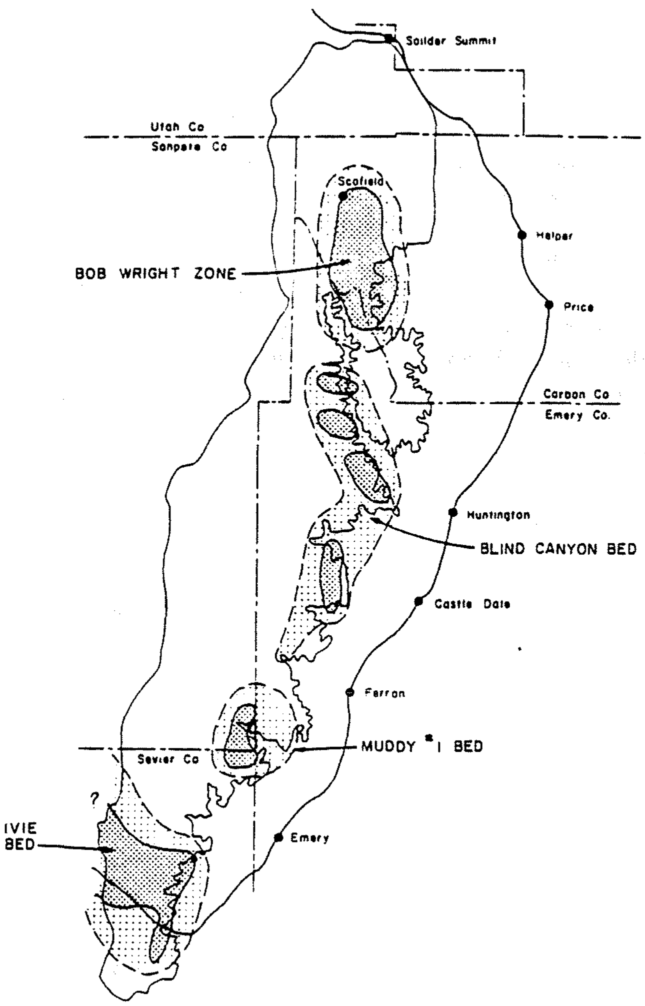
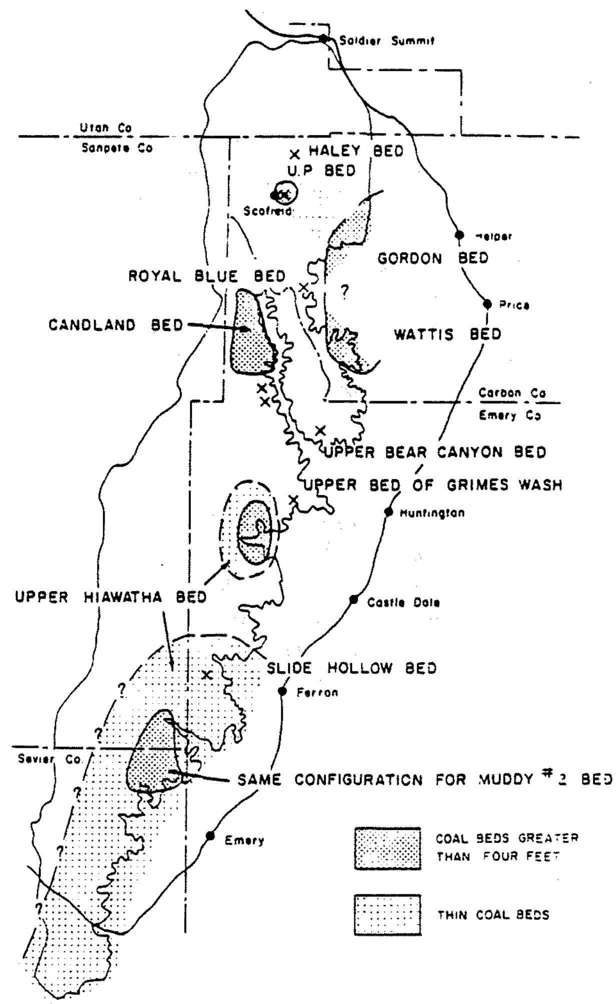


FIGURE 16. - Coal mining locations and coal seam development, Wasatch Plateau Coal Field



Soldier Summit
Utah Co
Sanpete Co
Scofield
Helper
BOB WRIGHT ZONE
Price
Carbon Co
Emery Co.
Huntington
BLIND CANYON BED
Castle Dale
Ferron
MUDDY #1 BED
Sevier Co
?
IVIE BED
Emery



Soldier Summit
Utah Co
Sanpete Co
HALEY BED
U.P BED
Scofield
Helper
GORDON BED
ROYAL BLUE BED
?
Price
CANDLAND BED
WATTIS BED
Carbon Co
Emery Co
UPPER BEAR CANYON BED
UPPER BED OF GRIMES WASH
Huntington
UPPER HIAWATHA BED
Castle Dale
SLIDE HOLLOW BED
Ferron
Sevier Co
SAME CONFIGURATION FOR MUDDY #2 BED
Emery
COAL BEDS GREATER THAN FOUR FEET
THIN COAL BEDS

4.3.4 Depositional Environment

The depositional environment of the Wasatch Plateau Coal Field sediments is comparable to that of the Emery Coal Field. Episodic deltaic stacking and progradation was followed by rapid subsidence. The coal deposits of the Blackhawk Formation are laterally extensive, but frequently thin or disappear in a landward direction. The restricted size of the lower coastal plain and proximity to the orogenic clastic source are reflected in the variety of depositional and postdepositional characteristics. Storm washover deposits are observed in the coal seam as rock partings or splay deposits. The coal seam is scoured, frequently rolls or undulates, and contains clastic dikes with sulfur concentrations in areas inferred to have been tidal inlets or tidal-flat deposits. Brackish water or lagoonal deposits are inferred where there is splitting or pinching-out of the coal seams. Differential compaction, and the presence of seam-splits, undulations, and scouring adjacent to and beneath channels, suggests the presence of distributary channels, levees, and splay deposits. Drowned interchannel deposits are probable where weak, clay rich, slickensided roof strata and mud slips occur (15).

4.3.5 Structural Geology

Coal seams of the Wasatch Plateau Coal Field generally dip gently to the west, with maximum dips of 7 degrees, and undulate in shallow synclines and anticlines. The Wasatch Plateau is transected by four major north-south trending normal fault zones with associated graben structures. These are the Nusinia, Joes Valley, Pleasant Valley, and North Gordon faults. Displacement along these structures ranges from 800 ft. to 2,500 ft. (15).

4.4 Book Cliffs Coal Field

4.4.1 Location

The Book Cliffs Coal Field is the largest producer of coal in Utah. The field extends for 70 miles from its western boundary at the North Gordon Fault Zone, where it adjoins the Wasatch Plateau Coal Field, to it's southeastern terminus at the Green River Canyon of Colorado. The field is frequently divided into its Utah and Colorado portions in the literature. This convention will be followed as necessary. Figure 17. shows the location and extent of the field, along with mining areas. The field is located approximately 125 miles southeast of Salt Lake City, and encompasses approximately 645 square miles. Coal seams are located at elevations between 6,000 ft. and 8,000 ft. within outcrops of the Blackhawk Formation, along the Book Cliffs escarpment.

4.4.2 Mining History

Coal was discovered in the Book Cliffs Field in 1874. In 1878 the Winterquarters Mine opened in Pleasant Valley. Between 1890 and 1900, over 200 coking ovens were built to coke the high quality coal. In 1919, the Sunnyside coke plant was the largest single "beehive" operation in the United States, with 819 large ovens (2). Many company towns developed in the vicinity of the remote mining areas. In 1920, six million tons of coal were mined, primarily from the Carbon County portion of the field. Through 1970,

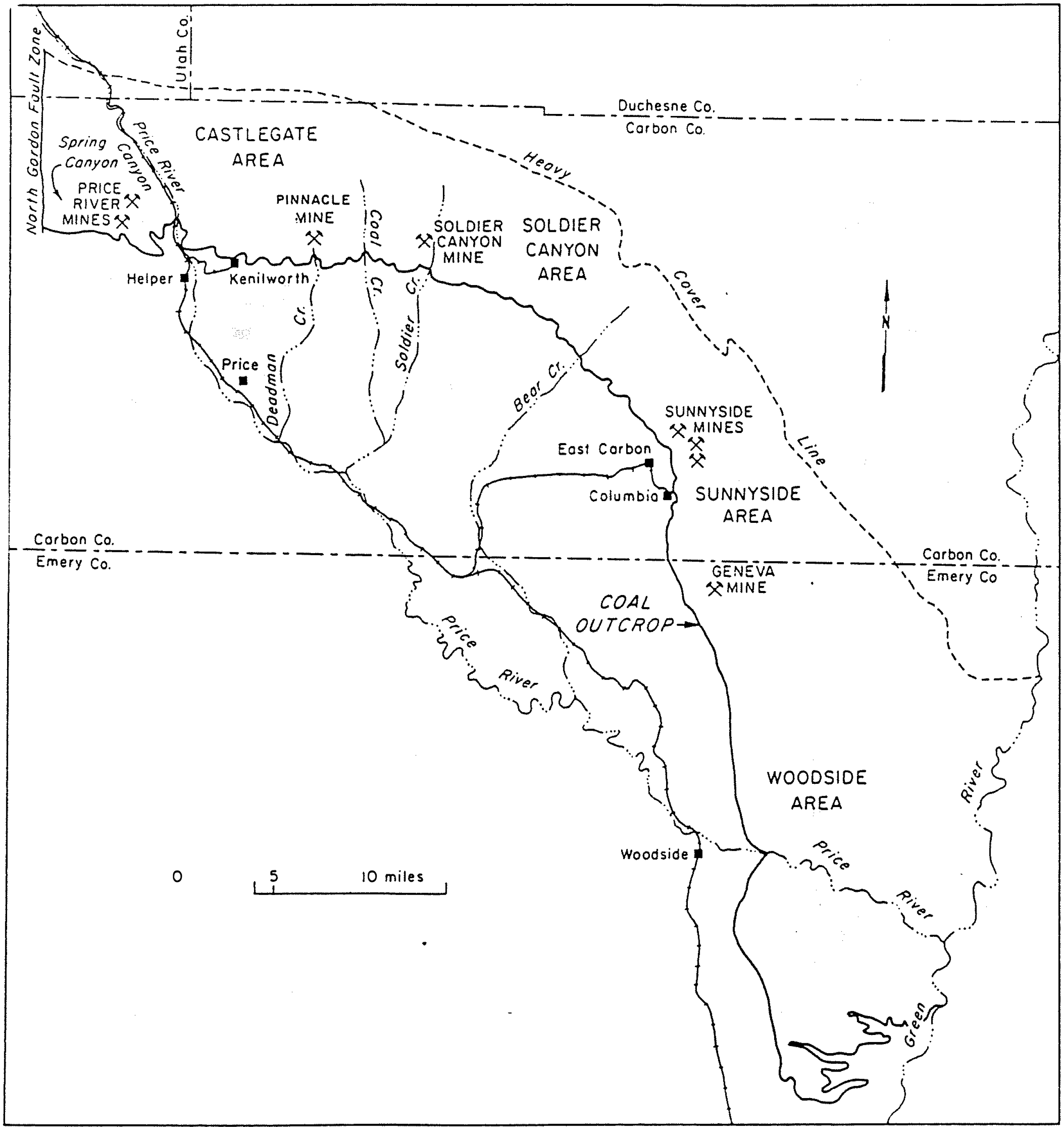


FIGURE 17. - Map of the Book Cliffs Coal Field, showing mining and coal outcrop locations (15).

the Book Cliffs Coal Field had mined 75 percent of Utah's total coal production. As of 1981, over 237 million tons had been produced from the Castlegate and Sunnyside regions of the field. Little information is available on the history of coal production in the Colorado portion of the Book Cliffs Coal Field. At the time of this study, six underground mines were operating in the Utah portion of the Book Cliffs Coal Field and two mines were operating in the Colorado portion of the Book Cliffs Field.

4.4.3 Mining and Geology

All mineable coal in the Utah portion of the Book Cliffs Coal Field comes from the Blackhawk Formation of the Upper Cretaceous Mesa Verde Group, which has been described in detail for the Wasatch Plateau Coal Field. In this coal field, the Blackhawk Formation consists of six prominent marine sandstone tongues which interfinger into the Mancos Shale, and disappear to the east. Lagoonal deposits of sandstone, shale, and coal are found between each tongue. Figure 18a. is a stratigraphic section through the Book Cliffs Coal Field showing important formations and coal seams. Figure 18b. shows two stratigraphic sections through the central and western areas of the Book Cliffs Field, and depicts the six interfingering tongues of the Blackhawk Formation. These tongues are, in descending order: the Desert Member, Grassy Member, Sunnyside Member, and Kenilworth Member of the central Book Cliffs Field, and the Aberdeen and Spring Canyon Members of the western Book Cliffs Field. The major coal seams mined in the Utah portion of the Book Cliffs Coal Field are the lower and upper Sunnyside seams, the Rock Canyon seams, and the Gilson seam. All seams average 4 ft. to 10 ft. in thickness. Figure 19. illustrates the extent of mineable coal seams in each area of the field, which are named A through J. The coal is rated as a high volatile B bituminous coal, and is of coking quality in the Sunnyside seams.

The Colorado portion of the Book Cliffs Field is contained within the Piceance Basin, a structural uplift containing over 25,000 ft. of sedimentary rocks. The majority of coal produced in the Colorado portion of the Book Cliffs Field comes from the Mt. Garfield Formation of the Upper Cretaceous Mesaverde Group. This 1,000 ft. thick unit is composed of alternating beds of sandstone, shale, and coal. Large sandstone tongues are contained within the Mt. Garfield Formation. Figure 20. is a stratigraphic column through the Colorado portion of the Book Cliffs Coal Field showing the major coal seams. Mining occurs in the Anchor seam of the upper Sego Sandstone Formation, a lithology similar to the Mt. Garfield Formation, and the Cameo and Cameo "B" seams. The Cameo seams directly overlie the Rollins Sandstone, which provides an excellent mine floor. Coal seams in the Colorado portion of the Book Cliffs Field range from 4 ft. to 11 ft. thick. Coals are rated as high volatile B and C bituminous.

4.4.4 Depositional Environment

The stratigraphic sequence observed through the Book Cliffs Field is inferred to represent littoral beach sands extending into a shallow sea environment. These beach sands were associated with construction of barrier bars, behind which fluvial sandstone, shale, and coal were deposited in deltaic and lagoonal environments.

System	Series	Stratigraphic unit	Thickness (feet)	Description
TERTIARY	Eocene	Green River Formation	–	Greenish gray and white claystone and shale, also contains fine-grained and thin-bedded sandstone. Shales often dark brown containing carbonaceous matter. Full thickness not exposed.
		Colton Formation	300-2,000	Colton consists of brown to dark red lenticular sandstone, shale and siltstone, thins westwardly and considered a tongue of the Wasatch.
		Wasatch Formation	3,000	Wasatch predominantly sandstone with interbedded red and green shales with basal conglomerate. Found in east part of field and equivalent to Colton and Flagstaff in west.
	Paleocene	Flagstaff Limestone	0- 500	Flagstaff mainly light gray and cream colored limestones, variegated shale, and fine-grained, reddish brown, calcareous sandstone.
		North Horn Formation *MINOR COAL*	350-2,500	Gray to gray green calcareous and silty shale, tan to yellow-gray fine-grained sandstone and minor conglomerate. Unit thickens to west.
CRETACEOUS	Danian			
	Maestrichthian	Tuscher Formation	0- 200	Light gray to cream-white friable massive sandstone and subordinate buff to gray shale that exhibits light greenish cast. Contains minor conglomerate and probably represents lower part of North Horn, only present in east part of field.
		Mesaverde Group: Price River Formation *MINOR COAL*	500-1,500	Yellow-gray to white, medium-grained sandstone and shaley sandstone with gray to olive green shale. Contains carbonaceous shale with minor coal and thickens along east edge of field.
	Campanian	Mesaverde Group: Castlegate Sandstone *MINOR COAL*	100- 500	White to gray, fine- to medium-grained, argillaceous massive resistant sandstone thinning eastwardly with subordinate shale. Carbonaceous east of Horse Canyon but coal is thin and lignitic.
		Mesaverde Group: Blackhawk Formation *MAJOR COAL SEAMS*	600-1,100	Cyclical littoral and lagoonal deposits with six major cycles. Littoral deposits mainly thick-bedded to massive cliff-forming yellow-gray fine- to medium-grained sandstone, individual beds separated by gray shale. Lagoonal facies consist of thin- to thick-bedded yellow-gray sandstones, shaley sandstones, shale and coal. Coal beds form basis of Book Cliffs coal field. Unit thins eastward grading into the Mancos Shale.
		Mesaverde Group: Star Point Sandstone	0- 580	Yellow-gray massive medium- to fine-grained littoral sandstone tongues projecting easterly separated by gray marine shale tongues projecting westerly.
		Mancos Shale: Masuk Tongue	4,300-5,050	Gray marine shale, locally heavily charged with carbonaceous material, slightly calcareous and gypsiferous, nonresistant forming flat desert surfaces and rounded hills and badlands. Separated mainly to the west into tongues by westward projecting littoral sandstone which eventually grade into shale. Sandstones are fine- to medium-grained, yellow-gray to tan and medium-bedded to massive and cliff forming.
	Santonian	Mancos Shale: Emery Sandstone		
	Coniacian	Mancos Shale: Garley Canyon Sandstone		
		Mancos Shale: Blue Gate Shale		
	Turonian	Mancos Shale: Ferron Sandstone *MINOR COAL*		
		Mancos Shale: Tununk Shale		
	Cenomanian	Dakota Sandstone	2- 126	Heterogeneous sandstone, conglomerate and shale, thin resistant cuesta former.

FIGURE 18a. - Stratigraphic section for the Book Cliffs Coal Field (2).

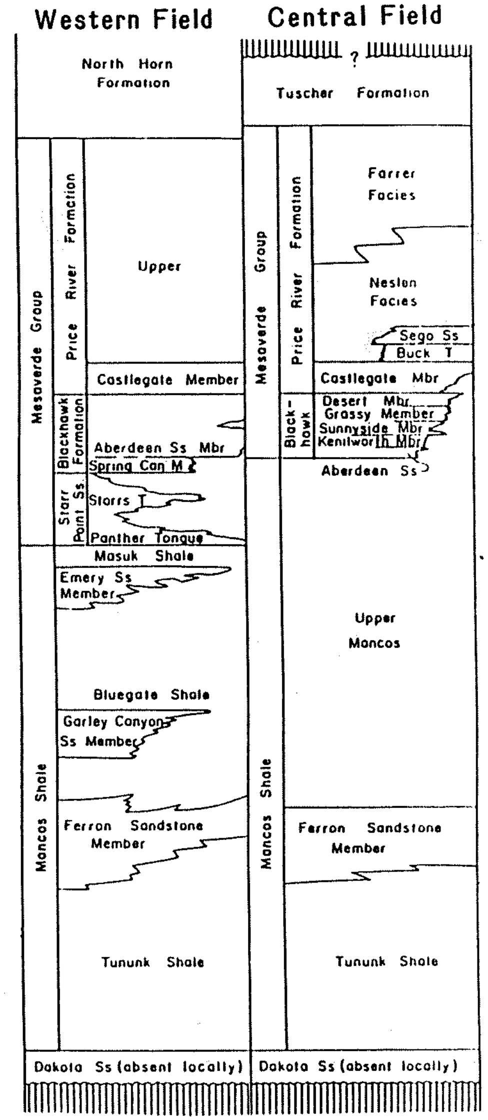
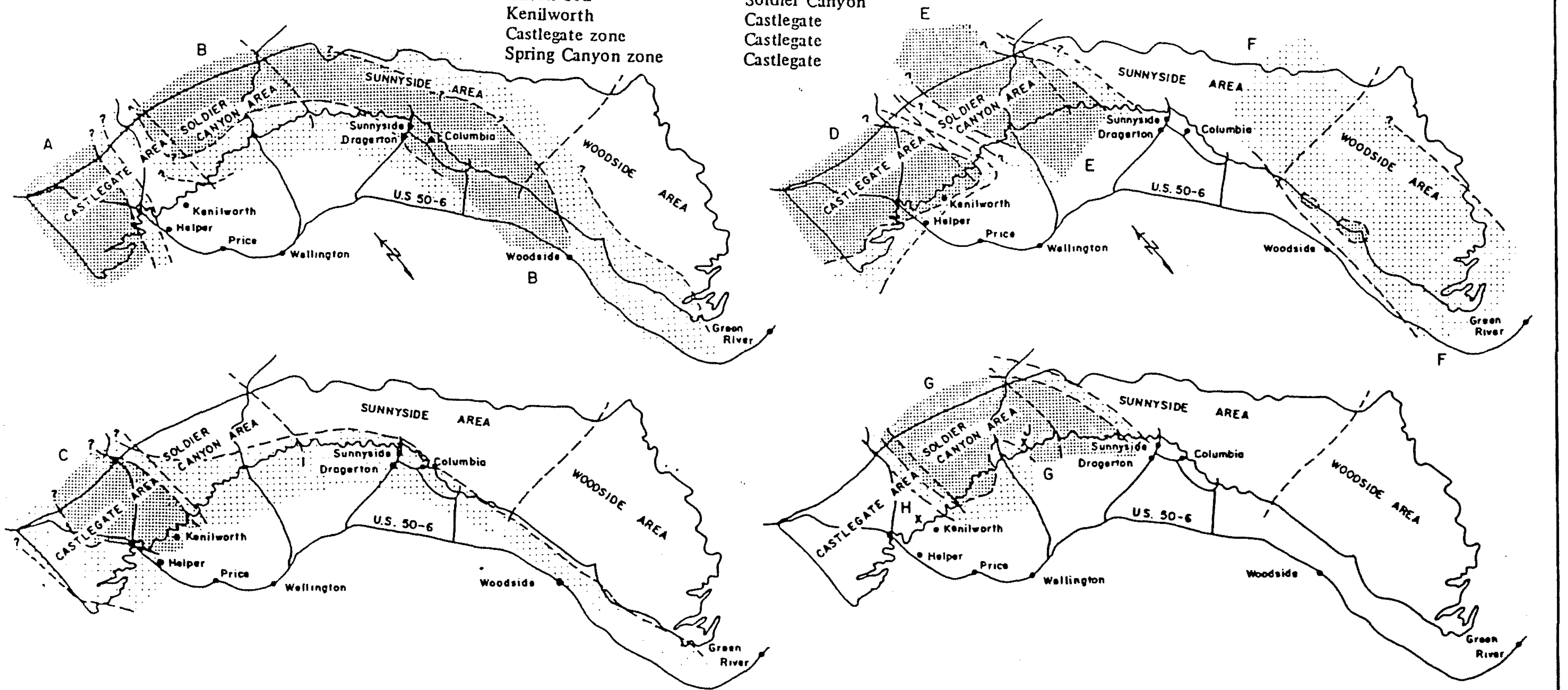


Figure 18b. - Stratigraphic sections through the western and central Book Cliffs Coal Field showing sandstone tongue members (2).

Coal bed or zone	Area of Importance
Beckwith zone	Woodside
Upper Sunnyside bed	Sunnyside
Lower Sunnyside bed	Sunnyside
Rock Canyon bed	Soldier Canyon and Sunnyside
Fish Creek bed	Soldier Canyon
Gilson bed	Soldier Canyon
Kenilworth	Castlegate
Castlegate zone	Castlegate
Spring Canyon zone	Castlegate



Approximate areas of Spring Canyon (A), Sunnyside (B) and Kenilworth (C) coal development, Book Cliffs coal field. Dark pattern indicates beds 4 feet or more thick, light pattern area of thin coal beds.

Approximate areas of Castlegate (D), Rock Canyon (E), Beckwith (F), Gilson (G), Royal Blue (H) and Fish Creek (J) coal development, Book Cliffs coal field. Dark pattern indicates beds 4 feet or more thick, light pattern area of thin coal beds.

FIGURE 19. - Location and extent of mined coal seams in each area of the Book Cliffs Coal Field (2).

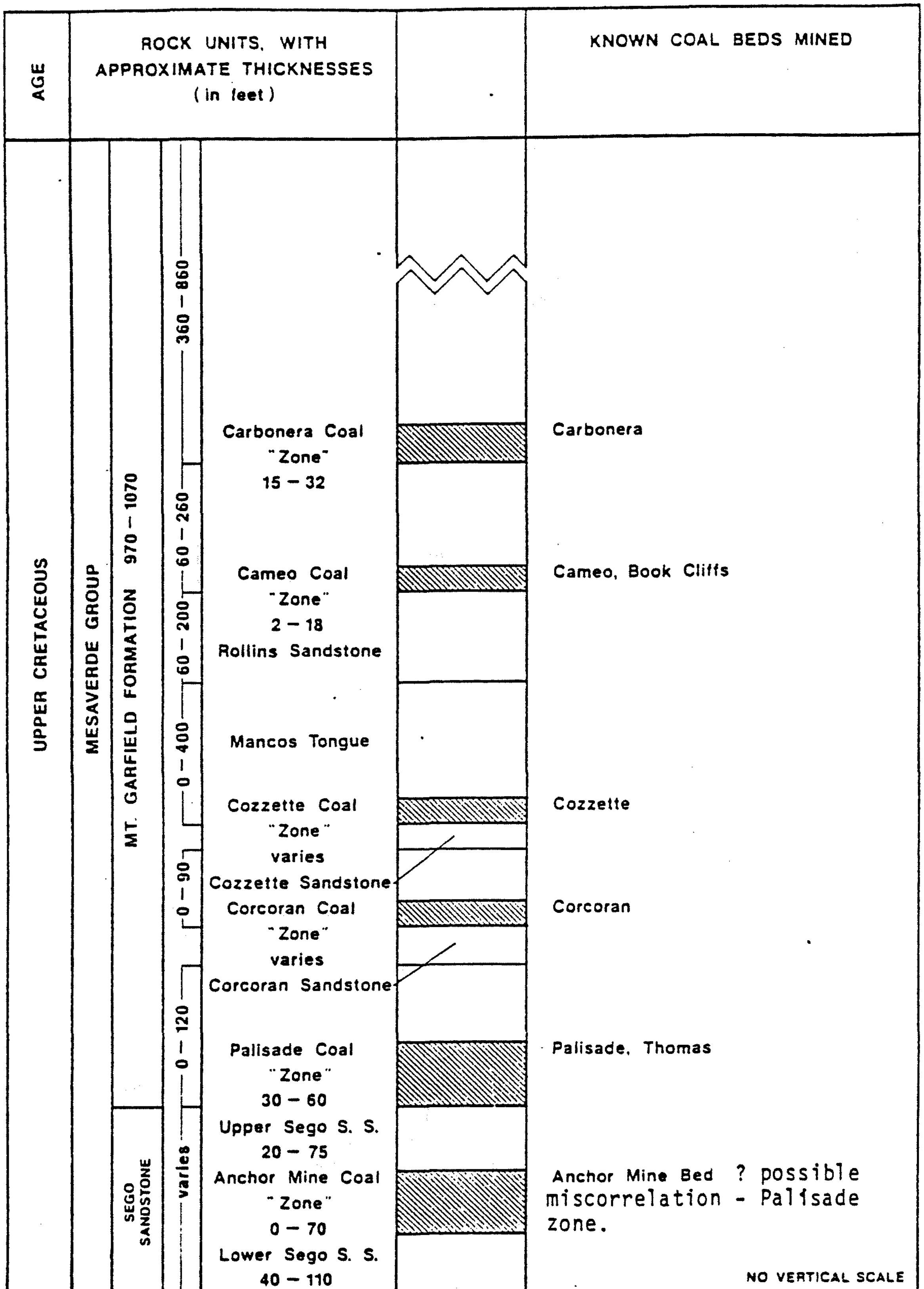


FIGURE 20. - Stratigraphic column, coal-bearing Mesa Verde Group, Book Cliffs Coal Field (1). 6/

4.4.5 Structural Geology

The Book Cliffs form a 185 mile structural uplift that extends from Grand Junction, Colorado north and west to Spring Canyon, Utah, and marks the southern boundary of the Uinta Basin. Strata along the Book Cliffs dip northward into the Uinta Basin, with an average dip of 4 to 7 degrees. North-northwest and east-northeast trending faults truncating the coal seams generally have moderate displacements, with maximum offsets of 200 ft. (2).

4.5 Grand Mesa Coal Field

4.5.1 Location

The Grand Mesa Coal Field is located at the southern edge of the Piceance Creek Basin, in Delta and Mesa Counties, Colorado. The field is situated on the southern and western flanks of Grand Mesa, a very large mesa landform capped by Tertiary volcanic flows. It extends from Palisades on the Grand River southeast to the West Elk Mountain, and from the southern flank of Grand Mesa north into the center of the Piceance Creek Basin (17).

4.5.2 Mining History

Little is known about the early mining history of the Grand Mesa Field. One underground mine was operative in the Grand Mesa Field in 1981 (1).

4.5.3 Mining and Geology

Coal is mined from the Mt. Garfield Formation of the Mesaverde Group, which has been described in Section 4.4.3. Coal seams occur in the Cameo coal zone and the Palisades coal zone of the Bowie Shale member, and extend continuously west into the Book Cliffs Coal Field. To the east, coal seams are intruded by igneous rocks (17). Coal rank is sub-bituminous A to high volatile bituminous C (1).

4.5.4 Depositional Environment

The depositional environment for the Mt. Garfield Formation has been discussed in Section 4.4.4. Coal seams overlie and interfinger with the Rollins Sandstone member, a regressive marine deposit, and were deposited in lagoonal and interdistributary delta-plain near-shore environments (18).

4.5.5 Structural Geology

Stratified sedimentary rocks in the northern portion of the Grand Mesa Field dip gently to the north within the regional structure of the Piceance Creek Basin. To the south, beds are irregularly folded, and exhibit variable strike and dip. Beds are disrupted by igneous intrusive rocks, such as Mt. Gunnison, and dip steeply away from igneous intrusive contacts. Coal-bearing sediments are locally upturned at the outcrop, and dip approximately 8 degrees toward the Grand Mesa landform. With these exceptions, the Grand Mesa Field exhibits only minor faulting and folding. Few seam-offsets along fault structures are reported (17).

4.6 Somerset/Paonia Coal Field

4.6.1 Location

The Somerset/Paonia Coal Field is located to the southeast of the Book Cliffs Field, within the Piceance Basin, in eastern Delta County and western Gunnison County, Colorado. Located to the north of the towns of Somerset and Paonia, this field is structurally related to the Grand Mesa Field. The field is occasionally treated as two distinct fields in the literature, with the Paonia Field being located to the southwest of the Somerset Field.

4.6.2 Mining History

Little information is available on the history of mining in the Somerset/Paonia Coal Field. At the time of this study, seven underground coal mines were operating in the area. Three mines in the Paonia field belong to the Bear Coal Co.; another, the Somerset Mine, belongs to the U.S. Steel Mining Company. The Somerset Mine is the largest underground mine in Colorado, producing approximately one million tons of coal per year (1).

4.6.3 Mining and Geology

All seams mined in this field are found within the late-Campanian to early-Maestrichtian age Williams Fork Formation of the Upper Cretaceous Mesaverde Group. The Williams Fork Formation, as shown in the stratigraphic column provided as Figure 21., consists of alternating sandstone, sandy shale, carbonaceous shale and coal seams, and conformably overlies the Trout Creek Sandstone member of the Iles Formation. The Williams Fork Formation is generally divided into three sections. A lower unit composed of shale, thin sandstone, sandy shale, and several coal seams, ranges from 900 ft. to 1500 ft. thick throughout northwestern Colorado. This lower unit is overlain by the Twenty Mile Sandstone member, a white, massive cliff-forming sandstone. The upper Williams Fork Formation is composed of interbedded sandstone, sandy shale, shale, and sandstone with coal seams (19). Total thickness of the formation is as great as 2300 ft. to the west. In the Somerset/Paonia area, six coal seams ranging from 1 ft. to 30 ft. in thickness are found in the lower Williams Fork Formation. These seams are designated A through F. Coal is rated as high volatile B and C bituminous with coking coal being produced at the Somerset Mine.

4.6.4 Depositional Environment

Regression of the Cretaceous Interior Sea during mid-Campanian time set the stage for deposition of the Williams Fork Formation. The coal-bearing sandstone and shale of the lower Williams Fork Formation were deposited in lowland deltaic, floodplain, and swamp environments. Coal-bearing sediments were deposited by fluvial channels migrating over swampy lowlands into coastal lagoons. Brackish and fresh water conditions prevailed with occasional oscillation of the shoreline resulting in deposition of marine sediments such as the Twenty Mile sandstone. Uppermost Williams Fork sediments were deposited during a transgressive event in upper-Campanian time (20).

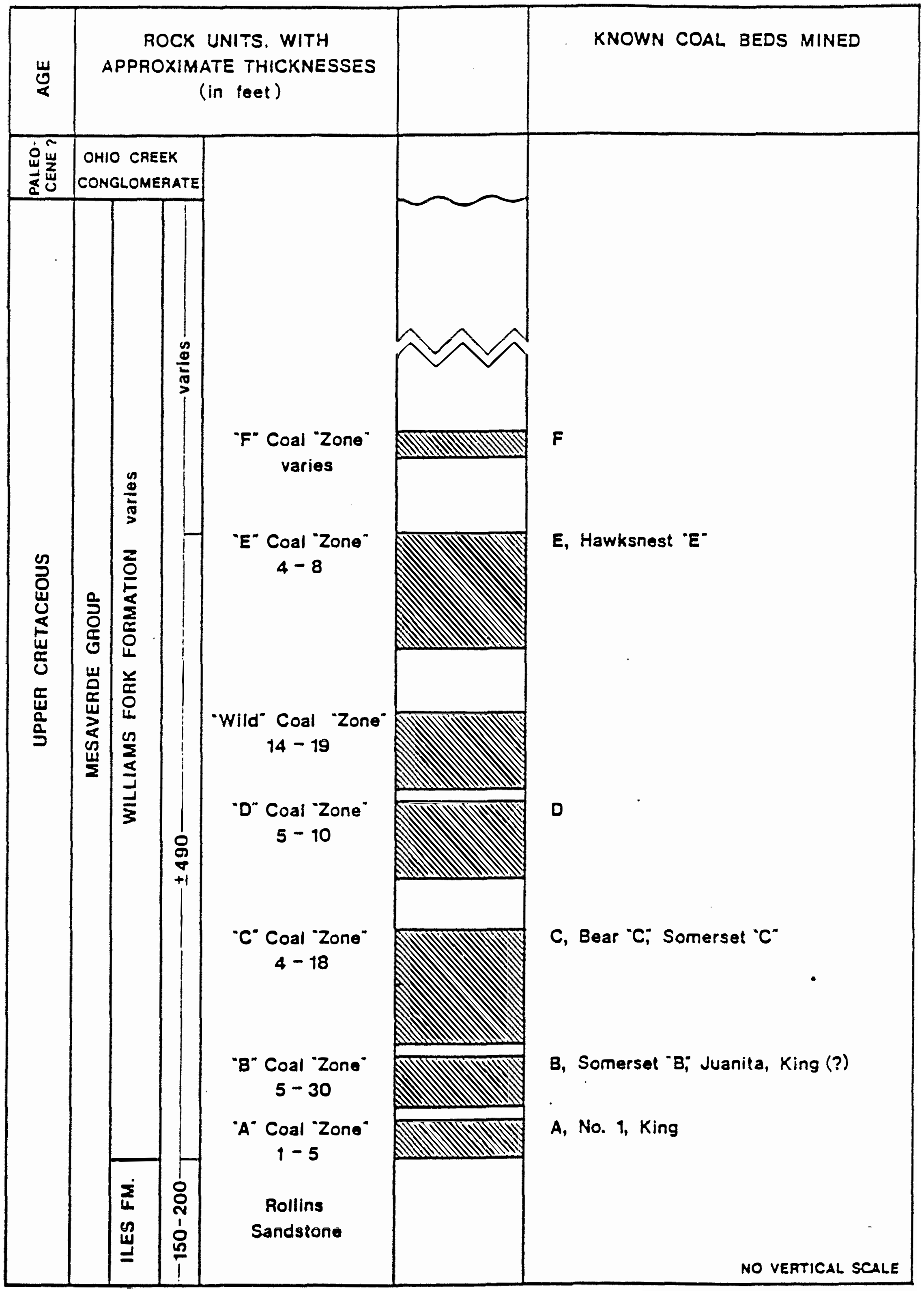


FIGURE 21. - Stratigraphic column, coal-bearing Williams Fork Formation, Upper Mesa Verde Group, Somerset/Paonia Coal Field (1). 7/

4.6.5 Structural Geology

Faulting occurs in the Somerset/Paonia Field.

4.7 Carbondale Coal Field

4.7.1 Location

The Carbondale Coal Field is located to the east of the Book Cliffs Field and to the west of the town of Carbondale and Highway 133 in Pitkin County, Colorado. The field is located within the eastern Piceance Basin.

4.7.2 Mining History

Coal mining in the Carbondale Field began in the 1880's and has continued to present, producing 22 million tons of coal as of 1976. Several mines operated until 1916, when Colorado Midland Railroad service was discontinued and large-scale production ceased. Production increased in the 1950's, with the greatest productivity (one million tons) in 1975 (21).

At the time of this study, five mines were operating in this field, four of which are owned and operated by Mid-Continent Resources, Inc. The Snowmass Mine No. 1 is partially funded by the U.S. Bureau of Mines, as it is the only steep pitch (26 to 34 degrees) longwall mine in operation in the United States (1).

4.7.3 Mining and Geology

Several coal seams are mined within the Williams Fork Formation of the Upper Cretaceous Mesaverde Group. The lithological characteristics of the Williams Fork Formation have been discussed for the Somerset/Paonia Field, in Section 4.6.3. The Mid-Continent mines extract coal from the B and C seams of the Fairfield Coal Group in the lower Williams Fork Formation. The Fairfield Coal Group directly overlies a tongue of the Rollins-Trout Creek Sandstone, which provides an excellent floor where encountered. Seams range, on the average, from 7 ft. to 12 ft. thick. The Snowmass Mines extract coal from the Sunshine A and B seams, and Anderson seam, which overlie the Fairfield Coal Group. The Anderson seam is located 780 ft. above the Sunshine seams. The Sunshine seams average 7 ft. in thickness, while the Anderson seam averages 9 ft. to 10.5 ft. thick. Figure 22. is a stratigraphic section in the vicinity of the Carbondale Field.

4.7.4 Depositional Environment

The depositional environment of the Williams Fork Formation has been discussed for the Somerset/Paonia Field in Section 4.6.4.

4.7.5 Structural Geology

The Piceance Basin is bound by the Uinta Uplift to the north, the White River Uplift and Elk Mountains to the east and southeast, the Elk and West Elk Mountains and the Gunnison Uplift to the south, the Uncompahgre Uplift to the southwest, and the Douglas Creek Arch to the west. The Grand Hogback, a

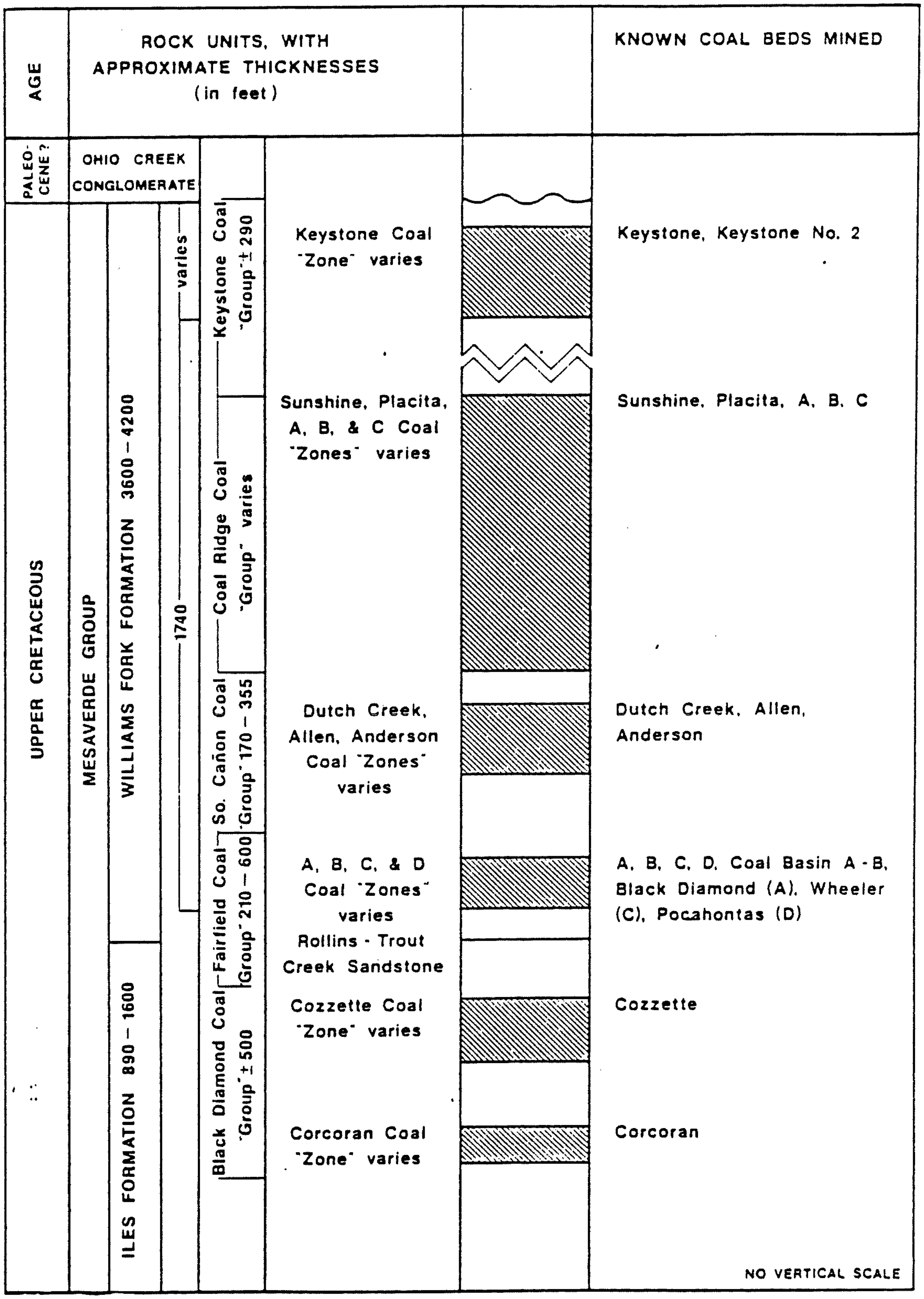


FIGURE 22. - Stratigraphic column, coal-bearing part of the Mesa Verde Group, Grand Hogback and Carbondale Fields (1). 8/

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westerly dipping monocline composed of the coal-bearing Mesa Verde Group, extends north for 90 miles from Marble, Colorado (21). Dips range from 10 to 90 degrees along the hogback structure (22). High-angle normal faulting within the coal-bearing units is observed in association with the monocline, particularly in the southern portion of the eastern Piceance Basin (21). Igneous intrusive rocks are also associated with coals in the eastern Piceance Basin.

4.8 Yampa Coal Field

4.8.1 Location

The Yampa Coal Field encompasses approximately 600 square miles and is located in northwestern Colorado in parts of Routt, Rio Blanco, and Moffat counties. The field extends from Steamboat Springs in the east along a west-northwest trend through Craig, Colorado, with mining to the southwest of Craig.

4.8.2 Mining History

Approximately 192 coal mines have operated in the Yampa Coal Field since the late 1800's, with 90 million tons produced as of 1979 (23). At the time of this study, three underground mines were in operation.

4.8.3 Mining and Geology

Coal is mined from the Isles and Williams Fork Formations of the Upper Cretaceous Mesaverde Group. Coal is presently mined from the 5 ft. thick Pinnacle seam of the Iles Formation, which is underlain by sandstone and overlain by 18 in. of sandy shale. The Iles Formation is a variable succession of coal-bearing sandstones and shales that grade downward into and interfinger with the Mancos Shale. A basal sandstone is overlain by a variable sequence of light-gray to pale-brown, medium-grained sandstone with interbedded dark-gray to brown carbonaceous shale and coal. Six major coal zones occur within the Iles Formation from 210 ft. above the base of the formation to the upper Trout Creek Sandstone of the Iles Formation. Seams range in thickness up to 12 ft. (23). The Iles Formation is 1350 ft. thick in the Yampa Coal Field, and is of mid to late-Campanian age (20). Figure 23. is a stratigraphic section through the Iles Formation. Three seams are mined from the Williams Fork Formation. These are the F, I, and P seams, which are indicated in the stratigraphic section shown as Figure 24. The Williams Fork Formation has been described in Section 4.6.3. The Lance, Fort Union, and Wasatch Formations are also coal-bearing in this area, although little data on mining and related geology is available (23). Coal is generally high volatile C bituminous in rank, but is locally higher in rank where associated with small igneous intrusive bodies (24).

4.8.4 Depositional Environment

The depositional relationship between the Iles and Williams Fork Formations is shown in Figure 25. The Iles Formation was deposited during a period of extensive regression during mid-Campanian time. Sediments represent a sequence of floodplain, swamp, and littoral marine conditions. Sandstone

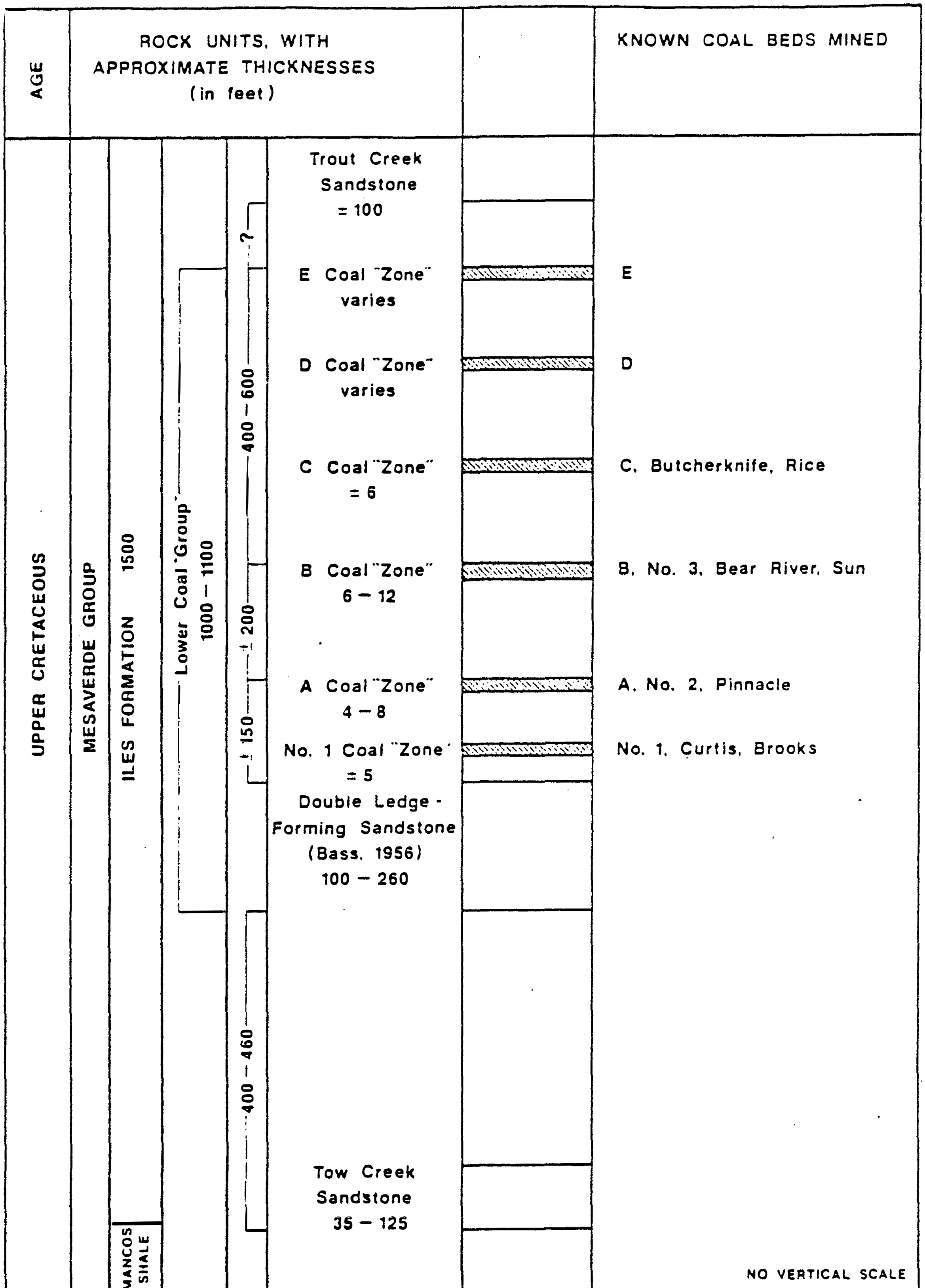

FIGURE 23. - Stratigraphic column showing coal-bearing portions of the Iles Formation, Lower Mesa Verde Group, Yampa Coal Field (1). [9]

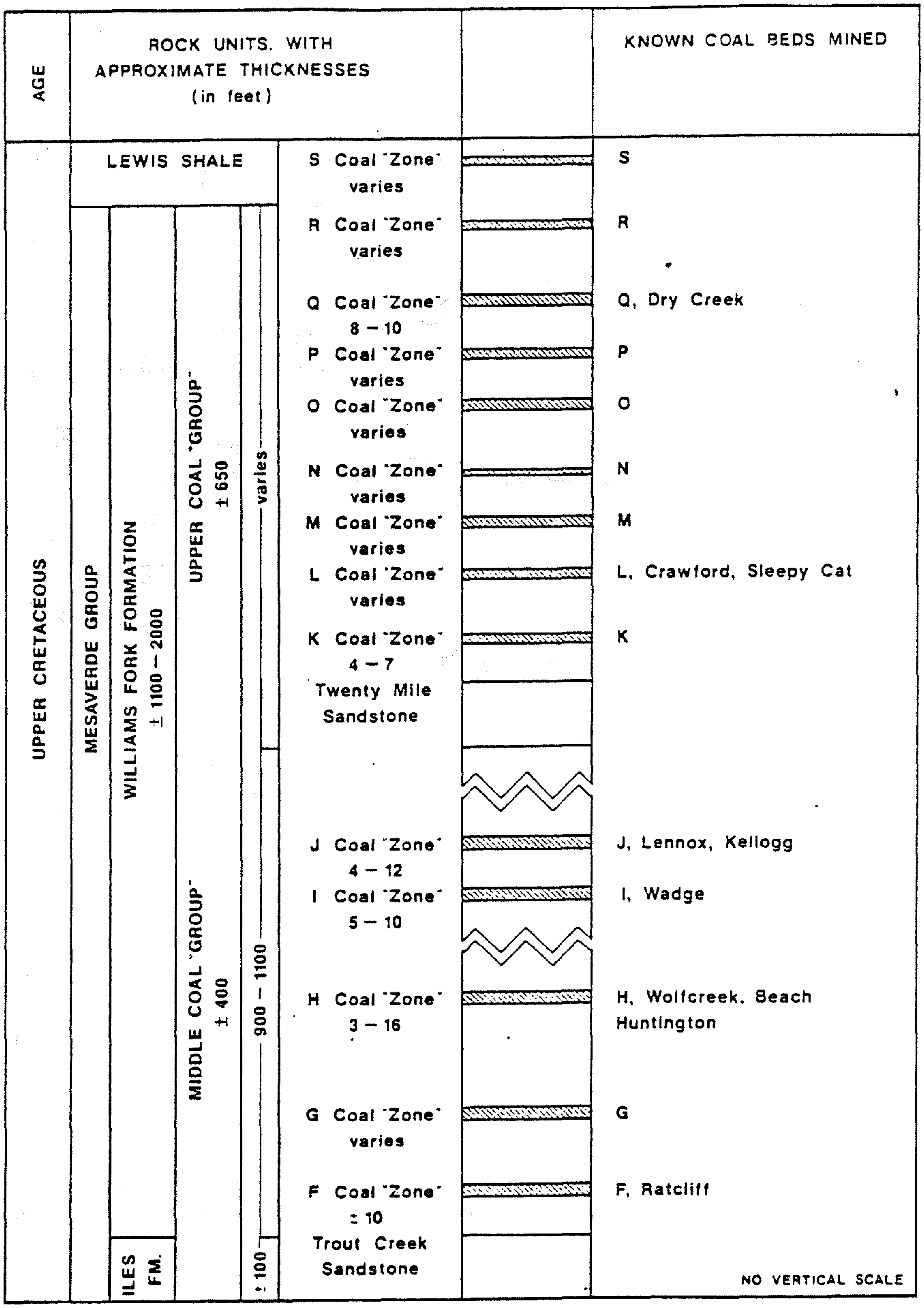

FIGURE 24. - Stratigraphic column showing coal-bearing portions of the Williams Fork Formation, Upper Mesa Verde Group, Yampa Coal Field (1). 10/

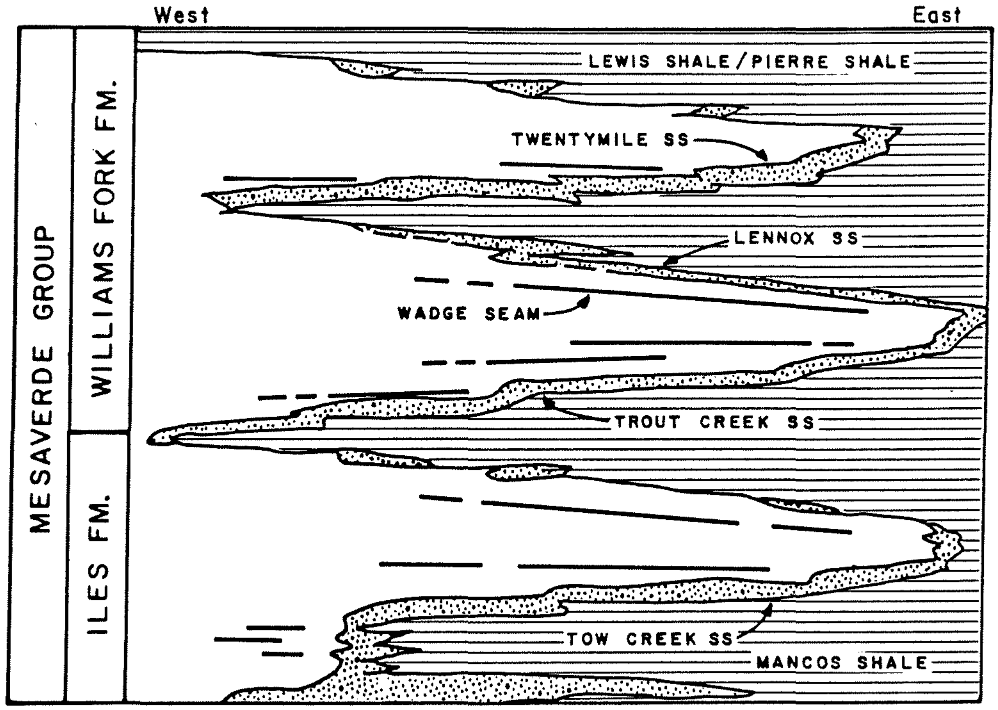

FIGURE 25. - Generalized cross-section through the Yampa Coal Field area, showing contact between the Iles and Williams Fork Formations, and interfingering sandstones (25).

beds suggest strandline depositional environments, while coal-bearing facies are of fresh or brackish water origin and include a variable assemblage of lenticular sandstone, shale, and coal. The Williams Fork Formation was also deposited during this regressive event, although depositional characteristics of the upper Williams Fork sediments indicate marine transgression in Maestrichtian time.

