PROCEEDINGS

FIFTH SYMPOSIUM ON THE GEOLOGY OF ROCKY MOUNTAIN COAL 1982

KLAUS D. GURGEL
Editor

UTAH GEOLOGICAL AND MINERAL SURVEY
a division of
Utah Department of Natural Resources and Energy

Bulletin 118 May 1982

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SYMPOSIUM PROGRAM AND CONTENTS

Wednesday, May 12, 1982

FOREWORD

The 1982 Symposium on the Geology of Rocky Mountain Coal is to be held May 12-13 in Park City, Utah. This symposium, the fifth in a series although the first to be held in Utah, is sponsored by the Utah Geological and Mineral Survey, the Utah Geological Association, the United States Geological Survey, the Colorado Geological Survey, and the Energy Minerals Division of the American Association of Petroleum Geologists. The symposium will be followed by a two-day trip to the coal fields of central Utah where underground mine geologic studies and depositional modeling investigations will be discussed.

The study, exploration, and development of Utah's coal resources have been an integral part of the state's history since early pioneer days. Mormon settlers entered the Salt Lake Valley on July 24, 1847 and less than three years later, a Mormon exploration party made the first coal discovery in southern Utah in what is today known as the Kolob Plateau coal field. In 1854 the Territorial Legislature, recognizing a growing demand for fuel along the Wasatch Front, offered a reward of $1,000 to anyone discovering coal within 40 mi of Salt Lake City. The reward was claimed in 1859 when coal was discovered in Summit County and the community of Coalville was established. Ever since then, coal has been an important part of Utah's economy.

The history of Utah's coal economy parallels national trends of boom and bust. As with most of the nation, the period from 1890-1918 was a period of increased coal production as coal replaced wood as fuel. From 1920-42 the coal industry suffered with the Depression and as natural gas and oil replaced coal. World War II brought boom times from 1942-47 followed by a bust that lasted through the mid-1960s. This was the greatest slump in Utah's coal mining history, 1954 being a national coal production low. The market rallied slightly from 1965-70 when electric utilities companies began to increase their use of coal, but slumped again in the early 1970s with the increased concern about pollution standards. With the energy crunch beginning in 1973, coal was once again brought out of retirement and touted as the reliable energy source to fuel the country's economic appetite.

Utah's coal mining history has not exactly paralleled that of other western states. Utah's coal economy did not rally during the 1960s and did not respond immediately to the boom brought on by the energy crisis. The dramatic growth in coal production from the western states resulted primarily from increases in the size of mines and the shift to surface mining. In 1961, the average western coal mine produced under 100,000 short tons per year. Presently, average production from western mines is almost 1.5 million short tons per year. The shift from underground mining to surface mining was also a shift from Utah coal mines to other western states, particularly Wyoming and Montana. Unitl 1967, Utah was the leading producer of coal west of the Mississippi, with an output of from 4-5 million short tons per year from underground mines. In 1961, Utah International opened the Navajo mine in New Mexico whose eventual production capacity alone exceeded Utah's yearly coal production. As a result of the shift to surface mining, Utah, whose production is from underground coal mines, has slipped almost to the bottom of the list of western coal-producing states. In 1980, only two western coal producing states, Arizona (10 million tons) and Washington (5 million tons) produced less coal than Utah (13 million tons); Wyoming, the leading state produced 94 million tons.

As a result, Utah's coal industry has had to become far more market specific in order to sell its high quality, but also high-priced coal. The state has been relatively successful, and last year total tonnages increased to 14.2 million tons, of which 38 percent was exported to other states and 23 percent was exported to the Far East and Canada.

Since the last Rocky Mountain Coal Symposium, held in 1980 in Golden, Colorado, the price of oil has fallen and instead of seeing long lines at the gas pumps, the decreased cost and abundance of petroleum products has softened the national market for coal. A recent headline from the American Mining Congress Journal reads, "Today's oil glut doesn't mean energy's security; America has to muster its own energy resources." This Rocky Mountain Coal Symposium and the innovative research on which the technical sessions report are one way of defining the role that coal will play in achieving energy security for the United States. The technical sessions, the special addresses, and the field trip are well designed to update geologists on recent work and thinking on a number of different aspects of the geology of coal and coal-related rocks. Several of the papers emphasize the petrology and chemical properties of different western coals. Others emphasize environments of deposition, while others relate these subjects to exploration techniques, mining methods, or consumptive uses. As western coals play an increasingly important role in the nations's energy supply picture, advances in our understanding of western coal will be applied by industry and lead to still other advances in technology.

The papers included in these Proceedings were solicited and contributed by researchers in industry. academia, and government. The papers have been edited and given a common format; however, their style and content have not been formally reviewed by the Utah Geological and Mineral Survey. Klaus D. Gurgel, the UGMS editor, devoted much energy to this project in order to have these proceedings ready for the symposium. He has been given considerable assistance by the following UGMS Staff: Nancy Close, Carolyn Olsen, Donald Powers, and Sandy Stewart; and by Rita Hortin and Dorinda Saunders, of the Utah Department of Social Services who typeset the manuscript.

Genevieve Atwood
State Geologist and Director
Utah Geological and Mineral Survey
April 29, 1982

Utah Geological and Mineral Survey, Bulletin 118, 1982
Proceedings — 5th ROMOCO Symposium, 1982

OVERVIEW OF UTAH COAL FIELDS, 1982

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INTRODUCTION

Coal deposits are widely distributed across Utah, in the Colorado Plateau and the Wasatch Mountains, covering about 15,000 sq mi or 18 percent of the state. Coal is present in 17 out of Utah's 29 counties, but mining activity has been largely concentrated in Carbon, Sevier, and Emery counties, in the Book Cliffs, Wasatch, and Emery fields of central Utah (Figure 1). These fields have sizable coal resources of high quality in relatively thick and continuous beds, and are near railroads. Production from other large fields, such as the Kaiparowits and Alton fields in southwestern Utah, has been hindered by lack of transportation, scarcity of water, and environmental concerns.

The purpose of this paper is to summarize the geology, coal quality, and production of the coal fields of Utah, and to present new information derived from recent drilling projects conducted by the Utah Geological and Mineral Survey and the U.S. Geological Survey.

GENERAL GEOLOGY OF UTAH COAL FIELDS

Coal has been found in Utah in rocks ranging in age from Mississippian to Tertiary. However, coal beds with continuity and reasonable thickness have only been found in Mississippian, Cretaceous, and Tertiary strata in nine geologic formations. Coal in Pennsylvanian and Permian rocks tends to be bedded, but is very thin, discontinuous, and of very poor quality. Coal in Triassic and Jurassic rocks is limited to coaly materials, such as logs, branches, and twigs, associated with uranium-bearing stream channels. Carbonaceous rocks have also been identified in Precambrian formations of the Wasatch Range, but these have heat values limited to a few hundred Btu/lb (Doelling, 1980, p. 226-227).

The more important formations of Mississippian, Cretaceous, and Tertiary age containing coal include the Manning Canyon Shale (Mississippian), Dakota, Ferron-Frontier, Straight Cliffs, Emery-Wanship-Sixmile, Blackhawk-Rock Springs-lower Mesaverde, Ericson-Price River (Cretaceous), North Horn (Cretaceous-Tertiary), and the Knight-Wasatch (Tertiary) formations (Figure 2). However, Utah coal resource evaluations indicate that coal of significant commercial interest can only be found in the Cretaceous strata, although there has been some past production from the others.

Most of Utah's coal resources (98 percent) are contained in four formations, all of Cretaceous age. The non-Cretaceous coal resources amount to less than a few tenths of one percent of the total (total Utah coal resources are estimated at over 39 billion short tons (Doelling, 1972b, p. 551)). During Upper Cretaceous time, marine waters extended into Utah from the east as far as the eastern edge of the present-day Basin and Range physiographic province (Wasatch-Las Vegas line). Sediments deposited in the sea and marginal to the sea were derived from western Utah and Arizona. From time to time, orogenic events elevated these source lands while the Cretaceous sea area of eastern Utah subsided. The marine shorelines migrated westward at first, oscillated for a time, and then moved eastward and finally out of Utah in response to these tectonic disturbances (Figure 3). Lagoons and swamps, which accumulated the vegetative matter that was eventually metamorphosed to coal, developed behind barrier beaches, in deltaic lowlands, or in other protected places marginal to the marine shorelines. Lagoons and swamps persisted long enough to collect the material necessary to produce the coal beds, some of which are over 25 ft in thickness.

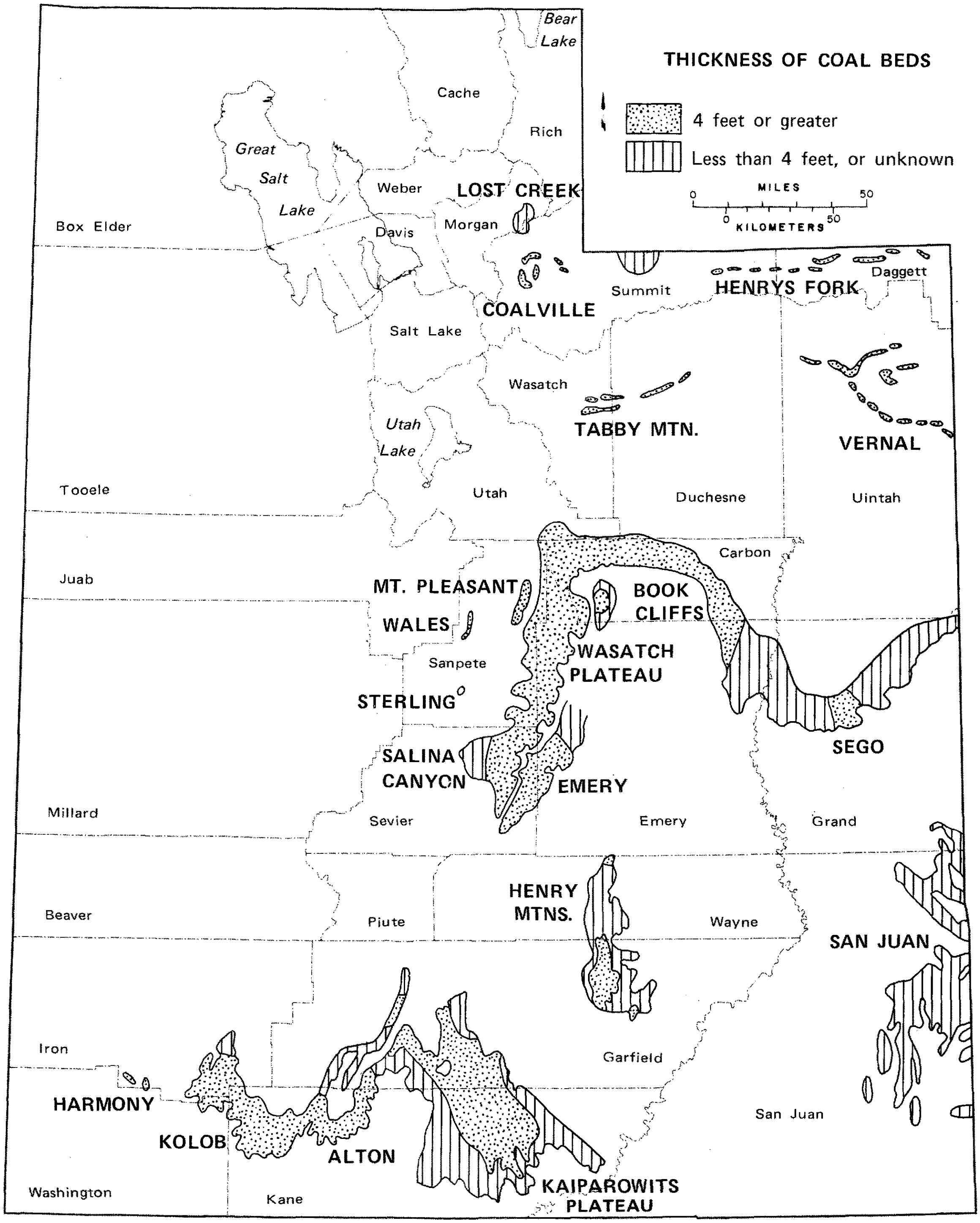

Figure 1. Locations of Utah coal fields.

The rocks that encase the coal, regardless of formation, area, or particular coal bed, primarily consist of sandstones, siltstones, and shale. Their character varies in response to the particular environment of deposition in which they were created. Sandstones are generally yellow gray, tan or

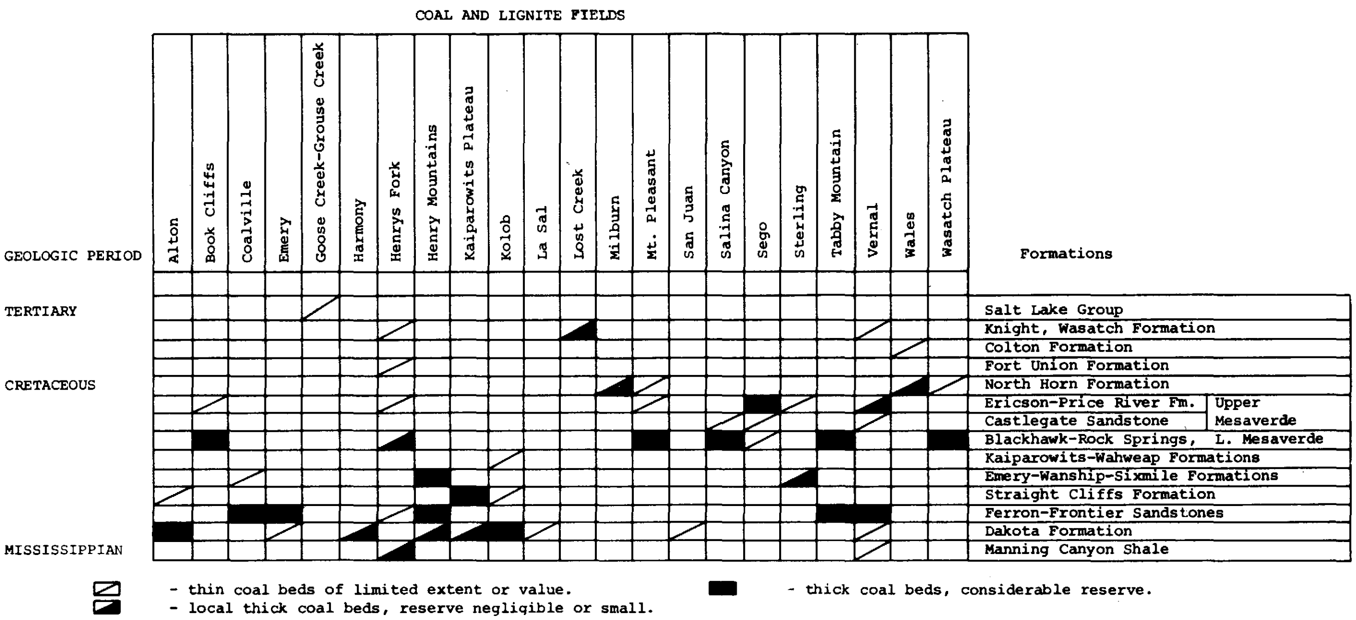

Figure 2. Coal bearing formations in Utah.

brown, fine- to coarse-grained, thin-bedded to massive and lenticular cliff-formers of littoral or fluvial origin. The siltstones and shales (mudstones), along with sandy and carbonaceous mudstones, are interbedded with the sandstone and coal. They come in shades of gray dependent upon the amount of carbonaceous material they carry. Many are fossiliferous, containing shellfish debris, dinosaur footprints, leaf imprints, tree stumps, and other vegetative debris. Sandstone-filled channels in many places cut into the mudstones and coal, and sandstone in the form of dikes and splits cut or divide some of the coal beds. Details of the encasing strata and their environments of deposition are recorded in works by Balsley (1980), Peterson (1969), Peterson and Ryer, (1975), Ryer (1975), Anderson (1978), and others.

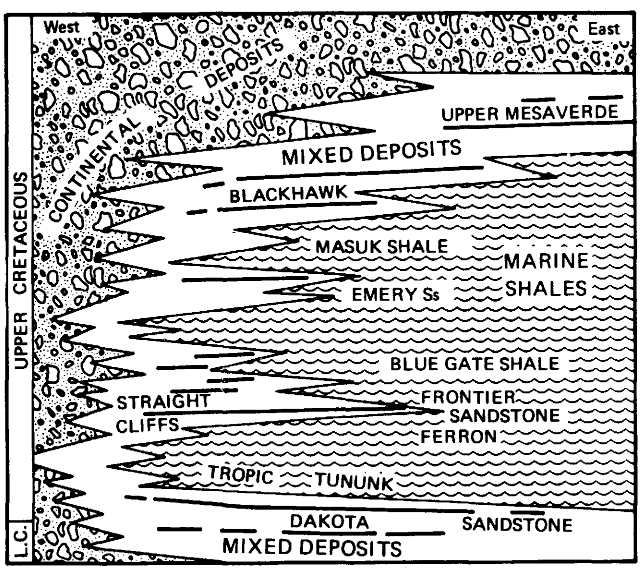

Figure 3. Generalized east-west diagram of Cretaceous environments of Utah.

Cretaceous strata and their respective coal beds were preserved from erosion in basins, the more important of which are shown in Figure 4. The largest is the Uinta Basin; it is very deep and coal strata are in places buried 15,000-20,000 ft beneath the surface. The Uinta Basin is asymmetrical, with its major axis trending generally east-west in the northern part of the basin, just south of the Uinta Mountains. Four coal fields are located around its margins: Book Cliffs, Sego, Vernal, and Tabby Mountain. The assumed stratigraphic correlations are shown on Figure 5; areas in which the coal beds, if present, are at minable depths (less than 3,000 ft) are stippled. Thicknesses of coal beds are denoted by numerals at the left of the heavy black lines (indicating coal) in the generalized columns of the figure. The larger thickness notation indicates the thickest seams generally mined in the coal field.

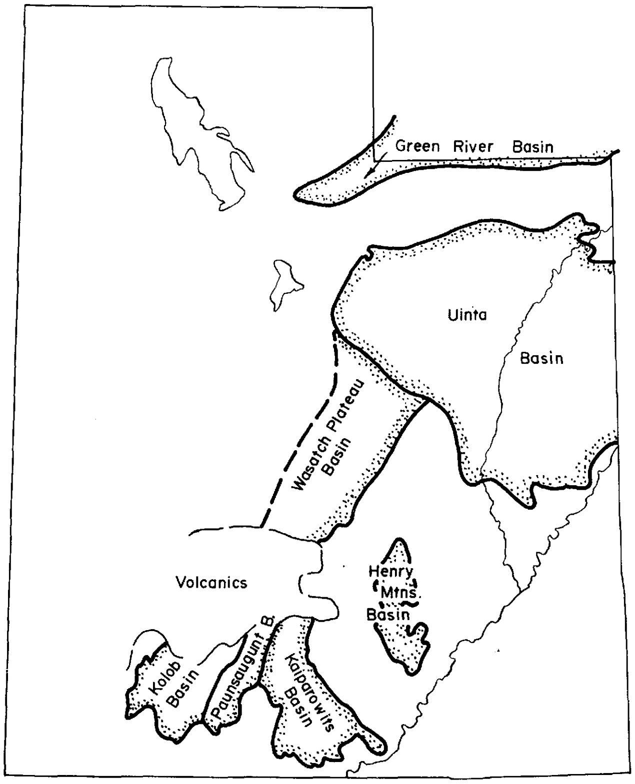

Figure 4. The more important coal basins of Utah.

The Wasatch Plateau Basin is half a basin and trends NNE; i.e., only the east half is preserved. Along its western margin, the coal-bearing formations and are truncated by a major unconformity at the base of the Upper Cretaceous Price River Formation. Five coal fields are ascribed to this basin in the literature: Wasatch Plateau, Mt. Pleasant, Salina Canyon, Sterling, and Emery (Figure 1). The Wasatch Plateau, Mt. Pleasant, and Salina Canyon fields are physically related; the latter two should probably be designated areas of the former. The Wasatch Plateau field occupies the outcrops of Blackhawk Formation coal along the east flank of the basin. Mt. Pleasant and Salina Canyon fields represent window outcrops of the Blackhawk Formation to the west. The Emery field is also located on the east flank of the basin, but with coal in the Ferron Sandstone, which is stratigraphically below the Blackhawk Formation. The Sterling field is another small window into the coal-bearing strata along the west margin of the basin. The coal beds are in the Cretaceous Sixmile Formation, which has not been successfully correlated to the east.

The Henry Mountains Basin is a synclinal basin trending north-south and is located immediately to the west of the Henry Mountains proper. The entire basin is assigned to the Henry Mountains coal field. There are three coal-bearing formations, but only two are interesting with respect to continuity or coal thickness. These formations have been correlated to the Wasatch Plateau by Peterson and Ryer (1975) and are shown by cross-section (Figure 6). The generally expected maximum coal thicknesses are indicated for each coal-bearing formation.

In southern Utah are three contiguous basins separated by faults (Figure 7) and correlations to the Henry Mountains have been worked out by Peterson and Ryer. The Kaiparowits Plateau coal field occupies a 12-mile wide band within the Kaiparowits Basin that trends northwesterly, with the more interesting coal beds being in the Straight Cliffs Formation. To the west, the Alton coal field, which is based on Dakota Formation coal, occupies the Paunsaugunt Basin. The Kolob coal field occupies the Kolob Basin and is also based primarily on Dakota Formation coal. All of these basins plunge northward under thick Tertiary strata and volcanics.

The edges of the south end of the Green River Basin extend into northeastern Utah. Coal is found in several formations, but in most places the beds are discouragingly thin, of poor quality, or are discontinuous. The Coalville coal field is the exception and is located on the western embayment of the basin. Coal has been produced from the Frontier Formation at Coalville.

The locations of the more important Utah coal fields are depicted in Figure 6, which also shows the areas where the coal beds have less than 3,000 ft of overburden on them. This amount of overburden is generally considered the upper limit to the present-day safe, economic recovery of the coal. These are the areas in which mining, exploration, and prospecting for coal can take place. While coal in Utah underlies perhaps 18 percent of the state, the coal exploration area amounts to only six percent of the state.

BOOK CLIFFS COAL FIELD

The Book Cliffs coal field of central Utah is located along the southwest edge of the Uinta Basin and extends 70 mi from Spring Canyon and the North Gordon fault zone southeastward to the Green River

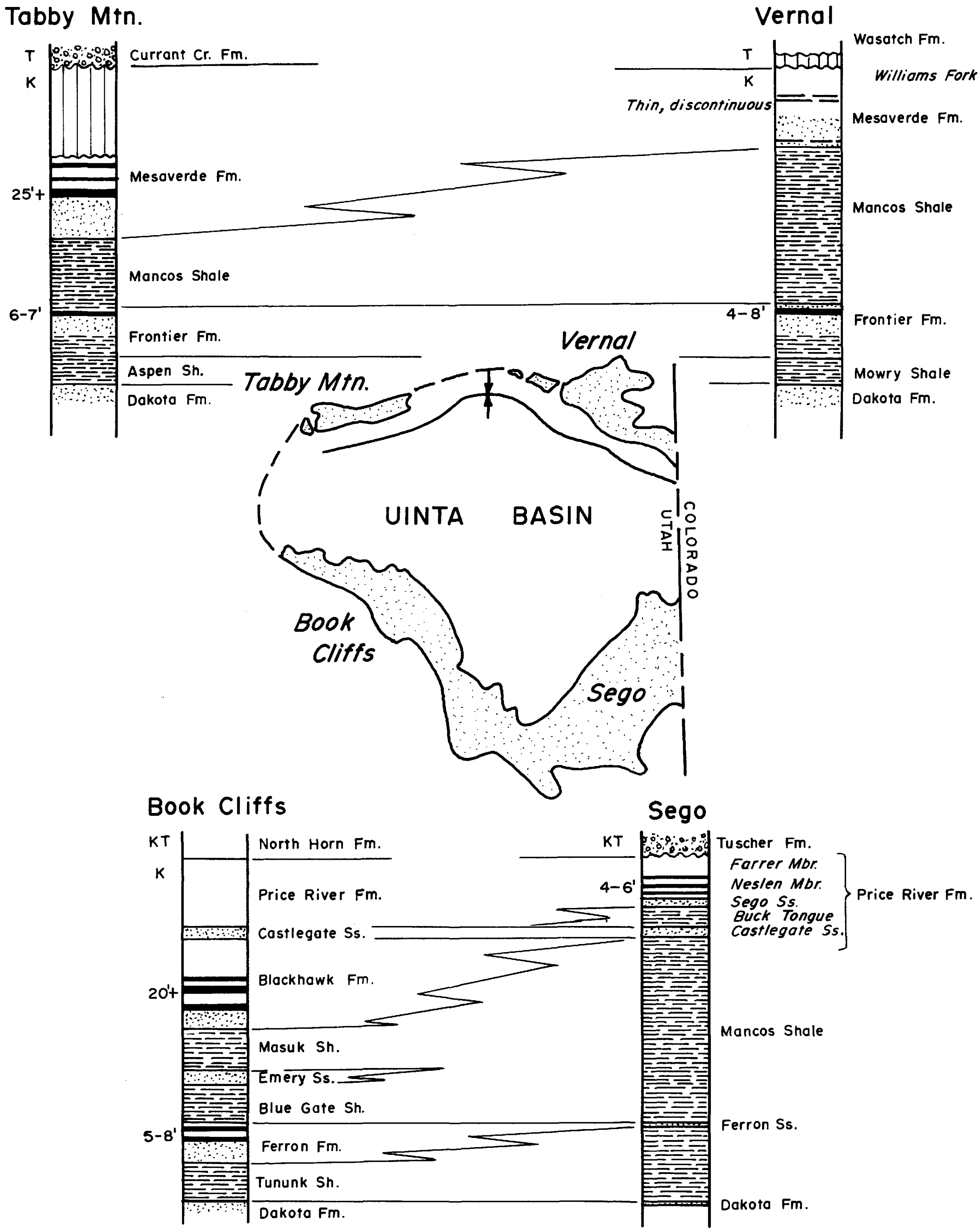

Figure 5. Correlations across and along the margins of the Uinta Basin.

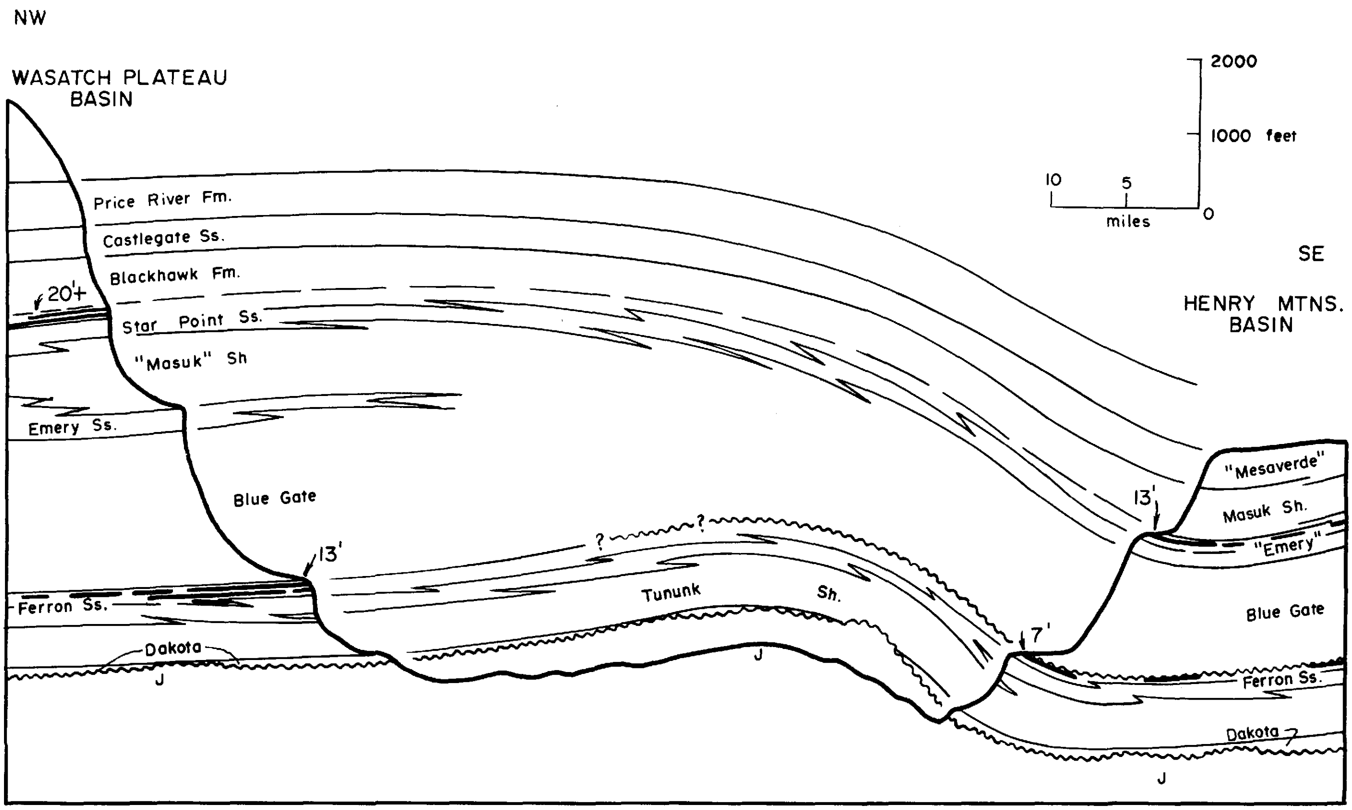

Figure 6. Correlations between the Wasatch Plateau Basin and the Henry Mountains Basin. (see Peterson and Ryer, 1975).

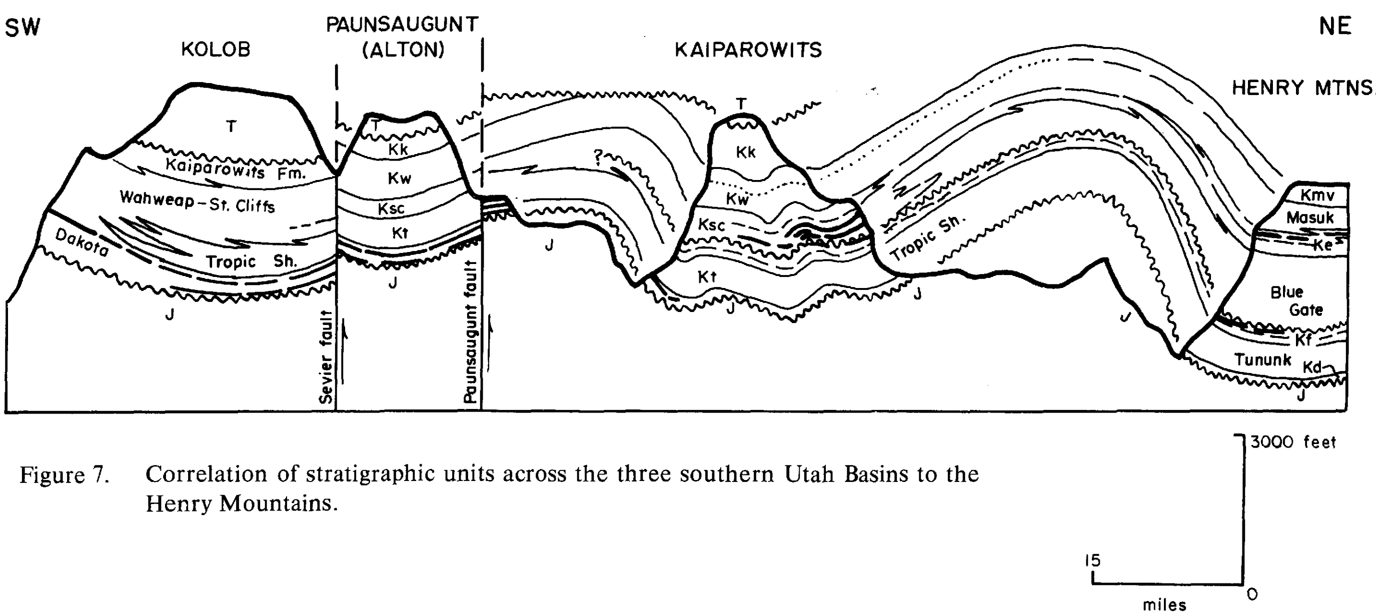

Figure 7. Correlation of stratigraphic units across the three southern Utah Basins to the Henry Mountains.

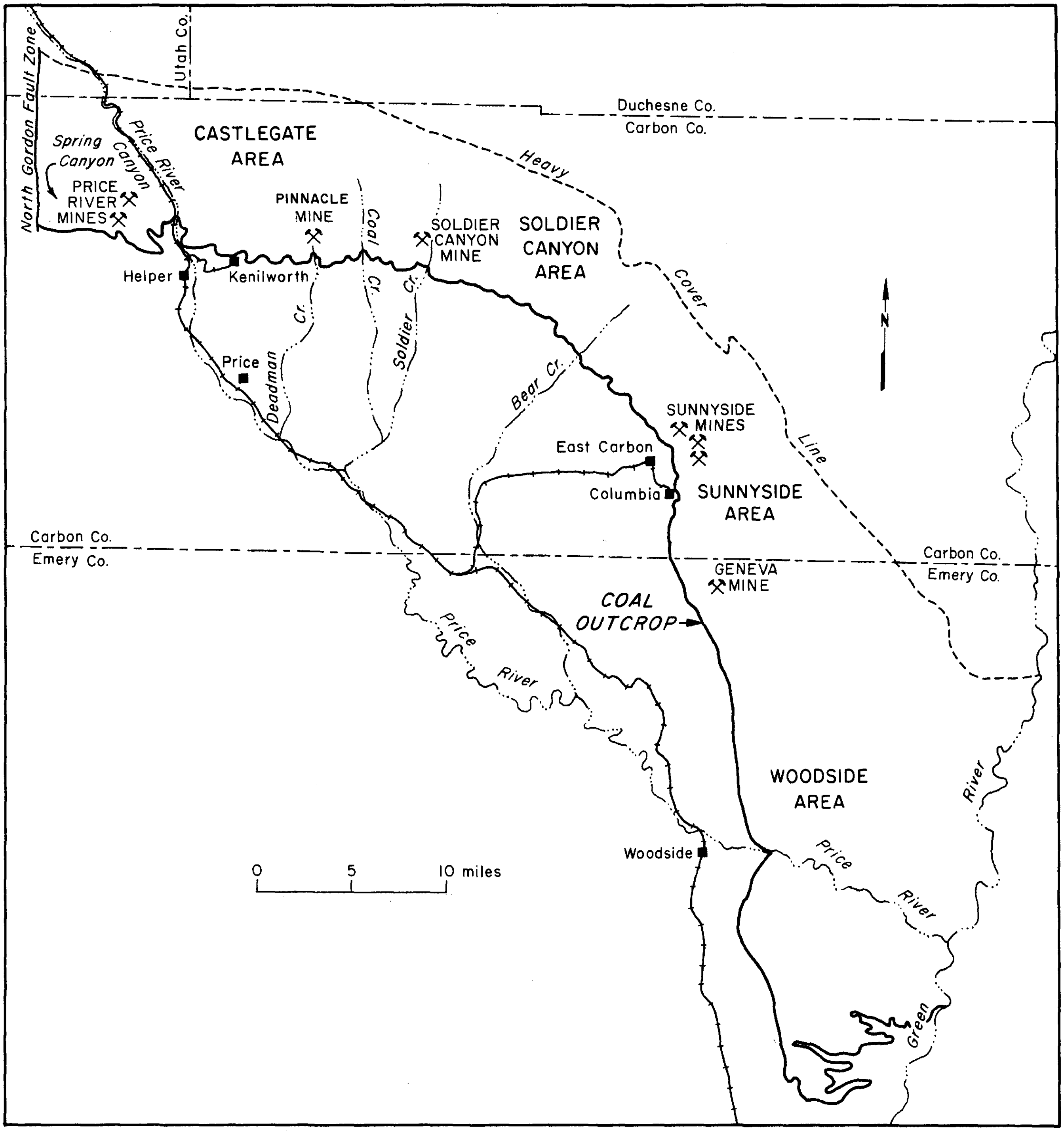

Figure 8. Map of the Book Cliffs coal field.

(Figure 8). The North Gordon fault zone forms a good boundary between the book Cliffs coal field and the Wasatch Plateau coal field to the west. To the east, the Green River forms a boundary between the Book Cliffs coal field and the Sego coal field, for at this point the coal-bearing Blackhawk Formation of the Book Cliffs field has all but disappeared and pinched out into the Mancos Shale. The coal beds

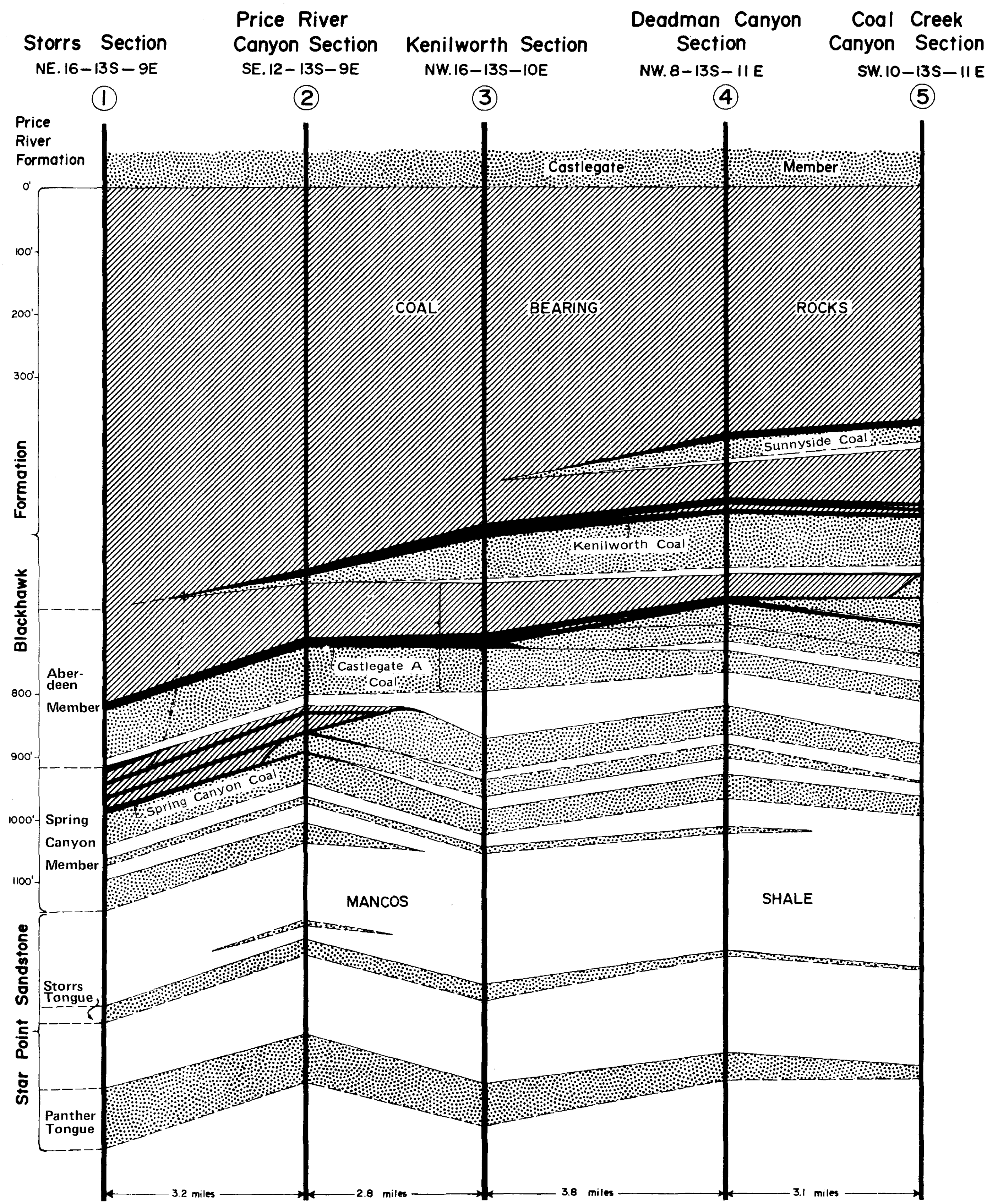

Figure 9. Stratigraphic diagram showing details of intertonguing in the Book Cliffs coal field. (after Young, 1955).

crop out along the Book Cliffs escarpment and are contained in the 600-1,000 ft Upper Cretaceous Blackhawk Formation.

The Blackhawk Formation is a heterogeneous unit of littoral, lagoonal, and fluvial sediments. The lower part consists of cyclical littoral and lagoonal deposits, the littoral units of which project eastward and rest upon and intertongue with the gray marine shales of the Mancos Shale (Figure 9). The littoral deposits are comprised mainly of thick-bedded to massive cliff-forming yellow-gray, fine- to medium-grained sandstones with individual beds separated by gray marine shale. These massive sandstones eventually thin and pinch out in the Mancos Shale in an easterly direction with each higher cycle initiated successively farther east. The lagoonal facies rest upon the littoral sandstones and are sandwiched between them; they consist of thin- to thick-bedded yellow-gray sandstones, shaly sandstones, shale, and coal. The coal beds of the lowermost cycles are best developed to the east. The uppermost Blackhawk Formation strata are dominated by fluvial (floodplain) deposits.

Each cycle has been named and its associated coal beds are best developed in different areas of the field. The Book Cliffs coal field is subdivided into four areas (from northwest to southeast): Castlegate, Soldier Canyon, Sunnyside, and Woodside. In the western part of the Castlegate area, in Spring Canyon, the lowermost cycle or member is known as the Spring Canyon and contains coal beds known as the subseams. There are three subseams, 1, 2, and 3 in descending order. The coal beds in this cycle thin out eastward and are replaced by two massive offshore bar sandstones near the town of Helper. The zone in which the minable coals occur consist of 60 to 100 ft of shales and sandstones.

The next cycle is known as the Aberdeen; it appears in Spring Canyon and its coals are best developed from the Price River Canyon eastward to Deadman Canyon. At the town of Kenilworth, the littoral sandstone is 88 ft thick and the overlying lagoonal sediments are 100 ft thick. The coal beds are known as the Castlegate Group of which three or four are developed to minable thicknesses (Castlegate A to C in ascending order). The coal beds are replaced by five bar sandstones between Kenilworth and Coal Creek Canyon.

The Kenilworth is the next cycle; the littoral sandstone tongue reaches a maximum of 85 ft and the overlying lagoonal beds reach a maximum thickness of 160 ft. The underlying littoral sandstone is recognized from Spring Canyon eastward to the Green River, but the overlying coals are thick only from the Price River Canyon in the Castlegate area, across the Soldier Canyon area, to Bear Canyon or to the western part of the Sunnyside area. The lowermost Kenilworth coal (sometimes called the Castlegate D bed) is thick from the Price River Canyon to Deadman Canyon, but it persists thinly well past Sunnyside to Columbia. In the Soldier Canyon area two and in places three other coal beds are thick and minable: the Gilson, Fish Creek, and Rock Canyon in ascending order. The Fish Creek bed is the least developed of the three.

The final cycle of interest is the Sunnyside Member. The Sunnyside littoral sandstone first appears near Kenilworth and extends along the outcrop to the Green River. The Sunnyside coal is known to be thick in the Soldier Canyon area in the subsurface to the north of the outcrops. It reaches its maximum thickness in the Sunnyside area and extends southward as a thick bed to Woodside. The bed thins eastward and the lagoonal rocks are replaced by littoral sandstones and marine shale near the Green River Canyon. This has been verified by drill holes east of the outcrops in the Woodside area. The Sunnyside coal bed is often split into two minable benches that have been called the Lower and Upper Sunnyside beds. Where joined, the bed is 12 to 18 ft thick.

Strata along the Book Cliffs dip northward into the Uinta Basin from 2 to 12° in the mines and along the outcrops, but the average is normally 4 to 7°. A few faults cut the coal measures, but most have small to medium displacements. The most serious area of faulting is in the Sunnyside area where NNW and ENE trending sets cut the coal with displacements to 200 ft. Fortunately, most displacements are much less and the faults are not too closely spaced, so that mining is not greatly hindered.

The Book Cliffs coals are mostly high volatile B bituminous in rank; Table 1 shows the average analysis for the various areas.

Coal has been mined in the Book Cliffs coal field since 1889 and most of the coal has been produced in the Castlegate and Sunnyside areas. Through 1981 over 237 million tons have been produced from the field with 118 million coming from the Castlegate area and 108 million from the Sunnyside area. All of the remainder (11 million tons) has been mined at

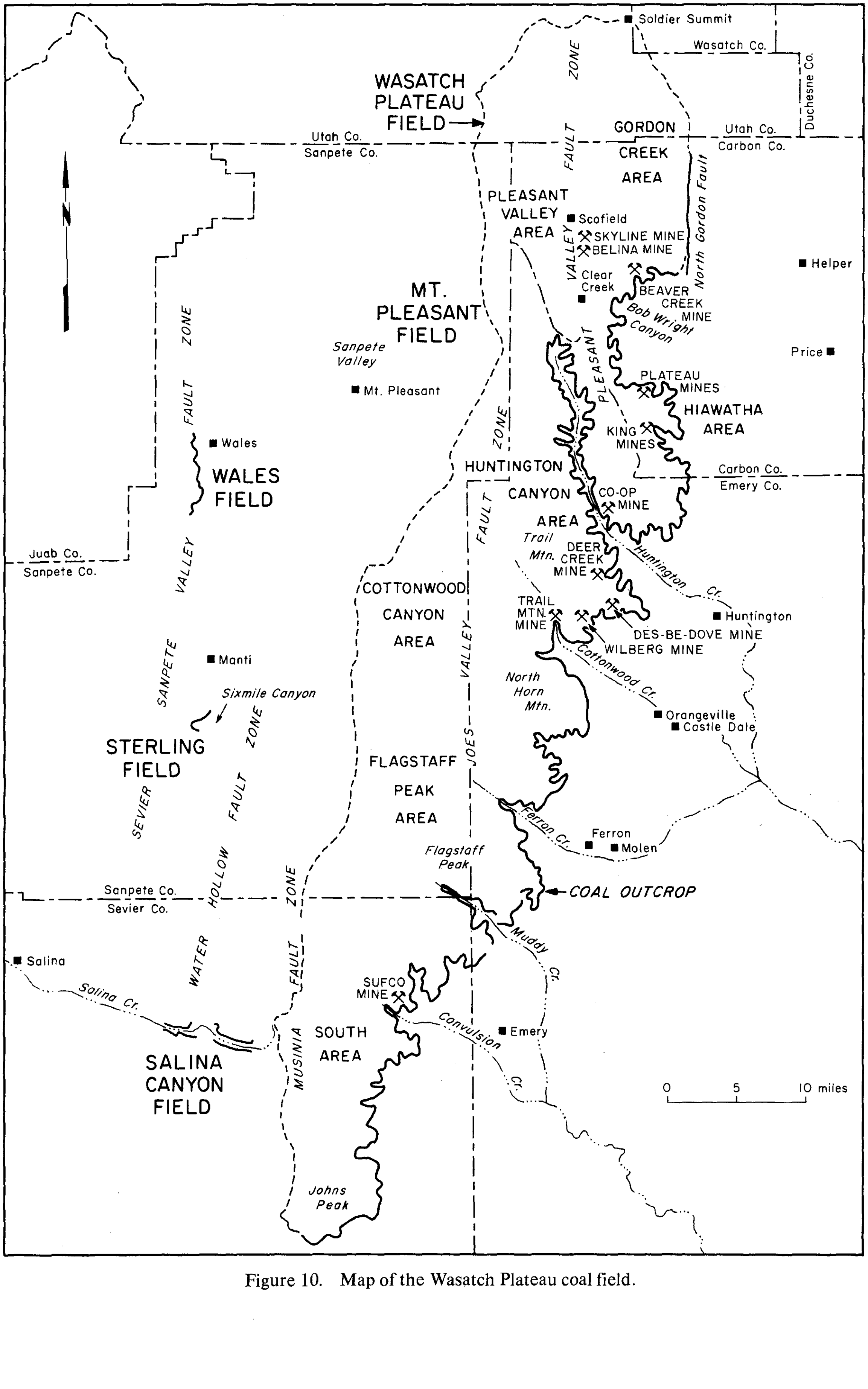

Figure 10. Map of the Wasatch Plateau coal field.

Table 1. Average analyses for Book Cliffs coals (as received).

Area	Castlegate	Soldier Canyon	Sunnyside	Woodside
Moisture %	4.3	4.8	5.0	5.5
Vol. Matter %	42.6	38.6	38.2	37.5
Fixed Carbon %	46.4	49.3	50.5	50.1
Ash %	6.6	7.0	6.4	6.7
Sulfur %	0.53	0.49	1.09	0.70
Btu/lb	12,825	12,531	12,648	12,664

Soldier Canyon. Coal mined in the southern part of the Sunnyside area is sometimes attributed to the Woodside area. Coal mined in the Sunnyside area is semi-coking and when blended with suitable coals can be used as metallurgical-quality coal. For this reason the Sunnyside bed has been favored in mining and one-fourth of all historically mined Utah coal has come from that bed.

The original coal in-place calculation (see Doelling, 1972b, p. 550) for coal beds 4 ft thick under less than 3,000 ft of cover and within 4.5 mi of a control point is 3,667.5 million short tons. Perhaps one-third of this amount will be recoverable (when compared with past mining recoverabilities). Considering what has already been mined and rendered un-recoverable, perhaps 1 billion short tons still remain to be mined.

WASATCH PLATEAU COAL FIELD

The Wasatch Plateau coal field of central Utah (Figure 10) is about 90 mi long and extends from U.S. Highway 50-6 near Colton, where the coal measures plunge deeply northward into the Uinta Basin, southward and slightly westward to Last Chance Creek, south of U.S. Interstate 70, where the Wasatch Plateau is covered by the heavy overburden of the higher Fish Lake Plateau volcanics. Most of the Wasatch Plateau Basin is underlain with coal, but traditionally only the east half, with a width of 7-20 mi and with coal beds exposed along the east-facing escarpment, has been termed the Wasatch Plateau coal field. The Wasatch Plateau Basin extends from Castle Valley on the east to the San Pitch Valley (Sanpete Valley) on the west, however. The west half generally has no outcrops and heavy overburden, but locally erosion has provided a window or two to the coal-bearing Blackhawk Formation. Two of these windows, the Mt. Pleasant and Salina Canyon coal fields, are really part of the larger Wasatch Plateau coal field, sharing the same host formation.

The Upper Cretaceous Blackhawk Formation contains the important coal seams for the coal field and most are contained in the lower 300 ft of the 700-1,000 ft unit. The Blackhawk rests on a group of littoral sandstones, collectively named the Star Point Sandstone, which some investigators believe should be a lower member of the Blackhawk Formation. The Star Point is immediately overlain by lagoonal deposits which contain the coal beds, intertongued with a few littoral sandstone beds and with some deltaic channel sandstones. The uppermost part of the Blackhawk is dominated by fluvial (floodplain) sediments. The cliff-forming littoral sandstones are generally yellow-gray to white, fine- to medium-grained, and thickbedded to massive. Individual beds are separated by thin gray shales or thinbedded, friable sands. Non-sandstone units form slopes and consist of various types of shale, shaley sandstone, siltstone, and coal. Clay shale is soft, granular and gray to green in color. Carbonaceous shale or siltstone is found in various shades of brown and black.

The coal beds on the Wasatch Plateau generally dip gently westward (Figure 6). Only rarely do the beds exceed dips of 6 or 7°. In reality the warping is complex and the strata undulate in very shallow east-west trending synclines and anticlines. Most of this warping is gentle except in the vicinity of faults.

The Wasatch Plateau is cut by a series of north-south trending fault zones, each of which is separated by 4-12 mi of relatively undisturbed ground; most zones feature a downdropped center block or graben. The easternmost zone is the North Gordon, which affects the coal in the northern part of the field only. The easternmost fault of this zone is taken as the boundary between the Book Cliffs and Wasatch Plateau coal fields. The next fault zone to the west is the Pleasant Valley zone which cuts coal strata in the Scofield-Clear Creek area (Pleasant Valley) and extends southward and out of the field near Orangeville. The Joes Valley fault zone forms the west boundary of the coal field to the north, cuts through the field starting near the head of Huntington Creek and emerges into Castle Valley along the mouths of Ferron and Muddy creeks. The Musina fault zone marks the west boundary of the southern part of the Wasatch Plateau field and separates it from the Salina Canyon field. The Water Hollow fault zone divides the Salina Canyon coal field. A few of the characteristics of these fault zones are shown in Table 2.

Table 2. Characteristics of Wasatch Plateau fault zones.

	Miles			
Fault name	Known length on plateau	Average width	Average distance from next zone east	greatest displacement in feet
Musinia	50	2	12	2,500
Joes Valley	75	2	5	2,500
Pleasant Valley	35	4	6	1,500
North Gordon	22	4	—	800

Correlation of coal beds from one part of the field to another is not yet complete, but thick coals are known to exist in most areas of the field in 1 to 3 minable beds, locally up to 4 minable beds. The coal bed names must therefore be considered tentative. Coal beds are best treated in terms of the area in which they are found. In the Pleasant Valley area (Scofield-Clear Creek area) coal beds are quite variable in thickness and the rock intervals that separate them. In the eastern part, the U. P. bed and Castlegate A bed have been termed the most valuable. These units undoubtedly correlate with those to the west where the Upper and Lower O'Connor beds are valuable. A profile of these beds is shown in Table 3.

In the Gordon Creek area the Castlegate A bed is the most valuable and in the eastern part Book Cliffs names are often used for the coal beds. Other coal beds and zones include the Hiawatha, Gordon, Royal Blue (?), and Bob Wright. (Table 4).

The Hiawatha, Huntington Canyon, and Cottonwood Canyon areas are similar with respect to coal beds. The most valuable in all three is the Hiawatha coal bed. It normally rests directly on or is found a few feet above the Star Point Sandstone as the lowest coal in the column. The Hiawatha bed is well developed in the entire eastern parts of these three areas, where it is 5-28 ft thick. The next bed of importance is the Blind Canyon, which is found 40-100 ft above the Hiawatha. A thick Blind Canyon bed, sometimes exceeding 25 ft, can be found in the eastern parts of the Huntington Canyon and Cottonwood Canyon areas. There are several other coal beds that are thick enough to mine, but they are all local in extent. The Wattis bed is 8-12 ft thick in the northern part of the Hiawatha area and is found 120-150 ft above the Hiawatha. Between the southern parts of the Hiawatha and Huntington Canyon areas the Bear Canyon bed is developed and found 40-60 ft above the Blind Canyon bed. It reaches a maximum of 10 ft in thickness. In the northern part of the Huntington Canyon area the Hiawatha and Blind Canyon are present but thin (0-4 ft), but the Castle gate A bed is 3-15 ft thick and found 200 ft above the Hiawatha or Star Point Sandstone. Forty to 75 ft above the Castlegate A is a Candland bed that reaches a maximum thickness of 16 ft. Under Trail Mountain only the Hiawatha bed is developed at 7-9 ft. In the eastern part of North Horn Mountain (Cottonwood Canyon east), both the Hiawatha and Blind Canyon are thick, but only the Hiawatha remains thick to the west.

Much less is known about the coal in the southern part of the Wasatch Plateau coal field. Recent drilling has established some information in the southern part of the Flagstaff Peak area and the northern part of the South area. Smith (1981) has

Table 3. Profile of Pleasant Valley area coal beds.

West (from selected drill holes)		East (Spieker, 1931)	
Beds	Thickness (ft)	Beds	Thickness (ft)
McKinnon coal beds	2-4 (2 beds)	Bob Wright beds	5-8
Rock Interval	400	Rock Interval	100-200
Upper O'Connor	17	Castlegate A	6-19
Rock Interval	57	Rock Interval	70-80
Lower O'Connor B	10	U.P. bed	0-30
Rock Interval	45	Rock Interval	1
Lower O'Connor A	9		
Rock Interval	75		
Flat Canyon beds	1-4 (3 beds)		
Rock Interval	0-20		

Table 4. Profile of Gordon Creek area coal beds.

Beds	Bob Wright Canyon (Feet)	North Central (Feet)	West Spring Canyon (Feet)
Unnamed upper bed	0-4	—	—
Interval	40-65	—	—
Bob Wright zone			
Upper	0-4	Individual	Castlegate "D" 1-4
Interval	5-25	beds up to	70
Main	3-10	15	—
Interval	3-20		—
Lower	2-8		Castlegate "C" 1-5
Interval	23-35	90-130	90-100
Royal Blue (?) bed	0-6	—	—
Interval	50-70	—	—
Castlegate "A" bed	6-15	2-8	2-14
Interval	160-200	60-120	90-125
Gordon bed	—	0-6	1-6
Interval	—	90-120	100
Hiawatha bed	0-3	3-10	upper split 2-6
Star Point Sandstone			

provided coal bed data for the area between Convulsion and Muddy Creek canyons. He has identified six coal beds in the Blackhawk Formation, including the Hiawatha, Upper Hiawatha, Muddy No. 1, Muddy No. 2, Ivie, and Upper Ivie (Figure 11). The two Hiawatha beds are the most valuable, the lower ranging from 1.5-23 ft thick in drill holes, the upper ranging from 1-14 ft. The higher beds are more local in extent; the maximum known thickness of the Muddy No. 1 bed is 6.5 ft, the Muddy No. 2 bed is 6 ft, the Ivie bed is 7 ft, and the Upper Ivie bed is 4 ft. A column indicating the positions of these coal beds with respect to the Star Point Sandstone and the intervals between them is given.

Other areas in the southern Wasatch Plateau are much less known and correlations are very insecure. Davis and Doelling (1977) drilled two holes south of U.S. Interstate 70 in the vicinity of Johns Peak. Very thin beds were found immediately above the Star Point Sandstone and a coal bed 3-7 ft thick was discovered 90-125 ft above and thought to be the Upper Ivie bed.

The Wasatch Plateau coals are mostly high volatile C bituminous in rank, except for the Hiawatha area, which appears to be a high volatile B bituminous coal. The heat value decreases somewhat from north to south in the field. (Table 5).

Almost 161 million short tons have been mined so far from the Wasatch Plateau coal field. Mining began in 1975 in Huntington Canyon and small

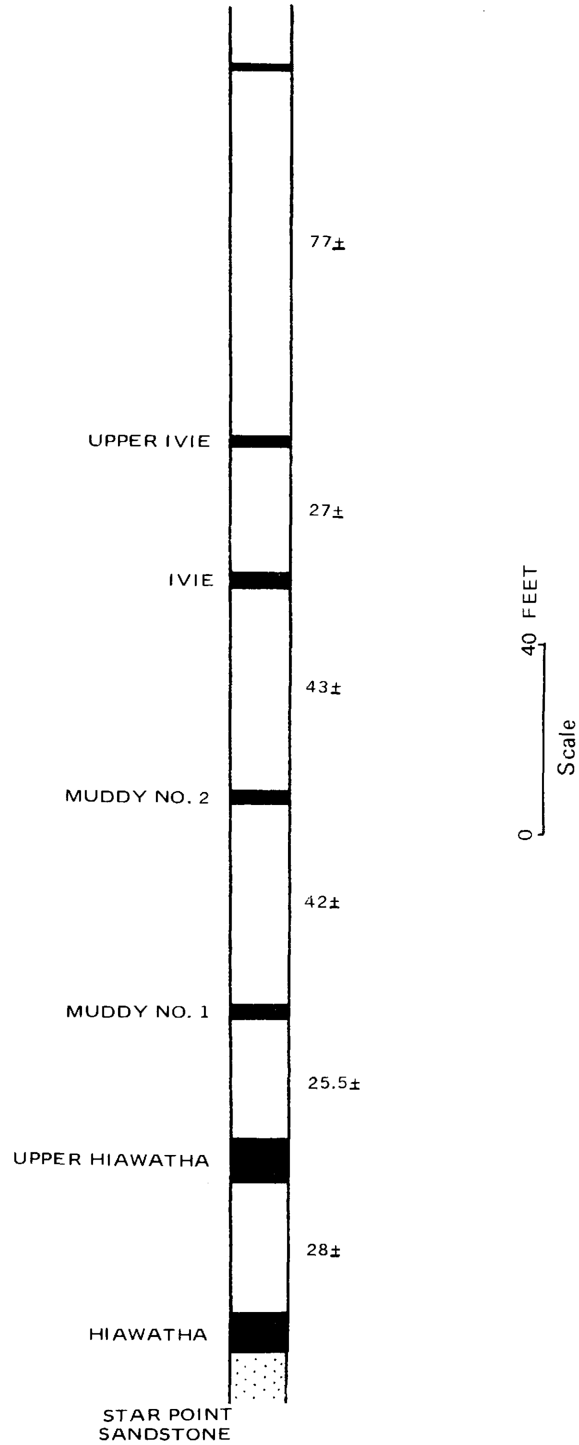

Figure 11. Section showing lower Blackhawk coal beds in Muddy Creek area.

tonnages were produced until about 1885. Production accelerated at that time and by 1970 almost 100 million short tons had been cumulatively mined. Over 60 million short tons were produced in the last

Table 5. Average analyses for Wasatch Plateau coals.

Area	North*	Hiawatha**	South***
Moisture %	7.2	5.4	8.8
Vol. Matter %	41.3	42.3	38.2
Fixed Carbon %	45.2	45.4	47.1
Ash %	6.1	6.6	6.7
Sulfur %	0.64	0.59	0.56
Btu/lb	12,200	12,744	11,727

*Scofield quadrangle (15 minute).
**Hiawatha quadrangle (15 minute).
***All areas south of the Hiawatha quadrangle.

11 years and since 1973 it has been the leading producing field in the state. In 1981 production exceeded 10 million short tons. All but about 15 million short tons have been produced north of Castle Dale, Emery County, or in the north half of the field. Practically all of the coal produced in the south came from one mine.

The original in-place coal resource for beds 4 ft or more in thickness, under less than 3,000 ft of cover and no more than 4.5 mi from a control point was calculated to be 6,714.4 million short tons (includes Mt. Pleasant and Salina Canyon resources) (Doelling, 1972b, p. 550-551). Past mining practice reveals that about one-third of this amount will be recoverable so that 2,077.1 million short tons can yet be extracted. Several areas exist where new exploration could add considerable tonnages to the budget, perhaps an additional 1.3 billion short tons of minable coal if favorable trends continue.

Wales Coal Field - West of the Sterling and Mount Pleasant coal fields, the Wales field lies near the middle of the eastern flank of the Gunnison Plateau (Figure 1). The coal crops out along a distance of about 5 mi, with dips westerly 17 to 25° and in places much greater. The area is broken by many faults.

The Wales field is one of the oldest in Utah; it was operated from about 1855 to 1955. Total production was 175,000 short tons, with most being mined before 1900. The principal resource is in the Wales coal zone of the Tertiary-Cretaceous North Horn Formation. An area of about 2.75 sq mi contains coal four feet or more in thickness and is not too deep to mine, providing about 1.2 million short tons of indicated reserves. The coal is low in moisture but high in ash and sulfur, making it doubtful that further mining will be seriously considered in this area in the near future.

EMERY COAL FIELD

The Emery coal field is also contained in the Wasatch Plateau Basin (Figure 12). The set of cliffs in which the coal outcrops are found lies below those of the Blackhawk Formation and are found on the east side of Castle Valley. The unit in which the coal is found is the Ferron Sandstone Member of the Mancos Shale. Coal beds are thickly developed along the outcrop along the northeast-trending cliffs from Molen southwesterly for 35 mi to a place where the Ferron cliffs become buried by the volcanics of the Fish Lake Plateau. Drilling into Castle Valley between Molen and Castle Dale indicates that minable coal is not present there nor along the outcrop, but that from Huntington northward several coal beds are present in the subsurface. Facies changes occur eastward in the Ferron Sandstone so that the northernmost outcrops contain no coal. Deep drilling in the Wasatch Plateau, to the west, indicates the presence of Ferron coal in many places, but at depths too deep to mine. The effective mining width in southern Castle Valley is 4-8 mi.

Coal beds are exposed under the unconformity at the base of the Price River Formation, in Sixmile Canyon near the town of Sterling on the west side of the Wasatch Plateau Basin. Richardson (1909) first described this small coal field where six thin coal beds, dipping 15-30°, crop out on the side of the canyon in the Sixmile Canyon Formation. A few of these thin coal beds fuse to form one of minable thickness but of local extent. The Sixmile Canyon Formation is thought to be Coniacian-Santonian in age rather that Turonian as is the Ferron Sandstone, but older than the Campanion Blackhawk Formation of the Wasatch Plateau coal field. The Sixmile Canyon Formation may correlate with the Emery Sandstone Member of the Mancos Shale on the east side of the Wasatch Plateau Basin. The Emery is exposed above the Ferron on the east side of the basin, but contains no coal.

The Ferron Sandstone Member dips are gentle and northwesterly in the area where coal beds crop out, mostly in the 1-5° range. A major fault system, extending southward across the Wasatch Plateau coal field, marks the west boundary of the Emery coal field. This is the extension of the Joes Valley fault

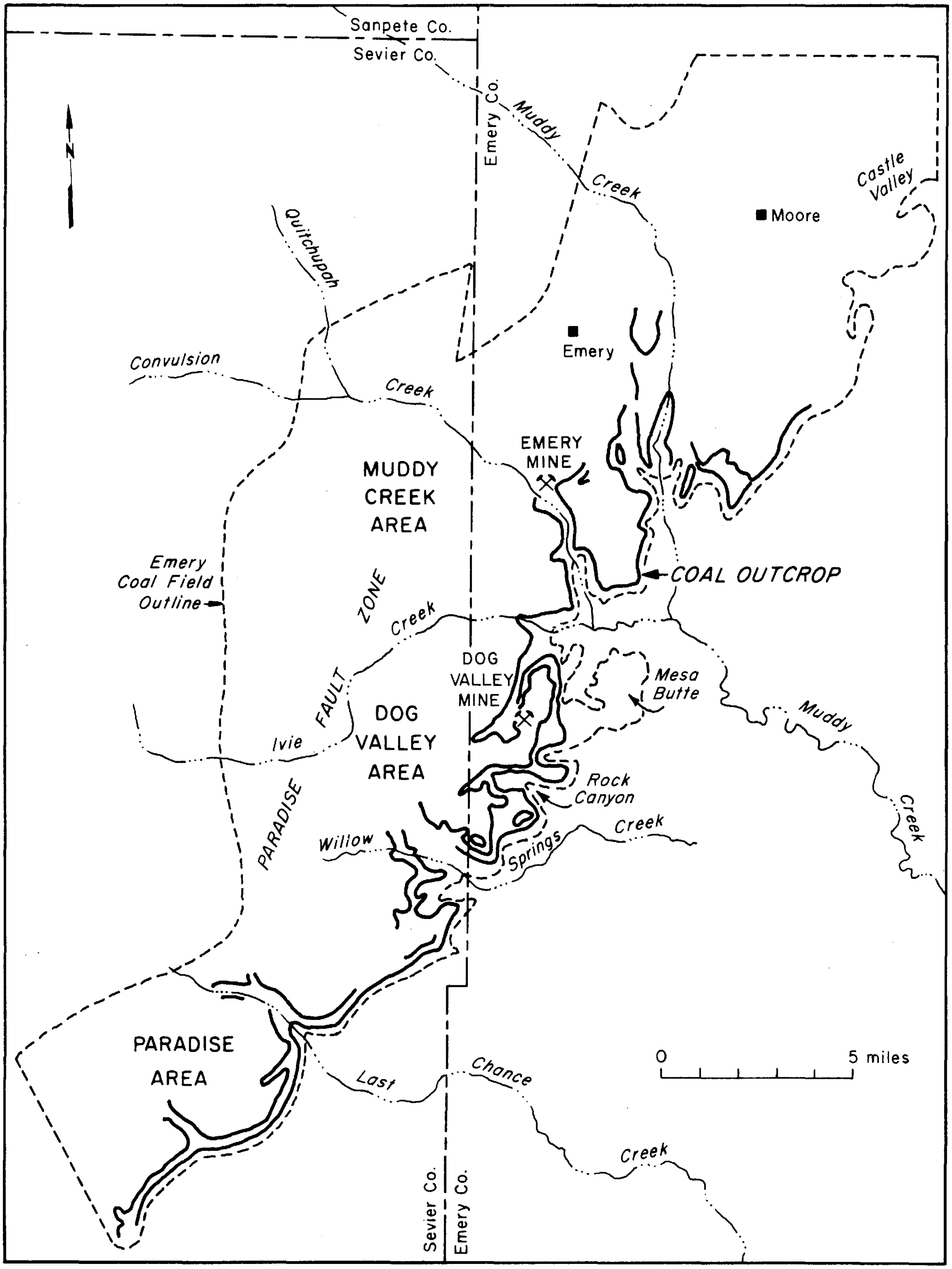

Figure 12. Map of the Emery coal field.

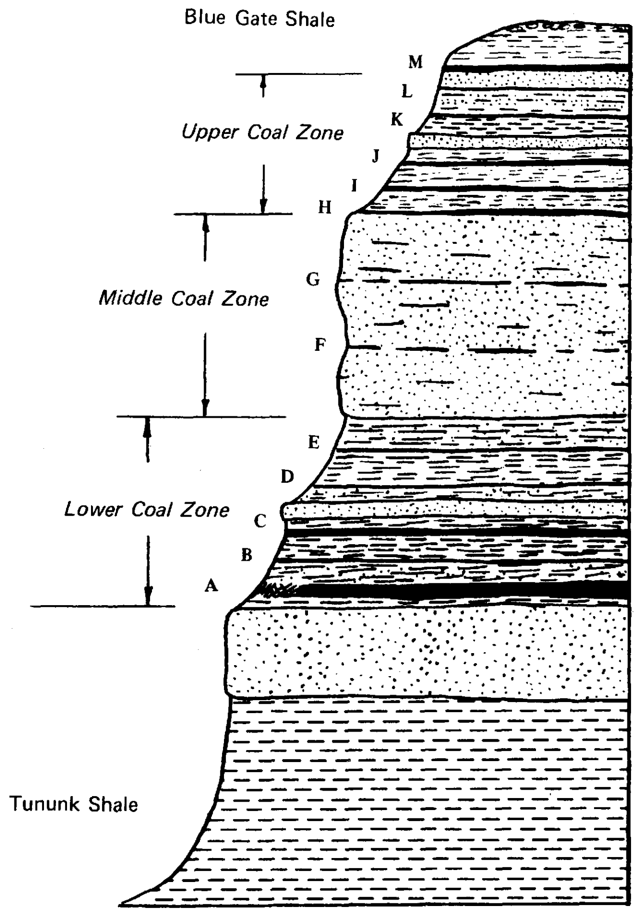

Figure 13. Ferron coal zones and beds.

zone, here called the Paradise fault zone. Just east of the town of Emery displacements of up to 1,000 ft occur in the fault.

The Ferron Sandstone Member is 300 to 800 ft thick and consists of alternating yellow-gray sandstone, sandy shale, and siltstone, and coal (Figure 13). The Ferron can be divided into six divisions and is discussed in ascending order. Thirteen coal beds have been recognized and given letter designations, A to M. Only a few are developed to minable thicknesses at any one place. At the base of the member is a littoral sandstone unit, 35 to 400 ft thick, that thickens to the south and contains no coal. Above this is a slope-forming unit, 25-115 ft thick, of lagoonal sediments forming a lower coal zone containing beds A to E. The next 75-200 ft of the formation are alternating, cliff-forming, lagoonal and littoral rocks, termed the middle coal zone, and contains the F and G beds. The upper coal zone lagoonal facies is 15-150 ft thick and is a slope-forming unit containing coal beds H to L. The fifth unit consists of littoral sandstones 10-150 ft thick and contains no coal beds. At the very top of the Ferron are 0-25 ft of slope-forming lagoonal rocks that contain the M bed.

In the lower coal zone, the A and C beds are the most valuable. The A bed is nicely developed from Quitchupah Creek Canyon southward to the Paradise area. The C bed is well developed north of Ivie Creek to Molen. The A bed reaches a maximum thickness of 13 ft near Willow Springs Wash and the C bed reaches a maximum of 20 ft in outcrops along Quitchupah Creek Canyon. In the middle coal zone only the F bed has some value. It exceeds 4 ft in thickness in a small area near Ivie Creek just east of Dog Valley; here it averages 5.5 ft in thickness. The upper coal zone beds have been the most valuable in the field in terms of production. However, the I and J beds, which achieve the suitable thickness, are only developed to the northeast between Convulsion Creek and Muddy Creek, extending as far south as Mesa Butte and Rock Canyon. The I bed is known to thicken to a maximum of 20 ft and the J bed to 13 ft near the Emery coal mine. The L bed thickens locally west of Dog Valley Wash and in the Paradise area, where it is 5-9 ft thick. The M bed at the very top of the Ferron Sandstone Member is locally over 4 ft thick; one such area lies between Rock Canyon and Willow Springs Wash and another south of Last Chance Creek in the Paradise area.

Subsurface drilling north of Huntington has shown the presence of several coal beds in the Ferron Sandstone Member at 800- 2,200 ft depths. The coal beds are divided into upper, lower, and middle zones, of which the upper and lower are the most valuable. The thickest coal bed is about 10 ft thick.

The coal beds of the Emery field are much more lenticular than those of the Wasatch Plateau coal field and are more variable with respect to quality. Many of the beds pick up high ash bands, splits or other discontinuities; others are quite high in sulphur content. Some samples contain up to four percent sulphur. The coal is considered to be high volatile C bituminous coal to the north, but may degrade to subbitiminous coal in southern exposures. Obtaining unoxidized coal samples in the southern part of the Emery field has been difficult; there has been no recent mining or drilling and subsurface samples taken in the future may indicate the coal to be of better quality. Average as-received analyses are given in Table 6.

Table 6. Average analyses for Emery coal field (as received).

Area	North	South
Moisture %	5.6	14.6
Volatile Matter %	38.9	33.5
Fixed Carbon %	46.1	38.5
Ash %	7.5	11.4
Sulphur %	0.82	1.78
Btu/lb	12,322	9,453

The original, in-place resource for coal beds greater than 4 ft in thickness and under less than 3,000 ft of cover and less than 4.5 mi from a control point is 1,430 million short tons. Unexplored areas west of the Paradise fault zone may raise this to 2,150 million short tons if known coal thickness trends continue in that direction.

Coal production began in the Emery field in 1881, but was intermittent until 1930. Since the 1930s a constant but modest amount has been produced each year. Over 5.7 million short tons have been produced from the Emery coal field through 1981; most of that production came from two mines. In recent years, coal production has been between 500,000 and 800,00 short tons annually. If one-third of the in-place resources will be recoverable, then 471 million short tons remain to be extracted. It is thought that new exploration will increase that figure.

HENRY MOUNTAINS COAL FIELD

The Henry Mountain coal field is superimposed on the Henry Mountains Basin, a huge island of Cretaceous rock immediately west of the Henry Mountains (Figure 14). The basin is 48 mi long and at its widest point is 18 mi across. Most of the basin is in Wayne and Garfield counties in southeastern Utah, northwest of the Colorado River. Three stratigraphic units contain coal, in ascending order the Dakota Sandstone, Ferron Sandstone Member, and Emery Sandstone Member of the Mancos Shale. Peterson and Ryer (1975) has pointed out that the Emery Sandstone Member in the Henry Mountains area does not correlate with the Emery Sandstone Member in the Wasatch Plateau Basin. The Henry Mountains Emery Sandstone is probably correlative with the Blackhawk Formation (Figure 6).

Dakota Formation coal is not economically important; most occurrences are thin and impure. The extent of thick coal beds is very limited and local in nature. The Ferron Sandstone Member overlies the Dakota by 600 ft and is 150 -350 ft thick. The Member consists of three parts; the lower part is interbedded littoral sandstones and marine shale and contains no coal. The middle unit is dominated by littoral massive yellow-gray to tan, fine- to coarse-grained cliff-forming sandstone. The unit contains a few thin lagoonal interbeds and partings of shale, carbonaceous shale and coal. The coal beds are generally thin, rarely exceeding 2.5 ft in thickness, although some are quite persistent. The upper unit is 50-100 ft thick and consists of interbedded, lenticular sandstones, shale, carbonaceous shale, and siltstone and coal. In most of the basin the coals at the top of the Ferron are thin, averaging 6 in to 2.5 ft in thickness. Thicknesses exceeding 4 ft are found at the very north and south ends of the Henry Mountains Basin.