4.8.5 Structural Geology

Structurally, the Yampa Field lies within the Sand Wash Basin, a broad northwest-plunging syncline. Significant structural deformation has affected the field. The south flank of the basin is locally folded, which is further complicated by faulting and igneous intrusions of late Tertiary age. In the Twenty Mile Park area, two deformation episodes produced normal and reverse faults, strike-slip shear fractures, and joints in N50W and N40E orientations (25).

4.9 Canon City Coal Field

4.9.1 Location

The Canon City Coal Field is located southeast of Canon City, in Fremont County, Colorado. The field is bound on the north by the Front Range Uplift, on the southwest by the Wet Mountains Uplift, and by the Apishapa Uplift to the south (1).

4.9.2 Mining History

Historically, more than 175 mines have operated in the Canon City Field, producing over 41.1 million tons of coal. In 1979, three underground mines were in operation.

4.9.3 Mining and Geology

Coal seams in the Canon City Coal Field are found within the lower 700 ft. of the Upper Cretaceous Vermejo Formation. Geologically, it is similar to the Raton Basin Coal Field. The Vermejo Formation consists of interbedded sandstone, siltstone, shale, carbonaceous shale, and coal, and is approximately 1200 ft. thick in the Canon City Field (23). Seven mineable coal seams split and rejoin in various configurations. Coal seams in the Canon City Field are extremely lenticular, and can achieve thicknesses of 20 ft. These coal seams are shown in Figure 26. The Radiant coal zone, located stratigraphically in the middle of the formation, is most frequently mined. The Radiant and Jack O'Lantern seams average 4 ft. to 6.5 ft. in thickness. Coal is ranked as high volatile C bituminous.

4.9.4 Depositional Environment

The Vermejo Formation represents a regressive event associated with deltaic progradation. The coal, claystone, and sandstone of the Vermejo Formation was deposited on a delta plain, in poorly drained interdistributary swamps and marshes that existed along the margins of upper delta-plain fluvial channels. Lenticular coal deposits were controlled by the orientation of major fluvial channels, with splits in coal seams caused by crevasse-splay deposits (26, 27).

4.9.5 Structural Geology

The Canon City Coal Field lies within the Canon City Basin, a down-faulted, synclinal structural sub-basin of the larger Denver Basin. Structurally, the Canon City Field is considered to be an extension of the Trinidad/Raton Fields of the Raton Basin to the south, that is separated from the Raton Basin by the Apishapa Uplift. Strata in the Canon City Field dip gently westward in the eastern portion of the field, and with moderate steepness at the western margin of the field. The field is also influenced by faulting along the east flank of the Wet Mountains.

4.10 Trinidad Coal Field

4.10.1 Location

The Trinidad Coal Field is located east of the Sangre de Cristo and Culebra Ranges in south-central Huerfano and northwest Las Animas Counties, Colorado. It extends to the northwest from the Colorado-New Mexico state line to just north of the town of Walsenberg, Colorado. The Trinidad and Raton Coal Fields are located within the Raton Mesa Coal Region, and are therefore treated as one field in parts of the literature. This convention will be followed as necessary.

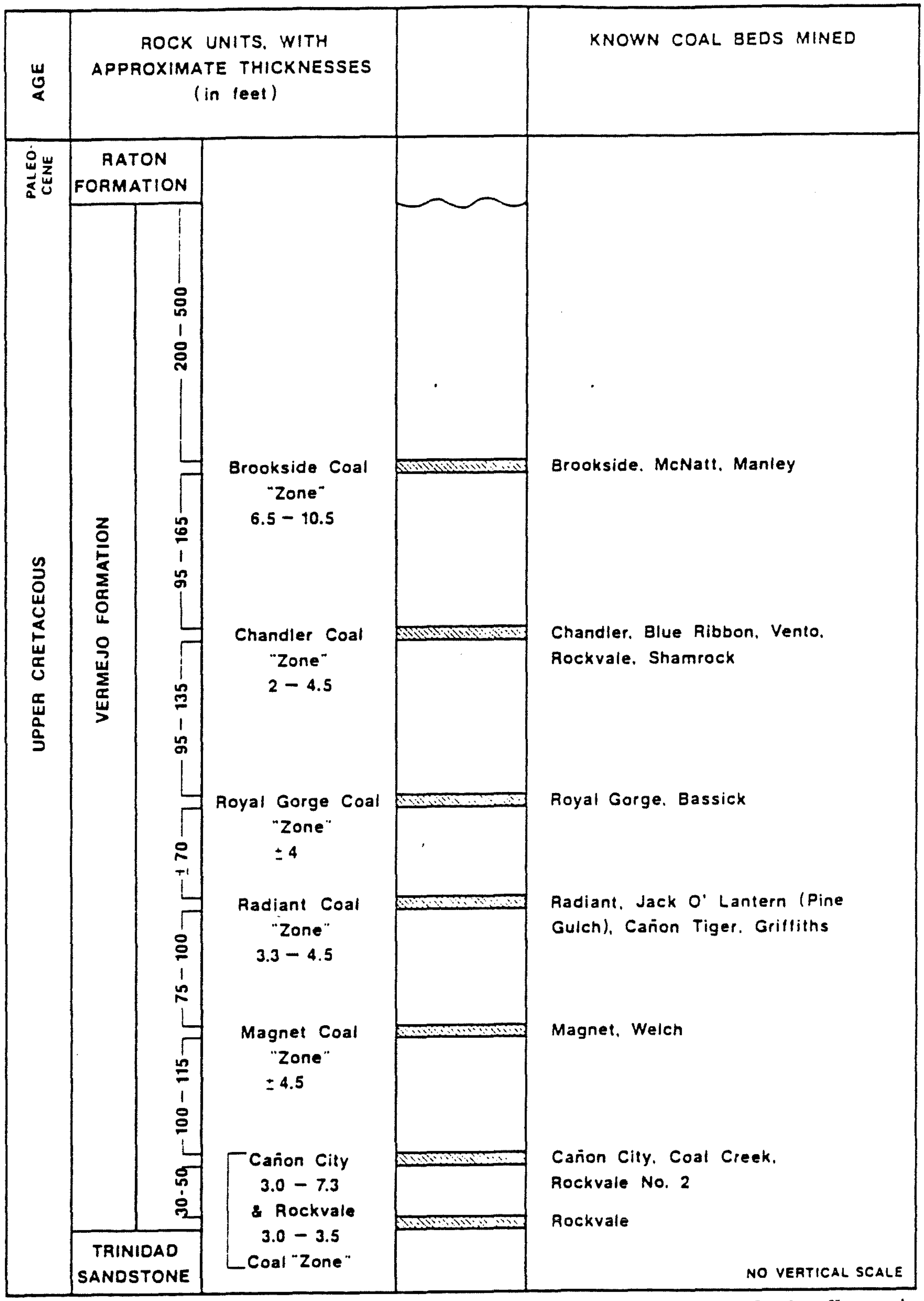

FIGURE 26. - Stratigraphic column, coal-bearing portion of the Vermejo Formation, Canon City Coal Field (1). 11/

4.10.2 Mining History

Coal of coking quality has been produced from more than 150 mines in the Trinidad Field since the late 1800's. A majority of these mines were underground operations. The Trinidad Coal Field has produced more than 247 million tons of coal, making it the largest producing field in the state of Colorado. At the time of this study, three underground coal mines were operating in the Trinidad and Raton Coal Fields, drifting into the slightly upturned seams at the eastern edge of the fields.

4.10.3 Mining and Geology

In the Trinidad Field, coking quality coal is mined from the Cameron and Kebler seams of the Vermejo Formation, which average 4 ft. to 6 ft. in thickness and are shown in the stratigraphic column provided as Figure 27. Coal in this field has been upgraded and partially coked by high-heat flow related to Tertiary age sills, dikes, and laccoliths (1).

4.10.4 Depositional Environment

The depositional environment for the Vermejo Formation has been discussed in Section 4.9.4.

4.10.5 Structural Geology

The Trinidad Coal Field is located within the Laramide-age structural Raton Basin, a south-plunging synclinal structure that is 186 miles long and 62 miles wide. The basin is asymmetrical, with a steep western limb and a gently dipping eastern limb (28). Strata are sharply upturned, and locally overturned, to the west along the faulted eastern margin of the Sangre de Cristo Uplift (1).

4.11 Raton Coal Field

4.11.1 Location

The Raton Coal Field is located to the west and southwest of Raton in Grant County, New Mexico.

4.11.2 Mining History

Coal has been mined in the Raton Field since 1870.

4.11.3 Mining and Geology

Coal is produced from several seams in the Upper Cretaceous Vermejo and Paleocene Raton Formations in the Raton Coal Field. The Vermejo Formation is 80 ft. to 550 ft. thick in the Raton Basin, and consists of buff to gray and green siltstone, slightly arkosic sandstone, carbonaceous and coaly shale, and coal. The Vermejo Formation stratigraphy in the Raton Basin is shown in Figure 28. The Vermejo Formation is separated by an erosional unconformity from the overlying Paleocene Raton Formation. The Raton Formation is 0 ft. to

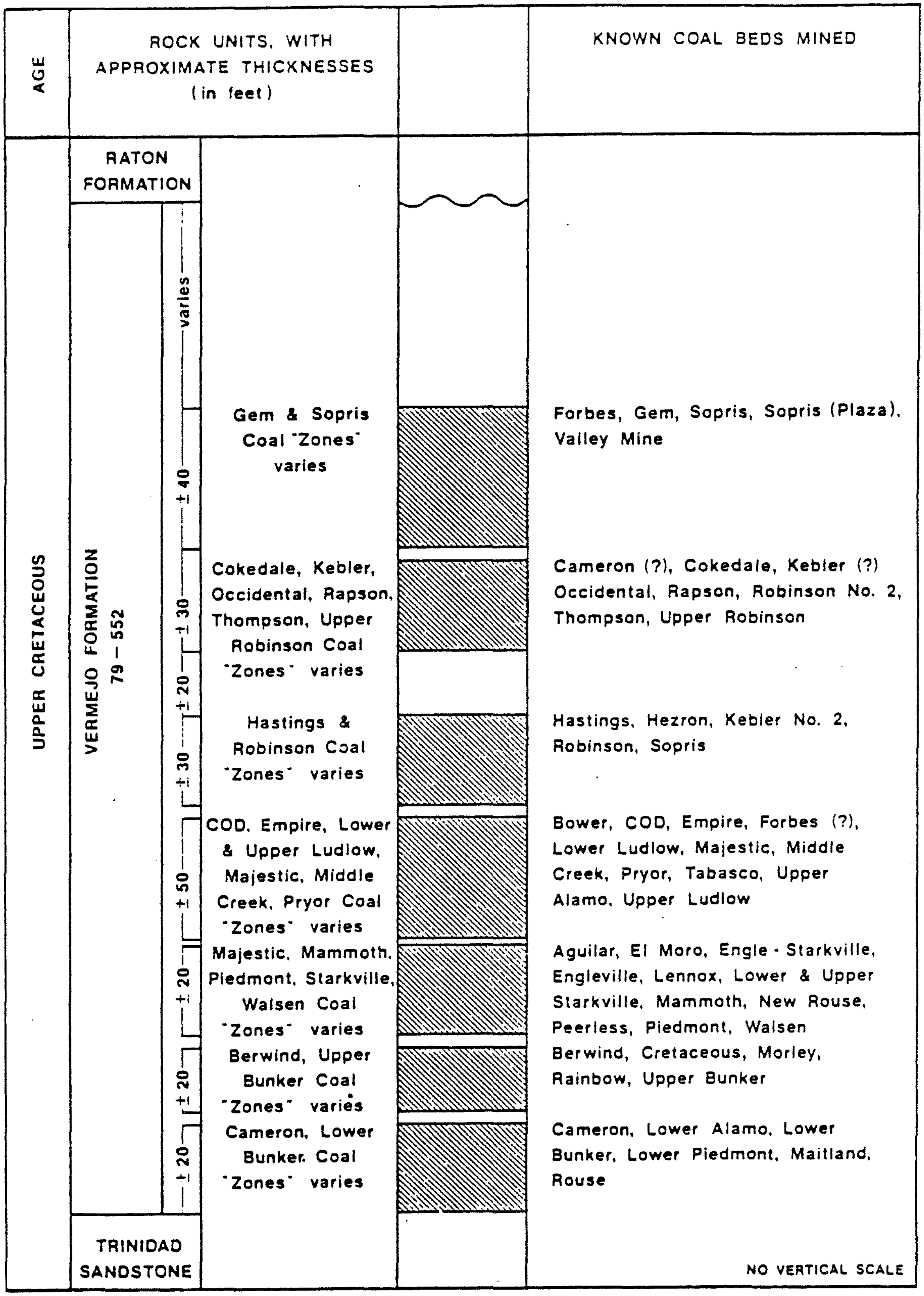

FIGURE 27. - Stratigraphic column showing coal-bearing portions of the Vermejo Formation, Trinidad Coal Field (1). 12/

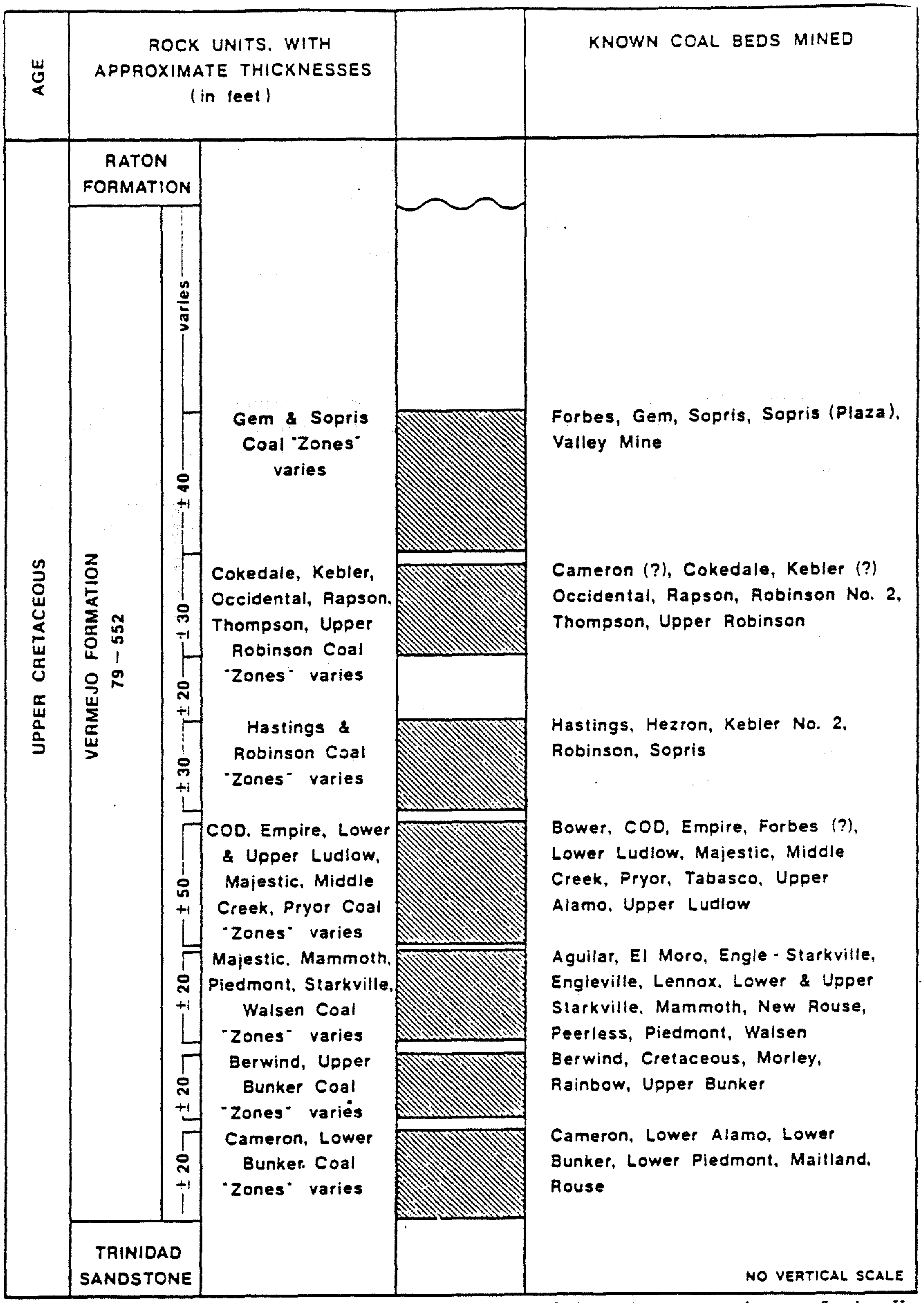

FIGURE 28. - Stratigraphic column showing coal-bearing portions of the Vermejo Formation, Raton Coal Field (1). 13/

1700 ft. thick in the Raton Basin, and consists of gray, fine to coarse-grained arkosic sandstone, shale, and several coal seams (29). The Raton Formation is shown in the stratigraphic section provided as Figure 29. Coal seams are lenticular in geometry, and have a maximum thickness of 10 ft. (1). In the Raton Field, major mined-seams include the Raton and Vermejo seams of the Vermejo Formation and the Tin Pan, Yankee, Left Fork, Cottonwood Canyon, Anchor Canyon, York Canyon, and Chimney Divide seams of the Raton Formation (1). Coal is ranked high volatile A to B bituminous coking coal.

4.11.4 Depositional Environment

The depositional environment for the Vermejo Formation has been discussed in Section 4.9.4. Major orogenic activity to the west of the Raton Basin occurred in latest Cretaceous time, resulting in erosion of the upper surface of the Vermejo Formation. Coarse clastic sediments derived from the uplift formed the basal conglomeratic sequence of the Raton Formation, which was covered by swamp and floodplain deposits during Paleocene time (29, 30).

4.11.5 Structure

The Raton Coal Field is located in the Raton Basin, which has been described in Section 4.10.5.

4.12 Summary

The depositional and structural geology of coal in the studied coal fields generally controls the types of geologic features affecting coal mine ground control.

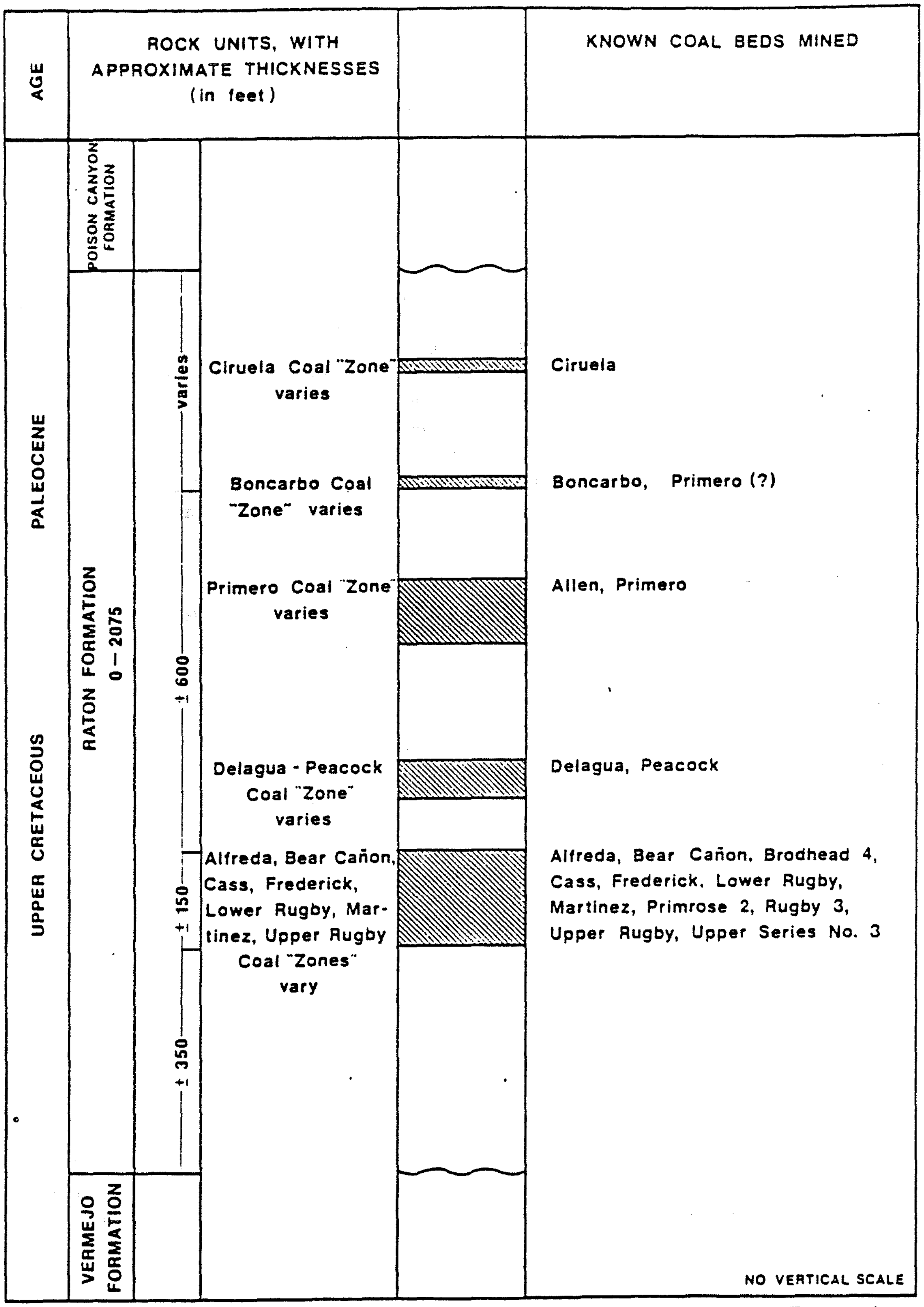

FIGURE 29. - Stratigraphic column showing coal-bearing Raton Formation, Raton Coal Field (1). 14/

5.0 GEOLOGIC FEATURES AND CONDITIONS AFFECTING GROUND CONTROL IN WESTERN UNDERGROUND COAL MINES

5.1 Depositional Features

5.1.1 Sandstone Channels

In analyzing those geologic features that adversely affect the roofs of western underground coal mines, sandstone channels and genetically related overbank deposits of siltstone and mudstone create the most difficult roof control problem for mines in the Rocky Mountain area. Data gathered both from existing literature and this study have verified that severe roof control problems are associated with sandstone channels. Several coal mines analyzed during this project contain roof rock composed entirely of river—delta deposits, including sandstone channels and associated overbank deposits of siltstone and mudstone. In mines with these conditions, large and potentially fatal roof falls are a constant hazard.

5.1.1.1 Environment of Deposition

An overview of the depositional environment of Rocky Mountain coal fields has been presented in Section 3.0. The marine/terrestrial interface of the Cretaceous Interior Sea, where the Rocky Mountain coals were deposited, was an extremely complex environment. The Cretaceous Interior Sea was a relatively shallow, epicontinental sea, characterized by debouching river deltas that were wave-dominated with pronounced longshore currents (10). Swamp, lagoonal, and other types of fluvial depositional environments were also common along the extensive coastal plains of this sea. Distributary fluvial channel sediments of these wave-dominated deltas were constantly reworked by wave action and longshore currents. Sand and silt was deposited as barrier islands, strand plains formed by accretion ridges, and linear sand beaches, which formed from longshore drift. Figure 30. is a generalized diagram showing features of a wave-dominated delta. Strand plains, which were later buried by prograding delta deposits, became sandstone tongues where coal formed in overlying and adjacent delta locations (31). Peat also formed in low-lying, swampy areas of the extensive coastal plains. However, these areas of peat formation were less influenced by fluvial activity and are not generally associated with sandstone channel roof hazards. For this reason, further detail on nondeltaic depositional environments is not provided.

Peat formed in several deltaic subenvironments, including fresh and brackish water back-barrier lagoons and interdistributary delta-plain areas. Along the landward side of strand plains, which were formed by stable accretion ridges, thick peat collected in brackish water lagoons where it was protected from overwashing sea water by the high elevation of the strand plain. As swampy lagoons filled with detrital sediment and organic debris, from both the landward side of the strand plains and the seaward side of the delta plains, they formed thick, elongated peat deposits (31). Where swamps formed on delta plains between distributary channels, thin to thick lenticular peat deposits were developed. These locations of coal development and other deltaic features are shown in Figure 31., which is a detailed diagram of the components of a wave-dominated delta.

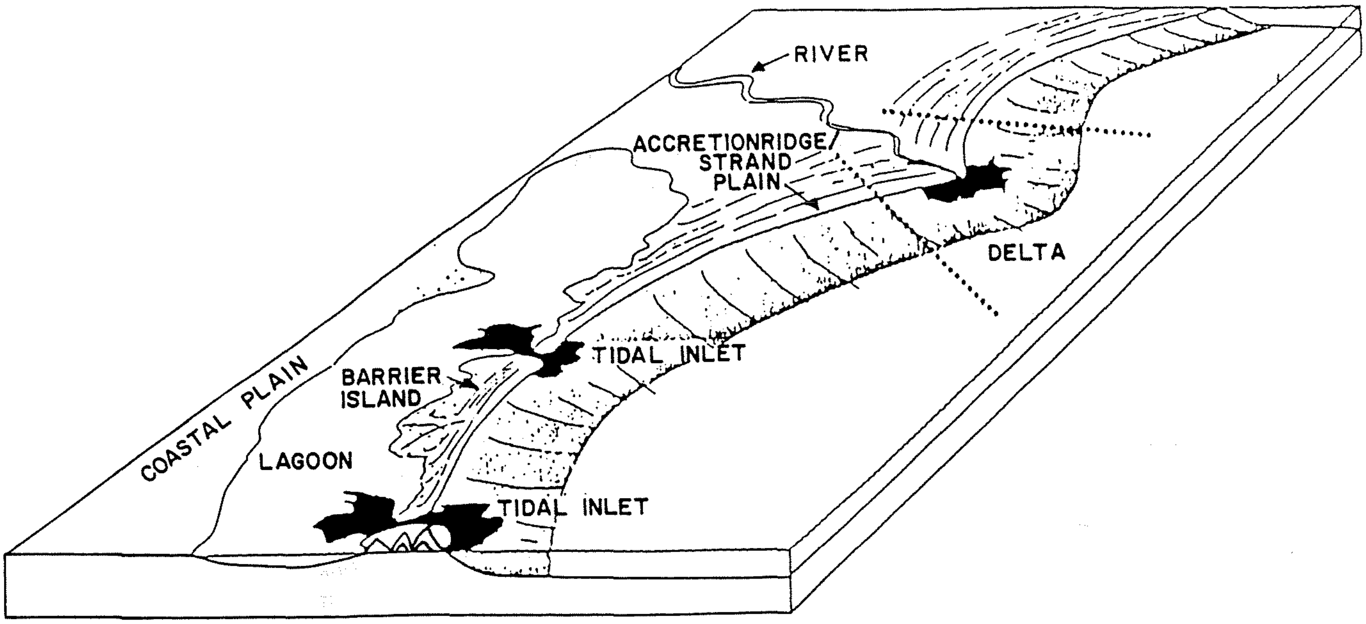

FIGURE 30. - Generalized diagram of a wave-dominated delta with associated strand plain, lagoon, barrier island, and tidal inlets (10). 15/

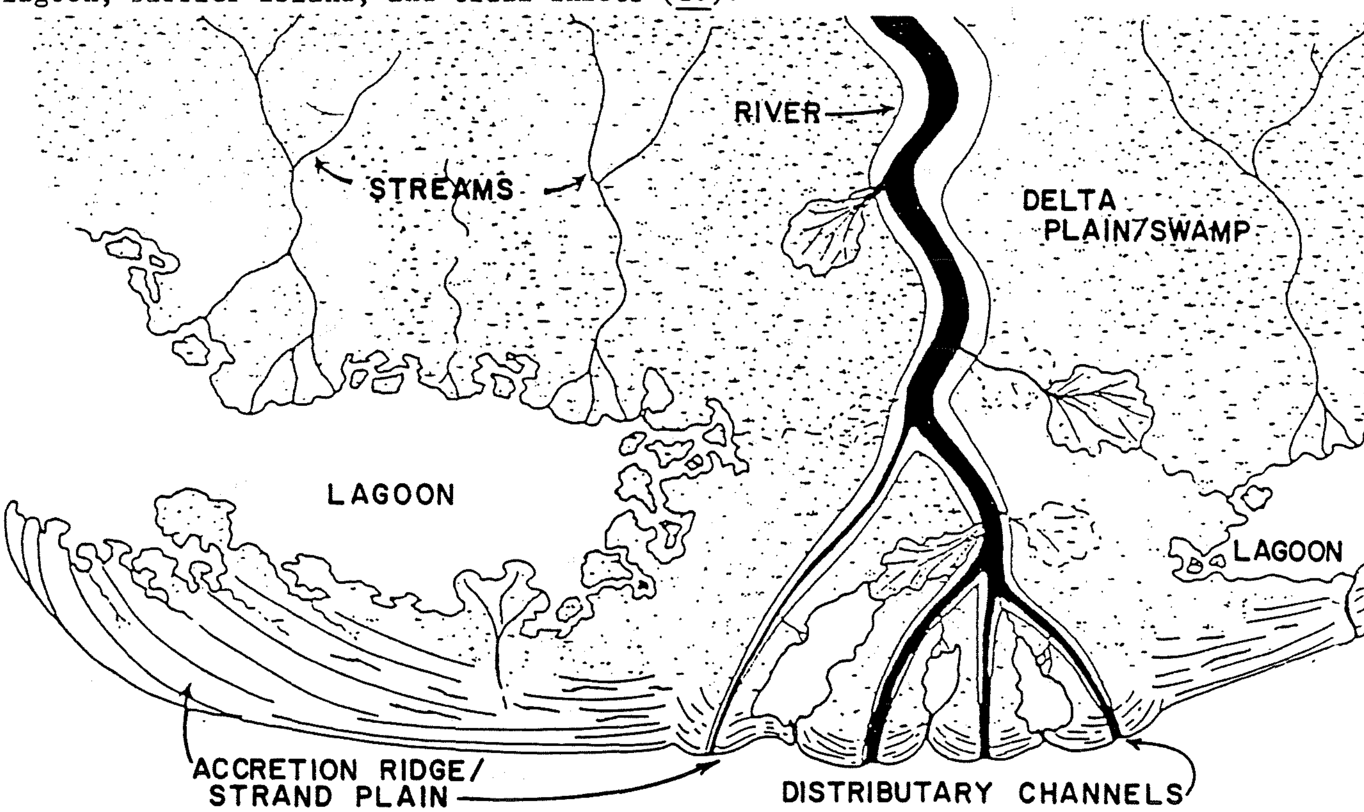

FIGURE 31. - Detailed diagram of wave-dominated delta showing locations for coal development (31).

Across the delta plain, the lobes and distributary channels of the delta were constantly shifting course by avulsion in response to upstream changes in discharge and sediment load. During flood stage, distributary channels breached their natural levees, which resulted in scouring followed by deposition of thin sand, silt, and mud sheets on the delta plain and formation of a crevasse-splay. A deltaic system exhibits a constant change in morphology throughout it's lifecycle. Depending on several variables, different portions of the delta may simultaneously be stable, advancing seaward, retreating landward, or migrating laterally in either direction. Consequently, sandstone units deposited by stream channels that migrate within the delta exhibit a variety of shapes and sizes. The situation is further compounded because many sand channel deposits have been reworked by younger streams. The resulting deposit is commonly a sandstone unit that is composed of many stacked channel sequences (32). Figure 32. shows the changing morphology of a delta through time, with respect to locations of peat deposition and marine trangression. Figure 33. is a detailed diagram showing the complex depositional and erosional features associated with the constantly changing subenvironments of a delta.

Sandstone channels documented by this study are considered to be contemporaneous with the surrounding peat development. The period of peat development may vary from several hundred to several thousand years. However, coal formed from this peat is considered to be of one geologic age.

Sandstone channels documented by this study are divided into two categories: those deposited by terrestrial fluvial processes, and those deposited by marine processes. Fluvial channels are generally sinuous on the upper-delta plain and straight on the lower-delta plain and delta lobes. Many types of fluvial deposits are observed in the channels. These include channel, point-bar, braided-stream, and crevasse-splay deposits. Sandstone deposited in the central channel is usually lenticular and massive, cross-bedded, medium to fine-grained, well-indurated, and well-sorted. The basal sand may contain rip-ups, channel-lag deposits, floating pebbles, tool marks, and flute casts. Fining-upward, stacked, and cross-bedded sequences of sandstone, siltstone, and mudstone are commonly observed in the fluvial channel. These deposits represent point-bar deposition. Overbank or crevasse-splay deposits, which have breached main channel levees during high-flow or shifting of the delta lobes, are made up of sandstone, siltstone, and mudstone. The sandstone is of the same composition as the main channel, but is often restricted in depth, resulting in thin sand sheets that are dispersed in a lobate pattern. Separating the sandstone sheets, in a vertical sequence, are thin siltstone and mudstone laminations (33, 34). Crevasse-splay deposits also contain carbonaceous laminations, which depict quiet—water deposition that followed the initial pulse of sand splaying into the floodplain.

Figure 34. is a portion of a mine map, from a mine in the northern Wasatch Plateau Coal Field, showing roof geology. Braided fluvial sandstone channels and their flow directions, extensive overbank flood deposits, and delta-plain deposits are shown.

Plate 1. is a large-scale photograph of a fluvial sandstone channel from an underground coal mine in the western Book Cliffs Coal Field of Utah. The photograph is oriented parallel to the flow direction, in order to depict a

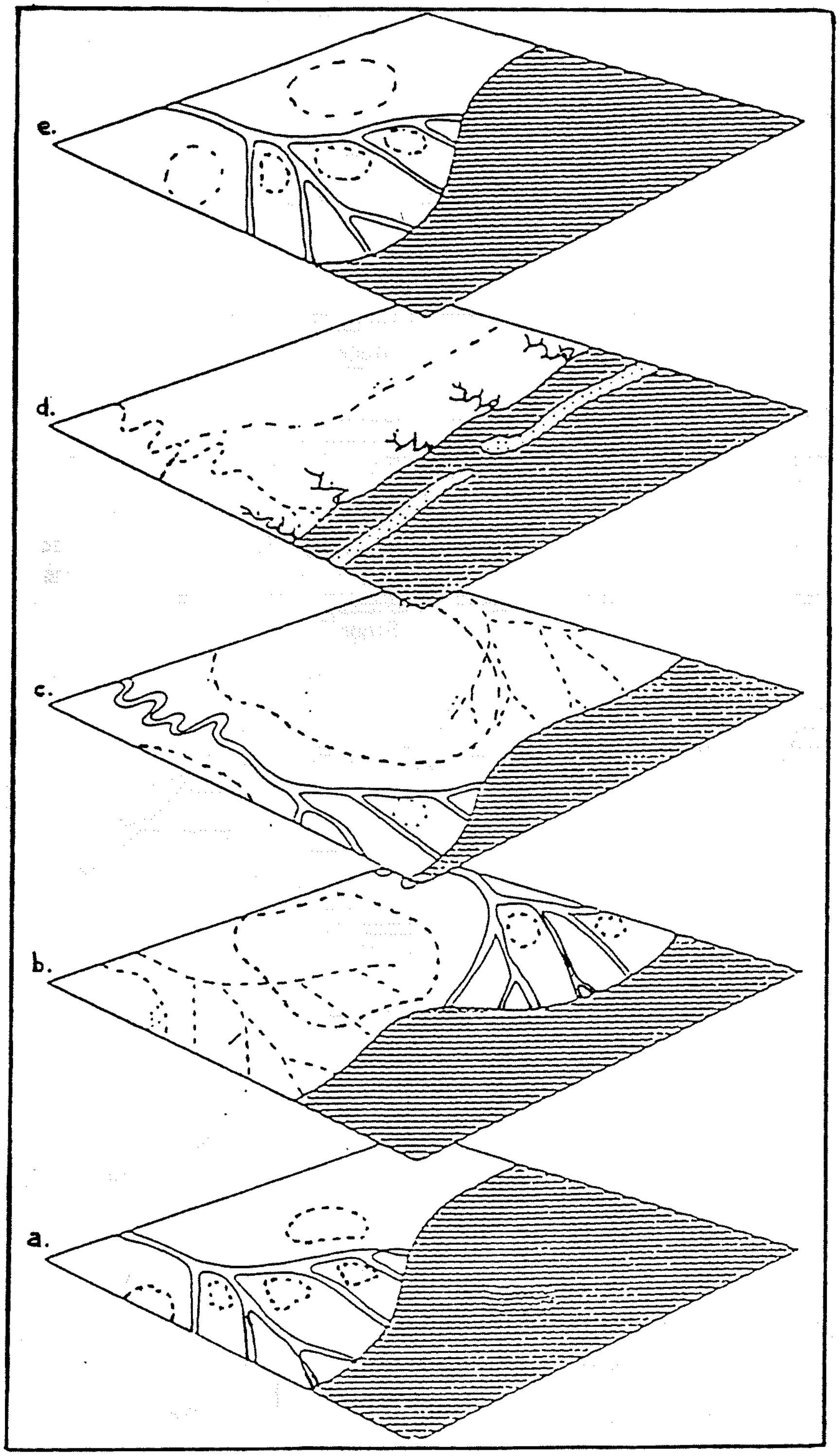

FIGURE 32. - Changes in deltaic sedimentation through time. Stages a. through c. depict a prograding shoreline with migrating and abandoned distributary channels and deltas. Dashed circular patterns indicate areas of peat deposition. Stage d. is a marine transgression resulting in barrier island development. Stage e. depicts marine regression with renewed deltaic progradation and peat deposition (adapted from 16).

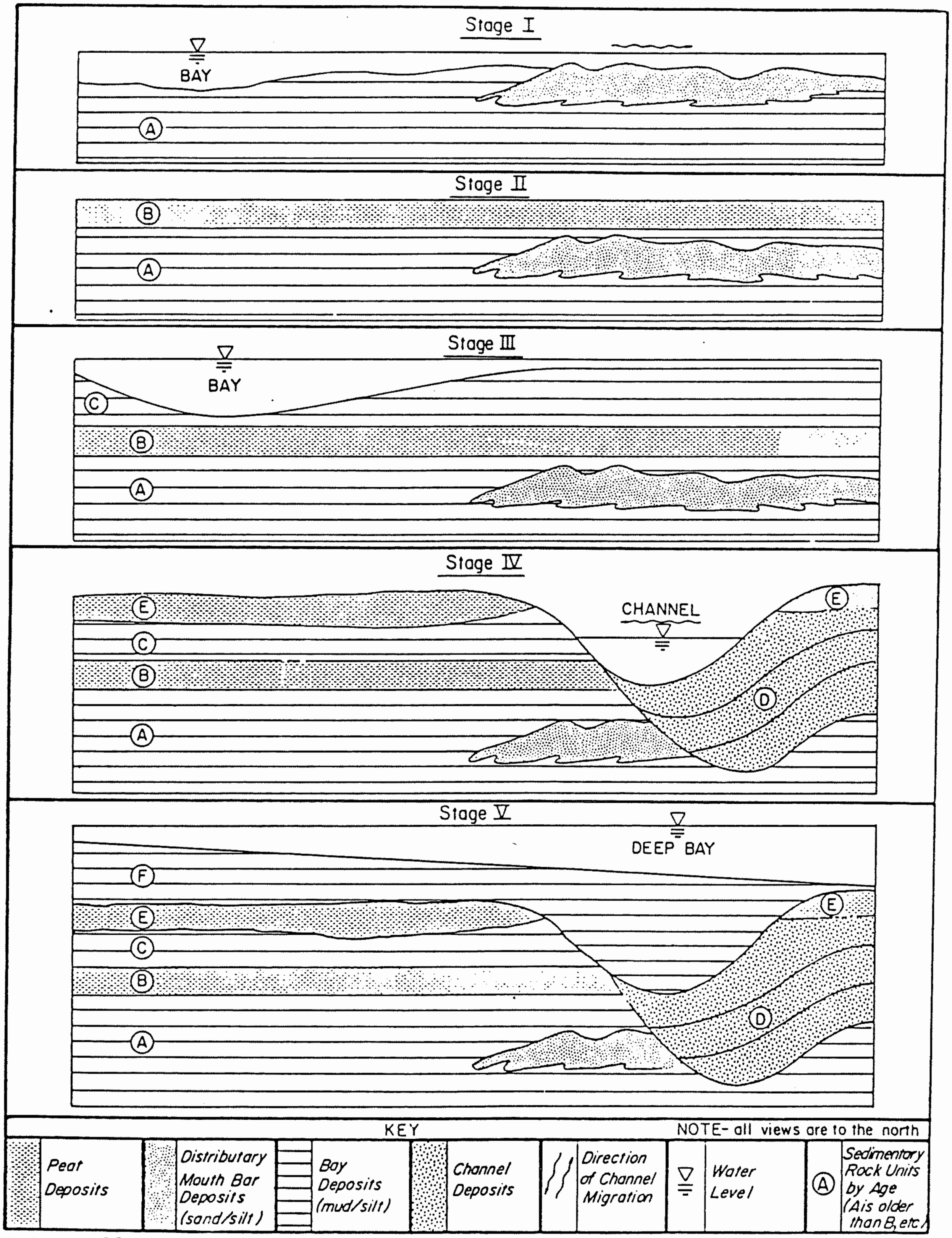

FIGURE 33. - Detailed cross-sections illustrating deltaic development. Cross-sections depict complexity of lithotypes and locations of erosion and deposition of sediments within and near the delta. Stage I represents the first cycle of prograding deltaic sedimentation. Stages II through V show peat deposition, migration of the distributary lobe, migration of the distributary channel, and finally, deep water deposition during a marine transgression (32).

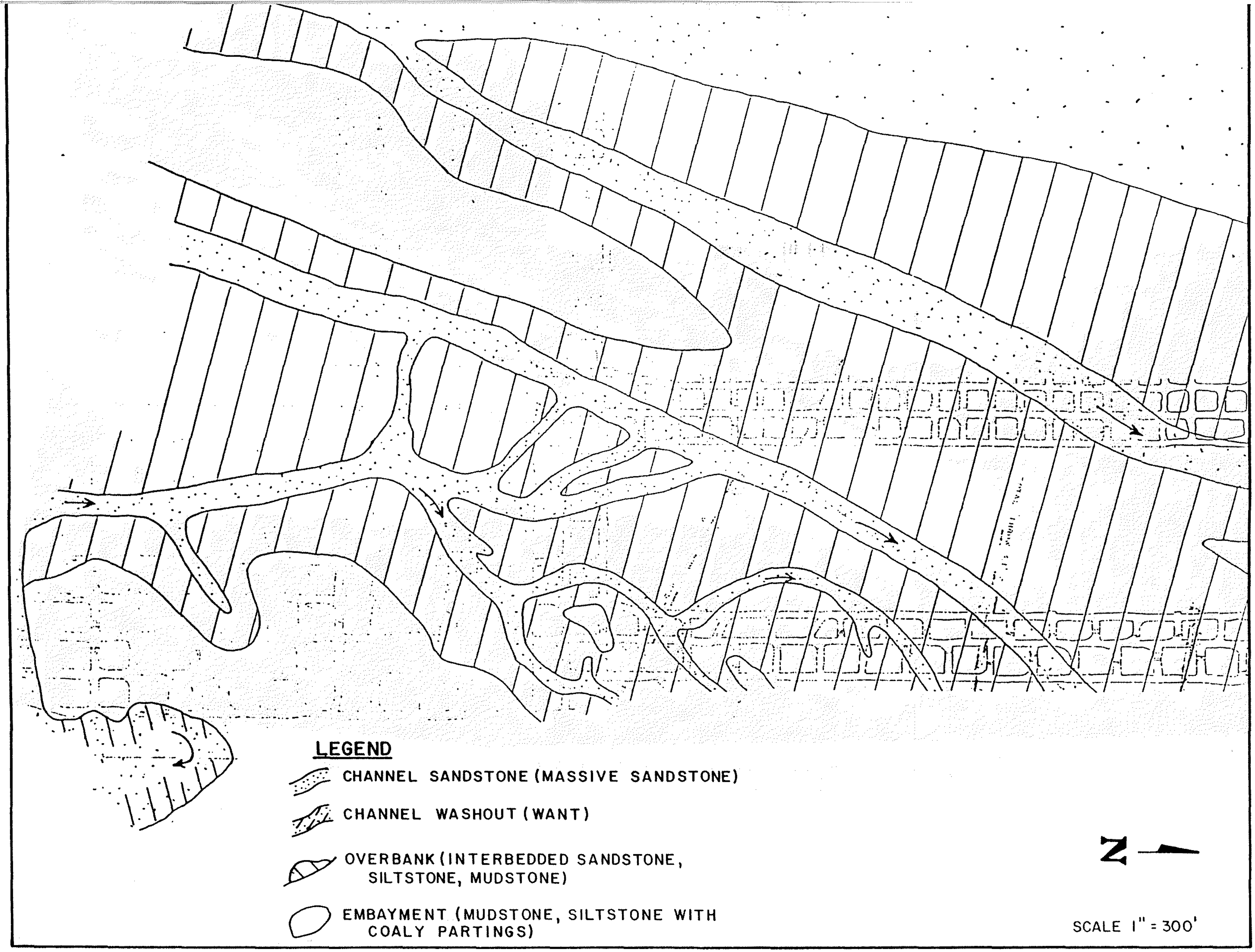

FIGURE 34. - Portion of mine map, from a mine in the northern Wasatch Plateau Coal Field, showing roof lithology.

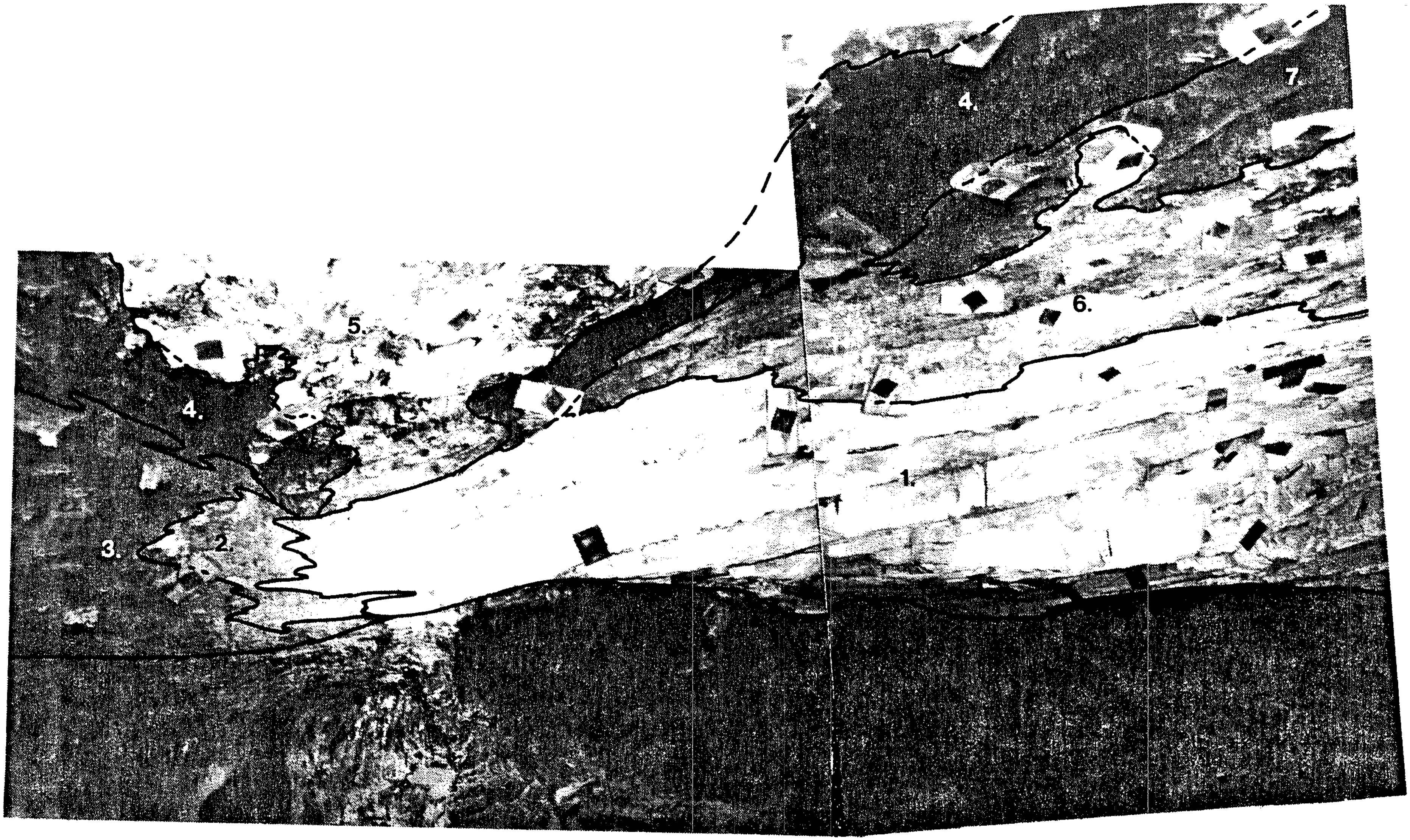

PLATE 1. - Photograph of a fluvial sandstone channel taken in a cross-cut of an underground coal mine in the Book Cliffs Coal Field of Utah. The portion of sandstone channel shown in this photograph is approximately 20 ft. wide by 12 ft. thick. Maximum width of this channel is 130 ft. and maximum thickness is approximately 30 ft. Cap blocks are 8 in. by 18 in. Geologic units are numbered and outlined on the plate. Unit 1. is a massive, well-sorted, fine-grained sandstone channel with beds separated by carbonaceous laminations; unit 2. is an outlined deposit of siltstone, possibly deposited on an inside meander bend; unit 3. is a deposit of mudstone fining outwards from the siltstone; unit 4. is shale of the delta plain; unit 5. is the base of another, stratigraphically higher, fluvial sandstone channel; unit 6. is very fine-grained sandstone that fines-upward to siltstone, deposited as the channel filled to floodplain level; unit 7. is mudstone, representative of deposition just prior to inferred stream avulsion.

PLATE 2. - Photograph of a small, lenticular fluvial sandstone channel, western Book Cliffs Coal Field, Utah. Mats are 8 in. wide. Arrow points to carbonaceous laminations.

cross-section through a representative sandstone channel. This channel, which has removed approximately 2.5 ft. of the original peat deposit, was entirely exposed following blasting of the roof for an overcast.

Plate 2. is a photograph of a small, lenticular fluvial sandstone channel located in the same area as the channel shown in Plate 1. This small channel probably represents a braided portion of a distributary channel. Plate 3. shows another sandstone channel. This channel is a massive sandstone that has scoured approximately 3 ft. of the peat deposit. Plate 4. is a photograph showing, in detail, the edge of a fluvial sandstone channel where it has scoured into the former peat deposit. Coal surrounds the edge of the channel.

Bases of main, distributary fluvial sandstone channels exposed in analyzed mine roofs depict a wide variation in width. Paleohydraulic modeling suggests that this change in width is directly related to the paleoslope of the coastal plain. The paleoslope, both parallel and perpendicular to the paleoshoreline on the western edge of the Cretaceous Interior Sea, increased in a northeasterly direction from the southern Wasatch Plateau area to the Book Cliffs area (31). Figure 35. depicts the increase in paleoslope to the northeast utilizing a block diagram of the southern Wasatch Plateau area. Sandstone channels are wider where low relief produced increased meandering, and resulted in wide coastal plain development to the southwest. To the northeast, the sea was separated from the orogenic highland by a narrow coastal plain. Coastal-plain relief was therefore greater, resulting in narrow, steep channel formation and prograding deltaic deposition.

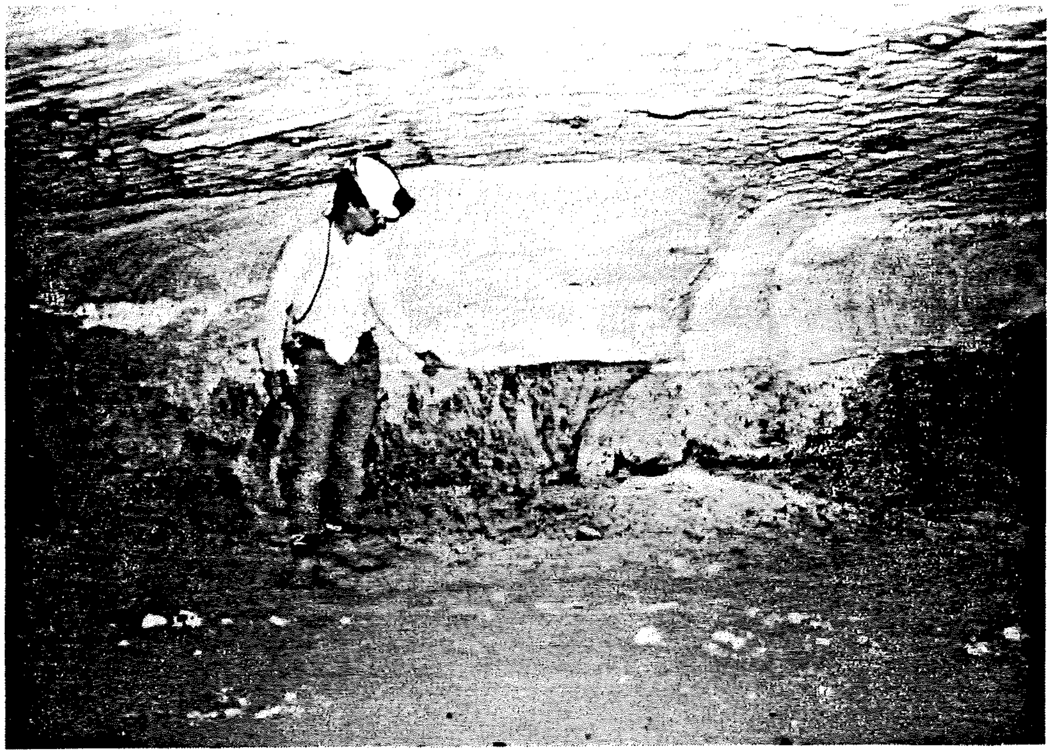

PLATE 3. - Photograph of a thin, 35 ft. wide, massive fluvial sandstone channel, Grand Mesa Coal Field. Channel has scoured approximately 3 ft. of the peat deposit. Floating pebbles are found in the base of this channel.

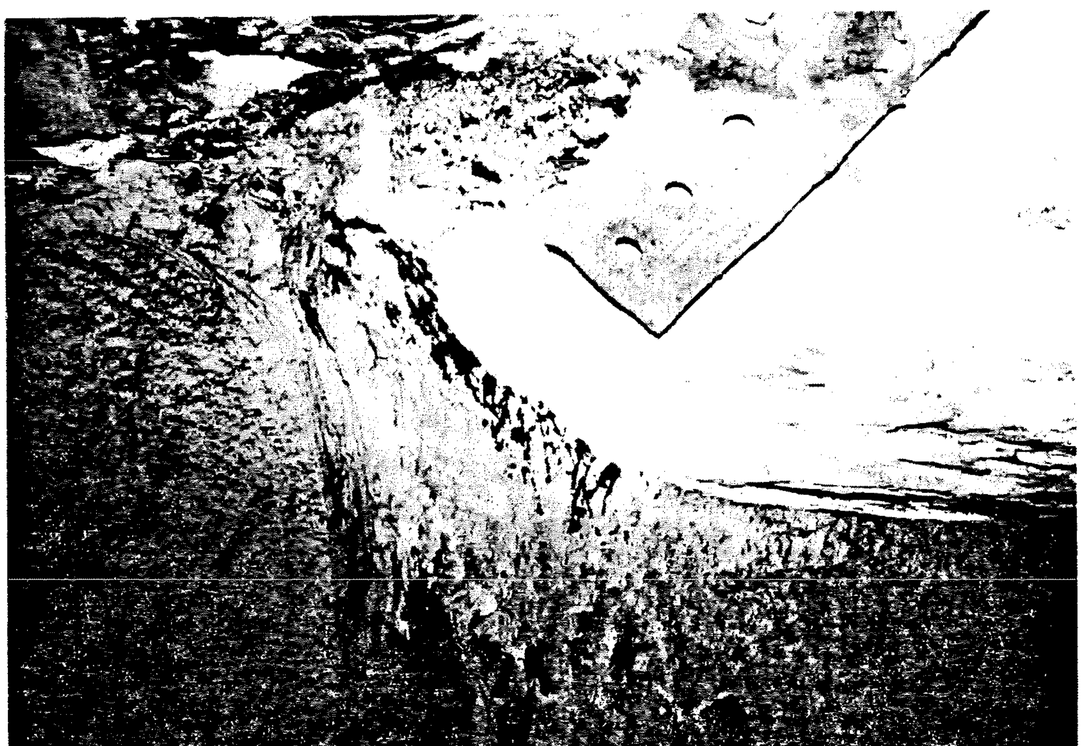

PLATE 4. - Photograph showing detail of edge of sandstone channel, Book Cliffs Coal Field, Utah. Mat is 8 in. wide. This channel has scoured into the former peat deposit. The dark-colored rock is coal and the light-colored rock is sandstone. Rock dust has been removed from the contact.

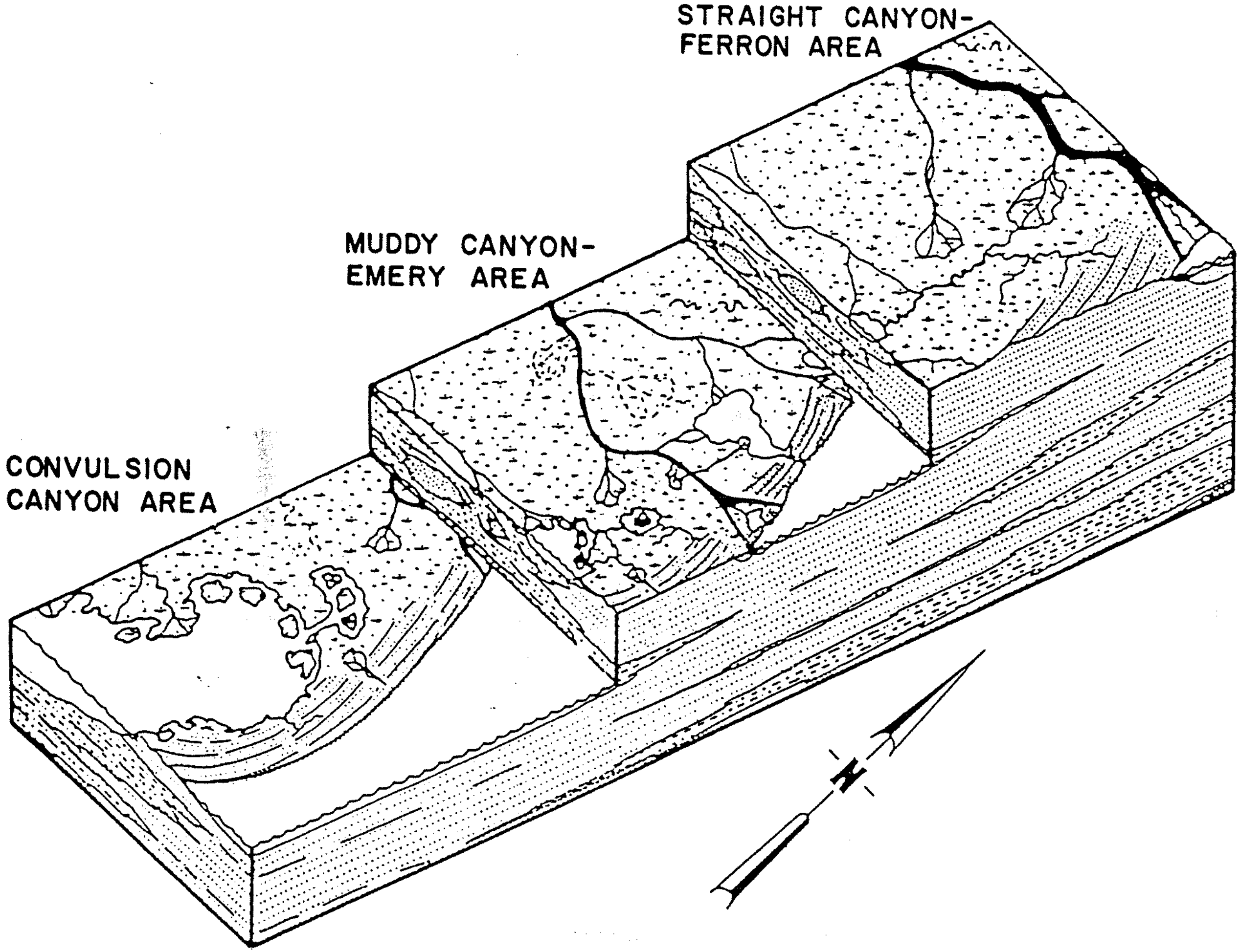

FIGURE 35. - Block diagram depicting the increase in paleoslope both perpendicular and parallel to the paleoshoreline in the southern Wasatch Plateau Coal Field (31).

The width of most fluvial sandstone channels analyzed in western coal mines averaged between 15 ft. and 60 ft. However, sandstone channel widths in the central Wasatch Plateau Coal Field can approach one mile (35) and channel widths in the northern Wasatch Plateau can be as wide as 2500 ft. (36). Channel widths in the Book Cliffs Field as wide as 1200 ft. have been documented (10). Thickness of fluvial sandstone channels is variable, and averages from 15 ft. to 40 ft.

The second type of sandstone channel was formed by marine processes. Sand and silt debouched from river deltas was reworked by wave action and longshore drift into strand plains and barrier islands, behind which formed lagoons. During high, winter, and storm tides, strand plains were breached by tidal inlets forming barrier islands. Flood-tidal deltas formed from tidal inlets. Washover fans were formed by wave action, through the erosion and deposition of sand and silt over and behind barrier islands or bars (10).

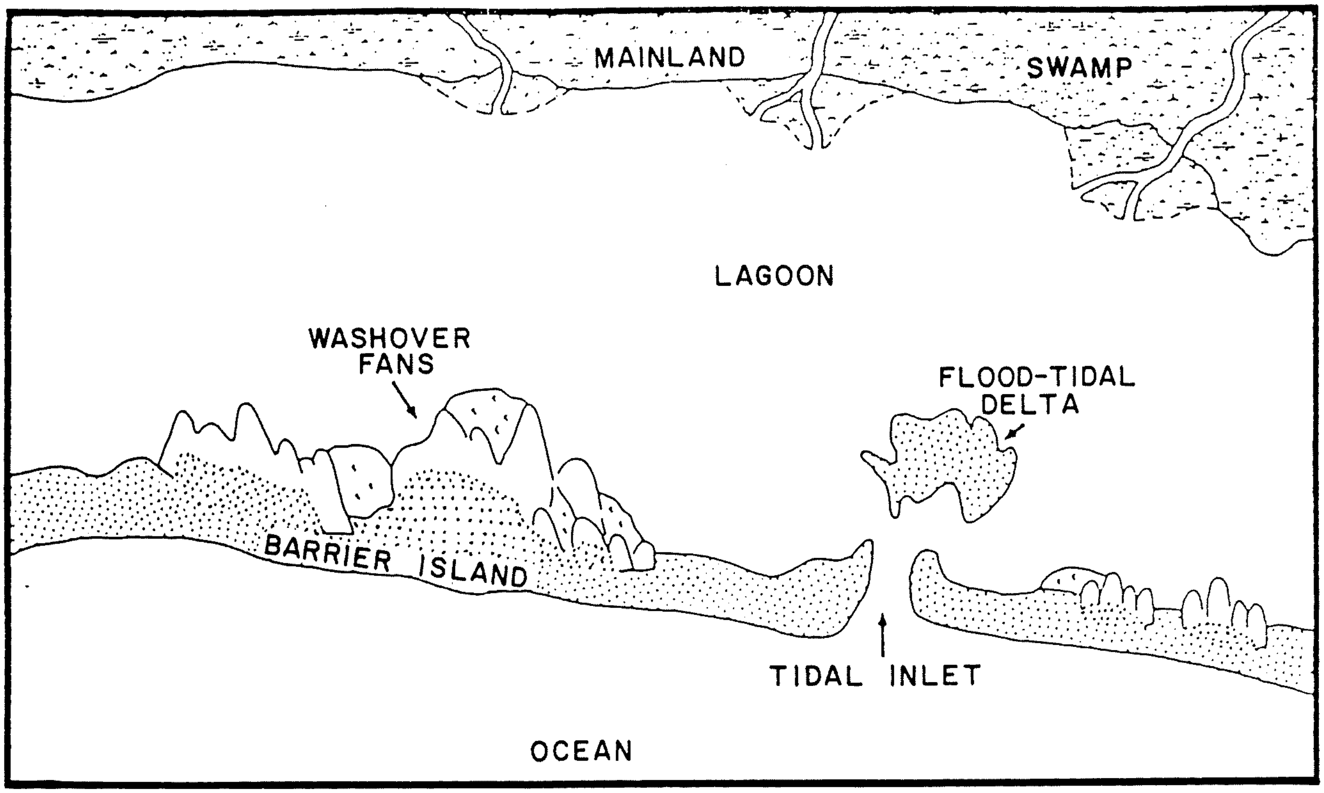

FIGURE 36. - Diagram showing features created by longshore current deposition along a barrier coastline (10). 16/

These features are shown in detail in Figure 36. Tidal inlet and flood-tidal delta deposits are made up of sandstone and siltstone, which was deposited onto lagoonal silts and muds. Upon burial by prograding deltas or transgressing seas, these features were preserved. Another important sedimentary sequence that has been preserved in the stratigraphic record is the barrier bar or island that is superimposed upon an abandoned delta. Marine transgression, delta-lobe abandonment, or realignment of the coastal plain are the mechanisms responsible for this stratigraphic sequence. This process is shown in Figure 37. When this process occurred, tidal inlets transgressed onto the relict delta plain and accumulated peat deposits, forming a marine sand channel (10).

Tidal inlet and flood-tidal delta facies (here used together and called marine sandstone channels) characteristically are composed of medium to fine-grained sandstone that fines-upward to very fine-grained sandstone and siltstone. Thin, laterally extensive beds are observed in the flood-tidal delta facies. Large scale, low-angle trough cross-set bedding is observed in the tidal inlet area. Tidal inlet facies show both flood and ebb directions of flow, with dominant flood-tide paleocurrents. The deep flute casts, rip-ups, pebble-lags, and high-angle cross-bedding that are observed in terrestrial sandstone channels are absent. Marine sandstone channels, especially where associated with the landward edge of the tidal inlet facies and the entire flood-tidal delta facies, may only show an aggradational base. In cross-

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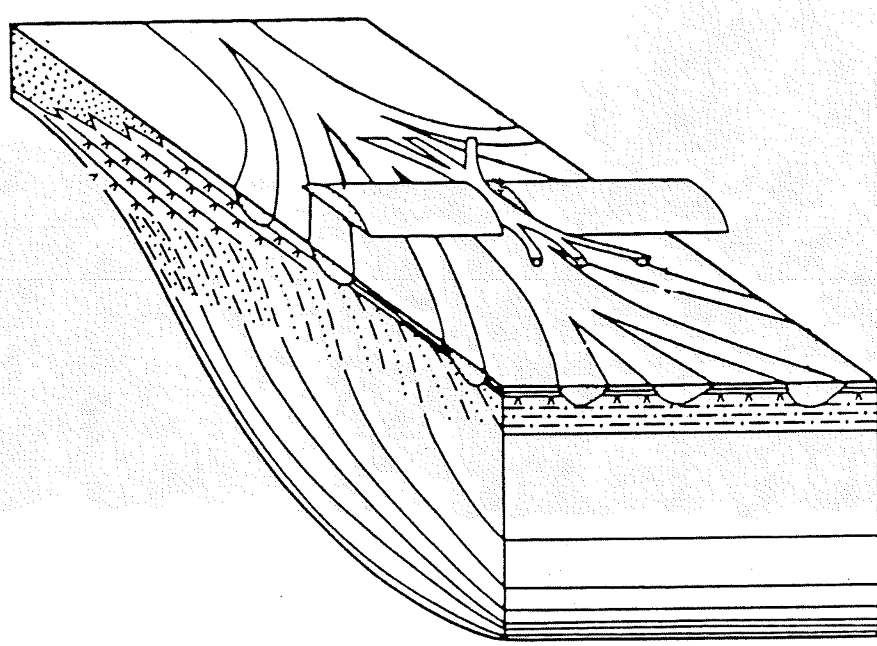

FIGURE 37. - Schematic diagram showing model of a barrier island and tidal inlet overlying a delta. Rapid transgression with minimal erosion could cause this superposition of depositional environments.

section, marine channels are less concave and display a more shallow, lenticular shape without the terrestrial sandstone channel, meander/point-bar configuration. However, distinguishing the characteristics and depositional environments of fluvial and marine sandstone channels is often difficult. In general, marine sandstone of tidal inlets and flood-tidal deltas tends to be more massive, featureless, and more cemented than sandstone deposited in terrestrial fluvial channels. The width of marine tidal inlets is variable, but generally is greater than fluvial channels.

Plate 5. is a photograph of an inferred marine sandstone channel located in the central Wasatch Plateau Coal Field. The photograph shows a massive, well-sorted, and fine-grained sandstone channel with a shallow, lenticular base. Plate 6. is a detailed view of the base of the sandstone channel depicted in Plate 5. The base of this channel shows an aggradational contact with no rip-ups, flute casts, or channel lag. This channel, possibly because of it's aggradational base and direct contact with the coal, does not present roof control problems. Mining height of the coal is reduced beneath the channel, but seam reduction appears to be more a consequence of compaction than erosion.

The subenvironments associated with the fluvial and marine sandstone channels can be utilized to differentiate between the two depositional environments. However, the subenvironment can also be difficult to identify.

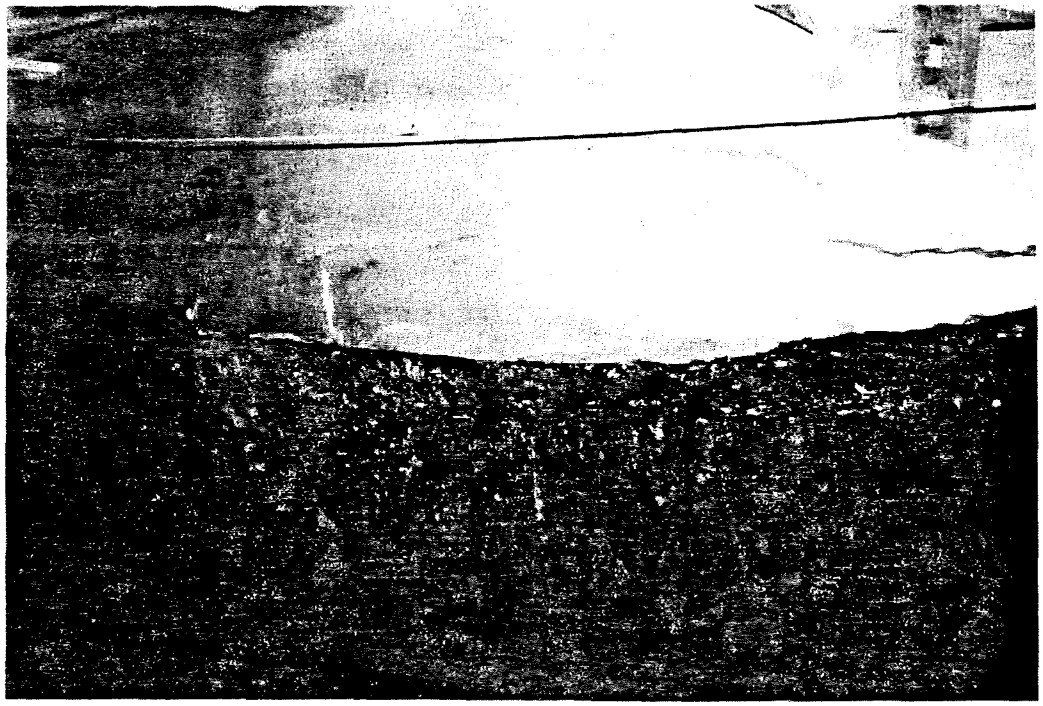

PLATE 5. - Photograph of an inferred marine sandstone channel, central Wasatch Plateau Coal Field. Lower contact is with coal. Sandstone is massive, well-sorted, and fine-grained with no bedding. Note the shallow, lenticular base with no deterioration of the underlying coal. View is perpendicular to a rib, mat is 8 in. wide. The entire channel is approximately 30 ft. wide.

PLATE 6. - Detail of base of inferred marine sandstone channel, central Wasatch Plateau Coal Field. Note massive sandstone, aggradational base and absence of channel lag, rip-ups, and cross-bedding. Pick head is approximately 12 in. long.

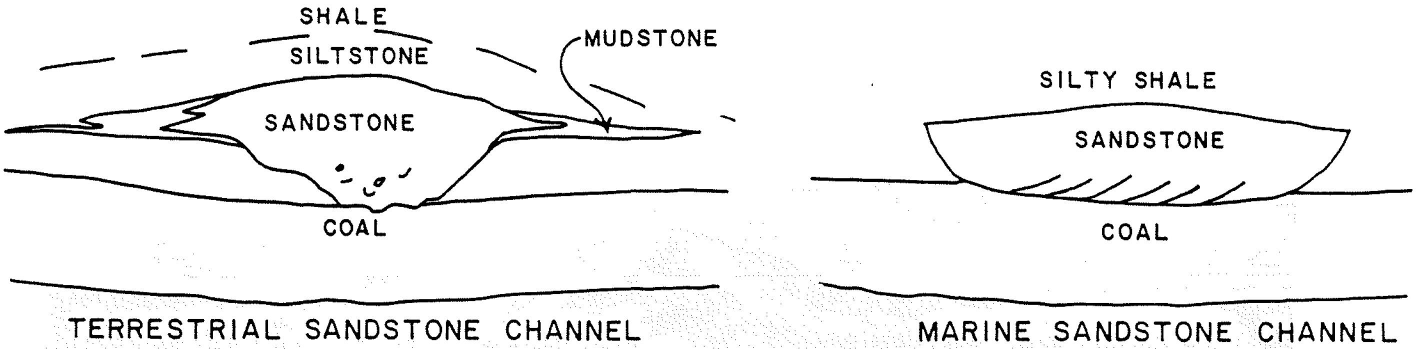

FIGURE 38. - Idealized cross-sections through a terrestrial fluvial sandstone channel and a marine sandstone channel. Major differences include channel lag and flute casts in the base of the terrestrial channel, low-angle trough cross-set bedding in the base of the marine channel, lithological associations, and channel geometry.

Sand and silt was deposited by scouring fluvial channels and crevasse-splays onto fine-grained flood-plain deposits of the delta plain. Sand and silt was also deposited by scouring marine tidal inlets onto fine-grained mud and silt deposits of lagoons. The distinction between the silt and mud deposits of delta plains, and the silt and mud deposits of lagoons is very slight. Progradation and subsequent interfingering of the delta plain in a seaward direction through lagoonal deposition behind strand plains and barrier islands further complicates assessment of the depositional environment by creating transition zones of like-sediments. However, some basic differences in surrounding lithology are apparent. In general, the marine channel has either aggraded or degraded directly onto the organic debris and peat of the lagoon, with no siltstone interbed deposit formed from lateral migration of fluvial channels. No mudstone overbank deposits or sand and silt crevasse-splay deposits are associated with marine channels, and neighboring lithologies are devoid of interfingering and transition zones. Figure 38. shows idealized cross-sections through both marine and terrestrially influenced sandstone channels, showing differences in basal and lateral morphology as well as surrounding lithology.

5.1.1.2 Ground Control Problems Associated With Sandstone Channels

Both terrestrial/fluvial and marine sandstone channels produce adverse roof conditions that create a hazardous working environment for mining personnel and machinery. Most major coal fields in the West are developed in areas of Cretaceous deltaic sedimentation. Marine and fluvial sandstone channels are thus often found in close proximity, due to contemporaneous deposition or transgression/regression cycles that produce the sedimentary features shown in Figure 37. As previously described, marine sandstone channels tend to produce less adverse conditions, possibly because they commonly have aggradational bases. Over 80 percent of sandstone channels encountered in mine roofs of the West are probably of fluvial origin. Although marine sandstone channels generally create slightly fewer hazards, both types of channels are usually

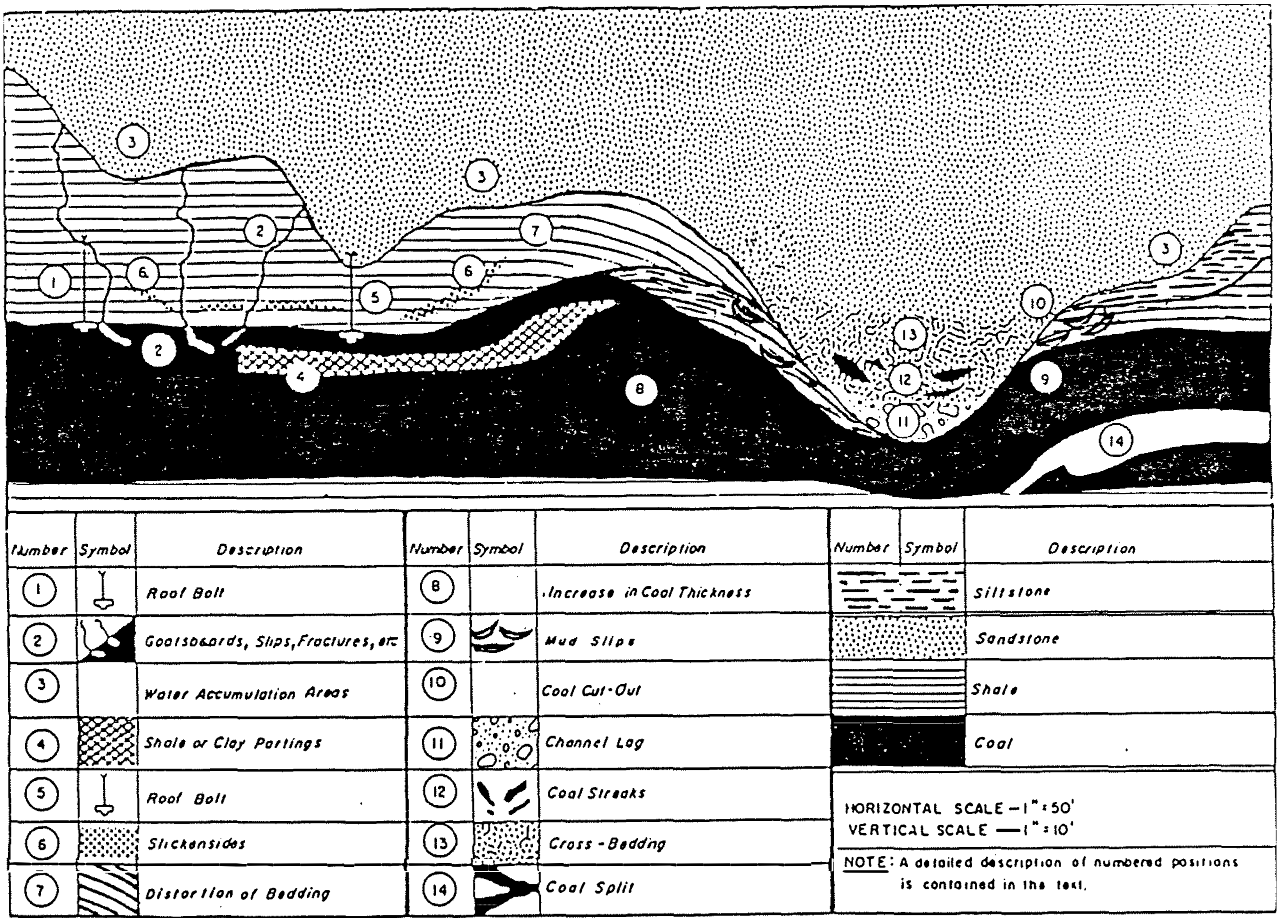

FIGURE 39. - Features and characteristics associated with sandstone channels (adapted from 32).

found in the same area and, due to the slight differences between the two in surrounding lithology, both types of channels can produce hazardous roof conditions.

In discussing the components of a sandstone channel and their possible adverse effects, overbank deposits of shale, point-bar deposits of siltstone and mudstone, crevasse-splay deposits of siltstone, sandstone, and mudstone, and the actual central sandstone channel deposit will be discussed as one morphologic unit termed a sandstone channel. Figure 39. is adapted from a description of sandstone channel features and related adverse conditions that occur in eastern and upper-midwestern coal fields of the U.S. (32).

Features associated with sandstone channels are numbered in Figure 39. and are discussed individually in the order shown. The type of sandstone channel, whether marine or terrestrial, that is associated with each feature will also be discussed.

1. Roof Bolts - One of the initial indications that coal mine development is approaching a sandstone channel is that roof bolts may

intersect fractures and/or moisture. As described in part 3. below, sandstone channels are frequently locations for water storage and/or movement. If the channel contains water, and bolts intersect fractured rock adjacent to a sandstone channel, water may enter the mine. Unless the roof bolt loosens a piece of fractured rock, there is usually no associated hazard at this location. However, moisture associated with roof bolts may indicate that a sandstone channel is nearby and therefore that caution is warranted. This condition is found with both marine and fluvial sandstone channels.

2. Goatsbeards and Fractures - As mining approaches a sandstone channel, the density of fractures and goatsbeards may increase. A "goatsbeard" is a mining term used to describe recrystallized gypsum or anhydrite on the roof of an underground coal mine. Where moisture is present in shale or siltstone roof rock, crystals of gypsum or anhydrite will often dissolve, be transported through fractures, and recrystallize into white, hairlike needles on the mine roof. The presence of goatsbeards may indicate a nearby sandstone channel that is supplying water. An increase in fracture density may be found in this area. Where fractures have propagated to the sandstone channel, petroleum seeps may also be found. The sandstone of the channel acts as a reservoir for petroleum, which may be floating on top of water.

   No major adverse conditions are associated with these features. However, they may indicate that a sandstone channel is nearby and therefore that caution is warranted. Whenever fractures are intersected by bolts, the potential for a roof fall increases.

3. Water Accumulation - Sandstone within the central portion of a channel is often the source for water migrating into the mine. The sandstone may produce a constant influx of water, in which case water moving through a fracture or from a mining cut will flow at a fairly constant rate. However, the initial rush of water into a mine will often cease or drastically reduce flow magnitude over time (34). This is usually indicative of sandstone with a limited, finite supply of water.

   Adverse conditions caused by water emanating from sandstone channels include weakening and deterioration of roof rock, deterioration of bolts, water accumulation on mine floors, and expansion of joints and fractures. In combination with a lithofacies change roof type (see Section 6.1.2), weak bedding planes, or fractures, water can increase deterioration of these features and contribute to severe roof falls. In underground locations where water is entering the mine, especially near sandstone channels, close monitoring for roof deterioration should be practiced. Water is commonly discharged to the side of mine entries or cross-cuts using overhead tarps to keep water from ponding and limiting the movement of personnel and machinery. Water entering the mine through bolt holes can erode the rock surrounding bolts, thereby loosening them and creating the possibility of roof falls. Rebolting and matting of the mine roof is often necessary in areas where water has significantly deteriorated the roof rock.

4. Shale or Clay Partings - In western coal mines, shale or clay partings that appear within the coal seam can signify the proximity of a sandstone channel. The parting is most often a shale, clay, or claystone layer that is usually approximately 1/4 in. to 2 in. thick. The parting, if associated with a sandstone channel, is usually encountered several hundred feet from the channel and represents sheet-flood deposition of very-fine sediment.

   Partings do not generally create hazardous conditions, but indicate a possible nearby sandstone channel. The parting is usually separated from the coal by a weak bedding plane, which can cause the underlying coal to separate and fall. As mining progresses closer to the channel, the parting may split the coal into two seams, which may have to be mined independently to maintain coal quality. The parting then becomes a "split". Partings occur only in association with a fluvial channel, as marine sandstone channels do not form overbank or crevasse-splay deposits.

5. Roof Bolts intersect Aquifer - If bolts are drilled directly into a water accumulation zone within a sandstone channel, a rapid influx of water into the mine can occur. While drilling into the sandstone, the bolter operator will see that sandstone, and possibly water, has been intersected. This would be the first confirming evidence that mine development has encountered either a marine or fluvial sandstone channel, and that caution is warranted.

6. Slickensides - Slickensides are highly polished, sometimes striated surfaces in the rock usually found adjacent to both fluvial and marine sandstone channels. The slickensided rock is usually composed of shale, silty shale, or siltstone. Slickensides are formed by differential stress between the sandstone and shale during compaction and lithification. When undermined, these poorly bonded, cohesionless masses of rock fall easily, producing large and possibly fatal roof falls. Slickensides are treated separately in this section due to their significant adverse impact on mining.

7. Distortion of Bedding - Roof rock adjacent to the sandstone channel may display bedding distortion. This distortion is inferred to have occurred when compaction, caused by the weight of overlying sediments, distorted the less competent beds that surround the sandstone channel. This distortion can produce fractures in the bedded rock. Fractured rock may break apart and fall when underlying coal is removed. Distorted and fractured bedding can occur in association with both marine and fluvial sandstone channels. However, because marine sand channels are more commonly deposited directly onto the peat and organic sediments of lagoons, distorted bedding below the marine channel is less common.

8. Increase in Coal Thickness - An increase in coal thickness may be noted when mining near a marine or fluvial sandstone channel. This increase in thickness is inferred to be caused by differential compaction of the surrounding sediments by overburden (32). Sandstone channel geometry and the greater tensile strength of the sandstone

causes the peat to become more compressed beneath the sand channel. Stress is released by expansion of the peat bed adjacent to the sand channel.

9. Mud Slips - The term "mud slip" is a mining term used to describe a clay or mudstone lense in roof rock adjacent to a fluvial sandstone channel. A mud slip may also be a clay gall. The mudstone lense is usually found on an inside meander bend of a fluvial channel where it was originally deposited as very-fine sediment in relatively quiet water. If the mud slip has the shape of a gall, it was probably originally deposited slightly inside the meander bend as coarse, light-weight bedload. Whatever the origin for the mudstone or claystone mass, a mud slip contains a plane of weakness on both sides. This plane of noncohesion is developed because the mudstone is dense, featureless, homogenous, and does not bond with surrounding rock. Often, the mud slip adjacent to the channel can cover a fairly large area, depending upon the size of the channel and meander bend. This type of mud slip can approach 30 ft. along strike, and be 10 ft. to 15 ft. wide and several feet thick. However, most often the mud slip will be approximately 3 ft. to 4 ft. in diameter and 2 in. to 5 in. thick. Both sides of the mud slip are usually cohesionless. Upon removal of the underlying coal, a large portion of roof rock can fall. Figure 39. shows the location of mudstone lenses deposited on inside meander bends and their relation to the roof rock above the coal seam. Figure 40. shows, in closer detail, mudstone lenses deposited during overbank flooding or as point-bar deposits. When grouped together, as shown in Figure 40., mud slips can create a fairly large area that is subject to large roof falls. Mud slips are deposited by overbank flooding, as point-bar deposits on the inside bends of stream meanders, or as clay galls deposited from upstream sources, and are therefore found only in relation to fluvial sandstone channels.

10. Coal Cut-Out - Coal "cut-out" is a mining term which loosely describes the actual downcutting and coal removal produced by a fluvial sandstone channel. A coal cut-out is not as important for it's mode or depth of erosion as it is for its associated roof control problems. The abrupt increase in lenticularity of the channel, as it scours into the roof rock, establishes weakly bonded, and disrupted bedding, increased differential stress, and a major, steeply angled, plane of weakness between the edge of the sandstone channel and the surrounding roof rock. Because of the significant adverse impact caused by coal cut-outs, they are treated separately in this section.

11. Channel Lag - In the base of a fluvial sandstone channel, channel lag deposits may be found. Channel lag is described as large, coarse fragments that are deposited in the swiftest-flowing part of the channel. Because fluvial channels migrate laterally, channel lag is found across the channel base. This channel lag does not present roof control problems unless the lag deposit becomes detached as one unit from the sandstone. However, channel lag deposits are usually very-well cemented in the channel.

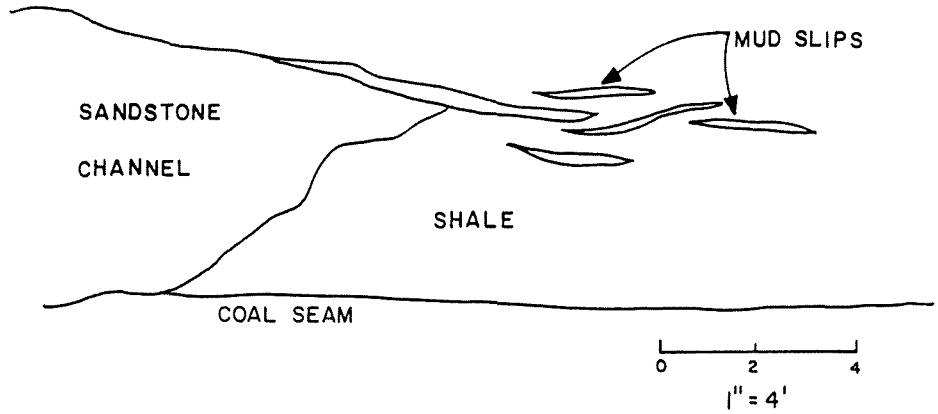

FIGURE 40. - Diagram showing idealized location of mud slips in relation to a fluvial sandstone channel. Each mud slip contains a plane of weakness that could cause a roof fall subsequent to undermining.

12. Coal Streaks - Coal streaks found within a fluvial sandstone channel represent roots, twigs, or tree limbs that have been transported downstream and deposited, most often on an inside meander bend. Through time, these organic fragments become coalified. No direct roof control problems are associated with coal streaks found within the sandstone channel. Occasionally, the coal streak, because it contains a plane of weakness separating it from the surrounding channel, can cause channel sandstone to detach and fall.

13. Cross-bedding - Above the channel lag and coal streaks, the sandstone of the channel may be cross-bedded. In general, high-angle cross-beds in sandstone show high energy flow conditions of fluvial channels, whereas low-angle cross-bedding represents lower energy flow conditions of marine tidal inlets (see Section 5.1.1.1). Cross-bedding has no effect on the roof conditions encountered when mining through or beneath a sandstone channel.

14. Coal Split - A coal split may be encountered several hundred feet from a fluvial sandstone channel and most often represents deposition of overbank or crevasse-splay deposits of siltstone or mudstone prior to or contemporaneous with the sandstone channel. A coal split may form from enlargement of a parting (see part 4.), frequently in association with a fluvial sandstone channel. A coal split may signal the proximity of a sandstone channel. The coal split can present poor roof conditions due to the weak bedding plane between the split and the "rider coal" above. Mudstone and siltstone of the split may contain bony coal and be poorly cemented causing the coal split to fracture and fall. Often, the coal will have to be mined in two lifts to ensure coal quality.

Slickensides

Slickensides, as a feature found in roof rock primarily adjacent to sandstone channels in western underground coal mines, were briefly discussed under part 6. of this section. However, because of the major adverse impact on coal mine ground control caused by this feature, slickensides are more fully discussed here.

Slickenside is a geologic term that has been applied to a feature found in roof rocks in underground coal mines. In general geological use, slickensides are the grooves, steps, and striations found on a rock surface, which are created by the movement of one rock against another. In a strict geological sense, slickensides are only found on the planes of faults. As a mining term, slickenside is used to describe a feature found in the roofs of underground coal mines, most commonly adjacent to sandstone channels. The rock is usually a shale, silty shale, or siltstone. The rock type must be sufficiently fine-grained so that highly polished and grooved surfaces can develop. Shale is composed of clay and silt-sized particles which polish easily. Slickensides are one of the major causes of large, dangerous roof falls, due to the lack of bonding between rock masses along the polished surfaces.

During the course of this study, two types of slickensided rock were differentiated based on the degree of structural deformation observed. Both types of slickensided rock most often occur adjacent to marine or fluvial sandstone channels. Slickensides occur primarily in shale and secondarily in siltstone. The first type of slickenside was most likely formed by contemporaneous generation of differential stress and deformation through compaction of fine-grained sediments relative to a sandstone channel, and is termed a compaction slickenside (37). The second type of slickenside displays much more structural deformation, with possible recrystallization and partial metamorphism apparently caused by extreme pressure. This type is termed a structural slickenside.

Compaction slickensides are most often found in shale or siltstone roof rock adjacent to sandstone channels. It is believed that compaction slickensided rock was formed from differential compaction of the two types of sediment. As the weight of deposited, overlying sediment increased, clay and silt adjacent to a sand channel was not only lithified through normal compaction diagenesis, but was also influenced by the adjacent, dense sand channel. As lithification continued, differential stress between the sand, clay, and silt was generated by the irregular sand channel geometry and density of the sandstone. This process produced masses of shale that would move in a cohesive manner against other masses of shale. This differential stress is manifested by slickensided rock masses with many cohesionless planes oriented in several directions. Plate 7. is a detailed photograph showing the features of an individual mass of compaction slickensided, extremely hard shale. The size of this fragment is just slightly below the average size of slickensided rock found within mine roofs of the West. Sizes of individual masses vary greatly, from approximately 4 in. in diameter and 1/2 in. thick to 3 ft. in diameter and 1.5 ft. thick. Individual masses are usually slickensided on both sides, often in opposing directions. Plate 8. is a photograph showing the roof fall where the slickensided shale of Plate 7. was obtained. This photograph shows a large roof fall located below a sandstone channel that was continuously caving at the time of the mine tours. Each broken piece of rock in the foreground is slickensided. Compaction slickensides were noted in all of the coal mines toured during this project.

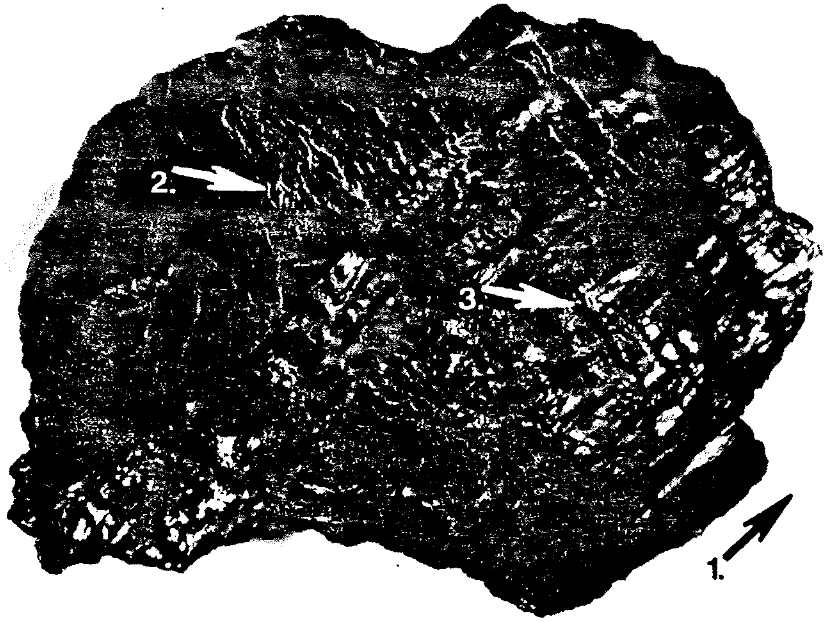

PLATE 7. - Detailed photograph of compaction slickensided shale from the Trinidad Coal Field. Fragment is approximately 8 in. wide. Arrow 1. shows direction of movement; arrow 2. shows steps in which recrystallized calcite has begun to form; arrow 3. points to steps and striations gouged into shale. Note the high polish.

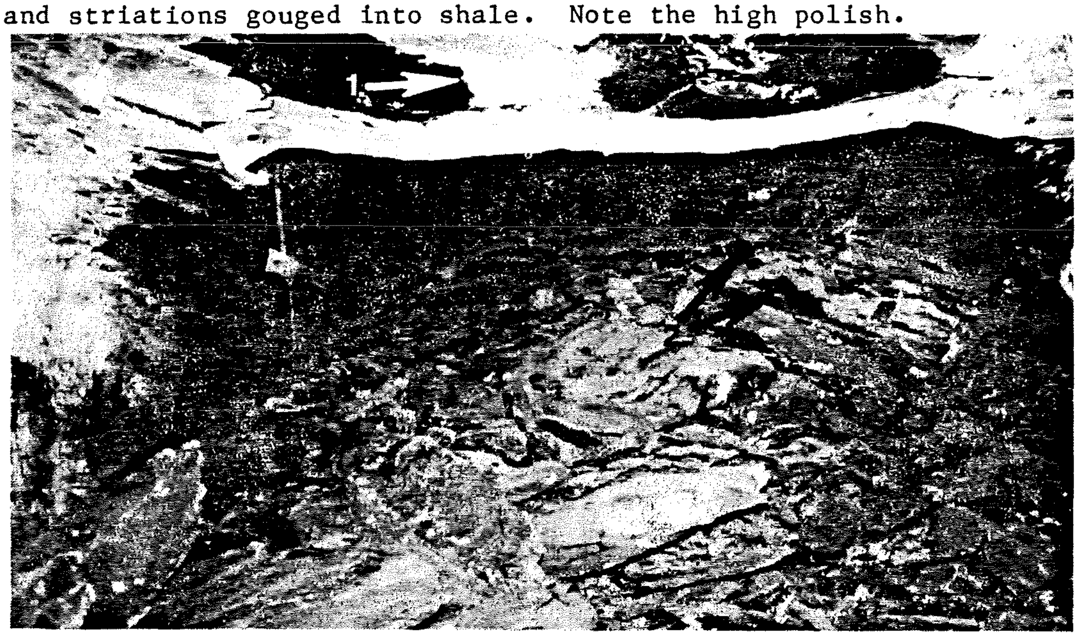

PLATE 8. - Major roof fall located approximately 40 ft. below a sandstone channel, Trinidad Coal Field. The roof fall is dome-shaped and collapsed within an intersection. Five ft. resin-grouted bolts on 4 ft. centers with mats did not control the roof, which caved upward through 15 to 18 ft. of slickensided shale. Arrow 1. points to rock dust and arrow 2. points to highly polished, slickensided pieces of shale roof rock. Slickensided shale is believed to extend another 20 ft. upward to the base of a sandstone channel. The piece of compaction slickensided shale shown in Plate 7. was obtained from this roof fall.