Thick coals, to 8 or 9 ft in thickness, are present in a 4 or 5 sq mi area north of Factory Butte. Only a few feet of shale and sandstone separate the principal coal beds from the overlying Blue Gate Shale Member of the Mancos. At the south end of the basin, below the Swap Mesa cliffs, the upper coal bed reaches a maximum of 5.5 ft in thickness; coal over 4 ft in thickness has an areal extent of 2 or 3 sq mi. Just below Cow Flat on the east side of Bullfrog Creek, near the old Stanton mine, the Ferron coal bed reaches a maximum of 5.5 ft, but is split. The area of thick coal may be less than 1 sq mi. In most of the area between Swap Mesa and Cow Flat the Ferron coal bed is 2-3 ft thick.

The Emery Sandstone Member lies 1,500 ft above the Ferron Member. The Emery Sandstone is 240-450 ft thick, of which the lower 150 ft consists of littoral sandstone. This unit is the Henry Mountains coal field's most important coal bearer. The upper part of the Emery contains a coal zone 25-100 ft thick, mostly consisting of gray shales and siltstones, thin lenticular sandstone beds and coal. The strata above the coal zone consist of resistant lenticular sandstone beds forming a step-like outcrop pattern. At the very top, shale and slope-forming siltstone dominate and grade into the overlying Masuk Shale Member. The coal zone contains up to 12 mostly thin coal beds, and in particular areas at least one is 4-13 ft thick without splits. Thick coals are found under Wildcat Mesa, in a mi-wide band 1 mi west of the King Ranch, under Cave Flat, and across the south half of Swap Mesa. Drilling has revealed the presence

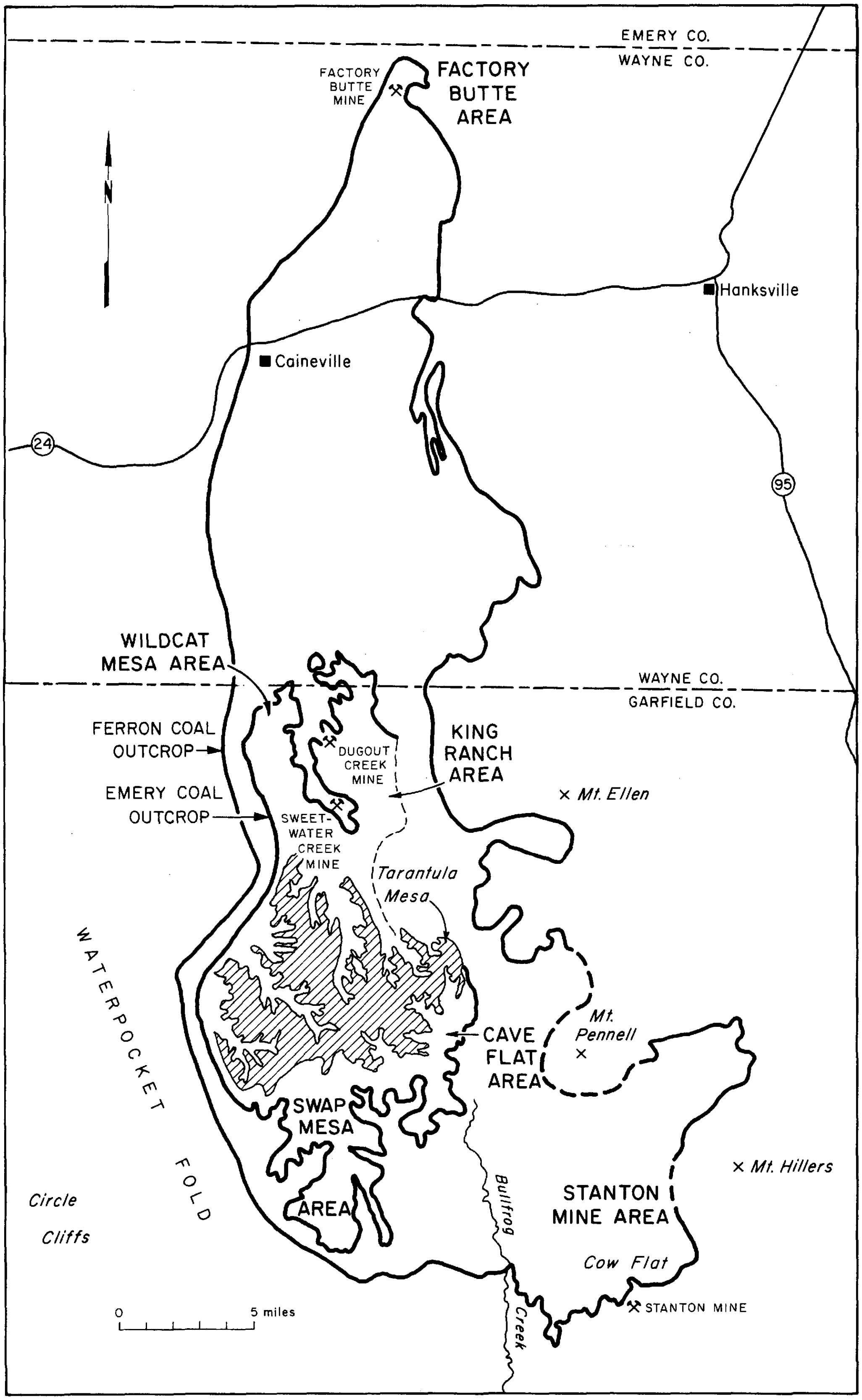

Figure 14. Map of Henry Mountains coal field.

Table 7. In-place coal resource estimates of the Henry Mountains coal field (in millions of short tons).

Area	Total Coal*	Thick Coal**	Strippable***
Wildcat Mesa	67.9	41.0	67.9
King Ranch-Stephens Mesa	107.9	68.3	28.0
Cave Flat	44.8	33.8	36.8
Swap Mesa	103.7	44.5	50.0
Tarantula Mesa	212.4	103.0	
Factory Butte	27.1	22.7	25.0
Grand Total	**563.8**	**313.3**	**207.7**

* Coal 28 in thick or greater

** Coal 4 ft thick or greater

*** Coal under less than 200 ft of cover over 28 in thick and including at least one seam over 4 ft thick.

of thick coal under Tarantula Mesa as well, but not enough holes have been drilled to prove any areal extent.

Structurally the Henry Mountain Basin is a long north-trending syncline, and excepting the east and west edges, dips are quite gentle, rarely exceeding 7°. The Waterpocket Fold is aligned along the west edge, and the Dakota Formation and Ferron Member outcrops dip steeply eastward into the basin. Dakota coal possibilities are very limited and the Ferron coal beds are very thin along the Waterpocket Fold. Faulting in the Henry Mountains Basin is rare and when found, of small displacement. Faults are serious in the Factory Butte area where such structures trend roughly east-west and are closely spaced, but the rocks and coal between them are not shattered, although displacements range to 30 ft. Several faults cut Ferron coal beds below Cow Flat, but these are widely spaced and offsets rarely exceed 10 ft.

Considerable drilling has been completed since UGMS published the Henry Mountains coal report in 1972 (Doelling and Graham, 1972) and has increased the known resource base for this coal field. Present resource estimates are shown in Table 7.

The Ferron Member coals appear to high volatile C bituminous in rank, but only Factory Butte area samples are available. Emery Member coal are subbituminous A to high volatile C bituminous in rank. Coal sample analyses are still few, but average analyses of those available are given in Table 8.

To date only 59,000 short tons of coal have been mined from the Henry Mountains coal field, and all but 2,000 short tons have been mined from the Ferron Sandstone Member. Except for small tonnages mined at the old Stanton Mine in the southern part of the field to run gold dredges on the Colorado River in the 1890s, all of this coal was mined in the Factory Butte area, operated intermittantly from 1908 to about 1945 and in 1978. Coal from the Emery Sandstone Member was mined from two small mines in the King Ranch-Stephens Mesa area, first opened about 1914.

COAL FIELDS IN SOUTHWESTERN UTAH

The four coal fields of southwestern Utah are separated by more-or-less parallel north-trending faults that are part of the system of faults separating the Colorado Plateau from the Great Basin to the west (Figure 15).

The easternmost field is the **Kaiparowits Plateau field,** located in Garfield and Kane counties south of the Wasatch Plateau-Emery fields. This field has larger coal resources than any of the other Utah

Table 8. Proximate analyses of Henry Mountains coal field samples.

Area	Factory Butte	Factory Butte	Wildcat Mesa	King Ranch	W-K (USGS)	Swap Mesa	Cave Flat
Moisture %	5.0	6.6	10.2	13.7	12.2	14.4	12.2
Vol. Matter %	34.6	33.8	35.5	33.2	34.9	35.4	37.5
Fixed Carbon %	45.2	46.3	43.2	38.5	40.2	41.0	44.3
Ash %	15.2	13.3	10.8	14.6	12.7	9.9	6.2
Sulfur %	2.0	2.1	1.0	0.6	0.8	1.1	0.6
Btu/lb	10,464	10,785	10,792	9,610	10,007	10,049	11,120

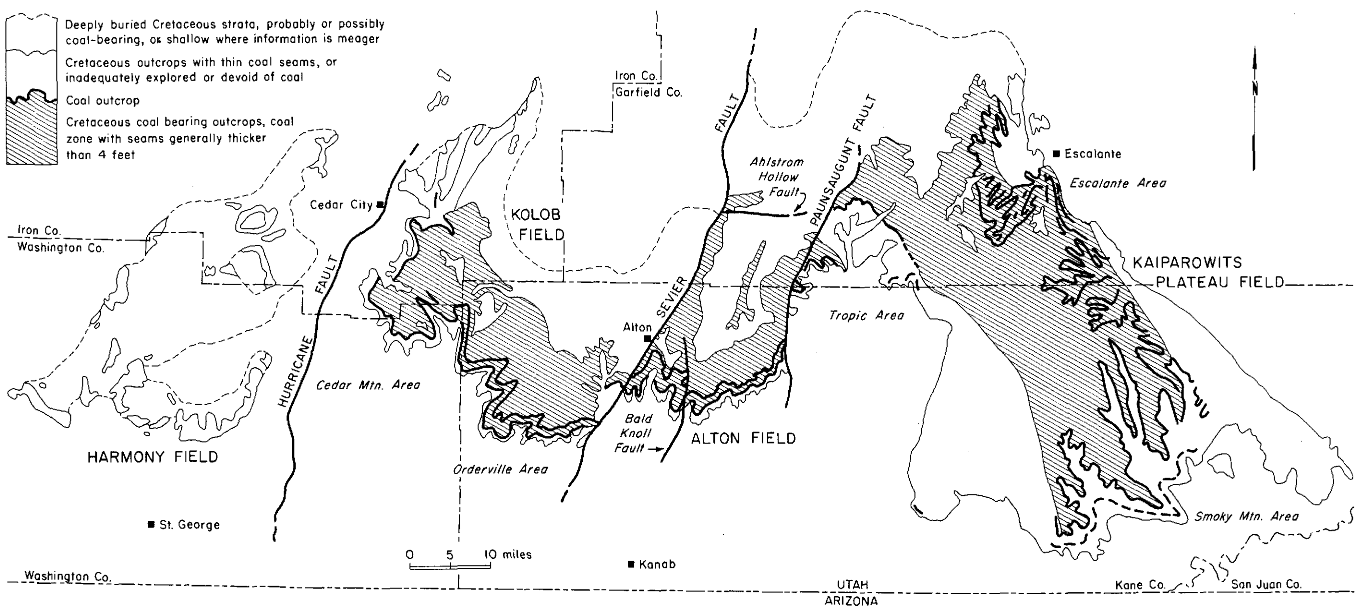

Figure 15. Map of southwestern coal fields.

fields, but its isolation and distance from markets kept it from being seriously considered until 1960, when it was first considered as a source of coal for coal-fired electrical plants to provide electricity for the Los Angeles area. A flurry of leasing and exploration was brought to a halt when environmental concerns blocked further development. Little has been done since then; coal producers are still waiting for political issues to be resolved.

Geologically, the Kaiparowits Plateau is a basin structure with a system of gentle northwest-trending anticlines and synclines plunging toward the central part of the basin. It is bounded on the east by the East Kaiparowits Kaibab Monocline, which dips into the Basin. On the north it is covered by Tertiary rocks; on the west it is cut off by the Paunsaugunt fault. To the south it is bounded by erosionally-formed cliffs. Internal faulting is relatively minor.

Coal in the Kaiparowits Plateau field is found in the Cretaceous Straight Cliffs, Dakota, and possibly the Tropic Shale formations. Most of the coal is in lenticular seams and confined to several zones of which the most important are the Christensen (Henderson), Alvey, and Rees, all in the Straight Cliffs Formation. All of the coal beds four or more feet thick are confined to a northwest-trending belt 18-25 mi wide paralleling old shore lines (Figure 15).

Calculations of coal resources, including all classes, total 15.2 billion short tons. Doelling (1972a) places nearly 4 billion short tons in indicated reserves, omitting coal in seams less than 4 ft thick from the calculations. The minable portion of the coal will fall between 33 and 50 percent of this amount; most will have to be produced from underground mines.

The quality of the coal will limit its use to power generation, and to gasification and liquefaction benification when these processes become competetive with natural petroleum and gas. Railroads or pipelines will be needed to export the coal.

The rank of the coal ranges from subbituminous B to high volatile bituminous C. Field averages for dry coal indicate 43.8 percent volatile matter, 47.2 percent fixed carbon, 8.9 percent ash, and 0.87 percent sulfur, with 11,712 Btu/lb.

The **Alton coal field,** directly west of the Kaiparowits Plateau, lies in Kane and Garfield counties on the Paunsaugunt Plateau, between the Paunsaugunt and Sevier faults (Figures 16 and 7). The field is roughly horseshoe shaped, with more than 35 mi of coal outcrop along the erosional cliffs to the south and east. The area between the faults is a gentle northeast-trending syncline plunging to the

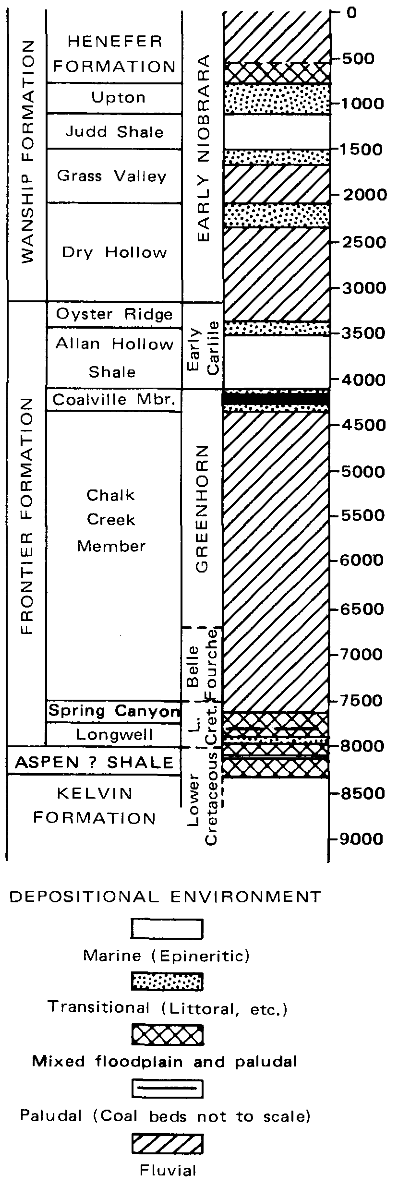

Figure 16. Coalville coal-bearing section.

north. It is bounded on the north by the Ahlstrom Hollow fault. On the southwest, the area east of the north-trending Bald Hollow fault is downdropped and displaces the coal beds by as much as 500 ft. Other faults in the area are relatively minor.

The coal lies in two zones, near the base and near the top of the Dakota Formation, which is at the base of the Upper Cretaceous. The lower or Bald Knoll zone is lenticular and is badly split. The upper or Smirl zone is thicker and contains the greater portion of the coal resources. Except where cut by the faults, the two zones are nearly horizontal. The Smirl zone is well developed in the west (Alton) and central (Skutumpah) areas; the Bald Knoll is well developed in the Alton and eastern (Cannonville) areas.

In the Alton area calculated coal resources are 2.1 billion short tons, of which 1.5 billion short tons are indicated. About 1.0 billion short tons lie under less than 1,000 ft of overburden; 0.2 billion short tons are under less than 200 ft and are strippable.

Coal ranges from subbituminous C to high-volatile C bituminous rank, generally improving from east to west. The Smirl zone has slightly better quality except for its sulfur content, which averages 1.3 percent. Bald Knoll sulfur averages .74 percent. Analyses for the Alton coal field show ranges of 14-28 percent moisture as received; 37.5-47.4 percent volatile matter; 40.5-53.8 percent fixed carbon, 4.7-14.9 percent ash, with 8,580-12,329 Btu/lb

The little development in the area is concentrated in the Alton area. Total production is less than 50,000 short tons. As in the Kaiparowits area, interest in the coal for use in power production has been high, but has also been blocked by environmental concerns. Lack of water in both areas may also be a critical factor for either generating plants built in the area or for coal-slurry pipelines, proposed to carry coal to the west.

The **Kolob-Harmony coal fields** lie west of the Alton and Kaiparowits fields, mostly in Iron and Kane counties (Figures 15 and 17). The Kolob field is separated from the Alton field by the Sevier fault. It is about 32 by 12 mi in extent and lies under the Kolob Plateau. The Hurricane fault makes its western boundary, separating it from the Harmony field.

The Kolob field is a homocline dipping 1-5° to the northeast, with dips increasing toward the major fault zones. Other faulting appears to be minor, but increases in areas covered with lava flows. The effect on the coal of the lava's rising through the coal beds is not known.

Important beds are found in the Upper Cretaceous Tropic-Dakota interval. Two zones are important: the Lower zone, near the base, is minable only in the southeastern part of the field; here seams are thin and badly split but in a few places reach a 4-foot thickness. The Upper zone is near the middle of the formation in the southeast, and near the top to the northwest in the Cedar City area; average thickness is 5-6 ft.

The Kolob field was discovered by early settlers during the winter of 1849-50 and was one of the first fields in the state to be mined. An early attempt to use the coal to produce steel from nearby iron deposits proved unsuccessful, and the only mining for the next 100 years was for local use. In 1948 a small coal-fired plant was built near Cedar City to provide electricity for the local iron mines and for irrigation. The last of the Kolob mines was closed in 1967. For a while coal was imported from the central Utah coal fields for the Cedar City power plant, but it is now closed.

Coal varies from subbituminous B to high volatile C bituminous rank. All areas have moderate to high sulfur coal. Analyses for the Kolob and Harmony fields are as follows:

Table 9. Average analyses for Kolob and Harmony coal fields (as received and mined).

	SE Kolob	NW Kolob	Harmony
Moisture content %	12.1	8.2	6.7
Ash %	11.5	10.8	26.6
Sulfur %	2.21	5.76	3.31
Btu/lb	10,344	10,500	9,100

The Kolob field has 2.0 billion short tons of coal in seams greater than 4 ft thick; of this, 1.9 billion short tons are in the Upper zone. All will have to be mined underground. Some cannel coal is present in Orderville Canyon in the southeastern part of the field.

Some of the coal in the Harmony field, west of the Kolob, is semi-anthracite, having been metamorphosed by a Tertiary intrusion. The reserves are relatively insignificant and the quality of the coal is poor.

SMALLER COAL FIELDS AROUND THE UINTA BASIN

Besides the Book Cliffs coal field, three others are found around the Uinta Basin. The **Sego field** lies to the east of the Book Cliffs field and follows the Book Cliff from the Green River to the Colorado border. The field is about 65 mi long and has an effective width of about 6 mi, making a total producible area of about 390 sq mi.

The coal occurs in five formations, but only the Neslen Member of the Price River Formation of Upper Cretaceous age has commercially interesting coal resources (Figure 5). The Neslen Member contains four coal zones: the Carbonera, the Chesterfield, the Ballard zone, and lowermost, the Palisade zone.

The Sego coal-bearing formations on the southeastern edge of the Uinta Basin dip gently to the north into the basin. A series of gentle anticlines, parallel to the Uncompahgre Uplift to the east, has warped the Upper Cretaceous sediments.

The first mine was opened in 1900, in the Ballard zone in Sego Canyon. Production from the zone was small; a few years later a mine opened in the overlying Chesterfield zone on the west side of the canyon and became the most important producer. Several other small mines supplied local markets, but their total production was small. Through 1950, production from the field averaged 100,000 short tons per year; production declined until 1954, when the mine was closed. Total production was 2.65 million short tons, mostly from Sego, Thompson, and Nash canyons.

The Sego coal field has an estimated 293.6 million short tons of coal in beds 4 ft or more thick. Of this, 116 million short tons are in the Chesterfield zone, 93 million short tons in the Ballard and 76 million short tons in the Palisade (Doelling and Graham, 1972). Most is in the western part of the field near Sego because the coals beds become thinner to the east.

The coal from the Sego field is high volatile C bituminous. Its moisture content ranges from 5-10 percent; volatiles range from 28-42 percent; fixed carbon from 38-52.6 percent; ash from 4-19 percent, sulfur from .37 to 1.00; Btu per pound ranges from 9,000-12,000.

The **Tabby Mountain coal field** is on the southeastern flank of the Uinta Mountains, about 60 mi east and a little south of Salt Lake City (Figure 5). The field extends for 35 mi along an east-west

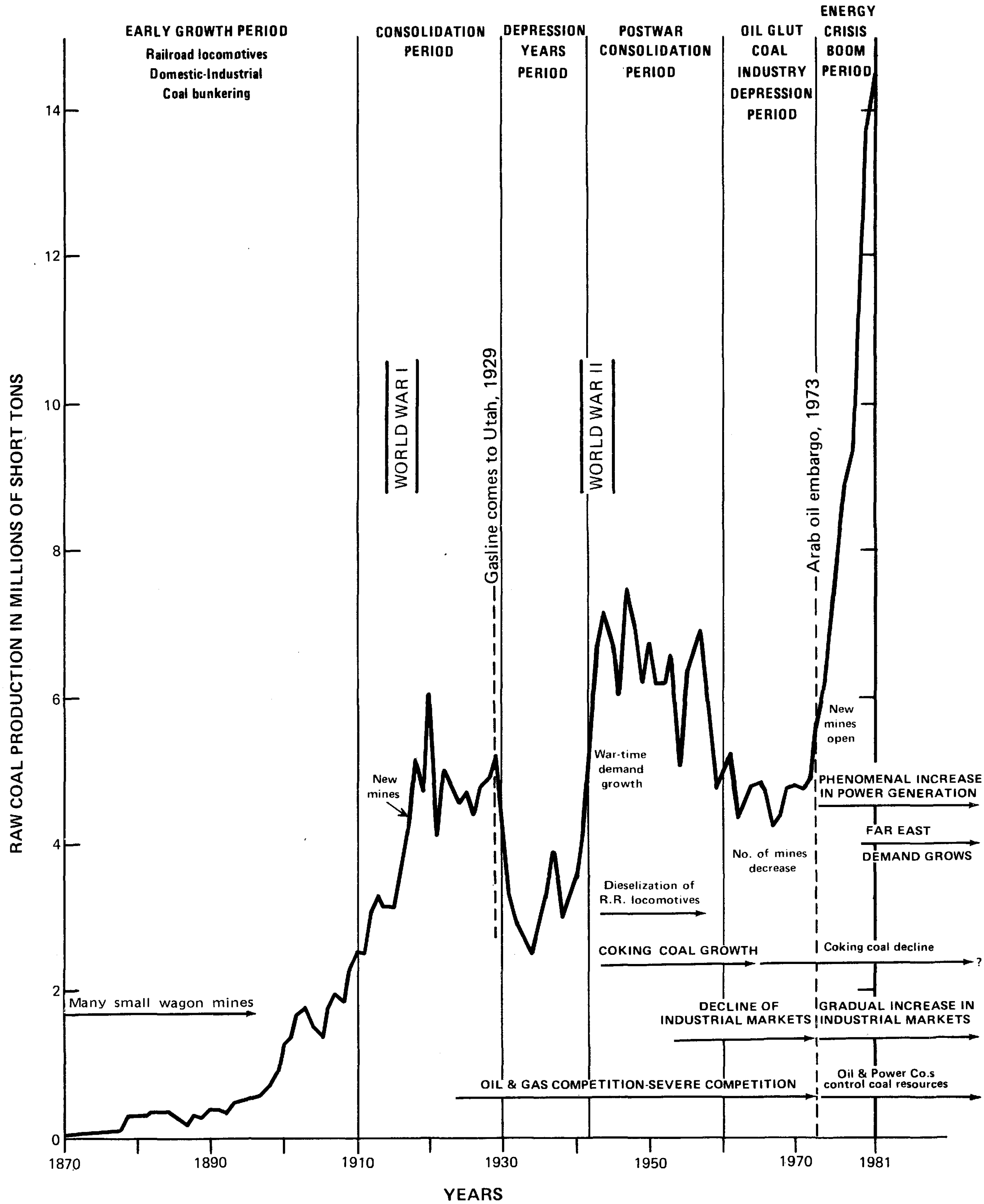

Figure 17. Utah raw coal production, 1807-1981, indicating historical events that have influenced the coal industry in Utah.

direction. The coal-bearing formations dip steeply to the south, so that the minable width of each zone is about one mile wide, giving a total area of about 70 sq mi.

The coal is found in the Frontier Member of the Mancos Shale Formation and the overlying Mesaverde Formation, both of Upper Cretaceous age. The latter is the more important, with numerous coal-bearing beds in the upper part. Coal beds in the Frontier are up to 10 ft thick; those in the Mesaverde up to 20 ft or more.

Dips in the coal beds range from 24-75° to the south and average 35°. Four major northwest-trending faults, .5 to 2 mi apart, cross the field between Red Rock Mountain and the Duchesne River, and have considerable displacement. Near Current Creek, on the west, the structure becomes more complex where it has been deformed by the Strawberry thrust, which makes an effective western boundary of the field.

Coal was known to be present in the Tabby Mountain field as early as 1844; early settlers mined a few tons from the Winchester prospect for local use. Between 1885 and 1910, significant outcrops were found, but after 1910 only one mine, the Red Creek, remained open. It was worked intermittantly until 1949; however, its production is unknown and probably insignificant. The coal rights in the field belong mostly to the Uinta and Ouray Indians.

Coal is subbituminous C rank, high volatile (33-38 percent), low sulfur (.7-1.0 percent), fixed carbon 36-40 percent; ash 6-10 percent, average Btu/lb 8,000 -10,000.

Estimated reserves are calculated to be 321 million short tons in beds more than 4 ft thick and under less than 3,000 ft of overburden (Doelling and Graham, 1972).

The **Vernal coal field** lies on the northeast edge of the Uinta Basin, on the southeastern flank of the Uinta Mountains, near the town of Vernal. The field is about 40 mi long in an east-west direction and 24 mi in the north-south direction.

The coal occurs mainly in the Cretaceous Sandstone; some is found in the Mesaverde Formation. Frontier coal beds are thin, rarely more than 5 ft in thickness, and are badly split. The beds dip steeply to moderately into the Uinta Basin. To the west, Cretaceous rocks are covered with younger sediments.

Coal was first mined in the 1880s to supply the needs of homesteaders in Jensen and Green River; in the 1890s many small mines were opened near Vernal. As many as 20 mines were active in 1900, with peak production in 1903-05, producing 13,000 short tons annually. After 1905, imported coal of better quality became available and in 1951 the last mine was closed.

Total production in the Vernal coal field was about 250,000 short tons. Reserves are estimated to be 177 million short tons, with 164 million short tons in the Frontier Formation. Most will be difficult to mine; recovery will be about 33 percent.

Coal in the Frontier Formation is a high volatile bituminous C, with volatiles averaging 39.4 percent fixed carbon 48.5 percent; ash 12.5 percent, sulfur 1.6 percent, and Btu/lb 11,510. The Mesaverde coal is subbituminous C with volatile matter, 42.7 percent; fixed carbon 39.9 percent, ash 17.5 percent, sulfur 0.8 percent, and Btu/lb 8,750.

UTAH COAL FIELDS ON THE GREEN RIVER BASIN

The **Coalville field** is about 40 mi east of Salt Lake City, in Summit County. The field is about 9 to 7 mi parallel to the predominant northeasterly structural trend of the strata. The coal-bearing rocks are exposed in a large irregular hole or fenster in the overlying Tertiary rocks.

Coal was mined from the Coalville Member of the Upper Cretaceous Frontier Formation (Figure 16), about 1,000 ft from the base of the 4,800 ft thick formation. Coal is also found in the Spring Canyon Member, near the base of the Frontier, and at the base of the overlying Wanship Formation. Both of these latter occurrences are local in extent and have little potential. Coal beds in the Coalville Member are up to 12.5 ft thick, averaging 8-20 ft. Outcrops are found around the badly faulted Coalville anticline; beds dip 10-90° west.

The Coalville field was discovered in 1859. Its nearness to Salt Lake City and the Park City mines provided a steady market from 1870 through the turn of the century. In 1900 alone, 75,000 short tons of coal were produced. The coming of the railroads brought competition from the better-quality

Wyoming and central Utah coal and after 1900 all but two mines were closed down. The last of these was closed in 1972.

Total production was 3.8 million tons. The coal resource is calculated at about 186 million short tons in beds four or more ft thick under less than 3,000 ft of overburden; recovery averages 50-60 percent.

The coal is subbituminous A with an average of 12 percent moisture, 4.5 percent ash, 1.32 percent sulfur, and 10,728 Btu/lb as-received. The coal has a high ash fusibility and crumbles or slacks on exposure to the air.

The **Henry's Fork coal field** is a series of small coal-bearing areas located along the southern edge of the Green River Basin and the northern flank of the Uinta Mountains. All are located south of the Wyoming line in eastern Summit and Daggett counties.

Coal occurs in the lower Eocene Wasatch Formation; the Paleocene Fort Union Formation; Upper Cretaceous Erickson Sandstone, Red Springs and Frontier formations, and in the Upper Mississippi Manning Canyon Shale. Only the latter has been prospected. There has been no activity since World War II; little coal has been removed.

The structure along the north flank of the Uinta Mountains is highly complex; most of the coal-bearing units dip steeply to the north and are cut by various types of faults with all degrees of displacement.

A few analyses indicate a high-volatile C bituminous coal, high in ash and sulfur. Some is probably of lower rank. Reserves have not been measured, since beds over 4 ft thick are very local.

SOUTHEASTERN COAL FIELDS

The **La Sal** and **San Juan coal fields** are located in southeastern Utah, mostly within the Grand and San Juan counties (Figure 1). The coal is in the 30-210 ft thick Dakota Formation of Cretaceous age, which forms a cap rock on the mesas and benches in the region around and between the Abajo and La Sal mountains. The La Sal field consists of scattered patches around the La Sal Mountains east of Moab, and the San Juan field is near the surface of the Sage Plain Plateau in eastern San Juan County.

Coal exposures are rare, covered in many places by colluvium or other surficial material. The coal appears to be in rather thin, discontinuous beds in the the middle member of the Dakota, and rarely exceeds 14 in. Potential area is about 70-25 mi, but extent of coal is unknown and thicknesses are sub-commercial.

Neither field has significant past production or reserves. Total past production is estimated at about 300 short tons (Doelling and Graham, 1972). No beds of 4 ft or greater thickness are known. Limited quality data show coal to have 3.5 percent moisture, 21 percent ash, 2.9 percent sulfur, and a heat value of 10,890 Btu/lb as received.

A summary of the original coal reserves of Utah prepared by Doelling (1972b) shows 24.3 billion short tons underlying 3,000 ft or less of overburden. Recent exploration has increased resources estimate of the Henry Mountains field. From one-third to one half of the original resource is considered recoverable (Table 10).

Table 11 summarizes the production of Utah coal by field. The production of Utah coal is closely tied to a variety of factors, including available transportation, nearness to markets, coal quality, competing energy sources, and general economic conditions. Figure 16 shows the history of Utah coal production, with its peaks and depressions. The peaks were caused by the coming of the railroads and general industrial growth following the World Wars

Table 10. Utah coal budget.

Field	Principal reserve x 10^6 (tons)	Recoverable reserve x 10^6 (tons)	
Kaiparowits Plateau	7,878.0	2,363.4	.3
Wasatch Plateau	6,378.9	1,814.2	.284
Book Cliffs	3,667.5	1,074.8	
Kolob	2,014.3	804.9	
Alton	1,509.4	754.7	
Emery	1,430.4	427.5	
Sego	293.6	129.5	
Mt Pleasant	249.1	99.6	
Tabby Mountain	231.2	69.4	
Henry Mountains	313.3	141.0	
Coalville	186.0	51.6	
Vernal	177.1	52.9	
Salina Canyon	86.4	29.8	
Wales	12.2	3.0	
Sterling	2.0	0.5	
Harmony	1.3	0.4	
Lost Creek	1.1	0.4	
Total	**24,431.8**	**7,817.6**	

[1]If part of coal is strip-mined (Doelling, 1972b, p. 554).

Table 11. Utah coal production by coal field, 1870-1981 (in 000's of short tons).

Year(s)	Book Cliffs	Wasatch Plateau	Emery	Coalville	Sego	Others	Totals
1970-1970	208,800	99,481	1,649	4,244	2,652	2,270	319,048
1971	2,738	1,722	142	12	–	12	4,626
1972	2,507	2,143	146	6	–	–	4,801
1973	2,467	2,953	230	–	–	–	5,650
1974	2,187	3,609	250	–	–	–	6,046
1975	2,241	4,562	134	–	–	–	6,938
1976	2,534	5,241	193	–	–	–	7,968
1977	2,722	5,764	348	–	4	–	8,837
1978	2,207	6,499	497	–	–	50	9,253
1979	2,725	8,640	732	–	–	–	12,097
1980	2,993	9,875	761	–	–	–	13,629
1981	3,365	10,190	650	–	–	–	14,205
Totals	**237,486**	**160,679**	**5,723**	**4,262**	**2,654**	**2,332**	**413,134**

NOTE: Last digits are adjusted to compensate for rounding. Compiled by H. H. Doelling and A. D. Smith.

and, most recently, the rising costs of petroleum. The slumps were caused by the Depression of the 1930s and by the discovery of apparently unlimited supplies of low cost oil and gas in the 1960s.

Today, Utah coal production is near capacity, with 28 mines reporting production in 1981. Several companies have plans for expanding or opening new mines.

Increased demand for coal is expected from the coal-fired plants now being built in Utah and on the west coast. There is a growing market for coal from overseas buyers and from industries converting to coal. It is expected that production of Utah coal will continue to grow from 1981's 14.2 million to about 30 million short tons by the year 2000.

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UTAH "COAL" PLACE NAMES

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The study of place names and their interrelationship with other phases of culture may help to illuminate significant aspects of Utah's cultural history, geology, and geography. Descriptive toponyms, based on coal-bearing formations and coal mining activities, provide just one example of that man-land relationship (Figure 1).

Mormon pioneers were the first English-speaking people to attach a coal-related name to Utah's landscape. While exploring Utah's Dixie in the winter of 1849-50 for possible settlement, a Mormon explorer party under the leadership of Parley P. Pratt made the first coal discovery. The coal was found along a stream on the edge of what is today known as the Kolob Plateau Coal field in Iron County. Initially called the Little Muddy, the stream was renamed Coal Creek (**1**) after the coal was discovered. In late 1851, Cedar City was founded near the discovery site, and coal production commenced in a small way by 1852. Despite the generally low quality of the coal and distance from markets, mining in the area continued intermittently but ceased in 1969.

As the pioneers expanded their settlements through Sanpete and Sevier valleys in the early 1850s, two men, J. E. Ruse and John Price, reportedly learned of the Sanpete coal deposits from a Ute Indian who called it "rock that would burn." Sanpete coal was first mined in 1854 at a place called Coalbed, then renamed Coalville and since 1869 it has been known as Wales. Named for the British principality, Wales was settled by Mormon immigrants from the coal mining regions of Wales. According to the 1980 U. S. census, Wales has only 153 inhabitants.

The tremendous influx of immigrants into the Utah Territory during the first decade of settlement intensified the need for fuel, especially in the Salt Lake City area where the bulk of the population had settled (the 1850 U. S. census reported 11,380 inhabitants for the Territory; 1860, 40,273). Coal then was too expensive because of distance to the market place and citizens were generally not yet convinced of its merits. During an address delivered on May 27, 1855 in the Salt Lake Tabernacle, Brigham Young discussed his visit to the Sanpete coal beds and the possiblility of shipping coal to Salt Lake "if persons in the city will encourage the business." He then pointed out that "if we turn our attention to coal for fuel, we can easily store away a winter's stock in our cellars, and turn the key upon it, and this will actually make some men practically honest, whereas, if your wood pile is out of doors, they may continue to be dishonest." Coal critics disliked the fuel because of the associated dust, but Brigham Young had some advice for them. Said he: "... I will offset that inconvenience with one to which we are subject when burning wood; then our houses are often infested with spiders, bugs, ants, and other insects, which has always been a great annoyance to me. I have often almost dreaded to bring an armful of wood into the house, lest such insects should drop from it."

To meet the growing demand for coal the Territorial Legislature offered in 1854 a reward of $1,000 to anyone discovering coal within 40 miles from Salt Lake City. The reward was claimed in 1859 when coal was discovered in Summit County by Mormon settlers who established the community of Coalville (**2**) the same year. Coalville eventually became the county seat for Summit County and had a population of 1,031 in 1980. Meanwhile, Coalville has become a center for oil and gas drilling and production in the Thrust Belt region.

Several other communities with "coal" place names occur in Carbon County. The name Carbon is in reference to the vast deposits of coal and hydrocarbon shale within the county. The county was

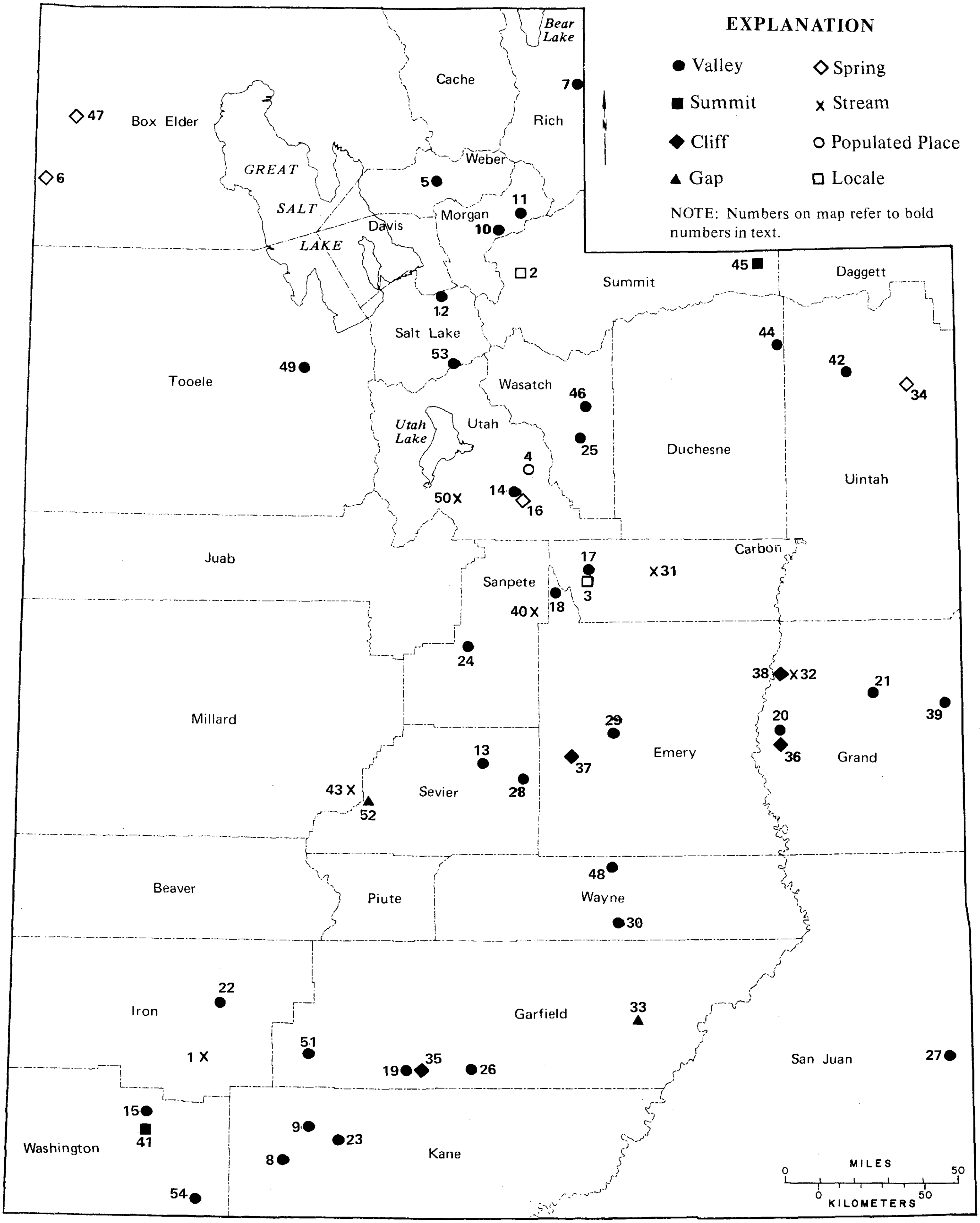

Figure 1. Distribution of Utah "coal" place names in Utah.

organized in 1894 and extends from the crest of the rich coal-bearing Wasatch Plateau eastward across the coal-rich Book Cliffs to the Green River. The population of Carbon County has always been of diverse ethnic backgrounds and small in numbers, but renewed mining efforts between 1970-80 caused a population increase from 15,647 to 22,179, a 41.7 percent increase. The other Utah "coal" counties, Emery and Sevier, experienced even greater population boosts (Emery, 122.9 percent, from 5,137 to 11,451 people; Sevier, 45.8 percent, from 10,103 to 14,727).

Coal City (**3**, Carbon Co.), nine miles west of Spring Glen, emerged in 1921 on the map but disintegrated in 1935 when coal production sharply declined due to the Depression and, finally, was abandoned by 1940. Another ghost town is Carbon (Carbon Co.), formerly known as Heiner (named for Moroni Heiner). One recreation site on Diamond Creek, approximately 23 mi south of Springville (Utah Co.), is named Coal Mine Campground (**4**).

In addition to these cultural coal-bearing place names, numerous other physical features in Utah have "coal" names attached to them. While almost all of the following names are found in areas with known coal deposits, some features carry "coal" names mistakenly. For example Coal Hollow (**5**, Weber Co.) and Coal Bank Springs (**6**, Box Elder Co.) are not associated with a coal field but run over black shale. Another Coal Hollow (**7**), located some eight miles NE of Randolph (Rich Co.), runs by a phosphate mine where no known coal deposits exist.

In addition to the above mentioned Coal Hollows there are eight more, making it the most numerous "coal" name in the state. It occurs in the following counties: Kane (**8, 9**), Morgan (**10, 11**), Salt Lake (**12**), Sevier (**13**), Utah (**14**), and Washington (**15**). One Coal Hollow Spring is located in Utah County (**16**).

The name Coal Canyon is used nine times: Carbon (**17**), Emery (**18**), Garfield (**19**), Grand (**20, 21**), Iron (**22**), Kane (**23**), Sanpete (**24**), and Wasatch (**25**).

Garfield and San Juan counties each have one Coal Bed Canyon (**26, 27**) and two valleys in Emery County are named Coal Wash (**28, 29**). In the Henry Mountains region we find a Coaly Wash (**30**, Wayne Co.), referring to the thin coal beds along the wash. Two Coal creeks are found in Carbon (**31**) and Grand counties (**32**).

Research from the USGS 7.5 and 15 minute topographic quadrangle sheets show that all other "coal" names appear only once as a landform or drainage feature on Utah's map. They include the following names: Coal Bed Mesa (**33**, Garfield Co.), Coal Bed Spring (**34**, Uintah Co.), Coal Bench (**35**, Garfield Co.), Coal Canyon Bench (**36**, Grand Co.), Coal Cliffs (**37**, Emery Co.), Coal Creek Bench (**38**) and Coal Draw (**39**) in Grand Co., Coal Fork (**40**, Sanpete Co.), Coal Hill (**41**, Washington Co.), Coal Mine Basin (**42**, Uintah Co.), Coal Mine Creek (**43**, Sevier Co.), Coal Mine Draw (**44**, Duchesne Co.), Coal Mine Hill (**45**, Summit Co.), Coal Mine Hollow (**46**, Wasatch Co.), Coal Mine Spring (**47**, Box Elder Co.), Coal Mine Wash (**48**, Wayne Co.), Coal Pit Canyon (**49**, Tooele Co.), Coal Pit Creek (**50**, Utah Co.), Coal Pit Wash (**51**, Garfield Co.), Coalbed Pass (**52**, Millard Co.), Coalpit Gulch (**53**, Salt Lake Co.), Coalpits Wash (**54**, Washington Co.).

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PALEOBIOLOGICAL FACIES AND COAL FORMING ENVIRONMENTS

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ABSTRACT

Invertebrate faunas of marginal marine, brackish, and fresh water origin are common components of depositional systems containing significant coal deposits. These biotas are only sparsely known, however, and are not presently utilized in the reconstruction of coal depositional systems or the development of exploration models. These faunas mainly consist of diverse molluacs, arthropods, generalized areraceous-foraminifera, and various soft-bodied trace making organisms that have evolved little from Jurassic to Recent time. Modern counterparts in the same deltaic, bay, lagoon, estuarine, and coastal swamp environments are highly sensitive to variations in the aquatic environments reflecting spatial and temporal changes in rates of sedimentation, turbidity, water movement, temperature, salinity, oxygen, and other chemical parameters which are also important in determining the inherited chemistry of associated and (by downward percolation or erosion) older underlying sediments, including peats and coals. Ultimately, coal quality strongly reflects the chemical environment of overlying waters, and/or of ground water derived from them prior to lithification and metamorphosis of the coal. Because invertebrate animals are the sensitive indicators of modern and ancient water chemistry, they should be valuable tools in reconstructing, coal depositional environments and in predicting coal quality over large areas. This is a preliminary report on research under way to test this hypothesis.

Previous investigations have suggested two predictive models for evaluating the size, geometry, and quality of coal deposits in the Cretaceous and Paleocene of the western interior United States: (1) Coal bodies are of small scale and irregular geometry during marine transgressive events representing eustatic sealevel rise because of the generally resticted nature of progradational coastal and deltaic sequences, rapid subsidence, basin geometry, and severe onlap erosion across the top of these sequences are the cause for this situation. Eustatic fall and epicontinental regression, however, are accompanied by basin filling, extensive stacking and offshore development of progradational sequences, resulting in large-scale development of coal beds with predictable geometries, protected subsequently by low energy fluvial or lagoonal/lacustrine sediments. Biotas associated with Cretaceous and Paleogene coal depositional systems can be used to differentiate between transgressive and regressive sedimentary suites, and in some cases provide important biostratigraphic data allowing correlation of coal deposits with global sealevel curves. Periods of peak transgression, slow regression and peak regression are prime times for accumulation of thick coal deposits in epicontinental seas.

(2) Coal quality is poor, with relatively high ash and sulfur content, in depostional settings where the original peats are associated with, overrun by, or later permeated by waters of moderate to high salinity (mid-brackish to normal marine). Such settings are most likely to develop during eustatic rise and epicontinental transgresion where swamps, lagoons, delta plains, and estuaries become progressively more saline with transgression, and where older peats are cut by transgressive disconformities and infiltrated with marine waters. Coal quality is best where fresh to slightly brackish water systems are associated with or override deposits, and where they are protected by fluvial, lacustrine, or bayfill sediments prior to ensuing marine regression. Eustatic stillstand at peak transgression and regression, and slow regression create environments for the formation and protection of extensive coal deposits in dominantly fresh water settings.

It is obvious, therefore, that any geologic, chemical or biological parameters that would allow prediction of salinity and oxygen levels in coal depositional systems, and correlation with global sealevel curves, would be extremely valuable in assessing and predicting coal quality, as well as the extent and geometry of coal bodies. In order to assess the value of fossil biotas in the interpretation of water chemistry and the prediction of coal quality, highly detailed stratigraphic and paleobiologic transects have been made across numerous coal depositional systems, from marine to fresh water settings. Stratigraphic sequences of faunas from each transect were compared and intercalated to formulate a bilogic model for salinity in Cretaceous marginal marine facies. From lower shoreface to freshwater facies associated with thick coal sequences the follwoing succession of paleocommunities has been determined along a decreasing salinity gradient; Numerically dominant taxa are listed as characterizing species:

1. *Inocemus-Thalassinoides,* middle shoreface community.
2. *Flemiostrea-Thalassinoides* upper shoreface community.
3. *Areniolites, Ophiorpha, Diplocrarion* upper shoreface community (with *Cymbophora* and *Cardiidae* in some cases).
4. *Skolthos, Arenicolites, Ophiomorpha, Protodonax* intertidal community.
5. *Crasstrea, Brachidontes, Barbatia, Anomia* back barrier, lower estuatrine, tidal channel community.
6. *Crasstrea, Corbula* (or *Caryoescorbula*), *Brachidontes* mid-brackish bay or estuarine community.
7. *Colabus* (or *Caryocorbula*) mid-brackish community.
8. *Corula, Corbicula, Tellina* mid-brackish community.
9. *Corcula* upper brackish community.
10. *Corcula, Plesielliptio* upper estuarine slightly brackish community.
11. *Unionid (Plesielliptio* or *Anodonta)* fluvial community.

Communities 7-11 are commonly associated with high quality, large scale coal deposits and represent fresh to slightly brackish water. A large group of lower estuarine, baymouth, and nearly normal marine communties known elsewhere in the Cretaceous are conspicuously missing between 4 and 5 above in coal depositional systems, but are associated with poor transgressive coals of irregular geometries.

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INFLUENCE OF TRANSGRESSIVE-REGRESSIVE PULSES ON COAL-BEARING STRATA OF THE UPPER CRETACEOUS ADAVILLE FORMATION, SOUTHWESTERN WYOMING

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INTRODUCTION

The Adaville Formation (Campanian) of southwestern Wyoming consists of marginal marine and nonmarine sediments that accumulated in a wave-dominated deltaic setting on the western margin of the Western Interior Cretaceous seaway. The formation is of geologic and economic interest for the extent and thickness of its coal seams. The basal coals of the Adaville Formation reach a thickness of 100+ ft. Detailed stratigraphic and sedimentologic analysis has permitted the construction of a possible model for the origin of the Adaville coals. This model has predictive values for the Adaville Formation as well as other coal-bearing sequences along the margins of rapidly subsiding foreland basins. The model expands upon environmental models given by Fischer et al (1969), Galloway (1975), Coleman (1976), Balsley (1980), Horne et al (1980), and others for both ancient and modern wave-dominated deltas, and is an extension of the predictive stratigraphic model of Ryer (1981) for Cretaceous coal-bearing strata of the Western Interior.

STUDY AREA

The Adaville Formation is genetically related to the upper shale unit of the Hilliard Formation, (Frerichs and Steidtman, 1971; Adams and Frerichs, 1973), the "Hinshaw Member" of the Hilliard Formation (Smith, 1965), and the Lazeart Sandstone Member of the Adaville Formation. These lithostratigraphic units are therefore included in this study. The rocks are exposed in a north-south trending linear belt along the eastern margin of the Wyoming Thrust Belt (Figure 1). The geology of the study area has been mapped by Veatch (1907), Rubey et al (1975), Vietti (1977), Worrall (1977), and M'Gonagle (1979).

STRATIGRAPHIC AND STRUCTURAL SETTING

Southwestern Wyoming was at the margin of an extensive interior seaway throughout much of the Cretaceous (McGookey et al, 1972; Williams and Stelck, 1975). The seaway underwent a series of major transgressions and regressions (Gill and Cobban, 1973; Kauffman, 1977), which caused the shoreline to migrate back and forth across the study area. The sea was bounded on the west by the Sevier orogenic belt (Armstrong, 1968), which consisted of an eastward advancing sequence of thin-skinned west-dipping thrust faults of late Jurassic to Eocene age (Armstrong and Oriel, 1965; Royse et al, 1975; Dorr, 1981). The upper plates of the thrust sheets served as sediment sources for terrigenous clastics shed into the western margin of the seaway. These sediments accumulated to a thickness of 18,000+ ft in a prominent foreland basin centered in western Wyoming (Jordan, 1981).

The stratigraphic and structural framework of the western Wyoming foreland basin is summarized in Figure 2. Progradation of the Lazeart Sandstone and Adaville Formation into the Hilliard sea had commenced by the early Campanian (Miller, 1977). Following initial progradation, a minimum of seven transgressive-regressive pulses produced a complex intertonguing of marine and nonmarine lithofacies. These pulses played a significant role in the formation of Adaville coals.

METHODS

Forty eight detailed measured sections,

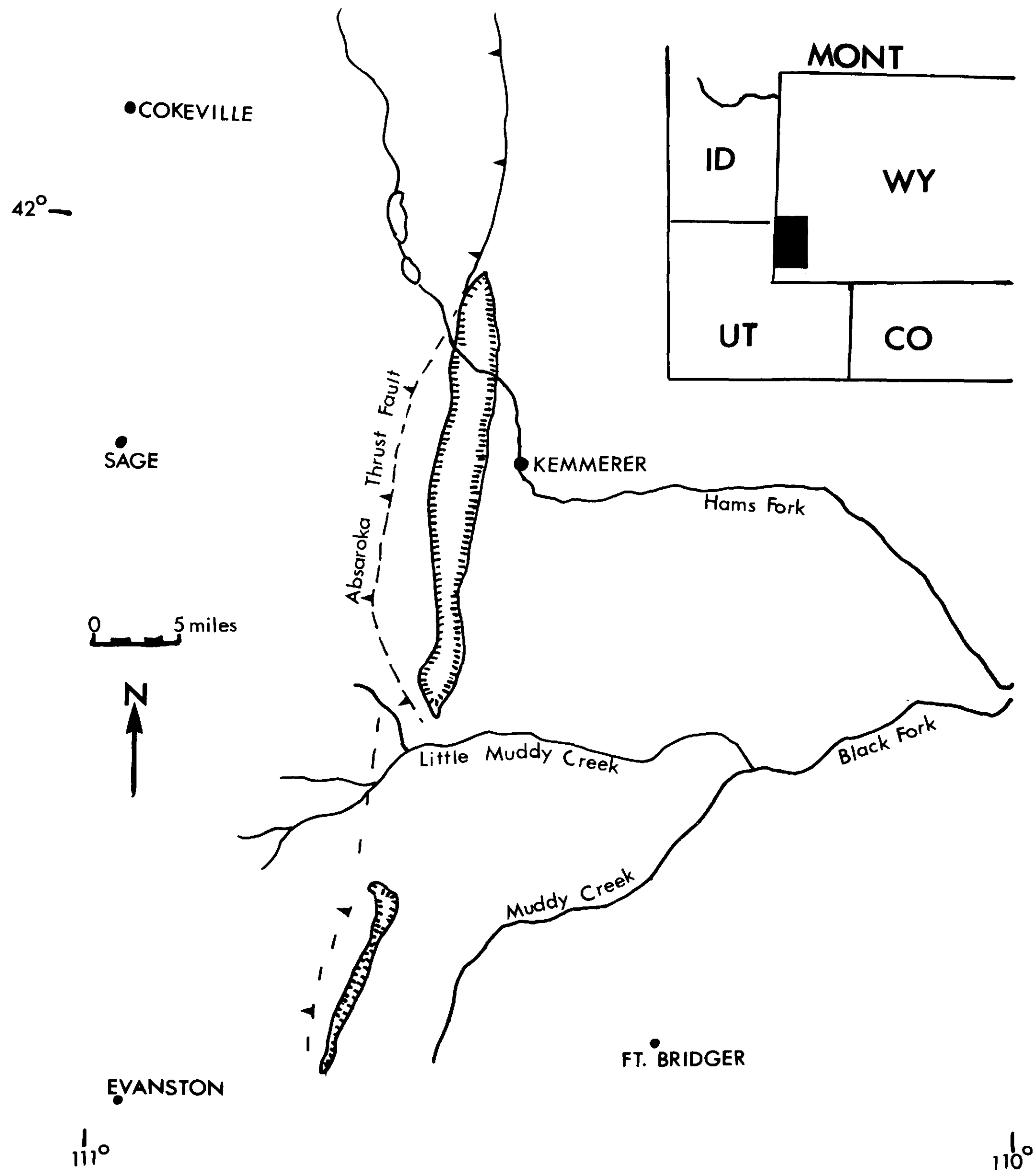


Figure 1. Location map of study area in southwestern Wyoming. The outcrop of the upper shale unit of the Hilliard Formation, the Hinshaw Member of the Hilliard Formation and the Adaville Formation, including the Lazeart Sandstone Member, is indicated by hachures.

averaging 400+ ft in thickness, form the basis for this study. Sections are concentrated within the upper Hilliard-Lazeart-Adaville Formation transition, though several sections extend more than 1,000 ft into the Adaville Formation. These measured sections have been supplemented by geophysical logs (natural gamma, neutron, gamma-gamma density, sp and resistivity) supplied by area coal companies. In addition, lithologic logs from both cuttings and cores have been utilized. Units were traced laterally on oblique and orthagonal aerial photomosaics. Mine highwalls and wingwalls were photographed, measured, and sketched to provide details of the normally poorly exposed delta-plain lithofacies.

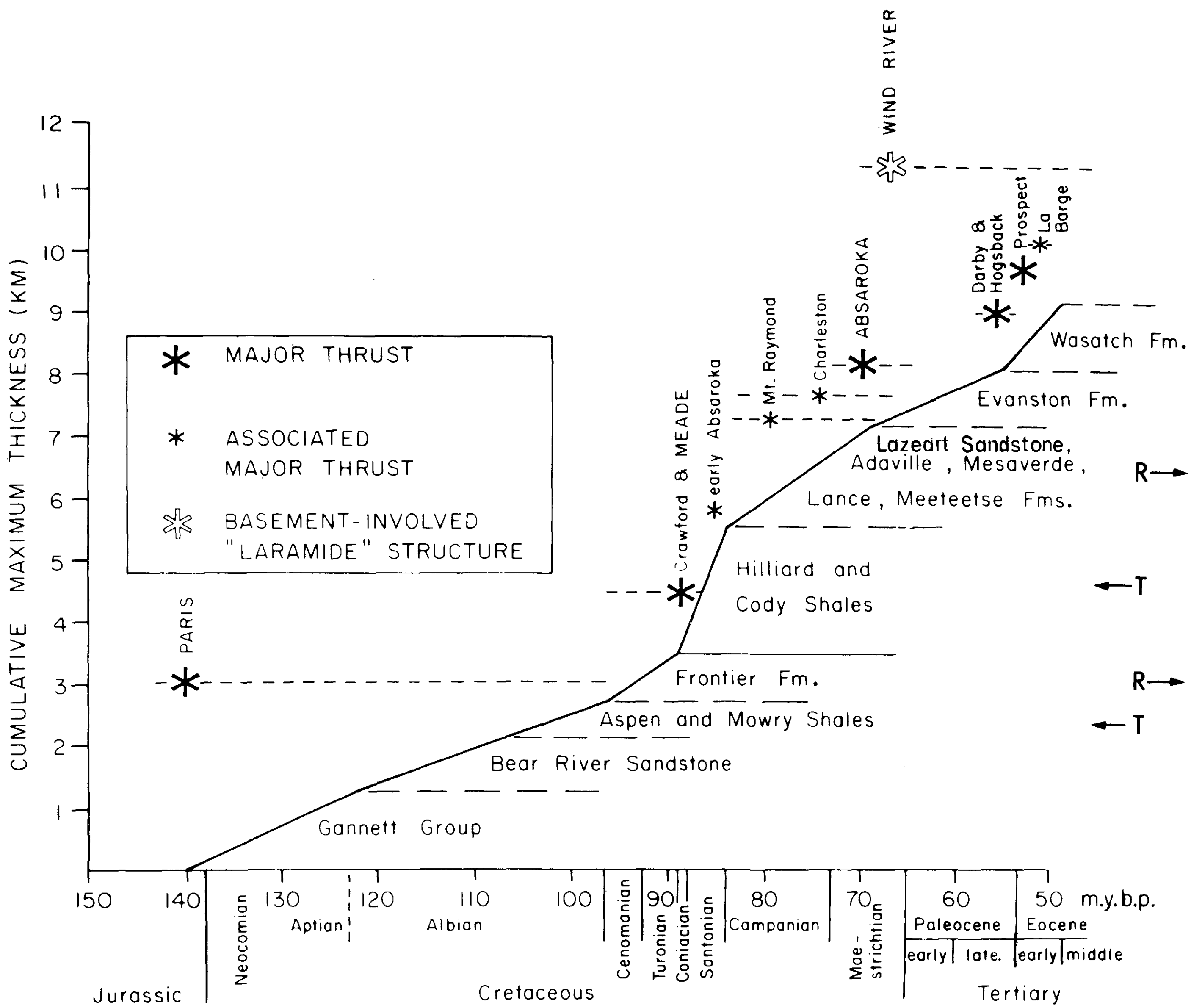


Figure 2. Position of the Hilliard Formation, Lazeart Sandstone, and Adaville Formation within the stratigraphic and structural framework of the Idaho-Wyoming Thrust Belt. Major Cretaceous transgressions and regressions are indicated (modified after Jordan, 1981).

Because of the proprietary nature of much of the data, no geographic coordinates are given in this paper for information relevant to thickness, geometry, and distribution of coal seams. In addition, sections have been partially restored, and details of individual coal seam variation ommitted.

FACIES TRACT

The major lithostratigraphic units genetically related to the development of the thick Adaville coals are shown diagrammatically in Figure 3. In general, the shallow marine and marginal lithofacies rise stratigraphically to the south. The sediments were deposited within a wave-dominated deltaic regime at various stages of construction and abandonment. The upper shale unit of the Hilliard Formation is the product of deposition in a prodelta (construction) and normal shelf (abandonment) environment. The

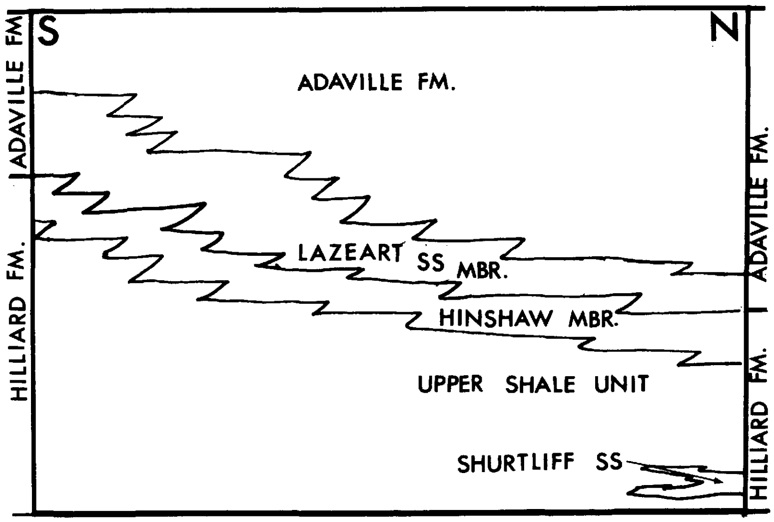


Figure 3. North-south schematic cross-section showing relationships between the lithostratigraphic units important in the interpretation of the origin of the Adaville Formation coals.

Hinshaw Member formed in a transition zone environment between the prodelta and lower delta front. The Lazeart Sandstone accumulated in lower, middle, and upper delta front, shoreface (delta flank spits and bars), flood tidal delta, and washover fan subenvironments. The Adaville Formation was deposited in lower and upper delta plain, coastal plain, and delta abandonment, lagoonal environments. Because the construction of a valid stratigraphic model is first dependent on the recognition of these subenvironments, the primary lithogenetic units and criteria used in their identification and interpretation are summarized below. Figure 4 is a highly schematic model illustrating subenvironments of the Adaville wave-dominated deltaic system at various stages of construction and abandonment.

LITHOGENETIC UNITS

Upper Shale Unit of the Hilliard Formation - Prodelta and Shelf - The upper shale unit is composed of dark gray fissile shale, massive silty calcareous mudstones, and silty fine-grained sandstones. It coarsens gradationally upwards and to the north where it intertongues with marginal marine and nonmarine strata of the Blind Bull Formation (Rubey et al, 1973; Frerichs and Steidtman, 1971).

Thin (1-3 in) sandstone beds rich in carbonaceous material increase upsection. Horizontal sand-filled burrows increase upwards in abundance. Pyritized shell material is present but not common. Macrofossils are rare, though several *Baculites* sp. have been found in the course of this study. Smith (1965) reports a low diversity marine fauna including *Clioscaphites, Inoceramus* and *Placenticeras*. Planktonic and bethonic foraminifera are present in widely varying ratios, abundance, and diversity (Adams and Frerichs, 1973).

The upper shale unit was deposited in a prodelta and normal shelf environment. Sedimentation in these environments is primarily from suspension. Thin organic-rich fine-grained sandstones may represent seaward transport of delta front and/or shoreface sands during storm events. Thinly laminated shales, paucity of macrofossils, decreased ratios of planktonic to benthonic foraminifera, preservation of "coffee ground" organic fragments, and low species diversity and abundance of both macrofauna and microfauna, attest to high sedimentation rates present in prodelta settings. Calcareous zones, massive bioturbated siltstones, and high ratios of planktonic to benthonic forams may signal delta abandonment and reduce sedimentation rates in a normal shelf setting.

"Hinshaw Member" of the Hilliard Formation - Transition Zone - The "Hinshaw Member" is an in-

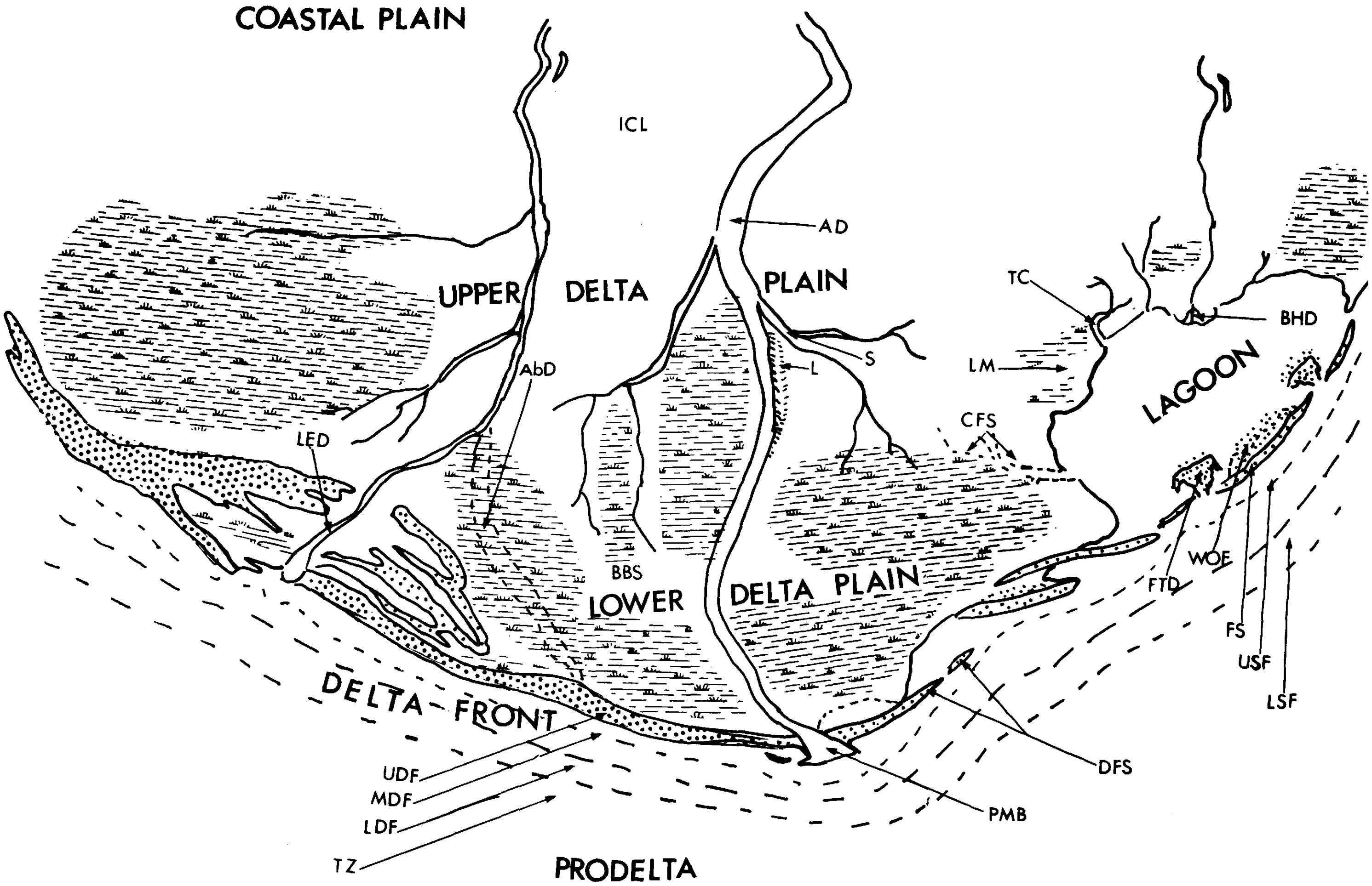


Figure 4. Possible model for the Lazeart-Adaville wave-dominated deltaic system. The illustration shows the depositional systems at various stages of construction and abandonment. All subenvironments shown did not exist within the delta at one time. Subenvironments are indicated by initials: LDF=lower delta front; MDF=middle delta front; UDF=upper delta front; TZ=transition zone; PMB=proximal mouth bar; DFS=delta flank spits and bars; FTD=flood tidal delta; WOF=washover fan; LSF=lower shoreface; USF=upper shoreface; FS=foreshore; LED=low energy distributary; AbD=abandoned distributary; BBS=back-beach swamp; L=levee; S=splay; AD=active distributary; ICL=interchannel lowlands; LM=lower marsh; CFS=channel-form slough; TC=tidal channel; BHD=bay head delta.

formal lithostratigraphic unit named by Smith (1965). It is gradational with the upper shale unit of the Hilliard Formation. The Hinshaw Member consists of alternating units of orange-tan fine-grained sandstones, silty shales, and siltstones. Thickness of shale intervals decreases to the north and upsection.

There are two genetically different orange-tan fine-grained sandstones. The first type is 1-3 ft thick, has a sharp planer basal contact, and is massive at the base to, locally, concordant-wedge across stratified insets up to six inches thick. The scale of bedding decreases upwards. Claystone and siltstone rip-ups are common in the upper thin sandstone beds. *Thalassinoides* is present in the upper portion of the sand. This first type of sandstone is interpreted to be the result of storm surge of sand from the laterally equivalent delta front, carried below normal wave base into a transition zone setting.

The second type of sandstone ranges in thickness to 20 ft. The base is gradational into bioturbated sandy siltstones. The upper contact is fairly sharp into silty shales; the bedding is massive.

Sorting increases and clay content diminishes upwards. Fragments of *Inoceramus* are present but not common. This type of sandstone is interpreted to have formed at the distal end of the lower delta front, below normal wave base, in an oxygenated environment. The massive appearance of the sands is due to the burrowing activity of infaunal marine organisms.

The silty shales, siltstones, and silty sandstones of the Hinshaw Member are heavily bioturbated. These lithologies usually have a mottled appearance. Burrowing appears to increase with a decrease in clay content upwards in the unit. Macroscopoic organic debris is common. Preserved macrofossils are rare, though locally *Inoceramus* fragments are present. The finer-grained units of the Hinshaw Member formed during periods of normal "background" sedimentation between storm events seawards of the lower delta front sands.

Lazeart Sandstone Member of the Adaville Formation - Marine influenced sandstone - The Lazeart Sandstone Member consists of eight different types of genetically distinct sandstone lithofacies: lower, middle, and upper delta front, lower and upper shoreface, wave-dominated proximal mouth bar, flood tidal delta, and washover fan. Recognition of these lithogenetic units is critical in reconstructing a history of transgressions and regressions.

Lower delta front sands - In a wave-dominated deltaic system, the lower delta front is that part of the submarine delta formed above average maximum wave base but below the breaker zone. The lower delta front is hydrodynamically equivalent to the lower shoreface of beach-barrier sequences.

The lower delta front sands are lower fine-grained, moderately well-sorted, and subrounded. The bedding is variable, consisting of 1) even parallel sets 5-6 in thick with planar bases containing thin, parallel, horizontal laminae; 2) low angular discordance hummocky cross-stratification; and 3) structureless intervals where primary bedding has been destroyed by bioturbation. Clay, silt, and organic content is sharply reduced relative to the transition zone below. In contrast to the mottled sediments of the transition zone, discreet burrows of *Ophiamorpha* are locally abundant. *Inoceramus* sp. and *Placenticeras* sp. are present but very rare.

The even parallel laminated sands were produced by deposition from sand transported seaward from the middle delta front, upper shoreface, possibly by rip currents, during fair weather periods. Hummocky cross-stratification is the product of interaction of storm-generated wave orbitals with the sea bed. The bioturbated intervals reflect periods of reduced sediment input.

Middle delta front - The middle delta front is that part of the submarine delta landward of the breaker zone and seaward of mean low tide. It is equivalent to the upper shoreface of beach and barrier sequences.

The boundary between the lower delta front and middle delta front is commonly associated with a color change from light tan to greyish white. Sedimentary structures of the middle delta front are medium-scale trough cross-stratification with multimodal current directions; and even parallel sets .5-3 in thick containing thin parallel laminae. The contact between the middle and lower delta front is often heavily burrowed by *Thallasinoides* and *Ophiamorpha*. Above this zone discreet burrows are rare.

Medium-scale trough cross-stratification was produced by migration of mega-ripples over the sea floor. Even parallel beds formed in response to sheet flow in the surf zone (Clifton, 1976). Processes operating within the middle delta front include wash and backswash, rip current flow, longshore drift, as well as landward and seaward directed wave surge.

Upper delta front - The upper delta front is the intertidal zone of the beach. It is equivalent to the foreshore in barrier sequences. Upper delta front sands are upper fine to medium-grained, subrounded and well-sorted. The bedding is low angular discordant sets of even parallel laminae, alternating with horizontal even parallel laminae. *Skolithos* burrows are locally common. The top of the upper delta front is often heavily rooted and iron stained. Sedimentary structures in the upper delta front form in response to conditions of plane-bed sediment transport generated by swash and backswash.

Wave-Dominated proximal mouth bars - The point sources for delta front sands within wave-dominated settings are not readily recognizable because of extensive wave reworking. The sands of proximal mouth bars therefore appear to be lithologically and structurally similar to delta front sands. Their identity, however, can be inferred from the following: 1) increase in sand thickness for a given lithofacies; 2) presence of avalanche foresets; 3) increase in convolute bedding and dewatering structures; 4) presence of carbonized logs and thin (.5 inch) very discontinuous allochthonous coals.

Shoreface sequence - Delta flank spits, bars, and barriers - The shoreface extends from average maximum wave base to mean low tide. Shoreface terminology applies to those sands within this hydrodynamic zone that are not directly associated with delta front progradation. Subenvironments included under this definition include delta flank spits, bars, and barriers.

To date, one well documented incomplete shoreface sequence has been recognized within the Lazeart Sandstone. The unit is bounded at its base by a transgressive disconformity. An idealized vertical sequence proceeds from a moderately to poorly sorted, mottled, fine-grained sandstone with abundant clay galls, into a moderately well-sorted fine grained sandstone with horizontal planar sets up to 2 ft thick with erosional bases, into a medium-scale trough cross-stratified standstone with minor clay galls at the base of some sets. In places, this sequence has been obliterated by bioturbation. Subhorizontal to vertical *Ophiamorpha* are present. The sequence is often capped by an oyster bank *(Flemingostrea)*. No foreshore is ever developed and it is likely that within the study area the sandstone body was entirely submarine. The unit is overlain by interdeltaic-lagoonal brown to gray siltstones containing a brackish water assemblage including *Brachidontes, Corbula, Anomia, Corbicula,* and *Crassostrea.*

The shoreface sequence is inferred to have formed after a trangressive pulse flooded the study area, and records the development of a submarine spit or bar on the flank of a wave-dominated lobate delta, distal from the primary distributary network, and seward of a brackish water interdeltaic bay or lagoon.

Flood tidal deltas - Flood tidal deltas form landward of tidal inlets in response to flood tidal currents. They are common features of microtidal and mesotidal coasts (Hayes, 1975). The major components of flood tidal deltas are flood ramps, flood channels, ebb shields, ebb spits, and spillover lobes (Boothroyd, 1978).