Structural slickensides are formed on the shale or siltstone laminations deposited by crevasse-splays adjacent to sandstone channels. Due to extreme unidirectional pressure, shale or siltstone has become extremely brittle, apparently partially metamorphosing to slate. This type of slickenside is not related to the miners "draw slate," which is a shale cap-rock that falls from the roof when the underlying coal is removed. Structural slickensides are developed adjacent to and beneath sandstone channels. They are due not only to differential stress between the sandstone and shale, but also to a high unidirectional, horizontal stress that is probably caused by a combination of dipping strata with an overburden thickness commonly greater than approximately 1500 ft. In western coal mines, commonly when overburden thickness is greater than 1500 ft. to 2000 ft., stress in rock surrounding the mined area increases significantly with depth (36). Under these conditions, siltstone or shale adjacent to sandstone channels deforms due to horizontal and differential stress displaying translation gliding, polish, slickensides, and possible recrystallization.

Plate 9. is a photograph showing, in detail, features of an individual rock fragment with structural slickensides. This fragment is from a mine in the western Book Cliffs Coal Field with an overburden thickness of 1600 ft. Of particular significance in this sample is the abundance of recrystallized calcite. Crystals that are originally aligned are most easily recrystallized out of the matrix onto the surface of a rock. Calcite crystals found within undeformed siltstone are aligned. In terms of structural geology, recrystallization shortens rock in areas of greatest stress and lengthens rock in areas of least stress. As shown in Plate 9., it is obvious that the calcite has recrystallized in rock steps where stress was least. Figure 41., below Plate 9., is a cross-sectional view of the structurally slickensided siltstone of Plate 9., showing locations of gouge and recrystallization.

Each individual, structurally slickensided fragment in this mine of the western Book Cliffs Field represents a lamination within a crevasse-splay deposit that is either stratigraphically above or below a sandstone channel, or a thin siltstone crevasse-splay lamination above and below a thick, sandstone crevasse-splay bed. Plate 10. is a photograph taken underground at the location where the fragment shown in Plate 9. was obtained. This photograph depicts the depositional environment for these structural slickensides and shows the base of a structurally slickensided sandstone channel, with associated crevasse-splay deposits, and structurally slickensided siltstone laminations. As this cross-cut was mined, bolter operators had extreme difficulty placing bolts. Active lateral movement in the roof caused drill bits to snap, and holes to be offset before bolts could be placed. Roof falls were constant. The photograph shows a bolt that was only partially inserted, illustrating the difficult process of bolting and matting this roof. Plate 11., also taken in the same area, shows the base of the sandstone channel and structurally slickensided siltstone with much recrystallized calcite. Plate 12. is a close-up photograph of the base of this slickensided sandstone channel that shows excellent examples of recrystallized calcite steps. Plate 13. is a close-up photograph showing, in fine detail, thin laminations of structurally slickensided siltstone and recrystallized calcite.

Compaction slickensided rock is apparently much more common in the West than structurally slickensided rock. Only one mine toured in the Book Cliffs

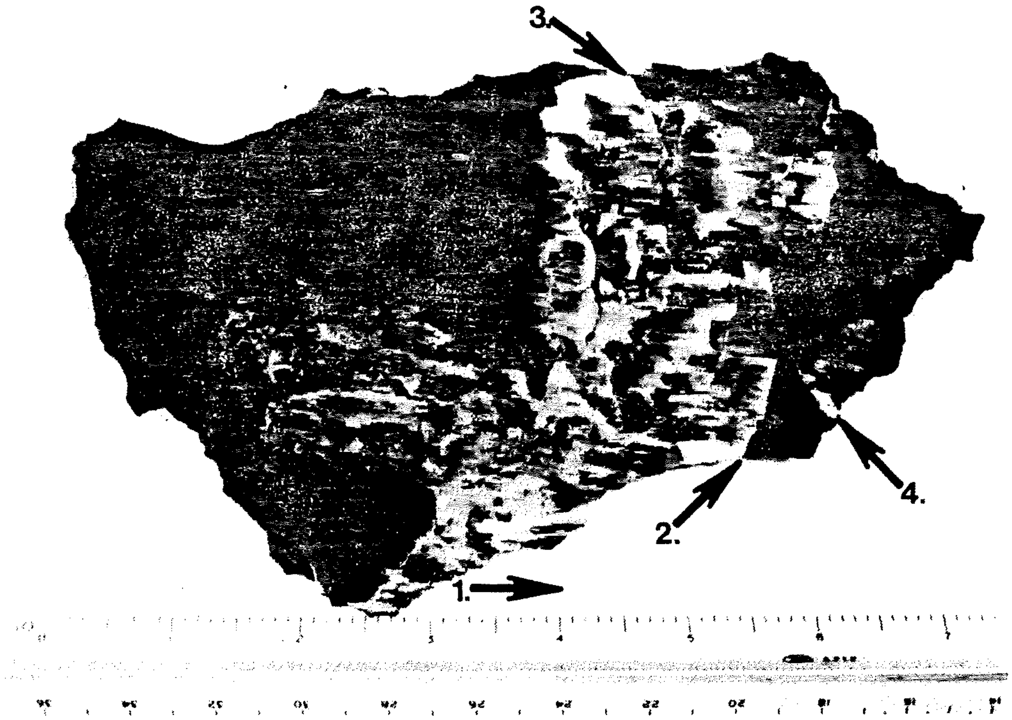

PLATE 9. - Structurally slickensided siltstone fragment, western Book Cliffs Coal Field, Utah. Dark areas are zones of gouge and slickensides, light areas are recrystallized calcite. Arrow 1. points to direction of movement; arrows 2. and 3. point to recrystallized calcite deposited as "steps"; arrow 4. points to reflection of light caused by highly polished slickensides.

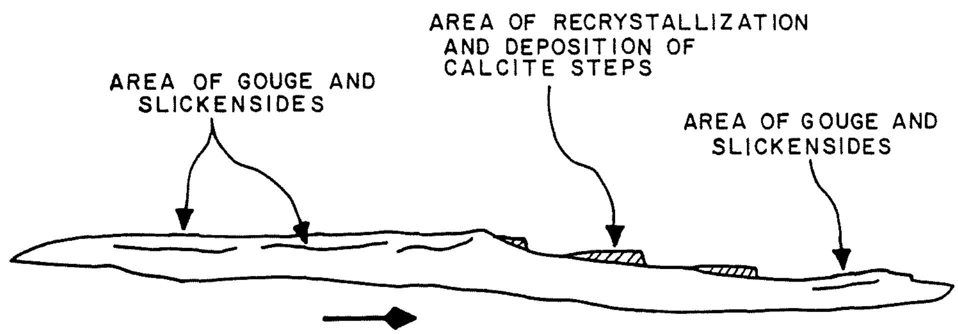

FIGURE 41. - Cross-section through structurally slickensided siltstone of Plate 9. Scale is actual. This perspective clearly shows locations of gouge and structural shortening and also the area of calcite recrystallization and deposition with structural lengthening. This siltstone is extremely brittle, and with respect to recrystallization, apparently has partially metamorphosed to slate. Arrow shows direction of movement.

PLATE 10. - Depositional environment of structural slickensides, western Book Cliffs Coal Field, Utah. Arrow 1. points to recrystallized calcite on the base of a sandstone channel; arrow 2. points to an 18 in. thick sandstone bed of a crevasse-splay deposit; arrow 3. points to thin crevasse-splay laminations of siltstone and sandstone. Each siltstone lamination has been structurally slickensided; arrow 4. points to a partially placed bolt, which, due to extreme lateral stress, could not be fully inserted; arrow 5. points to a pillar. Photograph is taken in cross-cut looking to an entry. This location is beneath 1600 ft. of overburden.

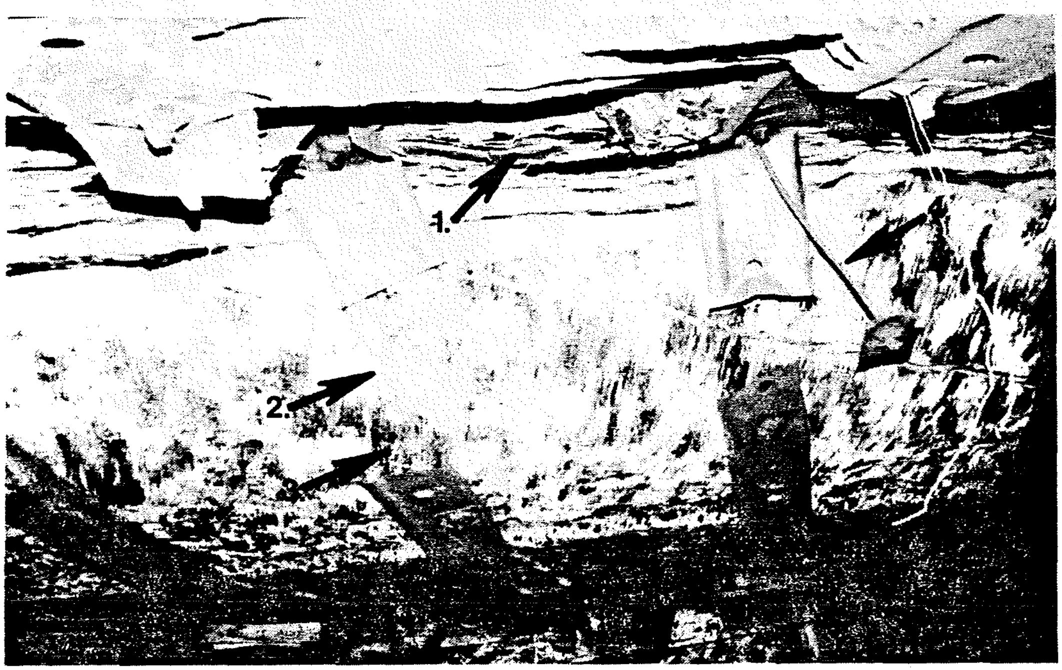

PLATE 11. - Photograph showing base of slickensided sandstone channel, western Book Cliffs Coal Field, Utah. Arrow 1. points to thin crevasse-splay laminations of structurally slickensided siltstone and sandstone overlying and adjacent to a sandstone channel; arrow 2. points to recrystallized calcite on the base of the channel; arrow 3. points to slickensided siltstone also on the base of the channel; arrow 4. points to a partially inserted bolt. View is perpendicular to a rib in a cross-cut.

PLATE 12. - Photograph of base of sandstone channel, western Book Cliffs Coal Field, Utah. Photograph shows structurally slickensided siltstone on the sandstone base. Arrows 1. point to recrystallized calcite "steps"; arrow 2. points to slickensided siltstone on base of channel; arrow 3. points to direction of lateral movement.

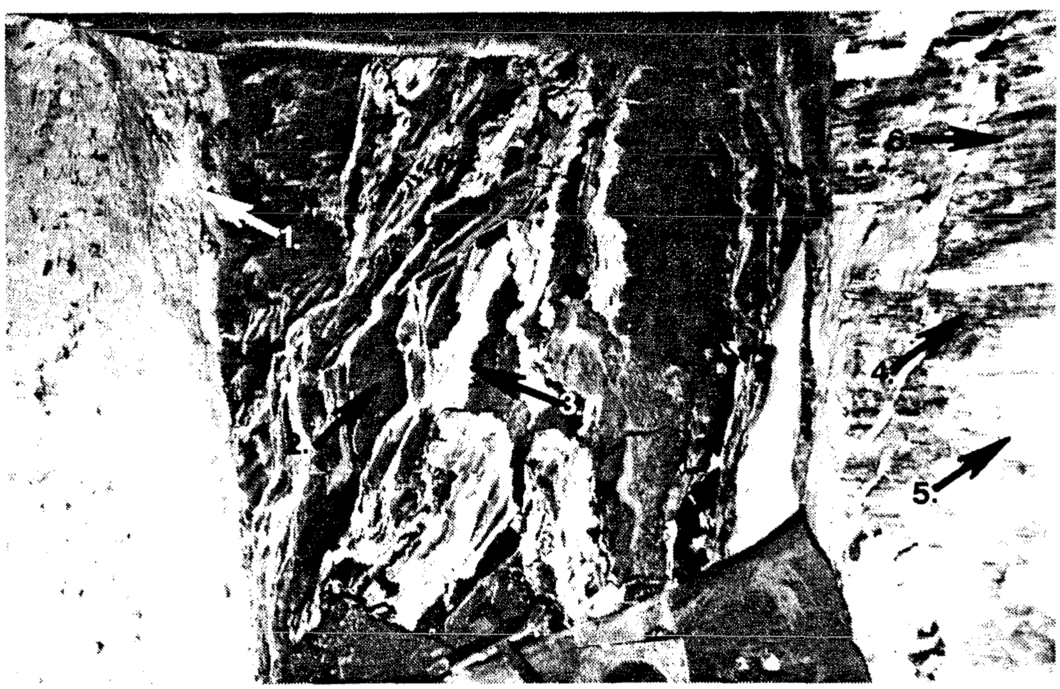

PLATE 13. - Close-up photograph showing details of structural slickensides, western Book Cliffs Coal Field, Utah. Arrow 1. points to 18 in. thick bed of crevasse-splay sandstone; arrow 2. points to structurally slickensided siltstone lamination; arrow 3. points to recrystallized calcite; arrow 4. points to slickensided siltstone on base of sandstone channel; arrow 5. points to recrystallized calcite on base of channel; arrow 6. shows direction of lateral movement.

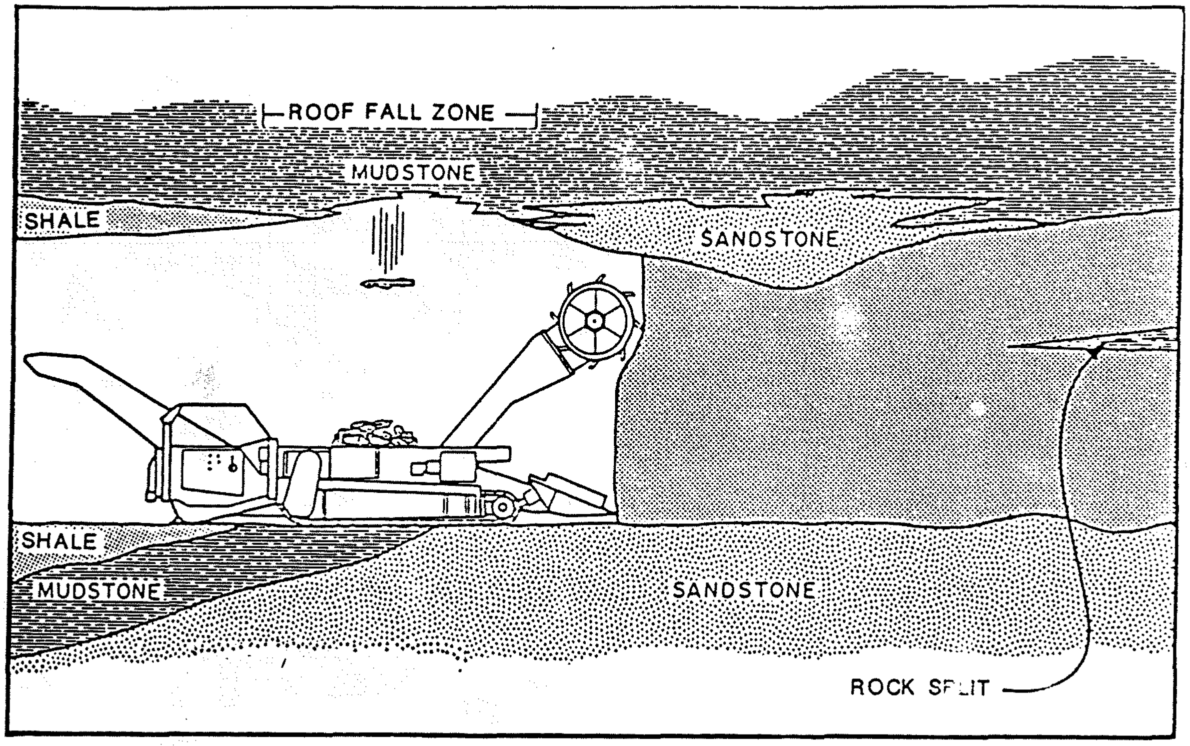

FIGURE 42. - Diagram showing the common location of roof falls that are associated with a sandstone channel. This zone of weakness in the roof may be caused by differential stress, slickensides, or by the weak, noncohesive contact between the sandstone of the channel and the surrounding lithology. Upon removal of the coal, differential stress between the two lithologies can cause severe roof failure (adapted from 38).

Field contained structural slickensides. However, this mine was overlain by an average of 2000 ft. of overburden, the strata dipped slightly, and several seams were mined that were superimposed upon one another. These conditions may be expected to produce structural slickensides in other western coal mines if similar mine development occurs.

Regardless of type, large and often unpredictable roof falls occur because of slickensided rock. Slickensides most often occur adjacent to either marine or fluvial sandstone channels. When a roof fall does occur in this type of roof rock, the fall can completely fill the entry or cross-cut. Efforts to control the fall with cribbing and mats can be dangerous and ineffective. Figure 42. shows the location where slickensided rock occurs adjacent to a sandstone channel, and the effect of the slickensides and differential stress on mining operations. Figure 43. is a portion of a mine map showing the locations of sandstone channels. This map shows the large number of roof falls associated with slickensided rock that is adjacent to sandstone channels.

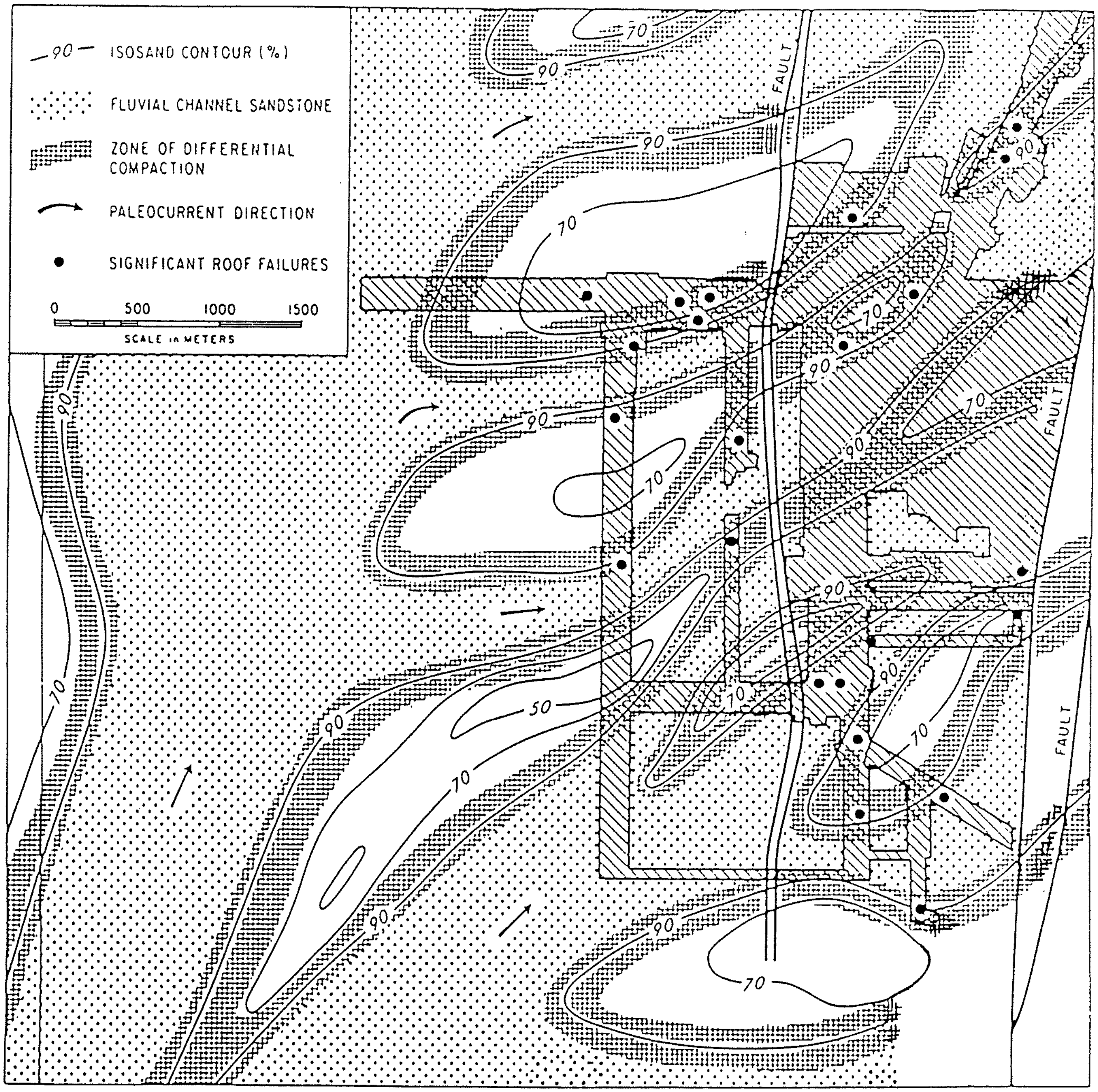

FIGURE 43. - Portion of a mine map showing sandstone channels, central Wasatch Plateau Coal Field. Mapping of sandstone channels shows paleocurrent directions and differential compaction zones producing slickensides. Map shows that location of most roof falls coincides with edge of sandstone channels, where differential stress and slickensides cause adverse roof conditions (adapted from 34).

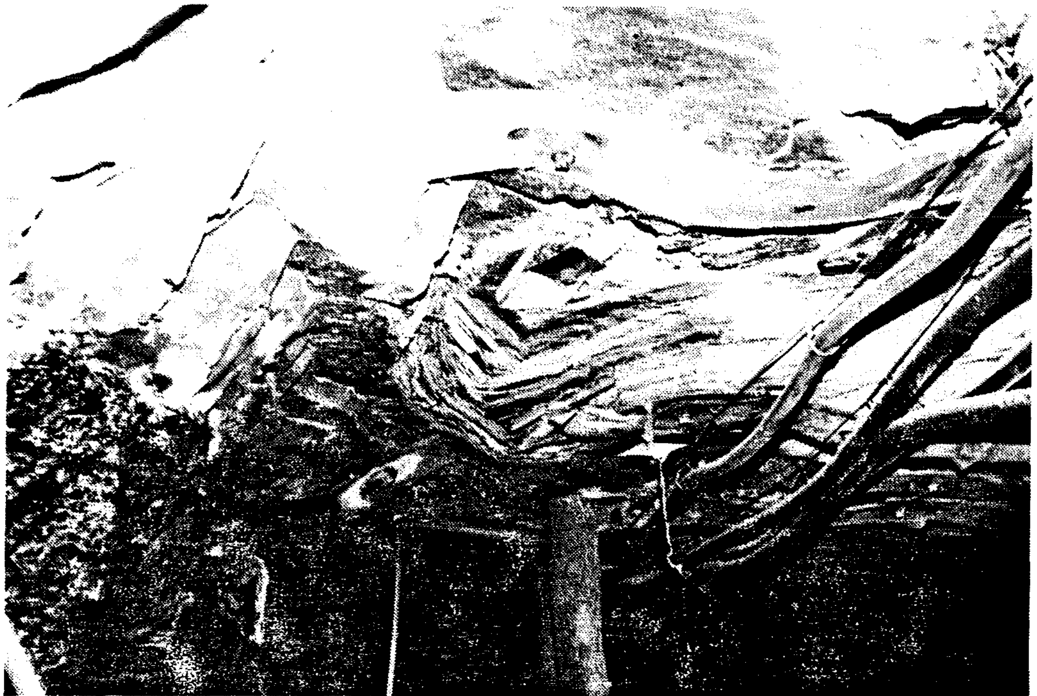

PLATE 14. - "Roof cutter" in crevasse-splay deposit, western Book Cliffs Coal Field, Utah. Brittle sandstone and siltstone laminations have fractured and delaminated adjacent to a pillar. Stress, produced by an overburden thickness of 1600 ft., is inferred to have contributed to this fracturing of the thin, brittle sandstone and siltstone laminae of a crevasse-splay deposit. Mats are 8 in. wide.

Crevasse-splay Deposits

The morphology and depositional environments of crevasse-splay deposits have been discussed in Section 5.1.1.1. Due to their thinly laminated and brittle characteristics, crevasse-splay deposits can create extremely adverse roof conditions. One mine in the western Book Cliffs Coal Field contains overbank siltstone and crevasse-splay deposits of sandstone and siltstone as roof rock over most of the mine (33). Overbank deposits of siltstone usually provide a stable roof rock. However, thin laminations of siltstone and sandstone, where overburden is equal to or exceeds approximately 1500 ft., become highly unstable. This is particularly true in the more open mine areas, such as intersections. The weight of overlying cover produces horizontal stress through pillar load transfer, and deforms the thin, brittle laminations of crevasse-splay deposits that are located adjacent to sandstone channels, producing large and severe roof falls. Plate 14. is a photograph of a "roof cutter" in a mine roof in the western Book Cliffs Coal Field. The photograph shows the fractured and broken nature of the roof rock produced by crevasse-splay deposits. Pressure, produced by an overburden depth of 1600 ft., was causing this weak rock to fracture. Figure 44. is a portion of a mine map for this mine showing sandstone channel geometries. Roof fall locations are also shown. As can be seen on this map, most of the roof falls have occurred in crevasse-splay sandstone deposits. Paleoflow directions indicate the crevasse-splay origin, with sediment transport perpendicular to that of the main channel.

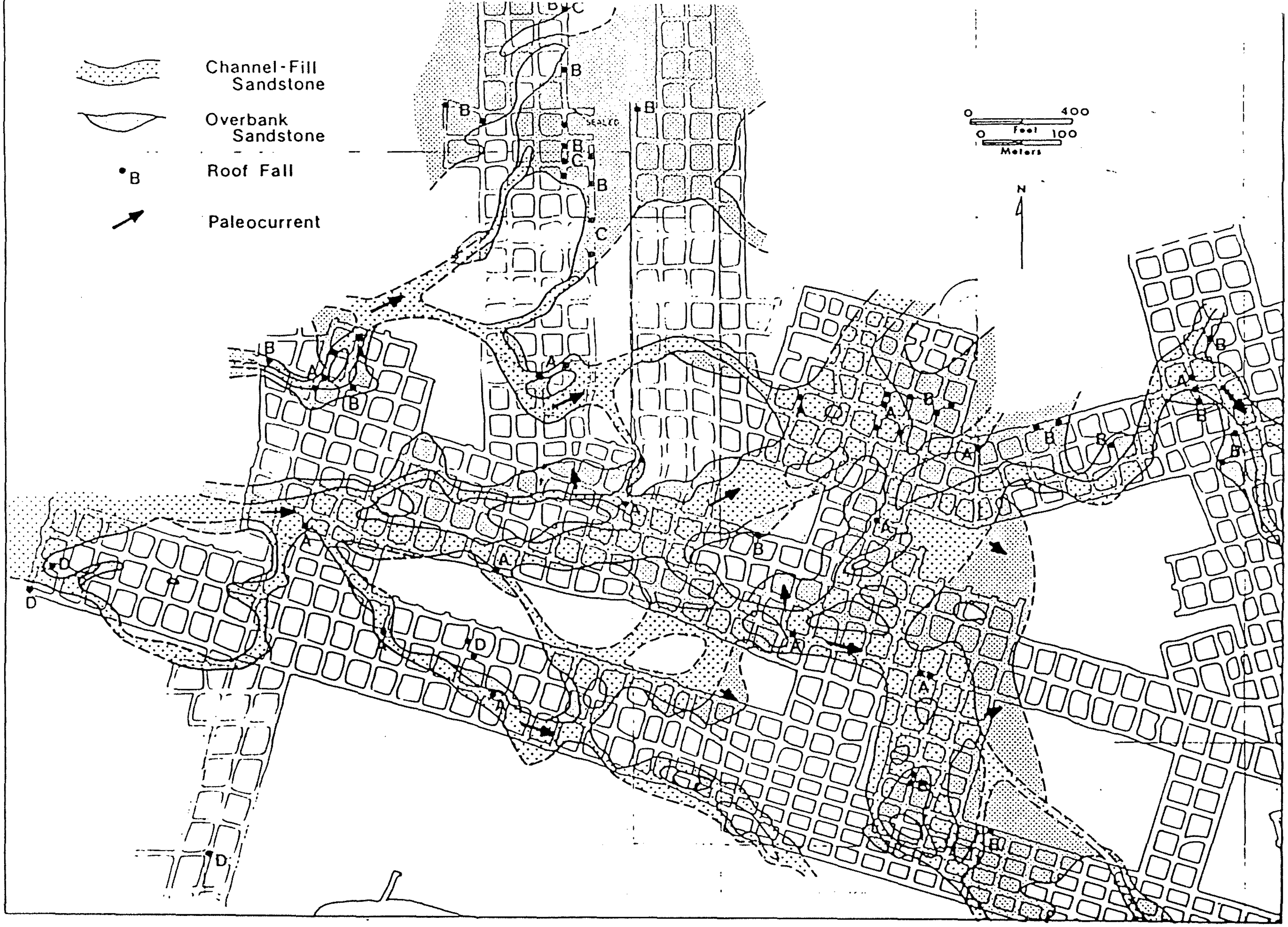

FIGURE 44. - Portion of a mine map, from a mine in the western Book Cliffs Coal Field, showing sandstone channel deposits. Majority of roof falls have occurred in crevasse-splay and overbank deposits (33).

Most coal mines in the West contain crevasse-splay deposits within their roof. Depending mainly on overburden thickness and related horizontal stress, this type of sedimentary feature can produce adverse mining conditions. Mines in the Book Cliffs and Wasatch Plateau Coal Fields contained more of this type of deposit than other fields. With increasing overburden thickness, this type of deposit can be expected to become more unstable and hazardous.

Overlying Sandstone Channels

Extremely severe roof falls occur in several western coal mines due to sandstone channels that are located from 5 ft. to 40 ft. above the coal seam. It appears that the overlying pressure and differential stress exerted by the sandstone channel on underlying, less competent shale and siltstone produces compaction slickensides and causes roof falls below the channel subsequent to coal-seam extraction. These roof falls are characteristically dome-shaped and may cave upward as much as 40 ft., to the base of a sandstone channel. As there is commonly no indication that a sandstone channel exists more than 5 ft. above the coal seam, large and severe roof falls can occur without warning.

Plate 15. is a photograph showing a dome-shaped roof cave that remained after a major roof fall in an intersection. This domed cave extends approximately 25 ft. above the top of the coal seam and has caved upward into an overlying sandstone channel. Plate 16. is a photograph showing the extensive roof control measures required to control the continual caving caused by an overlying sandstone channel. In this example, 5 in. by 7 in. fir cribbing has been built to the uppermost portion of the cave, which is approximately 24 ft. above the roof of the mine. In this situation, the same cribbing design had been previously employed subsequent to a roof fall. However, the roof caved again, due to the slickensided and noncohesive character of the rock below the sandstone channel. Figure 45. is a cross-sectional view of this type of roof fall. In this example, the sandstone channel is shown only 5 ft. above the roof of the coal seam. However, the same roof fall configuration has been observed to occur up to 40 ft. above the seam.

Coal Cut-Out

As discussed in part 10. of this section, the term coal cut-out loosely describes the actual downcutting and coal removal produced by a fluvial sandstone channel. The coal cut-out may only remove the top portion of a coal seam or, at the other extreme, may produce a coal "washout" or "want". Washout is a mining term that describes complete scouring and erosion of the coal seam through stream action. Figure 46. is a portion of a mine map, from a mine in the northern Wasatch Plateau, showing roof geology. A coal washout is mapped in the lower left corner of the figure. This washout is inferred to have occurred during an attempt by the braided stream channel to develop a new channel into the delta plain. A flow direction arrow shows the swirling action of the channel as it scoured into the peat deposit.

A coal cut-out can create significant roof control problems. The abrupt increase in the lenticularity of the channel, as it scours into the roof rock, establishes weak bonding, disrupted bedding, increased differential stress, and a steeply angled plane of weakness between the edge of the sandstone

PLATE 15. - Photograph showing domed roof cave caused by overlying sandstone channel, western Book Cliffs Coal Field, Utah. Cave is approximately 25 ft. high and 30 ft. in diameter in an intersection. Unit 1. is the overlying sandstone channel and Unit 2. is delta-plain shale. Top of steel set is visible in the lower right corner of the plate. Cap blocks are 8 in. wide.

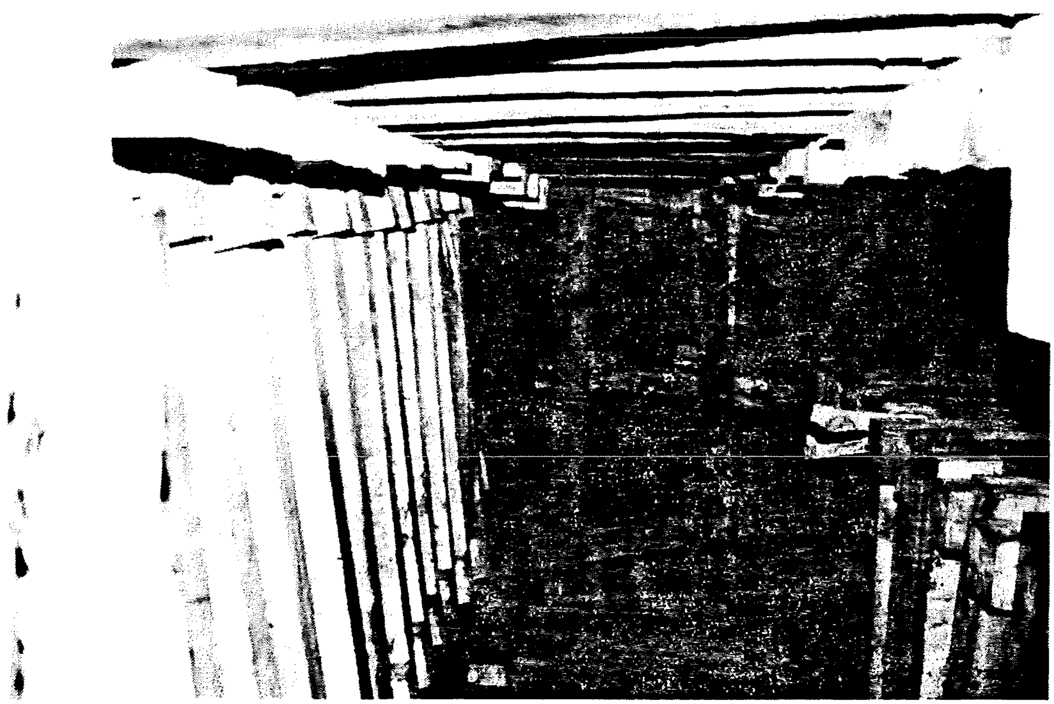

PLATE 16. - Cribbed roof fall, Trinidad Coal Field. Differential compaction and stress produced slickensided rock that caved below an inferred sandstone channel. Roof fall is approximately 24 ft. high. Cribbing timbers are 5 in. by 7 in. View is directly up into the caved portion.

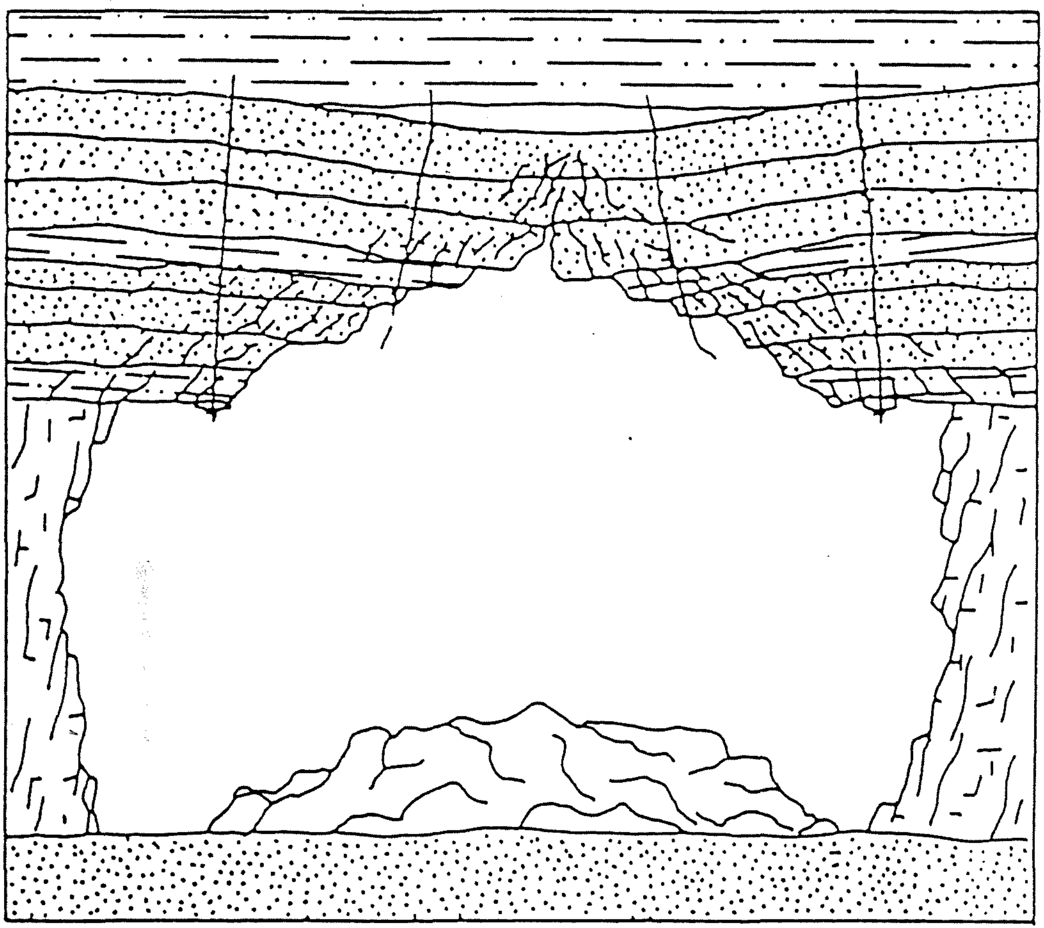

FIGURE 45. - Cross-section through a roof fall caused by an overlying sandstone channel. Roof rock above the coal seam and below the sandstone channel is approximately 5 ft. thick. The intervening strata between the coal and sandstone channel can cave up to 40 ft. in a thicker sequence (33).

channel and the surrounding roof rock. Plate 17. is a photograph of the edge of a fluvial sandstone channel near to the previously mentioned coal washout. The photograph shows a 60 ft. long, 15 ft. wide, and 8 ft. high roof fall in an entry that occurred along the steeply angled weak bedding plane of the coal cut-out. Of particular interest in the photograph is the failure above and alongside the 5 ft. resin-grouted roof bolts. In order for roof bolts to be effective, they must either anchor into competent roof rock above weak rock, or in the case of mechanical bolts, pull weak strata together to obtain support. Only 3 or 4 resin-grouted bolts anchored into the competent sandstone of the channel, as shown. The remaining bolts could not properly anchor into the loose, broken rock adjacent to the sandstone channel, and so failed to provide the required support. Plate 18. shows a fluvial sandstone channel cut-out, that has reduced the coal thickness by approximately 4 ft. This sandstone channel is atypical because of the blocky splitting and spalling of the channel, as demonstrated by the investigator. Wire mesh and mats located above the entry keep sandstone blocks from falling and causing injuries or obstructing movement. This coal cut-out did not affect surrounding lithology. Plate 19. shows the idle working face of an entry in a mine in the Book Cliffs Field of Utah, with a coal cut-out produced by a sandstone channel. Although

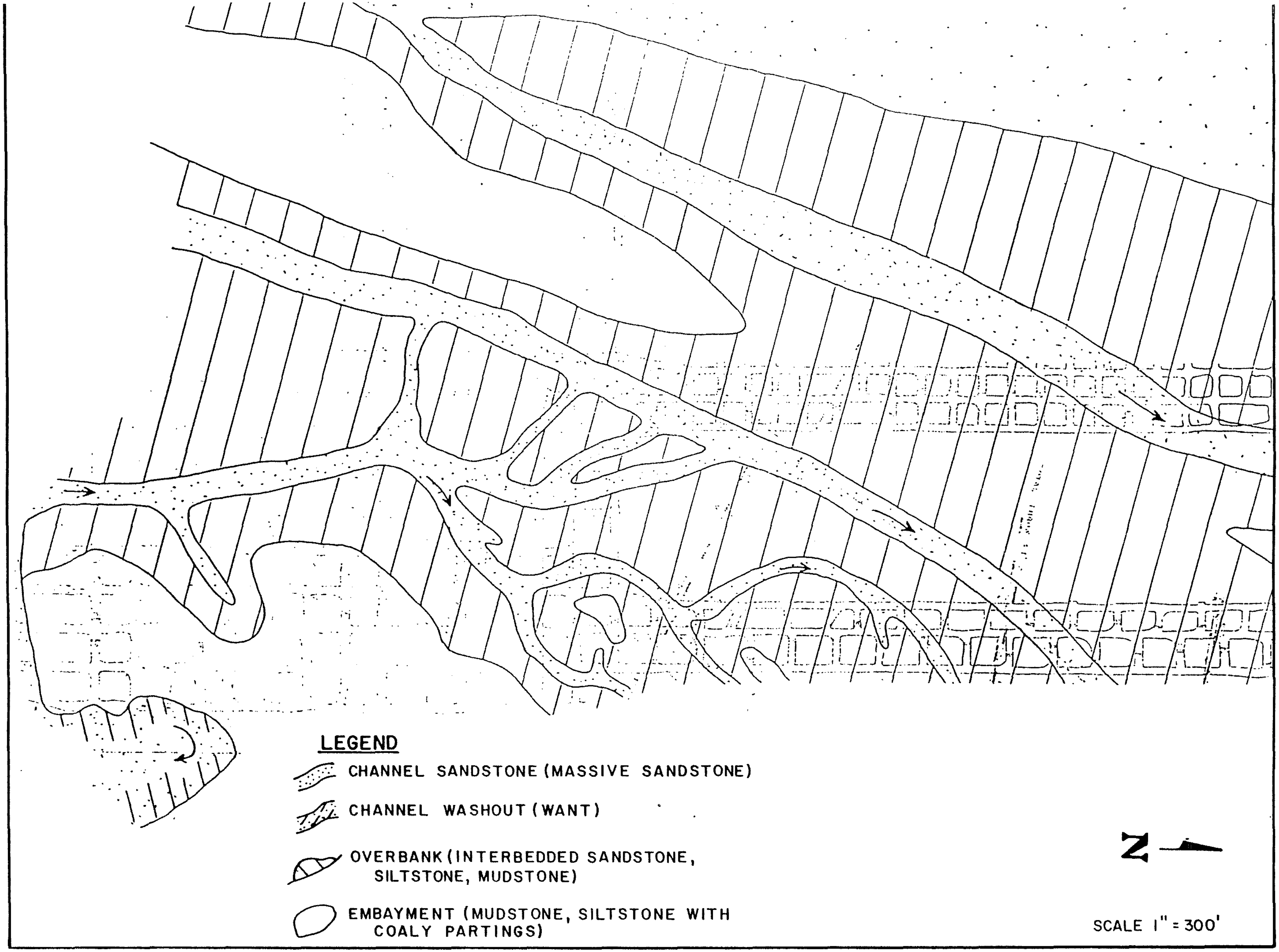

FIGURE 46. - Portion of a mine map, from a mine in the northern Wasatch Plateau Coal Field, showing roof lithology including a coal washout mapped in the lower left corner.

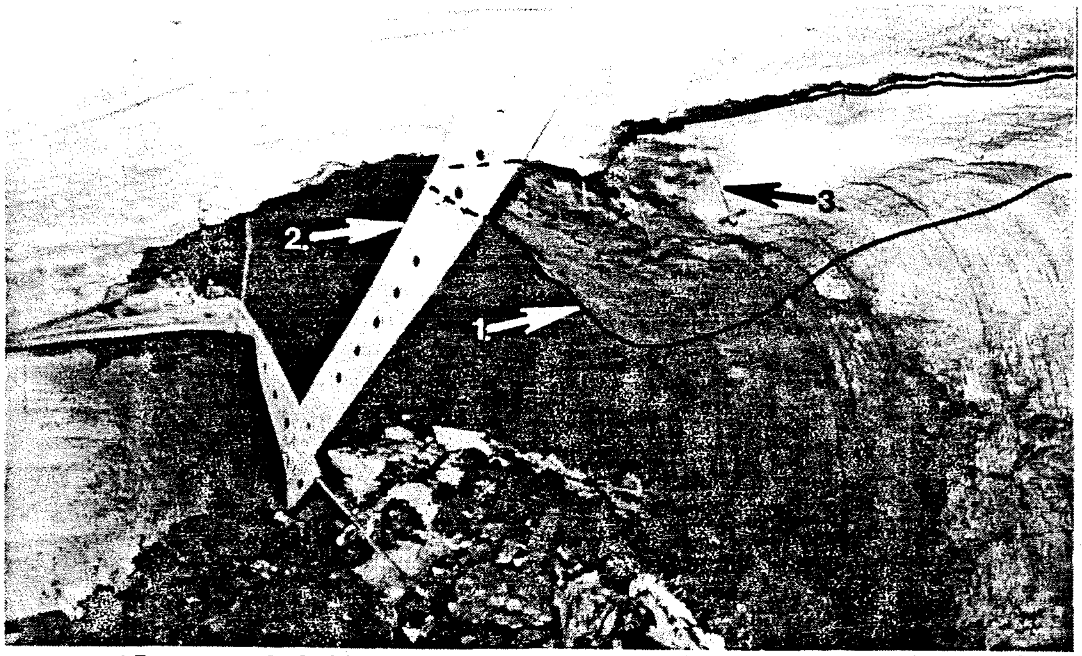

PLATE 17. - Roof fall adjacent to a coal cut-out produced by a fluvial sandstone channel, northern Wasatch Plateau Coal Field. The steep angle and density of the sandstone channel has caused differential stress, weak bonding, and fractured and disrupted rock adjacent to the channel to collapse. Arrow 1. points to outline of sandstone channel; arrow 2. points to roof mats torn away by the roof fall; arrow 3. points to remaining bolts anchored in competent sandstone. Roof fall measured 60 ft. long, 15 ft. wide, and 8 ft. high.

PLATE 18. - Fluvial sandstone channel and associated coal cut-out, central Wasatch Plateau Coal Field. Sandstone channel has removed approximately 4 ft. of the peat deposit. Channel has blocky splitting that causes much spalling. Arrow 1. points to mats and mesh needed to keep sandstone blocks from falling into entry; arrow 2. points to fracture causing blocky splitting; arrow 3. points to spalled sandstone blocks on mine floor.

the angle of this cut-out is not steep, roof rock below is easily detached. Plate 20. is a photograph taken at closer range, to the left of Plate 19. This photograph shows the slightly lenticular base of the sandstone channel where it scoured into the coal. Just above the vent tube, a piece of slickensided shale roof rock fell and killed a bolter operator. As has often been documented, the roof fall was not large (3 ft. in diameter and 8 in. thick) but nevertheless, proved fatal. Plate 21. shows the base of a sandstone channel that has not cut-out the coal. This photograph shows the plane of weakness between the base of the channel and the underlying shale. Plate 22. is a detailed photograph of the base of the sandstone channel shown in Plate 21., showing the slickensided plane of weakness between the sandstone and the shale. Without proper bolting and matting, this shale falls away in large slabs. The poorly bonded rock immediately adjacent to and below a sandstone channel can be extremely hazardous during roof supporting operations.

5.1.2 Lithofacies Change

A particularly hazardous type of coal mine roof, which presents the constant danger of large, undetectable roof falls, is characterized by specific lithofacies changes. Lateral facies change in rock composition and character of roof strata is due mainly to the subenvironment of sediment deposition within the coastal plain and delta environment. Roof rock may either be homogenous, with little lateral change in lithology, or show transitional and interfingering lithofacies change.

Examples of paleosubenvironments in the coastal plain and delta environment, which most often display relatively homogenous lithofacies characteristics and generally do not present hazardous roof conditions, are the sandstones of barrier bars, accretion ridge/strand plains, littoral beaches, and fluvial channels; and the shale and siltstone of the prodelta shelf, swamp areas, and stable portions of the delta plains. These subenvironments produce poor roof conditions in underground coal mines only if the subenvironment experienced rapid depositional change caused by shifting of delta lobes or marine transgression/regression. However, these were areas commonly characterized by relatively long term, stable deposition of like-sediments.

In general, subenvironments that contain transitional and interfingering lithofacies change experienced rapid depositional changes, such as those caused by localized, short-term marine transgression and regression. Areas of the coastal plain that were not influenced by deltas or lagoons did not experience rapid facies change. Subenvironments of the delta environment, which experienced rapid depositional change and subsequent development of transitional and laterally interfingering facies, were areas of unstable delta plain that were periodically inundated by transgressing marine waters, crevasse-splay deposits, widespread fluvial flood deposits, and shifting distributary channels. Another location with unstable roof rock characterized by lithofacies change are lagoons, where washover fans and flood-tidal deltas would periodically deposit silt and mud in wide deposits. Interfingering silt and mud deposits of delta plain streams, that prograded into lagoons and extended the delta plain, also developed laterally transitional lithofacies changes.

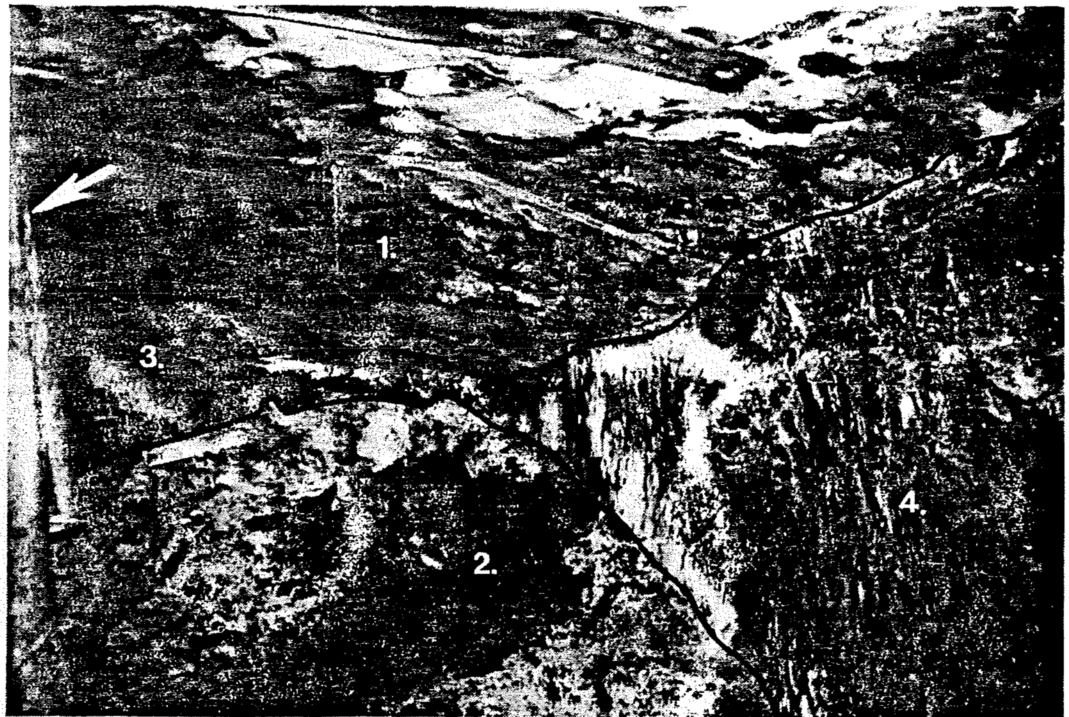

PLATE 19. - Sandstone channel base and coal cut-out, western Book Cliffs Coal Field, Utah. Unit 1. is the base of a sandstone channel that has removed 2 ft. of the coal deposit; unit 2. is gob; unit 3. is the working coal face; unit 4. is the rib. Arrow points to brattice curtain. Mats are 8 in. wide. This location is under 2600 ft. of cover.

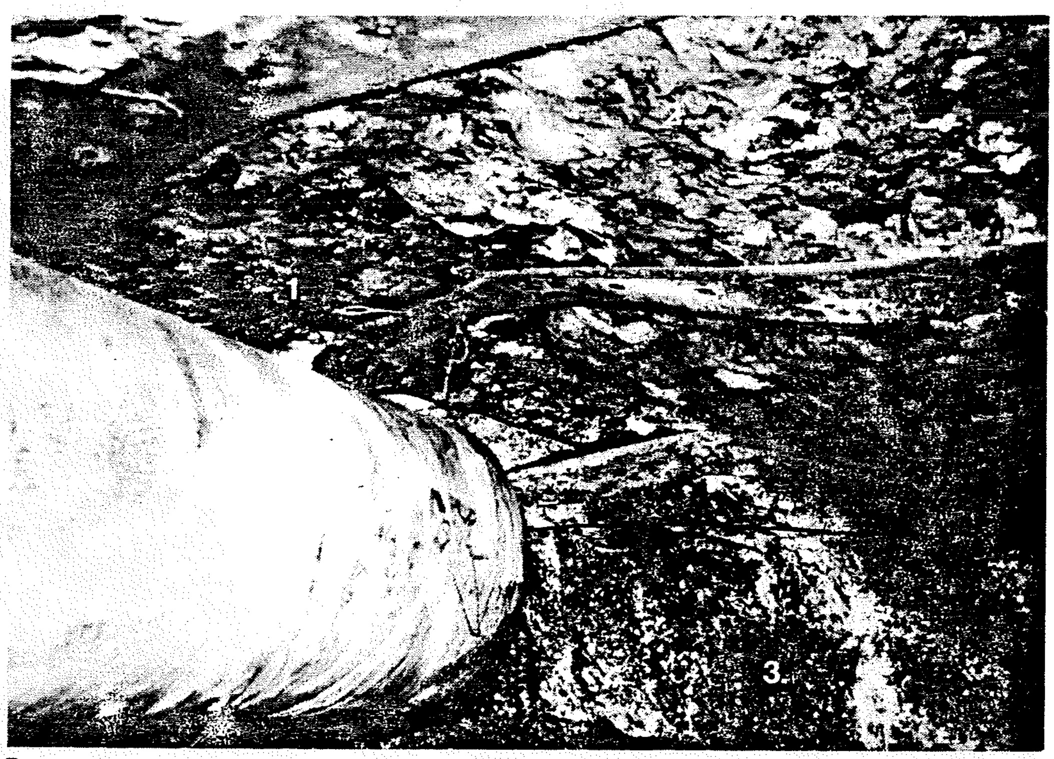

PLATE 20. - Base of sandstone channel with slickensides, western Book Cliffs Coal Field, Utah. Unit 1. is slickensided shale that is attached to the base of a sandstone channel where a 3 ft. by 8 in, piece detached and killed a bolter operator; unit 2. is the base of the sandstone channel; unit 3. is the rib. This location is under 2600 ft. of overburden.

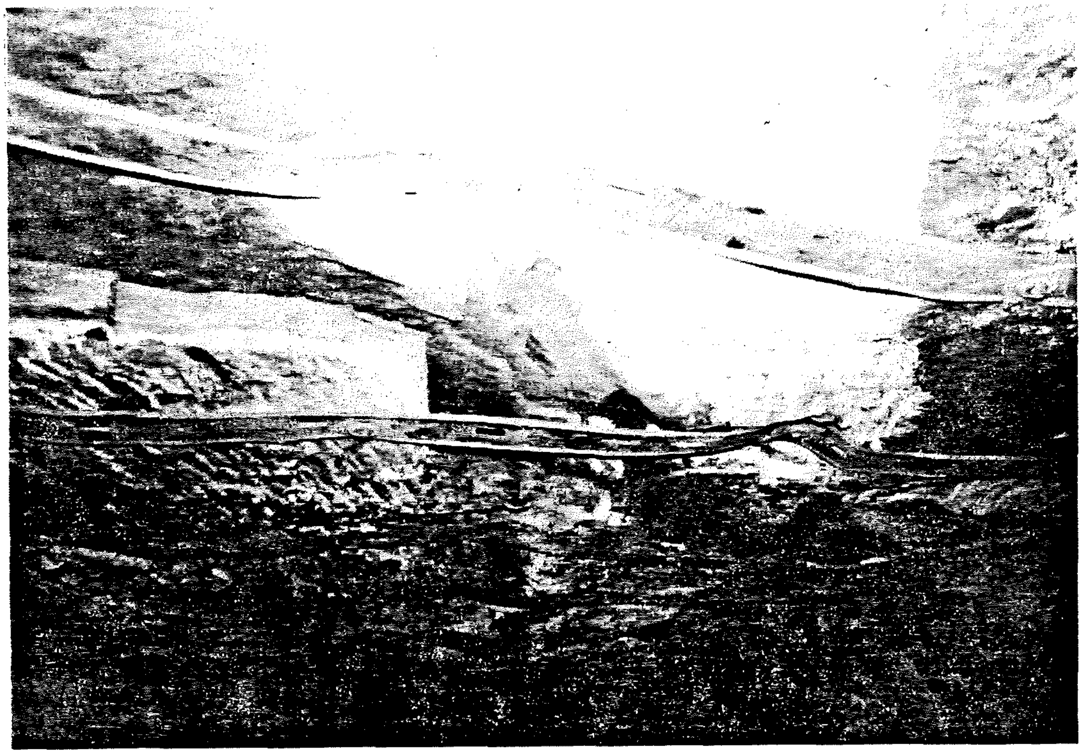

PLATE 21. - Slickensided base of sandstone channel, central Wasatch Plateau Coal Field. Light-colored rock is sandstone, dark-colored rock is silty shale. Contact between base of channel and silty shale is slickensided. Silty shale detaches easily along this plane of weakness. Mats are 8 in. wide and successfully control roof falls.

PLATE 22. - Detailed photograph of slickensided base of sandstone channel, central Wasatch Plateau Coal Field. This plane of weakness causes surrounding silty shale to detach and fall. Mat is 8 in. wide and successfully controls roof falls.

There are several diagnostic characteristics of lithofacies changes that result in unstable coal mine roof rock. This variable roof rock is composed of a thick unit (approximately 15 ft. to 25 ft.) of laterally interfingering shale, silty shale, and siltstone which displays color variations from black, through gray and brown, to light-tan. It is thin to thickly laminated and bedded, often with abrupt lateral changes in lithology. This roof type shows evidence of chemical alteration, which includes precipitated calcite and gypsum, and concretions. Fracturing, due to compaction and lithification, is haphazard and has no structural pattern. Slickensided rock is absent. Roof falls in this type of roof rock are characterized by their large size (greater than 8 ft. in diameter, and 4 ft. to 15 ft. in height). Accurate determination of when and where a roof fall will occur is difficult, and once this type of roof fall has occurred, caving control with cribbing and/or mats is often ineffective. Coal mine roofs displaying lithofacies change deteriorate slowly with air slaking and deteriorate rapidly with water influx.

Plate 23. shows a typical roof fall within coal mine roof strata that contains lateral facies change. Color variations and precipitated calcite in the roof surrounding the cave and in the rubble on the floor are evident. This fall is located in an idle portion of a mine in the Somerset/Paonia Coal Field. Bolts and mats, closely spaced on 2 ft. centers, did not stop this fall. The roof fall measures approximately 8 ft. in diameter and 4 ft. to 5 ft. in height. The fall has caved up to a thin carbonaceous layer that may be the primary plane of failure. Lateral caving around the sides was ongoing at the time of this mine tour.

Plate 24. shows another roof fall in the same coal field displaying lithofacies change with much color variation. A large concretion can be seen in the rib, at the upper left of the plate. Water is entering the mine at this location, contributing to the lack of cohesion in the roof rock and precipitation of minerals. Droplets of water can be seen on the roof of the caved portion, with precipitated mineral and ice stalagtites extending from the roof and rib.

The Grand Mesa, Somerset/Paonia, Carbondale, and Trinidad Fields frequently contain this type of roof rock. This type of roof can be very extensive underground. As a result, roof control can be expensive and is often only partially effective. Unless the seam is relatively thick with high-quality coal, this type of roof can prove too costly, both in terms of safety and capital outlay, for profitable mining operations.

5.1.3 Coal Rolls

The term "coal roll" has been widely used to describe conditions and/or features in the roofs and floors of underground coal mines. As a result, it has lost all sense of a specific definition. The term "horseback" is often used synonomously with a coal roll. The U.S. Bureau of Mines Dictionary of Mining, Mineral, and Related Terms defines the term as a, "local thickening of roof or floor strata, causing thinning of a coal seam" (39). Stahl (40) describes a coal roll as, "a shale intrusion which has protruded into the coal as if squeezed." A localized protrusion caused by compaction and lithification of dense clay and silt into a poorly compacted area of peat is the example that is pictured of Stahls coal roll (see 40, Figure 11.). Most

PLATE 23. - Typical roof fall within lithofacies change roof type, Somerset/Paonia Coal Field. Arrow 1. points to calcite precipitation; arrow 2. points to carbonaceous layer. Roof fall measures 8 ft. in diameter and 4 ft. to 5 ft. in height.

PLATE 24. - Roof fall within lithofacies change roof type, Somerset/Paonia Coal Field. Arrow 1. points to a concretion measuring 2 ft. long and 6 in. wide; arrow 2. points to droplets of water influxing from roof; arrows 3. and 4. point to mineral and ice stalagtites. This roof fall measured approximately 15 ft. in diameter and 10 ft. to 12 ft. in height.

often, the term coal roll has been used to describe a sandstone channel that has "rolled" down from the roof into the coal seam, causing the seam to thin (37). As illustrated by the above examples, the term has been erroneously used to describe a variety of features that protrude from the roof or floor of an underground coal mine, and cause thinning of the seam.

In western underground coal mines, probably because large-scale mining and production occurred more recently than in the East, the term coal roll is not used to describe a sandstone channel. Sandstone channels are described directly. In the West, a coal roll is defined as, "an undulation in the coal seam" (41). The seam will undulate and may thin in response to local thickening from the floor.

A likely explanation for coal roll formation, as defined for the West, is provided by imbricately structured, wave-dominated delta systems. Figure 47. is a block diagram of this type of delta, showing the location and development of accretion (beach) ridges. These ridges are produced by high-energy wave action. As the delta progrades, and sand and silt are deposited further seaward, beach ridges from past delta development are left inland. This creates an imbricately structured platform of abandoned sand accretion ridges. As the delta continues to prograde seaward, swamps become superimposed upon abandoned accretion ridges. Lithification of these sediments results in formation of coal that is draped over the accretion ridges.

Figure 48. is an idealized model of coal development over accretion ridges that could produce coal rolls within a mine. Various coal seam configurations can occur with compaction and lithification, as shown.

Coal rolls are observed in several western coal fields. In an area in the northern Wasatch Plateau Coal Field, coal rolls cause abrupt changes in the elevation of the top and bottom of the lower O'Conner A coal seam. This seam rests on the Storrs Sandstone Tongue of the Starpoint Sandstone Formation, a littoral sandstone deposit (41). An individual roll in this field can range in elevation from 5 ft. to 30 ft. along a horizontal distance of 30 ft. to 150 ft., and may exceed 3,000 ft. along a strike of N25E. The rolls parallel the paleoshoreline. Changes in the thickness of the lower O'Conner A coal seam commonly occur across the coal roll. Figure 49. is a portion of a mine map, from a mine in the lower O'Conner A seam, illustrating coal rolls and their undulating dip directions.

Adverse impacts to mining caused by coal rolls are mainly the loss of production and dilution of coal quality. Significantly hazardous conditions are not created by coal rolls. Production decreases are often caused by steep grades, which make movement of machinery difficult. In addition, troughs of coal rolls provide low areas where mine water ponds. Hazardous mining conditions occasionally occur towards the apex of coal rolls, where differential compaction has caused fracturing, development of compaction slickensides, and buildup of compressional stress. Differential compaction and subsequent strain of the coal seam and roof rock can cause roof falls. Adverse mining conditions caused by coal rolls have been documented primarily in the Wasatch Plateau and Book Cliffs Coal Fields. However, this is probably because these are the only coal fields in which these features have been adequately studied. It is likely that coal rolls influence mining conditions in other western coal fields.

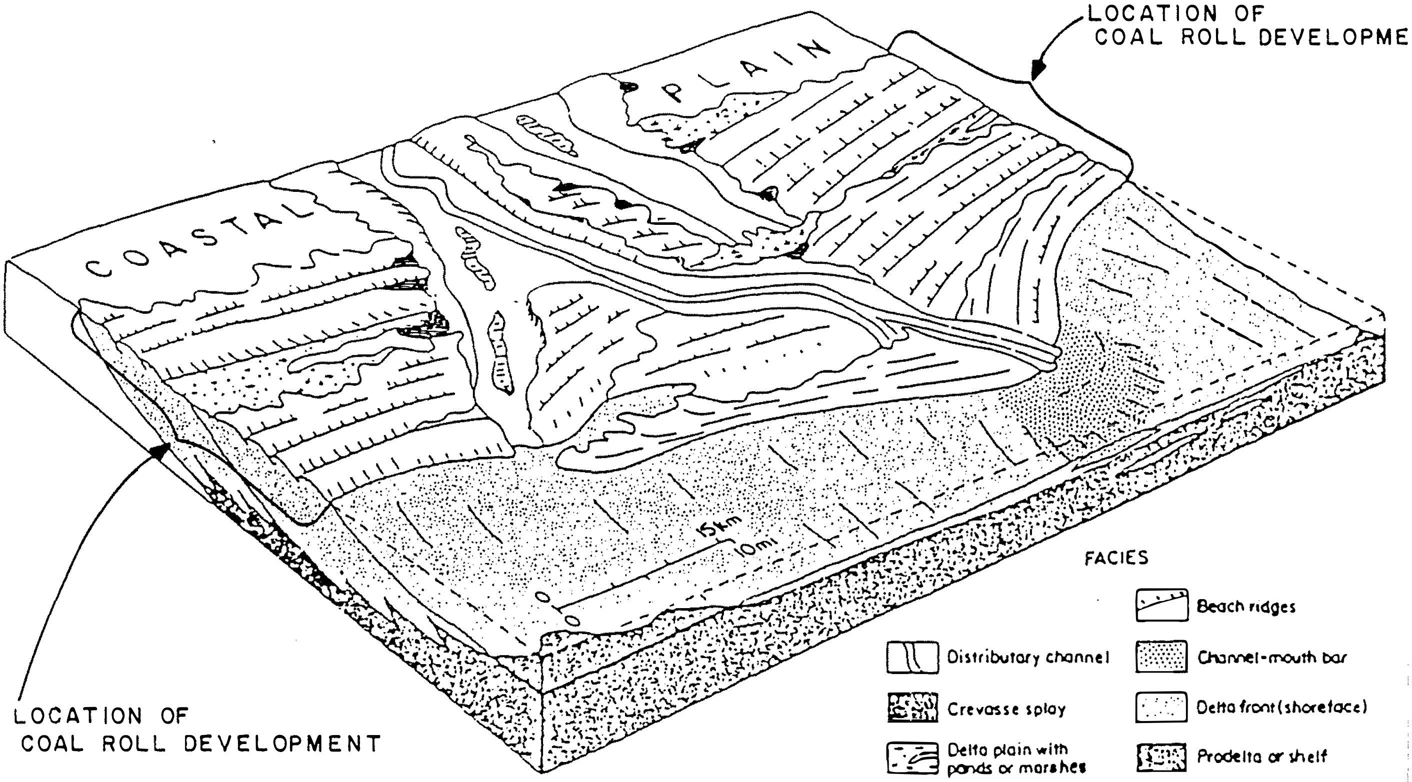

FIGURE 47. - Block diagram of an imbricately structured, wave-dominated delta system illustrating a probable location for coal roll development. Brackets show accretion (beach) ridges formed from storm and winter tides. In the West, coal rolls likely formed after swamps invaded relict accretion ridges and deposited peat in sheets that draped over the ridges (10). 17/

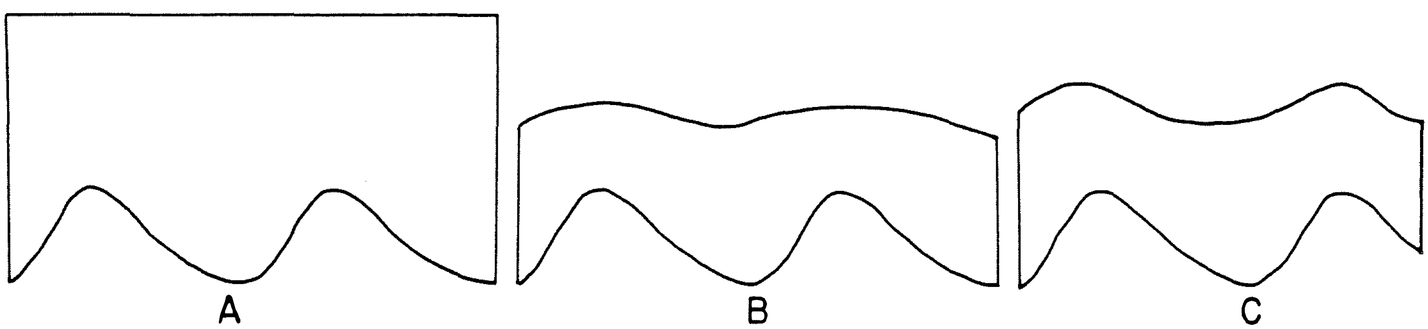

FIGURE 48. - Influence of differential compaction on coal roll geometry. A, peat deposition on abandoned accretion ridges; B, coal seam showing development of topographic low in top of seam through compaction; C, coal seam showing development of both topographi lows and highs in top of seam. Example B differs from example C due to differentia compaction.

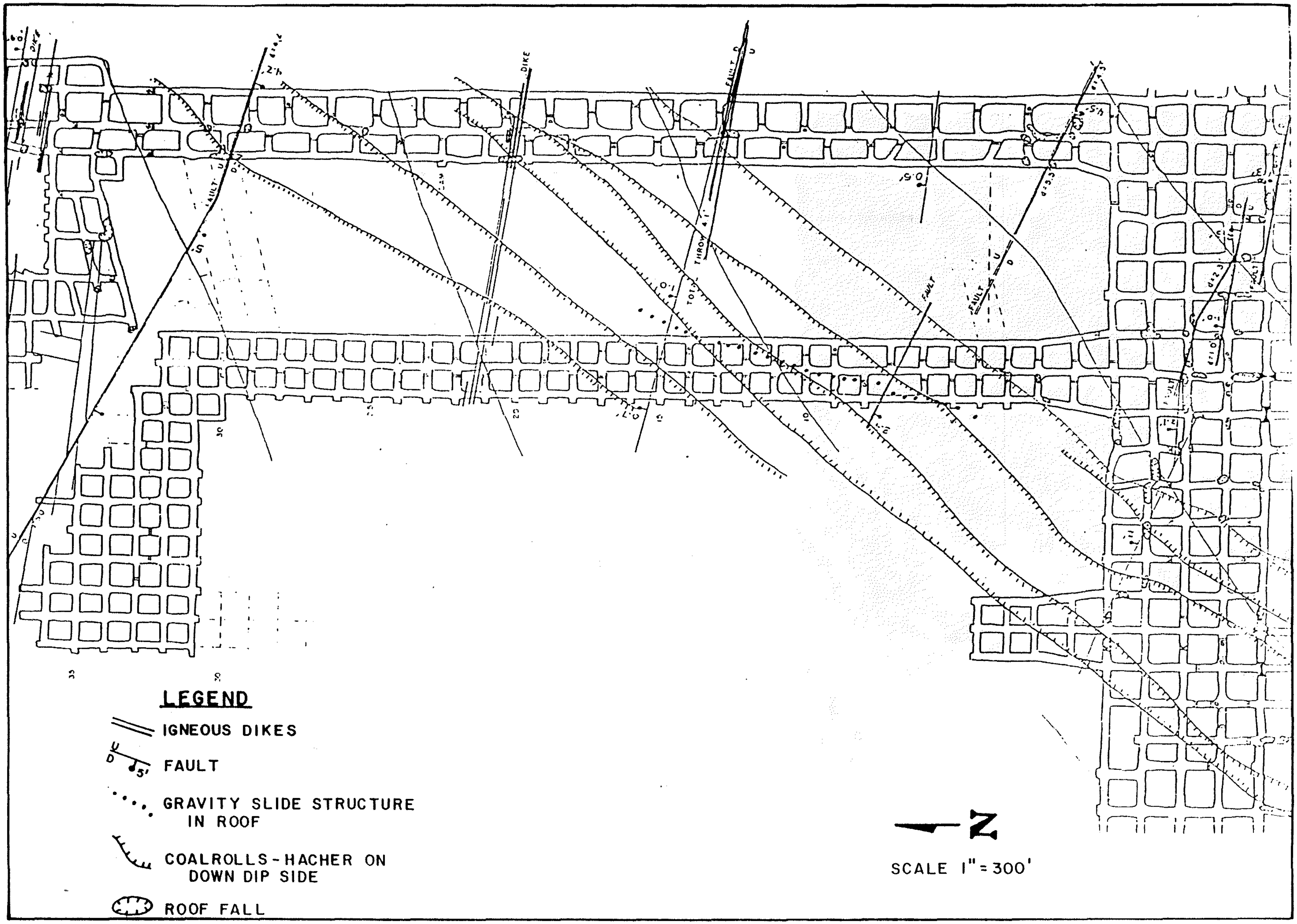

FIGURE 49. - Portion of a mine map, from a mine in the northern Wasatch Plateau Coal Field, showing structural geology including coal rolls.

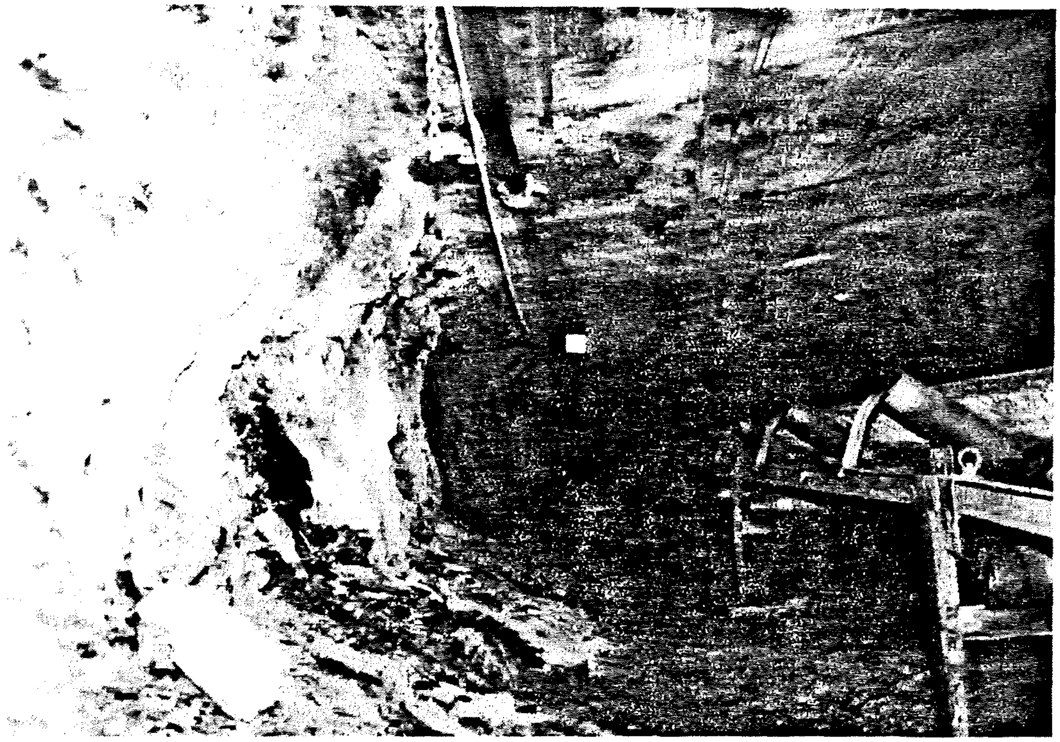

PLATE 25. - Photograph showing effects of a coal roll, northern Wasatch Plateau. Mine is developed in very slightly dipping coal seam. This photograph shows a main entry descending the inferred steep-face of a sandstone accretion ridge. Arrow shows point of inflection where seam begins a slight rise. Conveyor belt is approximately 4 ft. wide.

Plate 25. is a photograph showing a coal seam that normally contains a slight regional dip that is steepened over a coal roll. The floor of the mine at this location is believed to be developed on the steep-face of a sandstone accretion ridge.

5.1.4 Bedding Planes

As an adverse geologic feature in western underground coal mines, weak bedding planes within roof rock are not extremely hazardous. However, as has often been documented, a relatively small piece of rock delaminating from the roof can prove fatal.

Bedding planes represent a surface of weakness caused either by two periods of deposition of like-sediments separated by a time lag, or by deposition of two different lithologies with little or no time lag. Bedding planes most often noted in western underground coal mines that often presented adverse conditions in toured mines, were found in thick and locally massive deposits of shale. This shale was deposited in delta-plain areas; bedding planes within the shale represent periodic sheet-flooding by distributary channels of the delta. Individual beds found between bedding planes in this subenvironment of the delta ranged from 1 in. to 15 in. thick. This shale is usually extremely dense and hard. Plate 26. shows a typical shale bed with bedding planes that without the bolted mats, would delaminate from the roof and create a hazardous working environment.

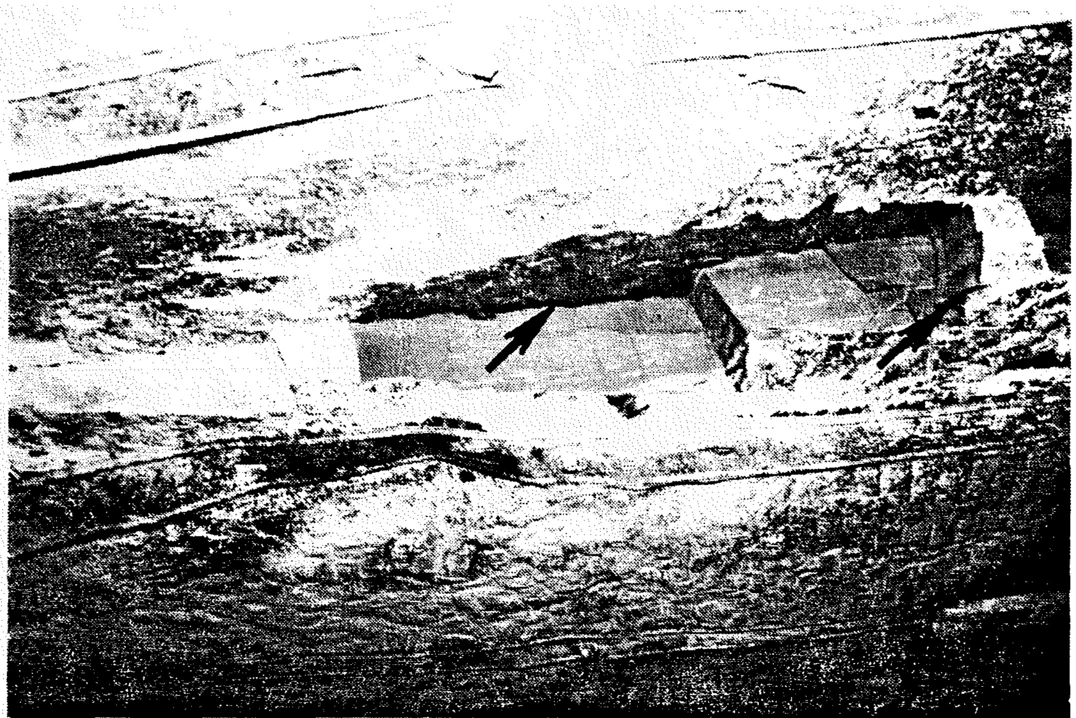

PLATE 26. - Photograph depicting weak bedding planes in shale, central Wasatch Plateau Coal Field. Arrows point to poorly bonded bedding planes in shale; bolted mats have stopped delamination. Mats are 8 in. wide.

Another type of bedding-plane weakness is related to crevasse-splay deposits, which have been described in Section 5.1.1.1. Bedding planes separate thin sheets of siltstone and sandstone that were deposited in a lobate pattern through levees breached during flood events. Individual sheets of siltstone and sandstone are thin laminae ranging from 1/16th in. to 3/4 in. in thickness, with sandstone being the thicker of the two lithologies and representing the initial flood pulse. Failure along this type of bedding plane is caused by the removal of underlying coal and can be accelerated by compressional stress that is generated by proximal sandstone channels.

Differences in strength and density between the sandstone channel and the thin laminations of crevasse-splay deposits result in differential stress, and can cause large roof failures. Plate 27. is a photograph showing bedding plane failure in a crevasse-splay deposit caused by undermining and compressional stress from overlying and flanking sandstone channels. Light-colored laminations are sandstone while dark-colored laminations are siltstone. Broken, thin sheets have delaminated from the roof and have fallen onto the floor at this site, as can be seen in the lower portion of the plate. These sheets have extremely sharp edges that can slice the rubber tires of mining equipment.

Adverse conditions caused by bedding-plane failures are found in all studied coal fields of the West and should be anticipated in certain areas of mines. An understanding of roof rock lithology and deposition is necessary in anticipating locations of bedding-plane weakness. This is only possible when a model of the depositional environment of the coal mine is available.

PLATE 27. - Photograph depicting bedding-plane failure in a crevasse-splay deposit, Book Cliffs Coal Field, Utah. Lateral and overlying pressure caused by sandstone channels has contributed to failure along already weak bonds between laminations of sandstone and siltstone. Continuous delamination has filled this entry with broken sheets that have extremely sharp edges. Arrows point to thin laminations of siltstone and sandstone.

5.1.5 Underclays

"Underclay" is a mining term used to describe a layer of clay, which is located immediately below the coal seam. This clay layer often directly overlies a major sandstone unit. The clay layer probably represents widespread deposition of quiet-water sediments before swamps invaded the area. In mining a coal seam overlying an underclay, coal is often left in the floor of the mine as a "bottom coal". In coal mines, particularly where water is present, the bottom coal serves as a shield against wetting of the clay. A wet clay floor causes slick, hazardous conditions for mining personnel and machinery. Occasionally, the underclay is thin enough to remove with the coal, leaving a competent sandstone floor. However, this procedure can result in excessive dilution of coal quality if the underclay is too thick.

Wetting of some portions of the underclay is inevitable in mines that produce water, even with a bottom coal. As a result, a type of floor heave occurs due to clay hydration and expansion. When floor heave, caused by wetted clay below a bottom coal occurs, up to 3 ft. long and 4 in. wide upturned cracks will appear in the floor. These cracks, with their upturned crusts, create a hazard for mining personnel. Clay expansion and related buckling of the bottom coal can also help to propagate "pillar punching" through the floor of the coal mine. Pillar punching lowers the roof, and may produce lateral stress, which further contributes to floor heave.

Underclays occur in several coal fields of the West, but were most apparent in the Carbondale and Grand Mesa Coal Fields. Underclays do not pose a significant hazard to mining personnel and machinery, but upon wetting can contribute to adverse mining conditions.

5.1.6 Kettlebottoms

The term "kettlebottom" is a coal mining term that is used to describe a slickensided, rounded protrusion of rock that commonly falls out of a coal mine roof and can cause serious or fatal injuries (39). The terms "bell" and "pot" have been used synonomously with kettlebottoms. For this, and similar studies (42), the term kettlebottom is defined as the fossil cast of a tree trunk, in growth position, that can become detached from the surrounding roof rock and cause serious injuries to mining personnel. Figure 50. is a diagram showing the position of a fossilized tree trunk or kettlebottom in relation to a coal seam.

Most kettlebottom studies have concentrated on kettlebottoms of the eastern and upper-midwestern Paleozoic coal fields (42). Paleozoic swamp forests contained Calamite, Lepidodendron, and Sigillaria trees as the dominant tree species. These types of trees had either small, poorly developed root systems or narrow rootlets that were widely spread-out. These trees were most often slender and tall. Upon submersion by transgressing marine waters, the tree would die causing the interior wood to decay, leaving the more resistant outer bark (42). Sediment would fill the vacant cavity inside the bark, and this organic structure would become buried and preserved to form a kettlebottom. Upon mining of the coal seam, the kettlebottom may detach and fall, as shown in Figure 51. Eastern and upper-midwestern Paleozoic kettlebottom bark is often coalified and slickensided forming a plane of noncohesion that causes detachment.

Western coal deposits are primarily of Cretaceous age. Swamps of the Cretaceous were affected by a temperate climate, as opposed to the tropical climate of Paleozoic coal swamps. In the Cretaceous aged swamps, the primary tree types were the conifers Araucaria, found in lower-deltaic and coastal-plain swamps, and Sequoia Cuneata, found in upper-delta and coastal-plain swamps (10). In full growth, these trees had large root structures that enabled them to withstand a seasonal climate. Plate 28. shows the root system of a young conifer in growth position. Mining of the coal seam has exposed this feature. The roots and trunks of these trees have lithified into vitrified coal. Plate 29. is a photograph showing a western coal field kettlebottom cave that is 14 ft. in diameter and 6 ft. high. The sides of this dome-shaped kettlebottom cave are completely slickensided and caused the kettlebottom to detach as one massive unit. As this photograph shows, the geometry of Cretaceous aged kettlebottoms is that of an inverted cauldron, as opposed to the eastern, Paleozoic age kettlebottom geometry of an upright cauldron. The type of kettlebottom-fall exemplified in Plate 29. contains no root structures or fossilized remains in the broken roof rock that detaches and falls to the floor. It is inferred that the roots have compressed and

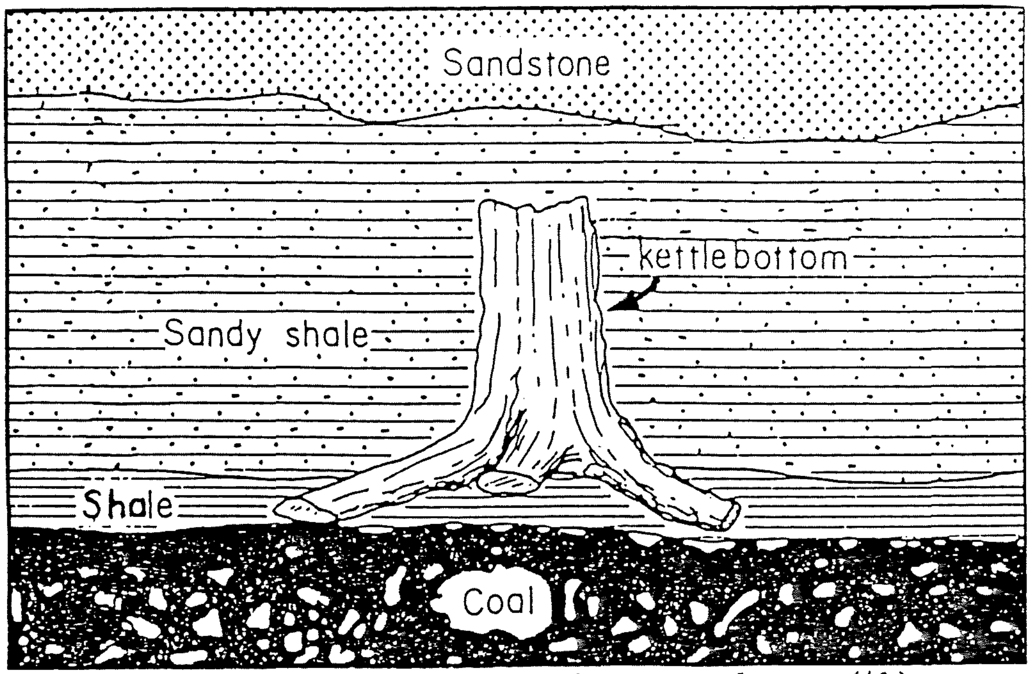

FIGURE 50. - Typical kettlebottom above a coal seam (41).

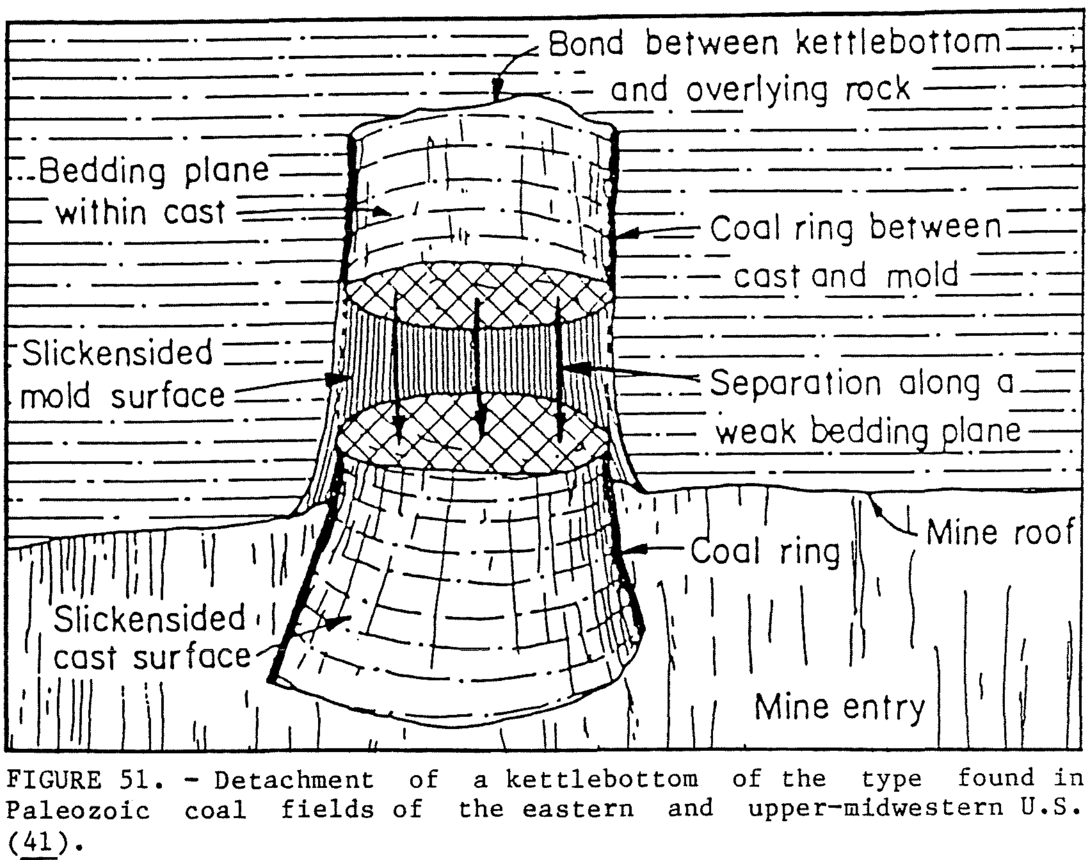

FIGURE 51. - Detachment of a kettlebottom of the type found in Paleozoic coal fields of the eastern and upper-midwestern U.S. (41).

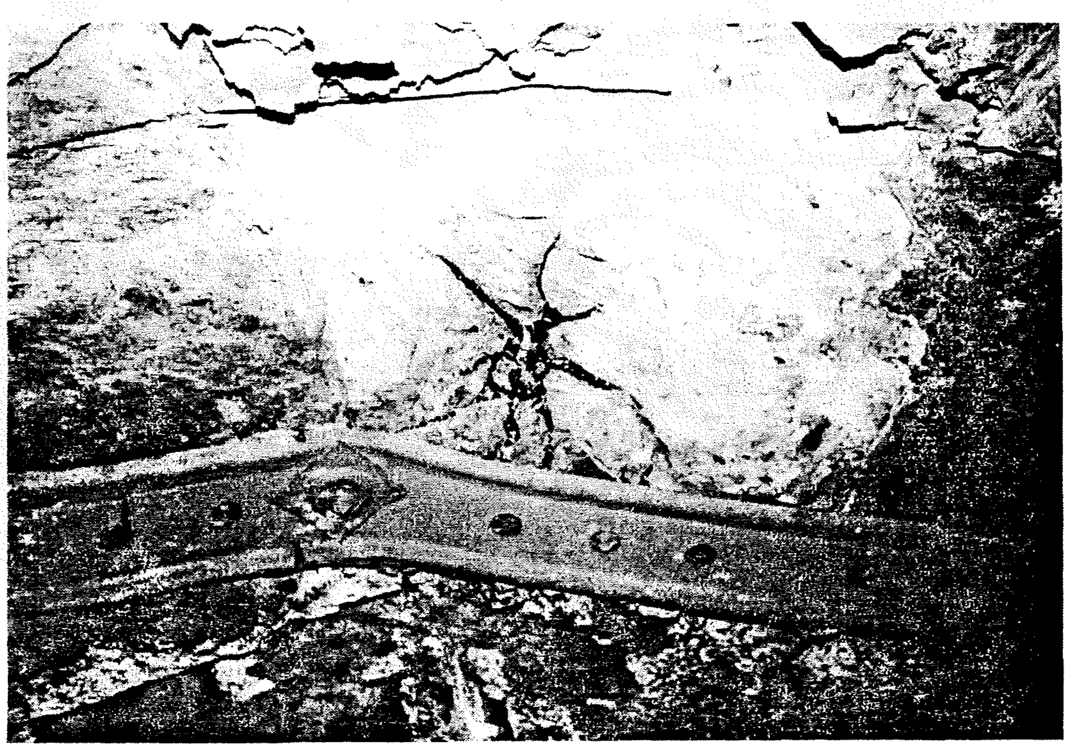

PLATE 28. - Coalified roots of small Cretaceous conifer in a mine roof, central Wasatch Plateau Coal Field. Mat is 8 in. wide. A 4 in. thick kettlebottom detached and fell from below these roots.

PLATE 29. - Large kettlebottom cave, Somerset Coal Field. This kettlebottom cave is 14 ft. in diameter and 6 ft. high. Sides are completely slickensided with imprints of root bark on the upper sides and top.

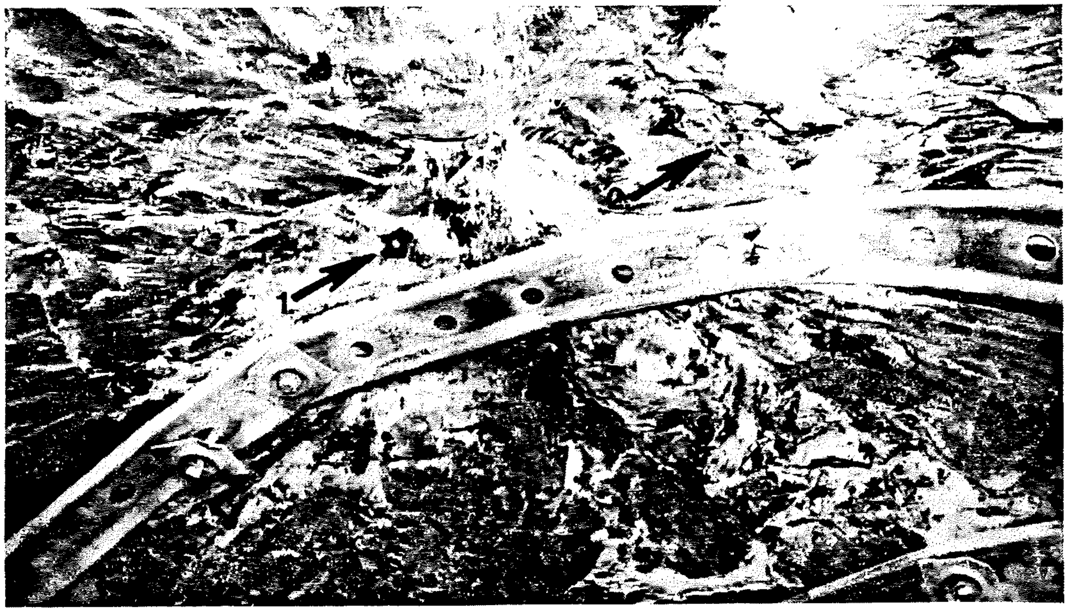

PLATE 30. - Top of large kettlebottom cave, Somerset Coal Field. This kettlebottom cave is 10 ft. in diameter and 4 ft. high. Mats are 8 in. wide. Arrow 1. points to coalified roots; arrow 2. points to imprints of root bark. Sides of cave are entirely slickensided.

decayed. This root compression aided in the development of the slickensided margins of the kettlebottom. It is these slickensided planes of weakness on the sides of the kettlebottom that cause it to detach and fall. A vitrinized trunk can usually be seen at the crown of the kettlebottom cave, as shown in Plate 30. Also, the faint outline of bark-covered roots can be seen on the sides of the kettlebottom.

It is obvious that this type of kettlebottom can be extremely hazardous to mining operations. Upon removal of the coal seam by a continuous mining machine, the roof of the mine below and adjacent to a kettlebottom looks exactly alike. There may be no evidence that a large kettlebottom exists within the mine roof. Plate 31. shows the edge of a kettlebottom, in the Somerset Coal Field, that has begun to detach from the roof. Immediate bolting and matting prevented it's complete detachment. This kettlebottom approaches 12 ft. in diameter and probably would have caved 4 ft. to 5 ft. upward. Most of the kettlebottom locations noted in western coal fields were several hundred feet away, in a perpendicular transect, from sandstone channels. It appears that the higher energy fluvial environment near the sandstone channels either prohibited the growth of large trees, or killed and destroyed the trees after development. Kettlebottoms noted during this study varied in size from approximately 10 in. in diameter, as shown in Plate 28., to 16 ft. in diameter as shown in Plate 29. These features had caved upward from 1 ft. for smaller kettlebottoms to 7 ft. for larger kettlebottoms. In 1969, three personnel from an underground mine in the Somerset Coal Field were standing below a kettlebottom that was discovered subsequent to mining an intersection. As they were trying to decide how best to add more roof support to the base of the kettlebottom, it detached and killed all three of the personnel (43).

PLATE 31. - Kettlebottom beginning to detach, Somerset Coal Field. Mats are 8 in. wide. Arrow 1. points to slickensided edge of kettlebottom and arrow 2. points to slickensided root-bark imprint. Notice the similarity of the kettlebottom roof with the surrounding roof. Had the kettlebottom not been bolted and matted, it would have caved upward 4 ft. to 5 ft.

From this description, it is obvious that kettlebottoms can be extremely hazardous in western underground coal mines. Although their incidence is less common than roof falls associated with sandstone channels, kettlebottom roof falls can be as serious. Western coal fields that contain many large kettlebottoms were the Somerset/Paonia, Grand Mesa, and Trinidad. Only a few small, isolated kettlebottoms were noted in the Wasatch Plateau and Book Cliffs Fields. The remaining western coal fields contained, on an average, only a few, moderately sized kettlebottoms.

5.2 Structural Features

5.2.1 Folding

Folding in strata is caused by large, compressive tectonic forces. In areas of slight stress, or where rock strength exceeds compressive stress, folding is gentle. In areas of high stress, tight isoclinal, overturned, or recumbant folds can be produced.

In western coal fields, folding is gentle to moderate and locally variable. Where folding is gentle, the seam may be inclined, but there is little effect on ground control within the mine. The gentle 4 to 7 degree dip of strata in the Emery and Wasatch Plateau Coal Fields is related to the San Rafael Swell, a monoclinal structure located in east-central Utah. Strata in the Book Cliffs Coal Field dip north 4 to 7 degrees into the Uinta Basin. Moderate folding occurs in the Yampa, Carbondale, Trinidad, and Raton Coal Fields. These folds are smaller, more local synclines and anticlines that were formed during the Laramide Orogeny. Section 4.0 describes the structural geology of each field.

Roof control problems associated with folding include fractures, joints, and faults that occur on the upper-flanks and crests of folds. Fracturing and jointing can be extensive in these locations, causing roof control problems in the form of lateral movement and roof-rock detachment between fractures. Problems with jointing and fracturing at the crests of anticlines were noted in the Yampa and Raton Coal Fields.

5.2.2 Joints

Jointing occurs in rocks under tensional stress, or through shear motion in rocks under compressional stress, as a result of regional physical or thermal processes. By definition, no movement occurs along joint surfaces. Space between joints varies from practically negligible to several feet.

Jointing can be a minor concern or can cause extreme pillar or rib failure, which can make mining dangerous and less profitable. The effects of jointing on ground control in western underground coal mines varies with joint patterns (as formed by intersection of multiple joint sets with differing orientations), joint density, and lithology of the affected strata. The joint orientation, with respect to the strike of mine workings, and the angle of dip on the joint are very important factors in the relative influence of jointing on ground control.

The degree to which joint sets parallel mine development dictates the magnitude of slabbing that is likely to occur. Figure 52a. shows the effect of joints that strike nearly parallel with entries or cross-cuts. Depending upon the degree to which the joints parallel the direction of development, in addition to joint dip and spacing, entire ribs can slab. If vertical pressure caused by a large thickness of overburden is sufficient, coal may burst outward with extreme force. Figure 52b. shows the effect of obtusely striking joints on pillars. In this example, only the corners of pillars are affected. Again, depending upon spacing, the pillar corner may slab only slightly with widely spaced fractures, or slab continuously inward with closely spaced fractures and eventually require roof support to compensate for the loss of the pillar corner.