Typical flood tidal delta exposures show a sharp basal contact, are extensively burrow mottled and contain clay galls and organic debris at the base, coarsen upwards, lose interbeds of siltstone and mudstone upwards, and show a decrease in bioturbation up-section. There is an upward increase in the scale of primary structures from small to medium-scale trough cross stratification. *Thallasinoides* is present and locally abundant over organic-rich lithologies. Flood tidal deltas show rapid lateral variation in structure and thickness in comparison to delta front sands. Scour and fill structure is common in the flood ramp and flood channel regions. Convolute bedding and dewatering structures are occasionally present in areas where the flood tidal delta overlies coals and brackish water mudstones.

Washover fans - Washover fans form during storm events by the landward transport of foreshore and upper shoreface sands into back-beach-marshes and lagoons. Transport may be by sheet flow or within washover channels (Hayes, 1967; Schwartz, 1975).

Sediments interpreted as washover fan deposits consist of fining-upward thin beds of sandstone with sharp basal contacts. The tops of individual beds are often iron stained and rooted. The percentage of thin silt and mud interbeds increases in a landwards direction. Where washover sediments have been transported into brackish water lagoons, the sands have been homogenized by bioturbation, and the tops of beds exhibit straight to slightly sinuous ripples. Washover fan lithofacies are commonly preserved within the facies tract at the landward pinchout of stacked delta front sands.

Adaville Formation - Delta plain and abandonment facies - The Adaville Formation was named for exposures east of Kemmerer, Wyoming, by Veatch (1907). Dominant lithologies are carbonaceous shales, gray silty mudstones, sideritic mudstones and coal. These lithologies formed in a number of different lower delta plain, upper delta plain, and deltaic abandonment environments. Depositional patterns within the Adaville Formation are highly variable and discontinuous, reflecting the diversity of processes operating within the delta plain environment.

Lower delta plain - The lower delta plain consists of poorly drained back-beach swamps, channel-form sloughs, low-sinuosity, low-energy distributary channels, and active sand-filled distributary channels. The number of active distributary channels is reduced relative to the upper delta plain, abandoned distributaries are more common, and sloughs and low-energy channels show evidence of brackish water inflow.

Low-sinuosity, low-energy distributary channels typically have a sharp base, high width to depth ratio, fine upwards, and contain abundant carbonaceous debris. A typical vertical sequence consists of a poorly sorted, light tan, very fine-grained sandstone with a sharp basal contact, discontinuous carbonaceous laminae, leaf imprints on bedding surfaces and beds 6 in to 2 ft thick grading upwards into nodular weathering gray silty mudstone. Levee deposits consist of 1-6 in thick beds of fine-grained sandstones with abundant carbonized roots, interbedded with dark gray carbonaceous shale. Frequent channel abandonment is evidenced by thin (1-2 in) coals interfingering with the above lithologies. *Teredo*-bored logs are present but rare in the lower reaches of these distributary channels. Coal rip-ups are common at the base.

Channel-form sloughs are mudstone and siltstone-dominated flooded swamp deposits which formed in response to base level rise in areas of local subsidence due to early compaction of peat. They are distinguished from low-energy distributary channels by lack of sharp basal contacts, evidence of slack water periods, interbedded dark gray mudstones containing pyritized brackish water fauna, and sometimes by replacement up-section by brackish water bay and lagoon sediments. Channel-form sloughs may signal the onset of delta abandonment as the lower reaches of back-beach swamps and distributaries were flooded by landward advances of the sea. Examples of channel form sloughs are today found in the Everglades.

Active distributaries consist of buff-white, very fine to fine-grained, "salt and pepper" sandstones. They are characterized by: 1) a sharp basal contact; 2) scour and fill structure; 3) common coal and silt/clay rip-ups; 4) beds 1-3 ft in thickness; 5) multi-story aspect with individual cosets separated by gray-green mudstones; 6) fining upwards of individual sets. Active distributaries grade into wave-dominated proximal mouth bars in a seaward direction and fluvial channels in a landward direction. The distinction between fluvial channels and active distributaries is based primarily on position in the facies tract.

Back-beach swamps form in poorly drained basins behind the protective barrier of the delta front sands. Characteristic lithologies are brown, heavily rooted, carbonaceous siltstones, dark gray carbonaceous shales, sideritic mudstones, and thick coals.

Upper delta plain - The upper delta plain is that part of the subaerial delta landward of the limits of brackish water influence. The dominant lithogenetic units are active distributary-fluvial channels, well-drained channel margin levels, and poorly drained interchannel swamps. Distributary channels are more common than in the basin of the lower delta plain. Sideritic mudstones are rare. Light gray green blocky fracturing claystones with slickensides and carbonized roots may indicate emergence and soil development along channel margins. Poorly drained interchannel swamp lithologies include dark gray mudstones with abundant "coffee grounds," dark gray carbonaceous shale, and coal. Interchannel swamp coals contain many splits, representing overbank flooding of the adjacent channels.

Abandonment lithofacies - Abandonment lithofacies form when the rate of subsidence or sea level rise exceeds the rate of sedimentation within the delta complex. Depending on position in the facies tract, sediments of the abandonment lithofacies were deposited in brackish water to near normal salinity bays. Lithologies include dark gray massive mudstones with minor carbonaceous material, sideritic mudstones, very fine silty sandstones, and siltstones. The sandstones probably represent distal washover fan deposits. They have a sharp basal contact, contain minor clay galls; and are laterally continuous. The top of the beds is often bioturbated and sometimes shows straight-crested to slightly sinuous, symmetric oscillation ripples.

Fauna collected from within the mudstones of the bay environment include *Corbula, Corbicula, Brachidontes,* and *Anomia.* In coarser-grained sediments, oyster reefs are sometimes present, composed almost entirely of *Crassostrea.*

Abandonment lithofacies form a widespread continuous unit over variable delta plain lithofacies and are therefore very helpful in correlation within the delta plain portion of the facies tract.

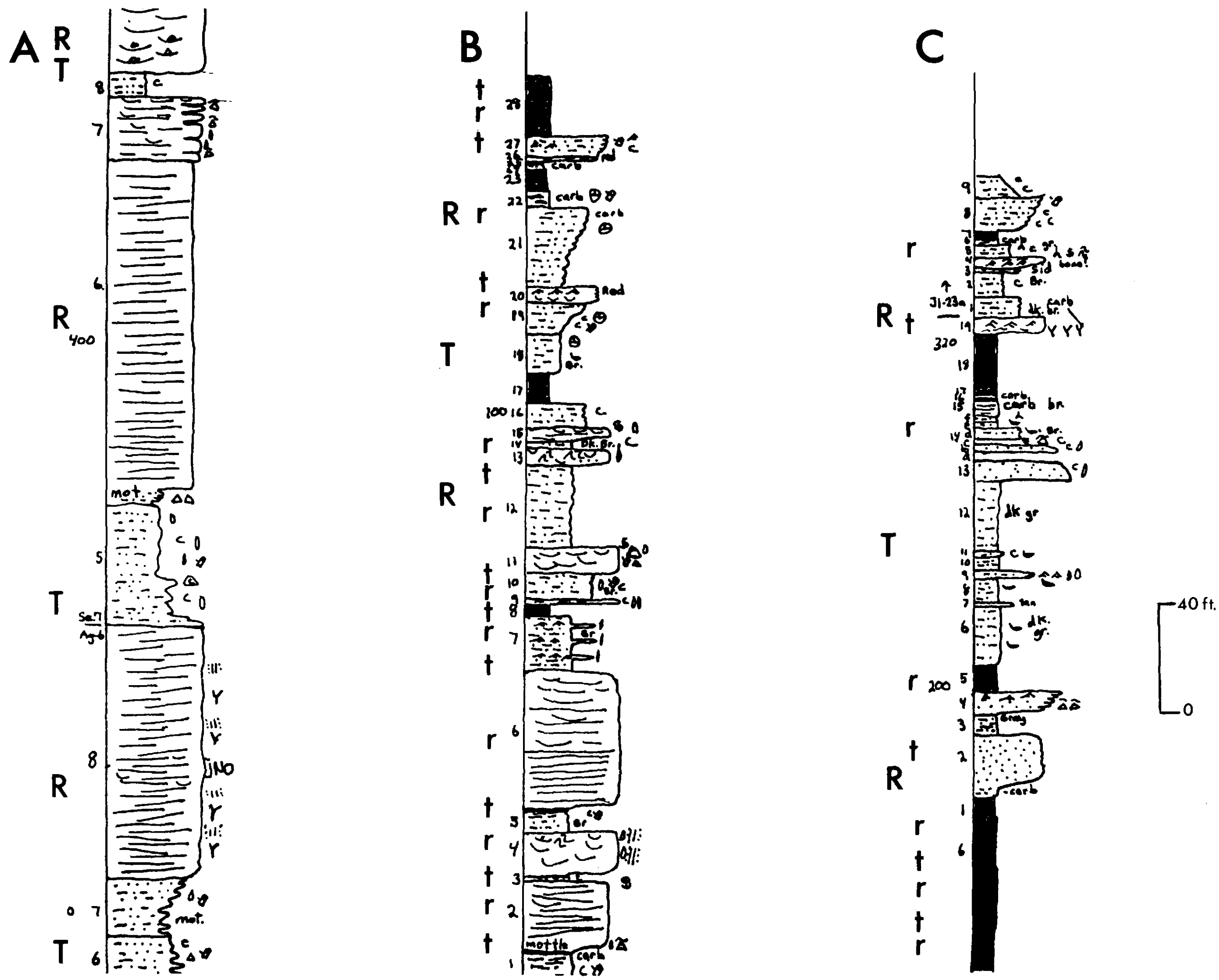


Figure 5. Portions of selected measured sections showing boundaries between transgressions and regressions. Large print indicates a major transgressive-regressive pulse, small print indicates minor pulses within the major cycles. Section A shows a small part of the seaward end of the facies tract. Sandstones formed in the lower delta front, siltstones in the transition zone and uppermost prodelta, Section B illustrates transgressive-regressive pulses near the landward pinchout of a delta front sand; upper delta front, washover, back-beach, salt water marsh, foreshore, and lagoonal facies are present. Section C is from a position in the facies tract landwards of the pinchout of a delta front sand unit. Back-beach swamp, abandonment phase brackish-water lagoon, distal washovers, upper delta front, and flood tidal delta facies are shown.

RECOGNITION OF TRANSGRESSIVE-REGRESSIVE PULSES

Emphasis was placed on the characteristics of the different lithogenetic units in the previous section because their recognition is critical in determining the nature and extent of transgressive-regressive pulses. During transgression, the shoreline migrates in a landwards direction and seaward lithofacies come to overlie landward lithofacies. The reverse holds true for regressions.

Transgressions and regressions are the geomorphologic products of the rate dependent

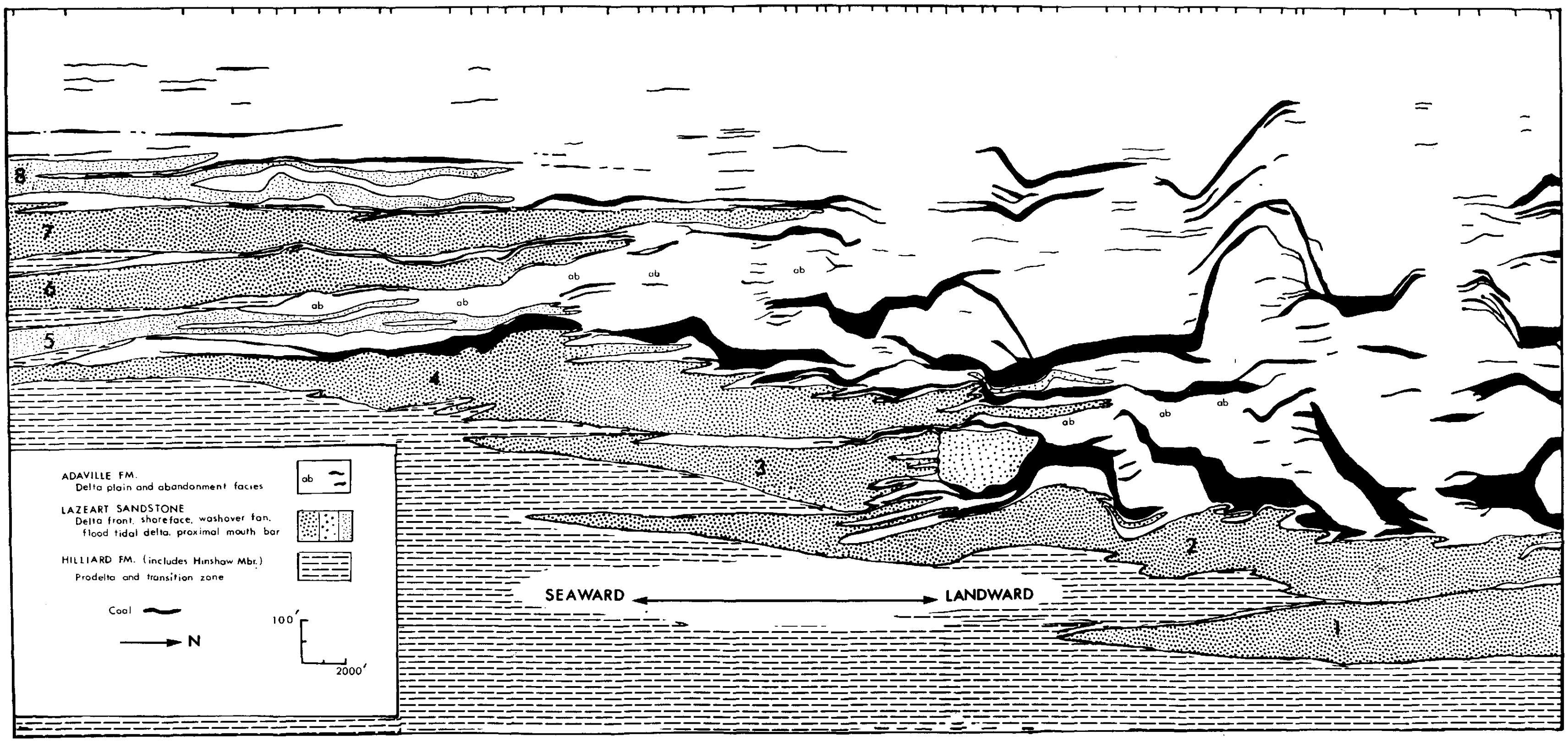


Figure 6. Simplified diagrammatic cross-section of the Hilliard-Adaville sequence in a portion of the study area. Section trends north-south. The general direction of regression was to the south-east. Sandstone numbering system is informal and may be modified when additional data are gathered. Tick marks on the upper border indicate control points (measured sections, geophysical logs, cutting and core descriptions).

processes of sedimentation, subsidence, and sea level rise. Weller (1960, p. 498-501), Van Andel and Curray (1964), Curray (1964), Curtis (1970), Vail et al (1977), and Kauffman (1977) have discussed general stratigraphic models for transgressions and regressions. Ryer (1977), Kraft (1971), Frank (1979), and Bourgeois (1980) have recently presented models detailing the response of shallow marine and marginal marine sediments to transgressions and regressions, and the resultant stratigraphic patterns produced by these events.

Regression can occur with rising sea level or high rates of subsidence if sediment input is high enough. This produces a stratigraphic sequence characterized by coastal onlap in the landward direction, and stratigraphic rise of marine facies in the seaward direction. Stratigraphic rise is accomplished by successive addition of marine lithofacies to the base of a section as the nearshore units prograde seaward. Resultant thicknesses of prodelta and offshore basinal facies are therefore thicker than would be expected if units prograded into a constant level sea (Ryer 1981b; Klein, 1974).

In general, nearshore facies are poorly preserved during transgression because of shoreface erosion (Swift, 1968; Ryer; 1977), though high rates of subsidence may substantially alter this (Bourgeois, 1980). Landward of the limit of shoreface erosion, however, complete transgressive sequences may be preserved as sediments aggrade to keep pace with rising base level. Sediment entrapment in the coastal region in this case will cause a reduction in sediment input to the shelf.

Given stable or rising base level, regressive sequences are generally well preserved. If base level subsequently falls, however, subaerial erosion may remove the upper (landward) facies in a given vertical sequence.

Within any one sequence produced by a regressive pulse (progradation) a characteristic vertical and lateral pattern is apparent (Horne et al, 1980). In any vertical section, landward facies overlie seaward facies. Landward of this section, marine facies are progressively lost at the base. In a seaward direction, first delta plain, and then delta front sands pinch out at the top of the sequence. This idealized sequence is usually complicated by minor transgressive-regressive pulses within a progradational sequence. Figure 5 illustrates examples of actual measured sections, with boundaries of transgressive-regressive events outlined.

STRATIGRAPHIC FRAMEWORK

The diagrammatic cross-section (Figure 6) illustrates the relationship between prodelta, transition zone, delta front, delta plain and abandonment lithofacies within a portion of the study area. Examination of this cross-section and the data used in its construction provides the following information:

1. The landward portion of the facies tract is to the north. In this direction marine facies are replaced by marginal and nonmarine facies.
2. Landward pinchouts of successive delta front sands are located to the south of preceding landward pinchouts. This indicates an overall southerly progradation for the entire marginal marine sequence. Note that the # 7 sandstone is an exception to this statement.
3. This general progradation was punctuated by a minimum of seven transgressive-regressive pulses. Regressive pulses were produced by progradation of wave-dominated delta front sands. Transgressions resulted from the abandonment of the delta. This may have been caused by increasing rates of subsidence, rise of sea level or reduced sediment input. Transgressive sequences are thin and heavily bioturbated within prodelta facies, represented by an erosional disconformity or transgressive lag within delta front sequences, and preserved as the previously described abandonment lithofacies landwards of the transgressing shoreline.
4. Individual delta front sandstone bodies rise stratigraphically to the south. This stratigraphic rise is most pronounced in the # 3 and # 4 delta front sands. Stratigraphic rise is associated with numerous minor transgressive-regressive pulses, producing both an imbricate structure to the delta front sand, and sandstone tongues extending landwards during general progradation. Where stratigraphic rise is small, as in the # 6 and # 7 sands, this imbricate structure is not as apparent, and the number of landward extending tongues is greatly reduced.
5. Thick (greater than 60 ft) coals occur above a

platform of stable delta front sands of a previous cycle, landwards of coeval prograding delta front sands exhibiting significant stratigraphic rise, and beneath brackish-water lithofacies associated with subsequent transgressive pulses. These coals are split by channel-form sloughs, low-energy distributary channels and one wave-influenced proximal mouth bar. The coals interfinger and pinch out into delta front sands in a seaward direction.

6. Moderately thick (greater than 30 ft) laterally discontinuous coals formed on a differentially subsiding platform of delta plain and abandonment facies, landward of the landward pinchout of coeval delta front sands displaying significant stratigraphic use.

7. Laterally continuous coals less than 20 ft thick form seaward of the landward pinchout of laterally equivalent and underlying delta front sands. These coals thin in a seaward direction and eventually pinch out into brown carbonaceous salt marsh deposits near the maximum seaward extent of the underlying upper delta front sand.

8. Moderately thin (6-15 ft), relatively continuous coals commonly cap coarsening up bay-fill sequences associated with renewed progradation following delta lobe abandonment.

9. Thin (less than 6 ft) discontinuous coals accumulated primarily in the upper portion of the lower delta plain, and in upper delta plain interfluvial areas.

10. Within upper delta plain settings, and in a landward direction of the cross-section, thickest coals occur during periods of a) abandonment and transgression over the lower delta plain, and b) progradation accompanied by subsidence and/or sea level rise.

11. Regions of expected maximum coal thickness, (immediately landward of the landward pinchouts of stratigraphically rising sands) are often instead replaced by channel-form sloughs and low-energy, low-sinuosity distributary channels.

STRATIGRAPHIC MODEL FOR COAL-BEARING STRATA OF THE ADAVILLE FORMATION

A valid stratigraphic model must be consistent

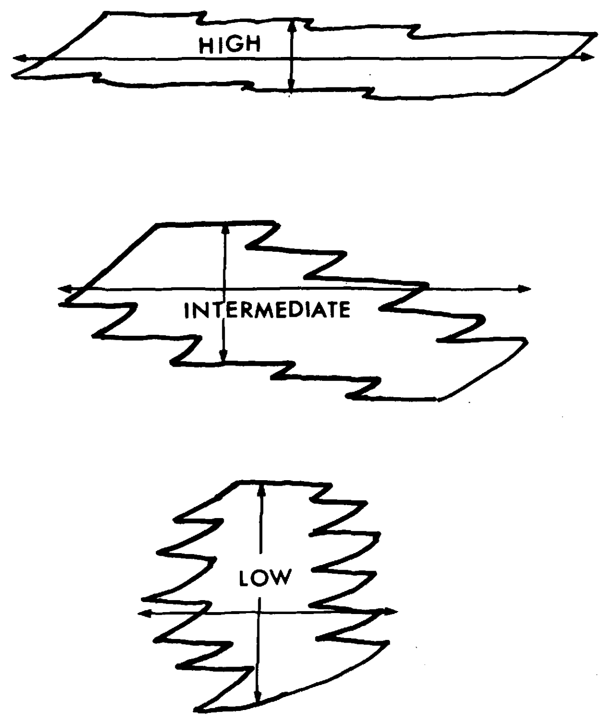


Figure 7. Relative magnitude of regressive pulses as indicated by gross geometry of delta-front sands. Horizontal line is maximum length in direction of depositional dip. Vertical line is maximum thickness of the sandstone body.

with all of the above observations as well as with the interpretation of depositional environments given in the previous section. The magnitude, frequency, geographic extent and number of trangressive-regressive pulses are observable features which should be considered in the stratigraphic analysis of coal-bearing rocks.

Magnitude of pulses - The magnitude of a regressive pulse reflects the distance the strandline moves in a seaward direction over a given period of time. The farther and faster a shoreline moves in a seaward direction, the greater the magnitude of the regression. Reduced subsidence rates, reduced rates of sea level rise, and/or increased sediment input may contribute to a higher magnitude regression.

The magnitude of a regressive pulse may be roughly estimated by the overall geometry of a delta front sand body (Figure 7). High magnitude

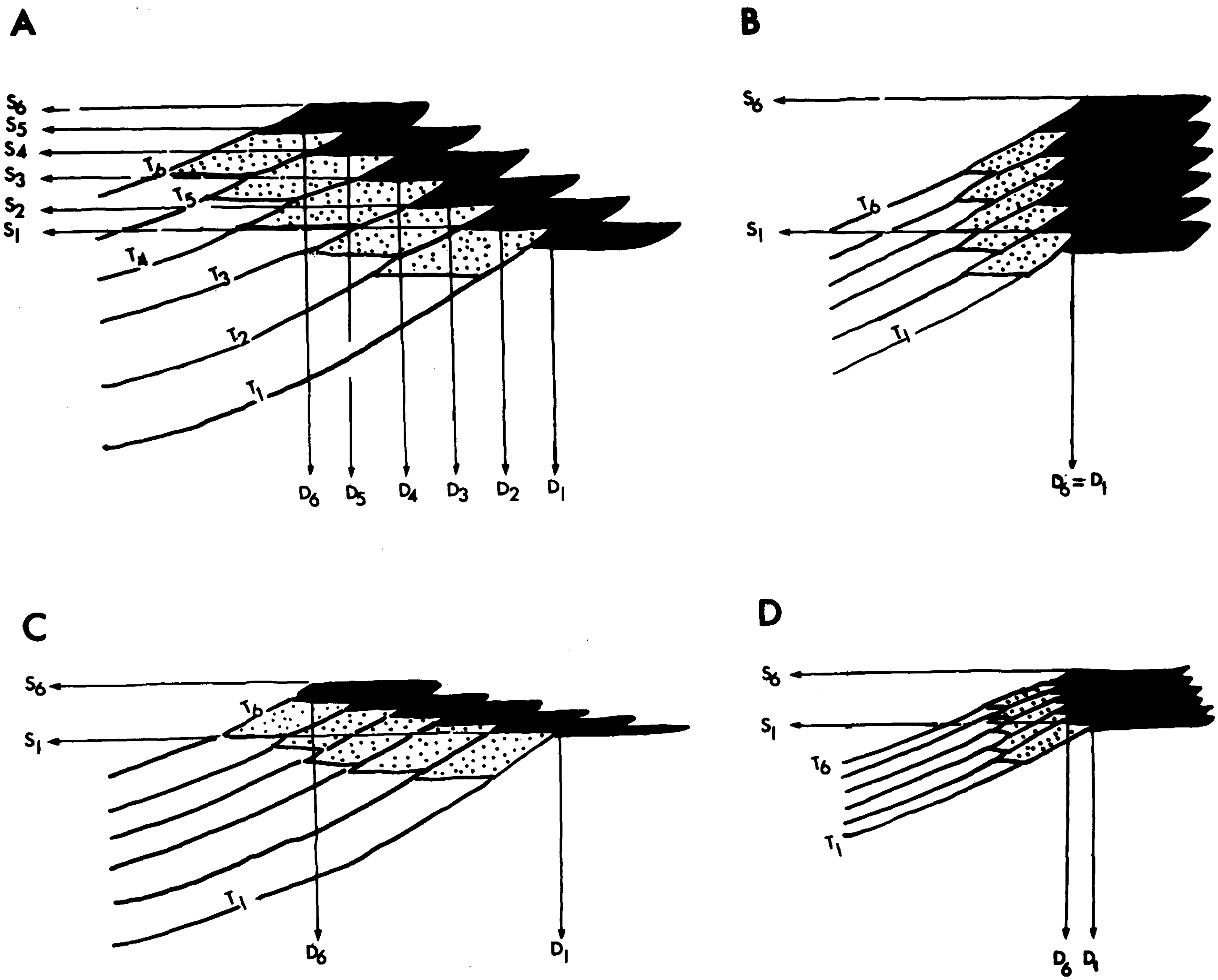


Figure 8. Model relating thickness and geometry of back-beach swamp coals of the Adaville wave-dominated deltaic system to the magnitude of the associated regressive pulse. S=sea level; T=isochronous time line; D=position of the landward pinchout of the delta front sands. Subscripts refer to stages in delta-front progradation. Each coal extends the same distance landward from the coeval delta front pinchout. Figure 8A shows an intermediate magnitude regression associated with substantial sea level rise and moderate rates of progradation. Figure 8B illustrates a very low magnitude regression (shoreline stacking). The amount of sea level rise is the same as in Figure 8A but the rate of progradation is much slower. Figure 8C shows a high magnitude regression. Sea level rise is minimal and progradation is rapid. Figure 8D shows a low magnitude regression. Sea level rise is the same as in Figure 8C, but rate of progradation is much slower. Comparison of rows shows effect of keeping sea level rise constant and varying rates of progradation. Comparison of columns shows the effect of keeping the rate of progradation constant and varying the amount of sea level rise. Local sea level rise may be due to basin subsidence or eustacy.

regressions produce tabular sheet sands with high ratios of depositional-dip length to maximum thickness. Low magnitude regressions produce stacking of lithogenetic units and lower ratios of depositional-dip length to maximum thickness. Examination of the cross section (Figure 6) reveals an inverse relationship between the magnitude of regression and thickness of the associated coals.

Thick coals are associated with low magnitude regressions (delta front sands #3 and 4).

Examination of Figure 8 provides an explanation for this. The thickness of the peat is limited by the change in base level between time 1 and time 6. The time that the back-swamp environment remains at a given point is determined by the rate of progradation. For slow rates of progradation the peat-producing swamp remains in one place for longer periods of time. It follows that the thickest coals would form from where peat could accumulate to its maximum thickness for the longest period of time. This situation is associated with maintenance of back-beach swamps due to base level rise during low magnitude regressions.

Frequency of pulses - Within low magnitude regressive pulses equilibrium is rarely maintained between marine and nonmarine processes, and therefore, frequent oscillations of the shoreline occur. Thsse oscillations are expressed by landward extending tongues of marine sandstone into the delta plain sequence. The tongues are sometimes physically traceable into transgressive disconformities caused by shoreface erosion of the landward migrating strandline. The frequency of minor pulses within a delta front sand body is inversely proportional to the magnitude of the associated major regressive pulse (4th order of Ryer, 1981a), and directly proportional to the thickness of associated coals. By estimating the number of "stacked" cycles within a delta front sand body it may therefore be possible to predict the thickness of the genetically related coal at the landward pinchout.

Geographic extent of transgressive-regressive pulses - In the Adaville Formation a general regression to the south is indicated by the southerly displacement of successive landward pinchouts of delta front sands. This trend is occasionally broken however. A laterally extensive abandonment facies of brackish water siltstones and mudstones, indicative of a transgressive pulse, extends landwards from the delta flank shoreface sequence of the #5 sand. As a result, coal thickness is minimal in the interval between the #5 and #6 sand. Another transgressive pulse, associated with shoreface retreat preceding deposition of the #4 sand, flooded the peat-producing swamps landward of the #3 sand.

When the extent of transgression is not so great, successive landward pinchouts of delta front sands and their associated back-beach swamps may overlap, resulting in stacking of temporally distinct peats into one seam with anomalously great thickness. This is the case with the thick (100+ ft) basal coal seam in the northern portion of the cross section (Figure 6).

Positition in facies tract - The influence of transgressive-regressive pulses on coal-bearing strata within the Adaville Formation is strongly dependent on position within the facies tract relative to maximum transgression and regression. For each regressive pulse, maximum coal thickness occurs within a belt extending approximately 5-7 mi landward of the landward pinchout of the associated delta front sand. Explanation for this has already been given under the discussion of magnitude of regressive pulses (see Figure 8), and by Ryer (1981b).

Transgressions produced flooding of back-beach swamps in the seaward end of the marginal marine facies tract. Landward of the maximum extent of transgression, a rise in the water table produced laterally extensive coastal swamps. Moderately thin to moderately thick peats accumulated in these swamps, split locally by fluvial and tidal channels. Maximum thickness of any these coals is 40 ft.

Zones of maximum expected peat accumulation are often instead zones of low energy-low sinuosity distributary channels and sloughs. The probable cause for this is early compaction of the peat, creating zones of localized subsidence in which the channels were established.

The lateral continuity of individual major coal seams is partly a function of the underlying delta platform. Coals overlying delta front sands tend to be more continuous than coals overlying delta plain deposits of a previous cycle. This is attributed to differential compaction of muds, peats, and sands of the delta plain platform creating localized zones of subsidence in the peat marshes.

Table 1 summarizes the stratigraphic model for coal-bearing strata associated with the different transgressive-regressive pulses affecting the Adaville Formation.

Number of pulses and total coal reserves Each transgressive-regressive pulse, with the

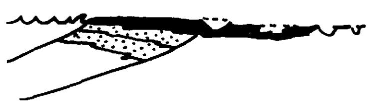
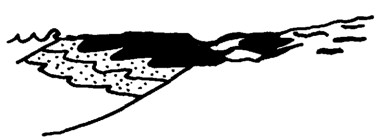
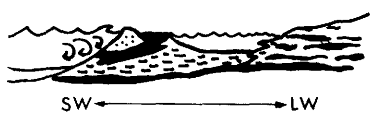
PROCESS	RESPONSE	SCHEMATIC DOWN-DIP CROSS SECTION	COAL DISTRIBUTION		
			SEAWARD OF LANDWARD PINCH-OUT TO MAX. SEAWARD ADVANCE OF SHORELINE	LANDWARD PINCHOUT TO UPPER DELTA PLAIN	UPPER DELTA PLAIN TO COASTAL PLAIN
$R_{si} \gg R_{\substack{sb\\slr}}$	Rapid progradation, high magnitude, laterally cont. back-beach swamp; encroachment of u. delta plain fluvial facies		Thin, continuous back-beach swamp coals accompany progradation	Mod. thin, discontinuous coals; may cap bay fill sequence landward of transgressive disconformity; erosional washouts by overlying fluvial system	V. thin interdistributary and interfluvial poorly drained lowland coals
$R_{si} > R_{\substack{sb\\slr}}$	Slow progradation; mod. magnitude; strat. rise by addition of marine lithofacies; coastal onlap; mod. thick, continuous back-beach swamps		Mod. thick to mod. thin back beach swamp coals thin seaward due to strat. rise and are split by landward extending tongues of marine sandstone	Mod. thick, mod. continuous coals form over older stable delta front platforms, mod. thick to thick discontinuous coals form over differentially compacting older delta plain facies	Thin, discontinuous interchannel coals; frequent channel avulsion
$R_{si} \approx R_{\substack{sb\\slr}}$	Strand line stabilization; low magnitude; coastal onlap pronounced, frequent minor transgressive pulses; vertical stacking of lithofacies; few active distributaries, extensive backswamps		Very rapid pinchout of coals in seaward direction because of large stratigraphic rise and intertonguing with marine sandstones	Thick to v. thick l. delta plain coals, split by distributary channels in landward direction, and by sloughs in seaward direction; continuity greater over stable delta front sands than over delta plain facies	Mod. thick to mod. thin discontinuous coals form in interchannel areas in reponse to base level rise; many splits
$R_{si} < R_{\substack{sb\\slr}}$	Delta abandonment, shoreface retreat, high mag. transgression; flooding of lower delta plain; slow offshore sed. rates; lagoonal, washover fan, and flood tidal delta facies preserved landward of limit of shoreface erosion		Coal removed by transgressive disconformity	Coastal swamps flooded; brackish water mudstones, distal washovers, and bayhead deltas replace lower delta plain coals in facies tract; thin mod. continuous coals cap bayfill sequence	Extensive coastal lowlands; salt marsh, tidal channel facies preserved; abandoned distributaries and sloughs; laterally continuous mod. thin to moderately thick coals

Table 1. Model for Adaville Formation coals associated with transgressive-regressive pulses. R_{si} = rate of sediment input; $R_{\substack{sb\\slr}}$ = rate of base level rise (local relative sea level) due to subsidence and/or eustacy.

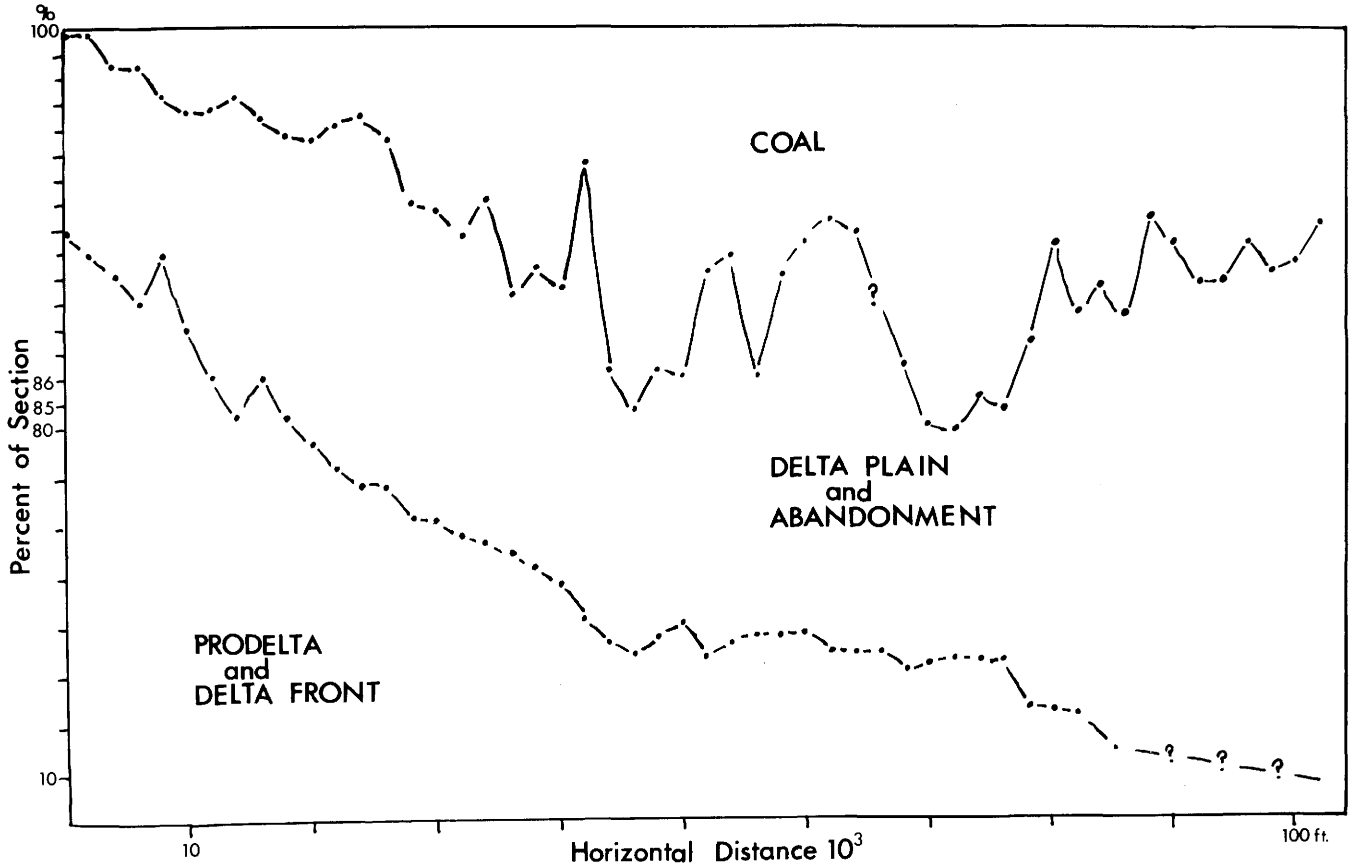


Figure 9. Cumulative percentage of coal, delta plain and abandonment facies, and marine facies within a 1,300 ft. stratigraphic interval of the Hilliard through Adaville sequence. The plot shows the distributionof coals associated with a major third order regression. Horizontal distance is measured in a north-south direction.

possible exception of the # 5 sand, is associated with a coal seam or group of coal seams. The number of pulses therefore controls the total reserves of the Adaville coal. Ryer (1981a) has presented a model predicting greater coal reserves for lithostratigraphic units exhibiting stacking of fourth order transgressive-regressive cycles. This study supports Ryer's model. Figure 9 is a plot of percentage of coal; delta plain and abandonment; and prodelta and delta front lithofacies within a stratigraphic interval of 1,300 ft within the study area. Maximum coal thickness occurs landwards of a zone showing greatest reduction in the percentage of prodelta and delta front sands. This zone corresponds to the landward pinchouts of the #3, 4, and 7 sandstones. Coals thin in a seaward direction due to replacement by marine lithofacies and show evidence of thinning in a landward direction because of replacement by upper delta and coastal plain lithofacies. The overall stratigraphic pattern of the third order major regression appears therefore to mimic, in a gross way, the patterns of its constituent fourth order pulses.

CONCLUSIONS

Extension of stratigraphic concepts developed for non-coal-bearing strata, in conjunction with sedimentologic and stratigraphic analysis to determine time-slice depositional systems, has permitted the development of a model relating coal-bearing strata of the Adaville Formation to transgressive-regressive pulses in the marine portion of the facies tract. Thickest Adaville coals are associated with low magnitude regressive pulses and are found landward of the landward pinchout of coeval wave-dominate delta front sands. Extensive transgressive pulses resulted in drowning of back-beach coal swamps. The distribution of fourth order cycles (transgressive-regressive pulses) within the study area controls the total distribution, geometry, and the thickness of Adaville coals within the Kemmerer coal fields.

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STRATIGRAPHY AND COAL DEVELOPMENT POTENTIAL OF UPPER MESAVERDE GROUP, CARBON COUNTY, WYOMING

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INTRODUCTION

The purpose of this paper is: 1) to present a more complete and detailed stratigraphy of the Upper Cretaceous upper Mesaverde Group; 2) to discuss probable associated depositional environments of the upper Mesaverde; and 3) to discuss coal development potential of Almond Formation reserves in the vicinity of Rawlins, Wyoming.

The discussion of Pine Ridge and Almond stratigraphy presented here is based on mapping and drill hole data acquired from four coal development projects on the Union Pacific Land Grant in Carbon County, Wyoming. The four areas were explored and mapped by RME from 1969 to 1980. These areas are located as follows: 1) Atlantic Rim—from 20 to 25 mi southwest of Rawlins, on the west flanks of Hatfield Anticline; 2) Kindt Basin—a small structural basin from 2 to 20 mi southeast of Rawlins; 3) Wild Horse Draw—from 12 to 18 mi northeast of Rawlins; and 4) Corral Canyon—from 24 to 30 mi northeast of Rawlins, both on the west flanks of the Hanna Basin (Figure 1). Each area has 38 to 130 drill holes spaced at intervals of 1,000 ft to 2 mi. Cuttings from each drill hole were described by a geologist on site. In addition, each hole was geophysically logged with natural gamma and single point electrical resistance functions. Most were logged with gamma-gamma density as well. The authors supervised two projects each, from initial planning to final evaluation.

Such concentrations of data have provided RME geologists with a unique opportunity to study the stratigraphy and depositional environments of a nondeltaic coal-bearing formation. Unlike the prograding, wave-dominated delta model developed for the lower part of the Mesaverde Group (Levey and Horne, 1979, p. 25-40) the upper Mesaverde, consisting of Pine Ridge Sandstone and Almond Formation, was deposited in a transgressive setting landward of and at the margin of the expanding epeiric Lewis Sea.

In southcentral Wyoming, the Mesaverde Group comprises a sediment package that records a major cycle of regression/transgression in the Late Cretaceous seaway. In Carbon County this package includes (from oldest unit to youngest unit): 1) Haystack Mountains Formation—a sequence of shallow water marine sandstones and shales. The Haystack Mountains Formation is almost identical to lower Mesaverde units described in the Rock Springs Uplift (McKenna, 1981, p. 49-98; Levey, 1981, p. 57-118), and Book Cliffs (Balsley, 1980, p. 9-105), and is probably the record of a wave-dominated deltaic system that prograded out into the epeiric Steele Sea. Supported on the last of these multiple sand platforms, known collectively as the Haystack Delta are a series of nonmarine sandstones, shales, and carbonaceous beds, with some sandstone and shale of brackish water and marine origin as well. This sequence is known as 2) the Allen Ridge Formation. Overlying the Allen Ridge is 3) the fluvial Pine Ridge Sandstone, and 4) the fluvial/paralic Almond Formation (Figure 2).

Apex of the regressive cycle is recorded by a regional unconformity at the top of the Allen Ridge Formation. This unconformity is well documented in some localities, assumed in others, and nonexistent in a few sites (Miller, 1979, p. 22-24; Gill et al, 1970, p. 29-31). Unlike the Haystack Mountains/Allen Ridge formations that clearly represent a prograding deltaic system, the Pine Ridge and Almond were deposited landward of, and at the margins of an

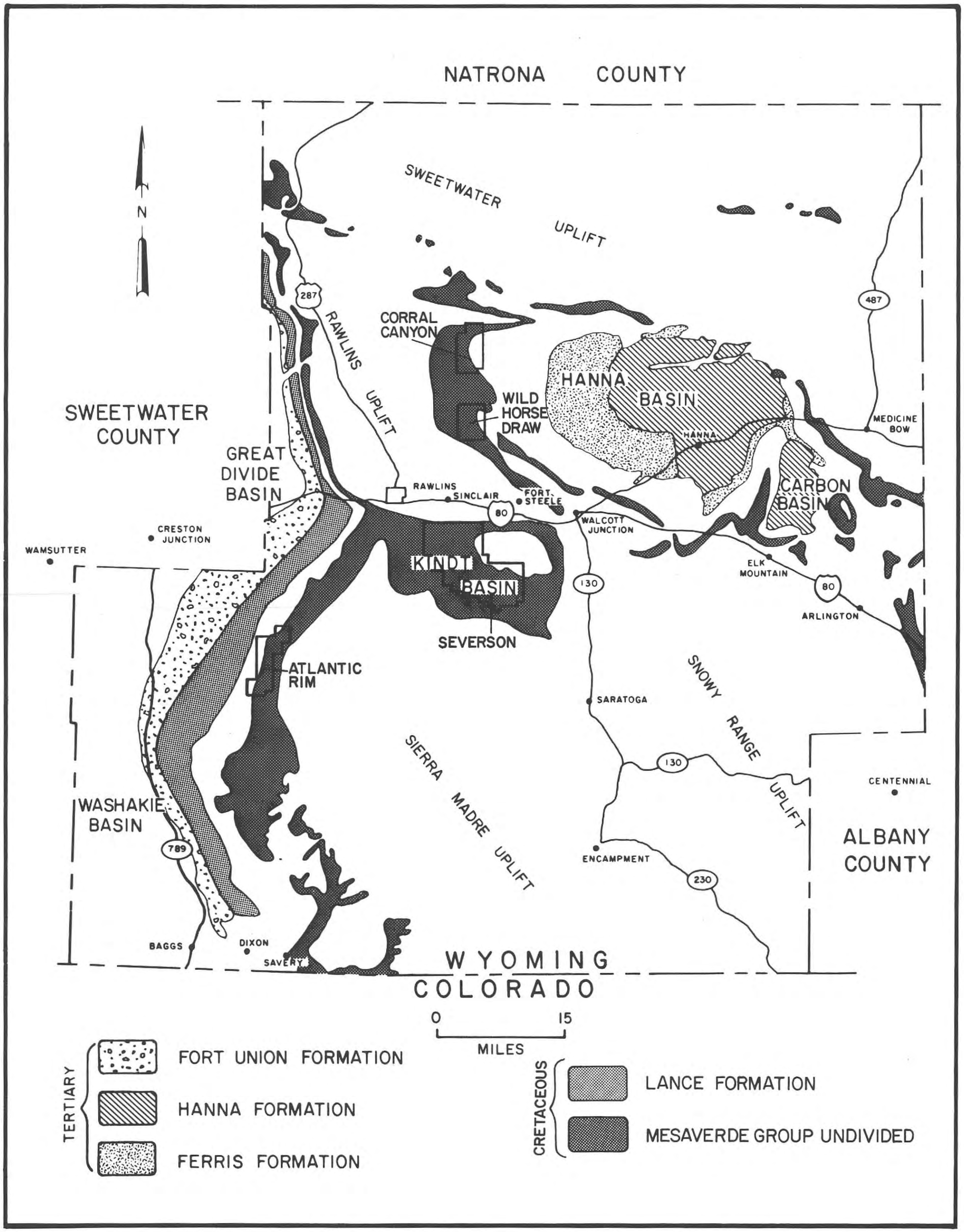

Figure 1. Geologic map of Carbon County, Wyoming.

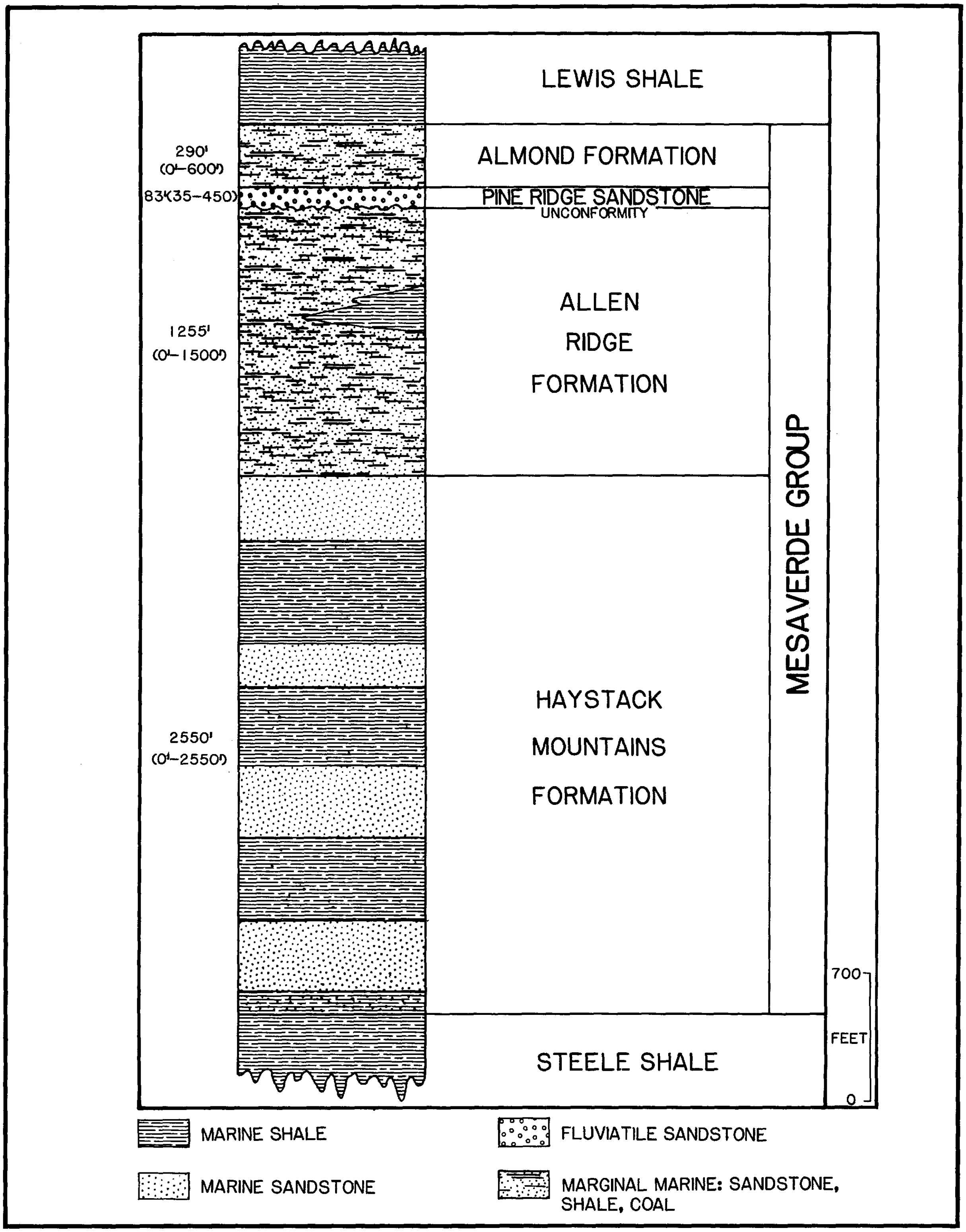

Figure 2. Generalized stratigraphic column, Upper Cretaceous Mesaverde Group, Carbon County, Wyoming.

expanding epeiric sea. Although generally, the Pine Ridge and Almond are known to be fluvial and paralic in origin, no detailed studies of their environments of deposition have been published for areas east of the Rock Springs Uplift.

PINE RIDGE SANDSTONE

The Pine Ridge Sandstone is described regionally by Gill, Merewether, and Cobban (1970) as a unit of fluvial sands, interbedded with carbonaceous shales, that was deposited in Late Cretaceous time following a period of emergence and erosion on the Haystack Delta. Ranging from 35 to 450 ft thick, it can be readily identified as a cliff-forming, tree-covered ridge (Gill et al, 1970, p. 29-31). This description is generally correct, although incomplete for outcrops in the Rawlins area. The "regional" unconformity can be categorically identified only in the Kindt Basin, of the four project areas, although this does not preclude its existence southwest and northeast of Rawlins. Poor exposures and perhaps a disconformable nature of the unconformity inhibits recognition a the base of the unit in many areas.

The Pine Ridge around Rawlins is predominantly composed of light to medium gray, very fine to medium grained, quartzose sandstone. The remaining 5 to 40 percent of the unit consists of gray siltstone, gray sandy shale, and dark gray to black carbonaceous shale. The unit in the four project areas averages 73 ft thick, ranging from an average of 38 ft in the Kindt Basin (its most seaward occurrence of the four areas), to 120 ft thick at Corral Canyon. The Pine Ridge is conformably overlain by shales of the basal Almond Formation.

Individual sandstone beds vary from 10 to 40 ft thick over the region. Approximately 60 percent of the sands occur in fining upward, accretion trough set sequences typical of river point bars. An excellent exposure of this type of structure can be seen in sec. 13 and 14, T.22 N, R.86 W. along the North Platte River, immediately south of Wild Horse Draw. The less common sands generally exhibit constant or slightly coarsening upward grain size and occur at the top of a coarsening upward sequence (from shales through thinly interbedded shales and rippled sands to a thick crossbedded sand). All Pine Ridge sandstones are well-cemented and form cliffs or conspicuous dip slopes. Weathered color ranges widely from white or very light gray, to reddish or brownish gray.

Published reports for most areas east of the Rock Springs Uplift have not discussed the Pine Ridge in detail. According to unpublished USGS data, the Pine Ridge undergoes a facies change south of Atlantic Rim from floodplain sands to restricted marine sands and shales. It cannot be lithologically distinguished from marginal marine units in the underlying Allen Ridge and overlying Almond formations (Barclay, 1981). Subsurface in the Washakie and Great Divide basins, the Pine Ridge continues to show fluvial characteristics, including overall sheetlike morphology, point bar accretion sets in individual beds, and a consistent thickness ranging from 70 ft in the south to 140 ft in the north (Balsley, 1981).

The Pine Ridge Sandstone correlates regionally with 1) part of the Ericson Sandstone on the Rock Springs Uplift (Miller, 1979, p. 22-24; Davis, 1966, p. 60-82); 2) the lower part of the Williams Fork Formation in northwest Colorado (Boyles, 1981, p. I-4; Gill et al, 1970, p. 31); and 3) the Teapot Sandstone Member of the Mesaverde Formation in the Powder River, Wind River, and Bighorn basins of Wyoming (Gill et al, 1970, p. 29).

ALMOND FORMATION

Lower Almond — The Almond Formation is generally described in the literature as two sequences of distinctly different lithologies. The lower sequence consists of fluvial sands interbedded with carbonaceous siltstones, carbonaceous shales, and coals. The upper sequence comprises open marine sands, silts, and clays, and associated restricted and marginal marine beds. The lower contact is conformable with the Pine Ridge Sandstone, varying from a sharp to an interfingering contact. The upper contact intertongues regionally with Lewis Shale (Gill et al, 1970, p. 32; Schultz, 1907, p. 256-262; Davis, 1966, p. 82).

RME data generally agree with published findings, with one major exception. Three of the four project areas document the typical lower fluvial/nonmarine history overlain by open marine/restricted marine deposits. The exception is the Kindt Basin in which probably only open and restricted marine units occur. RME data on the Kindt Basin support a similar conclusion reached in Davis' dissertation (1966). Such conclusions correlate as well with unpublished USGS data (Barclay, 1981) that document a major south-trending continential-to-marine facies shift in lower Almond rocks between Atlantic Rim and Baggs, Wyoming.

Where identified, nonmarine lower Almond ranges from 135 ft thick at Corral Canyon to 249 ft at Wild Horse Draw (Figures 3 through 6). Lower Almond beds consist of sandstone interbedded with shales and coals. The sands are light to medium gray, very fine to fine grained crossbedded units that generally fine upward, becoming interlaminated with shales and rooted at the top. A few sands near the top of the lower Almond coarsen up, with rooting at the top. Associated shales are dark gray to black, silty, clayey, or carbonaceous and commonly contain coalified or fossilized plant trash. These shales can be distinguished from overlying upper Almond shales by the general absence of mollusc shells and siderite beds. Numerous coals, ranging from 0.5 to 20.1 ft thick and averaging 5.1 ft thick, were deposited in the lower Almond.

The lower Almond can be interpreted as a fluvial, fresh water dominated system of channel, overbank, splay and swamp deposits typical of lower coastal plains. These environments retreated westward across southern Wyoming seaward of the Pine Ridge sands and in front of the expanding sea. Other studies have shown that typical lower Almond deposits pinch out along the eastern margins of the Hanna Basin and that the upper Almond thins to a feather edge in the Laramie Basin (Gill et al, 1976, p. 31-36). RME data and other unpublished data identify a northeast/southwest trend for the limit to lower Almond deposition. This depositional pinchout is located between Baggs and Atlantic Rim; Kindt Basin and Wild Horse Draw; and eastern Hanna Basin and Laramie Basin (Figure 7). Such conclusions are consistent when expanded to include published data and correlate well with a generalized northeast/southwest trending shoreline proposed for the area (Davis, 1966, p. 86-95; Gill et al, 1970, p. 31-36; Barclay).

Upper Almond — Upper Almond deposits occur in all four project areas and range from 360 ft thick at Atlantic Rim and 385 ft at Corral Canyon (the two most landward of the four project areas), to 628 ft in the Kindt Basin (the most seaward). Upper Almond beds consist of brackish water, sideritic shales; usually thin, discontinuous coals; and shallow marine sands and shales.

Upper Almond brackish water shales are typically dark gray to dark gray-green, intensely burrowed, silty and often interbedded with thin, rippled sandstones. The shales contain coalifed and fossilized plant trash, numerous siderite concretions and beds, and a brackish water fauna (*Crassostrea, Brachiodontes,* and *Corbula* in particular).

Upper Almond coals are generally more discontinuous and thinner than lower Almond coals, ranging from 0.5 to 9.0 ft, and averaging 3.1 ft thick. Seams associated with brackish water shales are thin and relatively high in sulfur.

Upper Almond shallow marine sands are very fine to fine grained, usually coarsening upward. They are white to medium gray or gray-green, often exhibiting a "salt and pepper" appearance. Most of the dark minerals appear to be chert rather than heavy minerals. Primary structures typify shoreface deposits, exhibiting trough cross-stratification overlain and/or underlain by planar, wave-rippled, sometimes burrowed beds. An excellent example can be found at Wild Horse Draw, where the E Sandstone (named for the overlying E Seam) exhibits 1) a gradational contact with brackish or marine silts below; 2) high trough sets overlain by horizontal, wave-rippled, parallel bedding akin to shoreface breaker zone and beach deposits; and 3) morphologically indistinct, sideritized vertical and horizontal burrows at the top of the sand.

Upper Almond offshore marine shales are dark gray to gray-green and silty. Gypsum crystals up to 7 inches across are abundant at Atlantic Rim.

Upper Almond sequence demonstrates that minor shoreline fluctuations occurred in addition to ultimate transgression by the Lewis Sea. At the Kindt Basin, at least five such pulses are recorded, whereas, one major advance is recorded at Atlantic Rim. At Corral Canyon three restricted bayfill sequences occur, each capped by a coal seam that averages 2.3 to 7.7 ft. Interestingly, at Corral Canyon, the Almond/Lewis contact is drawn at the top of the shoreface sand above the topmost coal seam. Basal Lewis there consists of three coarsening upward silt and sand sequences, indicating incomplete transgressive/regressive pulses. Four miles to the south at Wild Horse Draw, that same sequence is incorporated into the Almond Formation because the topmost pulse locally resulted in paludal deposition culminating in the G Seam (Figure 5).

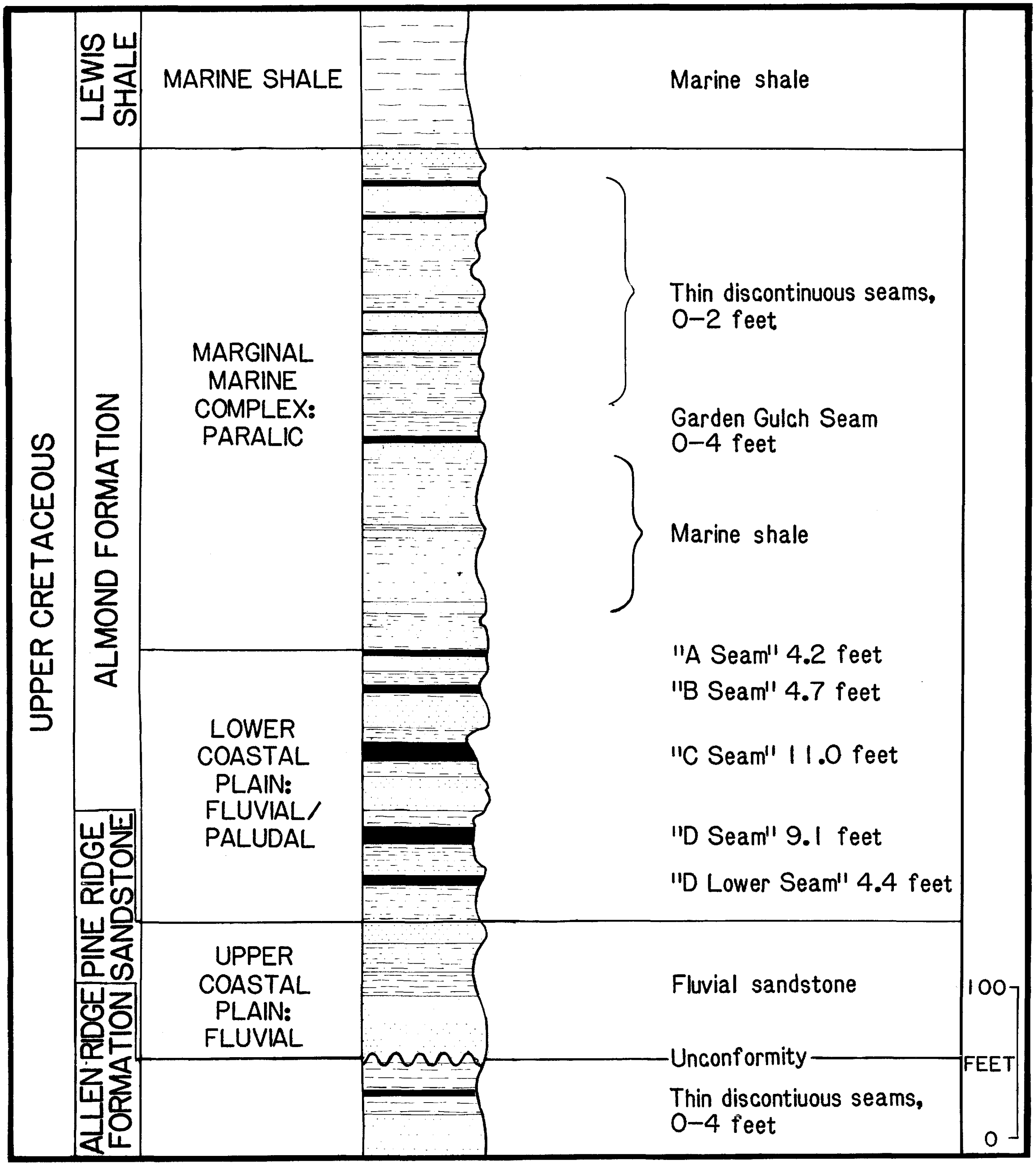

Figure 3. Stratigraphic column, Atlantic Rim, Carbon County, Wyoming.

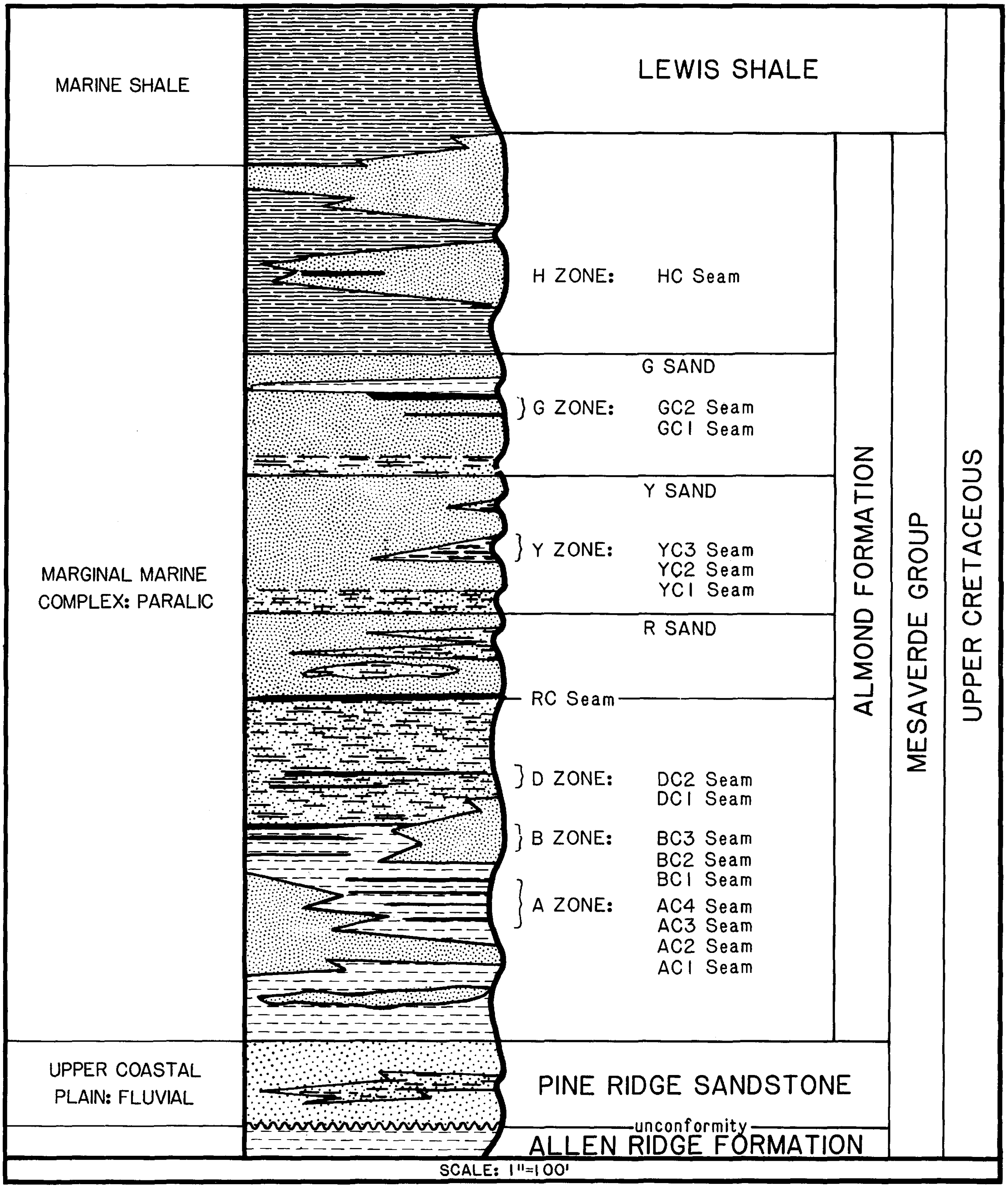

Figure 4. Stratigraphic column, Kindt Basin, Carbon County, Wyoming.

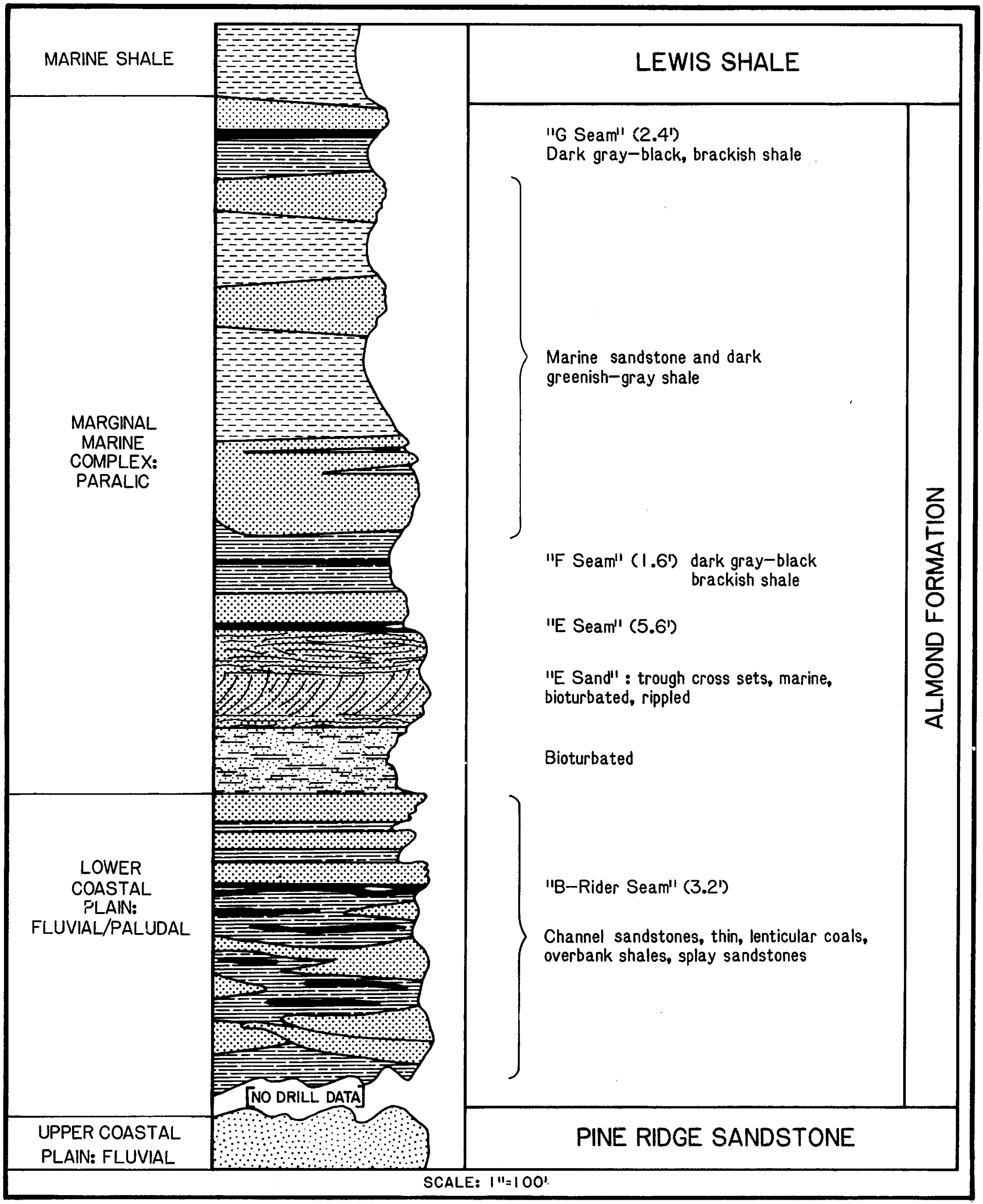

Figure 5. Stratigraphic column, Wild Horse Draw, Carbon County, Wyoming.

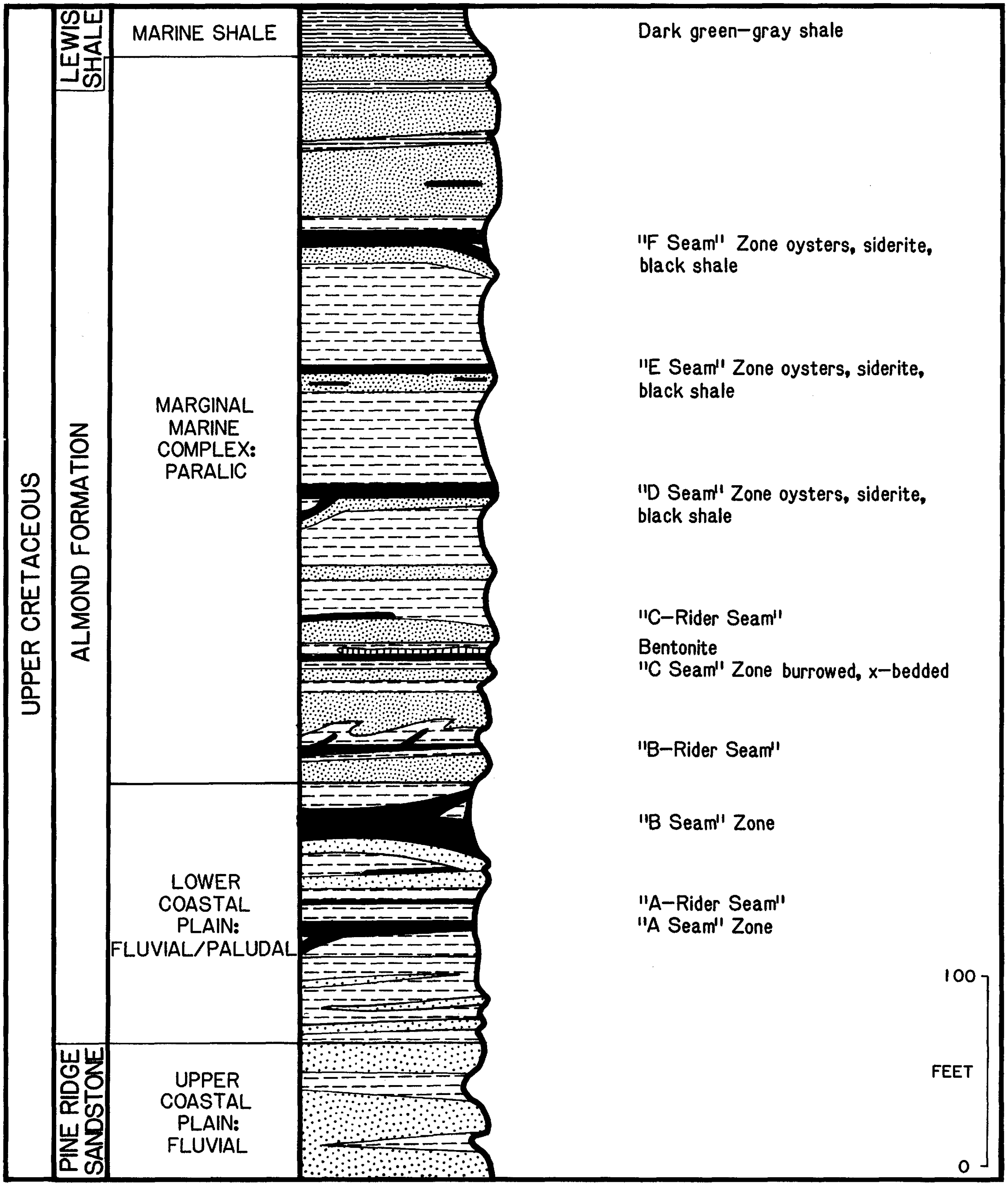

Figure 6. Stratigraphic column, Corral Canyon, Carbon County, Wyoming.

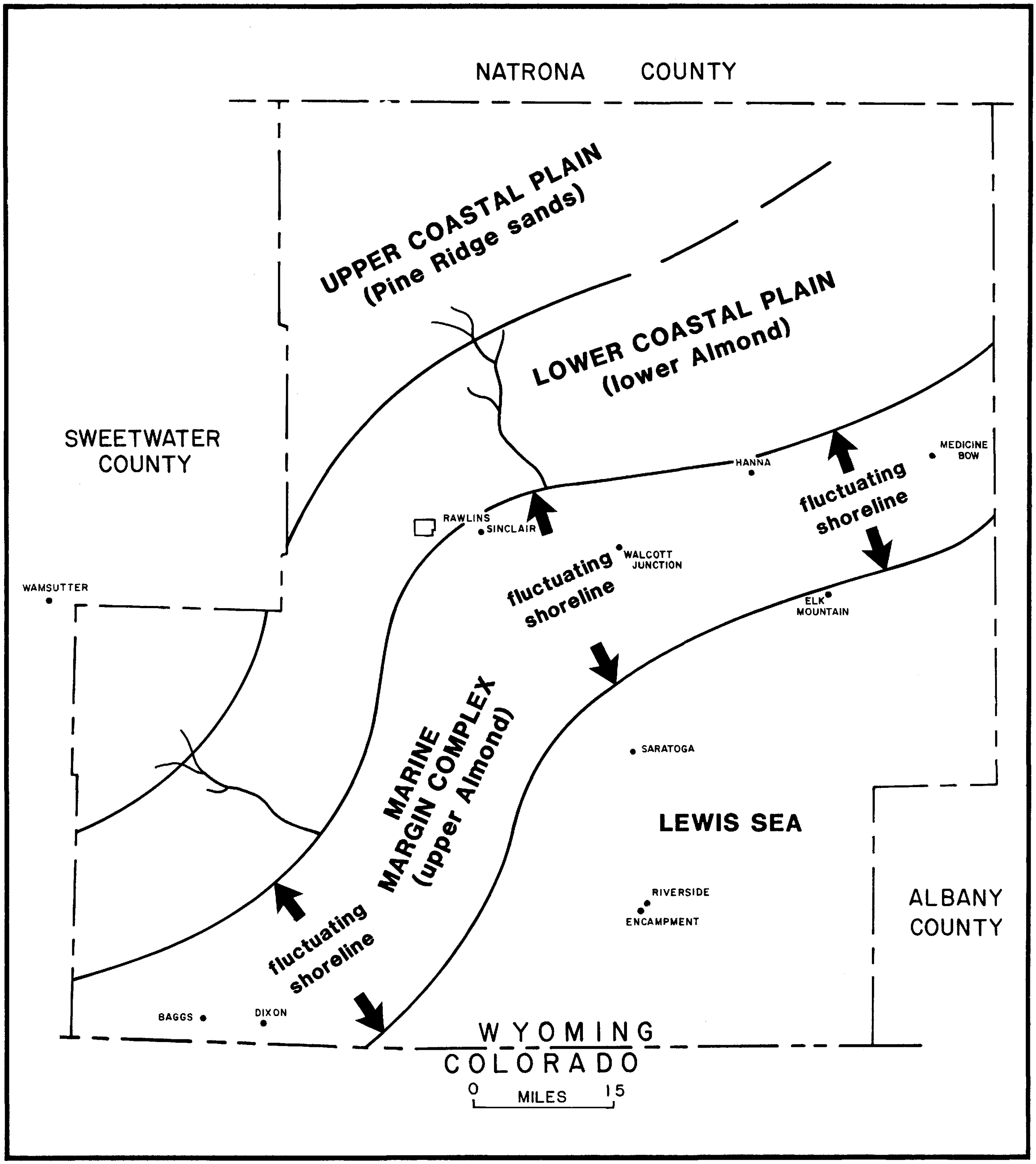

Figure 7. Paleographic map, early Almond time, Carbon County, Wyoming.