Plate 32. shows the effect of joints on a pillar. These joints strike nearly parallel to the cross-cuts in this portion of a northern Wasatch Plateau Coal Field mine, and dip approximately 75 to 80 degrees. The strike of these joints produce pillar slabbing like that shown in Figure 52a. In this particular example, there was enough area within the permitted boundary of the mine to adjust the mine plan to compensate for slabbing of coal from the pillars. A slight adjustment in the orientation of the entries allowed fracturing and slabbing to occur only on the corners of the pillars, rather than along the entire rib. Plate 33. is another photograph showing joints in

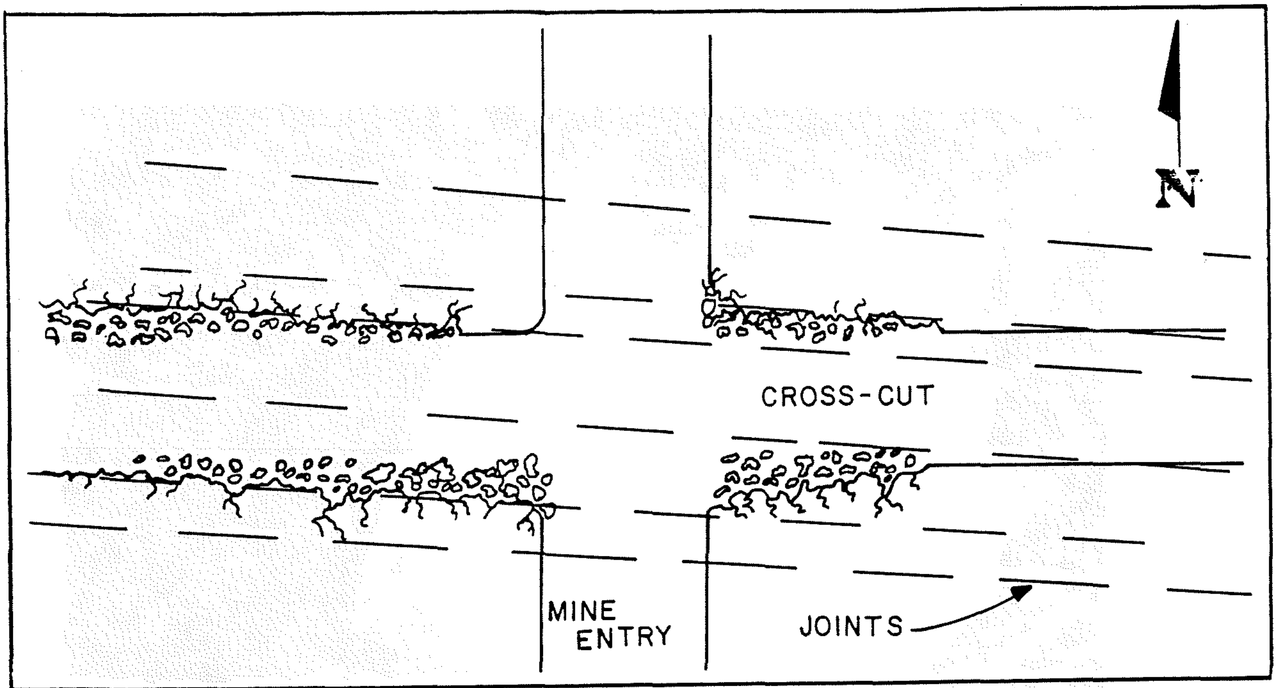

FIGURE 52a. - Diagram showing effects of closely spaced joints that strike nearly parallel with cross-cuts. Slabbing occurs along ribs of the pillars.

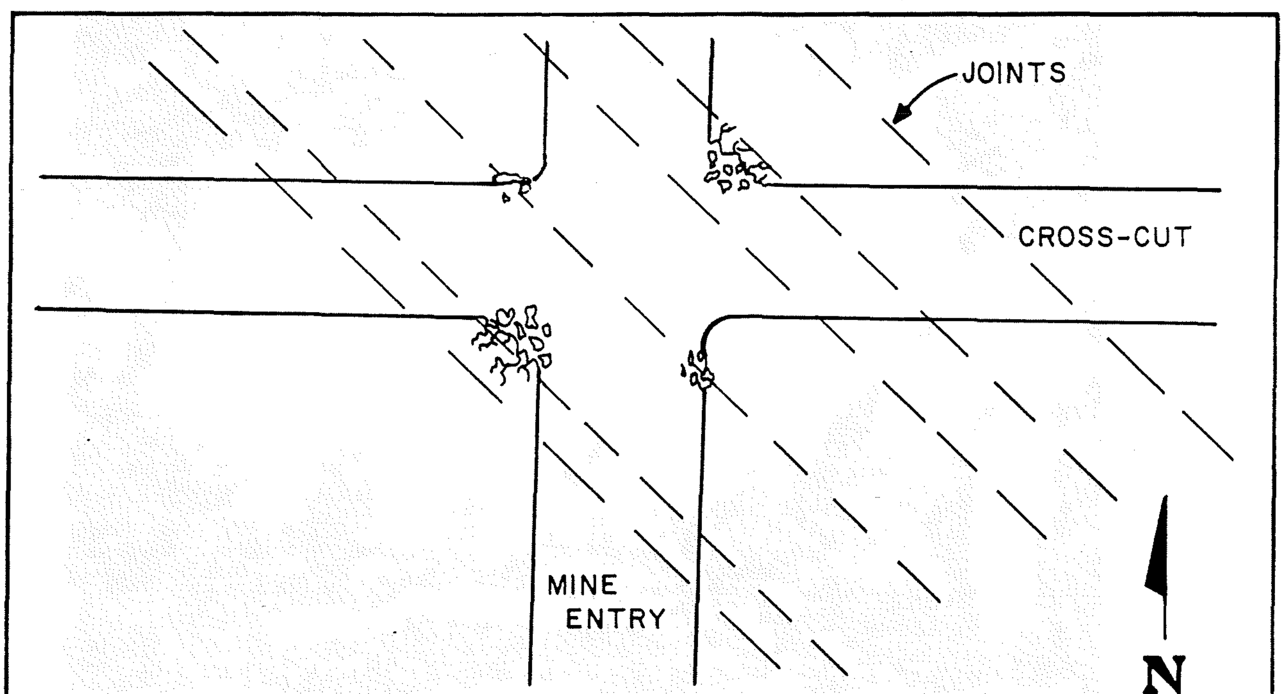

FIGURE 52b. - Diagram showing effects of closely spaced joints that strike at an angle to mine development. Slabbing occurs only on pillar corners.

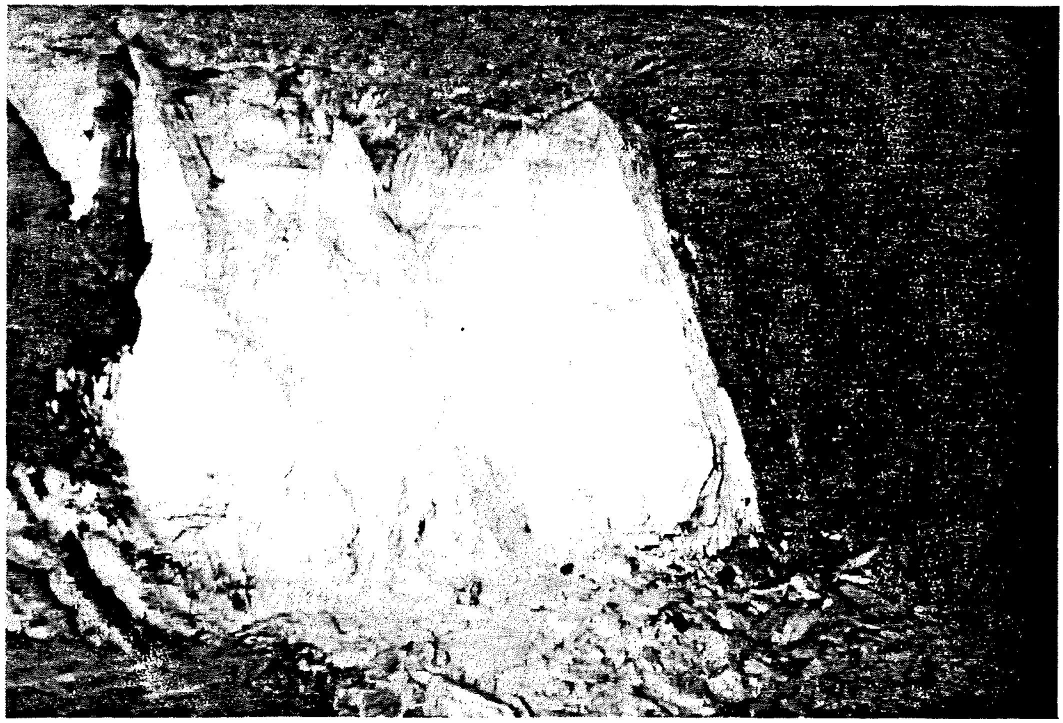

PLATE 32. - Effect of jointing on pillars, northern Wasatch Plateau Coal Field. Joints striking parallel with cross-cuts cause pillar ribs to slab.

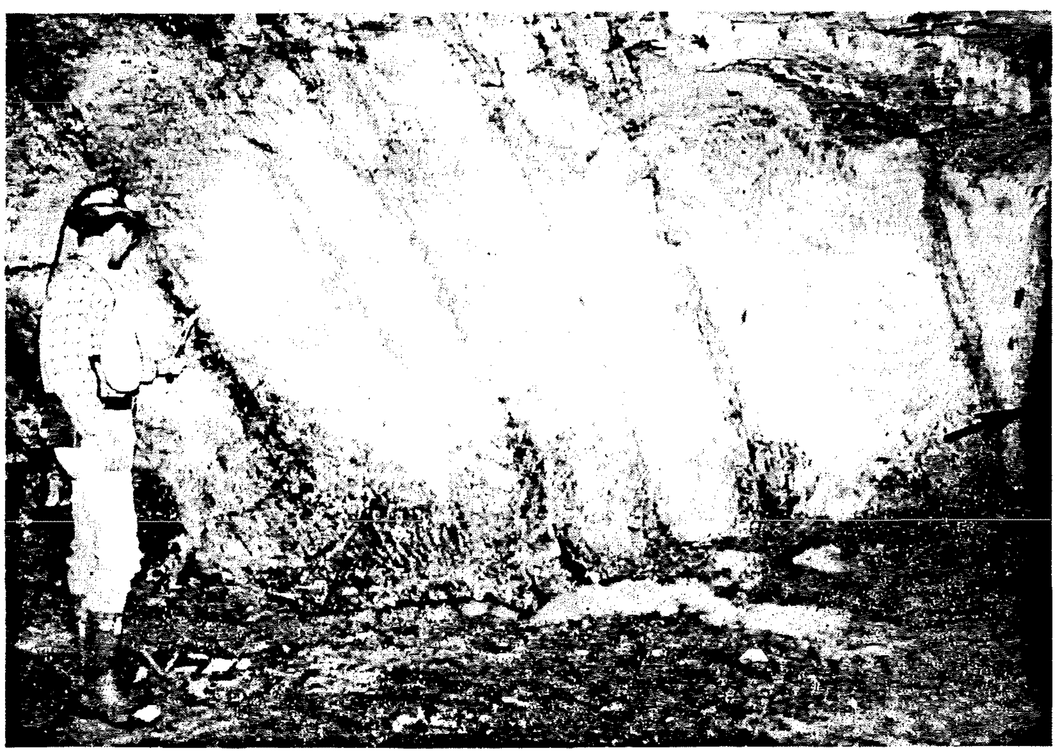

PLATE 33. - Joint set in a coal pillar, Yampa Coal Field. Observers hammer is on plane of joint. These joints strike at an angle to mine development. Arrow points to edge of coal pillar.

a pillar. This joint set has parallel fractures as little as 2.5 ft. apart that dip at approximately 65 degrees. However, the joints strike at an angle to mine development, similar to those depicted in Figure 52b. At an angle to mine development, joints do not usually cause hazardous pillar slabbing.

The degree of dip on the joints can also play a significant role in coal mine ground control. Joints with dips approaching 60 degrees, with wide spacing, will be less likely to cause severe inward slabbing of pillars than joints with close spacing and dips approaching 80 degrees. These effects are shown in Figure 53a. and Figure 53b. If a joint approaches 50 degrees in dip, severe pillar crushing can occur. However, no joints with dips of less than 60 degrees were noted in the Rocky Mountain coal fields.

Plate 34. is a photograph showing the effect of a steeply dipping joint on the corner of a pillar in the Yampa Coal Field. The corner of this pillar has begun to slab at the base. Eventually, this pillar will slab inward to the joint plane. When this occurs, the roof may require support to control possible roof falls. Plate 35. shows roof support measures implemented to support the roof, where a pillar corner has completely slabbed due to jointing in the coal. This Yampa Field mine based their mine development plans on this jointing, so that only the pillar corners would slab. Slabbing of the corners of pillars causes many fewer problems than does slabbing of the entire rib, as shown in Figure 52a. Plate 36. shows one joint of an interesting joint set whose fracture planes have widened. The joints are essentially vertical and remain open for hundreds of feet to the surface. The four joints that make up this set are all spaced approximately 10 ft. apart. These joints do not present roof control problems. There is no slabbing of coal from pillars, because the joints are few in number and strike through the central part of long pillars near the entries of the mine.

5.2.3 Coal Cleats

"Coal cleat" is a mining term for a near vertical joint pattern found within a coal seam. There is general disagreement as to whether the cleat forms during compaction and lithification or whether it is produced by tectonic forces. The cleat is regularly spaced throughout a coal seam, with spacing approximately 1 in. apart. The coal cleat found within coal seams throughout the West often parallels the strike of joints and faults, leading to the conclusion that the cleat is related to tectonic forces. The cleat forms a plane of weakness along which coal falls from the working coal face. Coal seams normally have two cleat systems, which are set orthogonally to each other. The major cleat, along which breakage occurs easily, is termed the "face cleat". The minor cleat, which does not break as easily, is termed the "butt cleat". In the past, when coal was mined with a pick, the mine was often developed perpendicular to the face cleat, as this was the most efficient angle to hand-pick the coal. The cleat was also used to orient mine development, as the cleat was often the only straight line in the mine.

The cleat of the coal seam affects coal mine ground control with the same effect as joints. Coal can slab off pillars and ribs along the cleat plane; mine development is therefore often controlled by the cleat. If the cleat does present significant ground control problems, mine operators in the West orient cross-cuts and entries at an angle of 30 to 60 degrees to the cleat

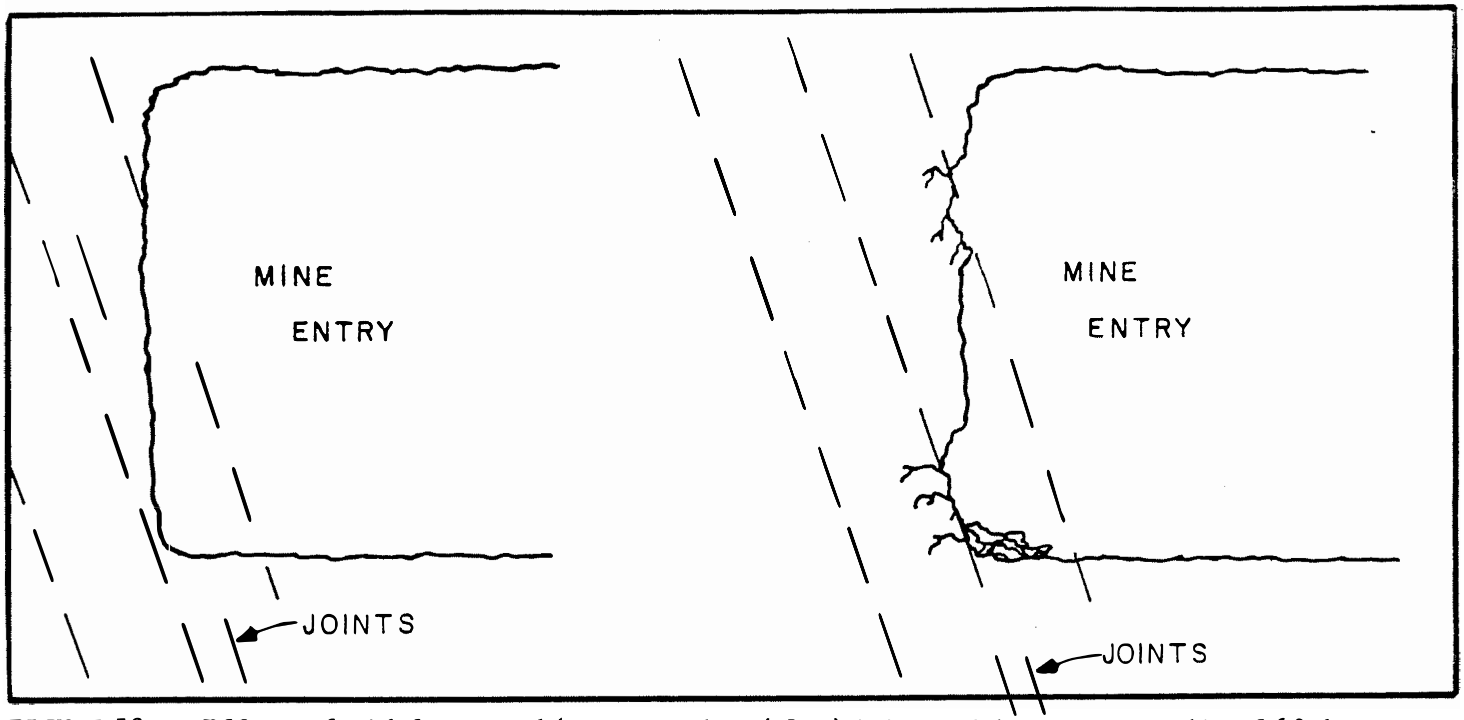

FIGURE 53a. -Effect of widely spaced (greater than 4 ft.) joints with an average dip of 60 degrees on ribs of mine entry. With less than approximately 1500 ft. of over-burden, damage is minimal. Greater overburden can cause severe failure along joint planes.

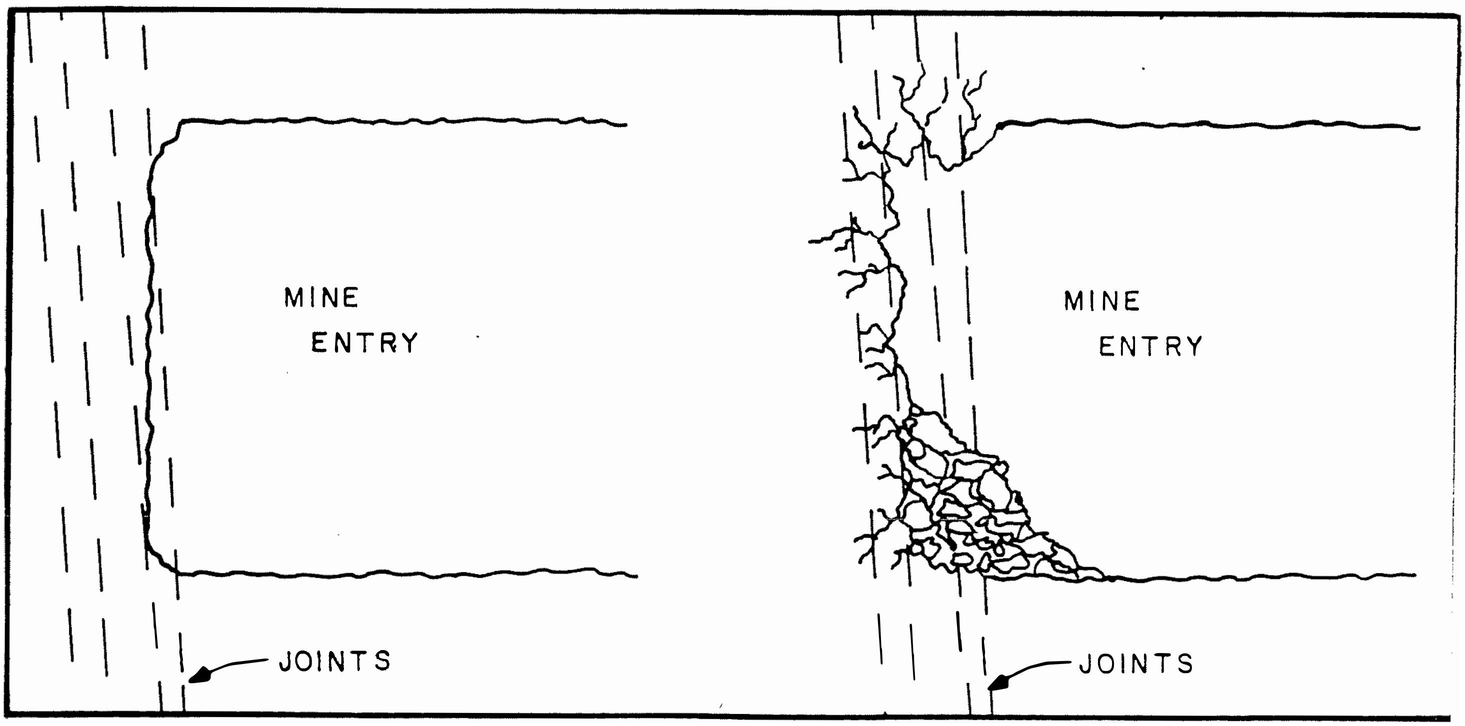

FIGURE 53b. -Effect of closely spaced joints (less than 4 ft.) with an average dip of 80 degrees on ribs of mine entry. Damage is more severe than that shown in Figur 53a., with an overburden thickness of less than approximately 1500 ft. Greater over burden will cause relatively less damage than would be caused in Figure 53a.

PLATE 34. - Effect of steeply dipping joint on pillar corner, Yampa Coal Field. Mine tractor provides scale. Pillar has begun to slab at base. Arrow points to fractured joint plane. Pillar will slab to this fractured plane and may continue to slab if another joint plane exists further inward.

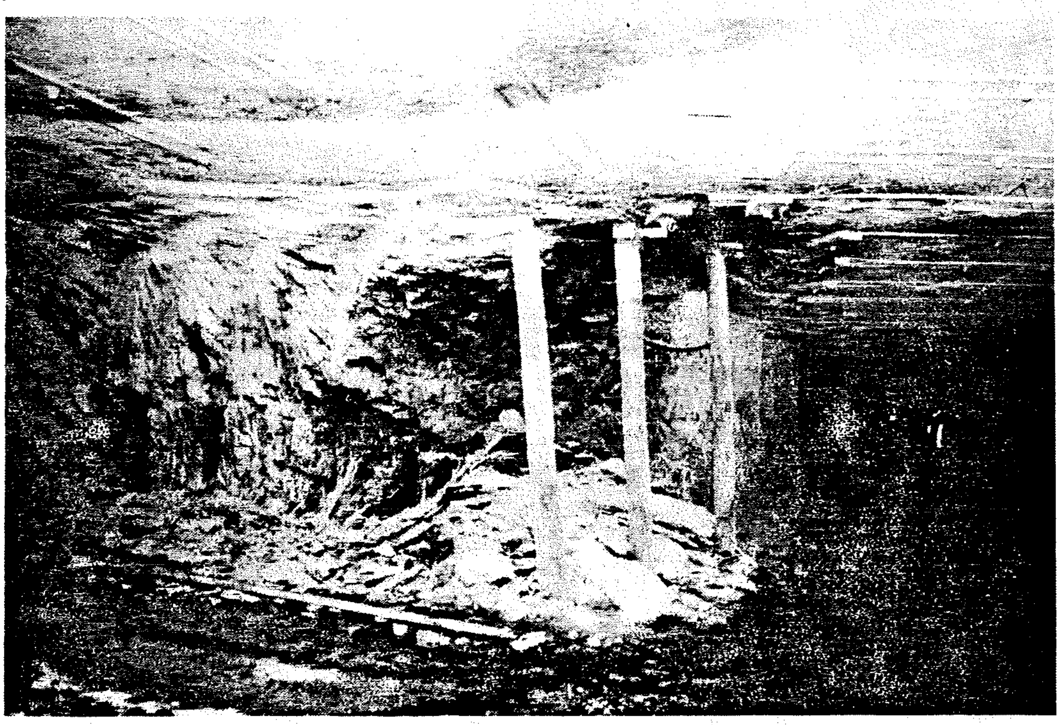

PLATE 35. - Effect of steeply dipping joint on pillar corner, Yampa Coal Field. Jointing is oriented at an obtuse angle to mine development. Seam is approximately 9 ft. thick. Timber supports have been installed to compensate for loss of roof support through slabbing of pillar corner.

PLATE 36. - Large open joint, Paonia Coal Field. This joint is one of a set of four. Hammer provides scale. Joint has affected coal seam. These joints remain open to the surface, several hundred feet above. These joints parallel mine cross-cuts. However, there are only four joints spaced approximately 10 ft. apart and mine development circumvented this problem. No roof or rib control problems are associated with these joints.

orientation; the optimum orientation angle is 45 degrees. Mine development oriented in this direction reduces pillar slabbing, and improves pillar and roof stability.

All studied coal fields in the West contained a cleat within the coal seam. The coal cleat in the Wasatch Plateau, Yampa, and Trinidad Fields has a significant effect on mining, and mining is oriented to decrease pillar and rib slabbing. The coal cleat in the Book Cliffs, Grand Mesa, Somerset/Paonia, and Carbondale Fields is not as significant to mine development. However, mine development in these fields is partially controlled by other structural features, such as faults or joints.

5.2.4 Faults

Faults are fractures in rock strata that have experienced movement. Movement along the fracture plane is what differentiates a fault from a joint; a joint has no movement along it's fracture plane. There are many classifications of faults based upon the direction, associated force, and angle of movement. The terms "throw" and "displacement" are used to describe the type and amount of movement that has occurred along the fault plane.

In western coal fields, several types of faults occur with varying amounts of displacement. The Wasatch Plateau and Emery Coal Fields contain the faults with the greatest amount of displacements of the studied coal fields. Faulting is predominately normal, with displacements ranging up to 2500 ft. Strike-slip faults also occur in these two fields. Remaining coal fields predominately contain normal faults with lesser displacements. Thrust faulting occurs in the Yampa Field and a large fault zone displaying oblique-slip movement is found within the Carbondale Field.

Minor to severe coal mine ground control problems occur in coal mines of the West in relation to faulting. During this study, many faults were noted that had only minor displacements of several inches along near vertically dipping planes. This type of fault has little effect on mine development or roof control. At the other extreme, one major fault zone has caused constant roof falls, creating significant hazards during mine development. A rock tunnel through this fault zone had to be completely timbered and cribbed.

In western coal mines, faulting can cause poor roof conditions in the area adjacent to the fault, due both to failure along the fault plane and to failure caused by fractures in rock adjacent to the fault. Along the fault plane, where movement has resulted in abrasion, fault "gouge" may be found. Gouge is the fractured or powdered rock that is formed between the two opposing fault planes by the pressure and abrasion associated with fault movement. Fault planes can be the source for water migration into the mine. This water, migrating along the fault plane, can weaken and deteriorate fractured rock, thus helping to propagate roof falls. Faults with large displacements can halt coal mining entirely or require that a rock tunnel be constructed (either angled up or down) to permit continued mining of the seam on the other side of the fault. This procedure is costly for mining operations.

In western underground coal mining, the primary ground control concern related to faulting is the weakening of nearby roof strata, which can cause large and severe roof falls. Faults often occur in sets in the West. In areas where faults occur in sets, and particularly where they are conjugate, intervening roof rock is very susceptible to detachment and roof fall. Like joints, faults that are closely spaced may cause fracturing of the intervening rock. Fault sets that have greater space between each fault do not affect intervening rock as severely. Faults in the West may also splay. With this type of fault, minor faults will splay from a major fault with similiar strike, dip, and type of movement. The fault splay may continue along with the major fault for some distance.

Figure 54. is a portion of a mine map, from a mine in the northern Wasatch Plateau, that shows mapped faults and associated roof falls. As can be seen on this figure, all faults mapped in this portion of the mine strike approximately N10-20E under the control of regional tectonic forces. Minor to major roof falls have occurred near these faults that have produced weak roof conditions. Several of the faults exhibit more than one direction of movement, due to repeated motion under changing regional stress through geologic time. These changes in stress and motion have significantly increased the fractured condition of rock adjacent to the faults. Figure 55. is a portion of another mine map, from a mine in the central Wasatch Plateau Field, showing structural and depositional geology. Several north-striking faults are

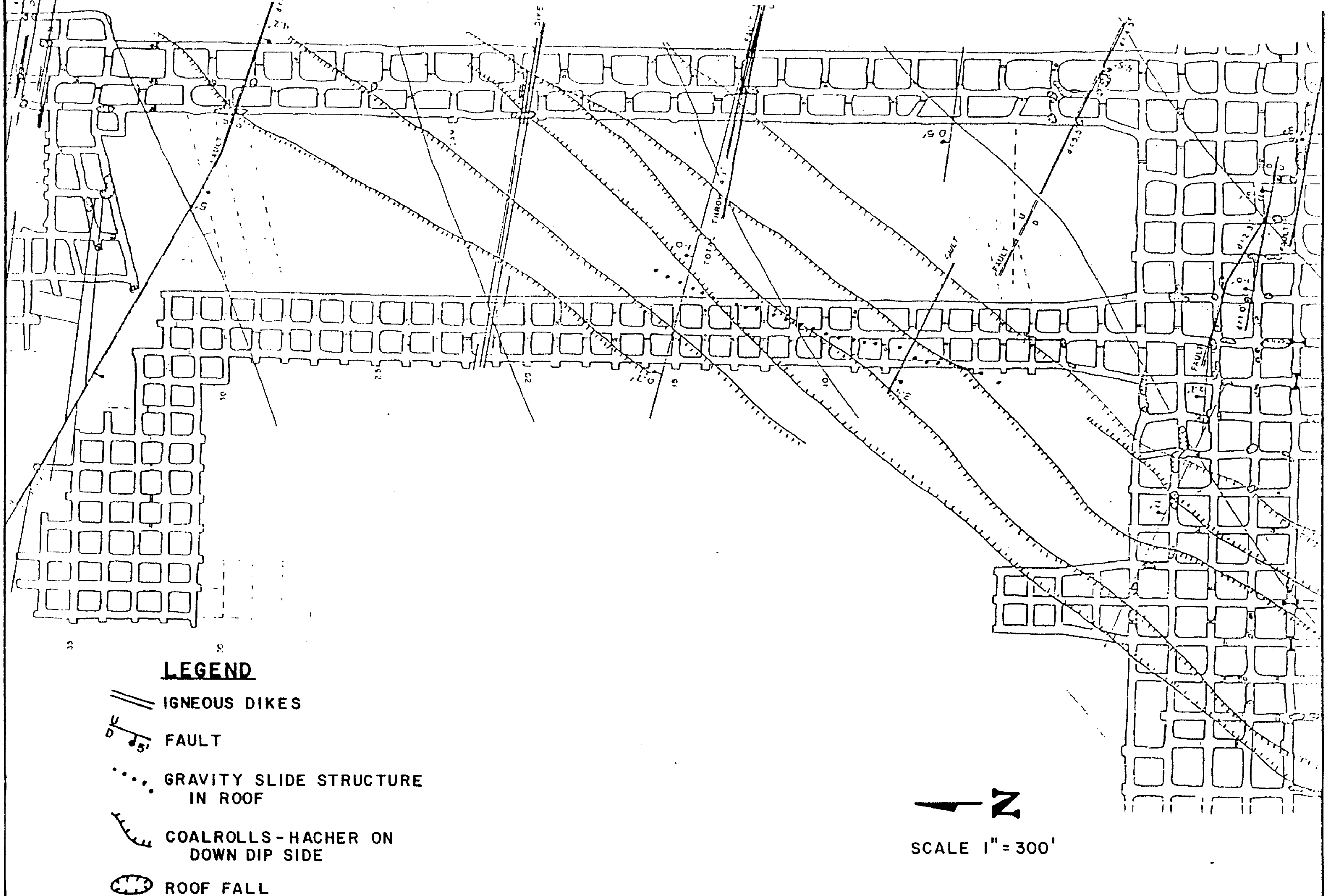

FIGURE 54. - Portion of a mine map, from a mine in the northern Wasatch Plateau Coal Field, showing structural geology. All faults are normal. Fault sets, splayed faults, and dike-injected faults are shown.

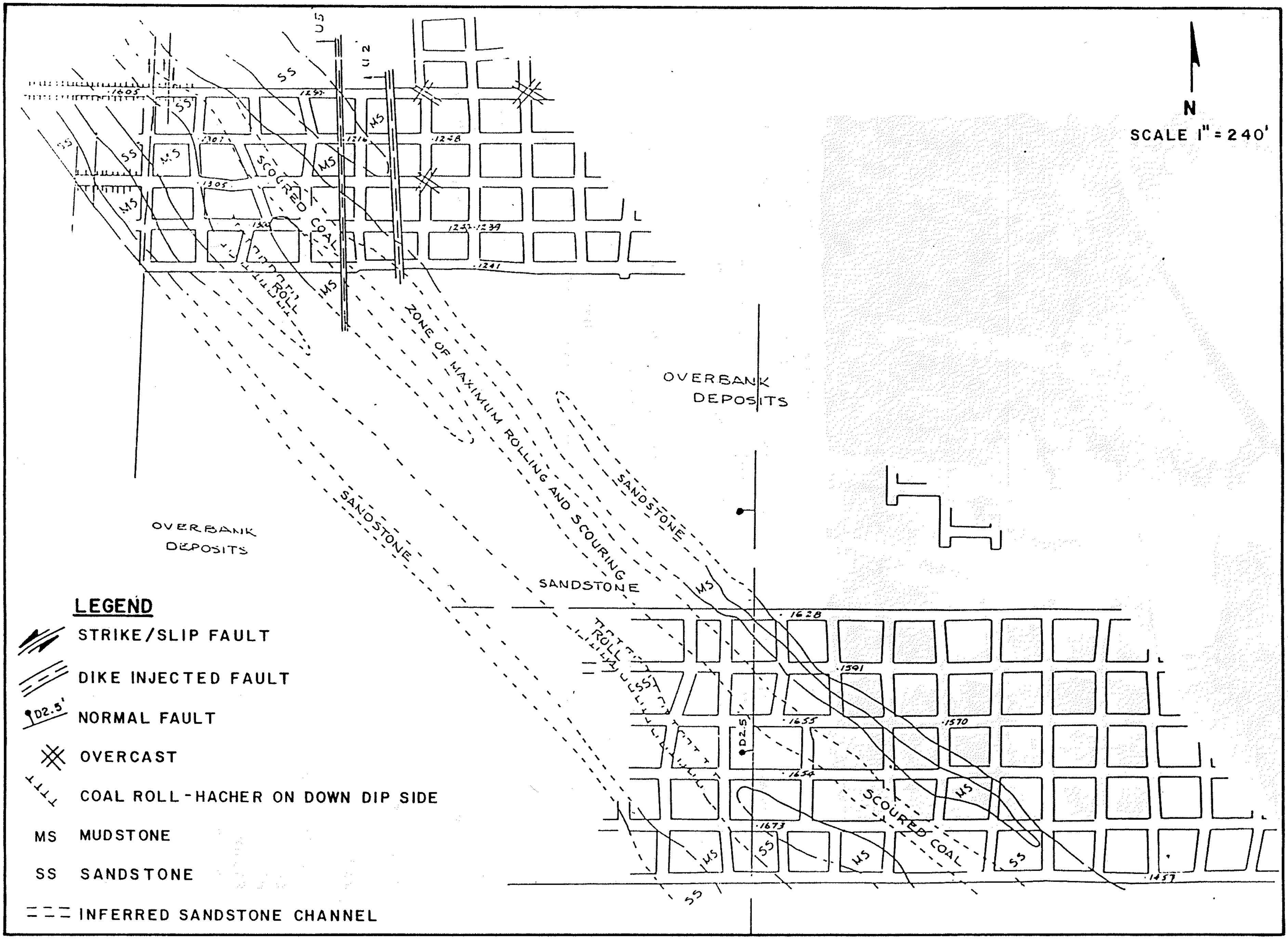

FIGURE 55. - Portion of a mine map, from a mine in the central Wasatch Plateau Coal Field, showing structural and depositional geology. Faults mapped show normal and strike-slip movement as well as dike injection.

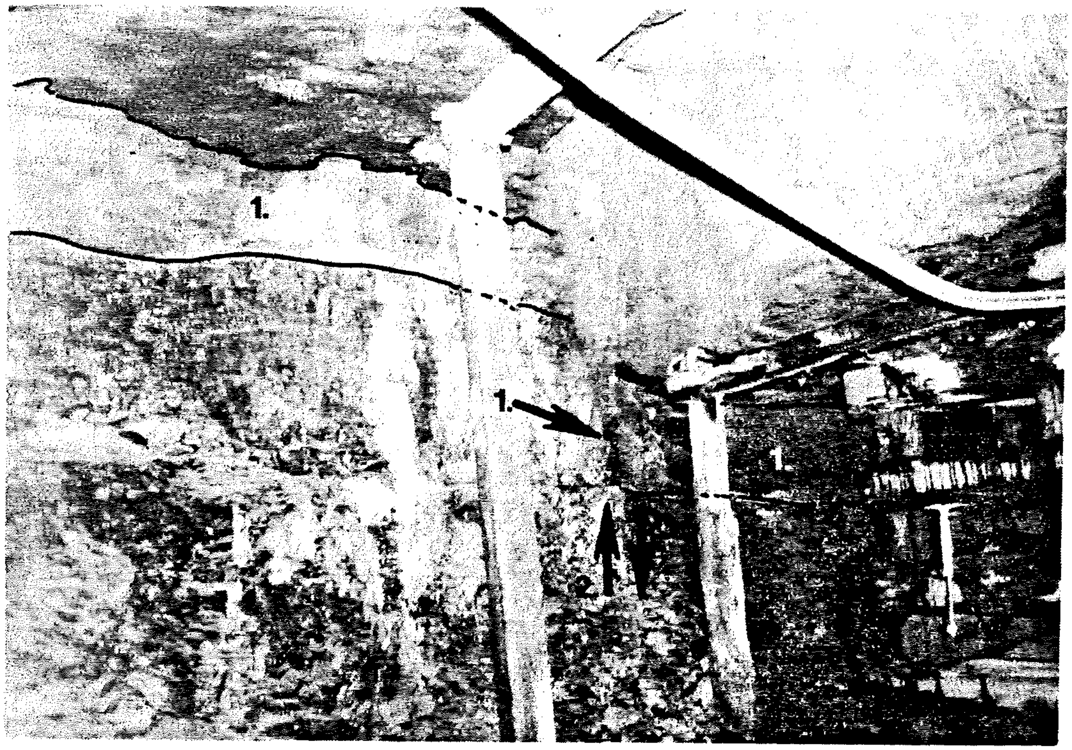

PLATE 37. - Photograph showing fault, central Wasatch Plateau Coal Field. Rock pick is approximately 3 ft. long. Fault has normal movement along a vertical plane. About 4.5 ft. of displacement has occurred. Unit 1. outlines displaced strata; arrow 1. points to plane of movement; arrows 2. show direction of movement.

mapped. No roof falls are mapped on this figure, but faulting, in combination with the sandstone channel, has produced areas with very poor roof conditions. The faults shown in Figures 54. and 55. have small displacements, with only moderate amounts of gouge. However, these faults have weakened adjacent roof rock and have caused roof falls subsequent to undermining. Plate 37. shows one of the faults from Figure 55. This is a fairly clean fault with very little gouge. Minor roof control problems were associated with this normal fault, which displaced about 4.5 ft. of strata. Plate 38. is a photograph showing the plane of movement along a thrust fault in the Yampa Coal Field. This type of faulting was induced by powerful compressional forces. Plate 39. shows a major roof fall below one of these low-angle thrust faults. This fall, which occurred in an intersection, was approximately 11 ft. high. Figure 56. is a cross-section through this roof fall, showing the conditions that caused the fall. The low angle of the thrust-fault plane, which is a major plane of weakness, combined with water influx along the fault plane, caused this roof fall. Figure 57. is a portion of a mine map from a mine in the Carbondale Coal Field. This map shows a major fault zone, in this example termed a "shear zone", which strikes diagonally across the entries of the mine. This shear zone caused major roof falls during mine development. Figure 58. is a cross-section through this shear zone that shows the direction and amount of movement on the fault, as well as the rock slope that had to be constructed to cross through the shear zone to the coal seam on the opposite side. Plate 40. is a photograph showing the sheared condition of the rock within the fault zone shown in Figure 58. Technically, this entire zone of sheared rock is termed fault gouge. The extreme roof control procedures needed to support this weak rock are also shown. Plate 41. shows a fault set within the same mine in the Carbondale Field. Total offset on this fault set is approximately 4 ft.

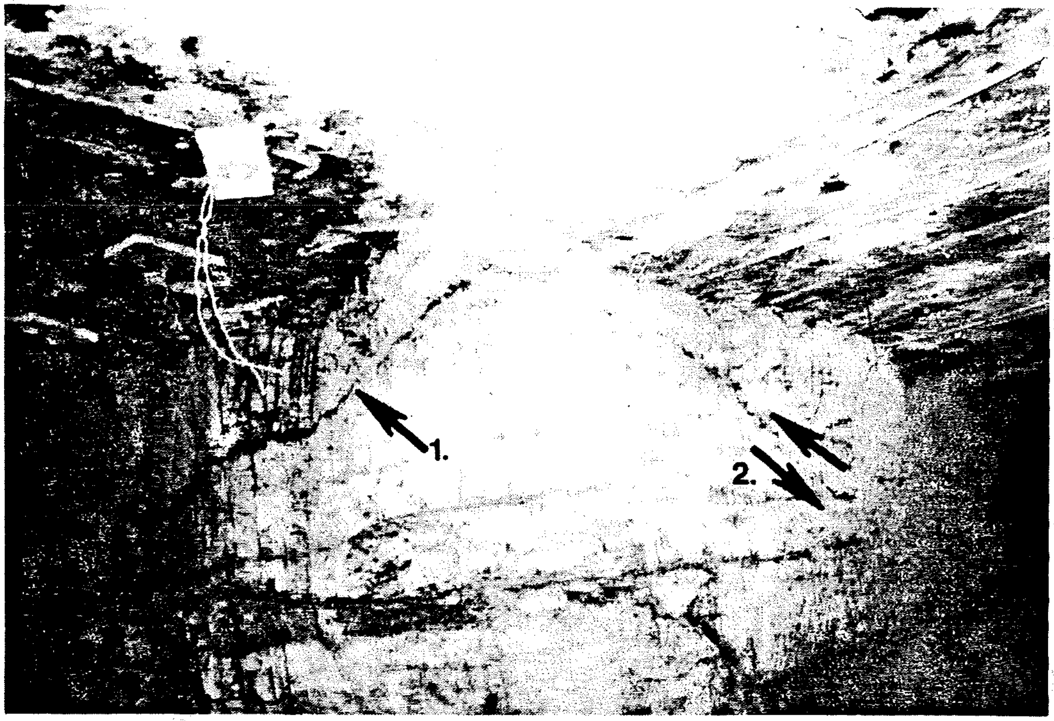

PLATE 38. - Photograph taken perpendicular to the plane of a thrust fault, Yampa Coal Field. Fault dips approximately 25 degrees. Arrow 1. points to plane of fault and arrows 2. point to direction of movement. Cap blocks are 8 in. wide.

PLATE 39. - Roof fall caused by plane of weakness produced by low-angle thrust fault and water influx along fault plane, Yampa Coal Field. This roof fall was approximately 18 ft. in diameter and 11 ft. high. Water infiltrating along the low angle of the fault plane contributed to this roof fall subsequent to mining an intersection. View is parallel with a 20 ft. wide entry.

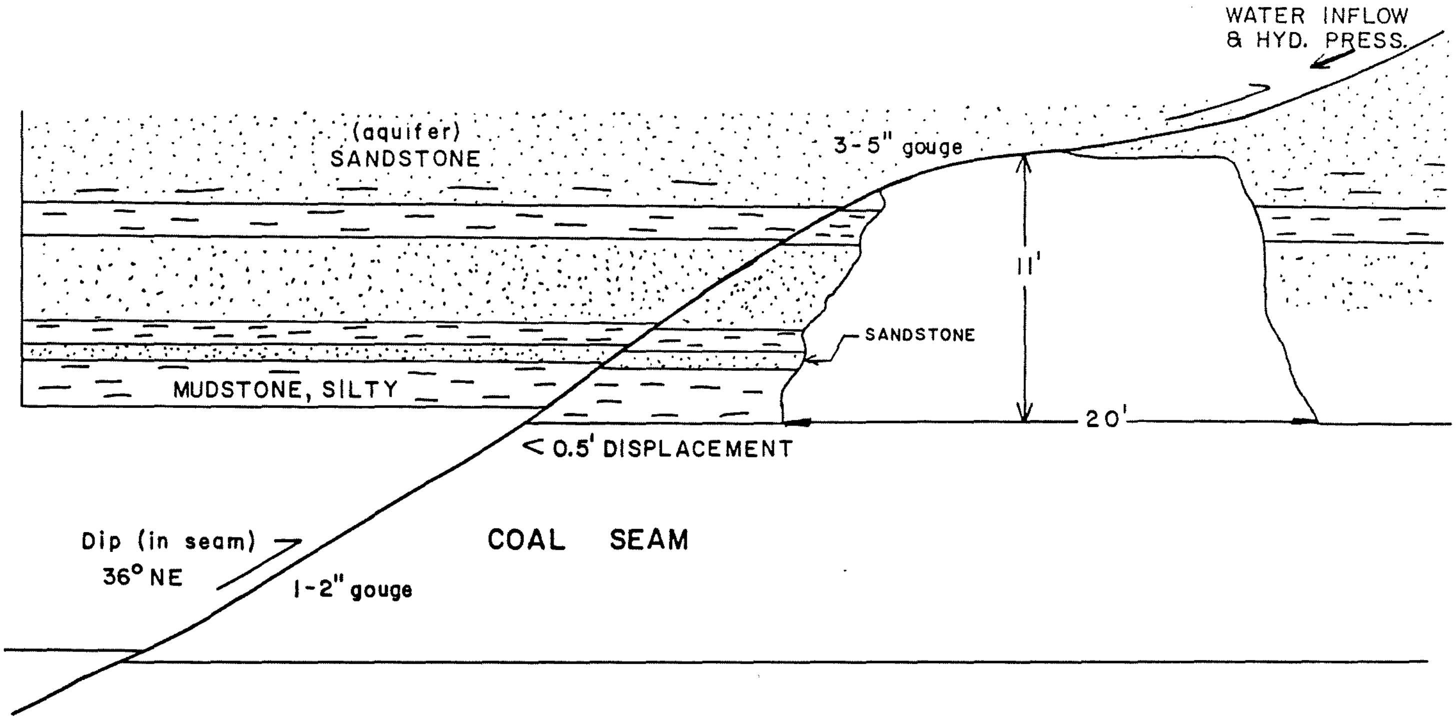

FIGURE 56. - Cross-section through roof fall caused by weak plane of low-angle thrust fault combined with water infiltration along fault plane, Yampa Coal Field.

5.2.5 Lineaments

Lineaments are, "a significant line of landscape that reveals the hidden architecture of the rock basement" (39). Lineaments can be the linear topographic expressions of subsurface features. These features include joints, faults, or igneous intrusions, such as dikes or sills. Lineaments may also be the present day surficial expression of paleotopographical features, such as river valleys. Lineaments often represent large, regionally produced structural features, which can be seen on aerial or satellite photography. Drainage and topography can be controlled by lineaments.

Lineaments are often plotted on aerial photographs and projected to the subsurface to predict mining conditions. Lineaments are thus often correlated with faults in mines. Entries driven parallel to and below lineaments often encounter poor roof conditions. This can result in extensive roof falls that may completely fill entries (44). Where lineaments intersect underground, they are often associated with severe roof conditions.

The main concern regarding lineaments is their utility as an indicator of underground conditions. Lineament plotting on maps and aerial photography is a predictive tool that is used by some mine planners.

5.2.6 Igneous Dikes

Igneous dikes are found in nearly all of the studied coal fields. Igneous dikes are intrusions of molten rock, which force their way upward through fractures and faults from magma chambers. In the Cretaceous, thousands of feet of sediment were deposited within the Interior Sea. The close of the Cretaceous is marked by increased mountain building activity associated with the Laramide Orogeny, which uplifted these sedimentary rocks. Many types of igneous intrusions, which altered the sedimentary rocks, accompanied the orogeny into the Tertiary Period.

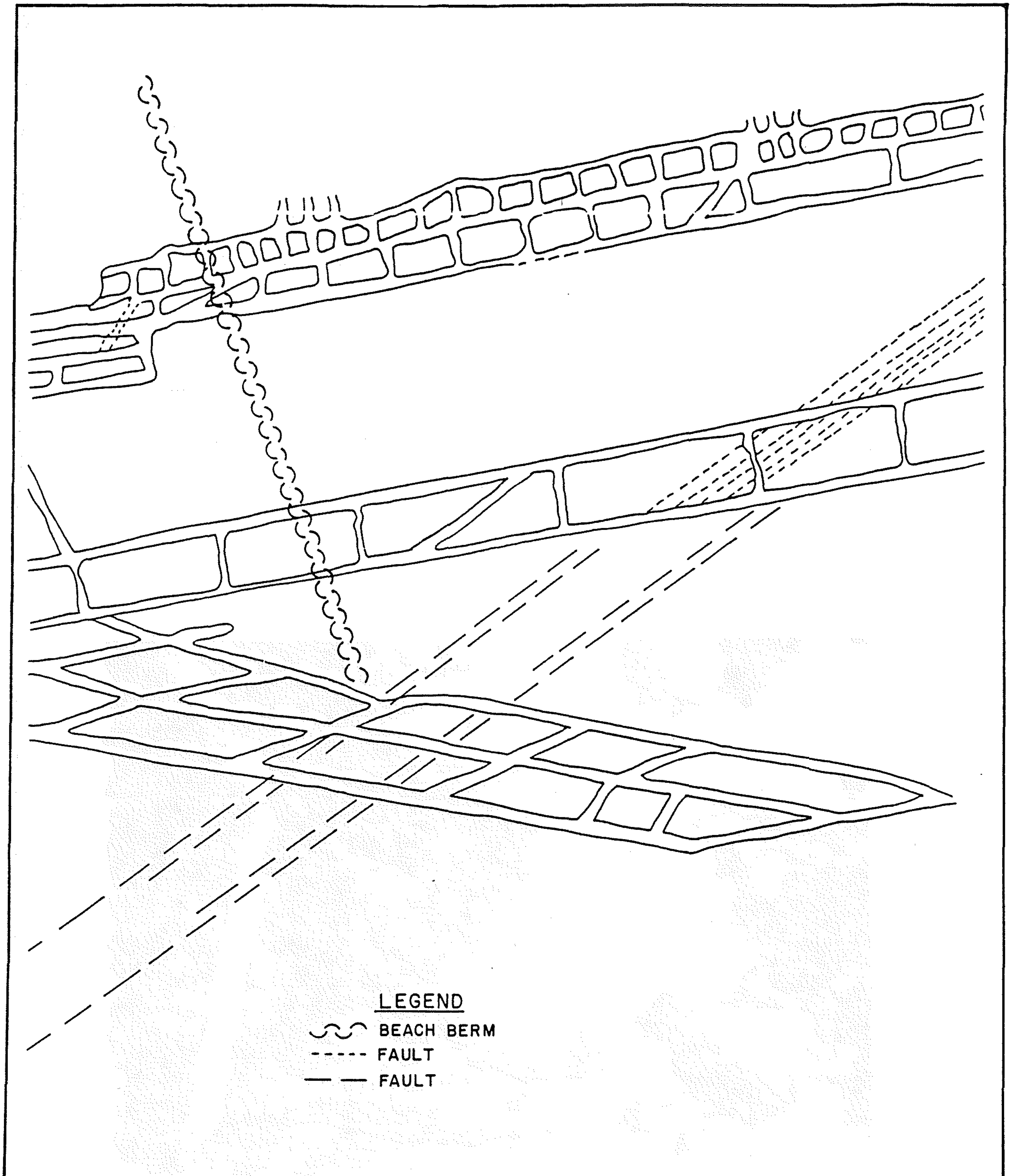

FIGURE 57. - Portion of a mine map, from a mine in the Carbondale Coal Field, showing the major faulted shear zone that transects this mine and caused significant problems in the development stage. No scale.

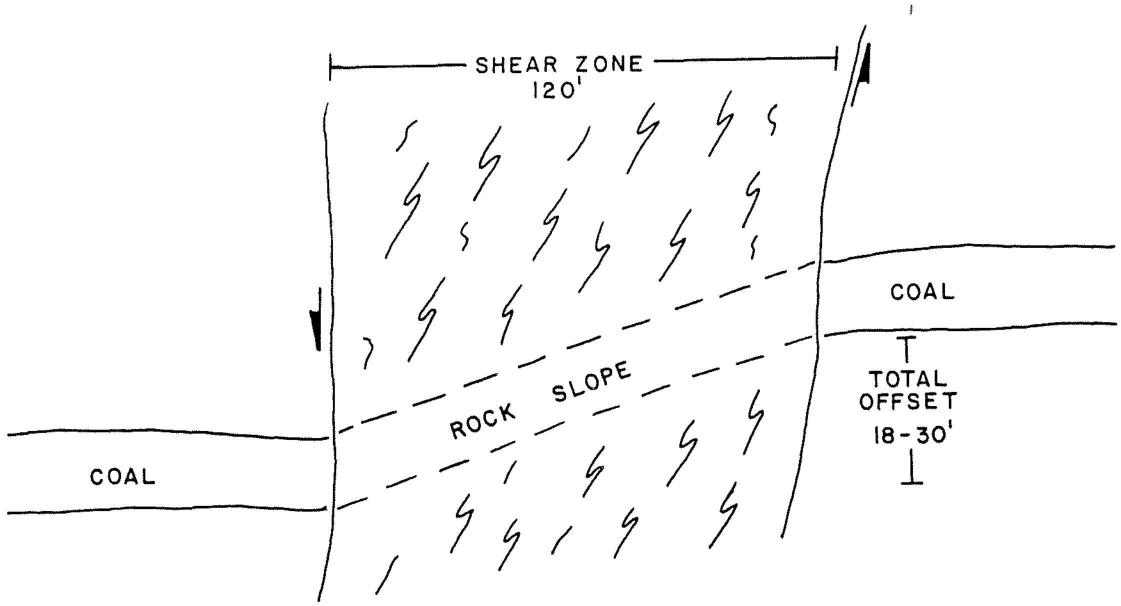

FIGURE 58. - Cross-section through faulted shear zone, Carbondale Coal Field. Shear zone is approximately 120 ft. wide. Fault shows oblique-slip with extensive strike-slip movement that produced sheared rock within fault plane boundaries.

PLATE 40. - Photograph of sheared and distorted rock of major fault zone, Carbondale Coal Field. Mat is 8 in. wide. Note fractured and crumbling fault gouge onto extensive roof control support (timbers, I-beams).

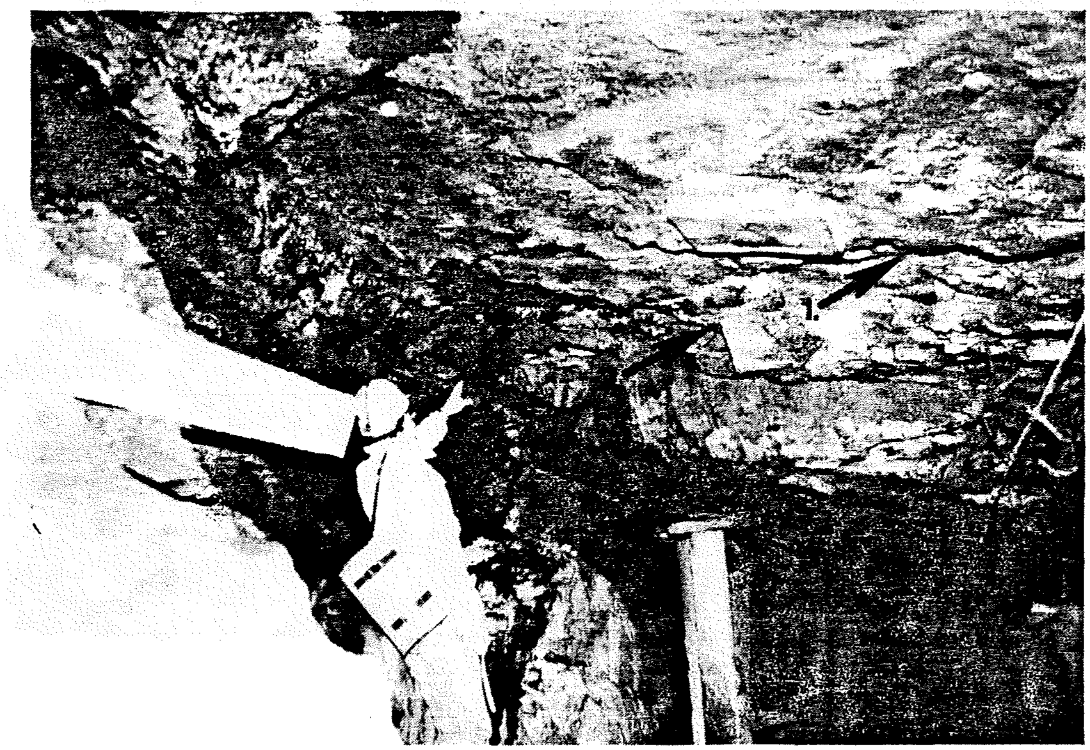

PLATE 41. - Photograph of fault set, Carbondale Coal Field. Observer is pointing to water infiltration along fault planes. Arrow 1. points to fault plane with approximately 2 ft. of displacement; arrow 2. points to second fault plane with 2 ft. of displacement. Note fractured rock separating two faults. Cap blocks are 8 in. wide.

Ground control problems associated with igneous dikes in western underground coal mines are usually not severe. The major problem associated with mining into igneous dikes is wear on the cutting heads of mining equipment. Individual dikes are usually no more than several feet thick. However, many individual dikes may be found in close proximity to one another. Often, dikes will intrude along pre-existing fault and joint systems. The dikes are therefore oriented parallel to structural features. Usually, high-heat flow associated with dikes will coke the surrounding coal to within a maximum distance of 30 ft. Occasionally, igneous dikes will cause roof control problems in the form of altered adjacent strata, which has lost integral cohesion through heating. The heat from the molten rock can cause cementing agents within the surrounding sedimentary rock to recrystallize, leaving a friable, loose rock adjacent to the igneous dike. Subsequent to mining of the coal seam, this rock will fall. Occasionally, the dike itself will be friable. Igneous dikes are commonly much harder than the surrounding rock. However, some igneous dikes, possibly because of volatile gases entrained in the magma, are weak and friable, and disintegrate fairly easily.

Figures 54. and 55. in Section 5.2.4 are partial maps of underground coal mines. Figure 54. shows dikes that have intruded along a fault or joint. The dikes have the same orientation as the faults. In Figure 55., dikes are shown to have intruded along two faults.

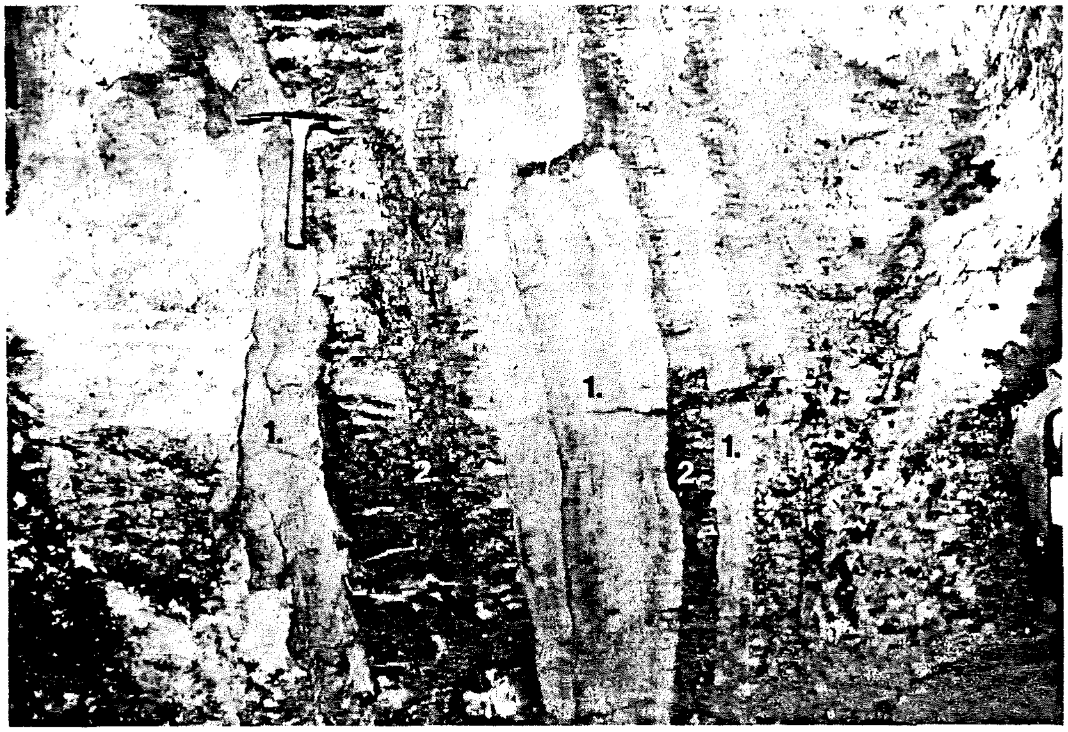

PLATE 42. - Photograph of an igneous dike, northern Wasatch Plateau Coal Field. Hammer provides scale. Rock units labeled 1. are dike injections; rock units labeled 2. are zones of coked coal.

Plate 42. is an excellent example of a small dike which has coked the surrounding coal in the northern Wasatch Plateau Field. Plate 43. is another photograph of an igneous dike intruding into a coal seam. Plate 44. shows a large igneous dike in the central Wasatch Plateau Field that has intruded the coal seam. This dike is composed of extremely friable igneous rock reported to be peridotite (45). The friable and noncohesive nature of this rock has required that extreme roof control measures be implemented, using steel sets.

No coal mine reported any major problems with igneous dikes, although most coal mines encounter them. Where igneous dikes have intruded along faults, such as in the Wasatch Plateau Field, moderate ground control problems occur. The large dike pictured in Plate 44. is atypical in that it is approximately 30 ft. wide and contains many hard minerals and so is difficult to mine through.

5.2.7 Sedimentary Dikes

Sedimentary dikes are more commonly referred to as "clastic dikes" when discussing intrusive sedimentary features within underground coal mines. Clastic dikes intrude coal seams and occasionally cause significant mine safety, operational, and economic problems. Clastic dikes of western coal fields are characterized by Lindberg, et al. (46) as:

> "...tabular, discordant, sheet-like bodies of sedimentary material. In appearance, shape and form, and in field relations, clastic dikes loosely resemble igneous dikes. Gradual infilling or forceful injection of unconsolidated sediment into fissures or fractures of a host rock are the most common ways these dikes form. Sediment textures of dikes range from conglomeratic to clayey but most commonly occur in the sandstone range."

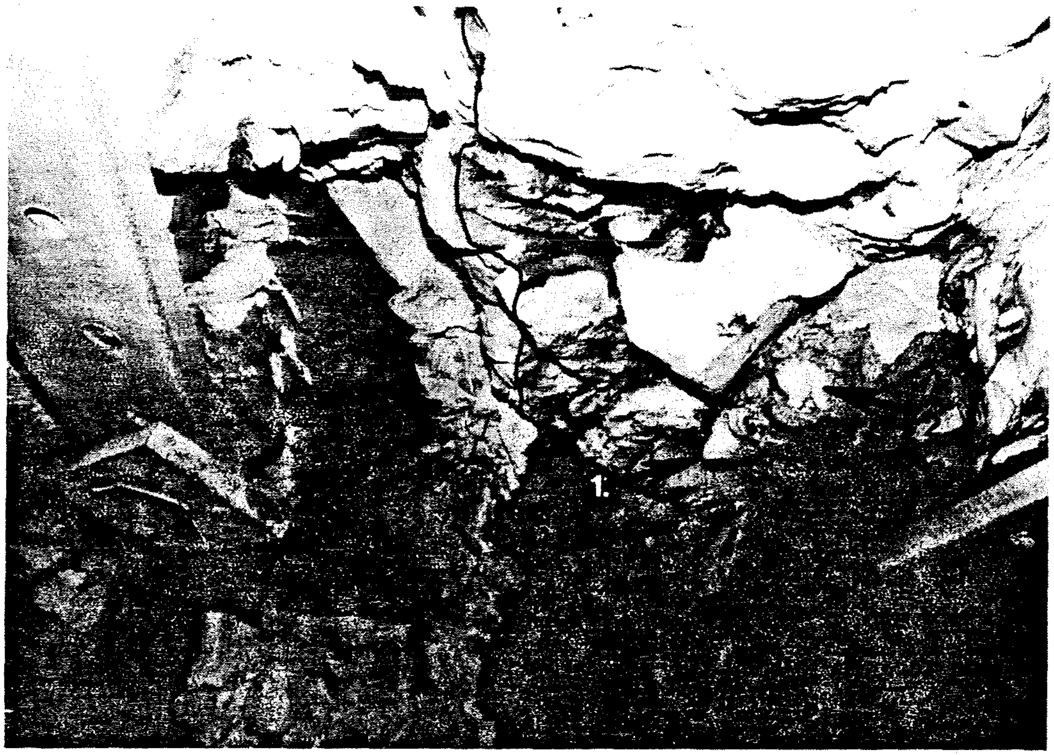

PLATE 43. - Igneous dike, northern Wasatch Plateau Coal Field. Igneous dike is outlined in the rib and the roof of this entry. Arrow 1. points to sand-filled cast of a claw from a three-toed dinosaur; arrow 2. points to a broken toe cast. Cap block is 8 in. wide.

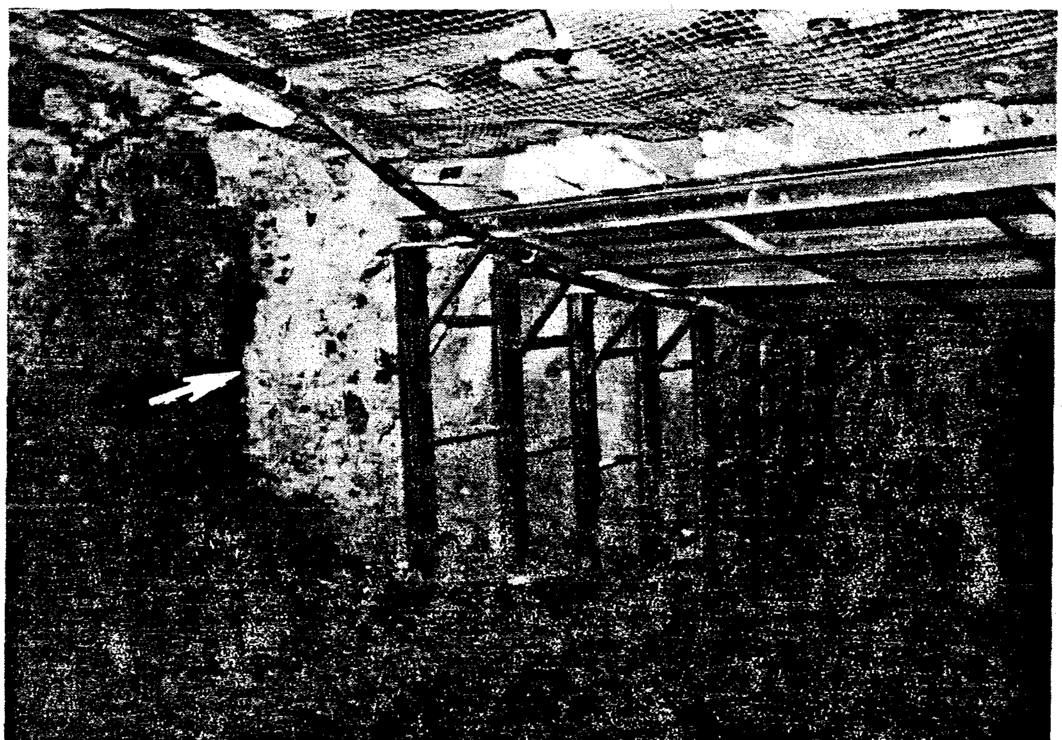

PLATE 44. - Large (30 ft. wide) igneous dike, central Wasatch Plateau Coal Field. Dike is light-colored rock. Arrow points to contact between dike and coal seam. Dark-colored rocks within the dike are coked-coal xenoliths. Note the extensive roof support required to control caving of this friable dike.

Based on Lindberg's, et al. 1983 data (46), more than 98 percent of the clastic dikes found in the Upper Cretaceous coal seams of Utah are composed of sandstone, with mudstone or siltstone dikes occurring infrequently. Clastic dikes often occur in swarms with common dip and/or strike directions. They average 2 in. to 8 in. in thickness but can range from 1/2 in. to 3 ft. They vary in length from less than 3 ft. to 3,000 ft. Clastic dikes most often exhibit a crenulated cross-section, apparently caused by significant vertical compaction following dike emplacement. More than 95 percent of the clastic dikes found in Utah coal fields are continuous with, and composed of, roof strata lithologies. Dikes injected from the floor strata of coal mines are generally only 1 ft. in length. Petrographic thin-section analysis shows that fine-grained sediment is located at the margins of the dike with coarser-grained sediment located in the central portion of the dike. This suggests liquification of the sediment during dike formation. Coal "country rocks" from the dike walls are found within the intruded sediment, which suggests forceful injection. Peat deposits are layered, yet no clastic dike formation spreads out laterally along bedding planes. Clastic dikes studied in the Utah coal mines parallel the orientation of other regional structures, suggesting a common tectonic origin.

Clastic dikes are composed of the same sandstone that makes up the roof or floor of the coal mine. This sandstone originates from marine or fluvial sand channels, crevasse-splay or overbank sheet-sand deposits, or littoral beach sands. Occasionally, clastic dikes will intrude very fine-grained shale or siltstone roof or floor rock, through the coal, up to distances of 3 ft. (46).

Many theories regarding the origin of clastic dikes have been presented. Most theories suggest that their origin can be traced to injection of sediments from below the peat bed caused by pressure from overburden. However, most dikes observed in Utah were injected from sandstone units in the roof. Because clastic dikes appear to be injected through "tears" in peat layers and parallel fault, joint, and coal-cleat patterns, a logical explanation for their origin can be found in earthquakes that were caused by orogenic activity. Coals of the Emery, Wasatch Plateau, and Book Cliffs Coal Fields were formed only a moderate distance from the Sevier Orogenic Belt. Tectonic shocks could easily have torn peat beds and liquefied the overlying or underlying sand that was injected along these tears (46).

Although clastic dikes rarely cause severe ground control problems within mines, differential compaction and slickensides have been noted adjacent to clastic dikes. Compacted and slickensided rock can easily fall away from the dike. Low-angle clastic dikes may cause roof falls if weak bedding planes exist between the sandstone dike and surrounding lithology. A thick clastic dike will not only produce sparks when mining into it, but may be interpreted by mining personnel to be a seam offset caused by faulting. This misinterpretation may cause mining to halt until the feature is interpreted correctly.

Plate 45. is a detailed photograph showing a piece of coal that has been intruded by a very fine-grained sandstone dike. The sandstone is well-sorted and cemented, and appears to be composed of the same sandstone that makes up thin laminations of related crevasse-splay deposits. Plate 46. shows the clastic dike in the rib of a coal mine in the northern Wasatch Plateau Field

PLATE 45. - Detailed photograph of clastic dike from the northern Wasatch Plateau Coal Field. Light-colored rock is very fine-grained and well-sorted sandstone; dark-colored rock is coal. Fragment is approximately 8 in. wide.

PLATE 46. - Clastic dike in coal, northern Wasatch Plateau Coal Field. Fragment in Plate 45. was obtained from this location. Arrow points to crenulated clastic dike in coal seam. Dike is composed of very fine-grained and well-sorted sandstone. Dike width varies from 1/4 in. to 2 in.

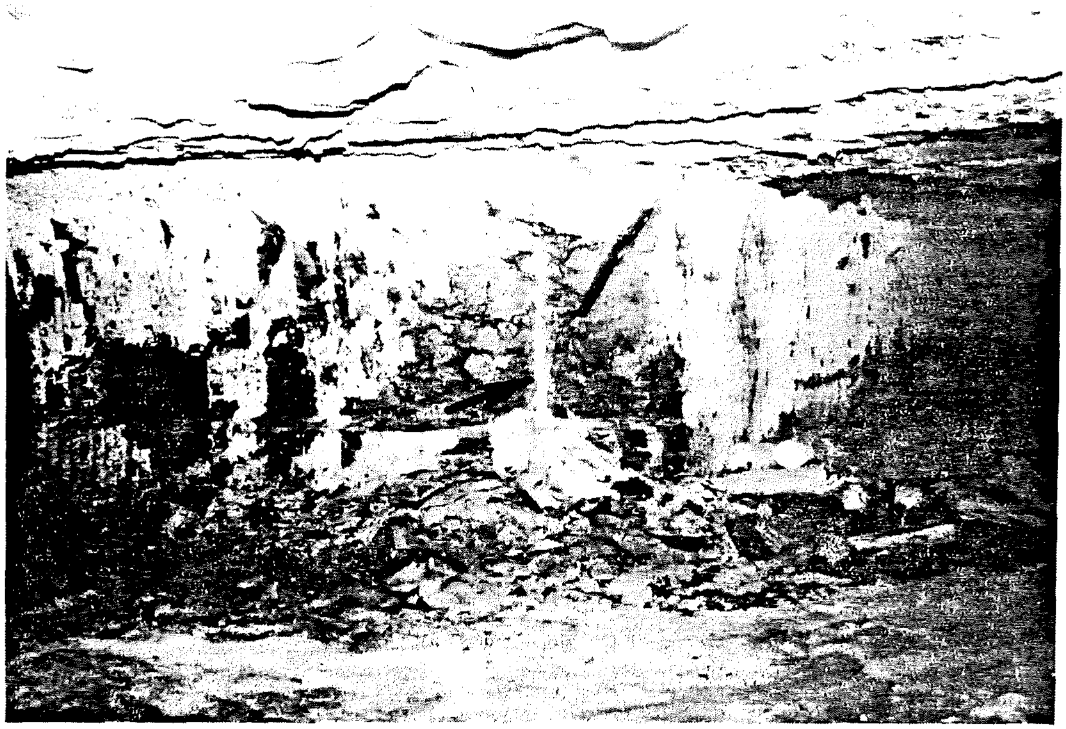

PLATE 47. - Clastic dike, Grand Mesa Coal Field. Arrow points to very fine-grained and well-sorted sandstone of clastic dike. Dike intrudes from the floor, which is a littoral marine sandstone tongue. Dike is 5 ft. high and is 6 in. wide at the base, tapering to 1.5 in. at the top.

where the dike fragment shown in Plate 45. was obtained. Plate 47. shows a 5 ft. long clastic dike that is 6 in. wide at the base and tapers to 1.5 in. at the top. This dike was observed in the Grand Mesa Coal Field. It emanates from the floor and pinches-out within the coal seam.

Clastic dikes were observed in the Wasatch Plateau, Grand Mesa, and Somerset/Paonia Coal Fields. They did not present significant adverse conditions with regard to roof control, but did cause wear on mining equipment.

5.3 Additional Geologic Conditions Causing Ground Control Problems

5.3.1 Water

Water infiltration into underground coal mines often creates severe ground control problems. Infiltration of water into the mine invariably worsens existing conditions. An excellent example was presented in Section 5.1.4, where water infiltration along the plane of a low-angle thrust fault aided in the detachment of a large portion of the mine roof. This fall may never have occurred, had no water been present to lubricate the fault plane. Water infiltration, in combination with the weak roof strata of a lithofacies change roof type (see Section 5.1.2), produces hazardous roof conditions associated with large, unpredictable roof falls.

Water enters the mine through faults or joints, which intersect surface or ground water. Sandstone channels may be aquifers that, when intersected, will allow water to deteriorate roof conditions and pond on mine floors. Not only will water infiltration aggravate pre-existing poor roof conditions, but upon entering the mine, will propagate air slaking of a shale mine roof. It can cause adverse working conditions where mine water ponds, and causes clay floors to expand and buckle with alternate wetting and drying.

Several coal fields studied during this project reported water problems as a foremost or secondary adverse ground control condition. Every coal field studied had some form of water problem. Coal fields that had significant water problems were the Grand Mesa, Somerset/Paonia, Yampa, and Trinidad Fields.

5.3.2 Stress

Horizontal stress within underground coal mines of the West has been briefly discussed in Section 5.1.1.2 in relation to the formation of structural slickensides. When mine development achieves an overburden thickness greater than 1500 ft., horizontal stress can be twice the value of vertical stress (36). This great amount of vertical and horizontal stress at depth will aggravate existing geological ground control problems. Major structural damage to coal mine roofs, ribs, and floors is primarily caused by horizontal stress. Damage is due primarily to in situ stress, and is accelerated in areas of weak lithology.

Initial ground control problems caused by high horizontal stress are related to lateral movement within the mine roof. Pillars will slab at the roof and pillar juncture, due to lateral movement. Very poor roof conditions occur where fracturing, delaminating, and spalling of roof rock is caused by lateral movement. Entries and cross-cuts may develop offset roofs and floors due to lateral movement. Cribs may bend and compress in relation to the direction of lateral movement.

Plate 48. is a photograph, from a mine in the northern Wasatch Plateau Field, showing the effects of high horizontal stress. Roof mats, originally bolted in line with each other, have been offset. Extensive fractures have formed in the roof, and trusses, which originally were emplaced to compress the roof, have buckled in on themselves. Large cribs have shifted and are offset; they are no longer plumb with the roof and floor. Approximately 1600 ft. of overburden overlies this location.

Plate 49. is a photograph taken near to the location shown in Plate 48. This plate also shows the extremely poor roof conditions that have been caused by high horizontal stress. A large roof fall is pictured that was caused by extreme fracturing in a siltstone roof. The roof is heavily timbered and cribbed in this location, with trusses that are not effectively pulling the roof together.

Horizontal in situ stress within coal mines of the West is not a geologic feature, but is a rock mechanics problem related to existing geologic conditions and mine development. Stress within a coal mine can produce hazardous geologic phenomena such as the structural slickensides that were discussed in Section 5.1.1.2.

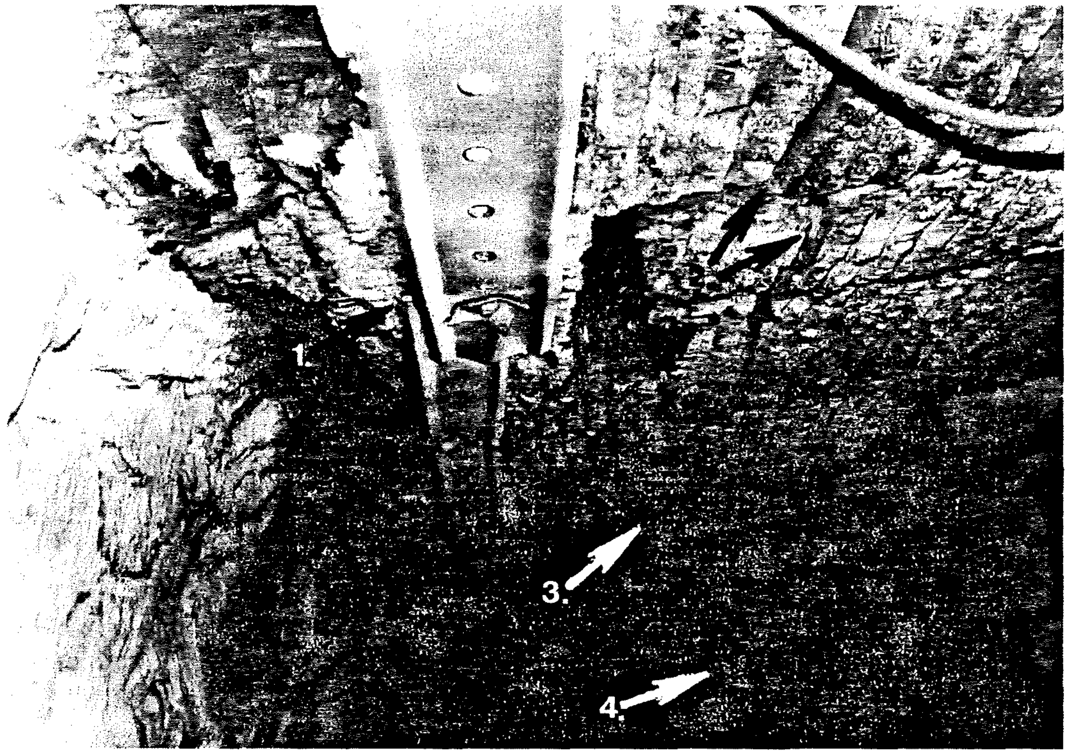

PLATE 48. - Photograph showing adverse effects of high horizontal stress, northern Wasatch Plateau Coal Field. Arrow 1. points to offset roof mats; arrows 2. point to fractures in roof; arrow 3. points to ineffective, buckled roof truss; arrow 4. points to extensive cribbing.

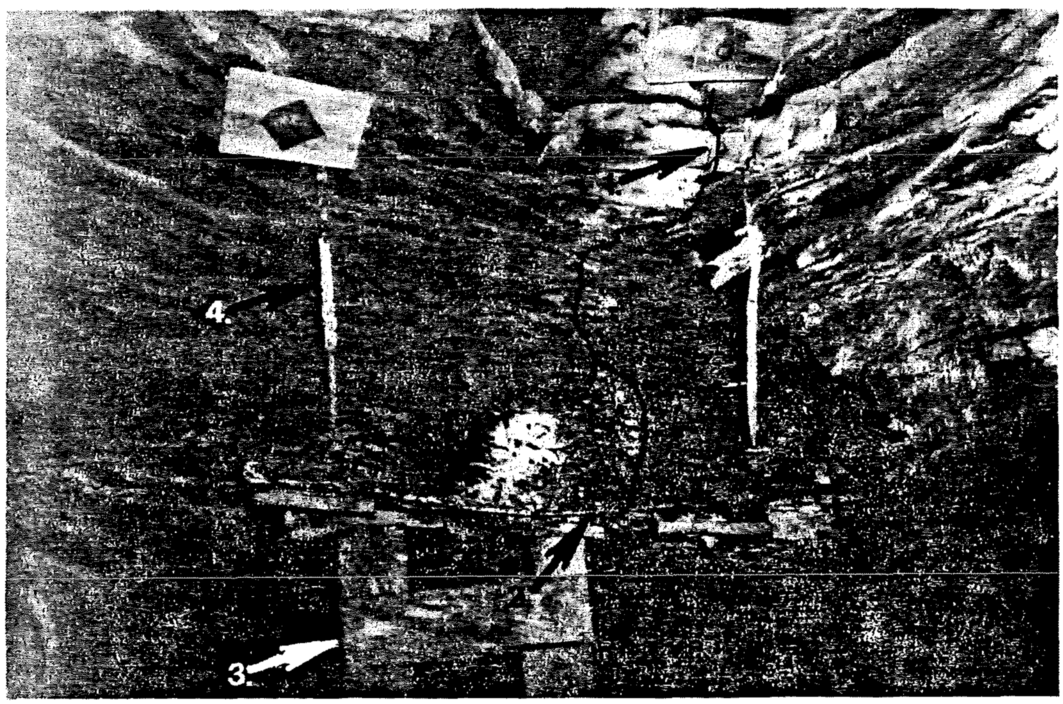

PLATE 49. - Photograph showing adverse effects of high horizontal stress, northern Wasatch Plateau Coal Field. High horizontal stress is causing siltstone roof to fracture and collapse. Arrow 1. points to highlighted fracture in roof; arrow 2. points to ineffective roof truss; arrow 3. points to crib; arrow 4. points to ineffective roof bolt that remained anchored subsequent to major roof fall.

Other phenomena associated with high stress, are "bumps" and "bounces". Bumps and bounces are caused by the rapid release of strain from a highly stressed volume of coal, resulting in the immediate transfer of load to stronger, nearby coal. The resulting loud report, a hollow "bumping" sound, or shaking of the mine (bouncing) is the physical unloading of this tension. Rock bounces, which can severely shake the mine, are often the cause of large and sometimes fatal roof falls. If the overburden thickness produces horizontal stress that is great enough to exceed the tensile strength of the rock, a "rock burst" can occur. If a volume of rock is strained beyond it's elastic limit, the burst can range in form from spalling of small slabs of coal to lowering of the roof with expansion of the pillars, overturning of the ribs, or to complete collapse of the roofs and pillars. Where extreme stress is placed on the coal mine workings, in association with a particular lithology, "rock flow" can occur. This is also known as plastic flow, which most often occurs in rock that has an abundance of aligned grains, such as clay or shale, and a low plastic limit. This rock can therefore, under extreme stress, behave in a viscous manner and flow without fracturing.

One mine in the Carbondale Coal Field has experienced rock flow due to the stress caused by over 2500 ft. of overburden. The coal seams dip steeply below a rapidly rising mountain front. Mines in the Wasatch Plateau Field, Book Cliffs Field of Utah, and Somerset Field experience high horizontal stress, which produces fractured roof rock, roof falls, bumps, and bounces. These fields all have mines that have overburden thicknesses greater than 1500 ft.

5.4 Additional Geologic Features

The following geologic features do not commonly present a significant hazard to underground mining operations. They are included as a separate group of features more out of general interest than as features related to coal mine ground control problems. It should be noted, however, that most rocks exhibiting sedimentary structures contain planes of weakness, and are thus structurally weaker than more massive sediments. In combination with more hazardous roof features, or where water saturation is common, these features are occasionally associated with roof control problems.

5.4.1 Dessication Cracks

Dessication cracks form through dessication of mud and other fine-grained sediments that experience episodic wetting and drying. In the marginal marine depositional environments associated with Rocky Mountain coal deposits, dessication cracks indicate estuarine, lagoonal, or intertidal bay mudflat environments of the coastal plain. These features can also be formed in river flood plain environments, such as between channels in a delta plain. Dessication cracks are commonly preserved as molds of the original cracks.

Dessication cracks can result in formation of a plane of weakness, and can cause roof rock separations up to several feet thick. Plate 50. is a photograph of dessication cracks in the Yampa Coal Field. In this case, 1 in. of roof rock has separated from the plane of weakness generated by the dessication cracks. Dessication cracks were only observed directly in the Yampa

PLATE 50. - Dessication cracks in mudstone mine roof, Yampa Coal Field. Approximately 1 in. of mudstone has separated from the weak bedding plane created by the casts of the cracks. Light-colored material is rock dust. Mats are 8 in. wide.

Coal Field, but probably exist in most underground coal mines of the West due to the similarity of depositional environments throughout the Rocky Mountain region.

5.4.2 Ripple Marks

Ripple marks are sedimentary features formed through current and wave motion in shallow water environments. Ripple crests are oriented normal to paleoflow direction. Low relief, sinuous, and symmetrical ripple marks were noted in mudstone associated with coal in the Yampa Coal Field, as shown in Plate 51. These ripple marks suggest a low energy, shallow water depositional environment with variable paleoflow directions influenced by tidal flood and ebb. This type of intertidal environment is commonly associated with coastal plain and interdeltaic lagoonal or bay locations.

As with the dessication cracks discussed previously, ripple marks are likely to be found in many of the Rocky Mountain coal fields due to the similarity of depositional environments throughout the region. The ripple mark structure also creates a plane of weakness within the host rock and can cause hazardous separation of several feet of roof rock if not properly supported.

5.4.3 Trace Fossils

Two types of trace fossils were observed during the mine tours. These were worm burrows and dinosaur footprints. Worm burrow trace fossils are

PLATE 51. - Ripple marks in mudstone mine roof, Yampa Coal Field. Rock dust covers ripple mark impressions. Mats and cap blocks are 8 in. wide.

sedimentary features formed by infilling of marine worm burrows. Burrows are generally found in sandstone of the lower shoreface, and are commonly preserved as casts of the original burrow structure. Casts form mounds and depressions that cross-cut bedding and are frequently better cemented than the surrounding sandstone. This difference in cementation results in differential lithologic strength between the burrow and the host lithology, which can create a plane of weakness surrounding the trace fossil. Plate 52. is a photograph showing an unusual group of polychaetes annelid burrows in a coal mine roof in the central Wasatch Plateau Field. This mass of worm burrows was observed beneath the silicified bark of a tree branch or trunk, where the worms apparently colonized in close proximity to organic matter.

Dinosaur footprint casts are fairly common in the roofs of western underground coal mines. The majority of dinosaurs were herbivores that lived in swamp and peat-bog areas with relatively high organic productivity. These were also the optimum environments for peat formation. Most dinosaur footprints consist of three forward toes with one rear "thumb", although four-toed dinosaur footprints are observed. Footprint trace fossils developed where dinosaurs crossed the spongy, uncompacted peat of the swamp. The weight of the animals caused the peat to compact, to the extent that the peat was unable

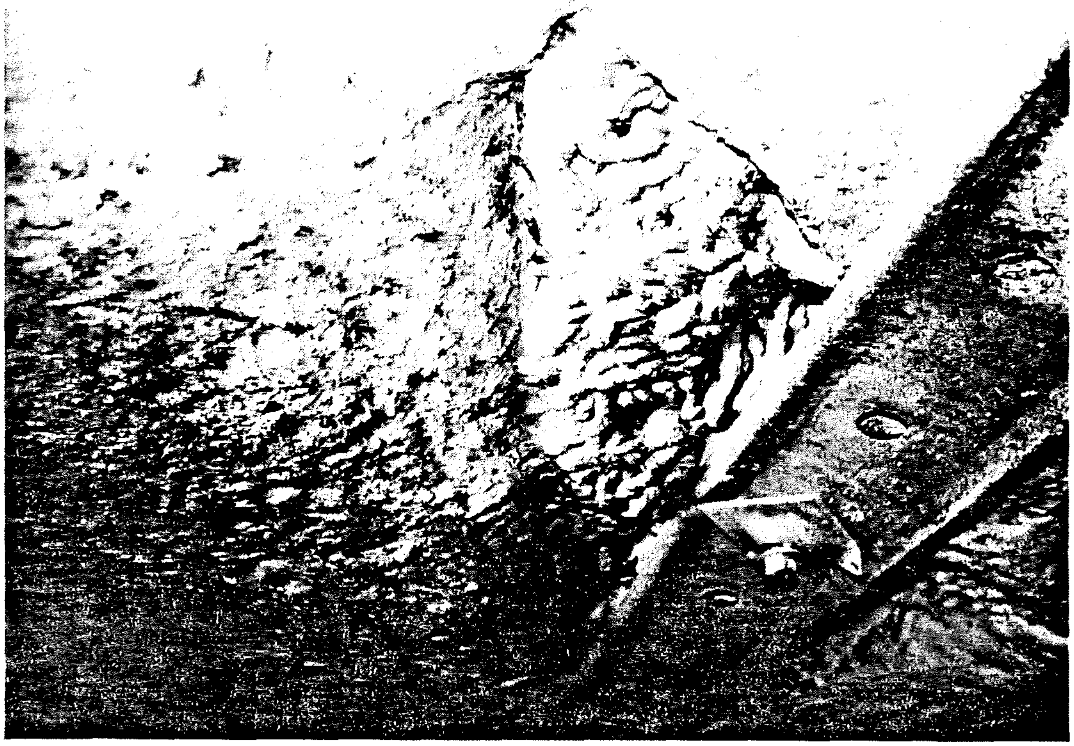

PLATE 52. - Worm burrows in sandstone, central Wasatch Plateau Coal Field. Casts of polychaetes annelid worms can be seen where they colonized beneath the silicified bark of a tree branch or trunk. Mat is 8 in. wide.

to rebound to its former configuration before the footprint casts were infilled by sand (10). Because the sandstone infill of the footprints is part of the overlying sandstone unit, dinosaur footprint casts are not easily separated from the mine roof. However, in rare cases, footprints do fall and can be hazardous.

Plate 53. is an excellent example of a sandstone filled, dinosaur footprint cast from the northern Wasatch Plateau Coal Field. Plate 54. is another example of a large, three-toed dinosaur footprint. This fossil cast, found in a mine in the western Book Cliffs Coal Field very near to the location of Plate 1. (see Section 5.1.1.1), is approximately 2 ft. across at its widest dimension. Plate 55. is a photograph showing large footprints (2.5 ft.) in a dinosaur "trackway" in the Grand Mesa Coal Field. This trackway can be followed for approximately 30 ft. A dinosaur "wallow", where numerous footprints are superimposed and in close proximity to one another, is shown in Plate 56.

Trace fossils are common throughout the coal-bearing Cretaceous and Tertiary sediments of the Rocky Mountain region.

5.4.5 Plant Fossils

Two types of plant fossils were observed during the mine tours. These are compressed logs and leaf imprints. Compressed logs are fossil plant limbs or trunks that have been compacted through lithification processes.

PLATE 53. - Sandstone filled dinosaur footprint, northern Wasatch Plateau Coal Field. Three-toed dinosaur footprint infilled with fine-grained, well-sorted, and well-cemented sandstone. Mat is 8 in. wide.

PLATE 54. - Large three-toed dinosaur footprint, western Book Cliffs Coal Field, Utah. Arrow points to footprint that is approximately 2 ft. across. Cap blocks are 8 in. wide. Light-colored rock is sandstone of fluvial channel. Base of footprint is slickensided shale.

PLATE 55. - Dinosaur "trackway", Grand Mesa Coal Field. Arrows point to large three-toed footprints that are approximately 2.5 ft. across. Mats are 8 in. wide. This trackway is approximately 30 ft. long.

PLATE 56. - Dinosaur "wallow", northern Wasatch Plateau Coal Field. Superimposed footprints indicate repeated dinosaur activity. Mats are 8 in. wide.

PLATE 57. - Compressed log cast, Grand Mesa Coal Field. Mats are 8 in. wide. Log is approximately 3/4 in. thick, 1 ft. wide, and 10 ft. long. Remains of compressed log in roof are composed of silicified and coalified wood. Arrow 1. points to log cast and arrows 2. point to dinosaur footprints from a trackway.

Frequently they are silicified, or "petrified", in situ. Plate 57. is a photograph of an excellent example of a compressed log from the Grand Mesa Coal Field. The log shown was originally approximately 1 ft. in diameter and 10 ft. long. It was compressed to a thickness of 3/4 in. and maintained its original length. The organic material of the log has been entirely silicified and partially coalified. The photograph also shows an adjacent dinosaur trackway. The extreme compaction of the organic material involved in creation of compressed logs produces dense rock that frequently falls from the mine roof when undermined. Differential strength between the log and the surrounding rock creates a plane of weakness, similar to that observed in association with worm burrows. The rarity of this feature prevents it from being a significant hazard to mining operations.

Leaf imprints create planes of weakness within the thinly laminated mudstone that is commonly associated with this type of trace fossil. Plate 58. is a photograph showing leaf imprints from the Grand Mesa Coal Field. The main (dark) leaf is about 8 in. across at its widest point.

5.4.6 Beach Berm

An inferred beach berm was observed during this study in an idle underground coal mine in the Carbondale Coal Field. This unusual sandstone feature protruded from the floor of the coal mine approximately 4.5 ft. in a dome shape that measured 5 ft. at the base and tapered to approximately 3 ft. at the top. The floor of the coal mine is composed of the Rollins Sandstone, a

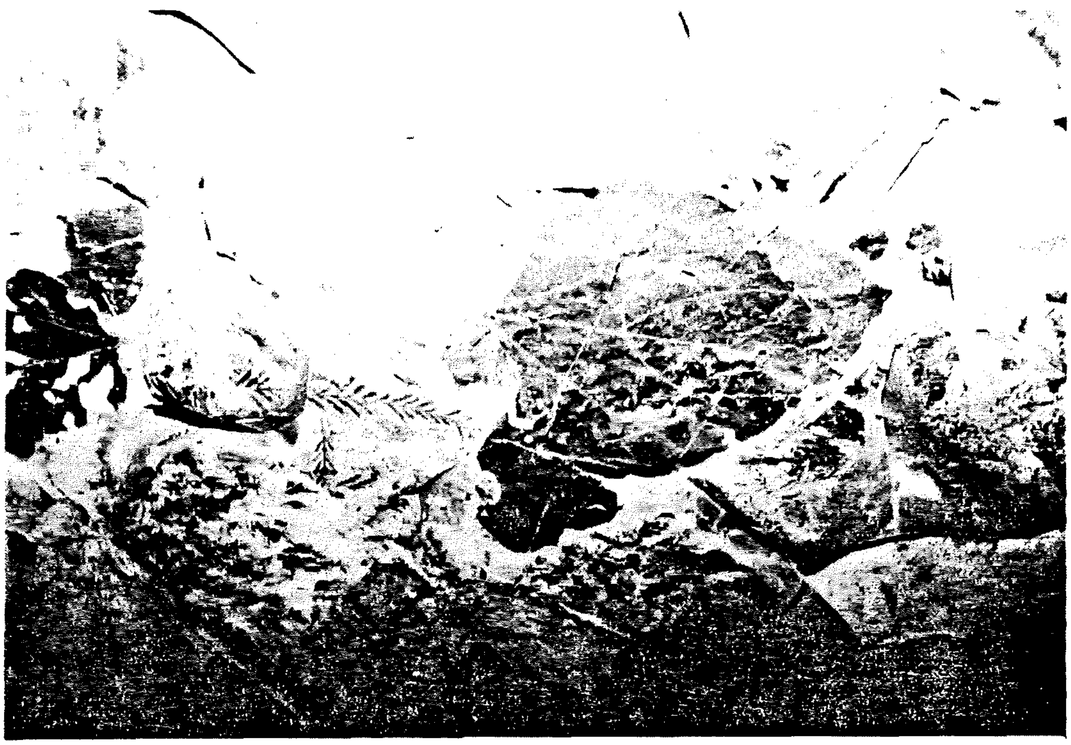

PLATE 58. - Leaf imprints, Grand Mesa Coal Field. Large dark leaf in center is approximately 8 in. wide at widest point.

littoral marine sandstone tongue underlying the mined seam. The sandstone protrusion, which was contiguous with the underlying marine sandstone, was composed of white to buff fine-grained, well-sorted, well-cemented, massive sandstone, with no internal structures such as cross-bedding or laminations. This feature was roughly located on the mine map after the mine tour and is shown on Figure 59. This sandstone protrusion maintained it's strike along the regional dip of the strata for the full width of the coal mine, a distance of several thousand feet, without significantly changing it's shape or size. Plate 59. is a photograph taken perpendicular to the feature in order to show a representative cross-section.

Because of it's small, localized morphology, continuous strike with little change in size or shape, and it's genetic relationship to the underlying littoral marine sandstone, this sandstone feature is interpreted as a winter-tide beach berm. Because time during the mine tour did not allow for further investigation, geological information was not mapped and plotted on the mine map, nor was there a mine geologist who might have studied the feature, this interpretation was the most logical. Beach berms frequently occur in groups parallel with the paleoshoreline. However, it is not entirely uncommon for a berm to be solitary. The feature was much too small to be considered an accretion ridge that formed part of a strandline beach. This feature was too large, and had not been compressed or crenulated, to be considered a clastic dike. Also, because the sandstone was massive, with no internal features, wave-wash processes of formation are likely.

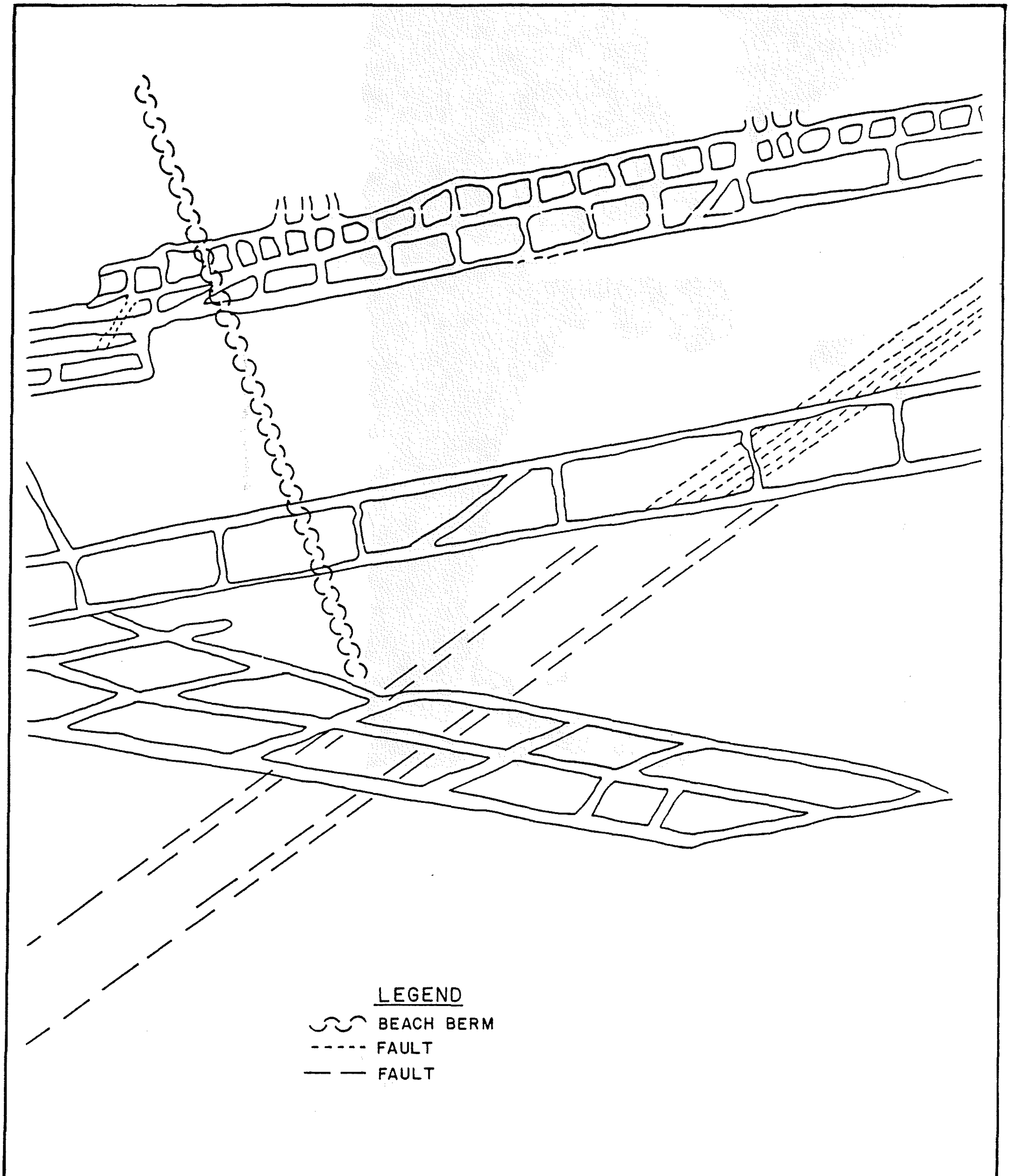

FIGURE 59. - Portion of mine map, from a mine in the Carbondale Coal Field, showing the location of an inferred beach berm.