The upper Almond can be interpreted as a complex open/restricted marine dominated system of barrier islands, lagoons, and lagoon-margin swamps. Shoreface sands such as described above are likely to occur only in a barrier, strand plain, or deltaic system. Deltas, by definition, must prograde over finer grained marine sediments—a condition not supported in the Almond rock record. A simple strand plain model would better explain the rock record, yet swamps behind a strand plain beach would tend to be less burrowed, dominated by fresh water fauna, and result in the formation of less siderite than in restricted marine environments. This leaves only the barrier/lagoon system as an acceptable model for the upper Almond—with one major qualification. Barrier systems have three major environmental components: 1) barrier islands, 2) backbarrier lagoons, and 3) interbarrier flood and ebb tidal deltas and channels (Reinson, 1979, p. 57-74). The third component has not been recognized to date. Thus a barrier model cannot be categorically proved until such units have been identified.

RESERVE POTENTIAL AND MINING METHOD

The method of surface mining coal from the Almond Formation in Carbon County will be strongly affected by a number of geologic factors: 1) occurrence of multiple seams, 2) thin seam thickness, 3) moderate dips, and 4) physical limits imposed by drainages that transect the minable areas. The following discussion refers primarily to Corral Canyon and Atlantic Rim because these two areas are the most advanced Almond mining projects studied in Carbon County by RME.

Seam Parameters — Thickness and number of minable seams in the Almond Formation increases landward from the old Lewis Sea shoreline. It is no accident that more minable reserves occur at Atlantic Rim and Corral Canyon than at Wild Horse Draw or Kindt Basin. The number of minable seams (2.0 ft thick or greater) ranges from four in the south half of Atlantic Rim to at least 14 at Corral Canyon. Average thickness of minable seams in these project areas ranges from 4.5 to 6.8 ft. Seams are separated by interburden rock ranging from 2.4 to 66.2 ft in average thickness.

Structure and Drainage — Almond rocks in Carbon County crop out along the margins of structural basins. Moderate dips ranging from 8 to 12 degrees in most of the project areas, combined with resistant sandstones, have resulted in beveled dip slopes. Coal beds commonly crop out along the back slopes of these sandstone dip slopes. Superimposed streams often transect the Almond outcrop, dividing the ridge into separate blocks.

Mining Method — Mining feasibility studies conducted by RME suggest that these multiple seams, combined with beveled dip slope topography, will result in a mining depth of approximately 400 ft without exceeding a maximum ratio (cubic yards of overburden to tons of coal) of 10:1. The desire to maintain a high quality product and the relative thinness of the seams to be mined may result in recovery factors of 85 percent or less. Total in-place reserves exceeding 300 mil tons are known to exist in these two Almond Formation project areas in Carbon County. Recoverable reserves will be substantially lower, however, because of buffer zones left along the transecting drainages for protection of alluviated stream valleys.

The surface mining methods considered by RME include dip-line stripping with truck-and-shovel, and draglines with truck- and-shovel support. Dip-line stripping appears to be appropriate because it will 1) provide a constant stripping ratio, 2) increase total reserve recovery, and 3) limit many of the environmental concerns. At Atlantic Rim all overburden greater than 100 ft over the A Seam will be removed by truck-shovel. A dragline would then strip overburden to the A Seam and interburden to the B Seam from the Highwall. The C and D Seams will be stripped by dragline from the spoil side (Pollard et al, 1981, p. 5-2). At Corral Canyon multiple seams, structure, and topography also suggest a dip-line open pit operation (Corral Canyon, 1981, p. 4-7, 4-8, 4-14). Additional project areas, such as Wild Horse Draw, are also under consideration for mine development.

Almond coals are more attractive for marketing than thicker, lower quality coals in the Lance, Fort Union, Wasatch, and Ferris formations because of higher heat content, high ash fusion temperatures, and low fouling characteristics. Coal from the Almond Formation typically has a heat content of 10,300 to 12,000 Btu per pound. Run-of-mine production from Atlantic Rim and Corral Canyon may average 10,400 to 10,700 Btu per pound. High ash fusion temperatures and low sodium contents indicate that the coal is useful as fuel in dry bottom, pulverized feed types of furnaces.

CONCLUSIONS

Drill and mapping data from four project areas in Carbon County, Wyoming, allow a more refined understanding of the Pine Ridge Sandstone and Almond Formation of the Upper Cretaceous Mesaverde Group:

1. The Pine Ridge Sandstone is a pervasive upper coastal plain fluvial deposit that thickens landward and thins seaward, ultimately undergoing a facies change, as documented by workers elsewhere.
2. The overlying Almond Formation records a landward and marginal marine record of the expanding Lewis Sea.
3. The depositional setting is thought to be that of a coastal plain fronted by a barrier island system. This shoreline system trended north east/southwest from the Hanna Basin to north of Baggs, Wyoming, and apparently fluctuated locally many times.
4. Minable coal reserves within the Almond are controlled by multiple thin seams deposits, moderate dips, and environmental restrictions. Dip-line mining methods may allow pit depths of up to 400 ft with minimum rehandle.

ACKNOWLEDGEMENTS

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MULTIPLE BARRIER ISLAND AND DELTAIC PROGRADATIONAL SEQUENCES IN UPPER CRETACEOUS COAL-BEARING STRATA NORTHERN KAIPAROWITS PLATEAU, UTAH

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INTRODUCTION

The coal reserves contained in the John Henry Member of the Straight Cliffs Formation in the northern Kaiparowits Plateau, Utah, were studied utilizing 24 core holes and extensive outcrop exposures (Figure 1). The coal reserves, in excess of one billion tons, are contained in three major coal zones which in ascending order are the Christensen, Rees, and Alvey. The three coal zones are associated with seven progradational littoral marine sandstones informally named the A through G with A being the stratigraphically lowest. The marine sandstones exhibit repetitious vertical sequences of sedimentary structures and lithologies characteristic of prograding shoreline deposits which have been described for many of the case deposits along the western margin of the Upper Cretaceous Seaway. The associated coal swamps were deposited in a 20 km wide belt landward of the marine sandstones. The eight coal seams of the Christensen coal zones are associated with the B sandstone, the six coal seams of the Rees zone are associated with the C and D sandstones, and the single seam of the Alvey coal zone is associated with the G sandstone.

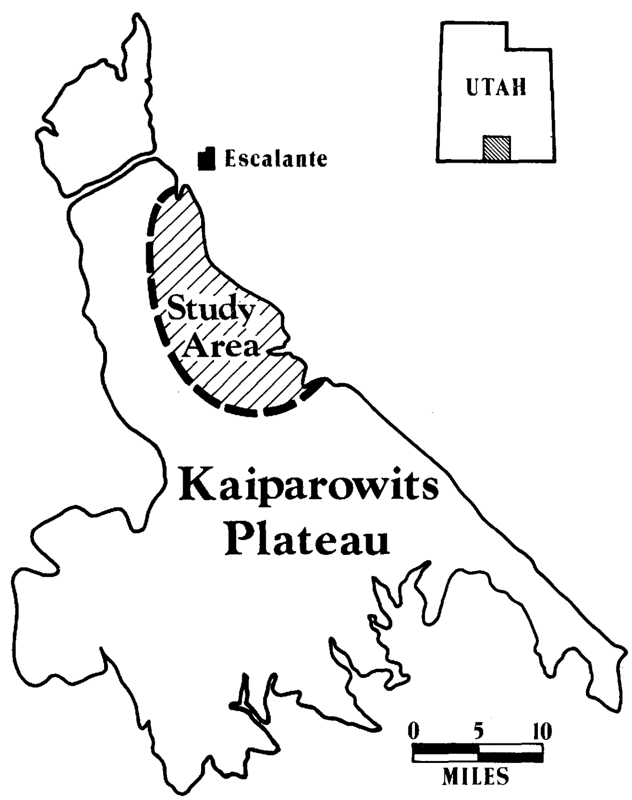

Figure 1. Location map of the Kaiparowits coal field.

PREVIOUS INVESTIGATIONS

The stratigraphic framework and nonmenclature of the Kiaparowits Plateau were first defined by Gregory and Moore (1931). Their investigations, with minor modifications, defined the regional stratigraphic relations upon which subsequent investigations elaborated. In the 1960's, economic interest in the Kiaparowits coal reserves initiated extensive mapping by the Utah Geological and Mineral Survey and the U.S. Geological Survey. Numerous geological maps were published by, Doelling and Graham (1972), Peterson (1969a,b), Zeller (1973a,b,c,d), and others to establish the geological characteristics of the area. Peterson (1969b) and Vaninetti (1978, 1979) emphasized the

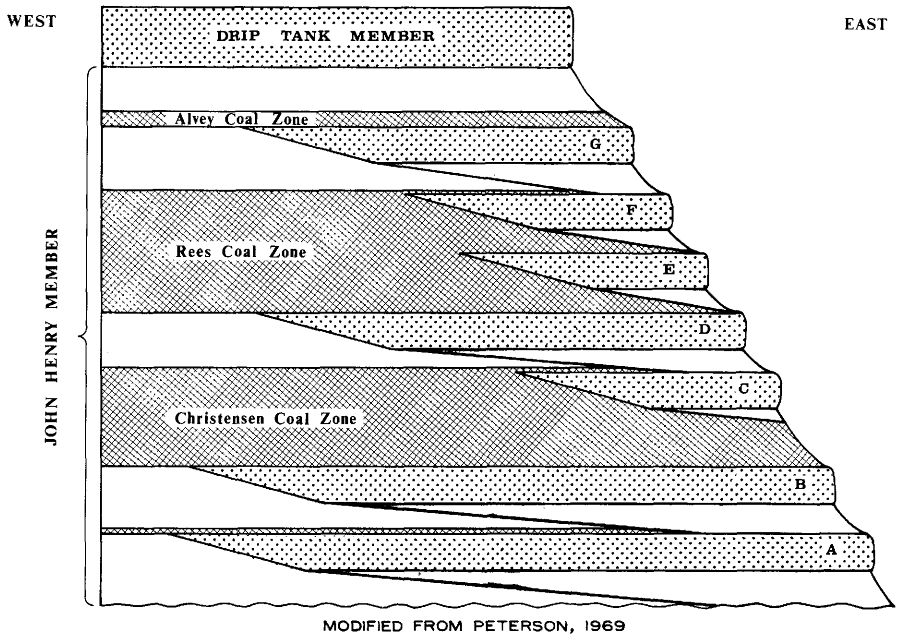

Figure 2. Stratigraphic units of the John Henry Member of the Straight Cliffs Formation.

geological framework and depositional styles which characterize the Upper Cretaceous strata of the area. Subsequent work by Peterson and others (1980) modified the regional stratigraphic correlations and relationships with equivalent strata in the Henry Mountains, Wasatch Plateau, and Book Cliffs areas.

STRATIGRAPHIC SETTING

The major coal reserves of the Kaiparowits region are contained in the Straight Cliffs Formation (Upper Cretaceous) which accumulated along the western margin of the Interior Seaway. The Straight Cliffs Formation is overlain by the Wahweap Formation and underlain by the Tropic Shale. The Straight Cliffs Formation is equivalent to the Toreva and Wepo formations to the south and the Blue Gate Shale and Ferron Sandstone members of the Mancos Shale to the north. The overlying Wahweap Formation is equivalent to the Star Point and Castlegate sandstones and the Blackhawk and Price River formations in the Wasatch Plateau and the "Emery" Sandstone and Masuk Member of the Mancos Shale Formation in the Henry Mountains region. The Tropic Shale is correlative to the Tunuk Shale Member of the Mancos Shale.

The Straight Cliffs Formation can be further subdivided into the Tibbet Canyon, Smokey Hollow, John Henry and Drip Tank members. The Tibbit Canyon and Smokey Hollow members mark the first major regressive sequence in the Upper Cretaceous Seaway during the Turonian and is correlative to the Ferron Sandstone in central Utah. Unconformably overlying the Tibbet Canyon and Smokey Hollow members are the John Henry and Drip Tank members which are correlative to the Blue Gate and "Emery" Sandstone Members of the Mancos Shale. These members were deposited in the second and third regressive phases of the Upper Cretaceous Seaway during the Santonian and lower Campanian. Associated with these regressive cycles are the vast coal deposits of the John Henry Member which contain the majority of the coal reserves in the Kiaparowits Plateau.

The John Henry Member of the Straight Cliffs Formation consists of repetitous sequences of mudstone, siltstone, sandstone, and coal beds associated with progradational shoreline deposits. Peterson (1969a) defined seven marine sandstone sequences associated with three major coal zones (Figure 2). The seven sandstones are informally named the A through G sandstones and the coal zones are named Christensen, Rees, and Alvey. The Christensen coal zone consists of eight coal seams which were deposited in the swamps landward of the B marine sandstone. The middle coal zone, the Rees, contains six coal seams which accumulated during

FACIES	DESCRIPTION
FLUVIAL-FLOODPLAIN	Sandstone; Fines Upward; Erosional Base; Poorly Sorted; Trough And Micro-Cross - Bedded; Scour And Fill Structures; Lense-Shaped. Mudstone And Interbeds; Light Gray; Slope Former
MARSH	Mudstone And Interbeds; Local Carbonaceous Material; Local Fluvial Channels; Slope Former
SWAMP	Coal Seams, Carbonaceous Mudstone, Local Fluvial Channels And Interbeds; Slope Former; Burn Common
LAGOON	Carbonaceous Mudstone, Oyster Reefs; Thinly Bedded; Local Sandy Washover Fans; Slope
FORESHORE	Sandstone; Medium-Grained; Massive Cliff; Horizontal And Herringbone Bedding; White-Cap; Clean And Well Sorted; Regular Bedding
UPPER SHOREFACE	Sandstone; Fine To Medium-Grained; Coarsens Upward; Trough Cross-Stratification; Very Regular Bedding; Low Angle Bedding; Minor Bioturbation
LOWER SHOREFACE	Sandstone; Fine-Grained; Coarsens Upward; Hummocky And Trough Cross-Stratification; Bioturbated; Regular Bedding
TRANSITION	Sandstone And Mudstone Beds; Very Fine-Grained Sandstone Beds With Sharp Basal Contacts; Profusely Bioturbated; Slope
OFFSHORE	Mudstone; Homogeneous; Slope Former; Intensely Bioturbated

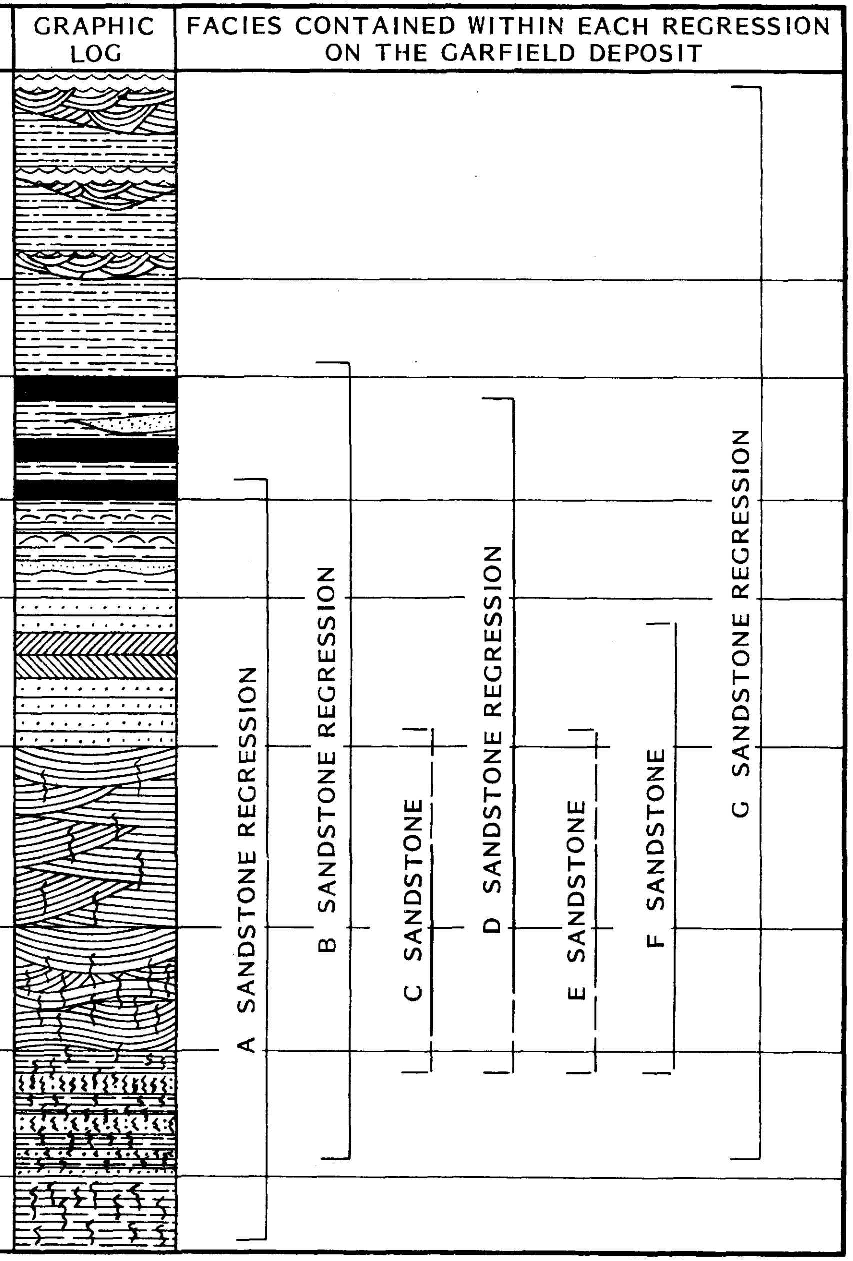

Figure 3. Generalized vertical sequence through regressive sandstone and overlying coal-bearing strata.

the C and D regressions. The Alvey zone consists of a single coal seam associated with the G sandstone which was the final regressive sequence of the John Henry Member. The A through G sandstones exhibit repetitious vertical sequences which show subtle lateral and vertical variations.

DEPOSITIONAL FRAMEWORK

Vertical sequences exhibited in the seven marine sandstones consist of generally coarsening upward sequences of shoreface sandstones overlain by paludal mudstones, siltstones, and coal. A typical succession exhibited in these sequences is offshore marine mudstones which grade upwards into interbedded sandstones and mudstones of the transition zone which is overlain by shoreface and foreshore deposits. Coals are typically separated from the shoreface deposits by mudstones and carbonaceous mudstones deposited in lagoons or bays. Overlying the coal beds are mudstones and sandstones deposited in marsh and fluvial floodplain settings. Figure 3 summarizes the characteristics associated with each of the facies in an idealized regressive sequence.

The offshore facies are typically homogeneous to horizontally laminated dark gray mudstones. Bioturbation is generally intense enough to destroy all bedding characteristics. These mudstones are interpreted to have been deposited in quiet open marine conditions. The offshore mudstones grade vertically into thinly interbedded, very fine-grained sandstones and mudstones of the transition zone. The sandstones have sharp basal contacts and range in thickness between 5 cm and one meter. They are typically hummocky cross stratified with occasional low angle, small scale, trough cross stratification. Upper contacts of these sandstones are generally diffuse or gradational due to bioturbation. The sandstones increase in thickness and number upwards as they grade into the shoreface deposits.

The shoreface deposits consist of coarsening upward sandstones and can be divided into upper and lower shoreface. The lower shoreface sandstones consist of large scale hummocky and medium to large scale cross stratification which is commonly bioturbated. The sands are generally very fine to fine, poorly to moderately sorted and sand grains are subangular to subrounded. The upper shoreface is marked by an absence of hummocky cross stratification, better sorting, decrease in bioturbation and is more regularly bedded than the lower shoreface. Herring-bone and trough cross stratification characterize the upper shoreface which was deposited above effective wave base.

The shoreface and foreshore can be replaced by tidal inlet or distributary channel deposits. These "replacement" facies are important in determining a deltaic or barrier island origin of the marine sandstones. Distributary channels associated with deltaic shorelines are characterized by abundant large scale, unidirectional, cut and fill trough cross stratification. The sandstones tend to be more angular, poorly sorted, coarser, more silty, and may contain more graded bedding than the associated delta front sandstones. Distributary channels vary considerably in size, but generally are several hundred meters wide and up to ten meters thick. Coarse lags and sharp basal contacts are also common.

Tidal inlets or channels, associated with barrier island sandstones are more difficult to determine, but do have some definitive characteristics. Crossbedding tends to be bi-directional with mixed marine and continental debris; for example, shark teeth and Inoceramus fragments associated with oyster fragments and twigs or logs. The tidal inlets tend to have more shell debris than the associated shoreface sandstones and shell lags are fairly common, often occurring in several horizons. Tidal inlets are generally ten meters thick with varying or undeterminable width. Tidal inlets are locally capped by flood tidal deltas which will be discussed later.

Overlying the shoreface sandstones are very clean, well rounded, and well sorted horizontally bedded sandstones of the foreshore. Foreshore sandstones are generally one to two meters thick and commonly bleached white (white cap) on outcrop exposures. They were deposited in the swash zone between mean high tide and mean low tide. The foreshore sandstones are generally overlain by thinly bedded, sandy-silty mudstones. Locally, oysters are very common as is sandstone which is lithologically similar to the shoreface and foreshore. These sandstone beds are thought to have been deposited in lagoons or possibly bays with local washover fans and flood tidal deltas.

Washover fans are generally about 30 centimeters thick with a general absence of well defined sedimentary structures. Coalified plant debris and shell fragments may be common. Sets of

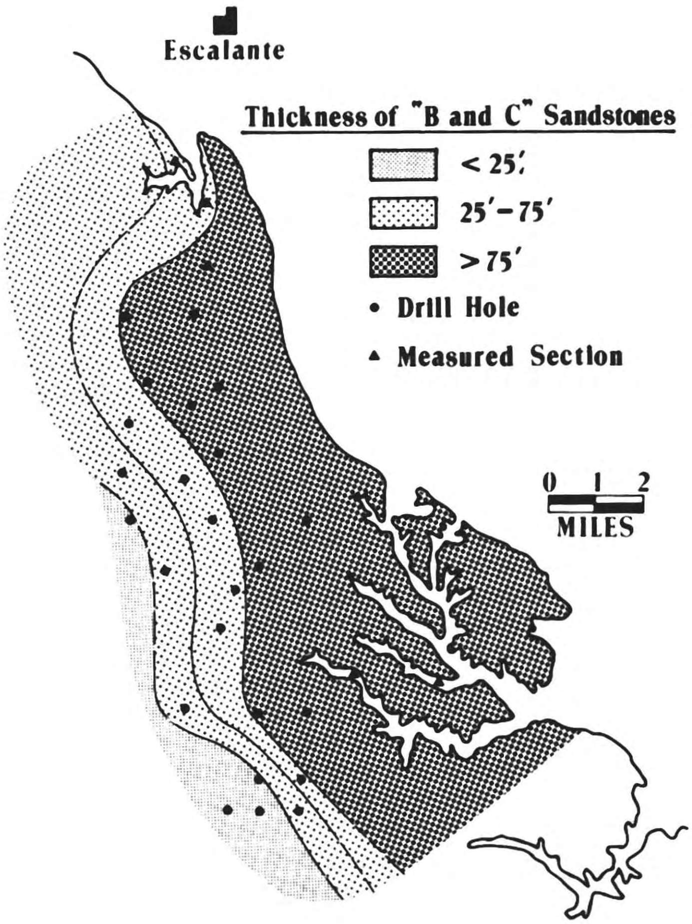

Figure 4a. Isopach map of the combined B and C sandstones.

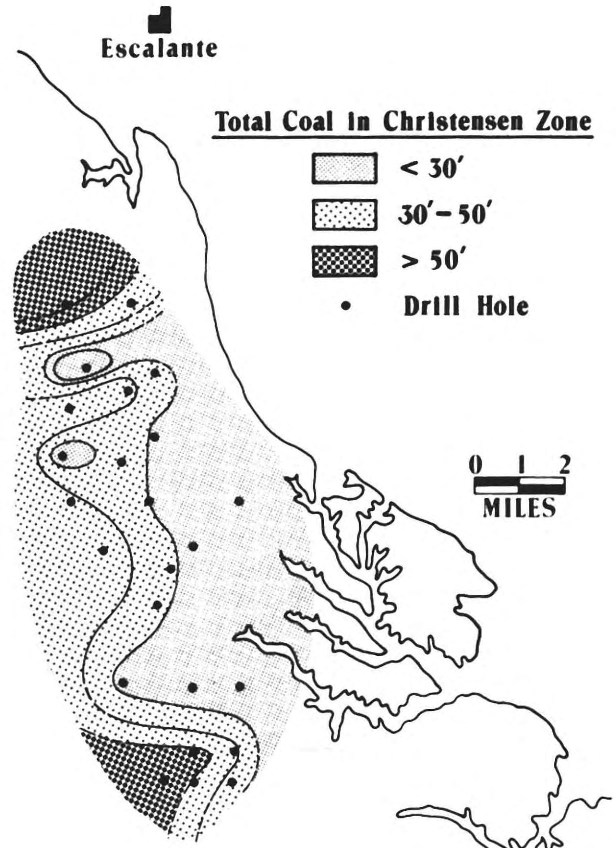

Figure 4b. Isopach map of total coal in the Christensen coal zone.

individual washover fans can be one to two meters thick and interfinger with lagoonal sediments. Flood tidal delta sandstones tend to be thicker, approximately 1 m each, and display a variety of sedimentary structures. In cross section the sandstones are lens-shaped with cross stratification and mud clast lags in the center grading to planar cross stratification towards the flanks. The current directions show both ebb and flood directions with flood dominating towards the center and ebb on the flanks. The flood tidal delta sandstones interfinger with mudstones and interbeds with locally abundant oyster fragments.

Overlying the lagoonal or bay deposits are swamp deposits characterized by coal beds, carbonaceous mudstones, and local small fluvial deposits. The coals, with one exception, occur as multi-seams and average approximately three meters in thickness, although they locally attain thicknesses in excess of six meters. Interbedded among and within the coals are dominately carbonaceous mudstones, mudstones and siltstones with minor amounts of fluvial sandstones. The fluvial sandstones are typically fine to medium grained, poorly sorted, angular and silty and generally do not exceed three meters in thickness.

The swamp deposits grade upward into deposits characteristic of marsh and fluvial floodplains, or delta plain. These sediments consist of sandstones, siltstones, mudstones, and interbeds of fluvial origins. There is a general decrease in visible carbonaceous material with sediments indicating higher energies. The fluvial sandstones are significantly more abundant and reach thicknesses of up to ten meters.

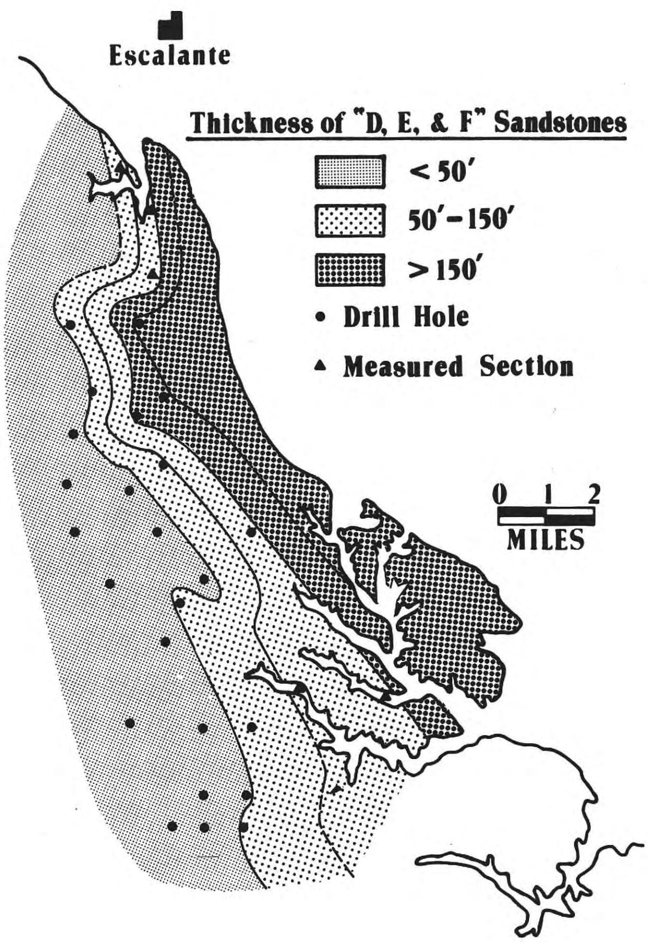

Figure 5a. Isopach map of the combined D, E, and F sandstones.

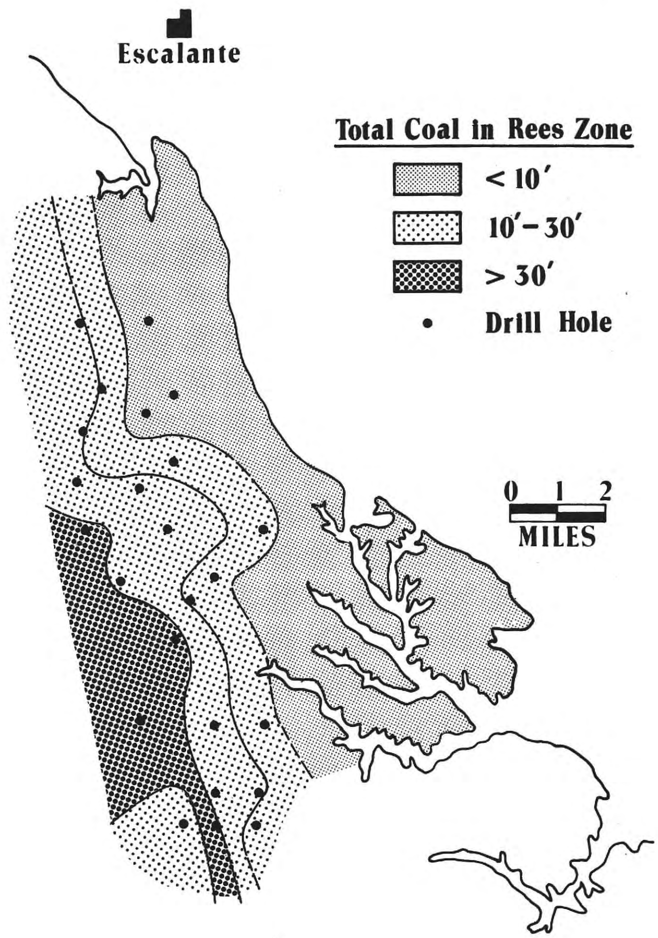

Figure 5b. Isopach map of total coal in the Rees coal zone.

DEPOSITIONAL MODEL

Variations in the vertical sequences and the ranges of facies present are the key to reconstruction of depositional environments and the depositional history of the area. Relatively major regressions are associated with the A, B, C, and G sandstones which are the only sandstone sequences that exhibit complete vertical sequences (Figure 3). However, the B, and C and D sandstones are associated with the multi-seam Christensen and Rees coal zones while the G sandstone just has the single seam of the Alvey zone associated with it. This difference can be explained by different genetic origins of the individual sandstone sequences or possibly by the extent of duration of the regressive cycles.

The relationship between the coal zones and the associated sandstones is shown in Figures 4, 5, and 6. The Christensen and Rees zones show a parallel relationship between the coal and the sandstones. The G sandstone shows a different relationship since the coal trends perpendicular to the marine sandstone. Examination of the facies associated with the sandstones show that the G sandstone exhibits features typically associated with deltaic deposits. The most striking feature is the abundance of channel sandstones above the G and that there is only a single coal seam. The C and D sandstones, however, exhibit characteristics which are more typically associated with barrier island sequences: lagoonal deposits, washover fans, flood tidal deltas, and multiple coal seams. Problems arise with the B sandstone which exhibits a linear shoreline like the C and D but does not show characteristics of barrier island sequences, except that there are multiple coal seams. In this case it is possible that the B regression was either very extensive in the seaward direction or the duration of the regression was slow enough to allow the extensive coal of the Christensen zone to develop.

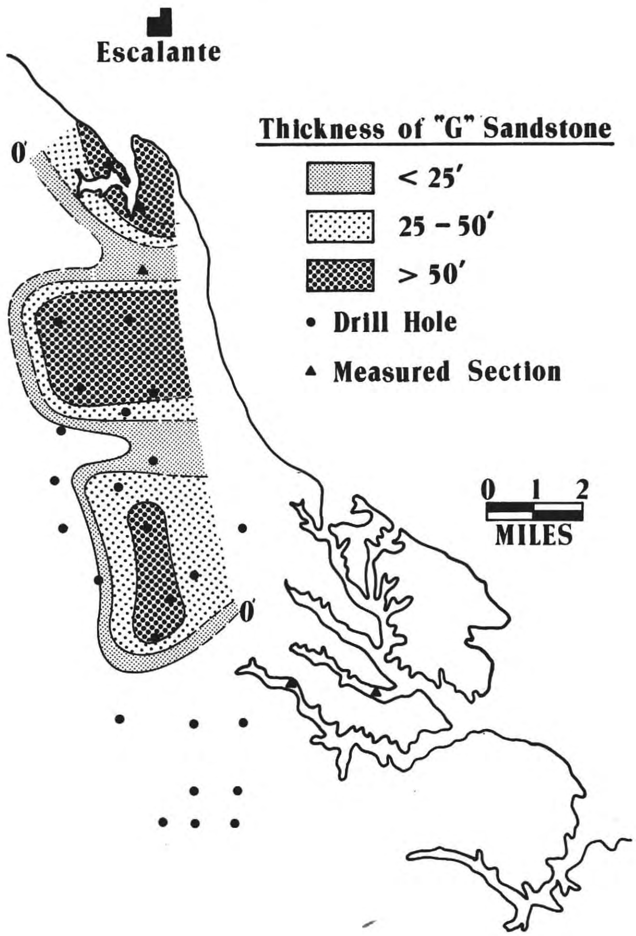

Figure 6a. Isopach map of the G sandstone.

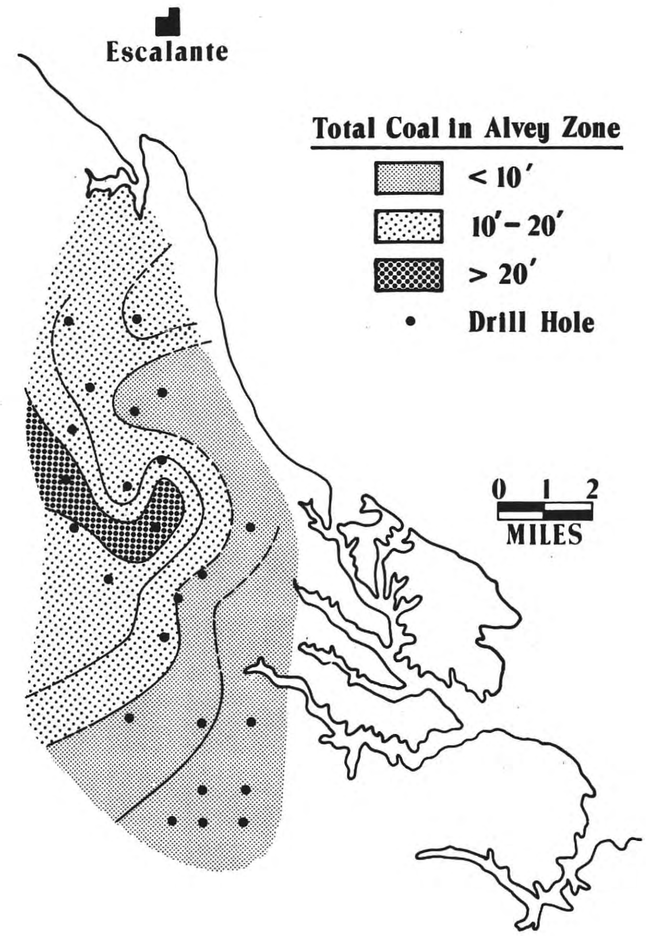

Figure 6b. Isopach map of the coal in the Alvey coal zone.

CONCLUSIONS

The coal deposits of the Northern Kaiparowits Plateau were deposited landward of prograding deltaic and barrier island shorelines. The nature of these marginal marine sandstones and the associated facies suggest a wave dominated/microtidal coast line (Table 1). The extensive coal reserves in the Rees and Christensen zones were probably deposited behind barrier island systems, while the Alvey coal zone was associated with a deltaic system. The key for the recognition of barrier vs. deltaic lies in the variations of the vertical sequences and the nature of the "replacement" facies.

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Table 1. Micro-Tidal Wave-Dominated Characteristics.

- Linear shorelines
- Well-developed lagoons
- Extensive washovers
- Flood tidal deltas
- Absence of ebb-tidal deltas
- Tidal inlet depth 8 meters
- Tidal inlet spacing wide
- Absence of tidal creeks
- Foreshore thickness 1-2 meters

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COAL CORRELATIONS AND DEPOSITIONAL ENVIRONMENTS OF CRETACEOUS BLACKHAWK FORMATION AND STAR POINT SANDSTONE, WASATCH PLATEAU, UTAH

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INTRODUCTION

A detailed study of the stratigraphy and sedimentology of the Upper Cretaceous Star Point Sandstone and overlying Blackhawk Formation has led to a reinterpretation of their depositional environment and a revised correlation of coal beds. The study area is a belt 50 mi long along the eastern escarpment of the Wasatch Plateau in central Utah (Figure 1). Networks of cross sections constructed from 480 closely spaced (about 0.25 mi apart) measured sections and 78 drill holes permitted paleogeographic reconstructions of time-stratigraphic facies and their associated economically important coal deposits. The study of depositional environments of this group of rocks was undertaken primarily to form a base of correlation studies of coal beds of the Blackhawk Formation.

The key to understanding the correlation of coal beds, particularly that of the widely mined Hiawatha coal, is the intertonguing relationship of the lowermost Blackhawk Formation and the uppermost Star Point Sandstone (Figure 2). Zones of intertonguing of the Blackhawk Formation and Star Point Sandstone occur repeatedly along the outcrop belt and result in a stratigraphic rise toward the northeast. A previous study of this group of rocks (Speiker, 1931) described a sharp, horizontally continuous contact between the Blackhawk Formation and Star Point Sandstone. This conclusion led to the interpretation of the rocks as tabular bodies (e.g., Star Point Sandstone) and correlation of Sandstone as a continuous bed along the length of the Wasatch Plateau. The consequences of these concepts are two fold: 1) the interpretation of the Star Point Sandstone as a sheetlike body of beach-barrier and littoral origin (Speiker, 1931, 1949; Young 1955, 1966) provided a widespread platform on which the Hiawatha coal accumulated and 2) the presumed extensive distribution of the Hiawatha coal resulted in its being mapped as a continuous bed for as much as 70 mi along the outcrop belt.

Thus, this model for the anatomy and mode of deposition of the Star Point Sandstone and Blackhawk Formation has created problems in unravelling specific environments of deposition of the Blackhawk coal deposits as well as their correlations. These problems are particularly highlighted by the economic importance of the Hiawatha coal, whose exploration and mining depend upon precise correlation.

DEPOSITIONAL ENVIRONMENTS

Along the length of the Wasatch Plateau, the uppermost Star Point Sandstone intertongues with lowermost Blackhawk Formation; the oldest to youngest intertongue zones are recorded from southwest to northeast (see Figure 2). Each major intertongue is about 5 to 10 mi in length. Three-dimensional stratigraphic control shows that the tongues of the Star Point Sandstone pinchout on a line trending from northwest to southeast with the orientation of the line varying from N20°W at the southwest to N10°W at the northeast.

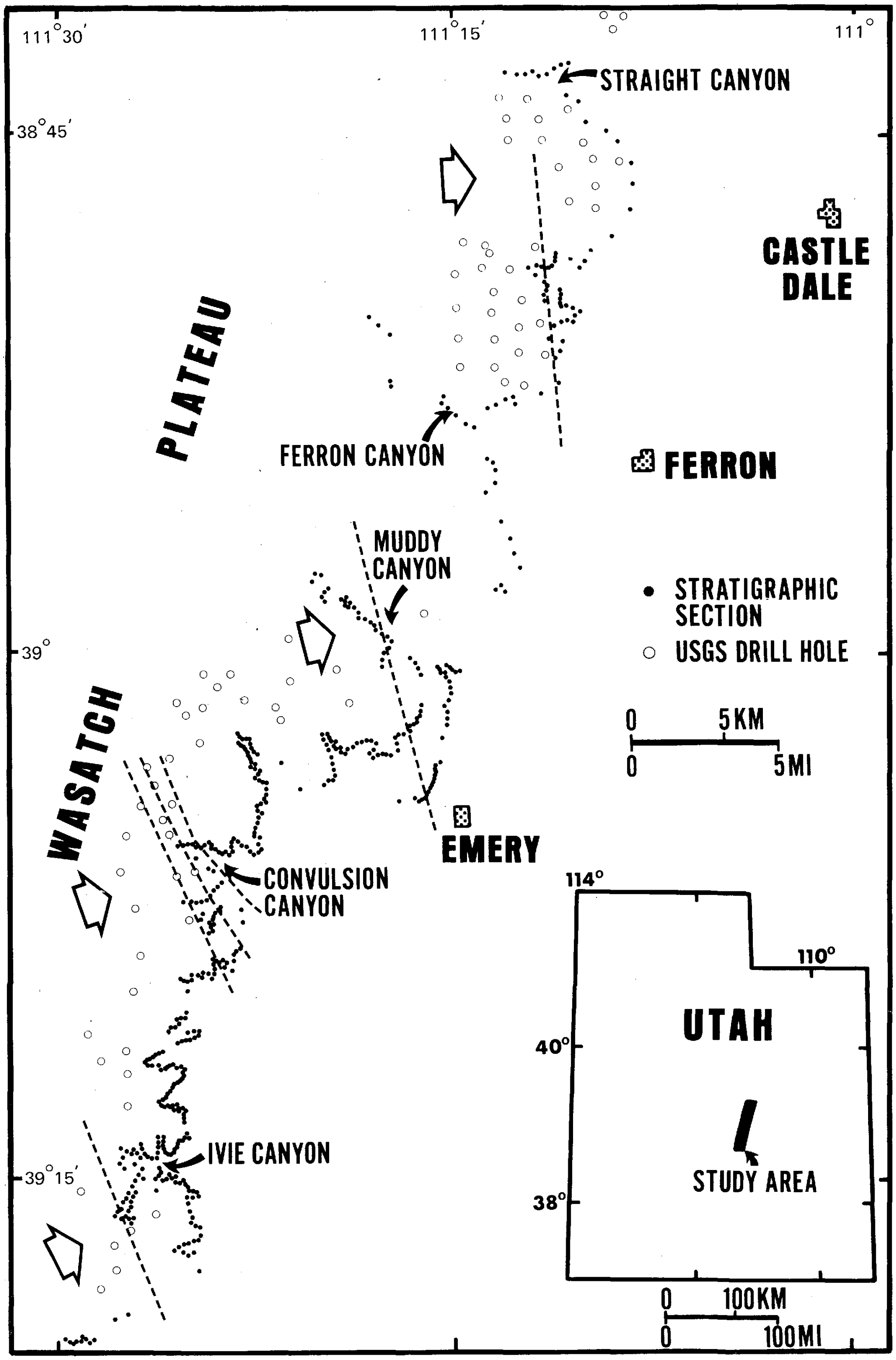

Figure 1. Location map showing study area in the Wasatch Plateau and locations of measured sections as well as drill holes. Line of pinchouts of Star Point Sandstone tongues (dashed lines) and directions of progradation of delta systems (large arrows) are also indicated.

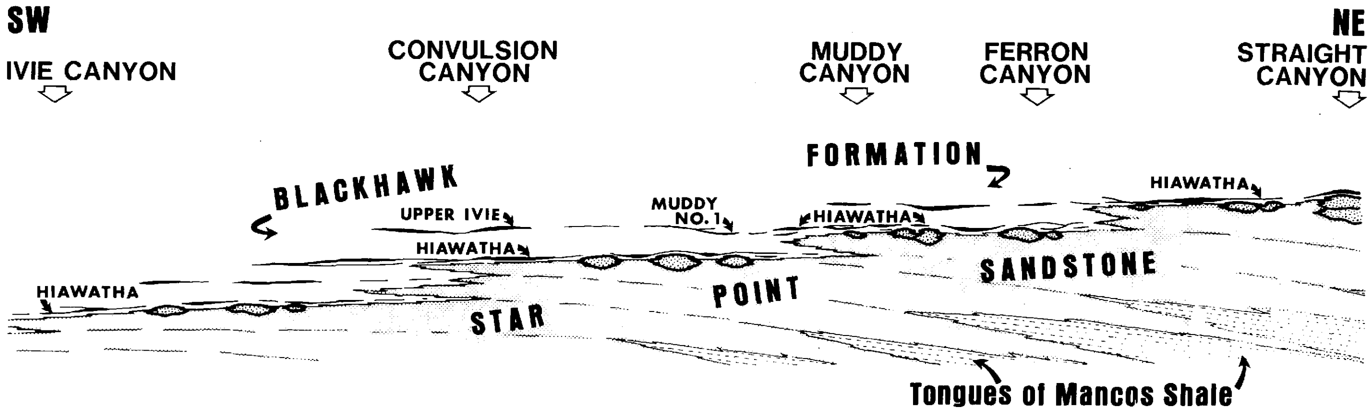

Figure 2. Diagrammatic cross section showing intertonguing relationship of the lowermost Blackhawk Formation and uppermost Star Point Sandstone and correlations of Hiawatha and laterally equivalent coal beds. See Figure 1 for general location of cross section.

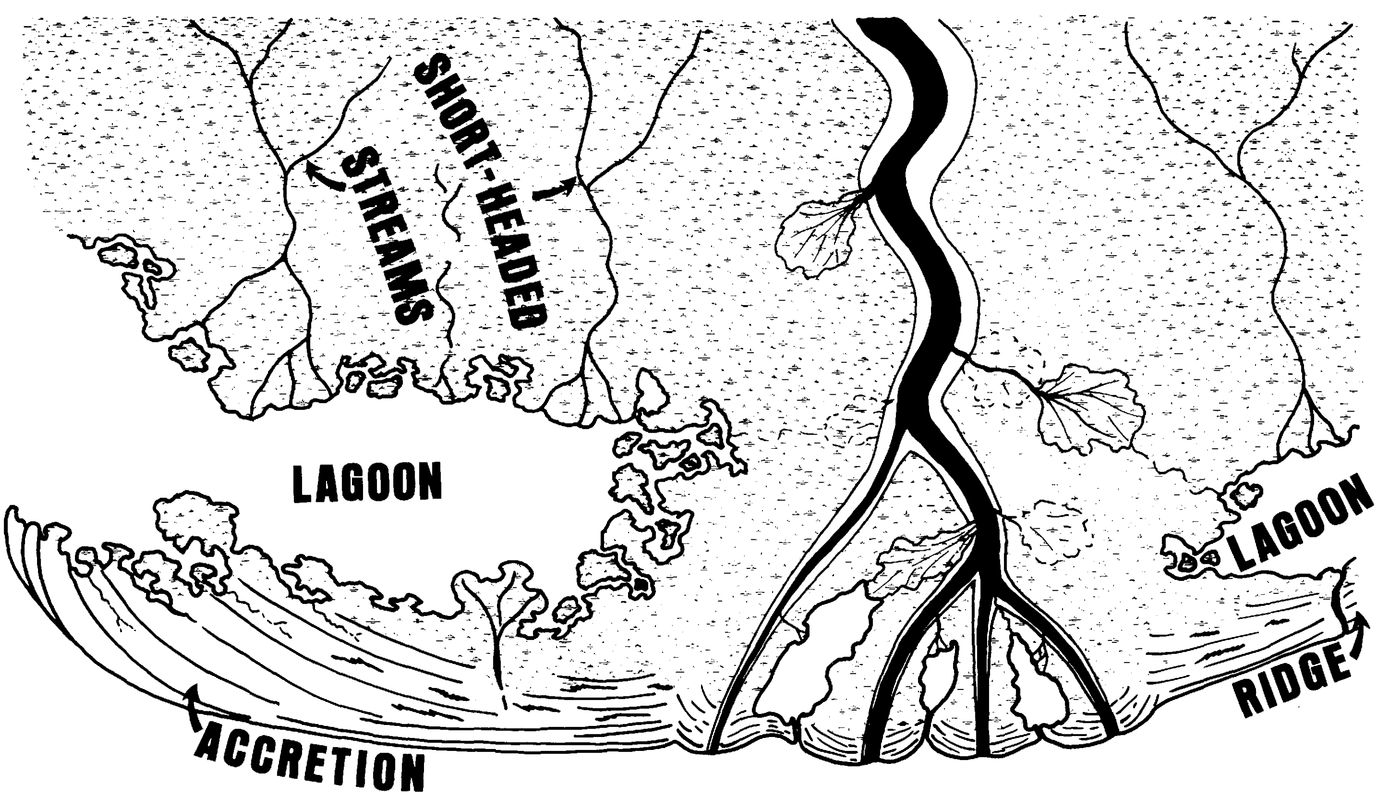

Figure 3. Diagrammatic reconstruction of environments of deposition of time-stratigraphic facies of the intertongue zone of the Star Point Sandstone and Blackhawk Formation. Modified from Marley and others (1979).

Each tongue of the Star Point Sandstone represents a subaerial accretion ridge formed by wave- and current-reworked distributary channel-mouth bar sediments of major fluvially-influenced deltas (Figure 3). Excess sediment supply of these major deltas was reworked downdrift in a southeastward direction by longshore currents. The accretion ridges, which were locally dissected by washover, acted as barriers lateral to the east-northeasterly prograding delta systems. The accretion-ridge deposits grade laterally west-southwestward into the swamp and lagoonal deposits of the Blackhawk Formation, which in turn pass landward into delta—plain deposits formed by minor short-headed streams. These deposits grade laterally into deposits of the major distributary channels that cross cut the lagoons.

The Hiawatha and other coal beds of the Blackhawk Formation accumulated in swamps in the back-barrier and delta-plain environments and local processes in these environments controlled the characteristics of the coals. On the landward sides of the accretion ridges, the swamps, which were limited on their landward side by lagoons, were subjected to beach, overwash, and flooding by brackish water. Under these conditions, the swamps became sites for the accumulation of carbonaceous shale or dirty coal. Along the lagoonal side of stable accretion ridges near major distributary channels that cross cut lagoons, thick peat collected in swamps protected from overwashing by high barrier elevation. Where swamps formed on delta plains of minor short-headed streams at the landward side of the lagoons, they became sites of accumulation of thin to thick and lenticular peat deposits. As the lagoons were filled with detrital sediment, swamps from both sides of the lagoons encroached over the filled surface and accumulated thick, elongate organic deposits. These marginal coastal settings served as important sites of accumulation of mineable coals in the lowermost Blackhawk Formation in the Wasatch Plateau.

The lithofacies relationships, sequences, and associations of the Blackhawk Formation and Star Point Sandstone differ from those of fluvially-dominated delta deposits (Fisher and McGowen, 1967; Coleman, 1976) and from those of wave-dominated delta deposits (Balsley, 1980). The major deltas of the Star Point and Blackhawk formations are characterized by distributary channel-mouth bar facies and flanking accretion ridge or barrier facies representing sites of optimum detrital output and accumulation. However, moderate current and wave reworking of the excess delta detrital output caused redistribution of sediments along the coastline and formation of accretion ridges or barriers. Thus, in the Star Point—Blackhawk fluvially-influenced deltas, numerous distributary channels served as point sources of sediment that were redistributed in a coastwise direction. In addition, the distributary channel deposits in the Star Point—Blackhawk deltas grade laterally with abundant interdistributary bayfill deposits that contain brackish-water bivalve fossils and crevasse splay deposits. More importantly, concentration of detrital deposition in delta and coastal areas accompanied by minimal detrital influx from other sources created ideal conditions for the formation of thick coal deposits in sediment-filled lagoonal swamp platforms. In modern wave-dominated deltas fed by one or two distributary channels (Coleman and Wright, 1975; Coleman, 1976; Psuty, 1966), open water lagoons or bays are absent. In addition, in some wave-dominated deltas such as the Senegal delta (Coleman, 1976), parallel- to near parallel- oriented distributary channels are present behind beach ridges. Perhaps the most critical feature of the Star Point—Blackhawk delta systems of the Wasatch Plateau is the rate of east-northeastward progradation which concentrated detrital deposition in four main sites (see Figure 1). Figure 4 displays the prograded and overlapped delta systems with accompanying barriers developed in the Convulsion Canyon, Muddy Canyon-Emery area, and Straight Canyon-Ferron area. Here, episodic progradation and subsequent realignment of the paleoshoreline are indicative of autocyclic construction of deltaic coastal plain typical of fluvially influenced or fluvially dominated delta systems. In contrast, progradation in many modern wave-dominated deltas proceeds at such a rate that coarse accretion-ridge sediment is spread across the delta front in ajoining coastal area. The resultant delta front-coastal sand complex, which consists of imbricated bodies, is sheetlike and forms a platform that supports regionally extensive peat swamps.

COAL CORRELATION

The autocyclic shifts of delta progradation placed a rigid control on the paleogeographic distribution of the Hiawatha coal bed. The successive progradation accompanied by northeasterly shifts of major deltas and barriers caused northeast pinchouts in successive bodies of the Hiawatha coal. These conditions of deposition also resulted in the stratigraphic rise of about 200 ft of the Hiawatha coal bed from southwest to northeast. Thus, the environmental-stratigraphic offlaps have created serious problems in regional as well as local correlations of the Hiawatha coal bed, in that the Hiawatha becomes a zone of partially related coal bodies. Nomenclature problems exist where the

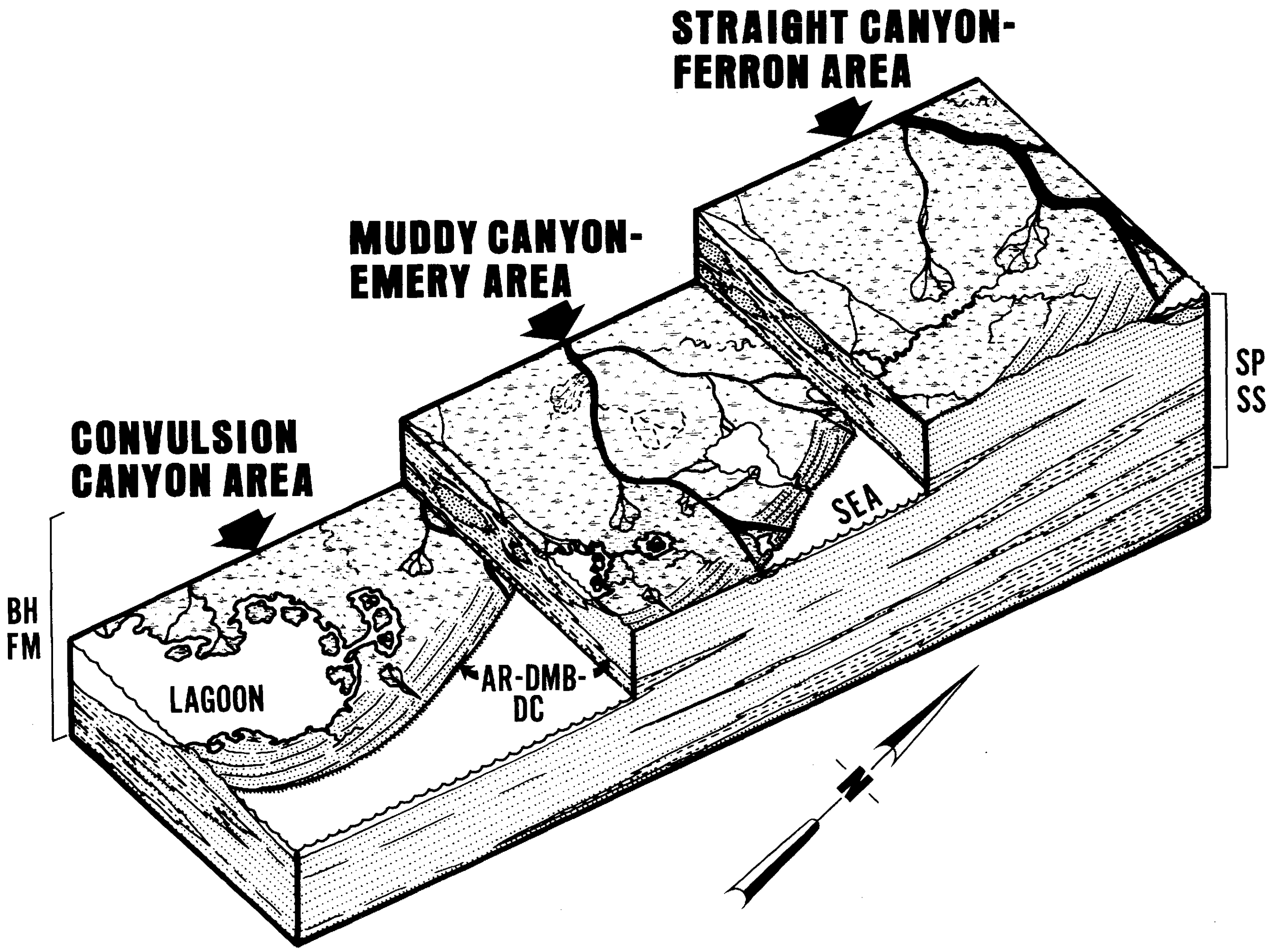

Figure 4. Block diagram of successive episodes of delta-barrier progradation and autocyclic shifts from southwest to northeast. BH FM=Blackhawk Formation; SP SS=Star Point Sandstone; AR—DMB—DC=accretion ridge, distributary mouth bar, and distributary channel.

exact stratigraphic relationships are not well known. For example, in the Muddy Canyon-Emery area, the Hiawatha coal lying directly above the Star Point Sandstone pinches out landward and is laterally equivalent in the west with Muddy No. 1 coal. The Muddy No. 1 coal, where traced farther west-southwestward to Convulsion Canyon, is laterally equivalent to the Upper Ivie coal, which is about 85 ft above the top of the Star Point Sandstone. Such problems become particularly serious in leased tracts where the leasee is required to identify coal beds that are targeted for exploration and/or development. These problems are further compounded by the very uncertain mappability of the coal beds.

In addition, calculations of coal resources are unreliable in a leased tract where zone of intertonguing occur but are not correctly mapped. For example, in the Muddy Canyon-Emery area, the total identified coal resources in coals greater than 3.5 ft in thickness was estimated to be 164.4 million tons by Doelling (1972) prior to recognition of the intertongue zone in the area. Hayes and Sanchez (1980), using Flores and others (1979) and Flores and Marley (1979) environmental-stratigraphic data, recalculated the total identified coal resources as 143.1 million tons. Thus, the recalculations of the coal resources based on a correct stratigraphic framework has reduced the original estimate by about

13 percent. An important aid to calculation of coal resources resulting from the understanding of environments of deposition is the shape and orientation of coal deposits. Back-barrier coals are elongate with their long dimensions near parallel to the paleoshoreline. Delta- plain coals are lenticular with long dimension subparallel to distributary channels or at an angle to the paleoshoreline.

SUMMARY

In summary, the key to unravelling the paleogeographic controls to coal accumulation and their correlation in the Wasatch Plateau is the facies associations of the zones of intertonguing of the lowermost Blackhawk Formation and uppermost Star Point Sandstone. Failure to recognize this relationship in the past has led to discrepancies in the genetic interpretation of the rocks as well as miscorrelations of the coal beds and miscalculation of coal resources. It is therefore prudent to be aware of the intertonguing relationship of the Blackhawk Formation and Star Point Sandstone and to consider this relationship in the modification of their regional stratigraphy.

Finally, it is stressed that the thickness and areal distribution of the economically important Hiawatha coal in the Wasatch Plateau are more erratic than previously determined. This coal is offset to the northeast and locally occurs as narrow, lenticular to broad, elongate bodies. These trends of the Hiawatha coal are believed to reflect east-northeast progradation of major deltas and accompanying barriers.

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A TECTONIC-FLUVIAL MODEL FOR PALEOCENE COAL-BEARING SEDIMENTS, WILLISTON BASIN, SOUTHWESTERN NORTH DAKOTA

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INTRODUCTION

Recent coal resource surveys and studies associated with increased coal utilization in North Dakota have provided an opportunity to develop a regional assessment of the geologic conditions under which these vast coal resources were deposited. This paper summarizes the results and interpretations of recent regional stratigraphic and depositional environment studies conducted in southwestern North Dakota.

LOCATION AND GEOLOGIC SETTING

Test hole and outcrop data were examined for a 13,000 square mile area of the Williston Basin in the southwestern quarter of North Dakota (Figure 1). Studied were the upper part of the Paleocene Bullion Creek Formation and the lower part of the Paleocene Sentinel Butte Formation (Figure 2). Nomeclature is that used by the North Dakota Geological Survey (Clayton and others, 1977).

The sediments were deposited in a nonmarine fluvial setting (Royse, 1970; Jacob, 1972, 1976; Nesemier, 1981). The sediments consist of fine clastics usually no coarser than fine sand, lignite coals, and occasional pods of limestone or limey fine clastics. Paleocurrents measured in the field in the southwest part of the area trend east-southeasterly to southeasterly. Limited paleocurrent data for the northeast part of the area show easterly to northeasterly trends (Logan, 1981).

Recent studies have shown that most major coals can be traced over hundreds of square miles in the northeast part of the study area (Hemish, 1975; Groenewold and others, 1979). Rehbein (1977) attempted to correlate the Hanson and Harmon beds, the coals of the lower Bullion Creek Formation (Figure 3). He traced these beds throughout the southwest quarter of North Dakota, noting they were interrupted by sand-rich belts trending from the northwest to the southeast.

PURPOSE AND METHOD

The purpose of this study was to expand the regional correlations of Groenewold and others (1979) to the south and west, and to evaluate possible tectonic controls on the distribution of coals and associated sediments. The study was conducted with a regional emphasis.

A network of cross sections was prepared for 225 sites shown in Figure 1. Coals were correlated to surface outcrops in the northwest and southwest, and to outcrops and detailed subsurface correlations in the northeast (Groenewold and others, 1979; Winczewski, 1982). Sedimentation units were defined, each consisting of underlying clastics and overlying coals, clays, or limestones. Seven such units were chosen for mapping intervals (Figure 3). Structural, isopach and lithologic maps (sand, silt, coal, and clay), coal thickness and split maps were prepared for each interval (Winczewski, 1982).

RESULTS

Stratigraphic — Major coals shown in Figure 3 can be correlated over the study area. The HT Butte coal, which is a marker for the contact between the Bullion Creek and Sentinel Butte formations in southwest North Dakota, fades to a carbonaceous

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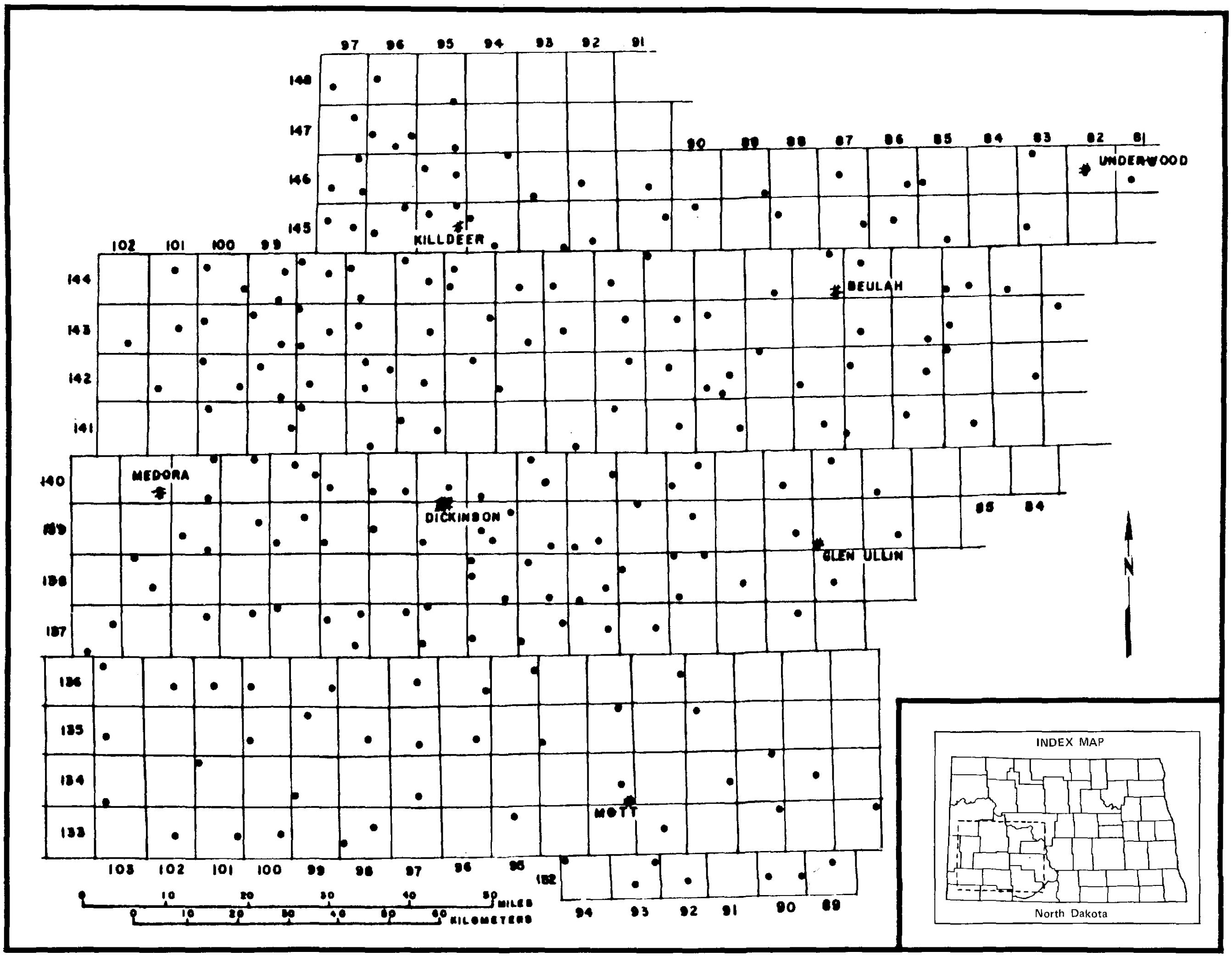

clay interval to the northwest, and to a clay, limestone, or limey clastic to the northeast.

Structural — The surfaces of the coals generally follow the present overall structure of the Williston Basin. Isopach maps indicate, however, that the basin was elongated to the south during early to middle Paleocene time. The axis of the basin was then approximately 30 mi west of its present location in the southern part of the area (Figure 4). The basin depocenter was the southwest part of the study area. The depocenter moved toward the northeast part of the study area during middle to late Paleocene time, while sediments were rather uniformly deposited over the area. During and after latest Paleocene time, the south end of the study area rose approximately 1200 feet relative to the north, deforming these beds and producing the present subcircular southern margin of the basin. The basin depocenter migrated to its present position northwest of the study area.

Anticlines in the northwestern part of the area (Figure 4) were relatively inactive during Bullion Creek time, but were apparently active during Sentinel Butte time. Bullion Creek coals conform to the structure of the anticlines; Sentinel Butte deposits are thin over the anticlines. These structures apparently significantly influenced patterns of depositional environments near them.

Lithologic Trends — Figures 5 through 11 summarize the distributions of lithologies observed for the intervals. The trends include:

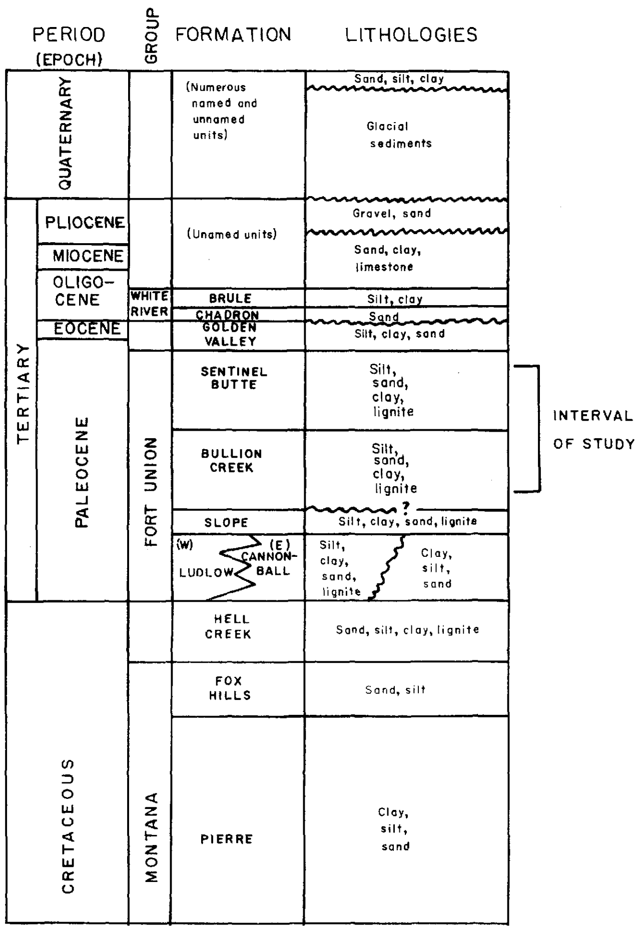

Figure 2. Uppermost stratigraphic units of the Williston Basin.

1. Clastic sediments fine upward within each interval and within formations, to the top of the Twin Buttes coal;

2. linear sand belts align northwest-southeast parallel to the axis of the basin;

3. coal and clay are dominant lithologies southwest of the axis;

4. diffuse southwesterly-northeasterly trending sandy belts exist north and east of the axis;

5. sentinel Butte lithofacies patterns are unstable over the anticlines in the northwestern part of the study area;

6. limestone or limey clastics were deposited mostly northeast of the axis, with little or none near the axis (Figure 12).

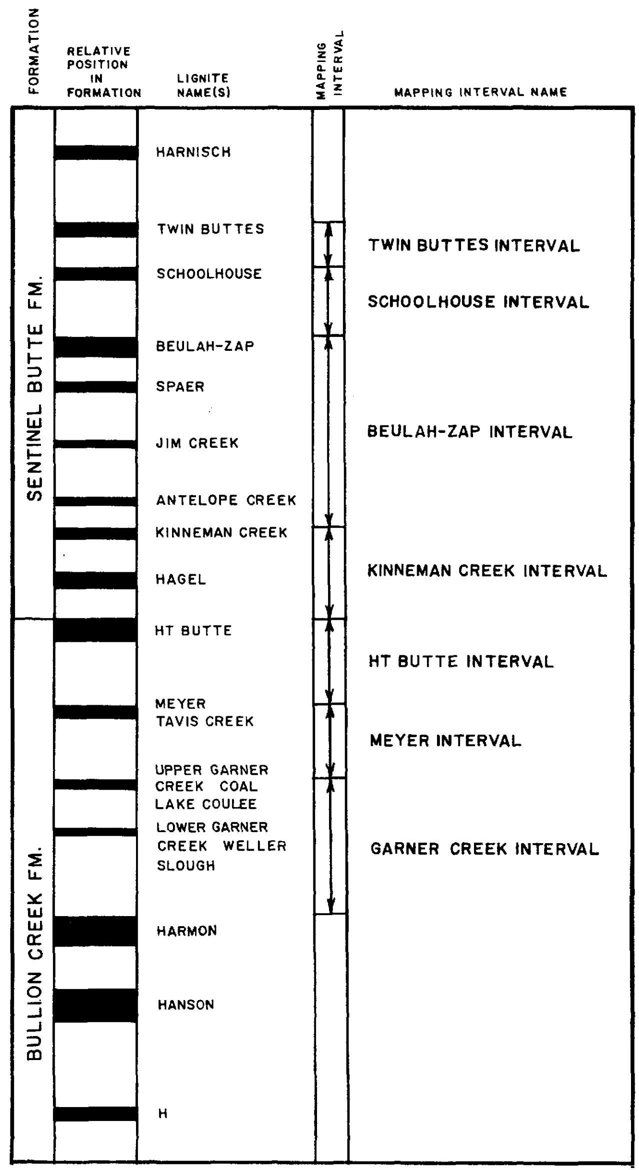

Figure 3. The names of coals and the intervals mapped in this study.

INTERPRETATIONS

Sediment Source - The source of Paleocene sediments for the study area has been problematical. Obvious sources were directly west and southwest, if the Black Hills were available. Paleocurrent measurments required less convenient sources to the northwest.

The Cedar Creek anticline lies between the Powder River Basin and the Williston Basin, across

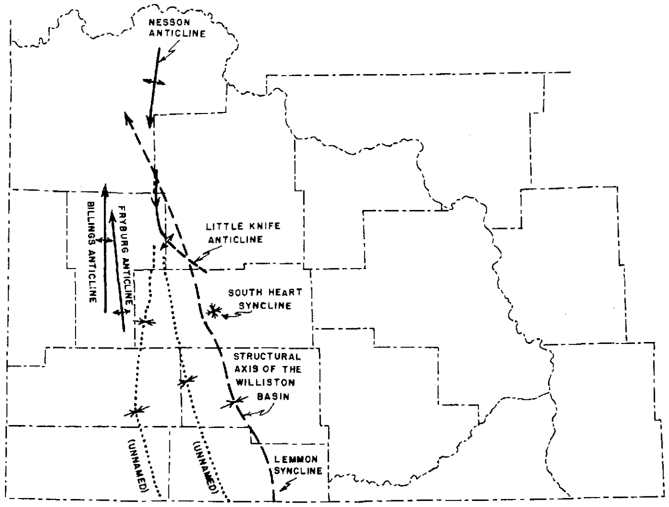

Figure 4. Williston Basin structural features in the study area.

the sediment path from the westerly sources. Recent publications for the Powder River Basin (Flores, 1981; Ethridge et al, 1981) show north-trending fluvial systems from these sources. We interpret the same sediment sources for the Williston Basin Paleocene deposits. The connection with the Powder River Paleocene fluvial system is discussed below.

Vertical Trends - Seven "cycles" were mapped as sedimentation units. Some of the mapped intervals contained lesser cycles within them. Each cycle consists of a lower sandy clastic section and an upper fine clastic or organic (lignite) section. We interpret each cycle to be the result of a temporary division of the Powder River fluvial into the Williston Basin, the mechanics of which are discussed in the next section.

There is a general fining upward of sediments in the Bullion Creek Formtion, parelleling the pattern in the Tongue River Member of the Fort Union Formation in the Powder River Basin (Flores, 1981). Discontinuous limestones or limey clastics occur at the top of Bullion Creek Formation in the Williston Basin and at the top of the Tongue River Member of the Fort Union Formation in the Powder River Basin.

The Kinneman Creek Interval, at the base of the Sentinel Butte Formation, contains basal clastics of medium to fine sands, breaking the overall fining-upward trend. The intervals of the Sentinel Butte Formation fine upward to the top of the Twin Buttes coal. Although the section above the Twin Buttes coal was not examined in detail, coarser sands dominate and clays and coals are not common.

Three "megacycles" are therefore observed: From the base to top of the Bullion Creek Formation; from the base of the Sentinel Butte Formation to the top of the Twin Buttes coal; above the Twin Buttes coal. Each is interpreted to be the result of large-scale changes in the amount and character of sediment supply to the basin, reflecting changes in intensity of tectonic activity at the source areas.

Lignites are few and thick in the Bullion Creek Formation; they are many and thin in the Sentinel Butte Formation. We interpret the Bullion Creek pattern to have resulted from deposition in a fairly unifornly subsiding basin. During Sentinel Butte time, however, anticlines were rising in the northwestern part of the area. These rose at a rate slower than the overall subsidence of the basin. As a result, Sentinel Butte fluvial systems were less stable than those of the Bullion Creek. Coals are thinner and multiple.

Lithofacies Trends - Three regional lithofacies trends must be accommodated in the sedimentation model. They are:

1. Sandy belts trend northwest to southeast, parallel to the paleoaxis of the basin;
2. coal and fine clastics dominated southwest of the axis;
3. diffuse distributary patterns of sandy belts are observed north and east of the axis.

Figure 13 summarizes the model for deposition of a cycle. As the Williston Basin axis subsided, it formed an area below the base level of the Powder River system to the west. When that system diverted into the Williston Basin, it entered where the basin axis passes between the Nesson and Cedar Creek Anticlines. The latter was probably actively rising throughout the Paleocene, presenting a moderately-effective barrier to sediment transport from the west.

Initially, the fluvial system flowed southeast, along the basin axis. The axis was probably plunging southeast then, and the basin margin was far southeast of the area. The control exerted by the axial through resulted in the northwest-southeast lineation

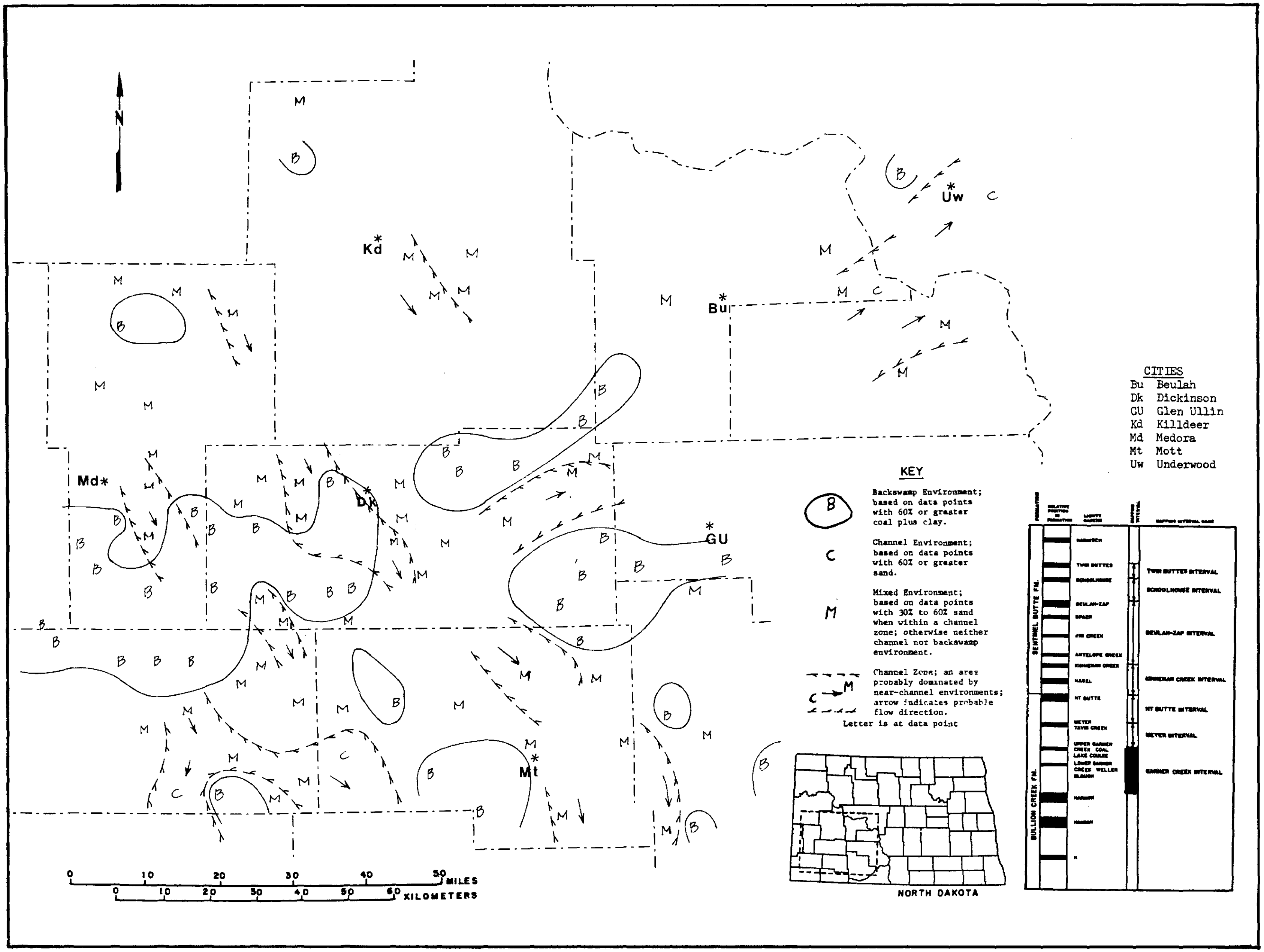

Figure 5. Depositional environments of the Garner Creek interval.

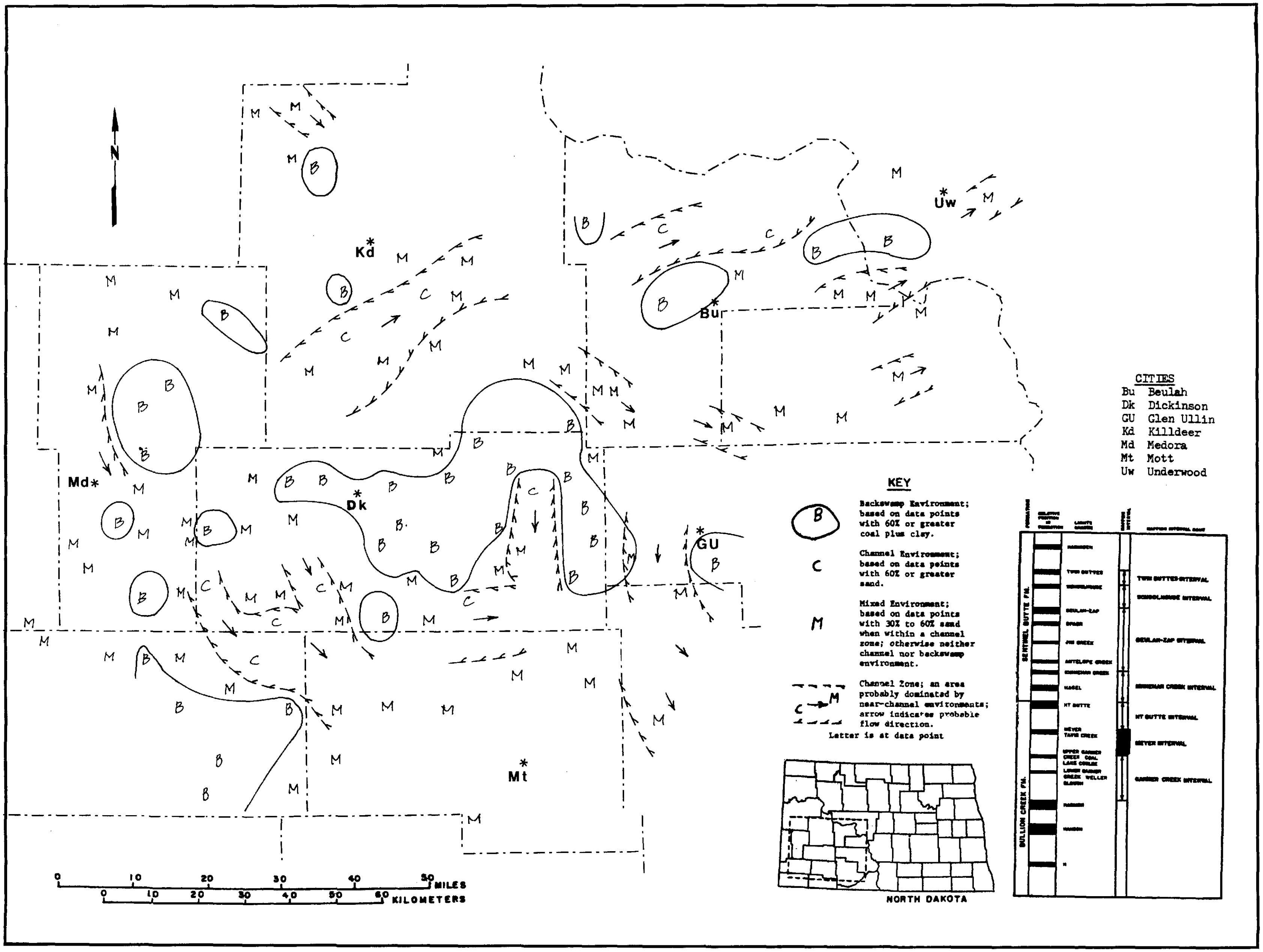

Figure 6. Depositional environments of the Meyer interval.

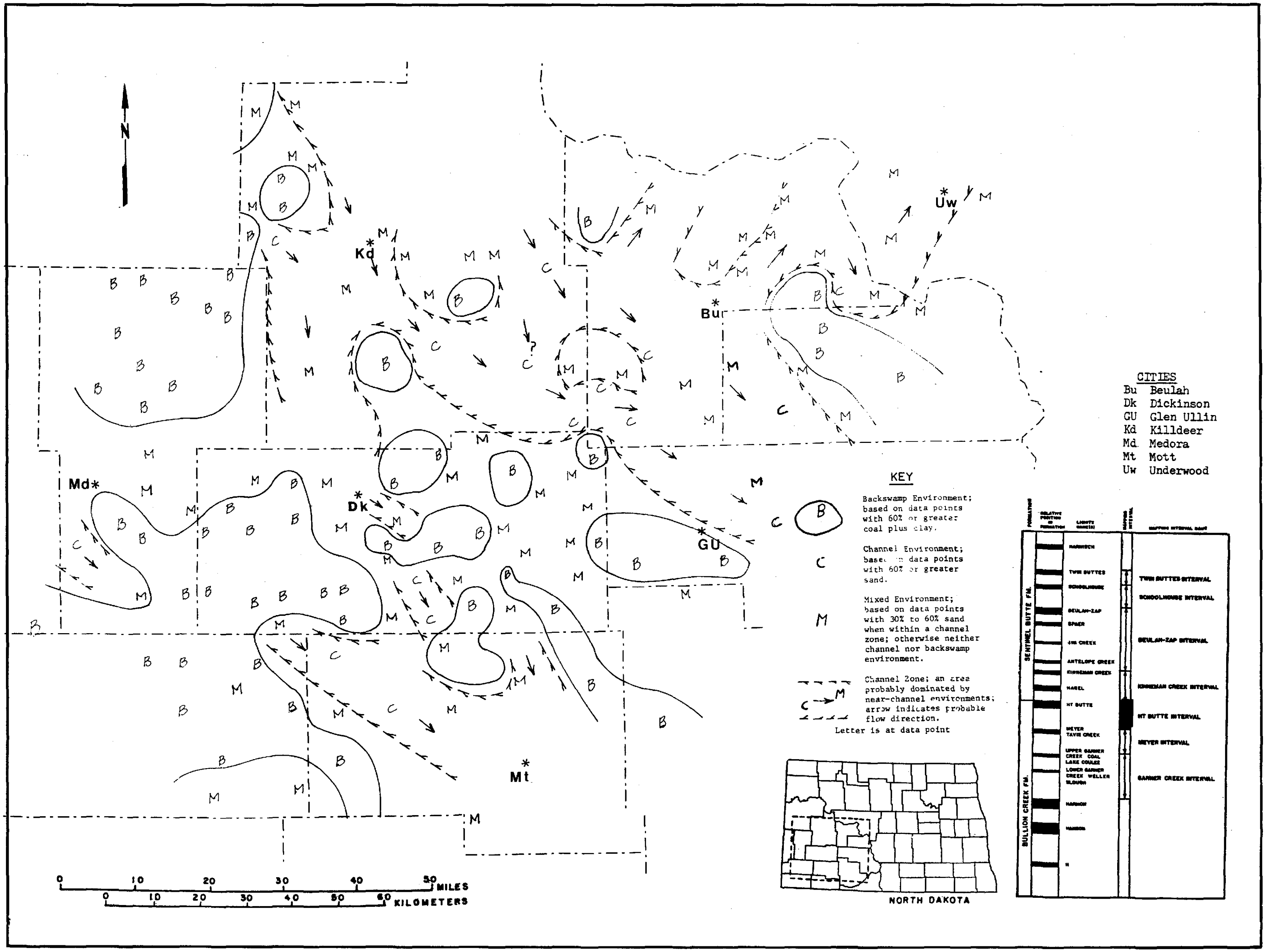

Figure 7. Depositional environments of the HT Butte interval.

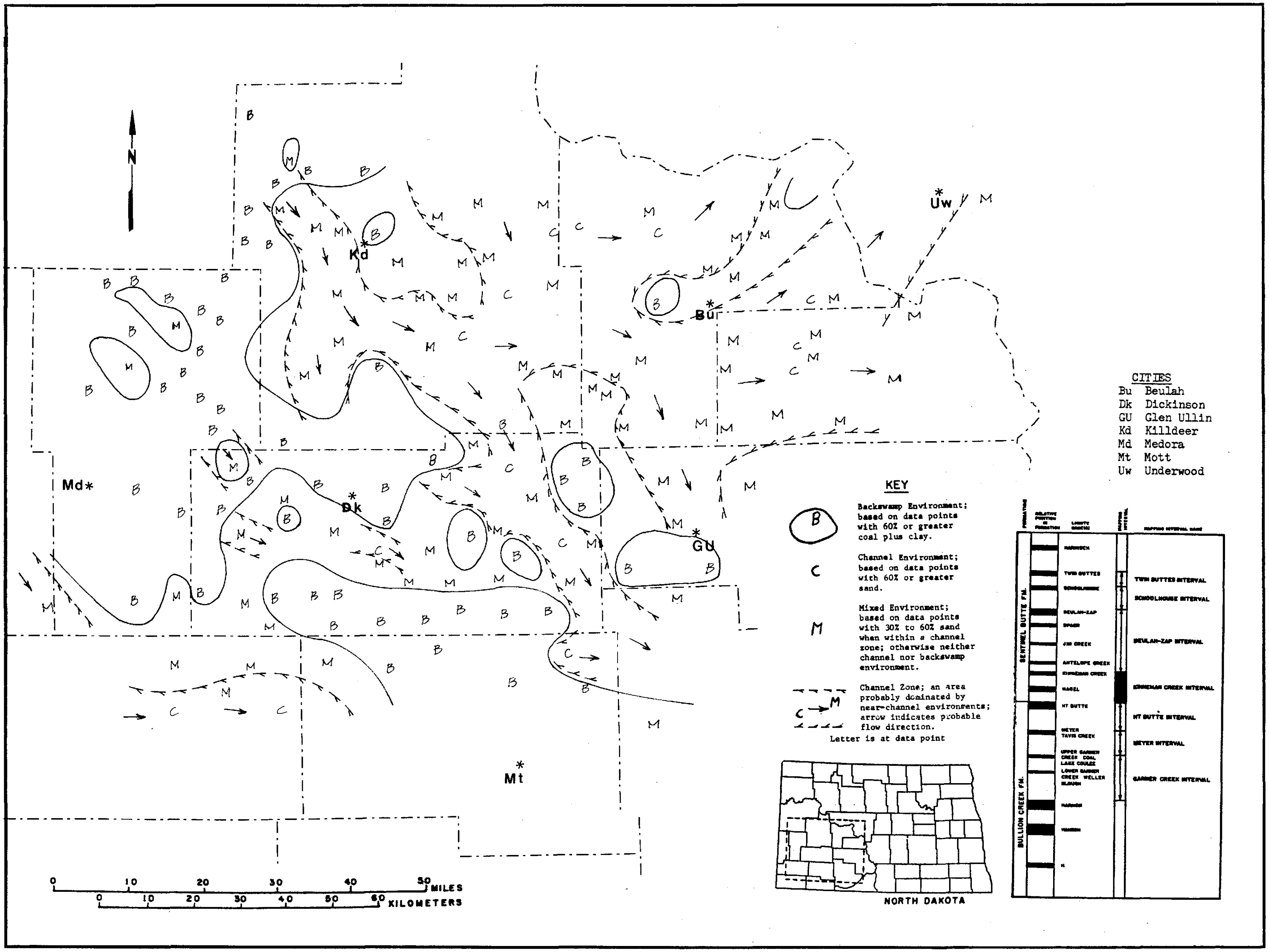

Figure 8. Depositional environments of the Kinneman Creek interval.

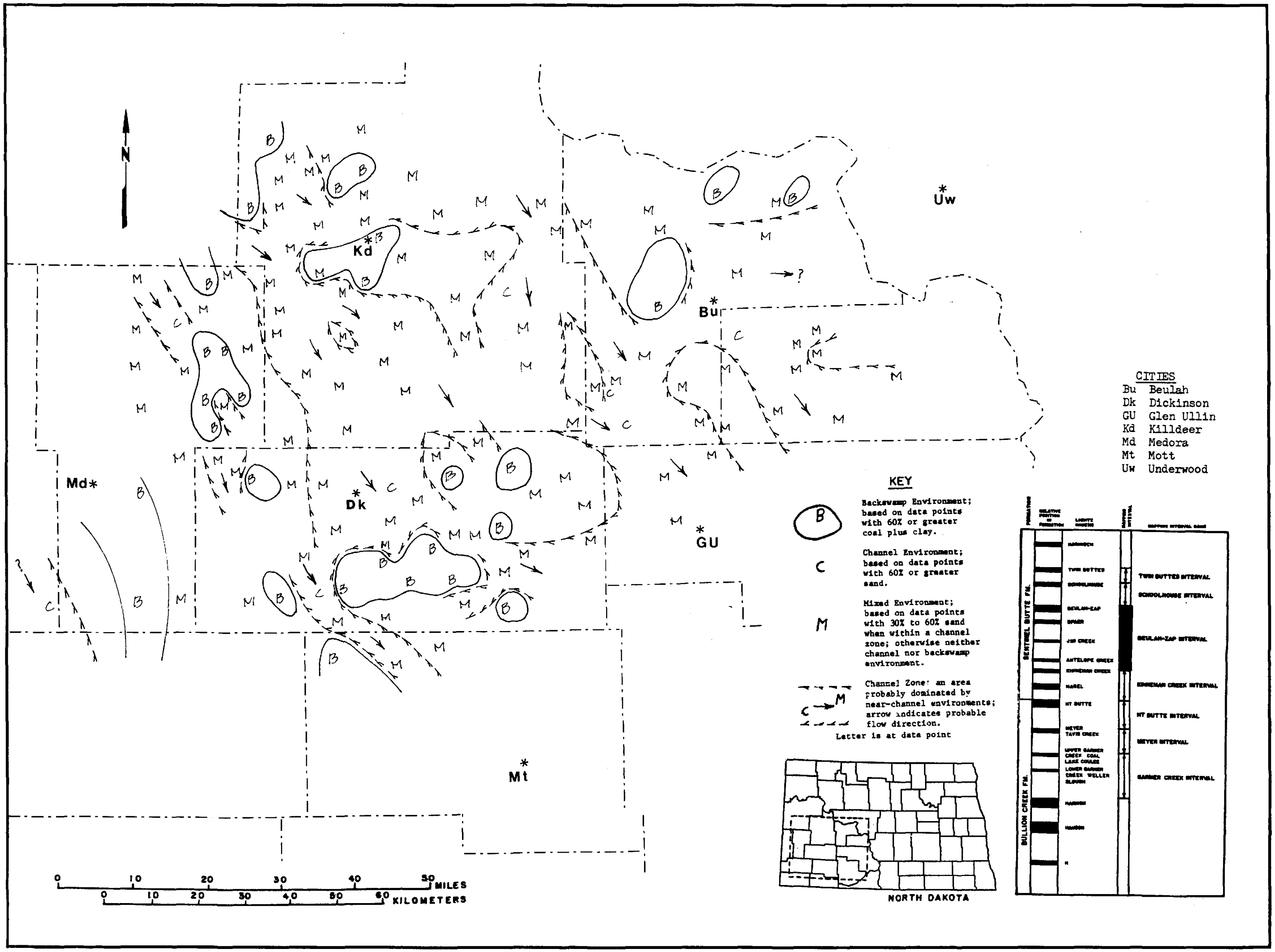

Figure 9. Depositional environments of the Beulah-Zap interval.

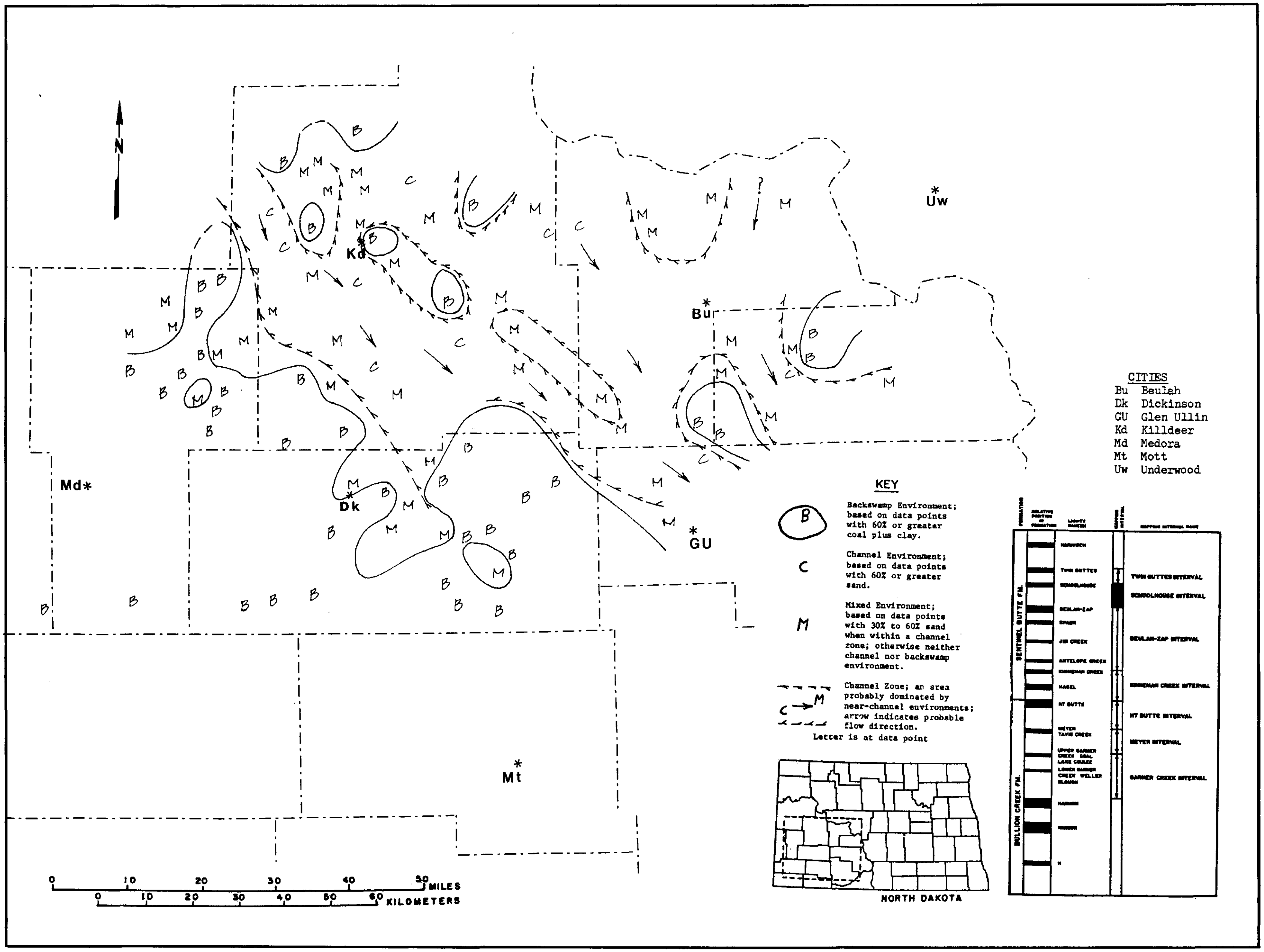

Figure 10. Depositional environments of the Schoolhouse interval.

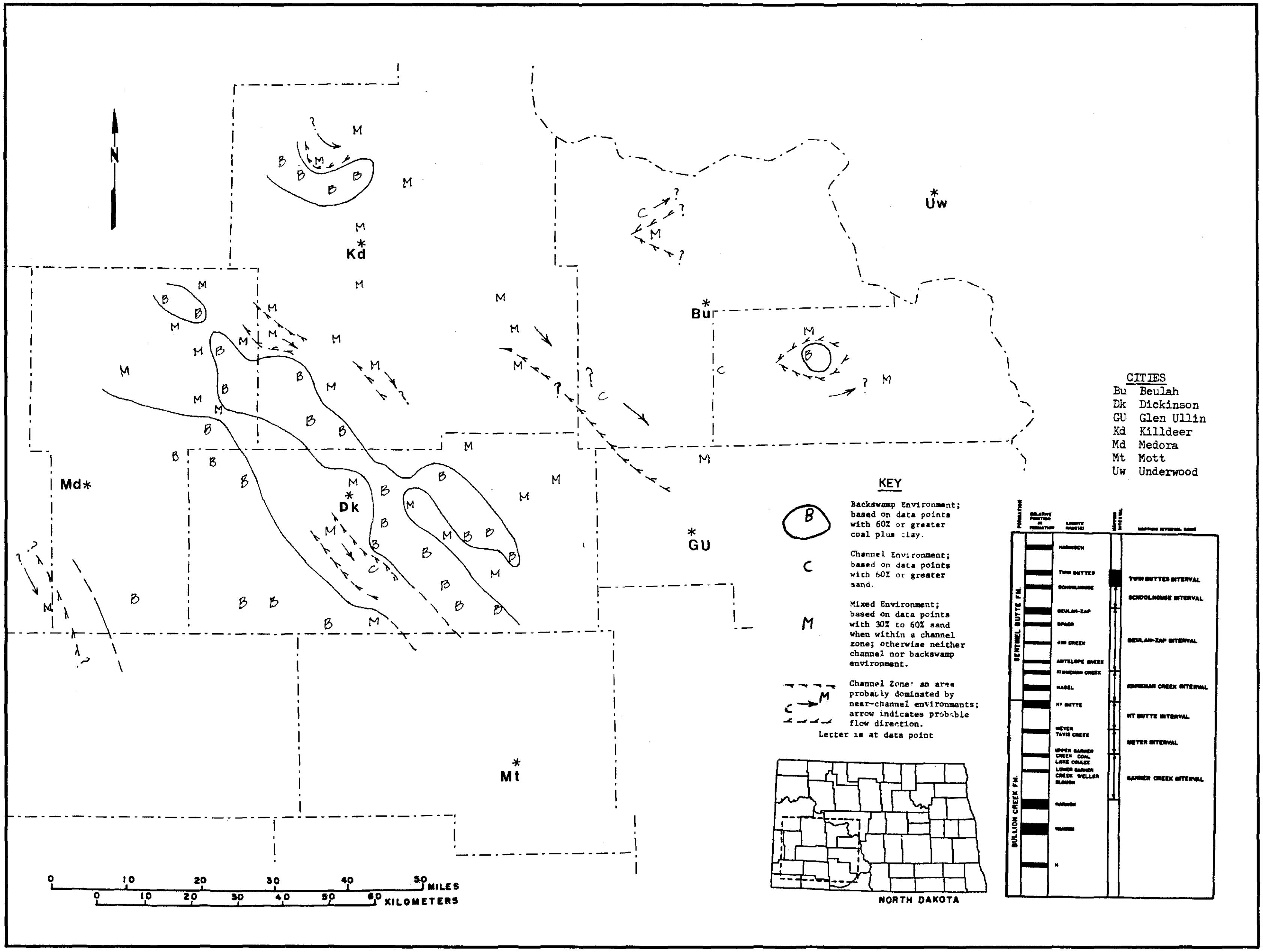

Figure 11. Depositional environments of the Twin Butte interval.

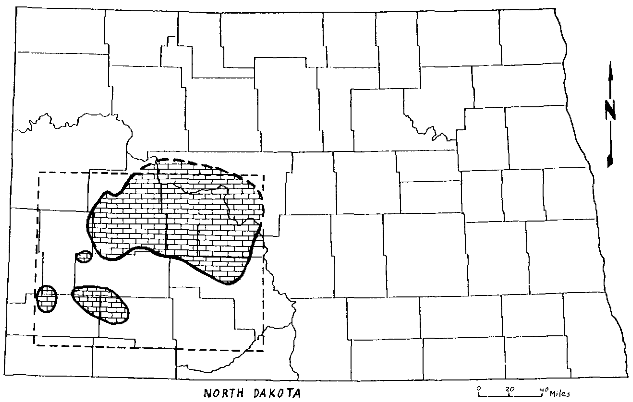

Figure 12. Distribution of limestones or limey clastics in the Bullion Creek and Sentinel Butte formations (undifferentiated).

of environments seen in the southwest part of the area. The first coals of the cycle began forming southwest of the axis. Environments there remained fairly stable, resulting in few and thick coals.

With continued sediment accumulation, the fluvial base level migrated north. Flow was gradually directed east to northeast in the direction of the regional paleoslope. These latter coal-forming environments in the northeast were less stable. Thinner coals as groups of multiple beds resulted.

Ultimately, sediment accumulation in the Williston Basin forced the Powder River system to resume its northerly flow. For the rest of the cycle, little or no sediments entered the area. The capping coals, limestones or limy clastics were formed during this final phase. Basin subsidence continued, however, setting the stage for the next diversion.

These cycles continued until after deposition of the Twin Buttes coal, late in Paleocene time. Later deposits conform to the present structure of the basin. Major structural changes, including uplift of the southern basin margin and reversal of axial plunge to the northwest, terminated conditions described here.

CONCLUSIONS

Cyclic sedimentation in the coal-bearing deposits of the Williston Basin was caused by periodic diversion of the Powder River system into the basin. The cycle began in the west, where flow patterns were structurally controlled by the subsiding basin axis. Later, sediment accumulation and base level migration northward caused the fluvial strunk to migrate across the eastern and northeastern parts of the area, depositing sediments in diffuse, almost distributary-like regional patterns. Finally, sediment accumulation cut off the diversion, and the Powder River system resumed its northerly flow. Coals continued to accumulate in the southwest, and widespread coal-forming environments formed elsewhere.

The anticlines in the northwestern part of the study area did not influence sediment deposition during Bullion Creek time but did so during Sentinel Butte Time. The structural configuration of the Williston Basin changed radically after deposition of Twin Buttes coal, ending the conditions for cyclic deposition of coals in the study area.

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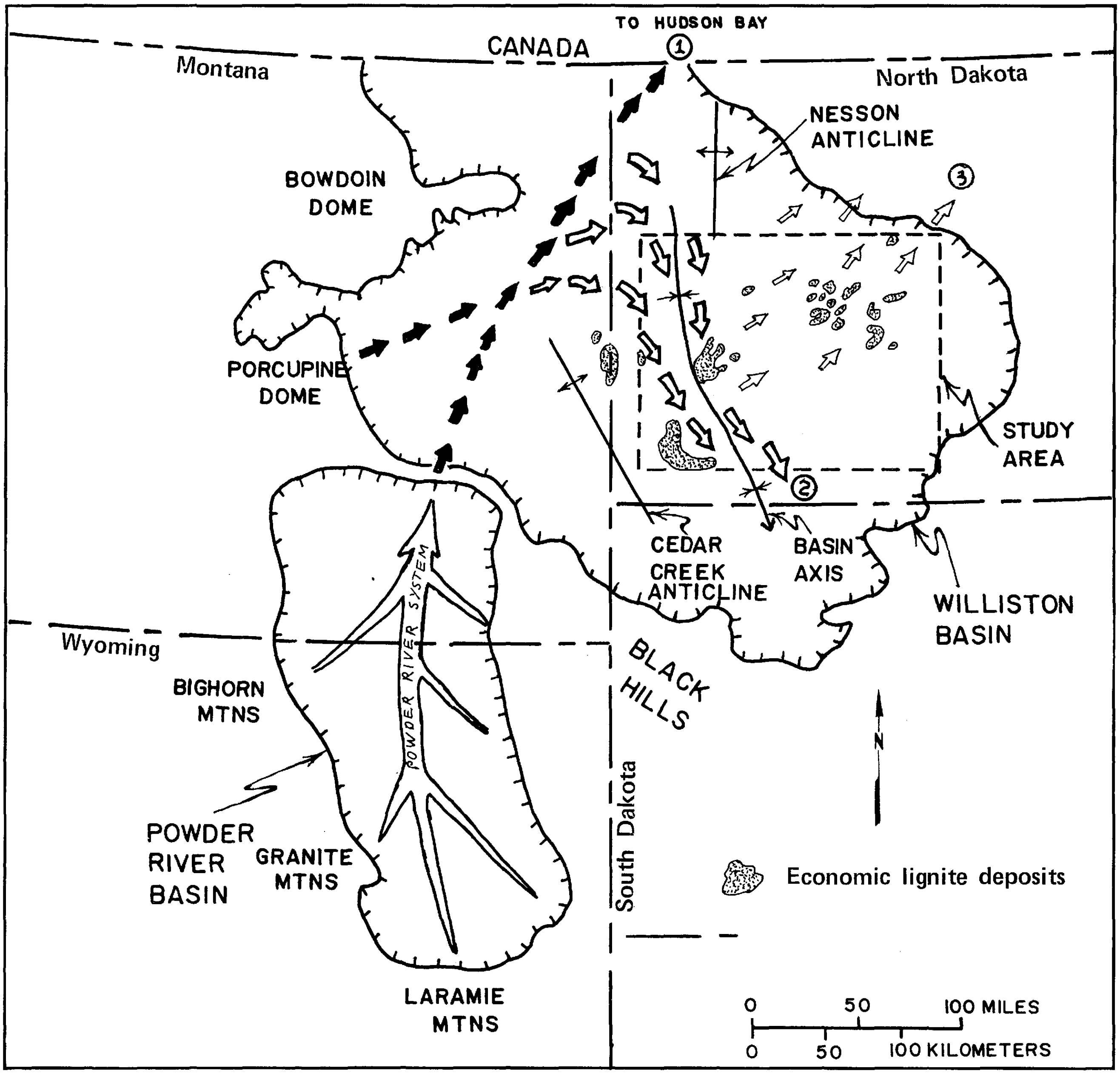

Figure 13. Paleocene regional fluvial systems and their relationship to major structural features in and near the study area. Three flow patterns are shown. Cycle flow in sequence is 1) black arrows, 2) large white arrows, and 3) small white arrows, and 1) again.

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POSSIBLE EUSTATIC CONTROL ON THE LOCATION OF UTAH CRETACEOUS COAL FIELDS

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Ever since the recognition and description of the cyclothem in the 1930s, the concept of a genetic relationship between transgressive-regressive cycles of sedimentation and the occurrence of coal beds has played an important role in coal geology. Nowhere can this genetic relationship be more clearly documented than in Cretaceous strata of the Western Interior of North America. Perhaps the most striking feature of strata deposited in proximity to the western shoreline of the Interior Cretaceous seaway is the cyclic repetition of facies produced by episodic transgression and regression of the shoreline.

The concept of cycles is applied differently by different authors, and there is no concensus on just what represents a "cycle." The generalized cross section presented in Figure 1 illustrates the nature of the problem. Some would view the entire Cretaceous System in the Western Interior as representing one transgressive-regressive cycle (e.g., the Zuni Sequence of Sloss, 1963)- the sea began to encroach upon the continent in Early Cretaceous time, reached the stage of maximum transgression in the early Late Cretaceous, and gradually withdrew throughout the remainder of Late Cretaceous time. This application of the concept, however, is too broad to satisfy most geologists. Kauffman (1977) has recognized ten transgressive-regressive cycles in Cretaceous strata of North America, each of which spanned several million years of time. His cycles correspond to third order cycles in the widely-cited scheme of Vail and others (1978). Both Kauffman and Vail attributed these cycles to eustatic rise and fall of sea level (Hancock and Kauffman, 1979). The Dakota-Tununk-lower Ferron deposits (Figure 1) would record one such third order cycle of sedimentation. Others (e.g., Ryer, 1977 and references cited therein) recognize still smaller cycles, which are interpreted as recording small-scale transgressive-regressive movements of the shoreline. They probably spanned no more than a few hundreds of thousands of years. Following and expanding upon the scheme of Vail and others (1978), these are here referred to as fourth order cycles. They are superimposed upon third order cycles in the fashion illustrated in Figure 2.

Fourth order cycles consititute the basic building blocks in Western Interior Cretaceous coal-bearing strata. Ryer (1981; article reprinted in this volume) has recently demonstrated a one-to-one relationship between fouth order cycles of sedimentation and individual coal beds in the Emery coal fields of central Utah. A model based on this relationship can be used to predict the locations of thick bodies of coal fields.

An examination of the stratigraphic positions of major Utah Cretaceous coalfields of Cenomanian through Santonian age reveals two important concepts: 1) the thickest coal beds, and therefore the major coal fields, tend to occur in the areas characterized by vertical stacking of fourth order cycles; and 2) the distribution of these areas of stacking in time and space is a function of third order cyclicity. These concepts are illustrated in Figure 3 and 4. The strata on the cross section record two third order transgressive-regressive cycles; schematically superimposed are a much larger number of fourth order cycles represented by prograded shoreline sandstone bodies.

The Dakota transgression across the eastern half of Utah was quite rapid. In most places, the Dakota and equivalent strata of the Frontier Formation in north-central Utah consist primarily of fluvial strata with a thin veneer of brackish-water or marine strata at the top. Coal is common in the Dakota, but occurs

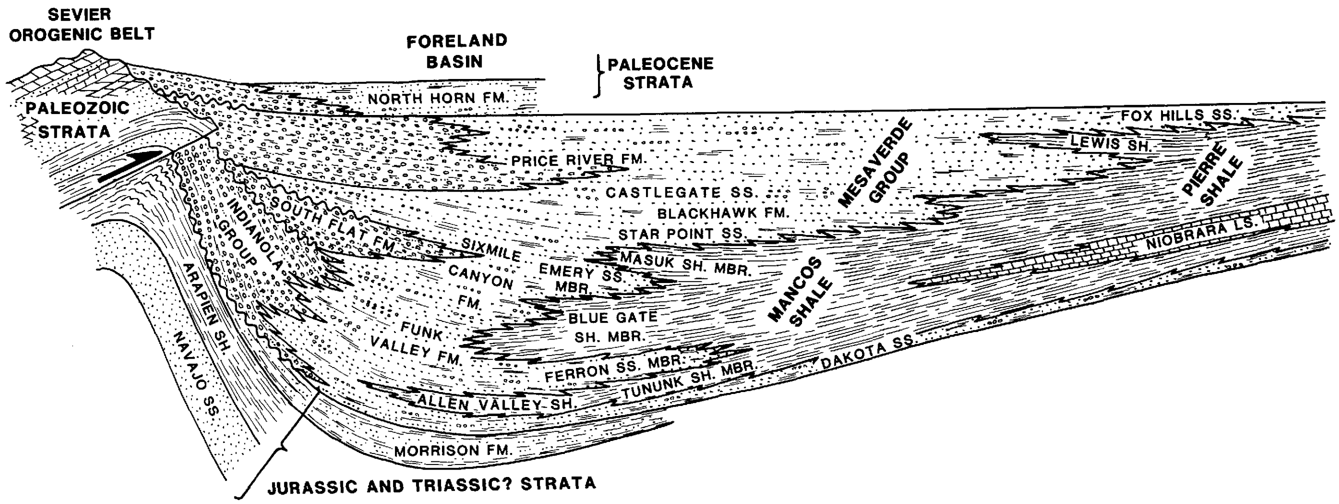

Figure 1. Diagrammatic, restored W-E cross section of Cretaceous strata extending from western Utah to western Colorado (modified from Armstrong, 1968).

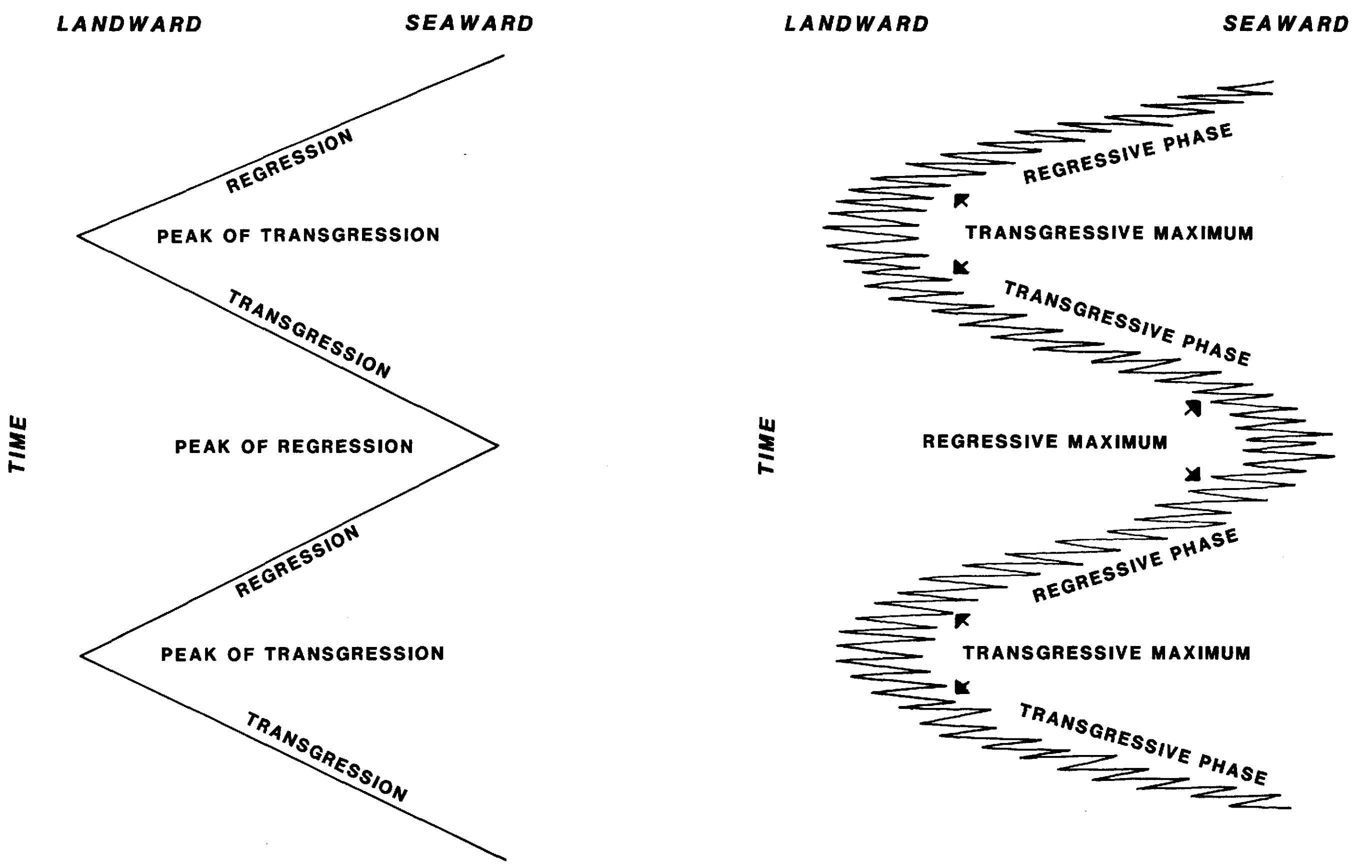

Figure 2. Diagrammatic representation of third order cycles, and, at right third order cycles with fourth order cycles superimposed.

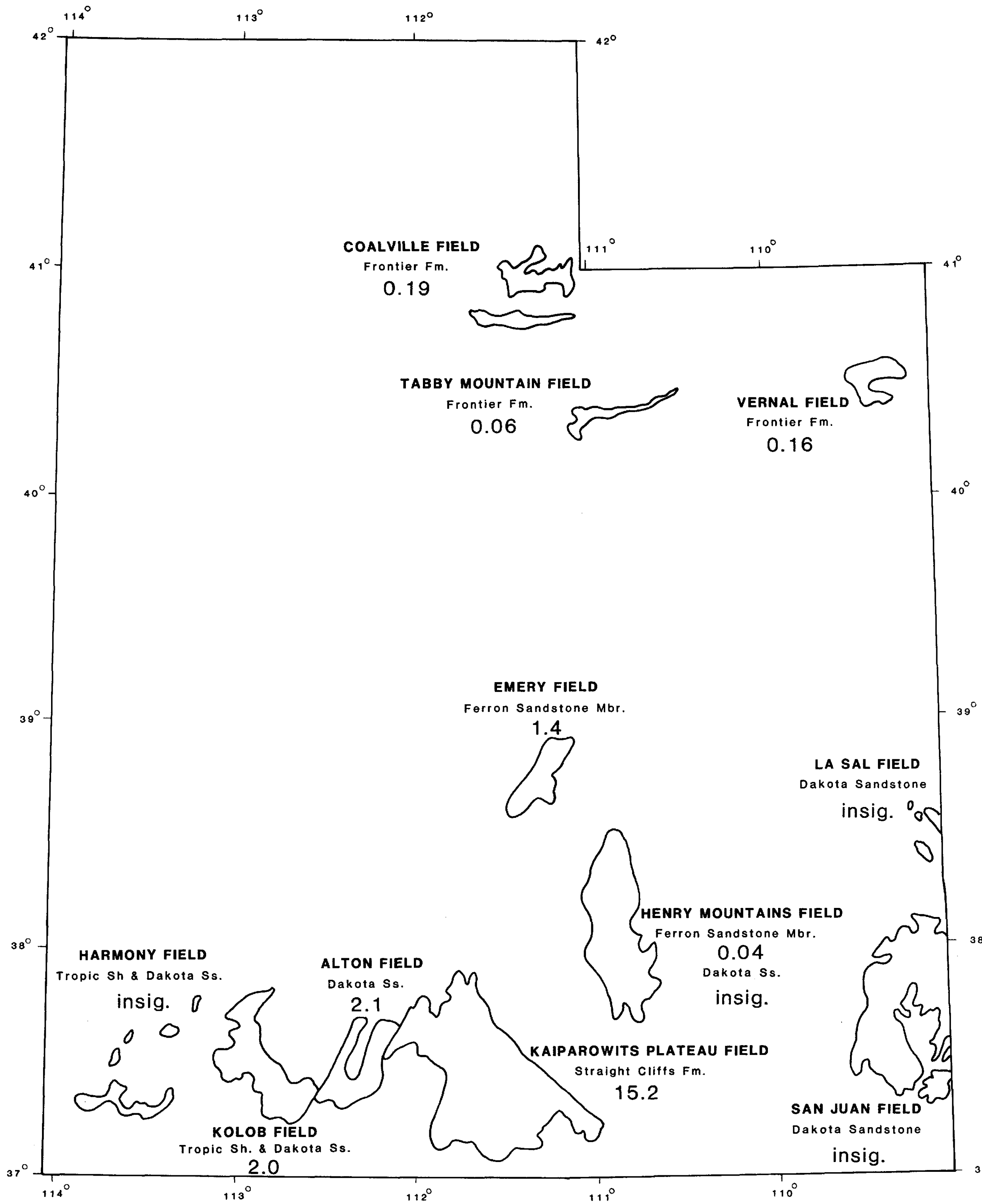

Figure 3. Utah coal fiels of Cenomanian to Santonian age. Coal resource values, in billions of short tons, from Doelling (1972) and Doelling and Graham (1972a,b). Location of cross section shown in Figure 4 is indicated.

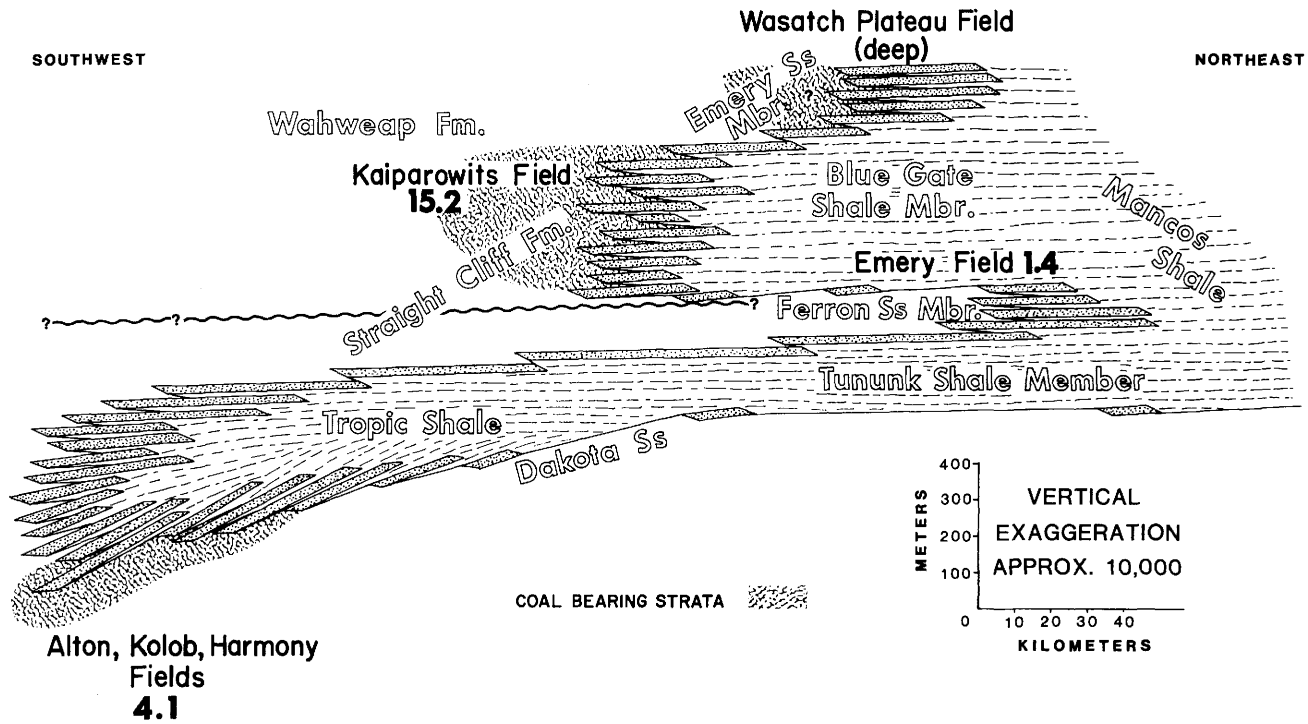

Figure 4. Diagrammatic, restored cross section of Cenomanian-Santanian strata in central and southwestern Utah showing stratigraphic positions of coal fields.

in thin, locally developed beds that are of little economic value (e.g., the San Juan, La Sal, Henry Mountains and Tabby Mountain fields). As the shoreline approached what would prove to be its transgressive maximum, the rate of transgression slowed and stacking of the deposits of fourth order cycles began to occur. Coals associated with these deposits account for the coal resources of the Alton, Kolob, Harmony, and Coalville fields. The Straight Cliffs-Ferron regression rapidly carried the shoreline eastward. A small amount of sub-economic coal occurs in deposits of this rapid regressive phase in the Kaiparowits Plateau and Henry Mountains fields; otherwise it is devoid of coal. The regressive maximum of the cycle is recorded by stacking in the Ferron Sandstone Member in central Utah. This stacking produced the coals of the Emery coal field. Strata of the Frontier Formation in the Vernal field occupy the same stratigraphic position, but in an area that underwent slower basin subsidence. The amount of stacking, and therefore the coal resources, are correspondingly less. Deposits of the succeeding Blue Gate transgression, like those of the Dakota transgression, contain little coal of economic value. The transgressive maximum of the cycle occurred in the vicinity of the eastern margin of the Kaiparowits Plateau and is responsible for the large coal resources of that region. The same episode of stacking can be identified in the eastern part of the Coalville area. The coal resources of this structurally complex area have never been adequately evaluated, but they do not appear to be large. Stacking occured one more time to produce deposits of the Emery Sandstone Member, which records the regressive maximum of the second of the two third order cycles shown in Figure 4. Only the seawardmost parts of the Emery can be examined on outcrops in central Utah. The coal-bearing parts of the unit occur in the subsurface beneath the Wasatch and Fish Lake plateaus. Logs run in oil and gas tests that penetrated the Emery indicate the presence of some thick beds of coal.

The Emery Sandstone Member illustrates the value of the relationships described in this paper in coal exploration. Deposited as the result of stacking of fourth order cycles at the regressive maximum of a third order cycle, the Emery is an excellent candidate for prospecting for deeply buried coal resources.

Subsurface data from oil and gas tests could be used to identify the trend of stacking of shoreline sandstones, and the location of the area of coal accumulation landward of the stacking identified. Emery coal beds are beyond the reach of conventional mining methods and are not of much immediate interest. In the future, however, coal resources of this type may prove to be important for degasification or in situ gasification. An ability to predict the occurrence of such coal resources could reap considerable savings in drilling expense

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DEPOSITIONAL ENVIRONMENTS AND ROOF STABILITY FACTORS AFFECTING MINE PLANNING

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INTRODUCTION

In order to understand and predict variation in the character of coal seams and their roof stability, a reconstruction of the depositional environment is very useful. The nature of the sediments deposited after peat development is a major factor controlling roof stability. Consequently, a depositional model identifying rock variability can be used as a predictive tool to determine potential minability and roof support systems relating to mine development.

This method of predicting variation in the roof material has been employed on an underground mine at Long Canyon, a proposed mine tract in southwestern Wyoming about 15 miles north of Rock Springs, in the No. 1 Seam.

REGIONAL GEOLOGY SETTING

The Rock Springs Anticline exposes upper Cretaceous formations including, in ascending order: the Baxter, Blair, Rock Springs, and Ericson formations of the Mesaverde Group. These formations were deposited along the western shoreline of a large epicontinental seaway which extended from the Arctic Ocean to the Gulf of Mexico. Uplift of the Sevier Orogenic Belt to the West supplied the terrigenous detrital material carried by streams which emptied into the western edge of this seaway. Because of the ample wave energy, wave-dominated delta systems were constructed at the seaward terminus of these streams. Figure 1 illustrates the position of the wave-dominated delta that prograded into southwest Wyoming upon which the No. 1 Seam and surrounding sediments accumulated.

METHODOLOGY

Data used for this study of the Long Canyon area consisted of 31 cored wells with geophysical logs (natural gamma ray, gamma gamma density and resistivity) containing intervals of roof and floor rock, 40 geophysical logs of drill holes without core, and surface observations of exposures above and below the No. 1 Seam. The rocks were described using a core book with photos of common rock types found associated with coal measures as a standard reference and assigned a three-digit code number (Fern and Melton, 1977).

Two types of roof maps were constructed to illustrate roof conditions above the No. 1 Seam: the sequence map and slice maps. The sequence map defines vertical and lateral variability of the entire sequence of rock types that occur up to ten feet above the coal. These rocks are examined and categorized into sequences that were deposited in different environmental settings and have varying stabilities as roof material. The slice maps display the lateral variability of rock types present at specific horizons above a coal. The sequence maps provide data on what rock types the roof bolts will penetrate. Figure 2 displays the characteristics of slice and sequence maps.

ROOF MAPS

To generate the sequence map, the rocks up to 10 feet above the No. 1 Seam were grouped into 16 sequence types. Based on in-mine mapping data from other underground mines in the western United States, these sequences were ranked from most to least competent. Figure 3 shows a typical example of each sequence type observed at Long Canyon and

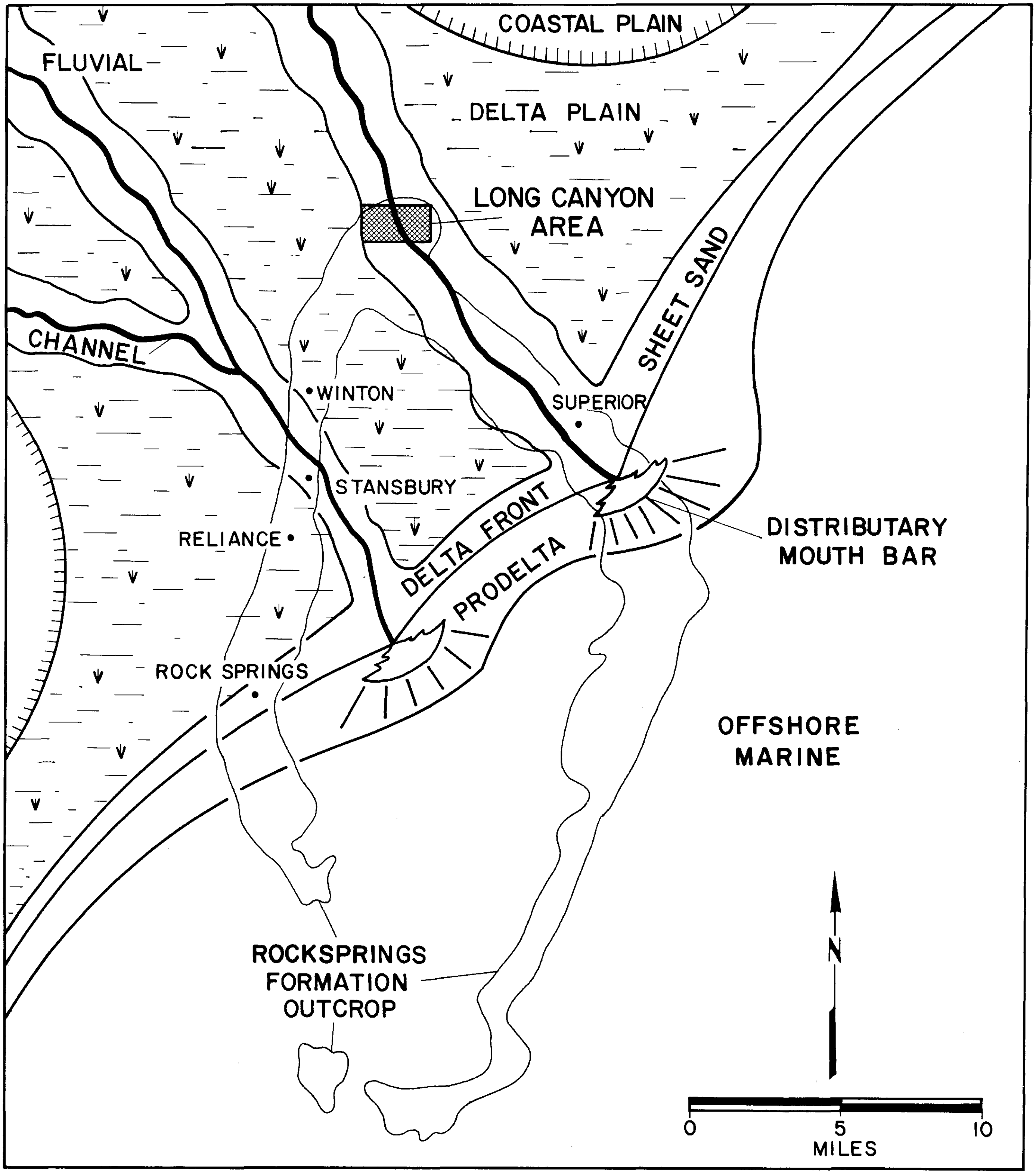

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Figure 1. Depositional setting for the roof of the No. 1 Seam.

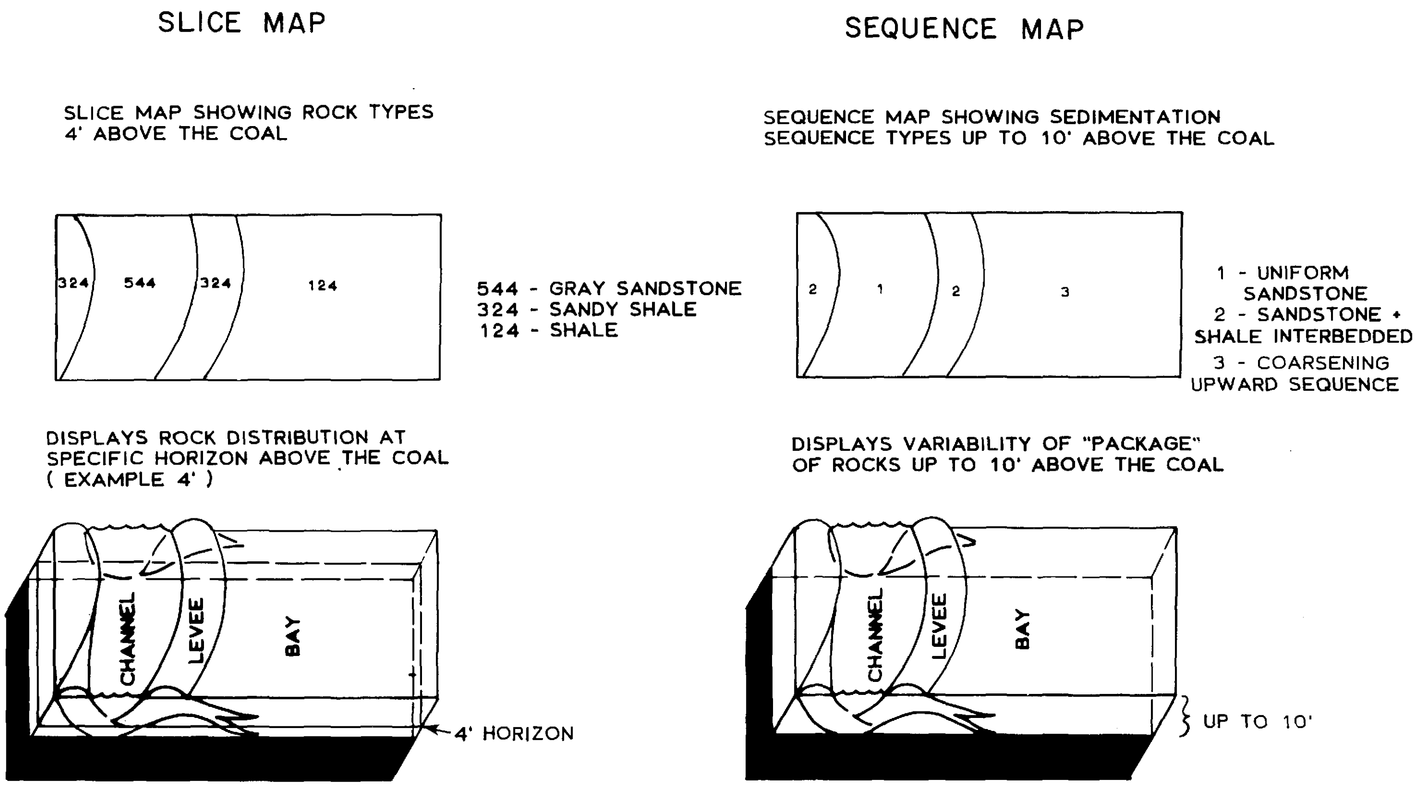


Figure 2. Roof map types.

Figure 4 is the sequence map for the rocks above the No. 1 Seam.

The sequences were plotted on a base map and a depositional interpretation was established by comparison of the rock sequences to modern analogs. The sequences deposited in channels (sequence types 1, 4, 9, 10, 11, 12, and 13) were oriented north-south. Adjacent to these channels, levee deposits (sequence type 6) accumulated. When the levees were breached during a flood episode, crevasse splays were formed (sequence types 2 and 3). Sequence types 5, 7, and 8 accumulated in interdistributary bays, and where swamps formed, rider coals developed which are represented by sequence types 14, 15, and 16.

Slice maps were constructed at 4 and 6-foot horizons above the No. 1 Seam (Figures 5 and 6) to develop specific data on what rock types would provide anchor points for conventional length roof bolts. The depositional model interpreted from the sequence map was also observed in the slice maps. Sandstones occupied channel and splay areas, while interbedded sandstones and shales were found on the levees. Figure 7 attempts to show how bays received finer-grained clastics (siltstones and shales).

ENGINEERING IMPLICATIONS

The channel deposits (sequence types 1, 4, 9, 10, 11, 12, and 13) generally offer competent support for roof in an underground mine, however, some problems can occur. The sandstones are potential aquifers that can cause water problems which require pumping, especially as mining progresses down dip. The lower portions of these channels often contain coalified logs and pebble lags which were carried as bed load. These layers are usually zones of weakness, but roof bolts will generally hold this material if they are anchored into massive sandstone above the lag. If the channel sandstone has not scoured into the top of the coal (sequence types 9, 10, 11, 12, and 13), intervening shales may have slickensides caused by the differential compaction between the sandstone and shale. This may result in significant problems for roof stability. The interval between the top of the coal and the base of the channel should be monitored to assure that proper length roof bolts are used so that anchor points are in the base of the sandstone. If these sandstones are aquifers, the roof bolt holes may serve as conduits for water to enter the mine. This water can also contribute to the weathering of the fine-grained rocks, decreasing their competence. Resin bolting may be necessary to stop the water

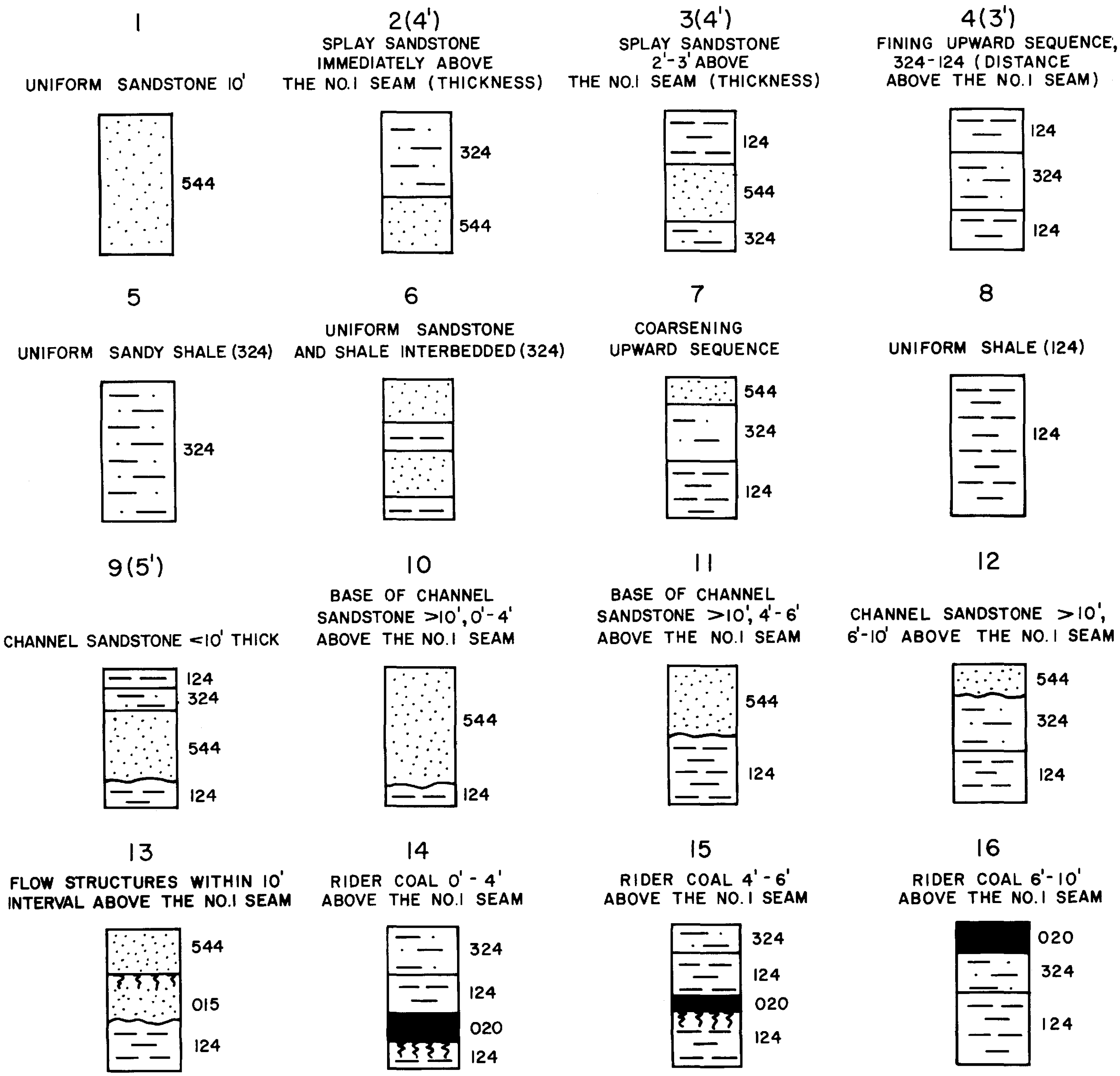
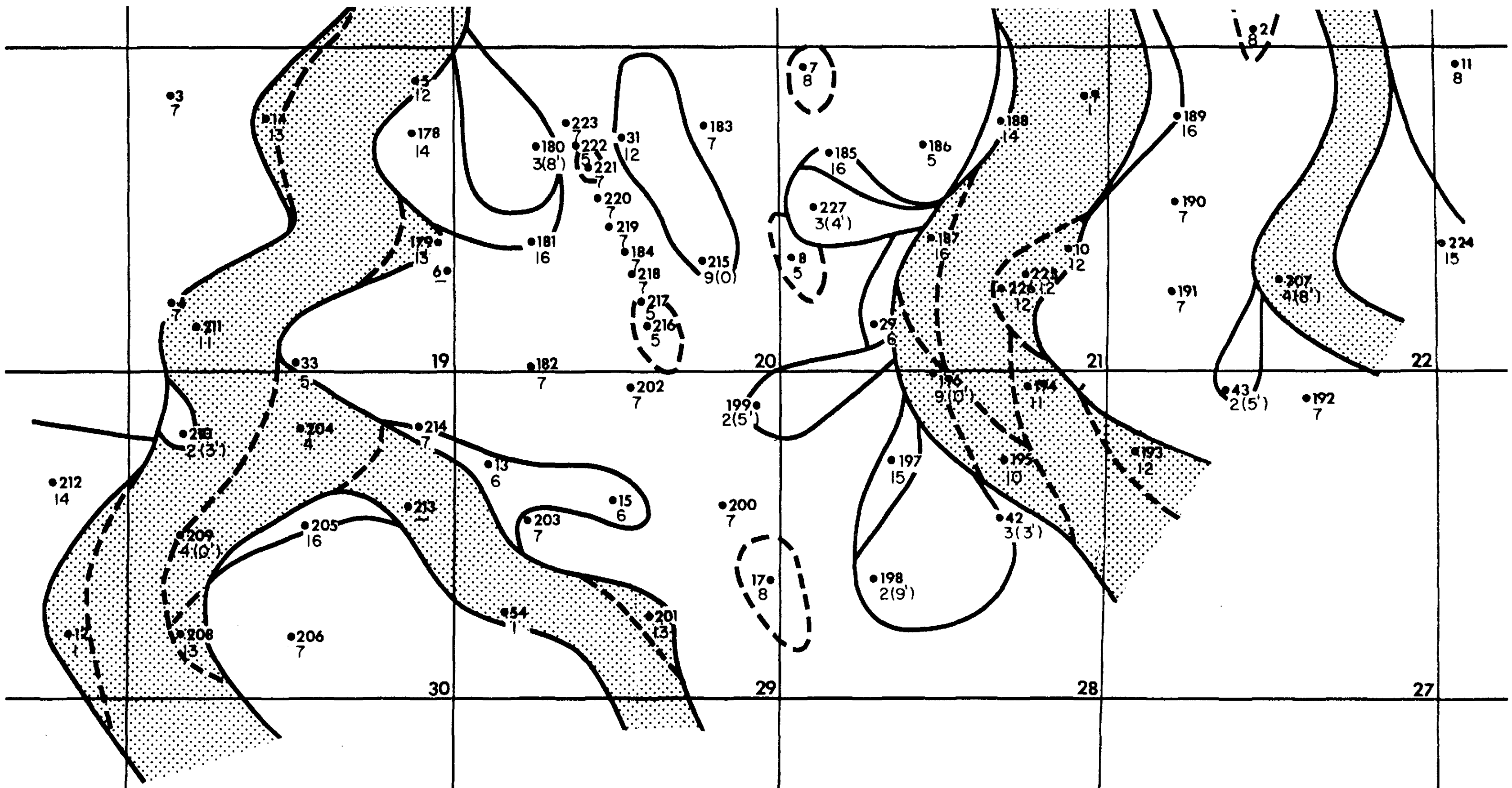


Figure 3. Typical rock sequences up to 10 feet above the No. 1 Seam.

flow. Sequence type 13 (flow deposit) occurs on the cutbank side of meander bends of the channels. When slumps occur, they contort the bedding and greatly reduce the rock strength; as a result, severe roof falls often occur. In general, the transition zones between channels and interchannel areas are unstable, and these areas should be approached with caution.

Levee deposits (sequence type 6) often are root-penetrated by plants. The rooting disrupts the bedding and reduces the rock strength. Occasionally, tree stumps "kettle bottoms" are preserved in place above the coal. Their precise location is not predictable, but they often occur in the levee setting. They should be bolted or forced down when found.

Rock sequences 2 and 3 are crevasse splay deposits. Roof bolts in these deposits would normally anchor into sandstone. Splays often provide a



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CHANNEL SEQUENCES

LEGEND

201	DRILL HOLE NUMBER
13	SEQUENCE TYPE
1	UNIFORM SANDSTONE 10'
2	SPLAY SANDSTONE IMMEDIATELY ABOVE THE NO. 1 SEAM (THICKNESS)
3	SPLAY SANDSTONE 2'-3' ABOVE THE NO. 1 SEAM (THICKNESS)
4	FINING UPWARD SEQUENCE, 324-124 (DISTANCE ABOVE THE NO. 1 SEAM)
5	UNIFORM SANDY SHALE (324)
6	UNIFORM SANDSTONE AND SHALE INTERBEDDED (322)
7	COARSENING UPWARD SEQUENCE
8	UNIFORM SHALE
9	CHANNEL SANDSTONE <10' THICK
10	BASE OF CHANNEL SANDSTONE >10', 0'-4' ABOVE THE NO. 1 SEAM
11	BASE OF CHANNEL SANDSTONE >10', 4'-6' ABOVE THE NO. 1 SEAM
12	CHANNEL SANDSTONE >10', 6'-10' ABOVE THE NO. 1 SEAM
13	FLOW STRUCTURES WITHIN 10' INTERVAL ABOVE THE NO. 1 SEAM
14	RIDER COAL 0'-4' ABOVE THE NO. 1 SEAM
15	RIDER COAL 4'-6' ABOVE THE NO. 1 SEAM
16	RIDER COAL 6'-10' ABOVE THE NO. 1 SEAM

LONG CANYON PROJECT

Figure 4. Sequence map of rock types up to 10 feet above the No. 1 Seam.