PLATE 59. - Inferred beach berm, Carbondale Coal Field. Timbers are approximately 8 in. wide. Berm is approximately 5 ft. at base tapering to approximately 3 ft. at top. Sandstone of berm is contiguous with a littoral sandstone that constitutes the floor of this mine. Feature is known to be at least several thousand feet long, along strike.

5.4.7 Oil Seeps

Oil is occasionally found in sandstone channels or lenses in the roof rock of underground coal mines. Oil forms in association with peat development, and migrates into the reservoir rock of the sandstone. Oil is often fairly high in quality and viscosity. Plate 60. shows a low-viscosity oil seep found in association with goatsbeards (see Section 5.1.1.2) in a Grand Mesa Coal Field mine.

Oil seeps do not generally present a major hazard to mining operations, but often require some cleanup. One mine in the Book Cliffs Coal Field of Utah places 55 gallon drums below it's oil seeps. When the drums are filled, the oil is recycled along with spent machinery and engine oil.

5.4.8 Concretions

Concretions are nodules or irregular concentrations of minerals formed by transportation and deposition of dissolved minerals around a nucleus. Concre-

PLATE 60. - Oil seep and goatsbeards, Grand Mesa Coal Field. Mats are 8 in. wide. Arrow points to droplets of low-viscosity oil emananting from an overlying sandstone channel.

tions are postdepositional features that may pseudomorph pre-existing structures or form new, irregular structures that push aside the surrounding sediment. Concretions are commonly harder than the surrounding lithology. Concretions are most commonly found in coal mine roofs that exhibit considerable lithofacies change with characteristically high degrees of chemical alteration and mineral precipitation (see Section 5.1.2). An example of a concretion 2 ft. in length is shown in Plate 61.

5.4.9 Sand Fill

A sand-fill sedimentary feature was observed during this study in a mine in the northern Wasatch Plateau Coal Field. Along the rib and roof of an entry to this mine, a sandstone split in the coal occurs. This split, filled with fine-grained, well-sorted and well-cemented sandstone, has a strike parallel to that of a nearby fluvial sandstone channel. If the sandstone split was perpendicular to the channel, it would be interpreted as a split formed from overbank or sheet-flood deposition. However, most partings and splits in coal seams are not only found perpendicular to the channel, but are also composed of very fine-grained sedimentary rock such as mudstone or claystone. This sandstone split parallels the strike of the channel, is only several hundred feet long, and at first, appears not to emanate from the sandstone channel.

The mine geologist interprets this feature to be a sandstone fill that was deposited by a river or large stream, behind a block of slumped bank material. As a stream channel meanders and erodes it's banks, the outer meander bend is eroded while the inside bend of the channel is a location for

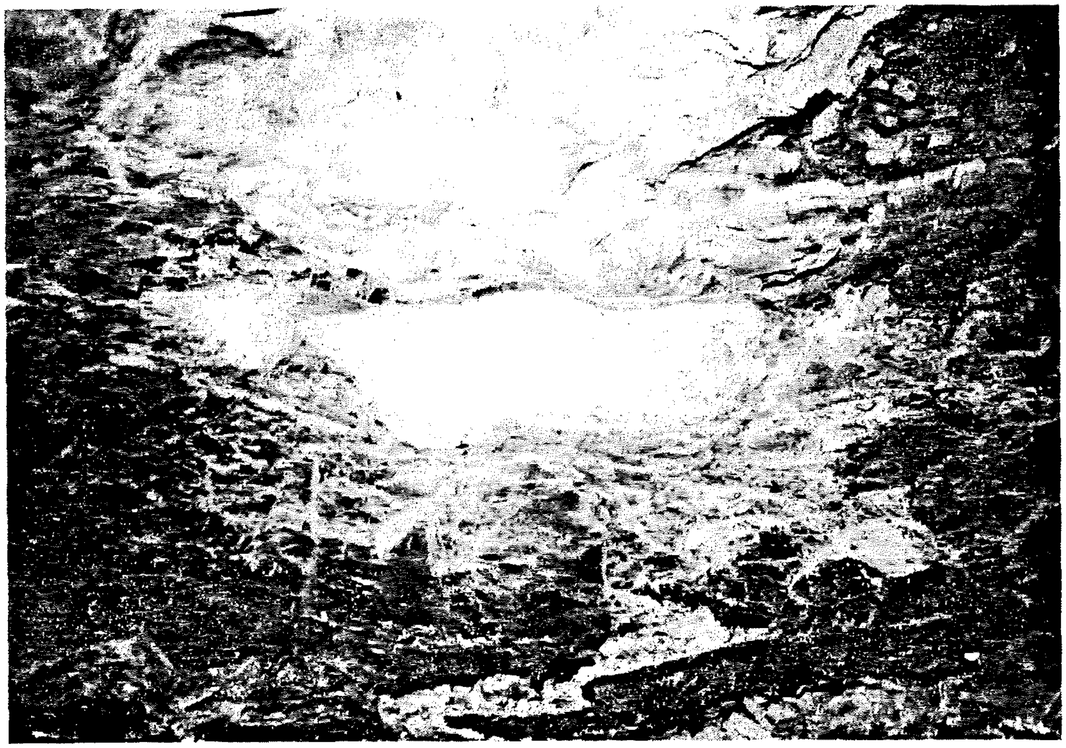

PLATE 61. - Concretion, Somerset/Paonia Coal Field. This concretion was observed in a lithofacies change roof type, where much chemical alteration and calcite precipitation was occurring. Concretion is approximately 2 ft. wide.

deposition of point-bar sediments. Sloughing of blocks of channel bank material into the stream channel, due to erosion and undercutting by stream flow on the outside meander bend, is commonly observed in modern stream environments. Figure 60. shows the geomorphic process responsible for the development of this sandstone fill feature. Strong and fast-flowing outer stream channel currents undercut the channel bank and caused a large slump block to slough into the stream. The block was cohesive enough to maintain its integrity, while sand from the channel was deposited behind the slump block. Upstream changes in flow caused the channel to avulse, leaving the slump block intact. Subsequent swamp invasion and peat development did not alter this sedimentary structure. Plate 62. shows the sand fill crossing the rib and continuing into the roof of the mine. A coal split would not show this configuration. The lithology of the rock separating the sandstone split and the main channel is primarily silty shale and shale that was most likely formed in a delta-plain environment.

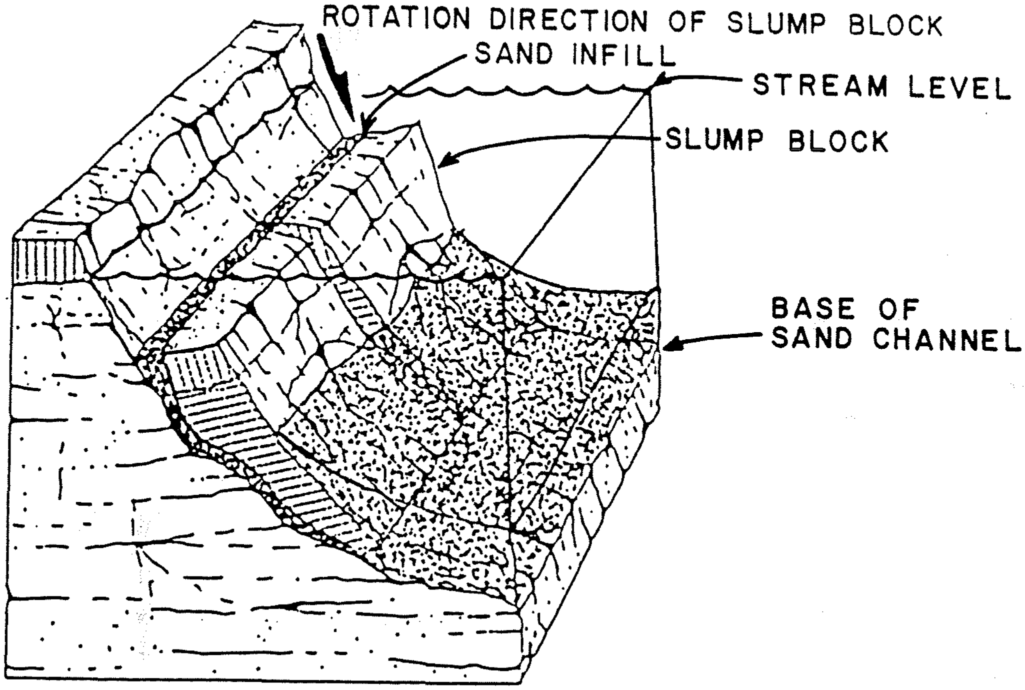

FIGURE 60. - Idealized model for development of sand fill behind slump block in stream or river channel.

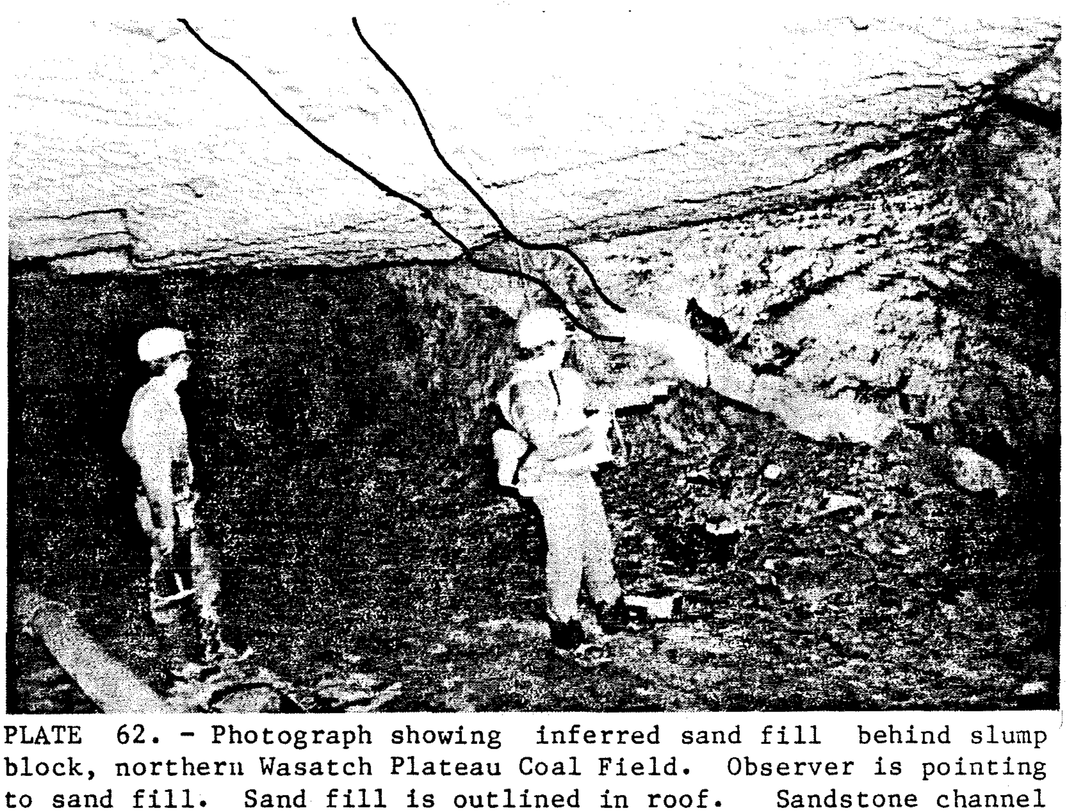

PLATE 62. - Photograph showing inferred sand fill behind slump block, northern Wasatch Plateau Coal Field. Observer is pointing to sand fill. Sand fill is outlined in roof. Sandstone channel is to right, out of photograph, approximately 100 ft. away.

6.0 ROOF CONTROL

6.1 Typical Roof Control Procedures for Western Underground Coal Mines

In underground coal mines, roof control is accomplished through the installation of bolts, mats, or timbers, which support the roof of the coal mine after the seam has been mined. Various levels and configurations of roof support are installed depending on the conditions that are encountered during mining. When mining entries or cross-cuts, a continuous mining machine commonly mines a 20 ft. cut of coal, and then moves to the next entry or cross-cut to mine while a bolting machine and bolter operators move into the previously mined entry to bolt and mat the roof. In poor roof conditions, a 10 ft. cut of coal may be all that can safely be mined before the roof is bolted or supported in some other manner, such as through the use of timber or roof trusses. The amount of roof support required is indicative of the quality of the rock overlying the coal seam.

The U.S. Department of Labor's Mine Safety and Health Administration (MSHA) establishes permitting regulations, which require that a roof control plan be submitted for approval along with the general mining plan before mining begins. This roof control plan must address the expected mining conditions, as determined through core drilling on the mine property, local geologic studies, and roof conditions in adjacent mines.

The roof control methods in general use throughout the coal mines of Utah, Colorado, New Mexico, and Wyoming are very similar. The roof in all entries and cross-cuts is immediately supported subsequent to mining. Bolts are usually 4 ft. to 6 ft. in length and are resin-grouted. Bolts are placed on 4 ft. to 5 ft. centers in rows that are 5 ft. apart. Usually, mats are 8 ft. long. Mats are bolted into place in a row across entries or cross-cuts, which are commonly 16 ft. to 20 ft. wide. Plate 35. shows a good example of bolting and matting in an intersection. Where dictated by roof conditions, bolts are placed on closer centers with 2 ft. to 4 ft. of spacing between rows. Bolts up to 15 ft. in length are used, where required, to support a large thickness of weak roof rock. Occasionally, a coal mine roof, or a portion thereof, will be strong enough to allow a reduction in roof control through an increase in spacing between bolts and rows of mats. If the roof conditions can be proven to be exceptionally good, due to slight overburden or a stable roof rock, an alteration to the roof control plan can be submitted for approval by MSHA. Reduced roof control requirements results in less expense, both in terms of labor and capital outlay. One mine contacted in Wyoming had ideal roof conditions. A massive sandstone beneath shallow overburden allowed the mine roof to be left completely intact, with no bolting, matting, or timbering required. However, this condition is very rare for western underground coal mines.

6.2 Methods of Roof Fall Control for Western Underground Coal Mines

Most western underground coal mines use the same general roof control procedures in areas susceptible to roof falls and where roof falls have occur-

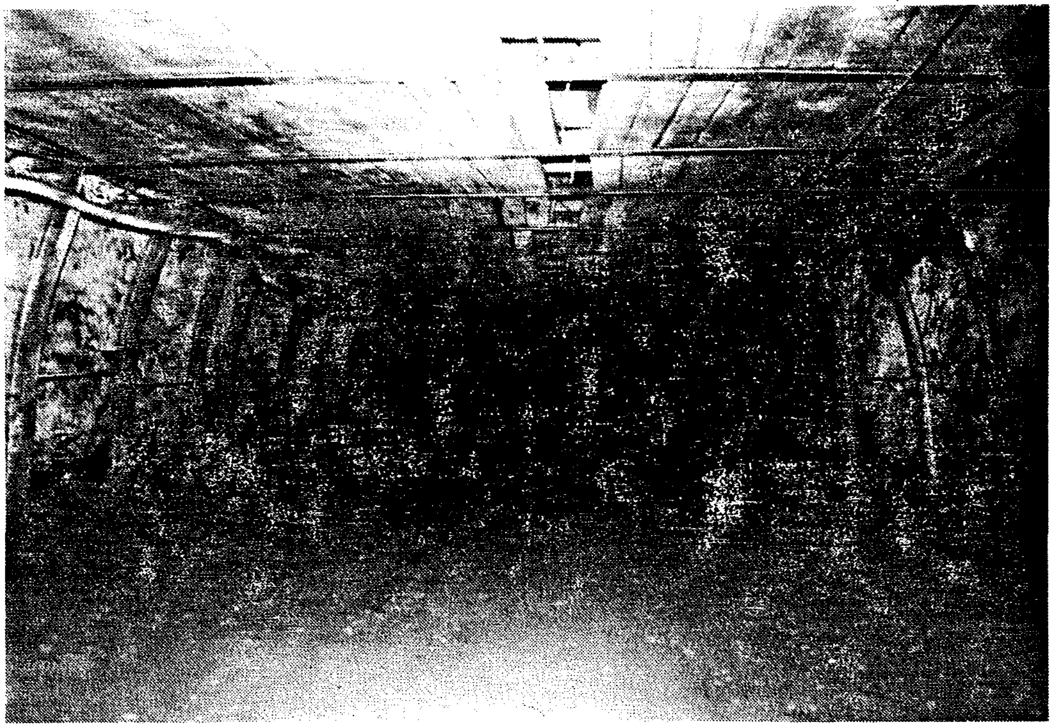

PLATE 63. - Main entry that is supported by steel sets, western Book Cliffs Coal Field, Utah. Steel sets control poor roof conditions caused by crevasse-splay deposits in conjunction with high horizontal stress under an overburden depth of approximately 2,000 ft. This entry is a main "roadway" that will carry much traffic.

red. This conclusion is based on observations made during the mine tours, information acquired from the telephone interviews, and analysis of the MSHA roof fall data for the years 1982 through 1984.

In areas of poor roof conditions, where roof falls are expected to occur, conventional bolting and matting procedures are supplemented either by increased use of bolts and mats, or by additional roof support mechanisms. If the roof has deteriorated in a portion of a mine to a fractured or weakly bonded condition, increased use of bolts and mats may be all that is necessary. If the fractured and noncohesive roof rock extends above the height of the conventional bolts, longer bolts may be required. In mines, where the roof is fracturing due to weak roof rock, or high vertical stress, roof trusses may be used in place of mats. Roof trusses are designed to screw together in the center to tighten and compress the roof, as shown in Plates 48. and 49. In general, the type of roof control required is dictated by the condition of the lithologic structure in the roof rock. In areas of water infiltration, poorly bonded and weak strata (such as a lithofacies change roof type), high horizontal stress, vertically extensive slickensides, or overlying sandstone channels, extensive timbering, cribbing, or even steel sets may be required. Conventional bolting and matting in these areas may prove to be entirely ineffective. Plate 63. shows a main entry roof that is heavily supported with steel sets. This entry is supported in this way not only because of poor roof conditions caused by crevasse-splay deposits in conjunction with high horizontal stress, but also because this main entry will receive much traffic upon resumption of active mining.

If a major roof fall occurs in the working area of a mine or in an air course, roof-fall debris must be removed immediately. New roof bolts and mats, or cap blocks, must be installed. These procedures are required by MSHA. In areas where bolts, mats or cap blocks will not control further roof caving, cribs must be built and extended to the existing roof of the caved portion, as shown in Plate 16. This procedure will commonly halt further roof failure. All coal mines toured during this project used these methods of roof control in areas of anticipated or previous roof falls.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions Regarding Geologic Conditions Affecting Coal Mine Ground Control in the Western U.S.

Study of geologic conditions and features affecting coal mine ground control in the West has shown that ground control is significantly affected by geologic conditions. The geologic features that adversely affect coal mine ground control in the West are more numerous, and often are significantly different, than the more studied geologic features affecting ground control in the eastern and upper-midwestern Paleozoic coal fields. Geologic features and conditions that adversely affect coal mine ground control in the West include sandstone channels and genetically related sedimentary deposits, slickensides, faults, joints, kettlebottoms, bedding planes, water infiltration, and vertical and horizontal stress within coal mines. Predictions of future increases in western coal resource development dictate that roof control problems and associated features be thoroughly investigated and understood.

In developing conclusions about those geologic features and conditions that adversely affect coal mine ground control, it is necessary to summarize geologic features, locations, and effects using all portions of this study. The initial literature search not only provided general information on western coal geology, and on the geologic features observed in both eastern and western underground coal mines, but also provided information on the depositional environment of the studied coal fields. This depositional information was critical to understanding the geologic features found in western underground coal mines. The literature search also provided recent studies by coal mine research personnel on adverse geologic conditions related to ground control. Acquiring the MSHA roof fall data base proved to be helpful in analyzing the causes, size, and locations for all reported roof falls for each field. This analysis provided useful data for field investigators during the mine tours. The investigators knew which features and problems to look for at each mine. Prior to the coal mine tours, visits with several coal mine research geologists provided background information that proved useful to field investigators, and was used in analyzing geologic features and their depositional environments. The mine tours themselves provided opportunities to analyze and photograph geologic features, and to discuss features or conditions and roof control problems with mine geologists or mining engineers. Dialogue between the investigators and coal mine personnel, that was recorded on a micro-cassette recorder and later transcribed and analyzed, proved to be exceptionally helpful.

Sandstone channels and related overbank and crevasse-splay deposits can be correlated with the most adverse roof conditions observed in the Emery, Wasatch Plateau, and Book Cliffs Fields in Utah. Channels are large and make up extensive portions of coal mine roofs in these fields. They have created areas of differential stress, slickensided rock, coal cut-outs, and have created large deposits of thinly laminated sandstone and siltstone that is often brittle and fractures easily. Mining adjacent to these sandstone channels can present significant hazards in the form of large roof falls along major planes of weakness associated with noncohesive slickensides and coal cut-outs. The Trinidad Coal Field contained sandstone channels 20 ft. to 40 ft. above the mined coal seam. This proximity of sandstone channels to mine workings produces large and frequently undetectable roof falls.

A lithofacies change roof type was observed to produce extremely poor and often hazardous roof conditions in the Somerset/Paonia, Grand Mesa, and Trinidad Fields. This roof type is composed of alternating and interfingering layers of shale, silty shale, and siltstone that has experienced much chemical alteration. This noncohesive rock caves without warning and produces large and hazardous roof falls. Where strata adjacent to the numerous fractures and bedding planes are deteriorated by water, as commonly occurs, this roof type becomes particularly hazardous.

Although not as common a feature in the mine roofs of western coal fields, kettlebottoms are a significant hazard. Large (up to 16 ft. in diameter and 6 ft. in thickness), slickensided kettlebottoms detach without prior warning in the Somerset/Paonia, Grand Mesa, and Trinidad Fields. Kettlebottoms were particularly obvious in the Somerset/Paonia Field. Because of their large size and undetectability, they are particularly hazardous features.

Faults were observed in nearly every coal field studied. On a relative scale, faults did not create extremely hazardous conditions. Faults in the Emery and Wasatch Plateau Fields had minor to large displacements. Where displacements were moderately large (20 ft. to 200 ft.), rock tunnels were constructed to continue mining on the opposite side of the fault. In general, these faults contained little gouge and only fractured surrounding rocks when associated with sandstone channels. Thrust faults were observed in the Yampa Field. This type of fault can be problematical when associated with water infiltration and undermining of a large area. Water lubricates the weak fault plane, and may produce a large roof fall. Faulting in the Trinidad and Carbondale Fields produced fractured strata between fault planes that contributed to poor roof conditions. One major fault zone in the Carbondale Field produced extremely poor roof conditions when mine development was forced to tunnel through 120 ft. of sheared and distorted rock.

Jointing and coal cleats significantly affected ground control in the Wasatch Plateau, Yampa, and Trinidad Fields. Mining is commonly planned to reduce the effects of jointing and the coal cleat by orienting mine development at an angle to the joint and cleat orientation. This orientation caused slabbing to occur only on pillar corners, as opposed to along the entire rib.

Stress, manifested as both vertical and, especially, lateral movement and structural damage to coal mine workings, has a significant and adverse effect on mines with greater than 1500 ft. of overburden. Mines with this thickness of overburden are located in the Wasatch Plateau, Book Cliffs, Somerset, and Carbondale Fields. If mine development continues, mines in the Raton and Trinidad Fields will also experience adverse ground control problems caused by horizontal stress produced by a thick cover. In areas of mines that are affected by high horizontal stress, roof conditions often become extremely poor and are frequently hazardous. These poor roof conditions can become more severe than those produced by sandstone channels and associated slickensides.

Water infiltration plays a significant role in propagating adverse roof conditions. Where water is transmitted along fault planes, underlying and adjacent strata are weakened and deteriorated, causing roof falls. Water entering mines also ponds on the floor, causing slick conditions for personnel and machinery. Where water is associated with a lithofacies change roof type, extremely large and dangerous roof falls can be expected. In association with sandstone channels, water infiltration is a significant hazard. Water transmitted through a sandstone channel causes underlying and adjacent strata to deteriorate and fall. Unlike sandstone channels, whose affects are produced directly, water is an indirect agent in the creation of poor roof conditions. Water serves to deteriorate strata by infiltration along fractures, faults, sandstone channels, and through general ground water movement. All coal fields in Colorado reported major roof control problems related to water infiltration. Coal fields in Utah generally had fewer problems with water infiltration, except in faulted areas.

The above reviewed features were the most significant, in terms of roof control, that were observed during this study. Dikes (both igneous and clastic), bedding planes, coal rolls, and folding all affected mining, but not as severely as those summarized above.

Regionally, the Utah coal fields were mainly affected by sandstone channels due to their paleodeposition centers with relation to wave-dominated deltas at the western shore of the Cretaceous Interior Sea. The Utah fields were secondarily, influenced by structural features, such as faults, coal cleat, and joints that were caused by large, regionally controlled tectonic forces. The Colorado coal fields were mainly affected by depositional features, other than sandstone channels, and by smaller, more localized structural features, including the normal faulting that defines the Laramide intermontane basins. Adverse depositional features observed in Colorado coal fields were lithofacies change and kettlebottoms, although overlying sandstone channels did produce hazardous conditions in the Trinidad Field. Structural features that caused adverse conditions were jointing, faulting (normal, oblique-slip, strike-slip, and thrust), and the cleat of the coal.

In conclusion, there are many geologic features that produce widely ranging conditions affecting ground control in western underground coal mines. These cover the spectrum of geologic features found in underground coal mines. This fact, combined with varying depositional environments of studied coal fields, produces several significant adversely affecting geologic features, roof types, and ground control conditions. A range of roof control plans and measures that are implemented to control hazardous roof zones were documented. These measures vary in complexity and success proportionate to the level of adverse conditions produced by geologic features. Geologic features play a decisive role in mine planning and development in western underground coal mines.

7.2 Recommendations Regarding Geologic Conditions Affecting Coal Mine Ground Control in the Western U.S.

The U.S. Bureau of Mines has initiated a multiphase research program to assess the geologic conditions affecting underground coal mine ground control in the western United States. This report describes the initial phase of this program that was intended to provide background geologic information on western coal fields, define and describe the geologic features and conditions that create adverse ground control problems in these fields, and characterize the behavior of these features in response to mining.

Further study of exploration methods of use in predicting the occurrence of hazardous geologic features is recommended. A review and analysis of the existing methods employed to locate and assess potentially adverse geologic features and/or conditions in western coal mines is suggested. Recent large increases in mining have promoted the development of several new predictive tools for use in coal resource evaluation and mine planning. Tools frequently used for prediction of mining conditions include lineament mapping from aerial and satellite photography, underground and surface drilling to delineate geologic conditions and features, and underground geologic mapping and projection of geologic trends. Several geophysical techniques are used to assess geologic conditions, including shallow, high-resolution seismic mapping, and downhole logging methods such as spontaneous potential, natural gamma radiation, and bulk density. Relatively recent developments in geophysical exploration have produced new tools, including radio wave and electrotelluric instrumentation. The data produced by each of the above tools should be evaluated to determine its use in producing data for input into mine-planning models. The potential for generating computerized planning models should also be investigated. A comprehensive review of the available predictive tools will allow determination of the limitations of existing techniques, in establishing the direction for further research and development.

As noted in this report, the extreme lateral and vertical variability of coal-bearing lithofacies throughout the Rocky Mountain region makes regional prediction of potentially hazardous geologic features difficult. More detailed, localized studies correlating depositional environments with observed hazardous geologic features may be useful in establishing procedures for similar investigations in mines throughout the western coal fields. Guidelines and procedures may be prepared for use by mine planning personnel. This type of investigation may provide answers to questions raised during the initial phase of this program regarding the presence or absence of specific features in different portions of the Rocky Mountain region. Coal mine operators intending to mine under deeper cover, or planning to extend their present mining boundaries, would benefit greatly from this type of predictive tool. As an example, it was observed during the initial phase of this program that kettlebottoms tend to occur at a certain distance from sandstone channels. If a statistically viable model of kettlebottom occurrence relative to sandstone channels could be developed, mine planners could predict the potential hazards associated with these features more effectively.

Further detailed study of the role that overburden thickness plays in ground control is also recommended. Several types of extremely adverse conditions associated with large overburden thicknesses were observed during this study. These included fracturing, structural slickensides, bumps, bounces, horizontal stress and lateral motion, and rock flow. The types of adverse geologic conditions caused by thick cover should be correlated with the coal fields in which they occur, and the hazards they present. The importance of understanding those features that are associated with large overburden thicknesses will increase with continued mine development throughout the Rocky Mountain region.

The above recommendations will improve the ability of mine operators to predict hazardous ground control conditions in advance of potentially fatal accidents. A comprehensive survey of existing roof control methods should be conducted to assess the adequacy of currently employed methods, and to investigate future research and development needs. Documentation of successful ground control methods would permit mine operators to more effectively manage previously unencountered problems correctly. This type of information is particularly necessary in the Rocky Mountain region, where extension of mine boundaries may commonly present the operator with an entirely new set of geological features and variables.

Successful application of the information collected during the development of prediction and roof control guidelines will require education of mine personnel in identification of adverse geologic features and conditions, and in the hazardous situations these features present. This education could be accomplished through training seminars using narrated videotape or slide presentations. Guidelines and criteria for investigation, geologic hazard identification, and documentation of successful roof control techniques employed in the western coal fields should be prepared, as suggested by one geologist in a toured mine. Education of mining personnel would benefit the coal industry as a whole, through an increase in coal production by mine planning based on adverse geologic conditions and through a reduction of the number of injuries and fatalities associated with roof falls.

In summary, the submittal of this report concludes the initial phase of this U.S. Bureau of Mines program to research underground coal mine roof control problems produced by geologic features and conditions in the western United States. The data characterizing geologic features and conditions associated with coal mine ground control that is presented here should be used as a foundation for further research. The fundamental objective of this research program is the development of comprehensive ground control guidelines for western underground coal mines. These guidelines should present criteria for the prediction of geologic features in advance of mining, documentation of successful roof control techniques, and programs for education of mining personnel. This first phase of study of the geologic conditions affecting coal mine ground control in the western United States is the first step in an ambitious and worthwhile research program that should provide significant benefits to the coal mining industry.

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APPENDIX A

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APPENDIX B

APPENDIX B

MSHA ROOF FALL DATA
1982-1984

FIELD	YEAR	FALL SIZE*	LOCATION	ACTIVITITY	GEOLOGIC CAUSES	COMMENTS
Bookcliffs	82	Sm	Face	Supporting	N/A	Roof Slab
Bookcliffs	82	Sm/Med	?	Maint.	N/A	Roof Slab
Bookcliffs	82	Lg	?	N/A	Frac./Int.Bed.SH.SS.	
Bookcliffs	82	Lg	X-Cut	?	?	
Bookcliffs	82	Lg	?	N/A	N/A	Abandoned Area
Bookcliffs	82	Lg	X-Cut	N/A	?	
Bookcliffs	82	Lg	?	?	N/A	Excessive Pressure
Bookcliffs	82	Lg	Intersection	?	?	
Bookcliffs	82	?	?	?	Fractured Roof	Excessive Pressure
Bookcliffs	82	Lg	Cross-Cut	N/A	Mud Slip/Moisture	
Bookcliffs	82	Lg	Pillar Section	Mining	?	Support Failure
Bookcliffs	82	Med	?	Removing Temp.Sup.	N/A	
Bookcliffs	82	Lg	X-Cut	?	?	
Bookcliffs	82	Lg	Slope	N/A	Slip	Slip above bolts
Bookcliffs	82	Med	Pillar	Retreating	N/A	
Bookcliffs	82	Med/Lg	?	N/A	Frac./Int. Bed.SH.SS	
Bookcliffs	82	Med/Lg	Cross-Cut	N/A	Strat.Sh./Ext.Frac.	
Bookcliffs	82	Lg	Pillar Section	Mining	?	
Bookcliffs	82	Lg	Entry	?	?	Support Failure
Bookcliffs	82	Lg	Slope	N/A	Slip	Slip above bolts
Bookcliffs	82	Lg	Pillar Section	Mining	?	
Bookcliffs	82	Med	?	Bolting	N/A	
Bookcliffs	82	Lg	Entry	?	?	
Bookcliffs	82	Med	Pillar Section	Mining	N/A	Final Retreat
Bookcliffs	82	Lg	Intake Entry	N/A	?	Support Failure
Bookcliffs	83	Med	Intersection	N/A	?	
Bookcliffs	83	Med	Intersection	N/A	?	
Bookcliffs	83	Lg	Bleeder Entry	N/A	?	Failure Above Bolts
Bookcliffs	83	Med	X-Cut	N/A	?	
Bookcliffs	83	?	?	?	Unconsol. Roof	Extensive Frac.
Bookcliffs	83	Lg	?	N/A	?	Fail. Above Bolts
Bookcliffs	83	Med	Intersection	N/A	?	
Bookcliffs	83	Med	Intersection	N/A	?	
Bookcliffs	84	Lg	?	?		Roof became weak
Bookcliffs	84	Med	?	?	Frac. Uncon. Strata	Fail. Above Bolts
Bookcliffs	84	Med	#39 X-Cut	N/A	?	Strata Became Weak
Bookcliffs	84	Med	Manway	N/A	?	
Bookcliffs	84	Lg	?	?	Thin Layered SS/SH	Loss of Lat Strength Beam
Canon City	82	Lg	X-Cut/Mains	?	?	Support Failure
Canon City	82	Lg	N/A	N/A	Hvy. Rain Infiltrat	
Canon City	82	Sm	N/A	App. Rock Dust	N/A	
Canon City	82	Lg	X-Cut	Idle	N/A	
Canon City	82	Sm	Face	Mining	N/A	
Canon City	83	Lg	X-Cut	N/A	?	Failure Above Bolts
Canon City	83	Med	Face	Barring Down	N/A	
Canon City	83	Lg	X-Cut	N/A	Moisture ?	
Canon City	83	Med	X-Cut	N/A	Moisture	

APPENDIX B

MSHA ROOF FALL DATA
1982-1984

FIELD	YEAR	FALL SIZE*	LOCATION	ACTIVITITY	GEOLOGIC CAUSES	COMMENTS
Canon City	83	Lg	X-Cut	N/A	?	Failure Above Bolts
Canon City	83	?	Face	Mining	?	Failure Above Bolts
Canon City	83	Lg	Intersection	N/A	?	Failure Above Bolts
Canon City	84	Lg	X-Cut	Idle		Failure Above Bolts
Canon City	84	Med	Intake/W.Mains	N/A	?	Support Failure
Carbondale	82	?	Face	N/A	?	
Carbondale	82	Med/Lg	Entry	Hauling Coal	?	
Carbondale	82	?	Haulway	Cleaning Track	?	Support Failure
Carbondale	82	Sm	?	Welding	N/A	
Carbondale	83	Lg	Belt Line	Timbering	Previously Heaved	Bolted
Carbondale	83	Lg	X-Cut	N/A	Floor Heaved	
Carbondale	83	Lg	X-Cut	N/A	N/A	Mined Aboved
Carbondale	83	Lg	Portal	N/A	?	
Carbondale	83	Med	Face	Bolting	N/A	Roof slab
Carbondale	83	Med	Headgate	N/A	Bounced	
Carbondale	83	Lg	?	?	?	
Carbondale	83	Med	?	Mining	Fracture Roof	
Carbondale	83	Sm/Med	Entry	Supporting	Fault	
Carbondale	83	Med	Portal	N/A	Sh./Gravel Roof	
Carbondale	84	Med	Face	Mining	?	
Carbondale	84	Med	?	Idle	?	Support Failure
Carbondale	84	Sm	Face	Bolting	N/A	
Emery	82	Lg	?	?	Snap Coal	
Emery	82	Lg	?	Idle	?	
Emery	82	Lg	Intersection	Idle	?	
Emery	82	Med	Entry	Idle	?	
Emery	82	Sm	Face	Mining	Mud Bands	
Emery	82	Lg	Face	?	?	
Emery	83	Med	?	Mining	Rib Bounces	Pulling Pillars
Emery	83	Lg	?	N/A	?	
Grand Mesa	82	Lg	Face	Cleanup	Lg Slickenside	
Grand Mesa	82	Lg	Entry/X-Cut	N/A	Moisture/Shale	
Grand Mesa	82	Lg	Entry/Airway	Inspect./Rounds	Var.SS.Thickness	
Grand Mesa	82	Med	Entry/X-Cut	Idle	Moisture	
Grand Mesa	82	Lg	Entry/Airway	Inspect./Rounds	Var.SS.Thk./Moist.	
Grand Mesa	82	Med	Entry	N/A	N/A	Deteriorating Roof
Grand Mesa	82	Lg	?	?	N/A	Deteriorating Roof
Grand Mesa	82	Lg	Entry/X-Cut	N/A	Moisture/Shale	
Grand Mesa	82	Lg	Face	Mining	Fractures/Moist.	
Grand Mesa	83	Lg	X-Cut	N/A	Moisture	
Grand Mesa	83	Lg	X-Cut	Idle	?	
Grand Mesa	83	Lg	X-Cut	N/A	?	
Paonia	82	Lg	Entry	N/A	?	
Paonia	83	?	?	?	Slaking	Support Failure
Paonia	83	Med	?	Supporting	Moisture	
Paonia	83	Lg	Entry	?	?	
Paonia	83	Med/Lg	Belt Entry	?	Fractured & Wet	

APPENDIX B

MSHA ROOF FALL DATA
1982-1984

FIELD	YEAR	FALL SIZE*	LOCATION	ACTIVITITY	GEOLOGIC CAUSES	COMMENTS
Paonia	83	Med	?	N/A	Moisture	
Paonia	83	Lg	Intersection	?	?	
Paonia	84	?	Main Returns	Idle		Failure Above Bolts
Raton	82	Lg	Entry	N/A	N/A	Support Failure
Raton	82	Lg	X-Cut	?	N/A	Support Failure
Raton	84	Lg	Main Haulage	N/A	?	Failure Above Bolts
Somerset	82	Sm	Face	Mining	N/A	
Somerset	82	Med	Face	Setting Jacks	N/A	
Somerset	82	Lg	?	N/A	N/A	Support Inadequate
Somerset	82	Med	?	N/A	N/A	Support Inadequate
Somerset	82	?	X-Cut	Loading	Fault	
Somerset	82	Sm	Haulageway	Scaling Roof	N/A	
Somerset	82	Lg	Escapeway	Idle	N/A	
Somerset	82	Med/Lg	?	Supporting Roof	?	
Somerset	82	?	X-Cut	N/A	?	
Somerset	82	Sm	Entry/X-Cut	N/A	N/A	
Somerset	82	Med	X-Cut	N/A	?	
Somerset	82	?	X-Cut	N/A	N/A	
Somerset	82	Sm	?	Supporting Roof	N/A	
Somerset	82	Med/Lg	Face/X-Cut	Mining	?	
Somerset	82	Lg	Main Entry	N/A	N/A	
Somerset	82	Lg	Intersect./Seal	N/A	?	
Somerset	82	Lg	Face	N/A	?	
Somerset	83	?	Face	Mining	?	
Somerset	83	?	?	?	?	No Info.
Somerset	83	Lg	Face	Mining	?	
Somerset	83	?	?	?	?	Bolted/Support Fail.
Somerset	83	?	Entry	?	SS.Roll	
Somerset	83	?	?	?	Excess Water/Faults	Beam Failure
Somerset	83	Med	?	N/A	?	Support Failure
Somerset	83	?	Entry	Removing Cribbing	?	Support Failure
Somerset	83	Med	Face	N/A	?	
Somerset	83	?	?	?	?	Bolted/Support Fail.
Somerset	84	?	?	N/A	SS/int.bed.SH/Fault	Fail. Above Bolts
Somerset	84	?	?	Mining	?	Pillar Extraction
Somerset	84	Med	Intersection	N/A	Slickensides/Moist.	
Somerset	84	?	?	Mining	?	Pillar Extraction
Somerset	84	?	?	?	?	Fail. Above Bolts
Somerset	84	?	Face	Robbing Pillars	N/A	Pushed out side fender
Somerset	84	?	5th W. Main	N/A	Frac./Moist.	Fail. Above Bolts
Somerset	84	?	Seal	N/A	Air Split	
Somerset	84	?	Intersection	N/A	?	Failure Above Bolts
Somerset	84	?	Face	Pillar Extraction	N/A	
Somerset	84	?	?	Mining	?	Pillar Extraction
Somerset	84	?	?	Mining	SS w/th. int.bed.SH	
Somerset	84	?	?	?	Moist./Delamination	Fail. Above Bolts
Somerset	84	?	Return Main	N/A	Delaminated Strata	

APPENDIX B

MSHA ROOF FALL DATA
1982-1984

FIELD	YEAR	FALL SIZE*	LOCATION	ACTIVITITY	GEOLOGIC CAUSES	COMMENTS
Somerset	84	?	?	N/A	SS/int.bed.SH/Fault	
Somerset	84	?	?	?	Fault/Moist.	Fail. Above Bolts
Somerset	84	?	?	N/A	Moist./Delamination	Fail. Above Bolts
Somerset	84	?	Face	Pillar Extraction	Local Rider Seam	
Trinidad	82	Lg	Entry/X-Cut	N/A	Moisture	
Trinidad	82	Lg	Entry	Haul Road	?	
Trinidad	82	Lg	Entry	N/A	?	
Trinidad	82	Med	?	Roof Control	Kettlebottom	
Trinidad	82	Lg	X-Cut	N/A	?	
Trinidad	82	Lg	Entry	?	Large Slip	
Trinidad	83	Lg	Belt Entry	Idle	?	
Trinidad	83	Lg	?	Idle	?	
Trinidad	83	Lg	East Main	Idle	?	
Trinidad	83	Lg	Entry/X-Cut	Mining	Massive Slip(Pot)	
Trinidad	84	Med	Pillar	Setting Timbers	N/A	
Trinidad	84	Med	X-Cut	N/A	?	Support Failure
Trinidad	84	Med	Intersection	Bolting	?	
Trinidad	84	Lg	Intersection	N/A	?	Support Failure
Trinidad	84	Med	X-Cut	N/A	Possibly water	
Trinidad	84	V.Lg	Intersection	N/A	Possibly water	Supt.Fail. Bolts & Beams
Trinidad	84	Lg	X-Cut	N/A	?	Failure Above Bolts
Trinidad	84	Lg	Intersection	N/A	?	Failure Above Bolts
Trinidad	84	Med	X-Cut	N/A	Water	
Trinidad	84	Sm	N/A	Scaling	Slipped Area	
Wasatch	82	Med	Face	Mining	?	
Wasatch	82	Lg	Air Course	N/A	Moist./Mined Above	
Wasatch	82	Sm	Pillar Section	?	Rock Burst	
Wasatch	82	Lg	X-Cut	N/A	Sm. Fault/Shale	
Wasatch	82	Lg	Intersection	N/A	N/A	Seams mined above
Wasatch	82	Lg	?	N/A	Unconsolid. Strata	Support Failure
Wasatch	82	Med	Entry	N/A	Shale	
Wasatch	82	Lg	Pillar Section	?	?	Support Failure
Wasatch	82	Med	Entry	Timbering	?	Prior to timbering
Wasatch	82	Lg	Pillar Section	Pillar Extraction	Dike	
Wasatch	82	Med/Lg	Entry	N/A	Saturated Strata	
Wasatch	82	Lg	Escapeway	?	?	
Wasatch	82	Lg	Panel Section	Mining	?	Prior to bolting
Wasatch	82	Lg	Intersection	N/A	Moisture	Support Failure
Wasatch	82	Lg	Pillar Section	Robbing Pillars	N/A	Pressure Transfer
Wasatch	82	Lg	Pillar Section	Robbing Pillars	N/A	
Wasatch	82	Lg	?	N/A	Incomp. Roof	Mud.Sh/Frac./Moist.
Wasatch	82	Med	X-Cut	Pre-Bolting	?	
Wasatch	82	Med/Lg	?	N/A	N/A	Mined Above
Wasatch	82	Lg	X-Cut	N/A	?	
Wasatch	82	Lg	Belt Entry	N/A	Mudst. Slip/Linear	
Wasatch	82	Lg	Pillar Section	Pillar Extraction	?	
Wasatch	82	Med/Lg	?	N/A	N/A	Mined Above
Wasatch	82	Lg	Main Track	N/A	?	

APPENDIX B

MSHA ROOF FALL DATA
1982-1984

FIELD	YEAR	FALL SIZE*	LOCATION	ACTIVITITY	GEOLOGIC CAUSES	COMMENTS
Wasatch	82	Sm	Face	Miner Repair	N/A	
Wasatch	82	Lg	Intersection	N/A	Fault Slip	
Wasatch	82	Lg	Intersection	N/A	N/A	Mined Above
Wasatch	82	Lg	Air Intake	N/A	Moisture/Temp.	Support Failure
Wasatch	82	Sm/Med	Intersection	N/A	N/A	Fell between support
Wasatch	82	Med	?	N/A	Slickenside & Sh.	Above bolts
Wasatch	82	Lg	Intersection	?	?	
Wasatch	82	Lg	Pillar Section	Pillar Extraction	?	
Wasatch	82	Lg	?	Mining	N/A	Ex. cutting before suppt.
Wasatch	82	Lg	Entry	N/A	Moist./Slickenside	Slick. above bolts
Wasatch	82	Lg	Intersection	N/A	Mud Slip	
Wasatch	82	Lg	Belt Entry	?	N/A	Support Failure
Wasatch	82	Lg	X-Cut	N/A	?	Between Supports
Wasatch	83	Lg	?	?	?	Exc. Override from Pillar
Wasatch	83	Lg	Entry	Mining	Excess. Pressure	Pillaring
Wasatch	83	Lg	1st Main/Entry	?	?	
Wasatch	83	?	Intersection	Idle	Fault Zone	
Wasatch	83	Lg	?	?	?	
Wasatch	83	Lg	?	?	?	
Wasatch	83	?	X-Cut	?	?	Wet/Heavy Top
Wasatch	83	Lg	Entry	Idle	?	
Wasatch	83	Med	2nd Left Pillar	Mining	N/A	Bump-Top Coal Fell
Wasatch	83	Med	X-Cut	?	?	
Wasatch	83	Med	Entry	?	?	Top Coal & Trash Mud Fell
Wasatch	83	Med	X-Cut	?	Weak Strata	
Wasatch	83	?	Intersection	?	Wk. Roof Strata	Exc. Pres./Mined Aboved
Wasatch	83	Med	Entry	?	?	
Wasatch	83	Lg	N/A	Strata Failure	Excess Moist. in Air	
Wasatch	83	Sm/Med	Entry	Idle	Fault Line	
Wasatch	83	Med	X-Cut	N/A	Fault Zone	Failure Above Bolts
Wasatch	83	Med	Main Return	N/A	?	
Wasatch	83	Med	#2 Entry/Portal	?	Fault	Fault Slip Above Bolts
Wasatch	83	Lg	?	N/A	?	No Details
Wasatch	83	Med	Entry	?	?	Broke Above Bolts
Wasatch	83	Med	Face	Mining	?	Pillar Extract.
Wasatch	83	Lg	Entry	?	?	Top Coal & Sand Fell
Wasatch	83	Med	Old N. Mains	Idle	N/A	Support Fail./Mined 77
Wasatch	83	Med/Lg	?	N/A	?	Failure Above Bolts
Wasatch	83	Lg	X-Cut	?	?	
Wasatch	83	Med	Face	Mining	?	
Wasatch	83	Lg	1st Main	?	?	
Wasatch	83	Lg	Inter./Entry	?	?	Fail. Above Bolts
Wasatch	83	Lg	Return Entry	Mining	Inter. of Creek Chnl	Water Seepage
Wasatch	83	Lg	?	N/A	?	Failure Above Bolts
Wasatch	83	Med	Beltline/X-Cut	N/A	?	
Wasatch	84	?	Pillar Section	Pillar Extraction	?	
Wasatch	84	?	Pillar	Pillar Extraction	?	

APPENDIX B

MSHA ROOF FALL DATA
1982-1984

FIELD	YEAR	FALL SIZE*	LOCATION	ACTIVITITY	GEOLOGIC CAUSES	COMMENTS
Wasatch	84	Med	Trolley Line	N/A	Strata Delamination	
Wasatch	84	Lg	Entry/Intersect	Mining		Retreating
Wasatch	84	?	?	?	Sand Channel	Water
Wasatch	84	Med	Face	Pillar Extraction	?	
Wasatch	84	Med	W.Main Sec	N/A		Deterior. of roof by H2O
Wasatch	84	Med	?	?	Top coal deterior.	Improper bolting
Wasatch	84	Lg	Entry/LW sec	?	Wet Mudst. & Sh.	Bolted
Wasatch	84	Lg	X-Cut	N/A		Support Failure
Wasatch	84	Med	?	N/A	N/A	Mined Above/Exc. Press.
Wasatch	84	Sm/Med	N/A	Pillar Extraction		Final push, pillar rob.
Wasatch	84	Lg	X-Cut	N/A	Floor Heave	Tailgate cribs failed
Wasatch	84	Med	Intersection	N/A	Fault/Water Slips	
Wasatch	84	Med	Entry	Idle	?	
Wasatch	84	Med	Beltline/Inter.	N/A	Strata Delamination	Rider coal/Shale delam.
Wasatch	84	Med	Intake Main	N/A	?	
Wasatch	84	Med	Face	Mining		Failure Above Bolts
Yampa	82	Lg	Entry/Mains	Mantrip	Delaminations	
Yampa	83	Med	X-Cut	N/A	Slip	Top coal collapsed
Yampa	83	Med	Entry	Mining	Pinching Coal	Top coal collapsed
Yampa	84	Lg	Intersection	N/A	Thrust Fault/Moist.	Support Failure
Yampa	84	Med	X-Cut	N/A	?	Unsupported Roof
Yampa	84	Sm/Med	X-Cut	Mining	?	Box Cutting

*Roof fall size estimated from MSHA report descriptions using the following criteria:

CLASS	DIAMETER	DEPTH
Large	> 10 ft	> 2.5 ft
Medium	3-10 ft	1-2.5 ft
Small	< 3 ft	< 1 ft