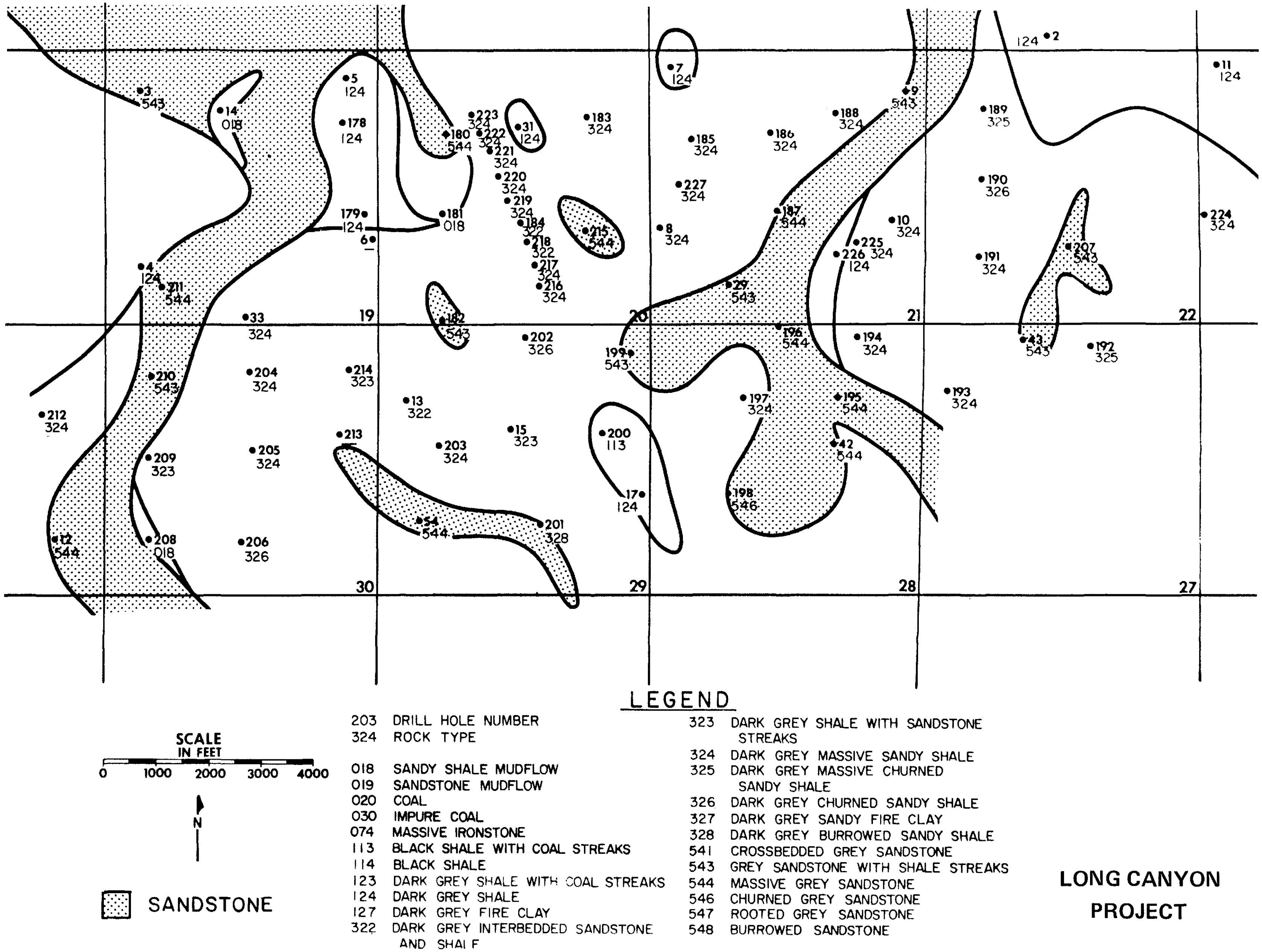
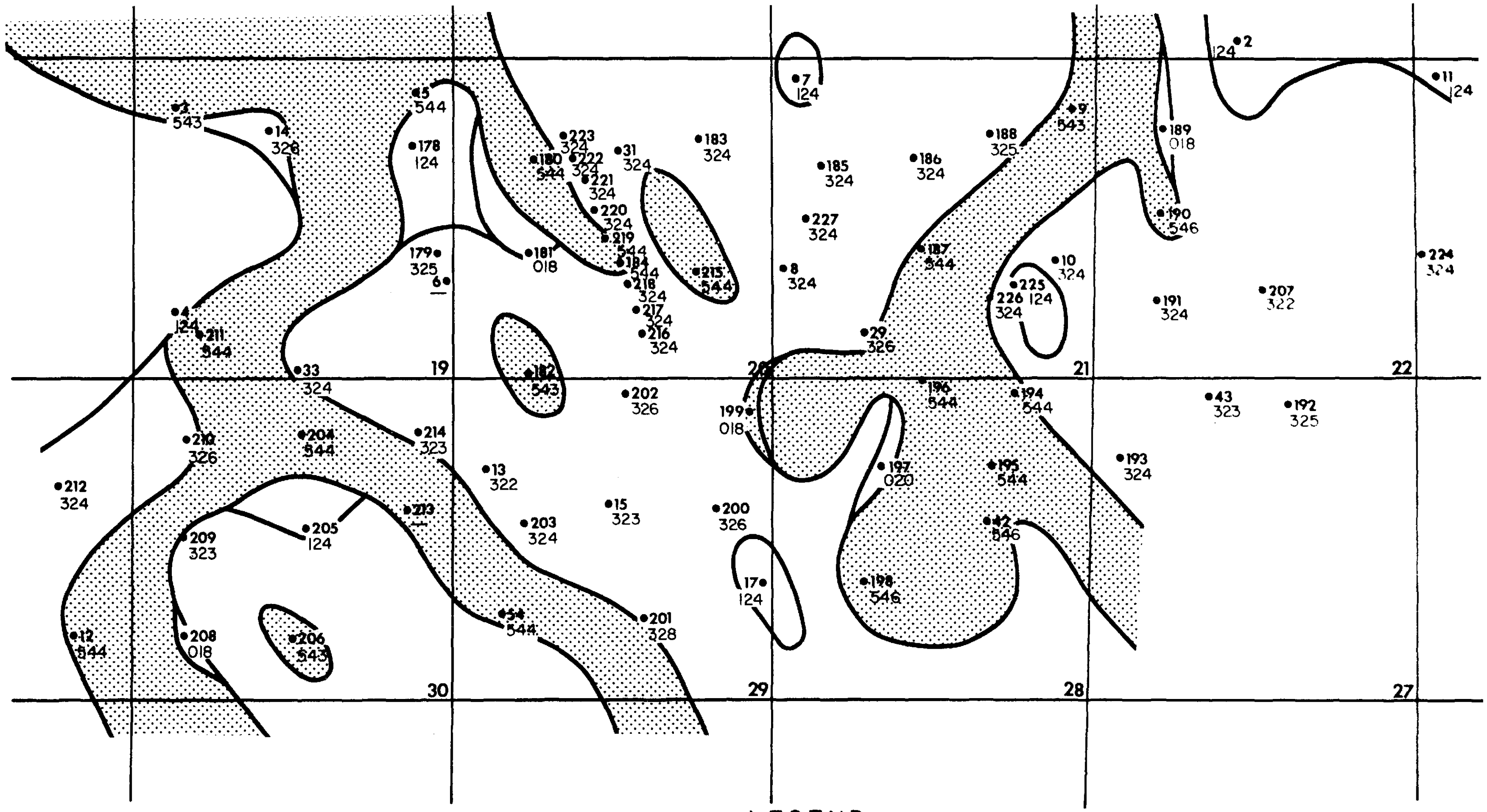


Figure 5. Rock types 4 feet above the No. 1 Seam.



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SANDSTONE

LEGEND

203 DRILL HOLE NUMBER
324 ROCK TYPE

018 SANDY SHALE MUDFLOW
019 SANDSTONE MUDFLOW
020 COAL
030 IMPURE COAL
074 MASSIVE IRONSTONE
113 BLACK SHALE WITH COAL STREAKS
114 BLACK SHALE
123 DARK GREY SHALE WITH COAL STREAKS
124 DARK GREY SHALE
127 DARK GREY FIRE CLAY
322 DARK GREY INTERBEDDED SANDSTONE AND SHALE
323 DARK GREY SHALE WITH SANDSTONE STREAKS
324 DARK GREY MASSIVE SANDY SHALE
325 DARK GREY MASSIVE CHURNED SANDY SHALE
326 DARK GREY CHURNED SANDY SHALE
327 DARK GREY SANDY FIRE CLAY
328 DARK GREY BURROWED SANDY SHALE
541 CROSSBEDDED GREY SANDSTONE
543 GREY SANDSTONE WITH SHALE STREAKS
544 MASSIVE GREY SANDSTONE
546 CHURNED GREY SANDSTONE
547 ROOTED GREY SANDSTONE
548 BURROWED SANDSTONE

LONG CANYON PROJECT

Figure 6. Rock types 6 feet above the No. 1 Seam.

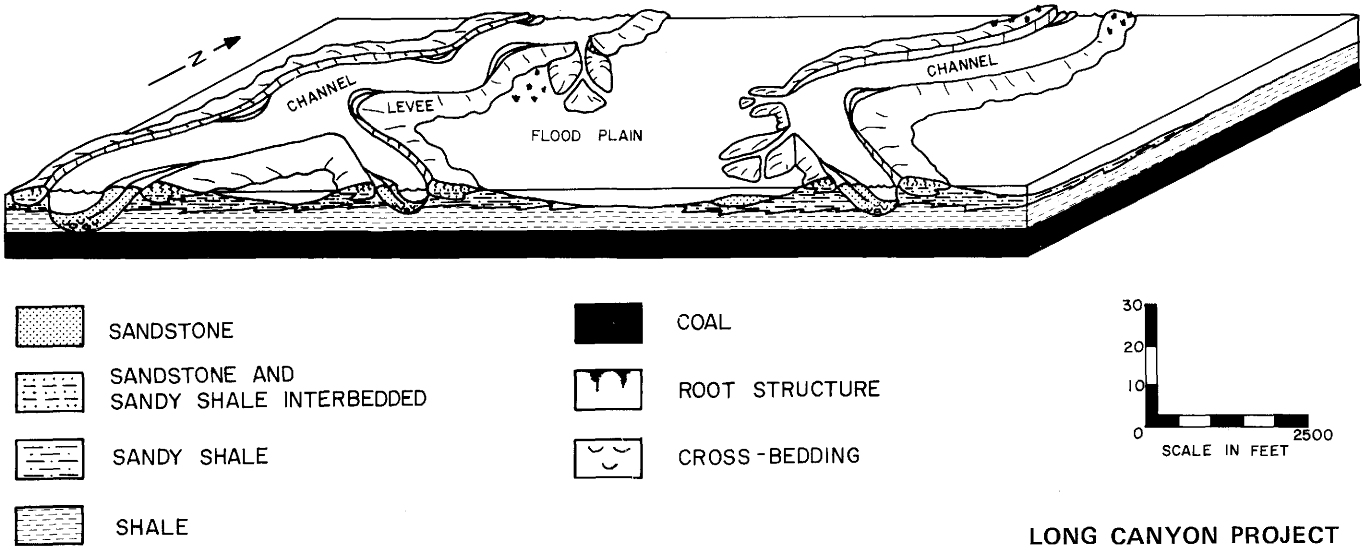

Figure 7. Block diagram of depositional setting above the No. 1 Seam.

platform for coal development which would produce a weak zone. The interval between the splay and the coal as well as the splay thickness should be monitored to assure that bolt lengths are sufficient for anchor points to be sandstone or above rider coals.

Bayfill deposits (sequence types 5, 7, and 8) are normally competent, especially if roof bolts anchor into the coarser material near the top of the bay. However, exposure to air can contribute to rapid weathering and slaking of shales.

Rider coals above the No. 1 Seam are the least competent sequence types. Not only are the coals weak horizons, but the shales under them are usually root-penetrated and weak. The worst case is sequence type 16, where the rider coal occurs above the length of conventional roof bolts. The distance between the No. 1 Seam and rider coals should be monitored closely. In these areas, resin bolts should be used as well as additional supports in the form of metal ribs.

CONCLUSIONS

Depositional modeling of the rocks above a coal seam can be used as a predictive tool for roof conditions increasing productivity, and enhancing safety programs underground. The Long Canyon area is an example where this process has been employed in the planning stage prior to mine development. The sequence and slice maps display rock variation in the roof of the No. 1 Seam and have been interpreted depositionally. Rock deposits in different environments (channel, levee, bay, splay, and swamp) have different stability characteristics for an underground mine. These maps should be used together as a predictive model of rock variability to anticipate roof conditions during underground mining.

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DEPOSITIONAL STUDIES OF THE EARLY PALEOCENE JIM BRIDGER COAL DEPOSITS AND ITS APPLICATION TO SURFACE MINE PROBLEMS

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INTRODUCTION

The Jim Bridger coal field is situated on the northeastern flank of the Rock Springs Uplift, a north-south trending asymmetrical anticlinal structure which separates the Green River Basin, to the west, from the Great Divide and Washakie basins to the east (Figure 1). Stratigraphically, the Jim Bridger coal deposits occur within the "Deadman Coal Zone" of the lowermost portion of the Paleocene age Fort Union Formation (Figure 2).

Within the immediate mine area, the strata are composed of thin-to-massively-bedded, fine-grained, well-sorted sandstones interbedded with siltstones, claystones, thin discontinuous carbonaceous stringers , and subbituminous coals. Currently, there are five identified economically minable coal seams designated in ascending order, D-1 through D-5. Within the mine permit area, these seams exhibit a bifurcating geometry which increases toward the northwest and southeast (Figure 3). As a result of coal seam splitting, individual coal seams thin and interburden thicknesses fluctuate rapidly.

During the past four years, 43 continuous core holes have been drilled, described, and analyzed for textural and geochemical quality parameters. These core hole data points (approximate density of 1 hole per 160 acres) have provided the basis upon which a mine-level depositional model was constructed. This model represents detailed geological interpretations of genetic rock units (i.e., sandstone, siltstone, claystone, and coal) with specific inference made to relative areal distribution and controlling depositional processes.

Detailed data concerning depositional environments and their areal distributions are basic to successful coal exploration, mining and post-mining operations, as well as delineation of potential environmental effects of mining. In addition, such information is valuable to planning surface and underground reserve extraction, mine hydrology, geochemistry, and coal quality, (Horne and others, 1978; Groenewold and others, 1981).

METHODOLOGY

Reconnaissance geological mapping used to determine the initial depositional framework was restricted to the active highwall and scattered exposures within the mine permit area. Field characterizations and description of coals and associated lithological units were accomplished by the physical measurment of detailed stratigraphic sections along approximately eight miles of active highwall. In addition, sedimentological data, including recognition of bedforms, vertical and lateral facies relationships and/or discontinuities, delineation of active water percolation zones, macroscopic grain size trends, and megafloral transport data were collected to aid establishment of lithological and facies relationships.

Description of closely spaced measured sections (approximately 1500 ft apart) and noted visual observations between highwall data points allowed the accurate correlation of lithological units. Field observations and correlation of drill hole data allowed the construction of a detailed cross-sections along strike (Figure 3).

Laboratory analysis of core sampled strata, inclusive of textural and geochemical parameters, were evaluated to assess the characteristics of the overburden, interburden and underburden strata. Utilizing particular aspects of the data base, it is possible to construct maps which illustrate parameter

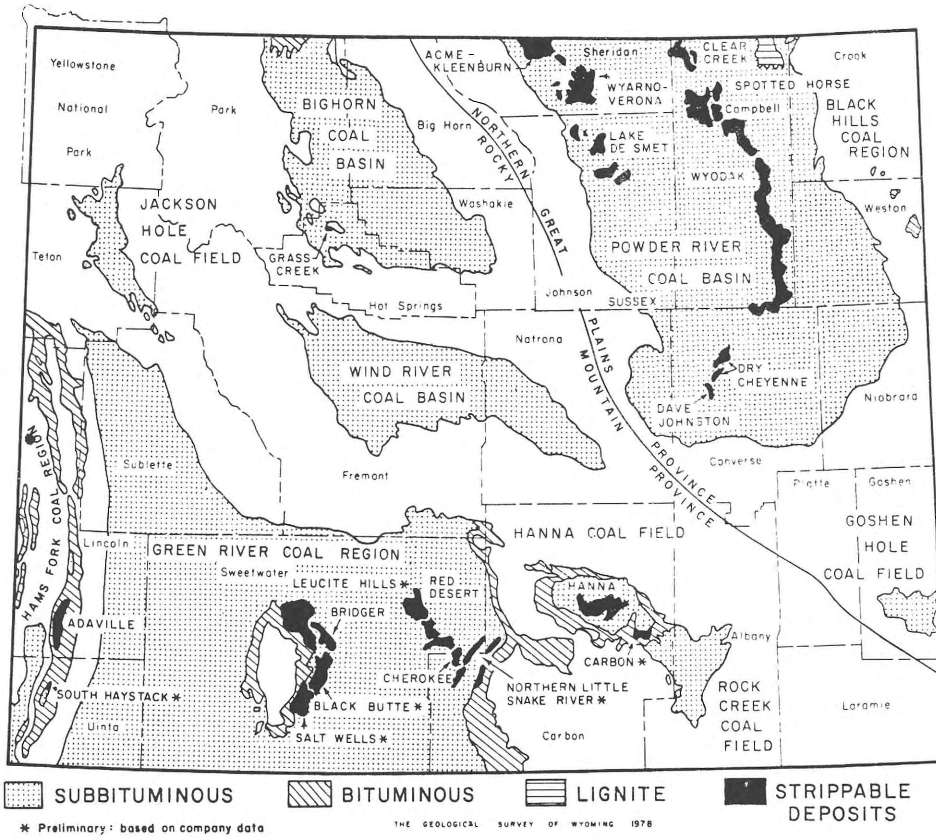

Figure 1. Wyoming coal-bearing areas (after Glass, 1978).

trends. Specifically for this study, sandstone geometries have been delineated and mapped.

Systematic changes in sediment texture occur laterally and vertically during sedimentary processes (Reineck and Singh, 1973). Subsequently, depositional environment maps exhibit parallel to subparallel trends which existed within the ancient depositional systems. If the data of environmental analysis are presented in numerical form (i.e., sand percentage contour maps), it is possible to delineate anomalous patterns (i.e., sand depocenter trends) from the underlying broader pattern that characterizes the general depostitional setting.

With regard to the various lithologic units associated with the Jim Bridger coal deposit, sand percentages for four specific strata intervals were compiled from laboratory textural data. These data were then computer contoured by best fit linear least squares methods to help alleviate subjective bias.

Underburden strata (strata up to 10 ft stratigraphically below the D-1 coal) were analyzed where sufficient data were available (Figure 4). The 90 ft of overburden strata immediately above the D-5 coal were separated into three individual thirty-foot horizontal slice strata sections. Individual thirty-foot slices were then analyzed separately for sand percentage trends (Figures 5, 6, and 7).

Based upon the characteristics and subsequent deposits of modern analog depositional environments (i.e., floodplain subaqueous to subaerial swampy silvan conditions with fluviatile channel deposition and minor lacustrine influence), subareas containing values of greater than 40 percent sand on a weight percentage basis were investigated as possible ancient sand depocenters (i.e., crevasse splay, proximal overbank, and channel areas). It should be emphasized that this phase of stratigraphical analysis (horizontal slice analysis method) may yield interpretative discrepencies.

These analyses only identify specific sand depocenter trends within tightly constrained vertical controls. Modern and ancient depositional processes do not allow equal sedimentation rates, but are controlled by relative proximities to source areas, transport zones and relative velocities, biota variations, and diagenetic differential compactional traits of various sediment types.

Projected sandstone trends within overburden materials were substantiated further by detailed sandstone isolith and alternation frequency data (overburden strata occuring 60 ft stratigraphically above the D-5 coal) obtained from core hole descriptions, photographs, and geophysical logs. The isolith map (Figure 8) represents the aggregate thicknesses of all described sandstone occurrences, regardless of the thickness of the individual beds. Areas of greater total sandstone thickness are directly correlative with ancient sand depocenter sites. Comparison of the sandstone alternation frequency data (Figure 9) with isolith data (Figure 8) indirectly examines relative thickness of individual sandstone beds and identifies sequences consisting of alternating thin sandstone units from those composed of a few thick units. The sandstone isolith and alternation frequency maps in conjunction with grain size analysis maps aids delineation of subareas influenced by distal sandstone deposition from areas influenced by active sandstone deposition.

DEPOSITIONAL FRAMEWORK OF STUDY AREA

Within the northwest two-thirds of the mine permit area, observed lithological associations suggest interrelated depositional environments of a fluviatile-flood basin complex with extensive swampy silvan conditions and minor lacustrine influence. Five distinctive depositional environments are recognizable with respect to the stratigraphical framework:

1. poorly drained swamps
2. well drained swamps
3. lacustrine deposits
4. crevasse splay and distal overbank deposits
5. proximal overbank and fluviatile channel deposits

The products or resultant lithologies of these environments are found interrelated throughout the mine areas, the dynamics of the depositional processes are responsible for the present lithological configuration.

Detailed drill hole and sedimentological data on strata below the D-1 coal seam are sparse. However, data from available drilling and laboratory grain size analysis indicate dominant sand depocenter trends generally oriented in a southwest-northeast direction (Figure 4). These sand trends are interpreted to represent fine-grained, low flow regime, moderately meandering channel deposits, proximal overbank deposits, and crevasse splay deposits. In addition, these sandstones grade laterally into well-drained swamp deposits composed of highly fossiliferous (plant fossils), gray-colored siltstones and claystones.

Immediately overlying these deposits are laterally extensive subbituminous coal seams, D-1 through D-5, separated locally by carbonaceous gray-colored sandstone, siltstone, and claystone parting strata. Coal deposits are the result of extensive plant biomass accumulation within reducing flood basinal swamps, flanking synchronal channel complexes, which probably existed toward the west-northwest and east-southeast portions of the mine. Swamps account for the largest areal distribution (approximately 90 percent) when contrasted with adjacent and interrelated environs (i.e., channels, levees, splays, and lacustrine environments). Developing peat deposits and resultant coals are areally widespread, throughgoing, and locally interrupted by flood events induced by crevassing, avulsion, and overbank deposition.

With the exception of periodic flooding events. clastic detrital sedimentation rates within swamp environments are low to moderate. If water in the swamps is too deep, swamps and floral assemblings are drowned; likewise, if shallow water conditions persist, subaerial exposure and oxidation impede the accumulation of plant debris. Conditions such as a reducing environment induced by stagnant water and low sedimentation rates are extremely favorable for the establishment and development of a luxuriant floral assemblage. In the north central portion of the mine, five seams are joined together into the D-5/D-1 coal, indicating a locus of flood basin stabilization and continue development of reducing poorly drained swampy silvan conditions (Figure 3).

Laterally (east-southeast and west-northwest) and vertically, these swampy conditions persisted for

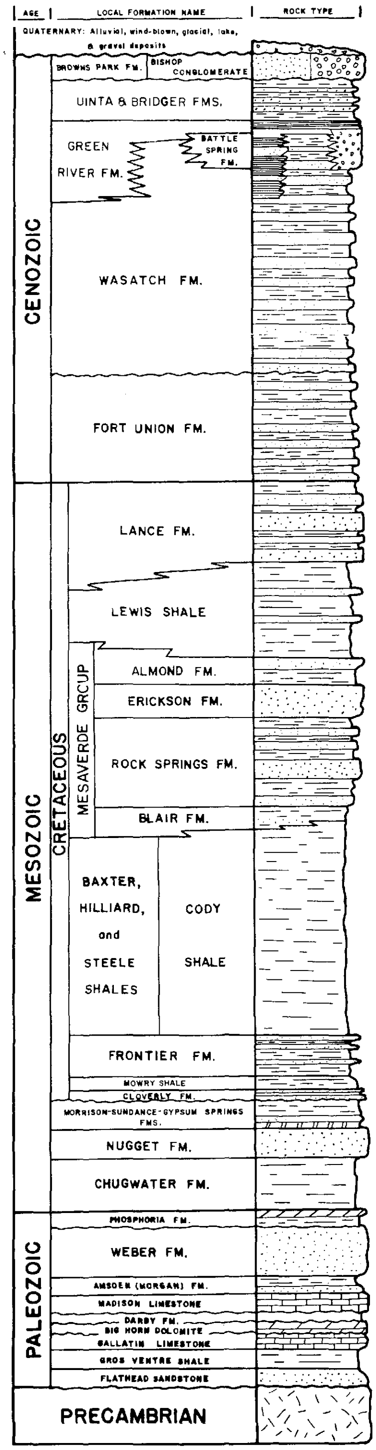

Figure 2. Stratigraphic column (vertical sequence of rock formations within Sweetwater County; after Root and others, 1973).

an interval of time, but were periodically interrupted by stages of increased detrital sediment influx as evidenced by partings. Partings are the result of synchronal active channel migration, overbank deposition, and crevasse splay sedimentation. These conditions are documented by parting extent and orientation, thicknesses, and grain size data. Allochthonous coalified plant debris are well preserved and range from being articulated to slightly disarticulated, thereby indicating a very small amount of transport with respect to the enclosing sediments.

Increased basinal subsidence and compaction of underlying sediments within the coal-forming swamps or increased sedimentation rates (probably due to lateral channel avulsion) resulted in the termination of widespread reducing swamp conditions within the mine permit area. Strata immediately overlying the D-5 seam are composed of varying amounts of fine-grained, well-sorted sandstone, siltstone, claystone,, discontinuous coal stringers, and rooted carbonaceous shale. On a lateral and vertical scale, these lithologies grade rapidly into each other.

Dominant channel trends, based upon highwall mapping, grain size analysis, sandstone isolith and alternation frequency data, and subsequent computer generated maps indicate meandering southwest-northeast orientations (Figures 5, 6, and 7). Sediment was probably transported via shallow, low gradient moderately meandering streams which migrated and became entrenched within stabilized subaerial to subaqueous swampy flood basinal areas. Thick sandstone bodies are interpreted to represent areas of channel, proximal overbank, and crevasse splay sedimentation. Sedimentary structures found indicative of moderate to rapid rates of sedimentation include erosional and scoured surfaces, ripple bedding, cross-stratification, downward convex basal surfaces in areas of channel entrenchment, and highly disarticulated allochthonous coalified plant debris locally contained within sand bodies. Channel sand bodies and lateral associations are highly discontinuous and grade laterally into the flood basin facies (deposits of well-to-poorly-drained swamp environments). These relationships are documented by thin sandstone beds enclosed within siltstone and claystone sequences of the floodbasin environs containing autochthonous plant debris. Locally, poorly drained swamp conditions became periodically established resulting in the formation of

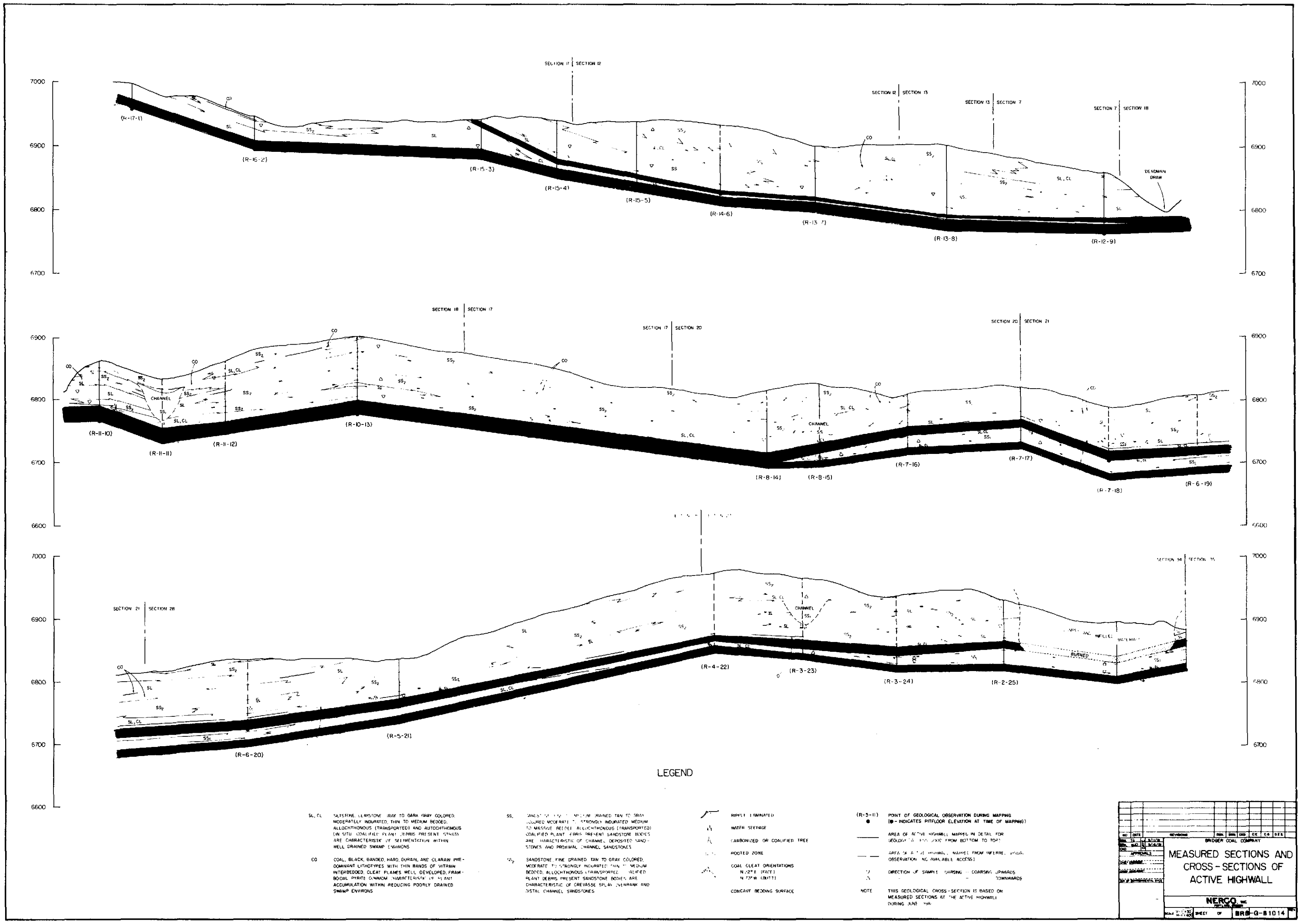

Figure 3. Measured sections and cross-sections of active highwall.

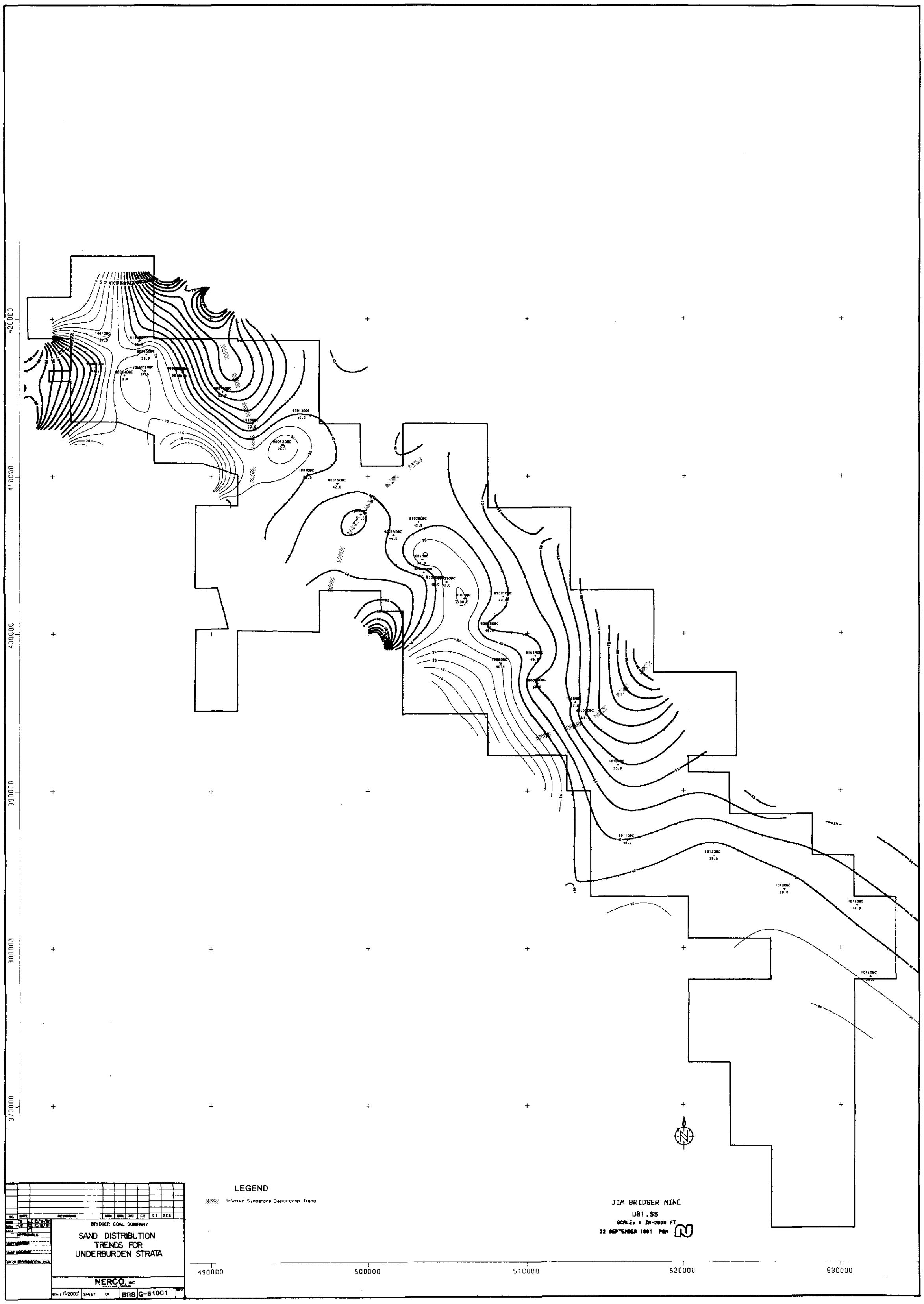

Figure 4. Sand distribution trends for underburden strata.

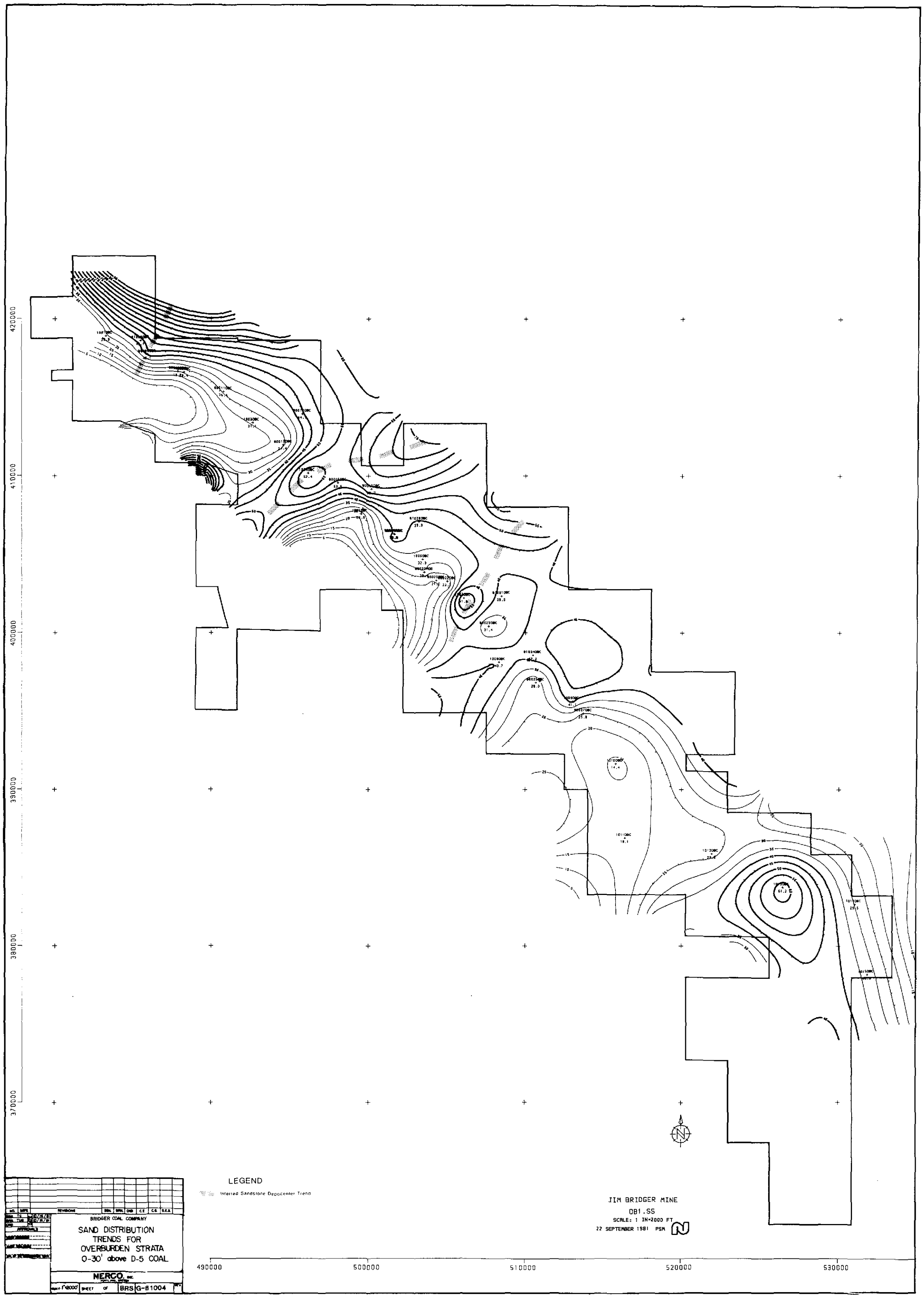

Figure 5. Sand distribution trends for overburden strata 0-30 ft above D-5 coal.

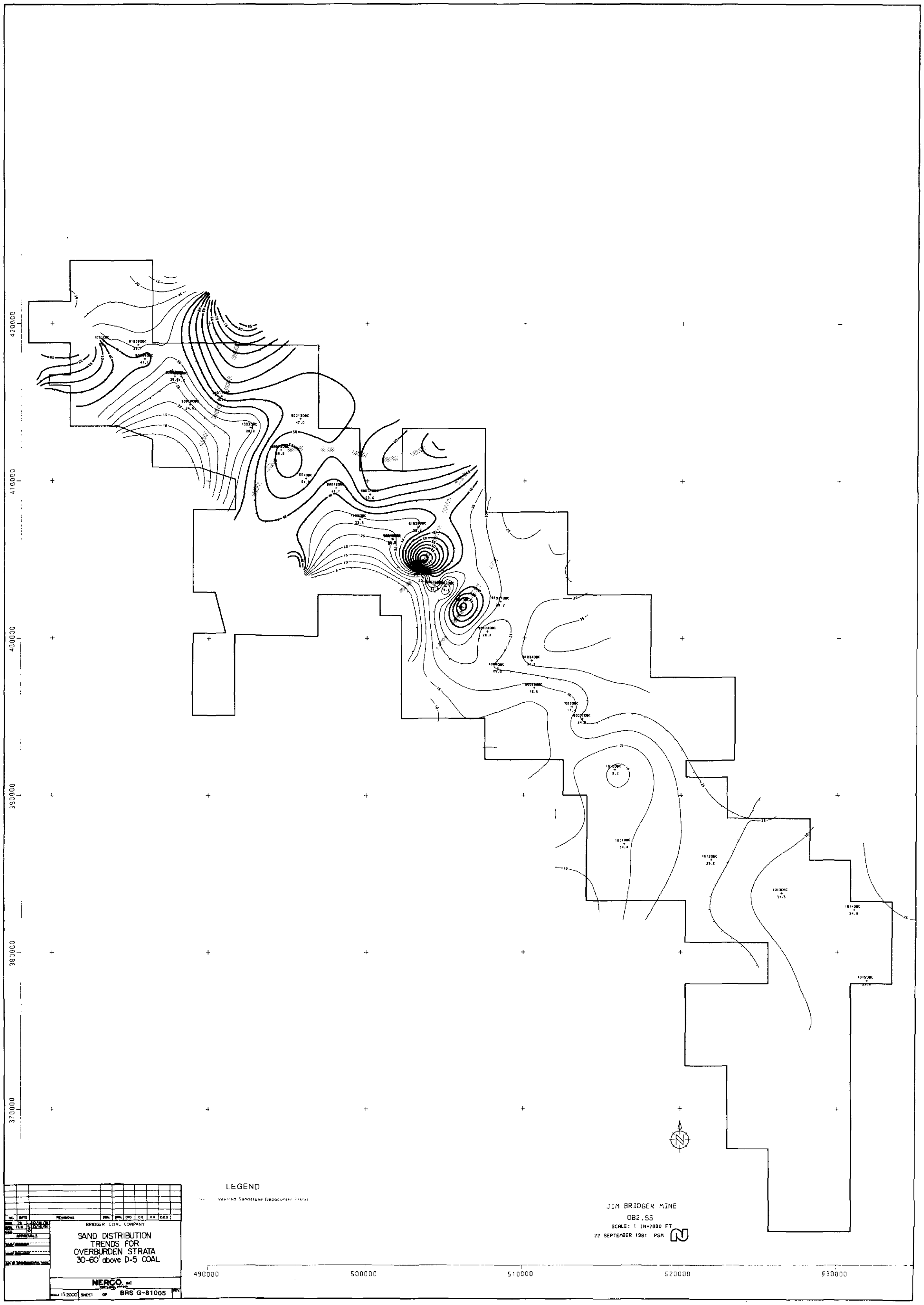

Figure 6. Sand distribution trends for overburden strata 30-60 ft above D-5 coal.

discontinuous coal stringers and rooting zones.

Drilling has indicated thin (less than 5 ft), discontinuous micritic limestone beds interbedded with flood basin deposits. Limestone is a common sediment, forming in both fresh and marine water environments, In freshwater environments, it typically forms in small lakes and flood basinal ponds (Beaumont, 1979). In addition, carbonate sediment present in localized ponds, within fluviatile environments typically results in thin, discontinuous, argillaceous, limestone beds containing few fossils (Picard, 1957; Royse,1970).

DEPOSITIONAL MODEL IMPLICATIONS UPON HYDROGEOLOGY PROBLEMS

Hydrogeological investigations at the Jim Bridger mine indicate that the overburden is sufficiently productive to be considered an aquifer. It is a discontinuous, confined aquifer flowing southwest from the Continental Divide toward the mine pits. Generally, the aquifer exhibits both horizontal and vertical movement of water through the system.

Three subareas exhibiting increased water seepage within overburden materials of the highwall were field mapped (Figure 3). Seepage directly correlate with mapped channel occurrences. These zones of water and specific sand depocenter trends were obtained from computer grain size analysis maps (Figures 5, 6, and 7). Increased water seepage occurs where highwall cuts intersect major saturated sand body systems. This increased seepage may be the result of higher permeabilities within the sand depocenters. If these sand depocenters are more permeable, subareas of increased water seepage should closely correspond with projected saturated sand depocenter trends. Elevational occurrences and areal distributions of channel trends within overburden materials to be encountered during future mining operations and the present potentiometric surface provides the basis for the delineation of potential pit water seepage areas (Figure 10).

OTHER APPLICATIONS OF DEPOSITIONAL MODEL TO MINING OPERATION

Distribution of clastic sediments is dependent upon fluctuations within depositional environments. Sediments deposited within various depositional environments are sedimentologically and geochemically distinctive.

As stated previously, coals are the result of plant accumulation within reducing environments, specifically poorly drained swamps within basins flanking stream channels. Silts and clays are deposited distally from channel areas within flood basins under slightly reducing conditions. Sands and coarse silts are typically deposited proximal to major sands depocenters (specifically channel and splay areas) under generally oxidizing conditions.

In examining total sulfur trends for the Jim Bridger coal deposits, a direct correlation is found between coals with low total sulfur value and subareas where the immediate overlying strata contain high sand contents (greater than 40 percent on a weight percentage basis). This correlation suggests that a portion of the available FeS_2 within the coal is a function of downward percolation of mineral-laden waters from the overlying flood basin facies, specifically the well-drained swamp deposits (reducing origin).

Laboratory analysis of overburden and interburden materials exhibit variations in geochemical parameters between drill holes, i.e., soluble salt electrical conductivity, exchangeable sodium percentage (ESP), sodium absorption ratio (SAR), boron, molydenum, etc. Based upon preliminary investigations, significant sand bodies (greater than 40 percent on a volume percentage basis) appear to correlate with corresponding low soluble salt electrical conductivity, ESP, and SAR values. Likewise, higher values of these chemical parameters are generally concentrated within zones of strata consisting of greater than 60 percent combined silt and clay fractions on a weight percentage basis.

A detailed understanding of the depositional system and distribution of lithological units may aid in the optimization of overburden blasting procedures, (i.e., locations and types of drill hole spacing, relative amounts of charges required, etc.). Basal areas of paleochannels are found to contain silty to clayey scour surfaces saturated with associated ground water seepage. Subsequently, these saturated zones can cause problems to drilling and blasting operations. Accurate delineation of dominant paleochannel trends provides a predictive model where saturated conditions and potentially problematic ground water infiltration will be encountered during blasting operations (Figure 10). In addition, where sand bodies are of maximum thickness (Figure 8), blast patterns may be altered to

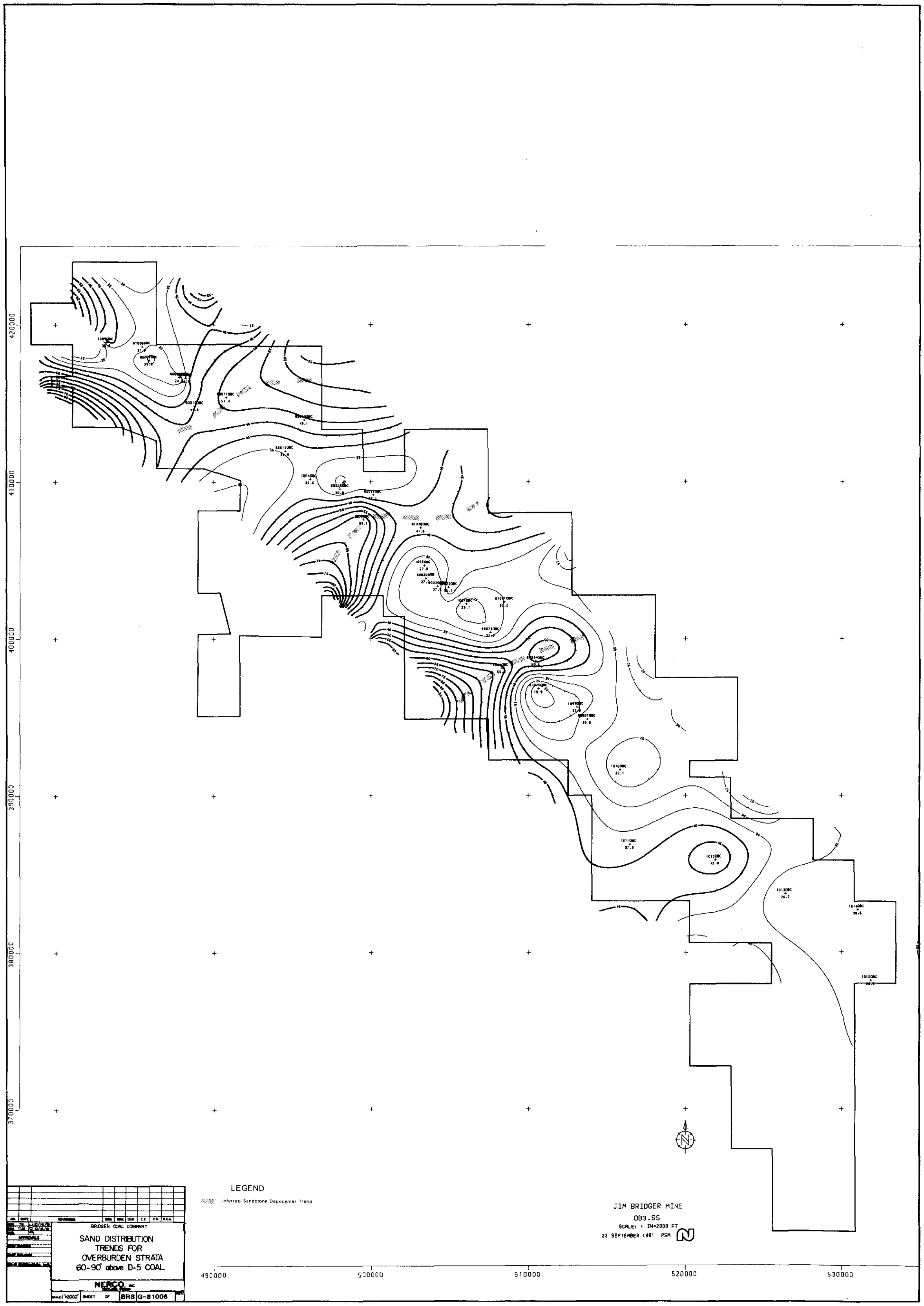

Figure 7. Sand distribution trends for overburden strata 60-90 ft above D-5 coal.

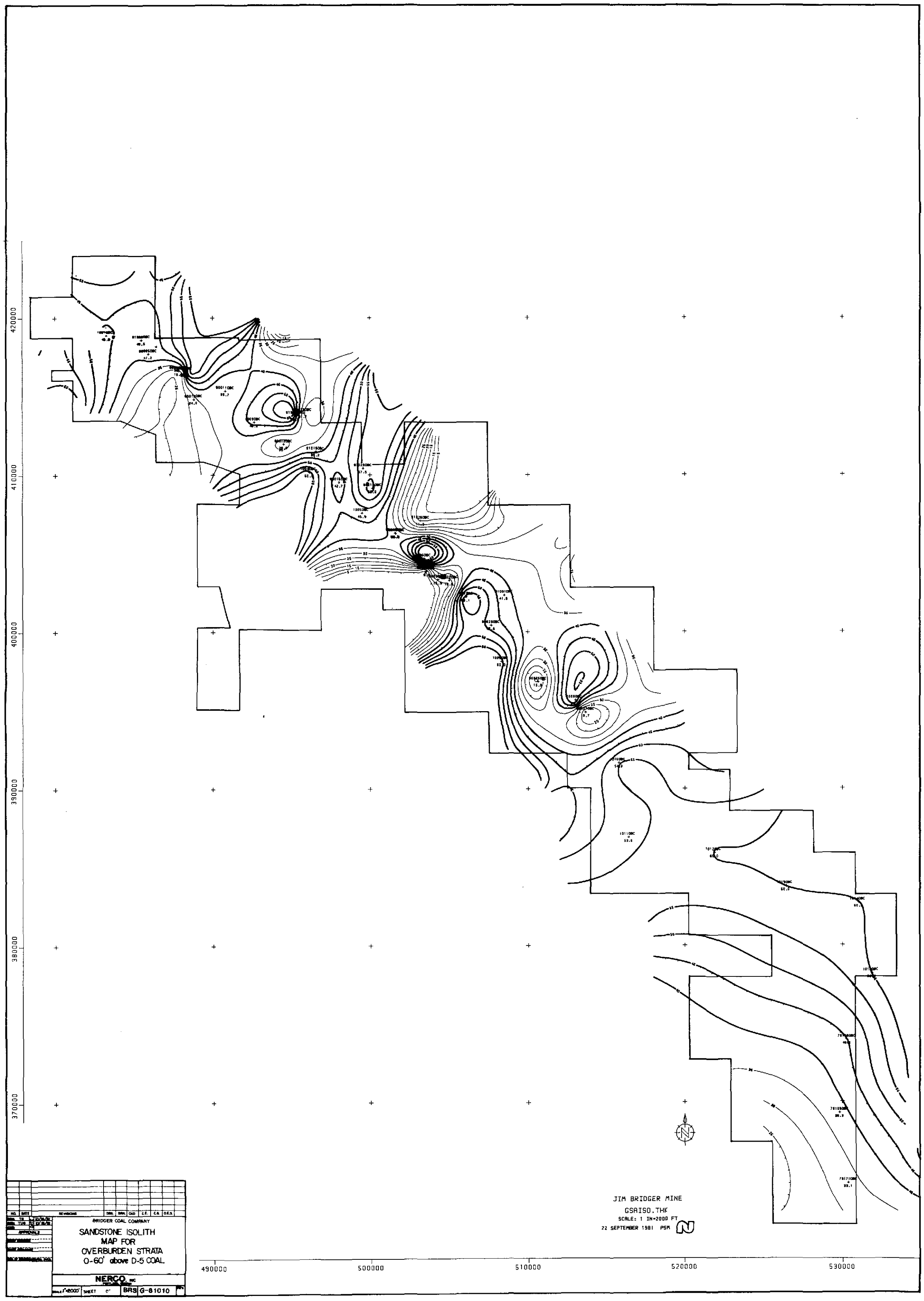

Figure 8. Sand distribution trends for overburden strata 0-60 ft above D-5 coal.

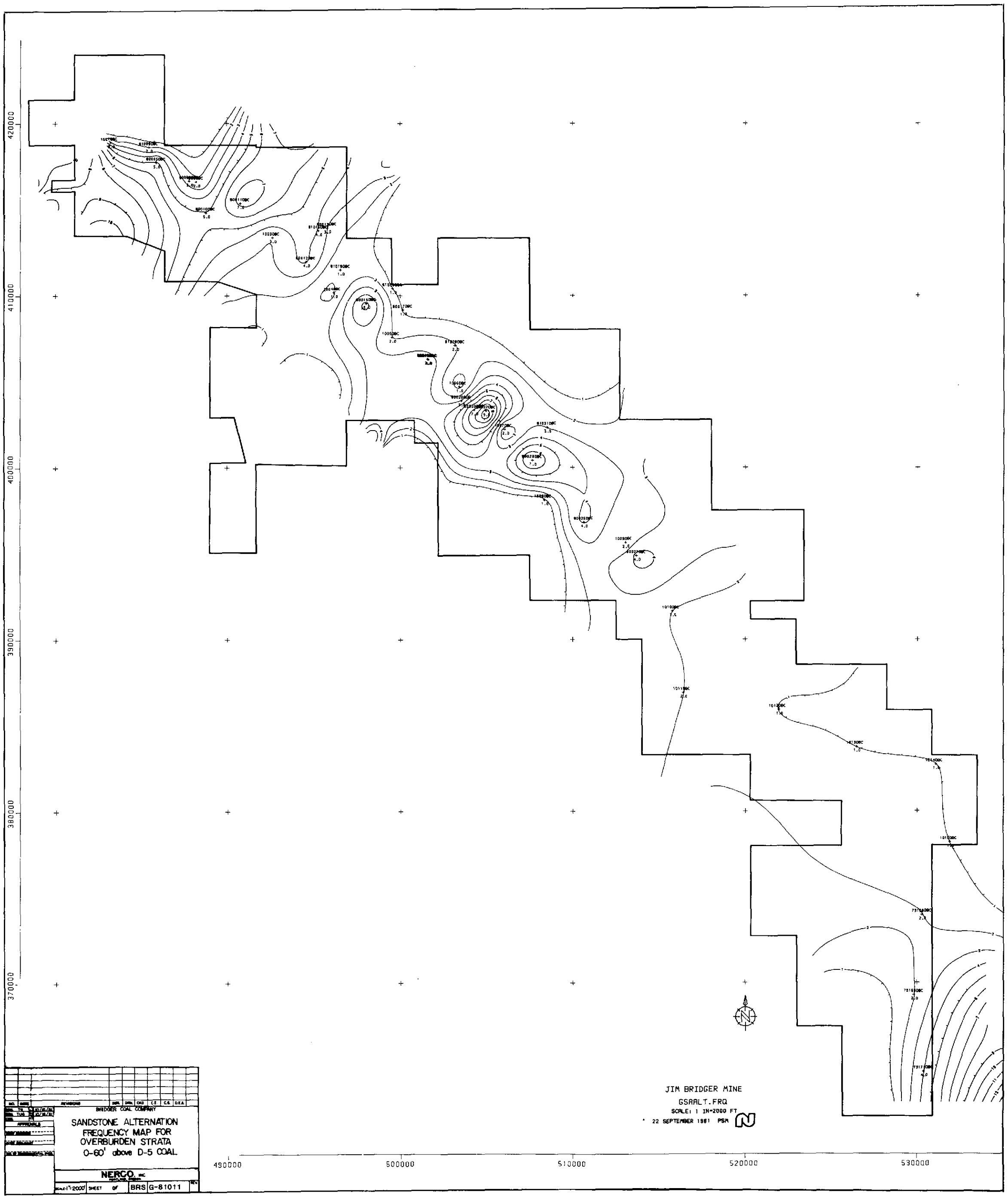

Figure 9. Sandstone alternation frequency map for overburden strata 0-60 ft above D-5 coal.

reflect increasing ground water effects and denser, more competent rocks. Likewise, channel flank areas (where channel systems grade laterally into the flood basin facies) should represent a more varied blasting medium (i.e., thinly-bedded, less competent rocks, decreasing water content).

SUMMARY

Investigations of depositional variations encountered at the Jim Bridger mine is a method applicable to the understanding of hydrologic, engineering, and environmental aspects of surface mine operation. The presented depositional model is

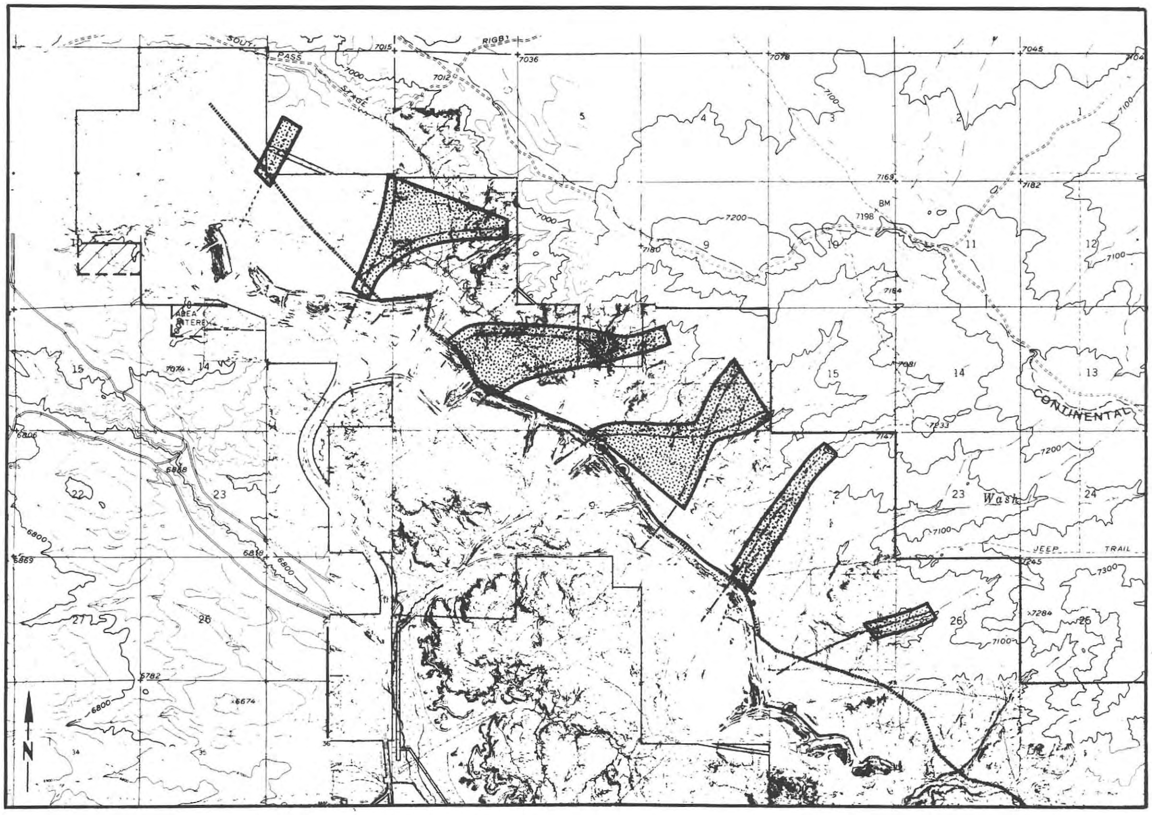

Figure 10. Potential aquifer zones relative to overburden sand distribution trends and potentiometric surface.

a prelimary evaluation of the active mine area (northern two thirds of the permit area) with additional work planned within adjacent future mine areas. Potential applications of this depositional model to mine planning include the following:

1. prediction of zones of increased ground water seepage in pit areas;
2. prediction of overburden geochemistry trends;
3. prediction of coal quality trends;
4. optimization of overburden blasting procedures.

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DEPOSITIONAL ENVIRONMENTS OF A SURFACE COAL MINE IN NORTHWEST COLORADO

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INTRODUCTION

The environments of deposition of two of four economic coal seams and their enveloping rock strata at the Trapper Coal Mine near Craig, Colorado, were studied from 1980 through 1981 (Massoth, 1982). Extensive drill hole data combined with sections measured in the mining pits were analyzed for coal and interburden characteristics, flora, fauna, sandstone petrology and sandstone facies relationships. The interpreted depositional environments include swamps , marshes, ponds or lakes, distributary channels, levees and crevasse splays of an interdeltaic swamp belt complex. This depositional information was used to interpret some past mining problems and can be applied to predict and help alleviate future mining problems.

The Trapper Mine is located about 6 mi (9.7 km) south of Craig, Colorado, in northwest Colorado. It is currently owned and operated by Utah International Inc. with the coal sold to the Colorado-Ute Electric Association, which owns and operates the 830 megawatt Craig Station mine-mouth power plant. The mine is a surface coal mine in which three pits, operating in a dip-line stripping fashion, produce about 2.5 million tons of subbutuminous coal annually.

GENERAL GEOLOGY

The mine takes coal from the Upper Cretaceous Williams Fork Formation of the Mesaverde Group, the major coal-bearing sequence in the Rocky Mountain states. Locally this group is divided into two formations, the lower being the Iles Formation and the upper being the Williams Fork Formation. These combine to form about 3,400 ft (1,037 m) of massive sheet sandstone interbedded with lenticular sandstone, siltstone, claystone and numerous coal beds. The Mesaverde Group represents the time of the last major epicontinental sea invasions into the mid-U.S., and it is composed of multiple eastward-prograding littoral and terrestrial clastic wedges interfingering with westward transgressing marine tongues (Kauffman, 1977). These sediments near Craig are deformed from their original, nearly horizontal attitude into *en echelon,* gently folded anticlines and synclines. This structural complexity arose from nearby uplifts of the Unita Mountains, the Park Range and the White River Uplift-all Laramide orogenic events of latest Cretaceous to Eocene time (Tweto, 1975). Locally, the mine strata strike almost due east-west and dip at about 8° northward.

LITHOLOGY

The lithologies encountered during mining are all sedimentary, being sandstone, siltstone, claystone, carbonaceous claystone and coal. By combining two-dimensional highwall views with three dimensional drill hole isopach and lithofacies maps, the geometries and lateral extents of these rocks were obtained.

The sandstone units occur in two geometries: 1) shoestring in plan view/lensoidal in cross section, and 2) lobate in plan/view/tabular in cross section. Both types are subarkose with well-sorted, subangular, very fine-to-fine-grained clasts. The shoestring varieties are 15 to 40 ft (4.6 to 12.2 m) thick, upward-fining units with undulatory and erosional lower contacts which often scour into underlying coal seams. Wedge-shaped siltstone units laterally interfinger with these sandstones. The lobate sandstone varieties are usually 3 to 6 ft (0.9 to 1.8 m) thick, have more gradational lower and upper contacts and display both upward-fining and upward-coarsening clastic trends.

Siltstone is a volumetrically small rock type and is often directly above or laterally interfingering with sandstone. Siltstones have numerous, thin horizontal and/or rippled cabonaceous laminations, leaf impressions of various palm and warm weather dicotyledons, and root casts.

Claystone, the dominate rock type, is tabular in shape and encompasses the various clastic bodies and coal seams. X-ray diffraction revealed the clay constituents to be kaolinite, smectite and K-mica, all varieties most likely to be found in warm, humid and slightly acidic swamp-like environments.

The coal seams are tabular, laterally continuous, display excellent cleating and often contain tonsteins—i.e., altered (to kaolinite) volcanic ash beds that are often useful as marker bands. Coal quality ranges are: 9,600-10,000 Btu/lb, 0.3-0.5 percent sulphur, 14-16 percent moisture, 5-10 percent ash. The coals occasionally display wants and often display rolls.

METHODS

There are four separate coal seams currently being mined. The strata between two of the four economic seams were analyzed to determine the depositional environments of those seams and their enclosing sediments. These seams are known as the "R" and "Q" seams. The rock interval which separates them varies vertically from 10 to 100 ft (3 to 30.5 m). Data to make this analysis were a combination of electric logs from 208 drill holes and 14 measured sections in the mining pits.

Isopach maps of the coal seams and isopach lithofacies maps of the rock interburden between coal seams were produced to show coal thickness trends and paleochannel systems. Coal seam geometry was found to be controlled largely by the the interburden lithology and thickness. When maps of the various strata were analyzed sequentially in ascending stratigraphic order, the significant effects of differential compaction became readily apparent: thicker portions of a coal seam overlie previous paleomarsh/pond environments (i.e., thin carbonaceous claystone or claystone units), while thinner portions of the coal seams overlie previous paleochannel/crevasse splay environments (i.e., thick sandstone or siltstone units).

Figure 1 shows diagrammatically three units from the study strata, and displays the effects of differential compaction. Panel A, developed from isopach data, shows the thin "Q3" marker seam. Panel B shows the various environments which inundated the area and essentially terminated the "Q3" paleopeat swamp. This panel was developed from analysis of the interburden's isopach and lithofacies map and from highwall studies.

Next, the area subsided enough to allow the remnant "Q3" swamp to expand and cover the entire area with what is termed the "Q2" coal seam. Thick, unsplit portions of "Q2" seam lie above previous marsh interburden area, while thinner portions lie above the paleochannels of the previous interburden.

The thicker portions of coal developed in localities in the paleopeat swamp environment which experienced maximum peat accumulation, most often due to greater subsidence of underlying strata. Poorly drained swamps developed in these areas and allowed for the preservation of downed tree and plant material. On the other hand, thinner portions of coal are due to minimal original peat deposition and/or post-depositional paleochannel scouring. These thinned coal areas were usually found to either: 1) overlay previous paleochannels and thus occupy slightly topographically higher and better drained swamp areas where vegetative material could be exposed to destruction by biochemical and atmospheric conditions, or, 2) be overlain themselves and scoured by paleochannels. Examples of thick and thin coal trends and paleochannel scouring are present in the intervals shown in the figure.

DEPOSITIONAL MODEL

The coal seams and rock strata at Trapper Mine were deposited in an interdeltaic setting. Evidence for this includes the region's paleogeographic setting and its coal characteristics. McGookey (1972) shows in a regional paleographic map representing Upper Williams Fork Formation time, that the Craig area lay to the south of a large, contemporaneous delta system in central Wyoming and to the north of a more lobate delta (?) in northeastern New Mexico. The majority of eroding material from the Sevier Orogenic Belt was transported to the Cretaceous epicontinental seaway via these delta systems and not via this sediment-starved region. Thus this interdeltaic setting allowed relatively stable coastlines and therefore stacked peat swamps.

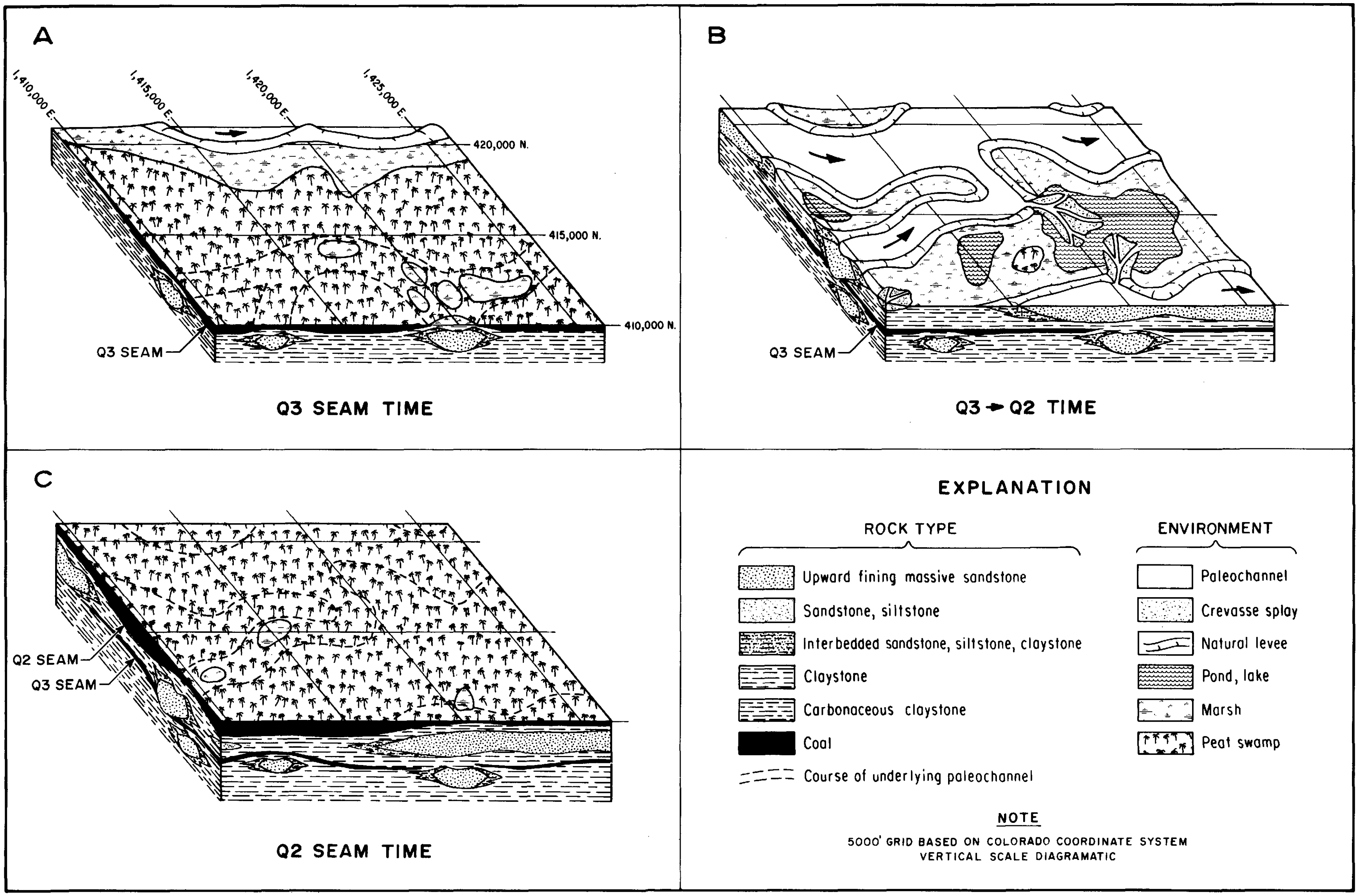

Figure 1. Block diagram of selected strata.

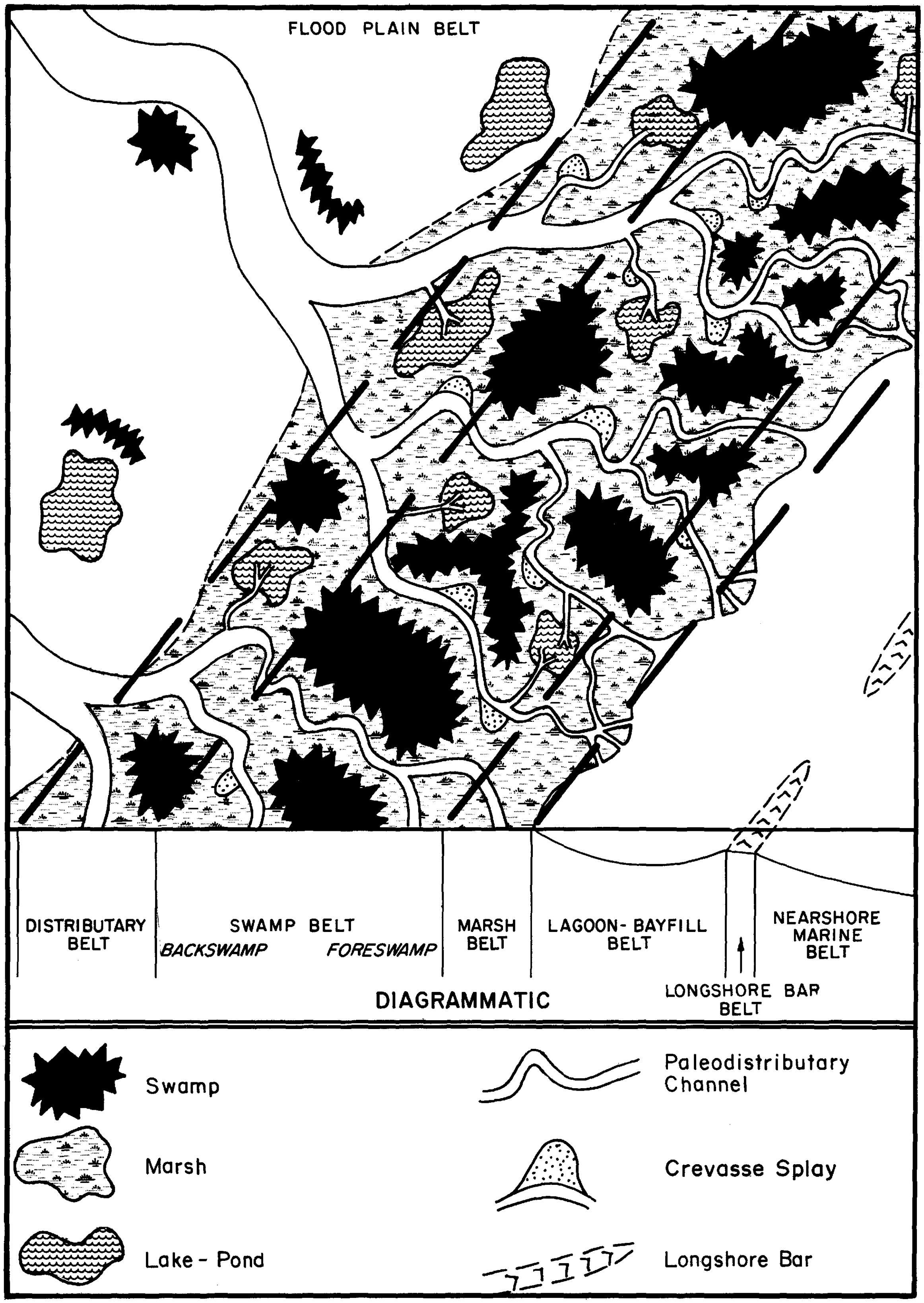

Figure 2. Depositional model for the Trapper Mine strata.

Coal seam characteristics such as geometry, continuity, thickness, frequency, quality and nature of interburden strata are variable and characteristic of various swamp environments known from the rock record: alluvial/fluvial, deltaic, interdeltaic, lagoonal (Vaninetti, 1979). Trapper Mine seams are tabular, laterally continuous for at least 30 sq mi (77 sm km) and range from 1 to 15 ft (0.3 to 4.6 m) with the economic seams 4 and 8 ft (1.2 and 2.4 m) thick. At least 12 separate seams exist in the 200 vertical ft (61 m) of strata being mined, with the interburden intervals being mud-rich.

These coal characteristics suggest an interdeltaic depositional environment similar to that portrayed in Figure 2. The suite of enviroments includes swamp, marsh, pond, crevasse splay, natural levee and distributary channels. The swamp belt complex of the "R" to "Q" seam coals was located between a more landward and fluvial coastal plain belt and a more seaward lagoonal/bayfill-offshore bar belt. The extensive coal swamps were intermittently flooded by river-derived sediments which locally interrupted or terminated peat-forming conditions. These sediments later lithified to form the various rock splits in the seams and the rock interburdens between the seams. With later continued upstream avulsions, local swamp conditions became re-established.

APPLICATION TO MINING

The objectives of this study were to determine the environments of deposition of the coal-bearing strata of the Trapper Mine and the factors controlling coal-seam quality and quantity. With an understanding of the environments and controlling factors, better coal seam correlations, more precise reserve calculations and greater efficiency in coal extraction can be obtained. The local environments were interpreted from an integration of highwall measured sections, close-spaced drill hole information and past investigations by others of coal-related depositional environments. Coal seam quality and quantity (geometry, thickness, and areal extent) were found to be a function of the swamp's position in the swamp belt complex. The stratigraphically lower "R" seam, deposited in the foreswamp position of the swamp belt (Figure 2), had higher sulphur values, lower ash values, and no splits or rider seams compared to the stratigraphically higher and more backswamp "Q" seams.

Mining methods can benefit from an understanding of the depositional environments found in this study. For example, development and pre-pit drilling should be concentrated in areas of paleo-channels to determine what effect the channels may have had on underlying or overlying coal seams. Coal reserves may be substantially reduced if these channels have scoured out underlying coals or have caused non or poor deposition of overlying coals. Coal rolls will also be greatest in these paleochannel areas due to differential compaction. This may affect haul truck and other mining equipment operation.

Drilling and blasting proficiency depends upon the lithologies encountered, and with depositional analysis lithologic trends can be predicted with greater certainty. Mining engineers may be virtually assured that the interburden rock present between two seams and laterally in the interfluves between rock distributary paleochannels in the interburden rock, will be mostly claystone, while within the channel zones the interburden rock will be overwhelmingly sandstone.

Highwall stability may also be affected by a pit's orientation with respect to interburden paleochannels. Presently, one pit's highwall lies perpendicular to a major channel. As future pit development proceeds eastward, the orientation of the paleochannel changes such that the highwall and paleochannel edge will be parallel. In such a configuration, rapid lateral lithology changes, coupled with differential compaction and slickensides in the levee area of the channel, may tend to cause highwall instability. Highwall failures (rotational slump block landsliding) have occurred in this pit before. Also, the channel is probably a perched aquifer, so water leakage into weak clay layers adjoining the coal seams may decrease highwall stability during mining.

Knowledge of the environments of deposition of coal-bearing strata is important to the coal geologists as it can aid in the prediction of coal seam correlation, geometry, and quality. Variations and trends in coal seam and interburden thicknesses can be best understood through application of depositional analysis. Results may benefit surface operations by developing insight into local conditions of coal wants, coal rolls, aquifer geometry, and highwall stability. Future underground mining may benefit from knowledge of roof and floor conditions, coal wants, rolls, and splits, and the potential minability of coal seams

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ROOF GEOLOGY AND STABILITY OF AN UNDERGROUND COAL MINE IN CARBON COUNTY, UTAH

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INTRODUCTION

The role of geology in underground coal mine development in eastern and central Utah coal mines has been relatively minor and unused in the past. As the demands for coal from this area increase, however, an understanding of the geologic factors which influence mine production and safety is vital for safe and efficient coal extraction. Of the many geologic factors which influence mine production and safety, geology of the immediate roof strata is one of the most important.

This study was undertaken in an attempt to determine the effects of roof geology on the roof conditions of an underground coal mine in eastern Utah. The studied mine is located in the westernmost portion of the Book Cliffs coal field, about 2 km northwest of Helper, Carbon County, Utah (Figure 1). The mine has been developed with continuous mining and longwall mining methods in the Sub-3 seam of coal, which has long been noted for its unpredictable roof conditions (Tomlinson, 1932). These unpredictable roof conditions not only present a safety hazard to mine personnel, but occasionally affect mine production as well.

METHODS

In order to delineate immediate roof lithologies within the mine, an in-mine mapping program was initiated under the direction of the Utah Geological and Mineral Survey, from April through September, 1981. Because no "top coal" is being left in the mine roof, the exposed roof lithologies and characteristics were readily mappable on 1:1,200 scale mine maps supplied by the mine company. To suppliment roof mapping, numerous stratigraphic sections were measured within the mine, and detailed descriptions were made of the various exposed roof lithologies.

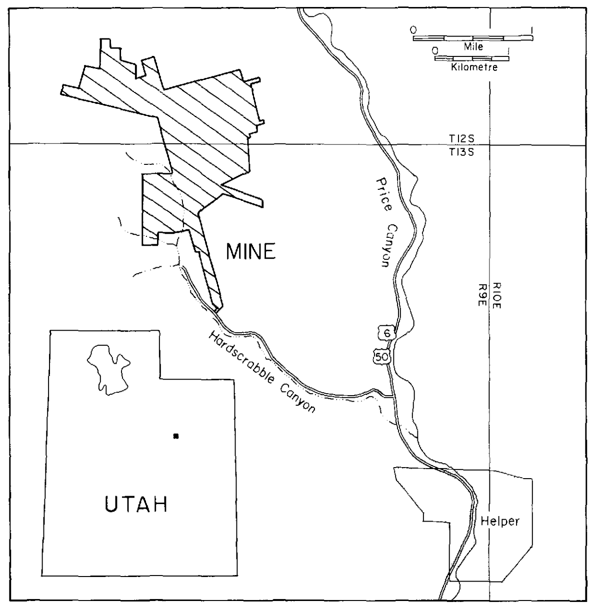

Figure 1. Index map of the studied mine area.

During mapping, particular attention was given to roof falls and overcasts, where larger intervals of the mine roof were exposed and could be described. Lithologic boundaries of the immediate roof, as well as other features such as roof falls and fracture zones were plotted on mine entries and cross cuts, and then projected across coal pillars. Paleocurrent orientations were also measured and plotted.

GENERAL GEOLOGY

The studied coal mine is located in the northwest portion of the Colorado Plateau, in the northwestern end of the Book Cliffs of east-central Utah. The rocks of the mine area consist entirely of

Upper Cretaceous sedimentary rocks that dip gently to the northeast.

Exposed rocks of the immediate mine area include part or all of four Upper Cretaceous formations, which include from the base up: the Mancos Shale, Star Point Sandstone, Blackhawk Formation, and Price River Formation. These units form cliffs, ledges, and intervening slopes, with sandstone units commonly forming the ledges and cliffs, and less resistant siltstone, shale, and coal beds forming the slopes. The Blackhawk Formation, named by Spieker and Reeside (1925), includes the major coal bearing rocks exposed in the mine area, consisting of about 300 m (1,000 ft) of sandstone, shale, and coal (Young, 1955).

The Sub-3 seam, in which the mine has been developed, directly overlies the basal Spring Canyon Sandstone tongue of the Blackhawk Formation, which is comprised of a massive marine sandstone. The Sub-3 seam is the lowest coal bed of the Spring Canyon coal group of the exposed Blackhawk Formation in the mine area.

Within the projected mine area, the seam, including 1 to 3 thin splits, reaches a thickness of slightly over 3 m (10 ft), but thins eastward and westward to less than 1.2 m (4 ft) (unpublished mine data). Rocks overlying the Sub-3 seam are laterally discontinuous and vary from fine-grained sandstone to siltstone and mudstone.

Spieker and Reeside (1925) interpreted the general depositional setting of the Blackhawk Formation to be a broad coastal plain. Later studies by Young (1955, 1957, 1966, and 1976) and Howard (1972) indicated that the major coals appear to have accumulated behind barrier islands that formed the marine sandstone sheets or tongues of the Star Point Sandstone and lower Blackhawk Formation. Balsley (1980) cited evidence to suggest that most of the sheet sands were deposited on wave-dominated delta platforms, upon which many of the major coal beds developed.

The area around the studied mine lies in the region of a gentle north to northeastward dipping homoclinal structure of the Book Cliffs. Rocks in the mine area, including the Sub-3 seam, generally dip 4 to 6 degrees to the northeast. No faults have been encountered in the mine and none are apparent in the projected mine area.

ROOF GEOLOGY

Lithology and stratification of beds immediately overlying the Sub-3 seam vary greatly in the mine. Such variation is largely produced by rapid lateral changes from one depositional setting to another. Because rocks of each of these depositional environments affect the mine roof somewhat differently, roof conditions may vary significantly in relatively short distances. These variations in roof stability occasionally create a safety hazard to mine personnel, and sometimes slow mine production for short periods of time.

Lithology of the immediate mine roof (the 3-meter interval above the coal seam) varies from siltstone to very fine-grained sandstone, with minor interbeds of mudstone, carbonaceous mudstone, and coal. Detailed mapping of exposed roof rocks differentiates three major depositional environments within the flood-plain setting. These depositional environments include channel-fill sandstone deposits; overbank deposits of sandstone, siltstone, and minor mudstone; and swamp deposits of carbonaceous mudstone and coal. These floodplain environments represent only a minor part of the overall environment in which coal and other sediments of the Spring Canyon coal group accumulated.

Unstable roof conditions in the mine appear to be closely associated with either lenses of channel-fill sandstone, or overbank sandstone and siltstone deposits. It was possible, during roof mapping, to classify types of roof falls by characteristics resulting from occurrences in various depositional environments.

Depositional Environments of the Mine Roof

Deposits of three major depositional environments occur in the mine roof, as mentioned earlier. These include: 1) fluvial channel-fill deposits of sandstone, 2) overbank deposits of sandstone, siltstone, and minor mudstone, and 3) swamp deposits of coal and carbonaceous mudstone.

Fluvial Channel Deposits - The fluvial channel deposits are represented by channel-fill sandstone bodies that are exposed at numerous locations within the mine (Figure 2). Many of these lenses are mappable for hundreds of meters in the mine roof until they pass into inaccessible or unmined areas. In general, the channel-fill bodies are massive,

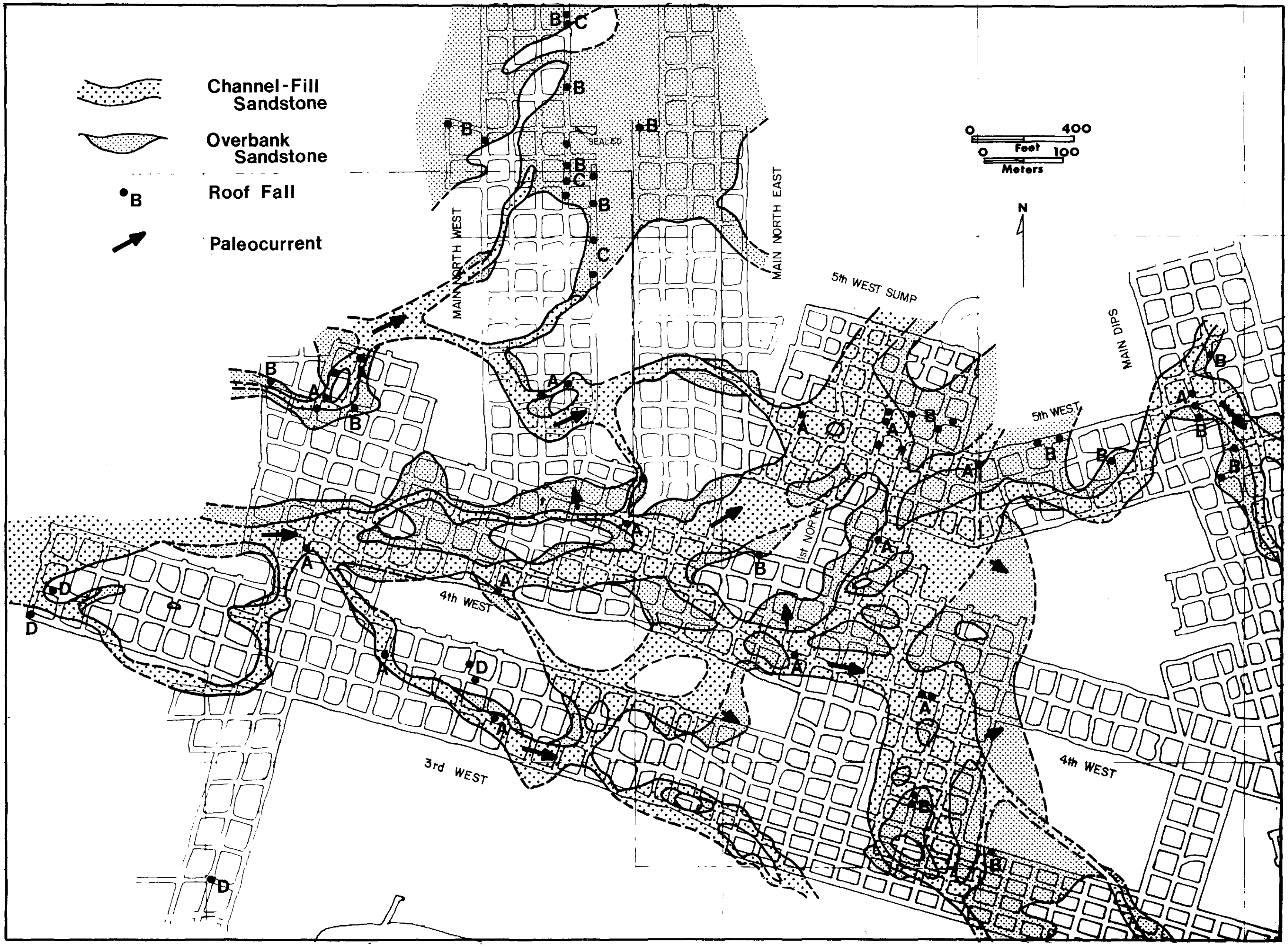

Figure 2. Roof geology map of a portion of the studied mine. The unpatterned roof is overbank siltstone.

crossbedded, very fine-grained, moderately well-sorted sandstone. The sandstone has a calcareous cement, and is moderately cemented and friable.

The exposed bases of fluvial channel sandstone bodies range from about 9 m to 60 m wide. The lenticular fills were observed to range from 1 m to over 4 m thick in overcasts and roof falls. In-mine observations, and observations in canyon outcrops near the mine portal indicate that dimensions of the channel-fill sandstone lenses are relatively small above the Sub-3 seam in comparison to channel-fill lenses observed in other coal mines of the Book Cliffs and Wasatch Plateau coal fields. For example, those observed by the author above the Castlegate "D" seam, about 150 m above the Sub-3 seam, reach a maximum width of approximately 600 m and a thickness of over 9 m. Mercier and Lloyd (1981) indicate that migrating fluvial channels above the Hiawatha and Blind Canyon seams of the Wasatch Plateau produced sandstone units with lateral dimensions which reach up to several kilometers wide and up to 15 m thick. It is possible that the smaller channel size increased lateral discontinuity of the roof geology, and thus increased the chances for unstable roof conditions to occur.

Because only relatively small protions of the base of the fluvial sand bodies are exposed, it is difficult to determine the types of channel-fills represented. It is assumed, because of their relatively small size, that these lenses formed by avulsion, or some other type of channel abandonment, rather than by point bar accretion. Where observed in roof falls and overcasts, the channel sandstones commonly contain trough crossbed sets from 30 cm to 1 m thick, may occur and commonly form slickenside surfaces by differential conpaction.

Basal surfaces of channel-fill sandstones in the mine roof are readily differentiable from other types of deposits by their characteristic lateral discontinuity, convex-down shape, undulating basal surface, content of siltstone or coal rip-up clasts, and occasional well-developed flute casts and tool marks. Trough crossbed sets and lenticular bedding are usually evident in the interior of the channel sandstone bodies.

Thin section analyses of 5 separate channel-fill sandstone lenses indicate that the sandstone ranges from very fine- to fine-grained quartz, with a calcite cement, and grains ranging from subangular to rounded. The 250 to 62 micron grain size dominates, with grains falling in the 62 to 31 micron range also making up a substantial part. All of the samples are well-sorted and relatively clean, with some clay included in the calcite cement.

Paleocurrent directions in the channel-fill sandstones commonly range from northeast to southeast (Figure 2). Flow directions were readily determined from trough crossbed sets, flute clasts, and ripple marks. In general, a western source is indicated for the observed channel-fills above the Sub-3 seam.

Effect on Roof Conditions - For the most part, channel-fill sandstone bodies make an excellent mine roof locally, especially when they are in direct contact with the coal seam and form the entire bolted roof. The sandstones are generally massive and are not subject to delamination and deterioration. They are commonly only slightly jointed or not jointed at all.

Minor roof falls have occurred in the paleochannel bodies (Figure 2), but all of these falls occurred along thin mudstone laminae which were highly slickensided during differential compaction. In a few cases, large blocks of these sandstone bodies have fallen, bringing down numerous rows of roof bolts. These falls are rare, and in general, the paleochannel sandstones exhibit good roof characteristics.

The most unstable roof conditions associated with paleochannel sandstone lenses occur where the sandstone is not in direct contact with the coal seam, but where the sandstone occurs in the mine roof from 20 cm to 2 m above the seam, and siltstone separates the coal and the channel-fill. In these areas, differential compaction apparently has created high stress situations within the brittle siltstone, and as mining proceeds beneath the paleochannel, residual stress release fractures form. When this occurs, roof conditions generally worsen dramatically after several days, until slabs and blocks of the siltstone begin separating and falling away from the sand body in sections between roof bolts. This condition is generally not serious, however, because deterioration occurs gradually and steps can be taken to stabilize the roof before roof falls develop.

Overbank Deposits - Overbank deposits cover the greatest area of any exposed roof lithologies in the studied mine. The overbank deposits consist mainly of siltstone, sandstone, and occasional mudstone interbeds.

By far the most common overbank deposit is the siltstone "caprock" that immediately overlies the Sub-3 seam virtually throughout the entire mine. The caprock is over 3 m thick in many areas, and forms an excellent stable roof when no thin interbeds of overbank sandstone or paleochannel sandstone lenses are present. The siltstone was apparently deposited over the entire mined portion of the Sub-3 seam prior to the migration of fluvial channels across the area. It is possible that the siltstone represents overbank deposits from a nearby fluvial system that developed immediately after peat deposition.

The overbank siltstone is only slightly calcareous, and is, for the most part, clean, hard, and brittle. As mentioned previously, it has a tendency to form concentric, parallel, fractures spaced from 3 to 20 cm apart when compacted. Where such fracturing occurs, unstable roof conditions develop which are sometimes difficult to stabilize.

Of the various roof lithologies present in the mine, overbank deposits of thinly bedded sandstone create the most treacherous roof conditons, particularly where the total overburden approaches or exceeds 600 m. These horizontal, thin-bedded sand deposits have generally accumulated along flanks of channel-fill sandstone bodies, and, in certain instances, form sheet sands of considerable lateral extent (Figure 2). It is possible that these sheet-like sandstones represent a type of crevasse-splay over-bank deposition from the small fluvial channels which are present in the mine roof.

These thin-bedded deposits range from about 10 cm to over 2 m thick, where observed in roof falls and overclasts. Individual sandstone beds range from 4 cm to 200 cm thick, with occasional interlamination of siltstone and mudstone. The thick sandstone beds are commonly ripple laminated and, in many cases, climbing ripples are present, indicating rapid deposition. The sandstone is very fine-grained, well-sorted, and moderately indurated, with a calcite cement. The overbank sandstones are composed almost entirely of quartz, and are compositionally similar to the channel-fill sandstones. The 250 to 31 micron grain size dominates, and the grains are well sorted and subrounded.

Paleocurrent directions in the overbank sandstone deposits are most commonly in a direction away from adjacent paleochannel sandstone bodies (Figure 2). This suggests that the thin-bedded sandstone units most likely had their source in the fluvial channels and were deposited as splays overbank deposition flooding from the channels. Moebs and Ellenberger (1982) use the term "crevasse splay" in a nongenetic sense for similar thinly bedded sandstone deposits found in Appalachian coal mines, even though many characteristics of a typical crevasse splay deposit may be absent.

Effect on Roof Conditions - As mentioned previously, some of the most hazardous roof conditions in the mine are produced by overbank sandstone deposits. The thinly bedded sandstone appears to delaminate and sag rather readily, until it eventually falls, in many cases bringing down the entire roof bolted interval of rock.

Overbank sandstone deposits, like the fluvial channel-fill bodies, are usually separated from the underlying coal seam by the overbank siltstone layer. This brittle siltstone commonly begins to fracture during the initial phases of roof sagging, and within several days, large slabs of overbank siltstone and sandstone begin to fall, sometimes without warning.

Swamp Deposits - Swamp deposits in the immediate mine roof are generally rider seams of coal and associated carbonaceous mudstone interbeds. The rider seams above the studied mine area are about 10 to 30 cm thick. These thin coal seams commonly split from the Sub-3 seam in some areas, and are separated from it by a siltstone. These siltstone layers generally thicken away from the area initial separation as the interval between the main seam and the rider increases. Rider seams in the mine extend up to several meters above the main coal seam.

These thin seams do not appear to adversely affect the mine roof. This is likely because all of the observed riders are located within the roof bolted interval, and separation can therefore not occur in the weak coal zone.

Roof Fall Classification and Description - Roof instability in the studied coal mine appears to be closely related to the various depositional environments represented in the mine roof. Four genetic types of roof falls occur in the mine, three of which are associated with specific depositional regimes, and one which is related to excessive stress fields around the mine entries. These four roof fall types include: 1) falls associated with channel-fill sandstone bodies, 2) falls associated with overbank sandstone deposits, 3) falls associated with fracturing of overbank sandstone deposits, 4) falls possibly caused by the advancement of an overlying coal mine or sudden variations in the overlying topography. Each of these categories of roof falls will be referred to as type A, B, C, and D, respectively.

Type A Roof Falls - Type A roof falls are those which occur in fluvial channel-fill sandstone deposits. Figure 2 shows the mapped locations of type A roof falls in the mine.

Falls of this type most commonly occur as slabs and blocks which delaminate from the bases of fluvial channel sandstone bodies immediately after mining and before roof bolting takes place. Occasionally this delamination from the paleochannel bases occurs over a period of time and the slabs and blocks of sandstone delaminate and fall around the roof bolts without actually pulling the bolts down (Figure 3). Delamination occurs along highly slickensided, clay-rich laminae within the bases of the paleochannels; and these slickensides are likely created by the differential compaction of thin mudstone laminae within the channel-fill sandstone bodies. The slickensides are obvious zones of weakness along which large slabs and blocks delaminate and fall.

In general, type A roof falls are relatively minor features which fall almost immediately after undercutting of the coal seam during mining. This presents little danger to mine personnel in that roof bolting usually stabilizes the problem areas.

Type B Roof Falls - Type B roof falls occur in overbank sandstone deposits and are, at present, perhaps the most common, and one of the most hazardous types of roof failure in the mine. The overbank sandstones are thinly bedded, as mentioned earlier, and commonly contain thin laminae of siltstone and mudstone. Delamination occurs readily at lithologic boundaries and along bedding planes, and large slabs of the overbank sandstone fall.

As with the type A falls, the sandstone slabs of type B falls most commonly fall away at the time of mining, before the roof can be bolted. After the coal has been removed from beneath the overbank sandstone, the roof begins to sag and sandstone slabs delaminate and fall away. Occasionally, however, serious roof falls occur after the roof has been bolted. The same process of sagging and delamination results in slabs delaminating and falling away around roof bolts (Figure 3). It is also not uncommon for delamination to occur above the roof bolted interval. In this case, large slabs, up to 2 m thick, containing numerous rows of roof bolts may fall. Large falls such as these are quite unpredictable and hazardous.

It should be noted that the number of large roof falls related to overbank sandstones increases with increasing overburden thickness. A high percentage of type B roof falls shown in Figure 2 are located under overburden which approaches and exceeds 600 m (2,000 ft) thick. In this setting, sagging of the roof is common and delamination readily occurs.

The most hazardous situation that exists with the overbank sandstone deposits occurs when roof bolts do not extend through the entire overbank sandstone interval. When this happens, delamination occurs above the roof bolts and the entire bolted sequence falls. To avoid this situation, roof lithologies should be carefully mapped and measured as mining advances underneath the overbank deposits. As long as the entire overbank sandstone sequence is included within the roof bolted interval, major type B falls will not likely occur; but if the overbank sandstone sequence extends above the roof bolts, further measures should be taken to support the roof.

Type C Roof Falls - Type C roof falls occur in the overbank siltstone which immediately overlies the Sub-3 seam in the mine area. These falls occur where residual stress release fractures form in the siltstone due to differential compaction beneath channel-fill sandstone bodies, or where extensional fractures form due to sagging of overlying overbank sandstone beds. In both instances, closely spaced, parallel, concentric fractures form in the siltstone, and blocks of siltstone delaminate and fall away between roof bolts at the siltstone/sandstone boundary (Figure 3).

Falls of this nature are relatively minor and commonly occur in combination with other roof fall types (Figure 2). They do, nevertheless, represent an unsafe roof condition and must be closely monitored.

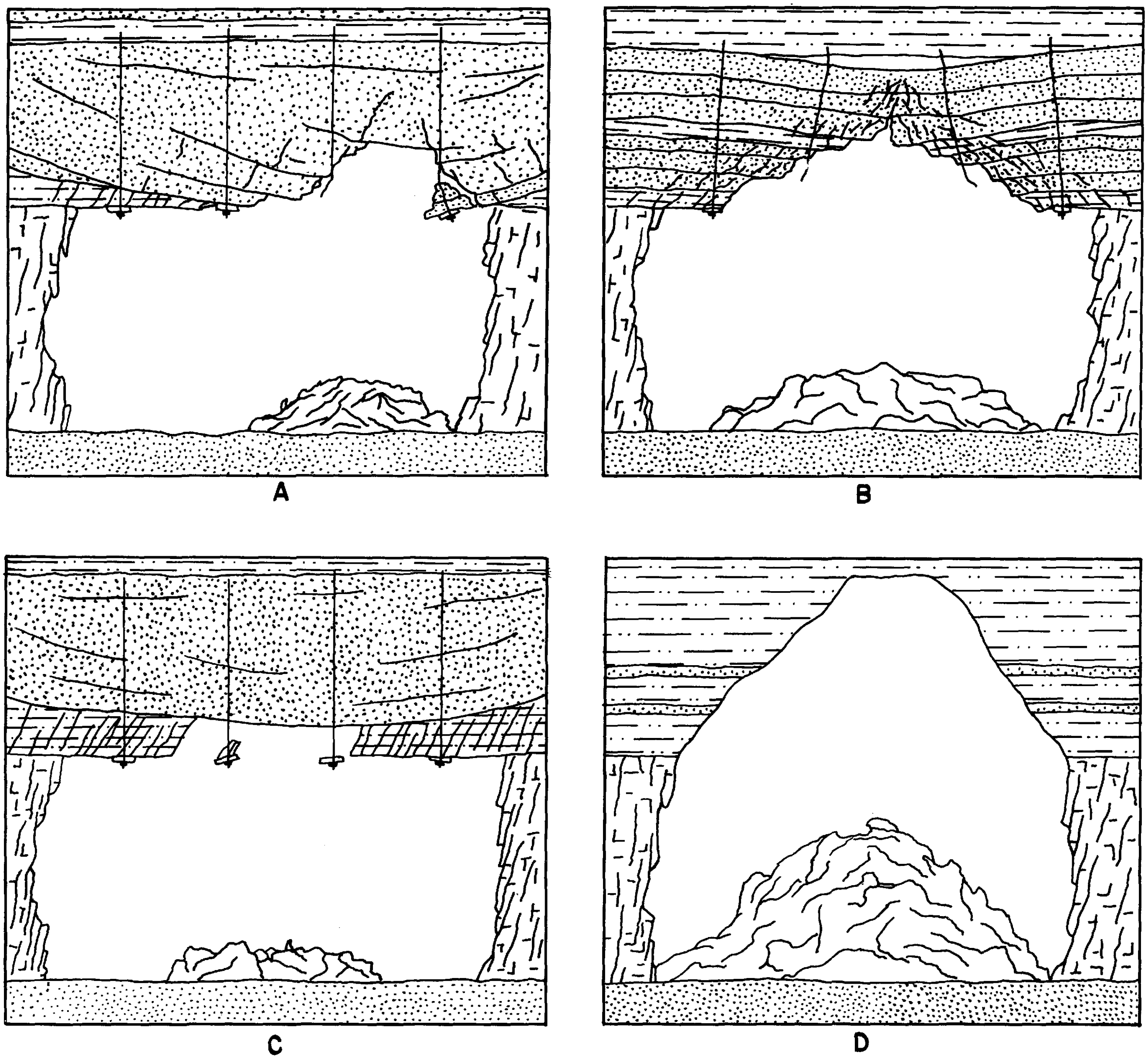

Figure 3. Roof failures in the studied mine, types A through D.

The fractures generally form within a few days of initial mining, and roof conditions worsen until type C falls begin to occur. If roof conditions are carefully monitored, unstable siltstone blocks can be pried down. It should be noted that type C roof falls are often the forerunner of type A and B falls, and measures should be taken to properly stabilize such areas.

Type D Roof Falls - Type D roof falls include all roof falls which do not appear to be related to any specific depositional regime in the mine roof. These falls have a characteristic dome or "cathedral" shape, and most commonly occur at intersections (Figure 3).

The cause of type D falls is uncertain. Only five such falls were observed in the mine, and those which have occurred in the westernmost portion of the mine could be related to stresses involved in the advancement of an overlying coal mine (Figure 2). It appears that others may be related to extreme variations in the overlying topographic relief or to topographic unloading.

Type D roof falls are extremely hazardous and are as yet very unpredictable. These dome-shaped falls seem to occur without warning and they commonly extend upward to over 8 m into the roof. No obvious fractures or indications of stress are present, and they occur regardless of roof lithology or stratification of beds. Excessive stress fields in the vicinity of the intersections undoubtedly exist, and much more study is needed to ascertain the exact cause of these roof failures.

SUMMARY AND CONCLUSION

Three distinct depositional environments are represented in the studied mine roof, and each affects roof conditions somewhat differently. These depositional environments include: channel-fill sandstone deposits; overbank deposits of siltstone, sandstone, and minor mudstone; and swamp deposits of coal and carbonaceous mudstone. Unstable roof conditions are primarily associated with channel-fill sandstone bodies and the associated overbank deposits.

Four major types of roof failure have occurred within the mine, three of which are related to specific depositional regimes, and one which is caused by excessive stress fields in the vicinity of mine entries. These roof fall types include: 1) falls associated with channel-fill and sandstone lenses and caused by delamination along slickenside surfaces within the channel base, 2) falls associated with overbank sandstone deposits and caused by sagging and delamination along bedding planes, 3) falls associated with overbank siltstone deposits, due to residual stress release beneath paleochannel sandstone bodies, and extensional fracturing beneath overbank sandstone deposits, and 4) falls possibly caused by the advancement of an overlying coal mine or extreme variations in the overlying topographic relief.

By careful monitoring and mapping of roof strata as mining advances, an understanding of the depositional environments in the mine roof and their relationship to roof conditions can be gained. This understanding is vital to mine safety and production, and proper measures can be taken to stabilize various forms of unstable roof, especially in the long-term entries. Existing drill hole information can also be used to project expected mine roof conditions into proposed mining areas.

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EFFECT OF GEOLOGIC FEATURES ON UNDERGROUND COAL MINE PRODUCTIVITY

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INTRODUCTION

In many coal mining organizatons, there exists a gap between geologists and mining engineers. Such gaps generally developed because neither party has sufficient awareness of the concerns of others. The result is often an incomplete understanding of the geologic aspects of coal mine development which can lead to inappropriate mine design.

The information presented in this paper is intended to help "bridge the gap" between geologists and mining engineers by defining, discussing, and prioritizing the relative importance of various geologic parameters to underground coal mine development. Such information will be of particular use to exploration geologists who are often only marginally aware of the importance of certain geologic parameters to the development of underground coal deposits. It must be recognized, however, that the subject chosen is a very complex one, which can not be summarized easily. Therefore, this paper should be regarded only as an introduction to the subject.

GEOLOGIC PARAMETERS

The physical characteristics, or geologic aspects, of a coal deposit which is to be developed by underground mining methods play an important role in the success of a mining venture. Other parameters which are of similar importance include: 1) mine design, 2) operational considerations, 3) financial concerns, 4) mining equipment and systems, and 5) intangibles (Manula and Suboleski, 1981; Toth, 1981).

There are several methods by which the success of an underground mining operation can be measured. In this paper, productivity (in terms of output per man-shift or unit-shift) is used as a basis for discussing and rating the geologic parameters which effect the success of a mining venture.

The categories into which these geologic parameters can be broken are listed in Table 1. Some of the more important parameters are associated with the coal seam and immediately adjacent strata (Figure 1). The component parts of the elements listed in each category are discussed in the following sections of the paper:

Table 1. Geologic parameters which affect coal mine productivities

1. Coal seam characteristics: thickness, splits, and methane.
2. Roof conditions: competence, lithology, scours, and rider seams.
3. Floor conditions: competence, lithology, and moisture.
4. Structure: faults, fractures, inclinations, rolls, and cleats.
5. Enclosing strata: overburden, interburden, multiple seams, and hydrology.

COAL SEAM CHARACTERISTCS

Coal seam characteristics which have a critical influence on underground mine productivities

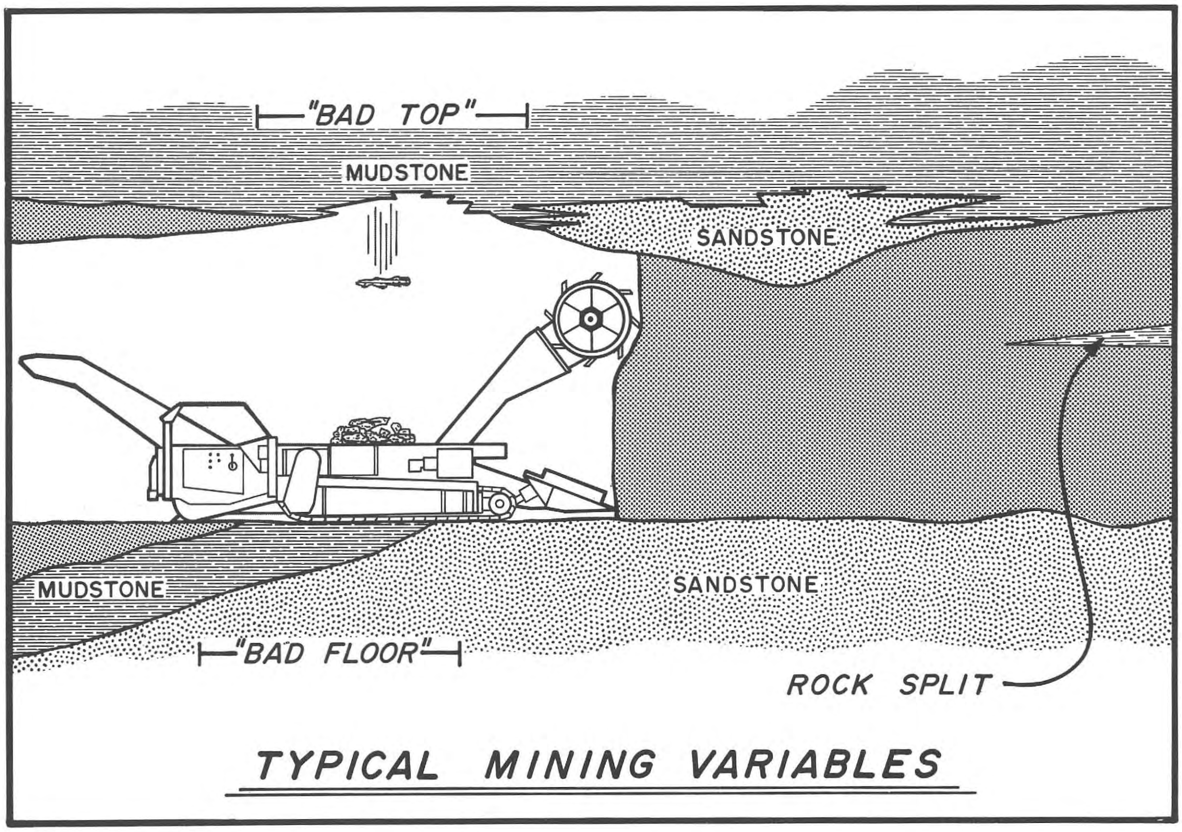

Figure 1. Geologic influences on underground coal mining (continuous miner for scale).

include: 1) seam thickness, 2) rock splits, and 3) methane emissions.

The thickness of a coal seam plays a major role in determining the minability of a deposit and the productivity of mining operations. Statistics for several dozen underground mines in the U. S. have been compiled by Toth (1981) and Manula and Suboleski (1981) which indicate that gradual decreases in productivities are associated with diminishing seam thickness. These and other data suggest a major decrease in productivity occurs for seam thickness below 6 ft. Presumably, the drop in productivity at that thickness is due to the change in types of mining equipment which must be used in thinner seams and the increased difficulty in working in an area which is less than standing height. This relationship appears to be more pronounced in the American West because of the industry's lack of experience in mining thin seams in that area.

Decreases in seam thickness also result in increases in the amount of out-of-seam dilution which is mined with the coal (Vaninetti et al, 1981). This is because the mining equipment operator has a tendency to gouge into the roof and floor rocks more often in thinner seams than in thicker sections when top and bottom coal can be left in place. Other things being equal, dilution from the roof and floor strata is likely to be the same for most seam thicknesses, but forms a higher proportion of the raw coal from a thinner seam.

Rock splits also reduce productivity. This is because the rate of mining advance must be slowed to permit the cutting of rock, which is generally much harder and more difficult to cut than coal. Generally, the thicker the rock split, the greater the loss in productivity. Rock splits which range to a foot in thickness are commonly mined with the coal, unless quality concerns preclude this practice. Rock splits greater than one foot thick are commonly avoided by mining the coal beneath and shooting the rock split, or by ramping on top of the split and mining only the coal above. This is only possible in thick coal beds. Room and pillar operations which use continuous miners, as well as longwall faces, cannot mine rock splits separately on a regular basis. On the other hand room and pillar operations utilizing cutting, drilling, blasting and loading (conventional mining) can mine some rock splits separately and effectively.

High rates of methane emission can seriously reduce productivity levels. The danger of explosion and concentration of non-oxygenated gasses in mines where methane emissions are excessive requires the institution of eleborate and time-consuming methods to ventilate working sections which result in decreased productivities. Mining equipment designed to shut down automatically at a pre-determined percentage methane may be idle a high percentage of the the time in a very gassy seam

ROOF CHARACTERISTICS

The character of the strata which immediately overlies a coal seam determines the severity of roof control problems in underground coal mining operations. Roof characteristics which are of concern include: 1) competence, 2) lithology, 3) scours, and 4) rider seams.

The competence, or degree of coherence, of the strata close to the top of a coal seam affects mine productivities. The thickness of roof strata which affects conditions varies depending on seam thickness, mining of other seams, overburden depth and method of mining. Strata within 6 ft of the seam worked is usually critical. Strata up to 40 ft or more will affect roof conditions where caving is practiced. If roof materials are poorly consolidated or incompetent, eleborate and time-consuming efforts must be undertaken to support the roof. Time spent compensating for the instability of roof strata reduces and interfers with the time which could be spent in mining coal. A weak roof will cause serious problems in maintaining permanent roadways and may reduce the width at which entries can be driven. On the other hand, a very strong roof which does not cave regularly, may cause serious problems in longwall mining or pillar extraction.

The lithologies present in roof strata determine, in part, the competence of the roof. Roof strata which consists of interbedded siltstone, sandstone, and mudstone which was deposited along ancient channel margins have been found to be particularly unstable due to differential compaction effects (Mercier and Lloyd, 1981; Vaninetti et al, 1981; Horne et al, 1978). An example of the relationship between channel margin lithologies and roof falls is shown in Figure 2. As noted in the previous paragraph, roof control efforts result in decreased time available for mining coal and decreased productivities. Roof lithologies can be grouped into the following genetic categories: 1) channel sandstones, 2) channel margin interbeds, and 3) overbank mudstones.

Scours, wants, or washouts in coal seams cause decreases in mine productivity due to the disruption of mining operations once these features are encountered. Detailed geologic analysis of outcrops and drill hole data from closely-spaced holes are required to allow the prediction of the paleochannels which are responsible for scours. Drill holes completed on 400 ft centers were required to predict the channel systems in which scours are likely to occur which are depicted on Figure 2. Scours can be classified on the basis of the amount of coal which remains under the scour and lateral dimensions (small, medium, and large).

Rider seams are thin coal seams in the roof strata. They provide planes of weakness for rock separations and may be poor anchor horizons for some roof bolts. As such, rider seams sometimes are responsible for unstable roof conditions

FLOOR CONDITIONS

The character of the strata which is located immediately below the base of a coal seam influences the mobility of men and mining equipment throughout an underground coal mine. Floor conditions are influenced by the 1) competence, 2) lithlogy, and 3) moisture level of the strata which immediately underlies a coal seam. All these factors are closely interrelated.

Productivity losses due to floor conditions are usually associated with wet, muddy, or soft floors where the mobility of men and equipment is constrained. Inferior floor conditions usually develop in areas where mining from rock-to-rock is practiced and mudstone in the underlying strata is exposed to water. In areas where seam thicknesses are such that bottom coal can be left in place, the floor rocks are not exposed and do not have the opportunity to deteriorate (Figure 1). An added negative feature of muddy and wet floors is the unavoidable contamination that occurs as bottom muds are incorporated into the mined coal.

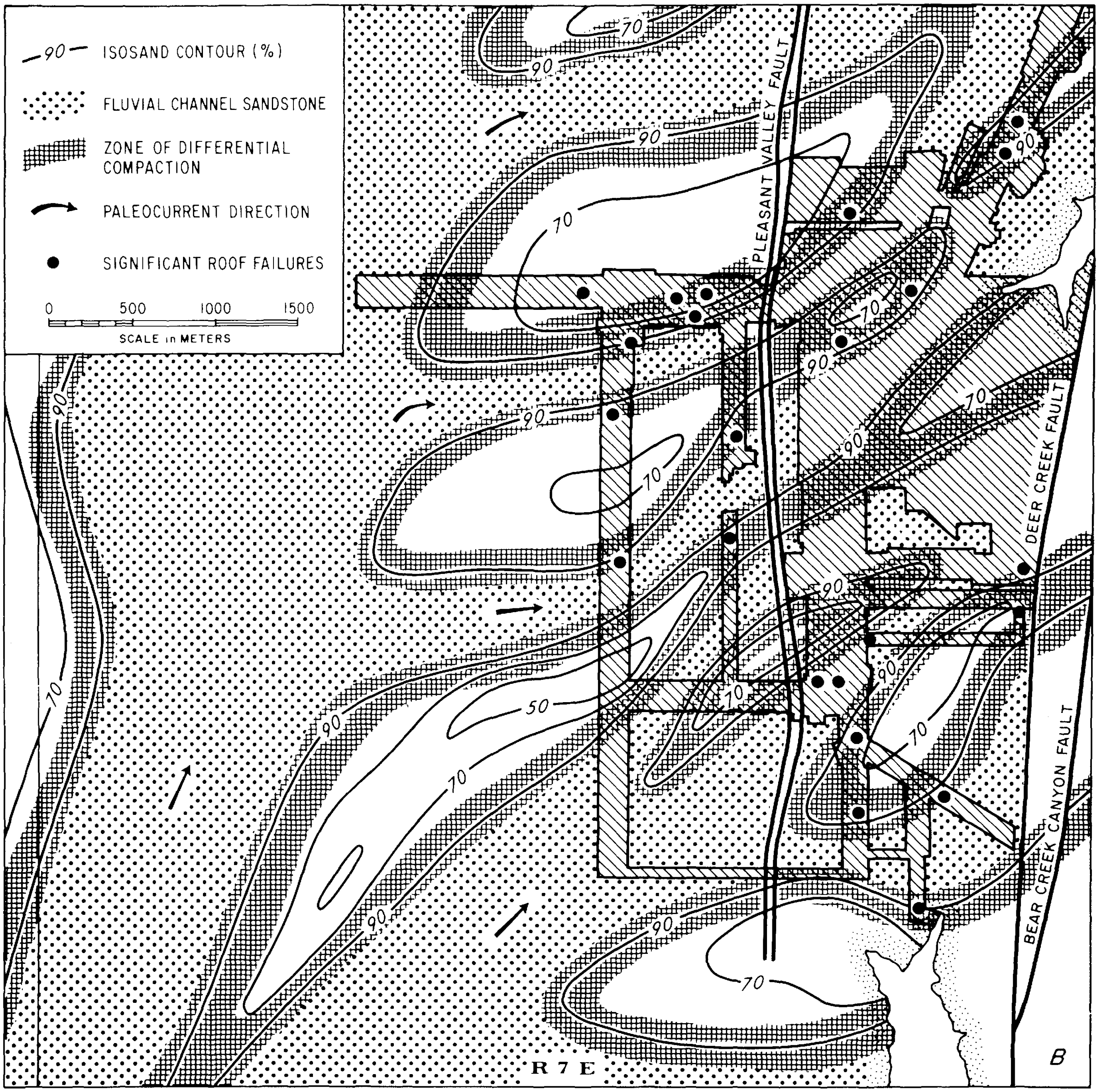

Figure 2. Roof lithology map showing location of roof falls (from Mercier and Lloyd, 1981).

The lithology of the strata which is immediately beneath a minable coal seam affects productivity when the floor rocks are exposed. Mudstones have a tendency to decompose more readily than sandstones or interbedded materials, particularly when water is present (Figure 1). Floor lithologies can be classified as sandstone, interbeds, or mudstone (fire-clays).

STRUCTURE

The structural characteristics of a coal deposit are of particular importance in determining the productivities associated with underground development. Structural features which are of major significance include: 1) faults, 2) fractures, 3) inclinations, 4) rolls, and 5) cleats.

The spacing, frequency, displacements, gouge, and inclination of faults all affect the development of an underground mine plan and associated productivities. Faults must be crossed in order to access different portions of a reserve and the time spent in determining fault displacements and constructing ramps to intersect a seam on the other side of a fault diverts efforts away from coal mining efforts. Such ramps are commonly bottlenecks to the movement of men, materials, and coal production. In some instances where fault displacements are less than seam thickness, ramping requirements are less disruptive to production activities. In addition, roof conditions are commonly unstable in a narrow zone which parallels the strike of faults.

Major faults, or rolls, can seriously disrupt a transportation system. Belt conveyors for example will operate effectively up to 17°. If a drivage through a fault exceeds this pitch the conveyor cannot be extended. Similar problems occur for trackless or rail transportation.

Fractures in the strata which enclose coal seams are of concern in developing mining plans that will result in efficient mining practice. The orientation and spacing of fractures is of major importance in determining mining techniques and the orientation of mine workings. Fractures which parallel main entries are not supported by remaining coal pillars and roof falls can be localized along them as the ground adjusts to weight and stress redistributions during mining. In the case of main entry development and/or room-and-pillar mining, fractures can result in unstable roof conditions. In the case of longwall mining, fractures in normally competent roof strata, such as sandstone, can result in much better caving characteristics than would normally be expected. Fractures must be evaluated differently for different techniques and the orientation of mine workings. Fractures should be classified in terms of orientation to entries (oblique, parallel, or perpendicular) and spacing (close, moderate, or wide) for longwall and room-and-pillar operations.

The inclination, gradient, grade, or dip of coal seams imparts a major influence in underground mine productivities. The more steeply dipping the coal seam, the less appropriate are conventional mine designs and equipment configurations which, in turn, result in decreased productivities. For example a continuous miner shuttle car system can, in dry floor conditions, operate at gradients up to 17°. Beyond this it is technically possible to operate if entries are driven at an angle to the full dip. However, side pitch becomes a problem and so does sumping in the machines. Gradients also affect caving of extraction areas since the weight tends to move to the dip side of the gob. Longwall mining is technically feasible at gradients beyond 17°. Special equipment is needed and productivity may be reduced. In thick soft seams of coal hydraulic mining may be considered when the gradient exceeds 10°.

Rolls are small-scale folds in the coal seam and enclosing strata which form in response to differentially compacted sandstone which is pushed into the coal seam during compaction. Rolls result in local readjustments of grade and the concentration of water in low portions of the mine. Such features interrupt the normal structural conditions within a mine and can sometimes result in decreased productivities. Rolls are generally associated with paleochannel sandstones in the roof stratum and as a consequence, can be predicted from maps such as the one shown in Figure 2.

Cleats or fractures in the coal generally consist of two main orientations normal to one another. The main cleat is known as the face cleat and the less well-developed cleat is referred to as the butt cleat. The angle at which mine cutting equipment approaches a cleat determines the ease with which the coal is cut from the face. An oblique approach to cleat orientations generally results in more difficulty in breaking the coal from the face and as a consequence, productivities are decreased. One generally attempts to approach the face cleat perpendicularly in order to maximize cutting efficiency. Face cleats should be classified on the basis of orientation to mine entries: 1) oblique, 2) parallel, or 3) perpendicular.

Cleats are particularly important in thick coal seams. If the cleats are prominent then strata pressure on the coal face often results in slabbing. This can seriously affect productivity on a longwall operation due to difficulities in clearing the large slabs of coal. The stability of entries or faces can be seriously reduced by slabbing.

ENCLOSING STRATA

The last category of geologic features which influences underground coal mine productivities includes the following elements: 1) overburden, 2) interburden between seams, 3) multiple soal seams, and 4) hydrology. These elements are diverse in nature, but all affect mine development from outside of the immediate mining area.

The thickness of overburden plays a major role in underground coal mine development and associated productivities. The greater the thickness of overburden, the greater the difficulty in supporting overlying strata. Again, as is the case with the other geologic features which affect roof stability, the more problems experienced with roof support the greater the losses in productivity. Experience in the underground mines of Utah indicates that strata support problems due to overburden pressure become critical at a thickness of 1,500 ft. Minimal amounts of overburden also affect the caving characteristics of longwall-mined areas to the point where caving characteristics are difficult to predict. In a general sense, longwall mining is more appropriate for deeper mines and may even be the only practicable method of mining safety and efficiently. Room and pillar is more applicable to shallower mines.

The thickness of the interburden between coal seams determines whether both seams are minable. In ideal circumstances, it is best to have about 300 ft of interburden between seams (Stemple, 1956). However, mining is commonly practiced in several seams where the interburden reaches a minimum of 35 ft thick. As one mines in coal seams where the interburden decreases from 300 to 35 ft, there is a progressive increase in operational and strata support problems which are ultimately reflected in productivity values (Stemple, 1956). The major problem associated with thin interburden is that non-uniform weight distributions which develop as an upper seam is mined can be transmitted to the strata below which forms the roof of the lower seams. Mining in the lower seam is then affected by unpredictable stress distributions in the immediate roof which have been transmitted from overlying strata. The severity of these problems tend to be somewhat diminished in longwall mining operations where overlying strata are homogenized by complete extraction and roof characteristics are not quite as important.

The number of superimposed seams to be mined in a given deposit affects the productivity attained throughout the mining operation. Several of the comments presented in the preceding paragraph regarding the weight interactions between superimposed seams apply to multi-seam deposits where several seams are of minable thickness. The more seams that are to be mined, the more effort must be exerted in engineering and mining to minimize weight interactions for the lower seams. Efforts to exactly superimpose pillars in main entries, and either superimpose or offset gate entries in longwall panels to minimize weight interactions, require substanial engineering, surveying, and supervisory control.

The hydrology of a coal deposit to be developed by underground mining techniques influences the productivity of the mining operation. Water is introduced into mining operations from the coal seam itself, immediately adjacent water-saturated strata, and roof strata that is fractured during the mining process. The impact of water introduced into the mining operation when mudstone floors are present has been discussed previously. Additional impacts include the ponding of water in the low points of main haulageways and at the face of dip drivages. If water inflows are substantial, extensive pumping and piping systems must be installed to collect and distribute the water to areas where water can be disposed of. In pitching seams the affect of water accumulations on drivages advancing to the dip can be very serious indeed. In these conditions, the rate of development of low side reserves can be very seriously reduced.

SUMMARY

Underground coal mine productivities are affected, to varying degrees, by the 19 geologic features described in the preceding sections of this paper. To give the exploration geologist an appreciation for the relative importance and influence of each feature, it is useful to estimate the relative productivity decrease from ideal conditions which can be associated with the individual categories for each geologic parameter.

Table 2 summarizes the relative order-of-magnitude productivity losses which can be attributable to the 19 geologic features described in terms of minor, moderate, and major losses. The critical values applicable to each category of productivity loss are shown for each geologic feature. The overall maximum potential productivity loss attributable to each geologic feature is summarized in Figure 3. The

MAJOR FEATURES	FEATURES	UNIT	POTENTIAL PRODUCTIVITY LOSS (PER MINING SECTION)		
			MINOR	MODERATE	MAJOR
COAL SEAM	SEAM THICKNESS	FEET	7.5–9.0	6.0–7.5	< 6.0
	ROCK SPLITS	FEET	< 0.5	0.5–1.0	> 1.0
	METHANE	CU. FT./TON	200–400	400–800	> 800
ROOF STRATA	COMPETENCE		MODERATELY COMPETENT		INCOMPETENT
	LITHOLOGY		CHANNEL MARGIN INTERBEDS		
	SCOURS	SIZE	SMALL	MEDIUM	LARGE
	RIDER SEAMS		WITHIN THE IMMEDIATE ROOF		
FLOOR STRATA	COMPETENCE		MODERATE	INCOMPETENT	
	LITHOLOGY		INTERBEDS	MUDSTONE	
	MOISTURE		DAMP	WET	
STRUCTURE	FAULTS	DISPLACEMENT	QUARTER SEAM	HALF SEAM	≥ FULL SEAM
	FRACTURES	ORIENTATION[1]	OBLIQUE	PARALLEL OR PERPENDICULAR	
	FRACTURES	SPACING	WIDE	MODERATE TO CLOSE	
	INCLINATION	DIP	5–10	10–17	> 17
	ROLLS		MODERATE	SEVERE	
	CLEATS	ORIENTATION[2]	OBLIQUE		
ENCLOSING STRATA	OVERBURDEN	FEET	800–1200	1200–1500	> 1500
	INTERBURDEN	FEET	100–200	50–100	< 50
	MULTIPLE SEAMS	NUMBER	TWO	MORE THAN TWO	
	HYDROLOGY		DAMP	WET	

NOTES:

1–Orientation with respect to main entries

2–Orientation with respect to direction of cutting

Table 2. Relative comparison of productivity losses due to geologic features.

diagram indicates the degree of severity within the three major categories of productivity losses.

Estimates of potential productivity losses from ideal conditions are extremely difficult to define inasmuch as numerous other non-geologic factors influence each individual operation. Some of these factors include mine design, operational considerations, financial concerns, adequacy of mining equipment and morale of the workforce. In practice many geological factors interact with each other in a way which can not be accounted for in this paper. However, it is hoped that the estimates presented in Table 2 and Figure 3 will provide a general understanding of the degree of importance of various geologic features. By so doing, it is hoped that exploration geologists will recognize the need to document the detailed characteristics of the geologic features which affect underground coal mine development.

ACKNOWLEDGEMENTS

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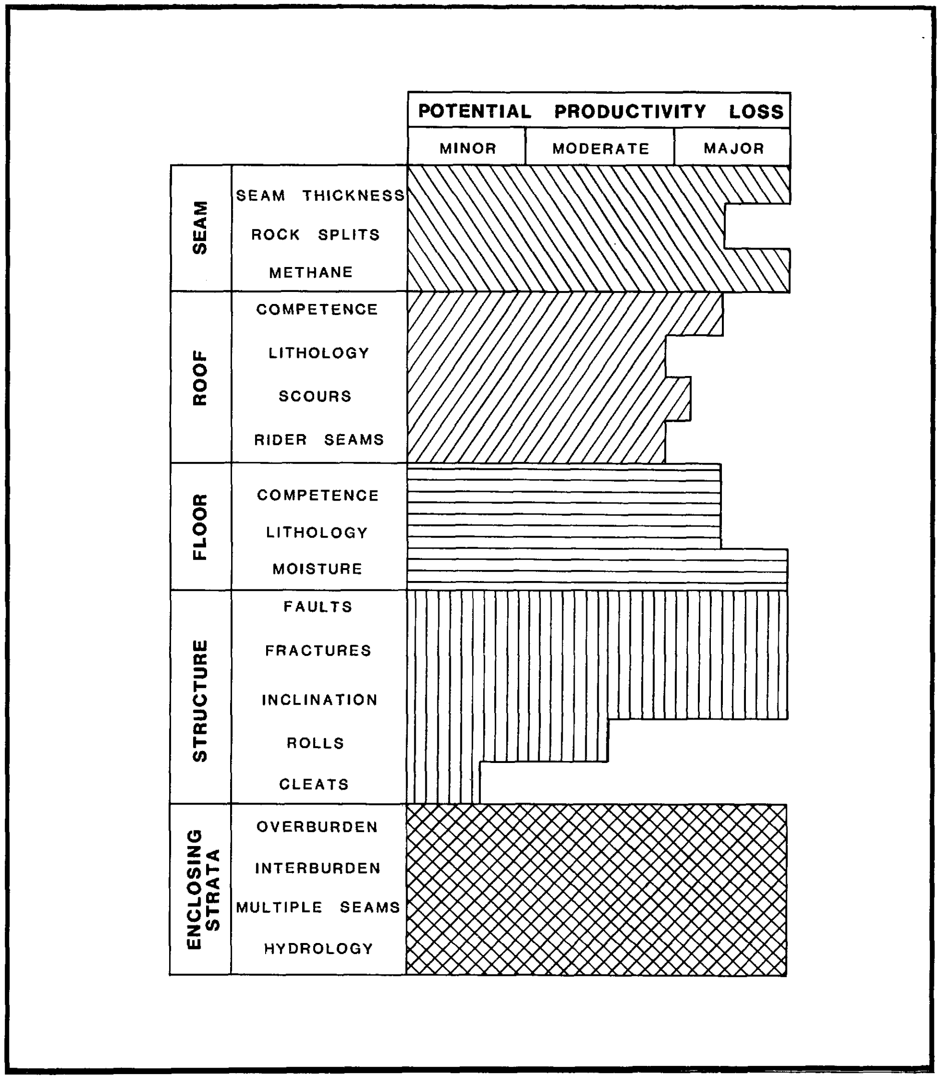

Figure 3. Maximum potential productivity losses for geologic features.

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THE COAL GEOLOGIST'S ROLE IN UNDERGROUND COAL MINE SAFETY

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INTRODUCTION

Safety standards and performances of underground coal mines in the United States have improved significantly over the last two decades. Some factors which have contributed to this improvement include:

1. adoption of improved training and awareness programs;
2. use of more efficient mining methods;
3. improved design of mining equipment;
4. greater understanding and application of advanced mining techinques.

In spite of this improvement there is one aspect of mine safety which, in the opinion of the authors, needs greater recognition. This is the significant role which the coal geologists can play in collecting information to be used in planning a safe mining operation. This information can be collected during exploration programs, from development drivages and from operating mines.

It is not the purpose of this brief paper to transform geologists into mine safety engineers; instead we wish to:

1. discuss how a geologist should fit into a team of professionals charged with the responsibilty of developing a safe and efficient mine; and
2. highlight some of the material and data which can be collected by the geolgist which will then be utilized to improve safety in the mine.

THE ROLE OF THE GEOLOGIST

Understanding mining engineering - Clearly the geologist who has a basic knowledge of mine engineering is better able to assist the project team with information. However, all of us in industry have met the geologist who considers himself an expert miner and the engineer who feels he has solved the mysteries of geology. Both these individuals can wreak a particularly damaging form of havoc, if left to their own devices. The authors believe that it is essential for the coal geologist to have an understanding of the basics of mining engineering. However, it is equally important for the geologist to involve the mining engineer in the exploration program from an early stage.

Any significant exploration program should be discussed with the mining engineer *before* field work commences. The engineer's involvement should also include advising on the preparation of the geological report and the representation of the data. After all, the next stage of any project is the completion of a feasibility study utilizing this geological report. As consultants and mining engineers it has been our experience that more than half of the geological studies we have been given to work with have required considerable modification before the material is in a form the mining engineer can utilize.

The geologist as a member of the project team - The successful mine geologist must be able to develop a relationship with mine supervisors and workmen which allows him to observe the underground operation regularly, discuss their work and conditions, and gain their confidence. A surprising quantity of useful data will be collected from his mine visits.

The relationship will work both ways. The geologist's observations of fracturing, jointing, lensing of roof strata, changes in sediments, etc. may be useful to the face men. However, he will have to learn to use mining language rather than geological jargon. He must work hard on developing his relationship with the miners, recognizing that the experienced face worker is often an observant amateur geologist.

In the long run the success or failure of the mine geologists will depend on involvement - The geologist who shuns involvement in the mining operation, who avoids any situation requiring predictions or interpretation of the features exposed by mining operations, will never be much use to the project. To be successful, the geologist must, paradoxically, take the risk of being proved wrong.

COLLECTION AND UTILIZATION OF DATA FROM EXPLORATION OR DEVELOPMENT

Adequacy of Data - Most geologists and mining engineers have been involved, at some time, in planning mines using inadequate data. Sometimes this occurs because funds are not made available, a false economy in many cases given the capital required for a modern mine. Often the inadequacy occurs because the point of diminishing returns has been reached, particularly in exploration of geologically complex areas.

The authors do not intend to try and define how much data are adequate. That has to be judged for each individual property. Instead, they wish to point out the dangers of commencing underground mines with insufficient geological information.

Figure 1 illustrates what can happen if such a situation develops. This mine was opened in 1976. The rugged topography and depth of overburden encouraged the operator to cut off surface exploration after a sparse drilling program had been completed. Underground drivages were utilized to provide additonal data, normal practice in complex geology. Fourteen drill holes had been completed for a reserve area measuring 5,000 x 2,500 ft. The holes were drilled on an 800 to 1,000 grid in the shallow half of the reserve; only two holes were drilled in the deeper half. The area was structurally complex, with steep gradients forming the boundaries of the reserve block. Continuous miners were capable of achieving economic production levels of over 280 tons/unit at gradients up to 17°. An important feature of the area was the very low strength of the coal in this 24 ft thick seam.

A decision was taken to commence development and Figure 1A shows drivages completed in 1976 and 1977. Three entry panels were driven to the N.E. and South. When gradients over 17° were encountered in the South, and a washout in the N.E., the width of the reserve block had been defined. Three entry panels were then advanced along the reserve boundaries and through the center of the block (1 East, 2 East, and 4 East). During 1978, depillaring commenced in all three panels and an additional panel was developed (3 East).

During 1979 an additional panel was developed (6 East) and extensive depillaring continued on three sides of the remaining reserve. Conditions deteriorated rapidly as widespread sloughing of pillars and separation of roof beds occurred, making pillar recovery extremely difficult. During early 1980, conditions deteriorated still further and, in February, a massive rock fall killed four men in a depillaring section of 6 East.

There were many reasons for the accident and the conditions leading to it. One major factor was the inadequate surface exploration program leading to an *excessive* reliance on widespread underground exploration in a friable coal seam. These drivages then deteriorated and were depillared, creating a very hazardous situation with an overdeveloped central reserve surrounded by caved areas on three sides.

The authors recognize that underground exploration is necessary and desirable to supplement surface exploration. The more complex the area, the greater the dependency on underground drivages. This must not be used as an excuse to stop surface exploration before sufficient data have been collected. Nor should the exploration drivages be so widespread as to disrupt good mining practices. Design of pillar sizes and entry widths is just as important in an exploration drivage as in a main entry panel.

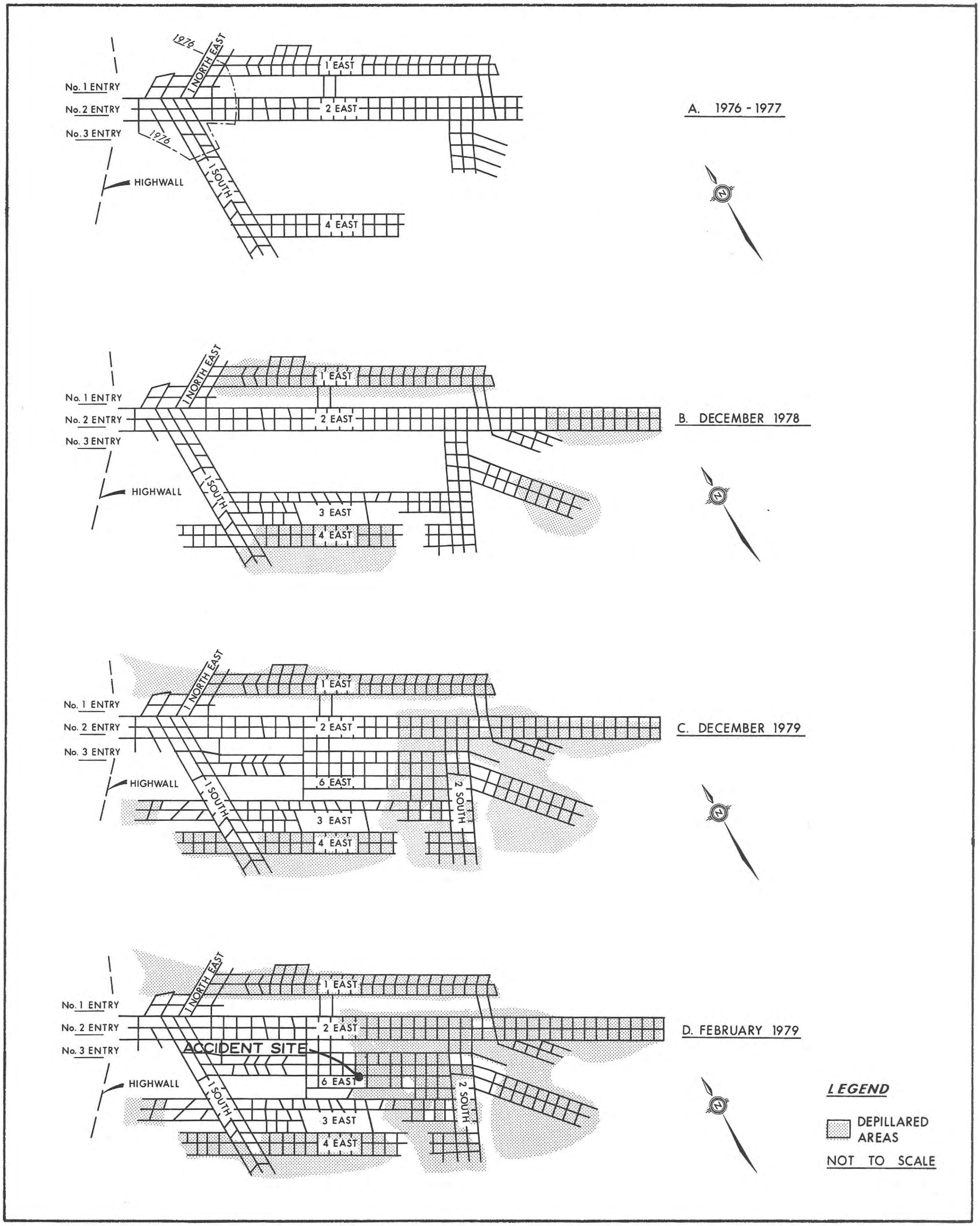


Figure 1. Development and depillaring.

Strata Control - Core samples and geophysical logs provide information for design of mining method or strata control program. Information on the roof strata is needed to determine:

1. type and dimensions of rock bolts required, anchorage efficiency of mechanical bolts in various strata etc;
2. the need for joists, mats, mesh or posts;
3. the "caveability" of the strata;
4. spacing of supports;
5. dimensions of entries;
6. safe methods of pillar recovery;
7. weathering characteristics of the roof.

Information on the underlying strata is needed to determine:

1. weathering characteristics;
2. influence of water;
3. resistance to wear and tear from tackless haulage systems;
4. bearing strength as a base for supports.

Geological/geotechnical properties considered important in strata control include, among others:

1. jointing and cleating (frequency and directions);
2. faulting and folding;
3. gradients;
4. weathering characteristics;
5. mechanical strength measured in various ways;
6. grain size and composition of strata;
7. thickness of individual rock beds.

The author's experience with core collected from exploration programs has not always been satisfactory. In almost half of the cases where the exploration program has already been completed before our advice was taken, the cores have been inadequate. Either insufficient core has been taken or the samples have been allowed to weather, and have become useless for geotechnical testing or detailed visual examintion. It is surprising, considering the high costs of exploration, how often the end product is handled carelessly.

One additional comment on strata in relation to mining methods needs to be made. The proportion of coal produced from longwall operations in the United States has been slowly but steadily increasing in the last 15 years. In spite of the high capital investment and the comparative lack of flexibility when compared to room and pillar, more and more operations are considering longwall extraction. While final decisions on the mining method will always be based on economics, the safety standards of the two systems are a serious factor in the comparison and may make or break the project economically.

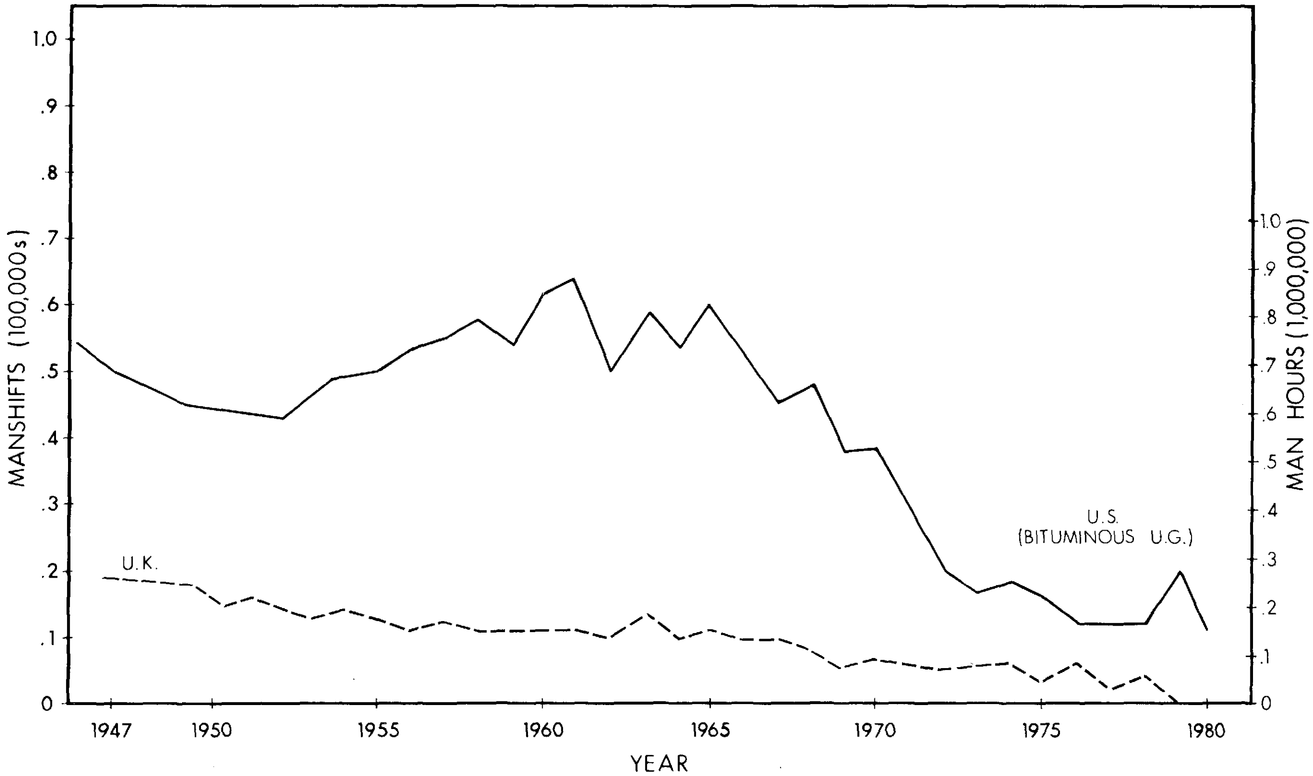
Longwall operations are relatively inflexible. There is less need for the miner or supervisor to make on-the-spot decisions. In room and pillar, such decisions are frequently required. Inevitably the wrong decision will, on occasion, be made, sometimes resulting in an accident.

Strata control on longwall faces is much more positive than in pillar extraction. The caving line is straight and no stumps are left to transfer weight to the face area. Men are protected by hydraulic supports which provide almost 100 percent coverage of the roof, floor, and gob.

The authors do not have data which prove conclusively that longwall mining is safer than room and pillar. They believe that this is generally true; however, each case must be judged separately. Some statistics are available which *indicate* that longwall has the better safety record; these are shown in Figure 2.

The fatality figures cover the period 1947 to 1980 and are based on exposure, not on production. Since most fatalities due to falls of ground occur at the face, the statistics do essentially compare the predominant mining systems in the two countries; longwall in the U.K., room and pillar in the U.S. There are of course other factors. In the U.S. the coal industry is privately owned, in the U.K. it is almost entirely nationalized. Conditions are also different. Advancing longwall using single entries under deep cover is predominant in the U.K. In the U.S. underground mines operate at shallower depths and the strata is stronger, containing a greater proportion of sandstone beds. However, in the auhtor's opinion, the graph provides a strong *indication* that longwall mining is *generally* safer than room and pillar.

Why is this important to the coal geologist? For three principal reasons:



FOR THE U.S. (BITUMINOUS UNDERGROUND ONLY)
1951 - 1970 150 FATALITIES/YEAR ($0.715/10^6$ M.H.)
1971 - 1980 46 FATALITIES/YEAR ($0.244/10^6$ M.H.)

Reproduced from: Marovelli, R. L., 1981, A comparison of American safety performance to other countries, Mining Congress Journal, August issue.

Figure 2. U.S.-U.K. Fatality rates for falls of ground in coal mines.

1. Longwall mining requires a more detailed knowledge of the geology than room and pillar before a go-ahead decision is taken.
2. The information required is different. For example, strong massive beds in the roof become a problem in longwall, not an advantage. Depth of cover is less important, and the strength of the floor takes on an added significance.
3. Exploration and development of longwall operations requires closer co-ordination between the geologist and the mining engineer, together with an understanding of the role that each disipline plays.

Heatings and Fires - The susceptibility of a mine to spontaneous combustion can be *very generally* assessed using the "RASCAL" system (Rapid Appraisal of Spontaneous Combustion Assessed Liability) (P.D.-N.C.B. Consultants, 1978). Factors taken into account include:

1. The rank of the coal, specifically its oxygen content;
2. presence of pyritic sulphur;
3. coal hardness;
4. humidity of the ventilating air;
5. strata temperature;
6. thickness of roof coal left in place.

Each of the above properties are valued and weighted to arrive at a risk factor.

However, the formula does not take into account other factors which influence susceptibility, *some* of which can be identified by the geologist. They are:

1. Mining of adjacent seams and fracturing between them;
2. floor coal left in place;
3. presence of exinite and vitrainite;
4. thermal conductivity of the coal;

5. high ventilating pressures.

The geologist should be aware of the importance of these factors, and ensure that his exploration program includes collection of the data for a risk assessment.

It is difficult to suggest how the mine geologist can play a part in preventing open fires (as opposed to heatings) other than by refraining from using what the Mine Safety Act refers to as "Smoking Materials" in the mine.

Methane emissions - The geologist should be aware of the methods commonly used to predict emission rates for a coal seam, since this will be a very important factor in ventilation planning. One of these, the direct (Cherchar) method, can utilize samples taken from the solid coal seam or from a drill core (Bertard et al, 1970). The U.S. Bureau of Mines has developed a direct system specifically designed to utilize cores obtained by vertical drilling (Deul et al, 1975). Both systems allow for methane lost between coring and sealing of the sample.

An indirect method of measuring gas emissions utilizes an exploration borehole after the core has been removed. The coal zone is sealed and the gas pressures in the seam are recorded. The pressure recorded is related to gas content by means of a family of empirical curves.

Methane drainage may be neccessary where high emissions are expected. In this case, a knowledge of the strata above and below the seam to be mined takes on a special significance. To illustrate this, an extreme example is provided. At Yorkshire Main colliery in England a longwall face was swamped by a sudden emission of methane at the rate of 4 million cu. ft. per day. This occurred despite the fact that a cross measure borehole drainage system, using 200 ft long up holes and 100 ft down holes, was in use. The emission resulted in a 25 percent content in the return airway from the face. Subsequent investigation showed a gassy coal bed above the seam being mined, just beyond the range of the cross measure boreholes. A better knowledge of the geology could have prevented this occurrence.

The mine geologist should be on the lookout for sources of methane such as other coal seams or porous beds of rock. This is particularly important when they are separated from the workings by impermeable beds which may be fractured by mining.

Historical Data - It is surprising how much information on mining conditions can be obtained from plans of other mines in adjacent reserves, even when the operations themselves have been abandoned and are inaccessible. The direction of main entries provides information on gradients. Faults, if not marked, can be detected by kinks in haulage roads driven at a favorable gradient for drainage and haulage. The size of pillars and width of rooms and entries give an indication of strata conditions.

Old reports, even recollections of the old timers, can be very useful. It is, surprising how much the experienced miner can recall until one remembers that, in those days, men spent long periods in the same mine and workings advanced relatively slowly. Since mechanization was non-existent or limited, geological conditions were much more important to the miner who had to undercut, drill, and load coal by hand.

The safe mine - The only *completely* safe coal mine is one which has been closed and the entrances sealed. With the best will in the world, the highest standards of training, the best equipment and first class engineering, accidents cannot be eliminated entirely.

Difficult conditions do not always result in the most hazardous mines. Complacency may be the worst hazard of all. For example, many explosions have occurred because employees have become accustomed to a mine environment clear of gas. Standards of gas detection, rock dusting, etc., are permitted to deteriorate. Then one day the unexpected happens, a small emission occurs and remains undetected until the gas is ignited.

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A COMPUTER ASSISTED LOGGING AND MAP PREPARATION SYSTEM UTILIZING THE THREE-DIGIT CODE CORE BOOK

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INTRODUCTION

The increase in demand for coal has produced challenges for sedimentary geologists that they have not previously encountered. First, although there is a general similarity between all sedimentary rocks, those that contain coal have properties that are in many ways unique. Secondly, the patterns of arrangement of these rocks, while similar to other sediments, have some peculiar characteristics that have direct bearing on the extraction and utilization of the coal. Finally, economically successful extraction of coal is highly demanding and the data used in preparing maps and cross sections must by highly organized, precise and capable of substantial manipulation.

The objective of this paper is to examine and compare alternative methods of data handling in coal exploration and development and to demonstrate a system of data handling that is more precise and rapid than some conventional methods. The topics to be treated are logging, data storage and retrieval of log data, and utilization of data in preparation of cross sections and maps.

LOGGING

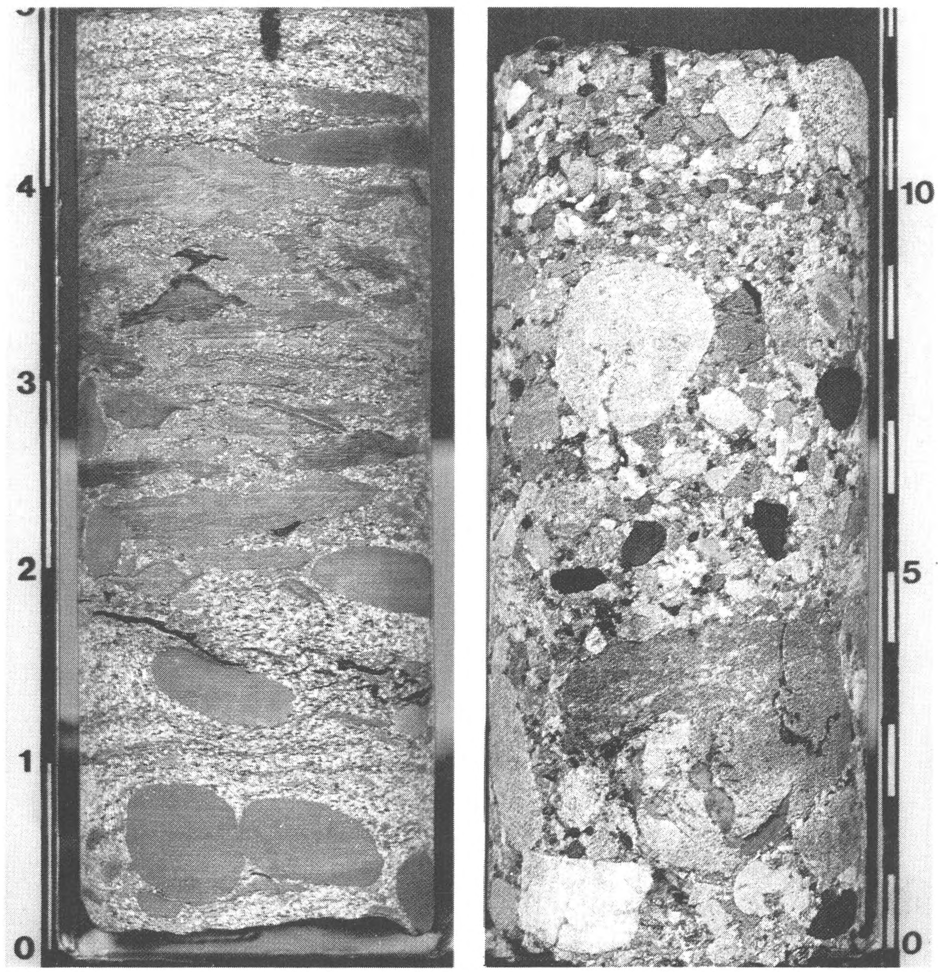
Most basic data in coal exploration and development are derived from bore holes from which rock and coal characteristics are obtained. In the western United States, these data are most frequently obtained by geophysical logging and supplemented by some coring. In the eastern United States, the opposite is true and most of the older logs were obtained from continuous coring. The subsequent discussion is based on the logging of continuous core but persons very familiar with geophysical logs could probably recognize analogous conditions.

There are two basic steps in logging core. The first is recognition of rock properties by the observer. The second is transmission of the information to a written record. The first step generally does not present serious problems; most drillers or engineers *see* rock properties or can be quickly trained to recognize them. Geologists are already trained in this respect and are often zealous in making such observations.

The main problem is one of transmitting observations to a written record that is precise, consistent, and concise; Table 1 illustrates this point.

Table 1. A comparison of typical drillers and geoligists logs of the same core (slightly modified from actual examples).

Drillers Log	Geologists Log
Gray sandstone........ 10'	Massive to moderately cross bedded sandstone. Medium to fine grained with slight reductions to very fine grained in the upper 6½ inches. Quarts content about 75 to 85 percent with some feldspars and abundant mica flakes........................ 10'
Dark gray sandy shale.................. 10'	Dark gray to very dark gray NRC 2-3 with some slight greenish brown tints in upper 1 feet. Grain size ranges from fine siltstone in the lowest 1½; through medium silt in the middle and coarse silt at the top.......... 10'



Gray Shale and Ironstone Pebble Conglomerate

(741)

Gray Rock Pebble Conglomerate

(745)

Figure 1. Sample page of photo core book illustrating format of illustration, rock name and rock code. Both rocks are conglomerates with a greywacke sand matrix but contain different kinds of pebbles.

The drillers log is concise but much of the detail is lost, The geologists log provides much more detail but this too is lost in long wordy sentences laced with terms such as "moderately" and "partly." And despite all of the detail, there is little parallelism in the descriptions, i.e., lots of bedding description in the sandstone but none for the sandy shale; detailed color in the sandy shale but none for the sandstone. This lack of parallelism in description can be avoided by using a check list entry form in which the logger is reminded of the properties that are to be noted.

Both the written or the check list methods suffer from the lack of recognition of the fact that rock properties are generally closely related, e.g., sandstones generally have more quartz than shales and that, for any given geographic region, the same *kinds* of rock are found over and over again. The operation of blindly recording the same properties time after time leads to an increasingly casual attitude toward descriptions. Evidence for this is found in logs of very long core holes in which descriptions such as those on the right of Table 1 evolve into those on the left.

The problems described above can be substantially reduced by building a rock classification in advance in which the rock classes embody most of the common sedimentary properties. Such a classification is given in Ferm and Smith (1981) and Ferm and Weisenfluh (1981)* in which the commonly occurring rocks of a region are illustrated by color, on a one to one scale photographs (Figure 1). Use of a standard system of this type, particularly when the rock types can be designated by numeric codes, vastly reduces the recording time, virtually eliminates fatigue and boredom associated with core logging, and at the same time, permits consistent reporting of most relevant attributes.

The major difficulty with such a system lies in the varying degree of detail desired by potential users. The manuals described above are the products of a number of experimental trials involving input from a number of potential users and represents a compromise between the amount of detail some users will tolerate and the lack of detail acceptable to others. Needs of specific users are taken into account by the system of recording. Those persons requiring only a general description can record only those characteristics that they require. For example, if the word sandstone is adequate for total description, then this single word or the general numeric code — "500" — is recorded. If more detail is required, additional terms can be recorded in the form of comments, e.g., a gray (i.e., graywacke) cross bedded sandstone with vertical fractures can be recorded as 541 VERT FRAC.

STORAGE OF BORE HOLE DATA

There are many alternative methods of storage, retrieval and utilization of bore hole data but the simplest and most expedient is the "one shot" approach in which coal thicknessess are taken directly from field notes, posted on maps which are contoured and final drafted (preferably in living color) and all basic data and preliminary copies are "dead stored."

One step beyond this is the "filing cabinet" method in which written logs are filed by geographical area or drilling program and, in some cases, cross indexed by geographic sub area or stratigraphic position. Such a system is preferably managed by a single person who 1)"knows the whereabouts of every piece of information and all idiosyncrasies of the system, and 2) makes sure that all materials are returned to their proper place. The major difficulties lie in their reliance on a single person who is subject to work changes, illness or simple mortality. Also, as the number of logs increases and file maintenance goes beyond the capabilities of a single person (and assistants) this system becomes progressively slower, more cumbersome and can eventually collapse.

The alternative is the utilization of the computer. The principal difficulty with this method is, however, the time and effort required to enter the field data into storage and it is probably the reason why the method has not been generally adopted. In addition, if careful consideration is not given to the method of data entry and storage, much time can be wasted and serious data losses incurred.

One entry method that is now widely used consists of translating the written lithologic entries from the field log into a set of codes on the computer entry data sheets. This system is perferred by computer oriented persons but has many difficulties for the geologist. Some of the features that he wishes to record are not found on the standard forms, and some features that are listed on the form are not included in the field notes or have no relevancy to the geologist. Moreover, he recognizes that the fact that filling out forms is a waste of his time. As a consequence, the task of data translation is often relegated to a subordinate who, also afflicted by the same frustration and boredom simply reduces the field logs to the simplest possible terms, thereby losing a large proportion of field data information.

The entry methods recommended here and used in the University of Kentucky COAL MASTER system is a simple verbatim transcription of the lithologic description found on the field log. In this system a field of 50 characters is available and this 50 has proven adequate for most logs. In the case of longer entries, abbreviations can be used as long as they are consistent, but a more accurate method consists of recording the description in the form of three digit codes and comments used in the photo book.

*A similar manual applicable exclusively for coal bearing rocks in the Rocky Mountain area is currently in preparation. A book applicable to the Cretaceous rocks in general is also available (see Ruby, Horne and Reinhart, 1981).

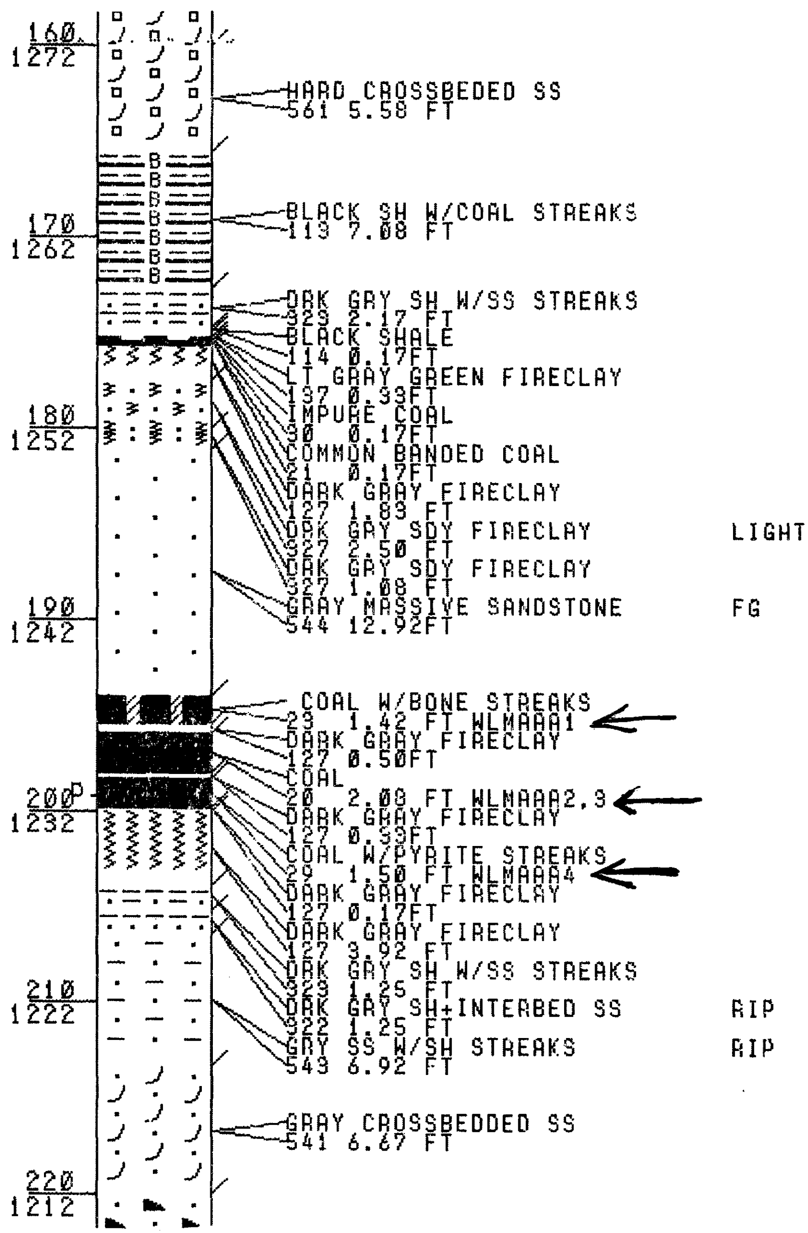


Figure 2. Sample of LOGPLOT output. Numbers on left of graphic plot indicate depth (above) and elevation (below) at every inch. Data on the right show for each rock unit, the English description followed by the litho code and thickness. Comments - light, fg and rip- are on the far right. Seam tags WLM AAA 1, WLM AAA 2, 3 and WLM AAA 4 are shown at arrows. WLM identifies the Williamson Seam, AAA identifies the project area and 1, 2-3, 4 indicates recognizable benches in the project area.

Data entry on a computer is very critical as mistakes are easily made. Systems involving repeated entry, such as double punching of cards, generally yields evidence for the remarkable capacity for making the same mistake twice. In the COAL MASTER entry, corrections can be made directly on the CRT or on a hard copy printout compared to the field log. The geologist who submits the log makes the final check before it enters storage.

No matter whether entry is by litho code or verbatim English, all storage is in English. At the final stage of entry all English litho phases are supplemented by litho code numbers by automatically comparing each phrase to about 2000 commonly used rock or coal terms to which three digit codes have already been attached. This procedure of code application permits rapid production of graphic logs during retrieval and utilization of log data.

RETRIEVAL AND UTILIZATION

The primary purpose of stored data is rapid and accurate access of relevant information for the preparation of cross sections and maps and it is in this process that the advantages of computer storage are realized. Misplaced or poorly maintained cross indices, misfiled or mislaid logs render most "file cabinet" systems slow, cumbersome, costly, and frustrating. In contrast, most computer systems permit withdrawal by both geograpghic or civil districts as well as by stratigraphic position.

The first step in data utilization consists of establishment of correlation of economically important seams. In some cases, the core hole spacing is so close that there is little ambiguity about correlation, and seams can be tagged (named) directly and map preparation can begin. In most cases, however, the only way to determine correlation is by comparison of graphic logs which can be manipulated to show similarity in sequence and geographic proximity. Conventional methods consist of drafted pen and ink drawings or sections, No matter which method is employed, hand preparation is infinitely slower, and more prone to error than computer plotted logs. The LOG PLOT portion of COAL MASTER consists of over 200 lithologic symbols plotted at any veritcal scale desired with depth and elevation plotted on the left side of the log and the litho code, English litho description, thickness and seam tag in the right hand margin (Ferm and Berger, 1979) (Figure 2). LOG PLOT can be used on both pen and electrostatic plotters and a program in preparation will permit plotting on a CRT screen.

With establishment of correlation, seams can then be identified and tagged (named) and the data are ready for map preparation. Map preparation is a two step process consisting of extracting data from the log, posting it on maps and adding interpretative data, such as contours and isopachs. When conducted by conventional hand methods the process of retrieval of data from logs and posting on maps is tedious, time consuming and prone to serious errors. Moreover, as more parameters are required from the basic data, continued search requires more time and increases chance for error.

The alternative method of computer retrieval and posting represents major improvements in both time saving and increased accuracy. The COAL MASTER map posting program now in preparation permits retrieval of coal thickness, seam thickness and calculated rejects for any tagged seam. Additional retrievable information is the thickness of the interval between two tagged seams or between a tagged seam and a specific rock type or types. Also retrievable for production of slice maps are the types of rocks occurring at specified intervals above or below a tagged seam. For any interval defined by a tagged seam and any other tagged seams, rock types or specified footages, the thickness of rock types, proportion of rock types, and the mean and maximum thickness of rock units can be obtained. Any of these parameters can be shown on a CRT or hard copy map.

Computer contouring and subsequent calculations are available in a great variety of programs. However, since the problem of contouring, computer assisted or otherwise, is one of the subjective judgement, there is no clear way of determining whether one is substantially better than another.

SUMMARY

Preceding sections have compared alternative procedures for producing maps and cross sections for reports describing coal reserves and minability of coal seams. Increased speed in precision has been stressed in comparing conventional methods in contrast to standardized computer assisted procedures. Table 2 presents estimates of time required for an example using conventional hand methods compared to core book type logging and computer produced maps and cross sections. The example assumed 100 continuously cored holes about 500 ft deep which include three minable seams. There are a great many variables that effect these estimates but it is clear that the computer assisted system can reduce production time between 50 and 75 percent. In addition, use of the computer assisted system reduces computation

Table 2. Approximate time comparisons for conventional and computer assisted coal property reports, assuming 100 holes, 500 ft deep with three minable seams (all times in man days).

Operation	Conventional	Computer assisted	Time saving Using computer assisted method
Continuous core logging	250 to 500	40 to 80	210 to 420
Input (Storage)	.5	1 to 4	-.5 to 3.5
Retrieval	.5 to 3	.5	0 to 2.5
Preparation of Graphic Logs	7 to 15	.5	6.5 to 14.5
Correlations and Seam Taging	5	5.5	-.5
Map Production (15 maps)	20 to 40	5 to 10	15 to 30
Drafting 15 maps, 5 cross sections	20 to 40	4 to 7	15 to 33
TOTAL	$300\pm$ to $600\pm$	$50\pm$ to $100\pm$	$230\pm$ to $500\pm$

and graphics errors and virtually eliminates the need for conventional drafting. Finally, and perhaps more importantly, the use of photo book logging and computer treatment of data allows technical and clerical personnel to perform many of the tasks now done by professionals and utilizes the latter's (presumably more costly time) only for those tasks requiring a high degree of training and experienced judgement.

The primary difficulty lies in initial costs. A highly trained operator is required to manage the computer, some clerical personnel are needed for input, and at least a part time programming capability is required. Savings in other personnel area, however, would probably offset and exceed these costs.

Capital outlay for computer hardware and software and for maintenance are reasonably high relative to conventional geologic hardware, but the rapid increase in capability and falling prices in computer hardware clearly points to substantial capital cost reductions on the order of 50 percent

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ENCORE - A COMPUTER PROGRAM FOR DRILL-HOLE DATA MANAGEMENT, COAL OREBODY MODELING, AND COAL RESERVE ESTIMATION

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INTRODUCTION

Use of a computer to greatly increase the productivity of the minerals industry professional is, at the minimum, cost effective. By manipulating and interpreting the large amounts of data required for a reserve evaluation with the assistance of a computer, the professional can eliminate from his workload the repetitive, menial tasks that are required with a manual evaluation. This potentially accomplishes two things: It allows the engineer to devote more time to the actual engineering functions and decisions; and it also provides the professional with the ability to evaluate several alternatives within the same time frame that would be required for a manual evaluatiuon. This has the overall results of the final evaluation. This is the primary objective behind the development of the ENCORE package; to provide the minerals engineer with a set of computer-based tools that are easily utilized in a coal reserve evaluation.

DESIGN OBJECTVIES

From the earliest stages of development of the ENCORE software package, the objective has not been to provide a better method for reserve evaluation and orebody modeling; but rather to combine into one software package a multitude of tools designed for ease of use, flexibility, efficiency, and cost effectiveness. The idea is to allow the geologist or mining engineer with little or no computer background to interface with the computer directly without having to rely upon a data processing specialist.

The software package is easy to use, for it is menu-driven. The user need only know how to log on and off the computer system and how to access the ENCORE package. Beyond that, all of the information supplied by the user is prompted for using an interactive terminal session with many default values allowed. Error checking routines are used extensively to avoid the possibility of erroneous data being input by the user.

ENCORE is extremely flexible in its input requirements, its graphical output, its reporting capability, and its reserve estimation methodology. The input can be either drill-hole data or digitized data and any shape of polygonal boundaries can be used to define the areas of interest. Numerous types of graphical output (discussed below) are available, all of which can be displayed on a graphical CRT terminal or plotted on a high-resolution plotter. The reporting capability of the package is primarily handled through a data base management system. Several types of reports to meet the user's report specifications. The actual reserve estimation process can be handled with the standard polygon method; using the government's measured, indicated, and inferred area of influence method; with contouring; and with geostatistics. The geostatistical software was derived from that developed by H.P. Knudsen and Y.C. Kim and modified by J.A. Shrivan and M.R. Karlinger (no date). A polygon intersection rountine is used to calculate reserves within any user-defined polygonal boundaries.

THE USER SYSTEMS

The user systems incorporated into ENCORE fall under the general categories of data base management and reporting correlation of drill holes, generation of contour maps, volume calculations, and estimation of reserves. Graphical output is available for all of the above- -named user systems, with the exception of data base management and reporting

DATA BASE MANAGEMENT AND REPORTING

For an exploration project progressing towards a preliminary feasibility study, about half of both the time and costs for all computer work of the entire feasibility study is devoted to drill-hole data base organization and maintenance. Once drill-hole results are quantified and verified to be correct, they are immediately accessible and are not subject to further transcription or reinterpretation of errors. The data base management system used in ENCORE is an excellent tool for handling large amounts of varied data and generating necessary reports from the data contained within. It is particularly useful in selecting subsets of the data base for an engineering evaluation.

In terms of the information to be stored in the data base, it is generally much better to load too much data rather than have to go back and load addtional data at some point after the evaluation is in progress. By design, ENCORE is able to handle large quantities of data parameters. For example, the following is a partial list of the drill-hole related information that can be loaded into the data base:

(1) State drill-hole located in
(2) County drill-hole located in
(3) Name of coal field
(4) Name of coal lease and lease number
(5) Quad name and series
(6) Section township and range
(7) Drill-hole identifier
(8) Province name
(9) Region name
(10) Geologist name
(11) Surface elevation
(12) Total depth of hole
(13) Local strike and dip angle
(14) Drill-hole coordinates
(15) Coal thicknesses and elevations
(16) Waste thicknesses, elevations and lithology
(17) Coal seam identifiers
(18) Free swell index
(19) Trace elements
(20) Percent moisture
(21) Percent volatile matter
(22) Fixed carbon
(23) Percent sulfur
(24) Btu/per pound
(25) Percent ash
(26) Percent coal to zone thickness

The above named parameters, and more, provide the user with extreme flexibility both in the types of analysis that can be performed and in the types of reports that can be generated from this data base.

CORRELATION OF DRILL–HOLES

One of the first steps in a an engineering evaluation of this nature is the correlation of the coal seams. As an alternative to taping logs onto a wall and penciling in the lines connecting the coal seams, ENCORE allows the user the option of displaying a series of drill-holes in cross-section on a hard copy plotter at any scale specified (Figure 1). There is also the option of displaying several drill-holes in a three-dimensional fence diagram. The use of these tools can greatly reduce the time involved to correlate the seams ina coal deposit.

GENERATION OF CONTOUR MAPS

In order to accurately model a coal deposit, contour maps of the various surfaces and thicknesses need to be generated. The ENCORE system provides thge user witha wide variety of options for this type of graphical display. The types of maps available to the user are as follows:

1. **Base Map** - used to display in plan view the drill hole locations and to post by each location pertinent information such as drill-hole identification, collar elevation, coal seam elevation, and coal seam thickness.

2. **Overburden Contour Map** - simply a contour map of the thickness of the overburden.

3. **Inferred Outcrop Map** - a contour of a seam outcrop based upon the plane where the surface elevation grid and the elevation at the top of the coal seam grid meet.

4. **Mining Ratio Contour Map** - a contour map based upon the ratio of overburden of coal thickness. Simply stated, this is the total depth

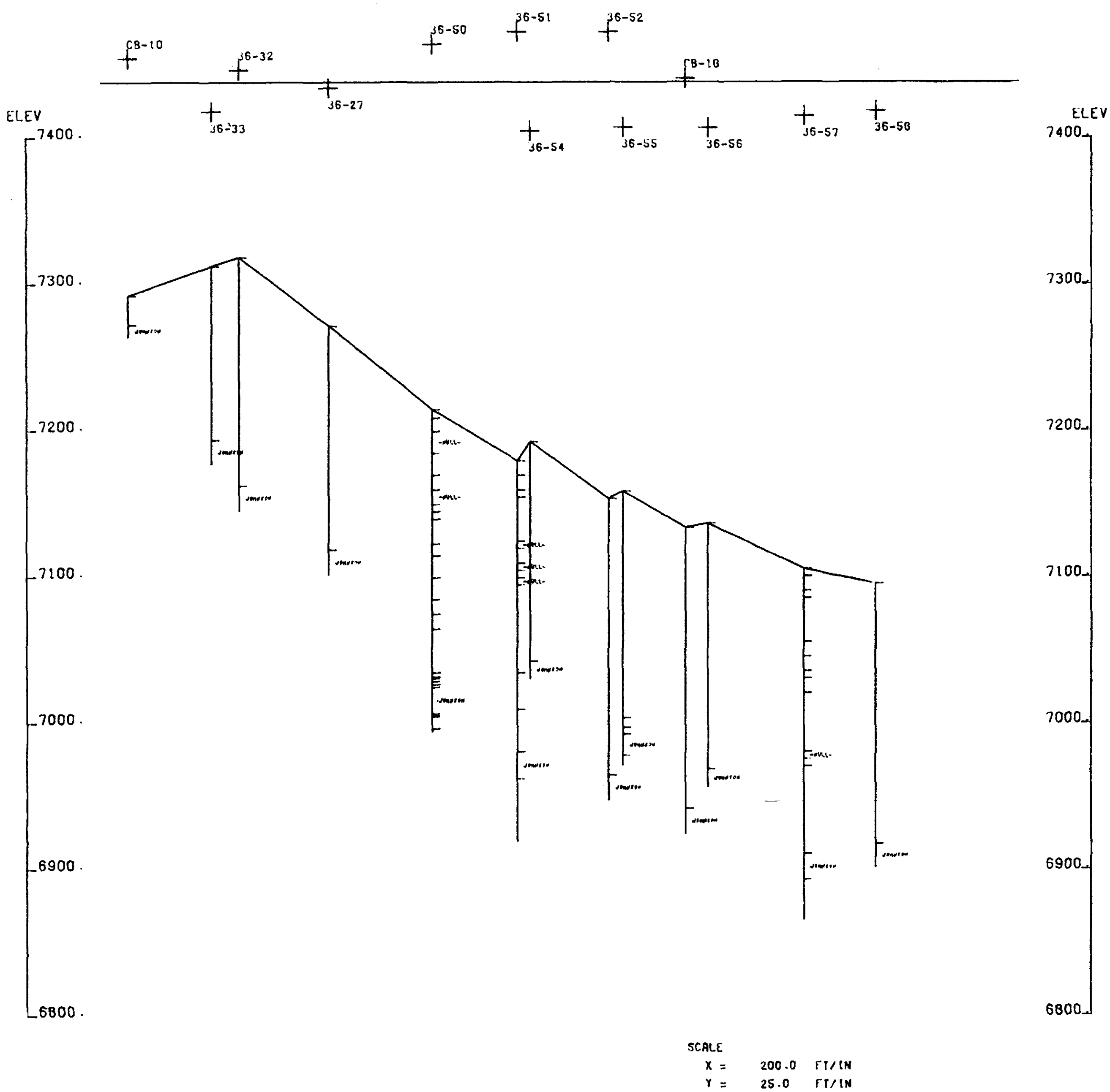


Figure 1. Example correlation diagram.

to be mined (excluding any mineable coal thicknesses) divided by the sum of all mineable coal thicknesses.

5. **Coal Thickness Contour Map** - a contour map of the thickness of a specified coal seam.

6. **Analytical Value Contour Map** - a contour map by seam of such analytical parameters as everage Btu/pound, average percent sulfur, average percent ash, and average percent moisture.

7. **Interburden Contour Map** - a contour map of the interburden thickness between two specified coal seams.

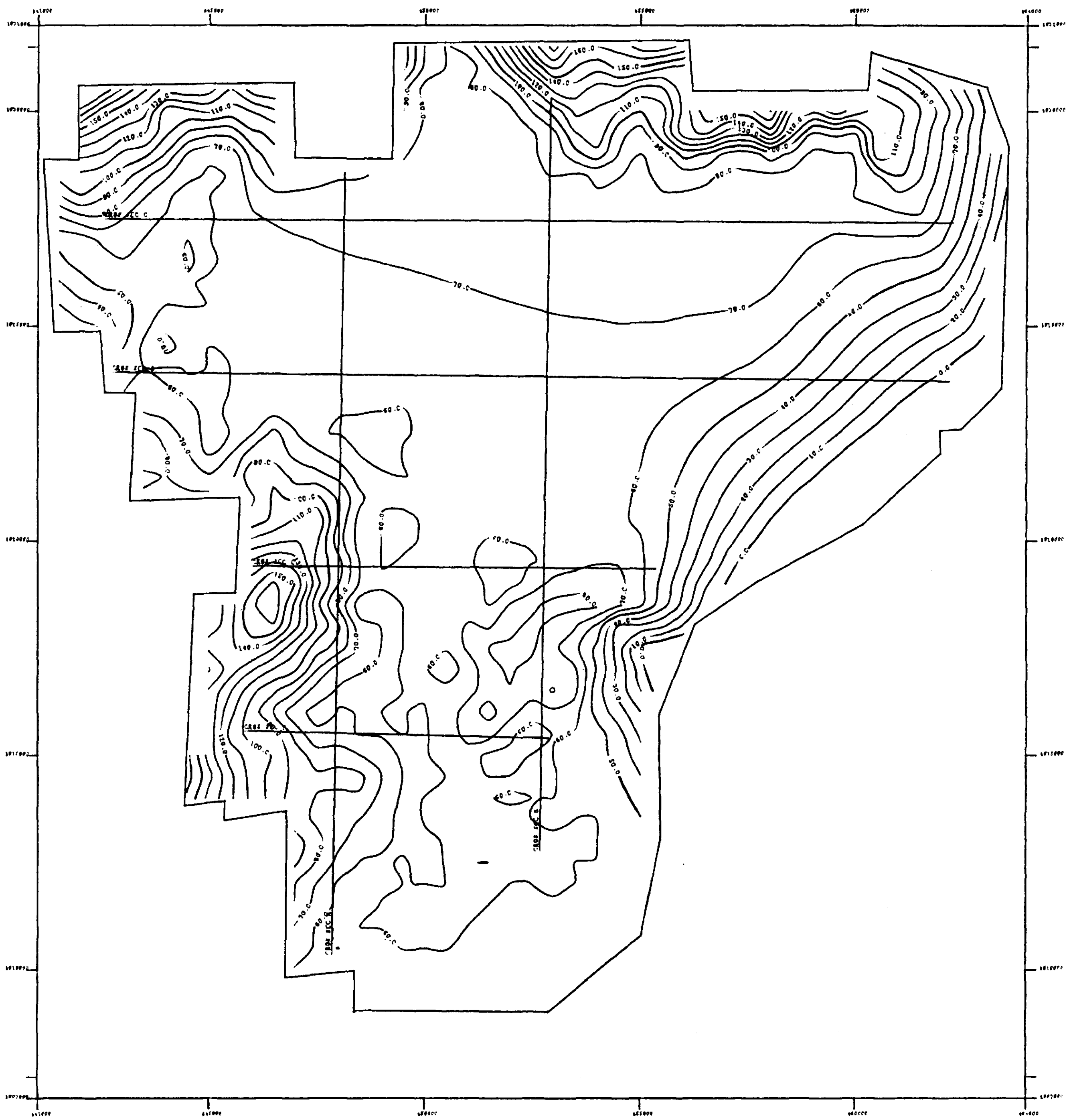


Figure 2. Coal thickness - Johnson seam.

8. **Elevation Contour Map** - the elevation contour maps that can be obtained are top of the coal seam, bottom of coal seam, pre-mining surface topography, post-mining surface topography, and an elevation differnce map of pre-and post-mining surface topography.

In addition to the above mentioned contour maps, the user can also obtain cross-sections of coal thickness, pre-and post-mining topography, top and

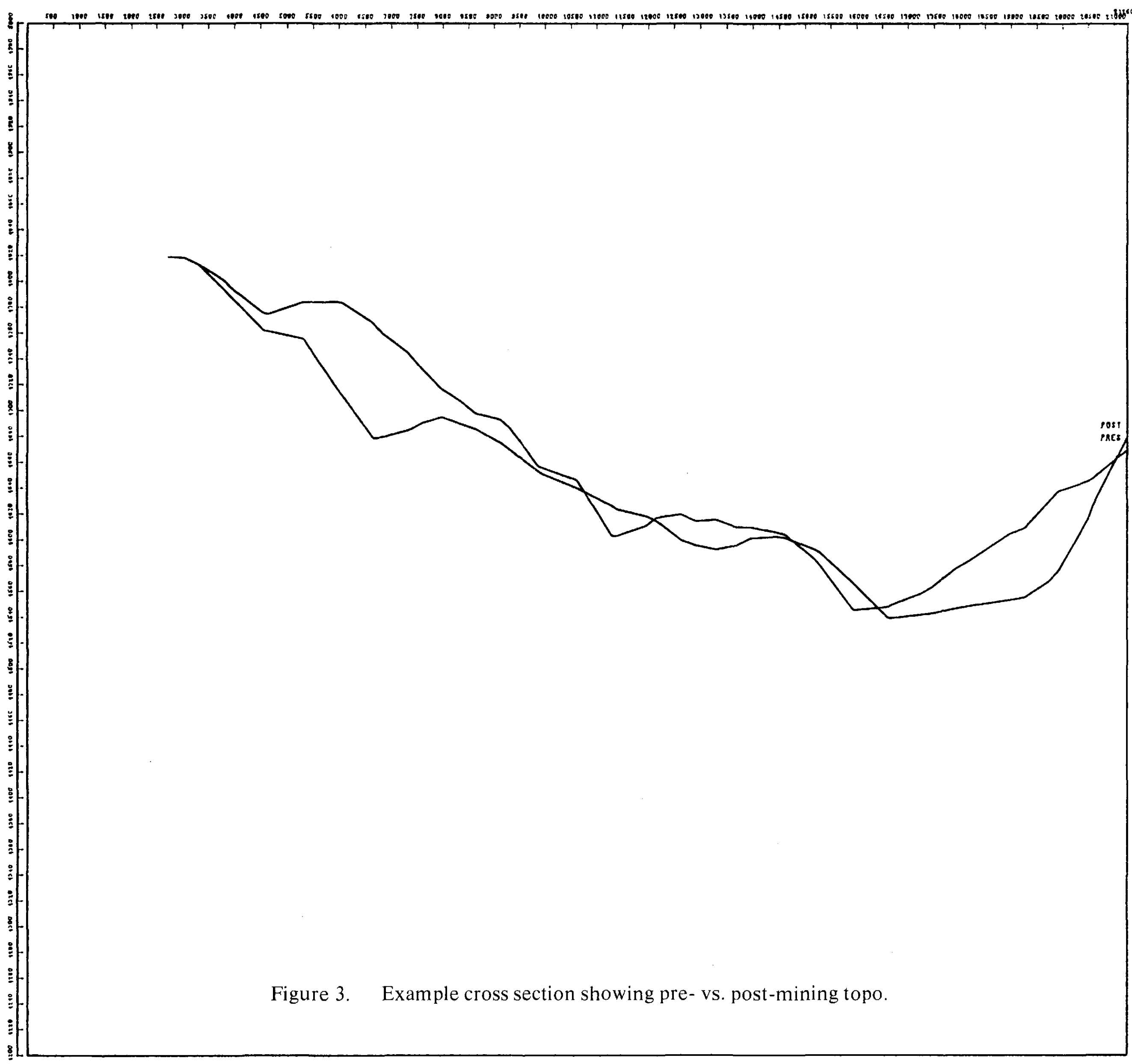


Figure 3. Example cross section showing pre- vs. post-mining topo.

bottom of seam elevation. Any or all of these can be displayed on the same cross-section map. Also, overburden maps, seam thickness maps, inerburden maps, and any of the elevation maps can be displayed as a three-dimensional perspective view. Figure 2 shows an example contour map, Figure 3 an example cross-section plot, and Figure 4 an example three-dimensional perspective view.

VOLUME CALCULATIONS

The ENCORE system also provides the user with the option to calculate columes of overburden, volumes of coal, and volumes of interburden. In addition, either the surface area or the surface area projected onto an X-Y plane can be calculated for overburden, interburden, coal seam thickness, coal seam elevations, and surface topographies. Any polygonal boundary or any user-specified minimum and maximum z-values can be used to completely restrict the volume or area being calculated. The coal volume calculations described here are using the polygon intersection routine. These are pure volumes whereas the calculations in the reserve

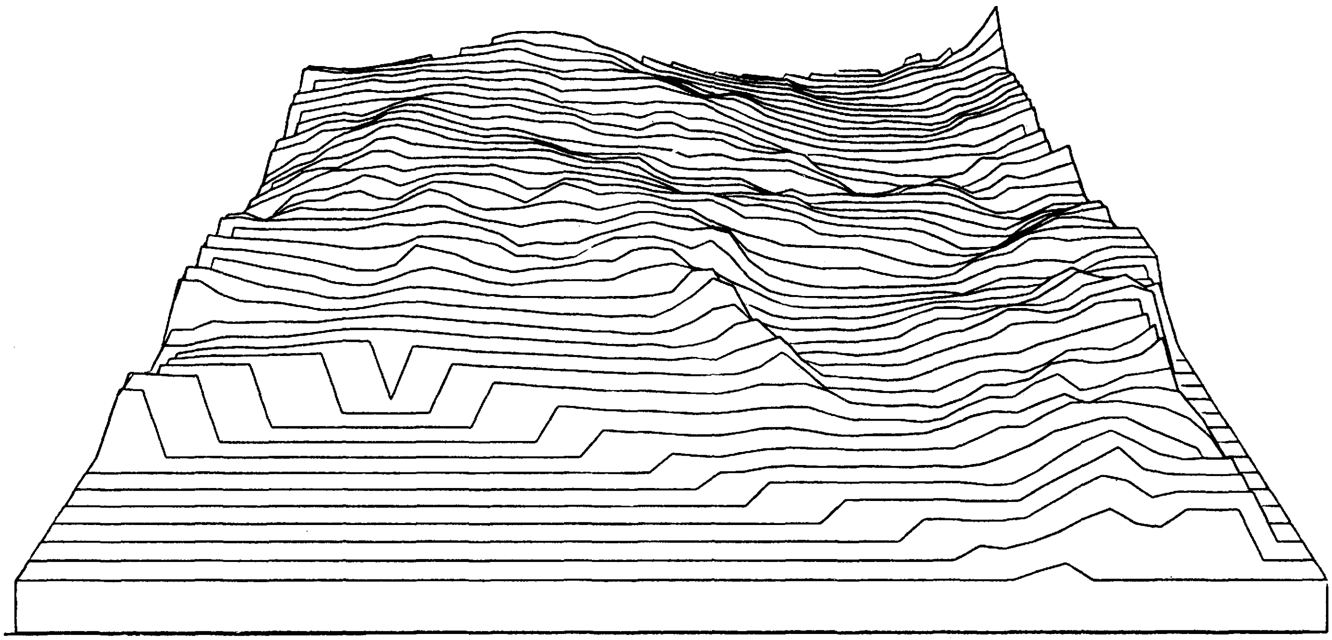


Figure 4. Example perspective view of surface topo.

rountine include tonnage factors and percent coal to zone thickness, which result in estimates of tons of coal and tons of waste.

ESTIMATION OF RESERVES

Within the ENCORE software package, there are four distinct methods of estimating coal reserves. These are the polygonal method; the U.S. government's measures, indicated, and inferred area of influence method; reserves estimated from the contoured coal thickness; and the geotatistical method. As is the case with the entire package, any polygonal boundary can be used to restrict the area of interest in any of the above reserve calculation methods.

The polygonal method is the standard prependicular bisector methodology. Any radius can be specified by the user to establish the required area of influence. A computer plot of the calculated polygonal areas is available to the user (Figure 5). The polygon intersection routine is used to restrict the reserve calculations to those contained within any user-specified boundary, as in the boundary chosen in Figure 5.

The U.S. government's measured, indicated, and inferred reserve categories are calculated identically to the standard polygon method, except that three radii of influence are used rather than one and the total reserves are divided into the three categories. The default values which are used for these radii are 0.25 miles, 0.75 miles, and 3.0 miles. Again, a computer-generated plot of a map showing the three areas of influence is available to the user.

The contouring method involves using the ENCORE-generated grid of the coal thickness (taking into consideration the percent coal to zone thickness) in conjunction with the polygon interesction routine. The total reserves calculated within a particular polygonal boundary are thus based upon the average thickness of all coal contained within this boundary. The grid that is used for this elevation can be generated using numerical approximation techniques or using geostatistical techniques.

The geostatistical capability of the ENCORE package included variogram estimation and display (Figure 6), variogram validation, kriging, statistical analysis routines, and associated plotting routines. The geostatistical routine will handle spherical, exponential, linear, and gaussian variogram models. They can be either horizontal or vertical variograms. Anisotrophies, if present, may be either geometric or zonal type. The kriging rountine is a two-dimensional point-kriging program that has the option of using either universal or simple kriging. The kriged mean

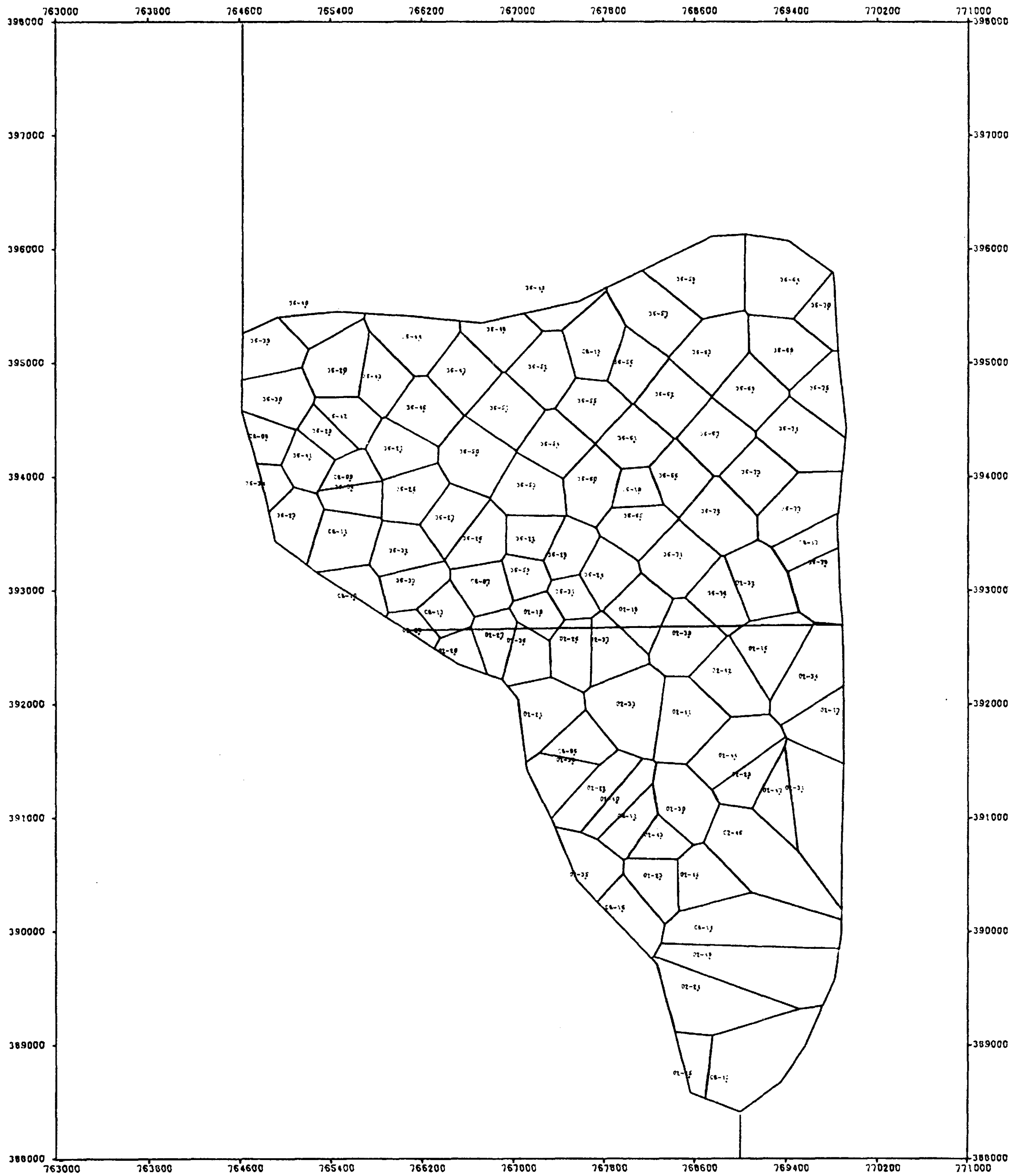
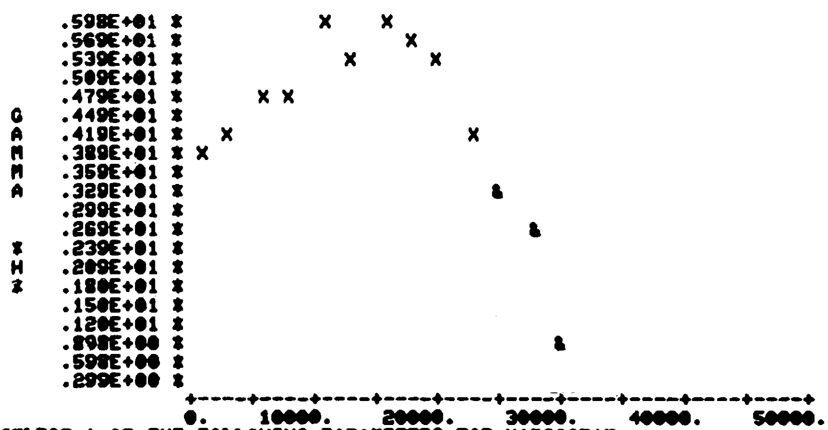


Figure 5. Computer plot of the calculated polygon areas.

```
                                                                     9-OPTIONAL PARAMETER 4
                                                                     10-OPTIONAL PARAMETER 5
                                                                     11-DIGITIZED COAL THICKNESS
                                                                     12-QUIT
                                                        I>
                                                 DATA USED IN CACULATIONS
DIRECTION     -  90.   WINDOW  90.               MEAN              -  .151E+02
CLASS SIZE    - 2500.0                           VARIANCE          -  .493E+01
MAX. DISTANCE -      50000.                      STD DEVIATION  -  .222E+01
LOGARITHMS   -NO         RELATIVE VARIOGRAM -NO  NO.OF SAMPLES  -     85
```

DISTANCE	PAIRS	DRIFT	GAMMA (H)	MOMENT CENT	AVER DIST
0 - 2500	151.	.826E+00	.374E+01	.356E+01	1678.02
2500 - 5000	429.	.640E+00	.397E+01	.393E+01	3805.85
5000 - 7500	512.	.856E+00	.461E+01	.466E+01	6175.42
7500 - 10000	580.	.562E+00	.453E+01	.453E+01	8674.70
10000 - 12500	456.	-.149E+00	.598E+01	.599E+01	11288.91
12500 - 15000	454.	-.661E-01	.516E+01	.518E+01	13669.79
15000 - 17500	434.	-.113E+00	.578E+01	.578E+01	16233.93
17500 - 20000	265.	.136E-01	.541E+01	.542E+01	18716.75
20000 - 22500	182.	-.131E+00	.520E+01	.522E+01	20963.64
22500 - 25000	74.	-.347E+00	.411E+01	.409E+01	23543.79
25000 - 27500	26.	-.192E+00	.309E+01	.308E+01	25829.01
27500 - 30000	6.	-.120E+01	.241E+01	.236E+01	28626.78
30000 - 32500	1.	-.120E+01	.720E+00	.720E+00	30408.63

COAL SEAM THICKNESS VARIOGRAM




```
SELECT 1 OF THE FOLLOWING PARAMETERS FOR VARIOGRAM:
        1-COAL THICKNESS BASED ON DRILL HOLE INFO
        2-BTU/LB
        3-PERCENT SULFUR
        4-PERCENT ASH
        5-PERCENT MOISTURE
        6-OPTIONAL PARAMETER 1
        7-OPTIONAL PARAMETER 2
        8-OPTIONAL PARAMETER 3
```

Figure 6. Coal seam thickness variogram.

value and the kriged variance of a specified parameter in a single block of any shape can also be computed.

The statistical rountines available allow the user to compute means, standard deivations, maximum and minimum values, correlations, histograms, and shi-square tests for normality. The computer-generated plotting capability of the system allows for display of variograms (Figure 7), histograms, and a kriged block or grid map.

PLANNED ENHANCEMENTS

The ENCORE software package is a dynamic system in which modifications and developments are being made but not interferring with the ability of the user to reliably use its existing tools. These are in part based upon suggestions from current users and obvious inclusions needed to bring the systems to a current, complete, state-of-the-art software package. Another major factor is the rapid evolution in computer graphics hardware which allows the

Figure 7. Coal seam thickness variogram.

expanding capabilities of the system at decreasing costs.

Enhancements which are currently in the planning stages are listed below:

1. Incorporation of a surface coal mine pit geometry simulator that would use standard surface coal mine design techniques to determine pit geometry based upon considerations of bench heights, bench widths, and pit slopes.
2. Incorporation of additional gridding routines into ENCORE to afford the user an option fir graphical contouring, volumetrics, etc.
3. The implementation of a color graphics terminal to display the ENCORE output.

The long-range enhancements fall under the general category of mine planning and mine design, with the possibility of some economic and financial evaluation capability to be included for purposes of completeness

CONCLUSIONS

The ENCORE software package provides the minerals engineer with an easy to use, flexiable set of tools to use for the modeling of a coal orebody and the estimation of coal ore reserves. It provides the user with the capability of displaying and editing data, displaying and correlating coal seam and strata layers, generating and displaying various contour maps, cross-section maps, and three-dimensional perspective view maps using a choice of four different methods. The final result from use of the ENCORE package is increased productivity realized by the minerals engineer in terms of both time and cost savings and an increased level of confidence in the resultant evaluation.

ACKNOWLEDGEMENTS

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PALEOECOLOGY AND SEDIMENTOLOGY OF THE FORT UNION FORMATION, HARDING COUNTY, SOUTH DAKOTA

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STRATIGRAPHY OF THE FORT UNION FORMATION IN THE NORTH CAVE HILLS

Rocks of Upper Cretaceous through Oligocene age are represented in the Cave Hills of South Dakota (Figure 1). The Hell Creek Formation, the Fort Union Formation, and the Chadron Formation of the White River Group may be found in the Cave Hills. The Ludlow, Cannonball, and Tongue River members of the Fort Union Formation occur in the Cave Hills. The study area encompasses approximately 9 sq mi of the North Cave Hills (Figure 2) and is situated within the southern margin of the Williston Basin. The Cave Hills are roughly 80 mi north of the Black Hills and 125 mi north of Rapid City, South Dakota.

Several stratigraphic sections were measured along the southeastern margin of the North Cave Hills and in the Riley Pass vicinity where the lower and upper members of the Fort Union Formation are well exposed. Stratigraphic correlation of the sections was accomplished through the use of an *Ophiomorpha* zone present within the Cannonball Member.

Depositional models are presented for the various stratigraphic units of the Fort Union Formation, based on stratigraphic relationships, sedimentary structure sequences, and the sedimentary textural parameters.

A non-marine, alluvial flood plain model is proposed for the fine-grained sandstones, siltstones, mudstones, and lignites of the Ludlow Member. The model implies a low-gradient flood plain occupied by meandering streams. Numerous fine-grained, fining-upward sequences occur throughout this member. Two major channel sandstones crop out at localities 2 and 5 (Figure 2) and approach 28 and 40 ft in thickness, respectively. The sandstones are stratigraphically separated by 50 ft and trend to the northeast. Smaller sandstone units adjacent to the larger channel sandstones, rapidly change character between localities. Paleocurrent data for the sandstones vary markedly from one locality to the next. Levee, overbank, swamp, and possibly lacustrine environments of deposition are interpreted for several of the sandstone, siltstone, and clay sequences.

A nearshore marine environment of deposition is interpreted for the Cannonball Member of the Fort Union Formation. The Cannonball is represented by two fine-grained, coarsening-upward sandstone units that wedge or pinch out west of the study area. The sandstones increase in thickness to the east and northeast.

A vertical succession of five sedimentary facies can be recognized in the lower Cannonball sandstone (D-sandstone, Figure 3). These facies are, in vertical succession: 1) basal interbedded sandstone, siltstone, and shale; 2) massive bioturbated sandstone; 3) trough crossbedded sandstone; 4) lenticular sandstone and conglomerate; and 5) low-angle, laminated sandstone.

Lower shoreface to upper shoreface/lower foreshore environments of deposition are interpreted for this lower regressive marine sandstone. The *Ophiomorpha* datum used in correlating the stratigraphic sections is within the upper three feet of the lower Cannonball sandstone in the low-angle, laminated sandstone facies. This unit also commonly contains shark teeth.

The upper Cannonball sandstone attains a maximum thickness of 70 ft at locality 4 (Figure 2). This finer-grained sandstone exhibits a

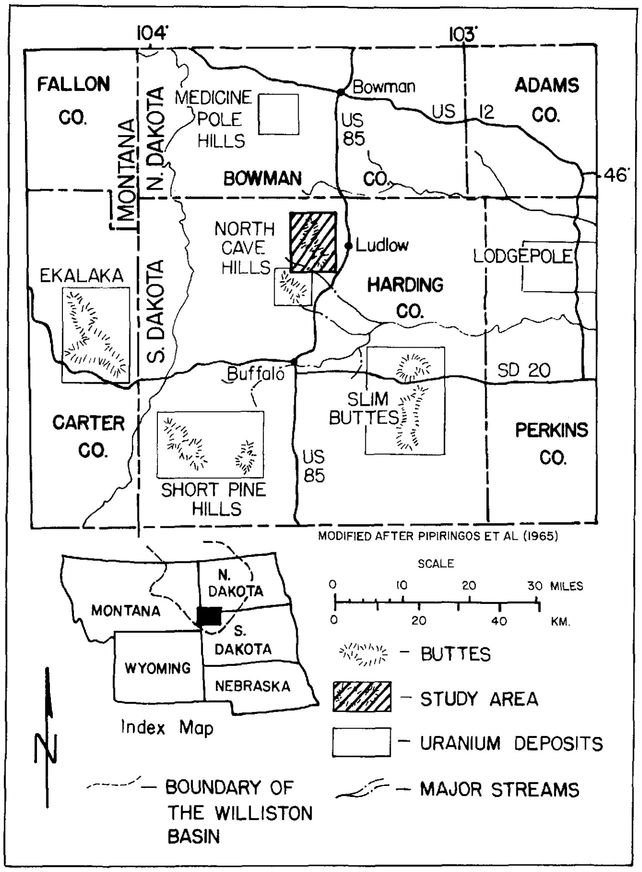

Figure 1. Location of study area.

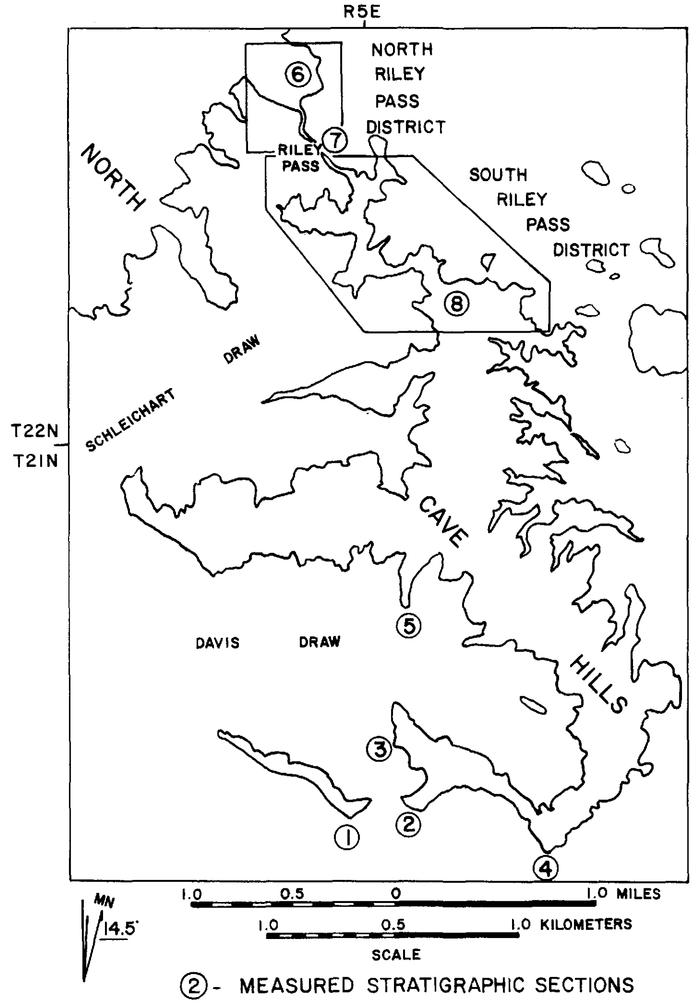

Figure 2. Locations of Riley Pass mining districts and measured sections.

coarsening-upward texture similar to that observed for the lower Cannonball sandstone. The upper unit can be subdivided into six sedimentary facies, similar in many respects to those of the lower sandstone. The vertical succession of these facies is as follows: 1) basal lenticular sandstone and mudstone; 2) tabular sandstone and mudstone; 3) cross-bedded sandstone; 4) lower laminated sandstone; 5) trough crossbedded sandstone; and 6) upper laminated sandstone.

Lower shoreface/offshore through lower foreshore depositional environments are postulated for the upper Cannonball sandstone. A north to northeastward depositional strike for the Cannonball strand is inferred from paleocurrent data (ripple marks and crossbedding). The sandstones of the Cannonball represent transgressive and regressive phases of the Cannonball sea interfingering with non-marine, fluvial environments of the Ludlow and Tongue River members of the Fort Union Formation.

The top of the Cannonball Member exhibits an undulatory or irregular surface with local relief of up to two feet. Overlying this surface is a thin lignite termed the E coal bed by Denson, et al (1959). Where this lignite has been excavated in the North and South Riley Pass mining districts, numerous carbonized impressions and molds of tree stumps are exposed. Forty-eight individual stumps, and numerous logs of varying lengths, are present along the floor of the North Riley Pass mine. These stumps and logs probably represent remnants of a cypress/*Metasequoia* forest or coastal swamp which stabilized the upper most sands of the Cannonball shoreline.

A non-marine, lower alluvial coastal plain model is proposed for the Tongue River Member of the Fort Union Formation (Figure 3). The basal

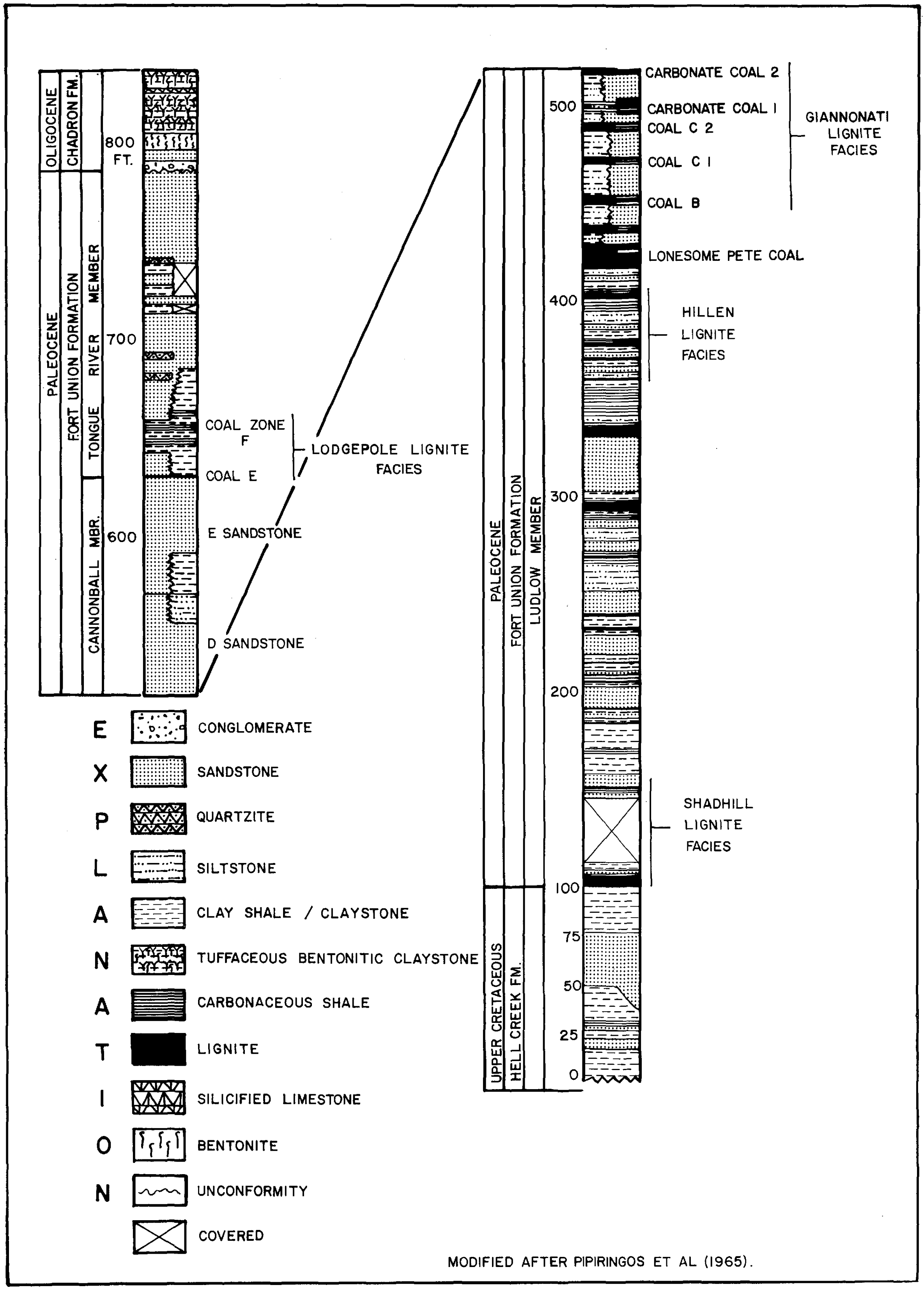

Figure 3. Generalized stratigraphic section of the Cave Hills area, South Dakota.

Tongue River is well exposed in the North and South Riley Pass mining districts, and at locality 4, where approximately 40-45 ft of lenticular sandstone, siltstone, mudstone, and thin-bedded lignite occur. This basal portion of the Tongue River was termed the Lodgepole facies (Petsch, 1956; Stevenson, 1956; Erickson, 1956, Figure 3). Numerous shallow channels trending to the east and southeast are well exposed along the northwest wall of the North Riley Pass mine. On the west half of the wall, a light gray sandstone, 9.3 ft thickness, grades laterally into a darker brown siltstone, mudstone, and shale. The sandstone fines-upward and displays a vertical succession of sedimentary structures characteristic of a point-bar including a sharp basal contact overlain by low-angle planar crossbedded, small-scale trough cross-bedded, and ripple bedded. This sandstone is overlain by a dark gray mudstone containing thin carbonaceous stringers. A lignite, 3 ft in thickness, overlies the interbedded levee/overbank deposit. These lignites are in turn overlain by more overbank deposits. The total sequence described is approximately 26 ft in thickness.

The Tongue River overlying the finer-grained Lodgepole facies is comprised of numerous massive sandstones measuring up to many tens of feet in thickness. Two such sandstones occur above the Lodgepole facies at the South Riley Pass mine. The lower and upper sandstone are 65-39 ft thick, respectively. These sandstones commonly exhibit a fining-upward texture, and often, an intra-formational conglomerate lag along the base. This conglomerate is often followed by abundant medium-to-large-scale trough crossbedding interspersed with horizontal to planar low-angle bedding. A large, slightly sinuous channel sandstone, mapped by Dane (1978) trends southeastward through the study area just south of locality 5 and to the northeast of locality 4 (Figure 2). A smaller channel sandstone present at locality 4 is oriented to the northeast. The sandstones in the South Riley Pass Mining District and at locality 4 may be related to the major channel mapped by Dane (1978). An east to southeast dipping paleoslope is inferred from paleocurrent data.

PALEOECOLOGY OF THE FORT UNION FORMATION, CAVE HILLS AREA

The sediments of the Fort Union Formation in the Cave Hills are a small part of what Flores (1981) has described as "a seaward extension of the trunk-tributary river system in the Powder River Basin," consisting of a "dichotomy of deltaic deposits in the lower part (of the formation) and fluvial deposits in the upper part." One should expect to find, therefore, a complex of paleobotanical remains which record the presence of several different plant communities, each occurring according to its tolerance for submergence, flooding, salinity, etc. This is certainly the case in modern coastal and deltaic plant communities, where species distribution is determined by several environmental factors. Rich (1981) presents a synopsis of work conducted in various modern wetland plant communities which illustrates this fact.

Few paleobotanists have investigated the Fort Union sediments in the Cave Hills region. The relationships which swamp-marsh communities may have had with the fluvial-deltaic-shoreline environments are, consequently, poorly understood. Stanley (1965) conducted a palynological survey of a portion of the Cave Hills section, and concluded that "climatic interpretations based on the fossil pollen and spores suggest a temperate climate for the South Dakota area during Paleocene time." Stanley identified a few modern sub-tropical genera in his samples, all of them ferns, including *Gleichenia, Azolla, Anemia,* and *Schizaea.* Temperate genera included, among others, *Alnus* (alder), *Betula* (birch, *Carpinus* (hornbeam), and Picea (the spruces).

Trotter (1963) worked on Paleocene sediments in the Slim Buttes, not far east of the Cave Hills. His palynological findings are similar to Stanley's, and Trotter observes that the "pollen flora contains a mixture of temperate and subtropical species," including modern genera such as *Sequoa* (redwood), *Thuja* (white cedar), *Corylus* (hazel), and a wide variety of fern and *Sphagnum* spores.

If one can accurately assume that the Paleocene counterparts of these modern genera had similar environmental preferences to the modern plants, one gets the impression that the Cave Hills Paleocene swamp flora was dominated by freshwater species. There must certainly have been a brackish water flora, especially where the ludlow and Tongue River sediments were deposited closest to marine Cannonball sediments. The brackish water flora has not yet been identified, though, and, in fact, there appears to have been such a rapid invasion of marine sediment surfaces by the Tongue River forests that, perhaps, the brackish flora never had much of a chance to become established. This is strongly suggested by the presence of what must be cypress/*Metasequoia* stumps and logs on the surface of Cannonball sands, immediately beneath Tongue River sediments. It is difficult to find a truly suitable modern analogue for this type of sedimentary sequence, as it is uncommon to find freshwater swamp floras living in such apparent close proximity to marine shorelines. The best modern analogue, in terms of species composition of the flora and sediment relationships, may be the Pine Barrens of southern New Jersey. There, in an area where freshwater swamps lie close to the shore, and nearly at sea level, we find an abundance of temperate zone conifers and hardwoods, and, indeed, *Sphagnum* and *Schizaea,* producing freshwater peats which lie directly over Pleistocene nearshore marine sands.

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PETROLOGICAL CHARACTERISTICS OF JURASSIC-CRETACEOUS COALS IN THE FOOTHILLS AND ROCKY MOUNTAINS OF WESTERN CANADA

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INTRODUCTION

A major proportion of the bituminous coals of western Canada occurs in the Kootenay Group (Jurassic-Cretaceous) in southwestern Alberta and southeastern British Columbia, and in the younger Blairmore, Bullhead, and Fort St. John groups (Lower Cretaceous) of west central Alberta and northeast British Columbia. In the latter region, strata belonging to the Minnes Group, underlying the Bullhead, also contain coal. The Minnes is believed to be at least partly equivalent in age to the more southerly occurring Kootenay sequence. Blairmore strata also occur in southern Alberta and British Columbia but there, do not contain coal. Occasionally in this paper the Blairmore, Bullhead, Fort St. John and Minnes groups may be referred to as the northern groups. Table 1 shows the relationships of the various groups and the formations contained within them, and Figure 1 shows their geographic distribution. The stratigraphy of the northern sequence has been described by Stott (1973, 1974, 1975, and in press). The Kootenay has been described by Norris (1959) and Gibson (1979, and in press).

GEOLOGICAL SETTING

The Jura-Cretaceous coal-bearing rocks occur in a narrow belt extending from just north of the U.S. border to at least 200 km north of the Peace River in British Columbia. The coal belt is parallel to the trend of the Rocky Mountains (Figure 1) and lies within the foothills and the mountains.

An important marker horizon is the Cadomin Formation, a mainly conglomeratic unit that occurs at the base of the Blairmore in the south, and at the base of the Blairmore and Bullhead Groups in the north. In the Kootenay Group, nearly all the coal is contained in the Mist Mountain Formation, whereas in the north, the Gething and Gates are the most important formations. Coal is also present, although in small amounts, in the Bickford and Gorman Creek formations of the Minnes Group. At some localities the Bickford, Monach, and Beattie Peaks formations cannot be differentiated. Equivalent strata are then referred to as the Gorman Creek Formation.

The coal-bearing sequences were laid down along the western margin of the western Canada sedimentary basin, the products of deltaic-fluvial environments. The Morrissey Formation at the base of the Kootenay Group may be a beach-ridge and dune deposit although no other marine indications have been detected higher in this group. The norhthern sequence contains several marine units, the most important of which is the Moosebar Formation.

The Kootenay and Blairmore groups have been affected by large-scale thrusting that is characteristic of the southern Canadian Rocky Mountains. A series of thrust faults with northeastward displacement of the hanging wall have moved some of the sections as much as 158 km (Gibson, in press). The northern sedimentary groups, in contrast, are mainly folded and thrusting is a considerably less important structural feature. Individual belts of coal-bearing rocks are exposed along the axes of folds.

PETROLOGY OF THE COALS

Maceral Distribution — Toward the base of the Mist Mountain Formation, a number of seams contain unusual amounts of inertinite, some with

Table 1. Groups and Formations.[1]

South		
System	Group	Formation
Lower Cretaceous	Blairmore	Ma Butte Beaver Mines Gladstone Cadomin
	Kootenay	Elk Mist Mountain Morrissey
Jurassic		Fernie Formation

North[2]		
System	Group	Formation
Lower Cretaceous	Fort St. John	Cruiser Goodrich Hasler Boulder Creek Hulcross Gates Moosebar
	Bullhead	Gething Cadomin
	Minnes	Bickford Monach Beattie Peaks Monteith
Jurassic		Fernie Formation

[1] Data from Stott, 1974; Gibson 1979 McLean, 1982.

[2] In the central and southern Alberta Foothills the Blairmore Group is considered equivalent to the Bullhead and lower part of the Fort St. John Groups.

inertinite contents of over 50 percent (Cameron, 1972); especially abundant are the low-reflecting macerals of this group, semifusinite and low-reflecting macrinite. Inertodetrinite is also an important constituent in some seams. The abundance of semifusinite suggests swamp conditions which were conducive to accelerated oxidation and/or bacterial and fungal attack on the accumulating vegetal matter. The presence of inertodetrinite suggests that physical degradation was also important during some stages in the peat swamp. Not all of the Kootenay coals, however, are high in inertinite; systematic study has shown a progressive increase in vitrinite and decrease in inertinite upward in the coal-bearing section. This distribution pattern is indicated on Figure 2A in which maceral data are plotted for whole seams in the Mist Mountain Formation a) up to 250 m and b) more than 250 m above the base of the unit. It can be seen that all seams at or above 250 m contain at least 60 percent vitrinite while most of the seams occurring less than 250 m above the datum contain smaller amounts of this maceral.

Data on maceral distribution in coals of the northern groups are shown in Figure 2B. Patterns of distribution for these coals are somewhat more diffuse than for those of the Kootenay Group because three formations are involved instead of one. Data for a relatively small number of coals from the Gates Formation of the Fort St. John Group, and for equivalent strata of the Blairmore Group, show rather low to medium contents of vitrinite: 56 to 71 percent. In the Gething Formation, the vitrinite content ranges widely: from 44 to 90 percent. Too few data are available for any one section of the Gething to determine any consistent pattern. The coals of the Minnes group show an interesting distribution: A group of samples from lower parts of the Bickford Formation show extremely low inertinite content (less than 5 percent). These appear on Figure 2B at the upper apex of the triangle. A second group of Minnes coals, from the upper part of the Bickford, shows a higher inertinite contents, with a range of 22 to 29 percent.

An interesting feature of the low inertinite Minnes coals is the presence of large amounts of algal material, petrographically classified as the maceral alginite in the Liptinite Group. Similar material has been found in coals in the upper part of the Kootenay Group and is at its greatest concentration in the so-called "needle coal" near the top of the group. Such material reaches a maximum concentration of 83 percent in some Minnes coals. This rather unusual maceral composition occurs in thin seams, mainly less than 0.5 m thick. An important relationship between the presence of alginite and the reflectance of the enclosing vitrinite has been noted by Kalkreuth (in press). Initial measurements of reflectance on a number of coal samples from the Minnes showed anomalously low values if one

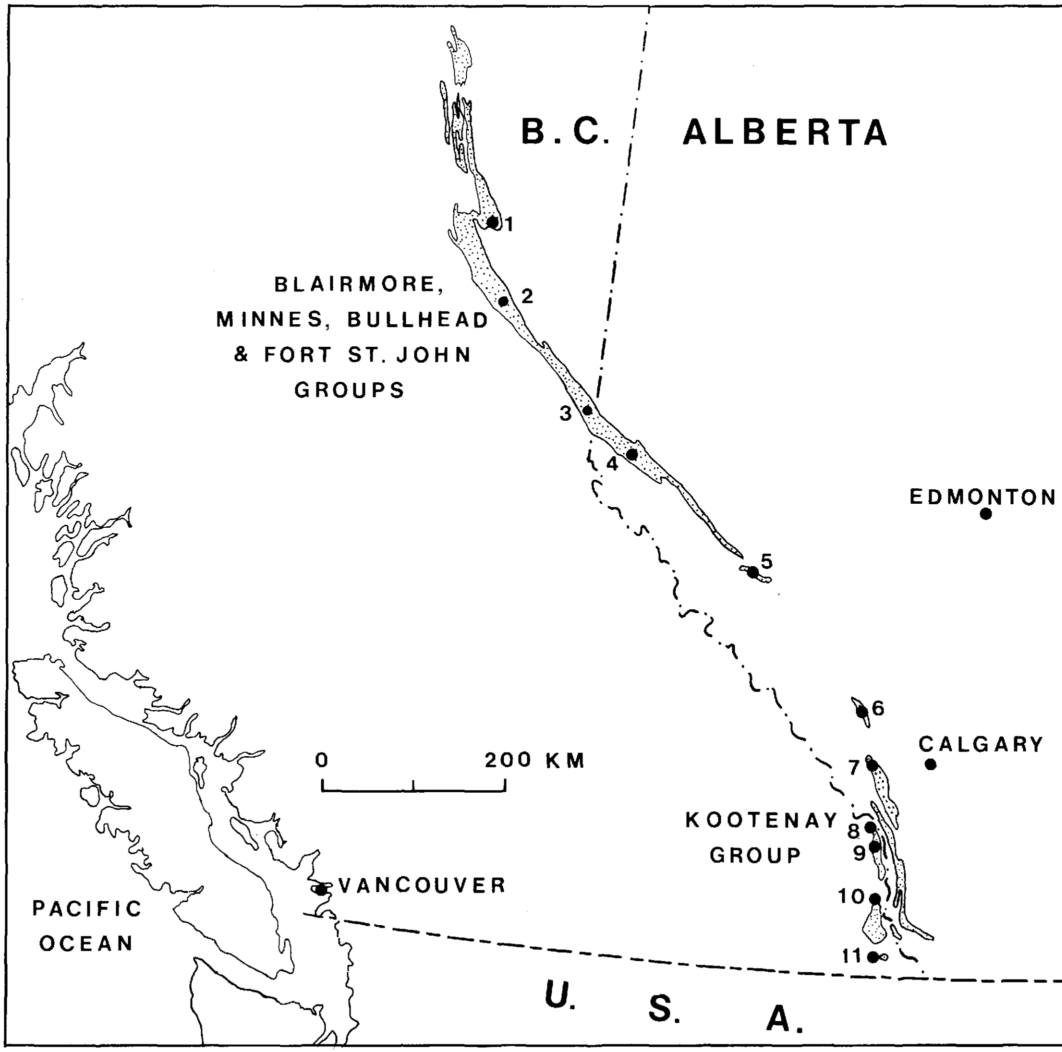

Figure 1. Geographic distribution of Jurrassic-Lower Cretaceous coal-bearing sequences in the Rocky Mountains and foothills, Alberta and British Columbia, and localities of representative sections for which reflectance data are available.

considers their stratigraphic position and their relationship to overlying coals, which have higher reflectance values. Reexamination of the Minnes samples showed that many of them contained substantial amounts of alginite; it seems possible that bituminoid matter from the alginite has infiltrated the surrounding vitrinite and depressed its reflectance.

Rank Variations — Rank studies on these coals have been reported on previously by Hacquebard and Donaldson (1974), Pearson and Grieve (in press) and Karst and White (1980). A wide range in regional rank is expressed by virtrinite reflectance values. Values for the Kootenay vary from 0.61 to 2.65 for the Fort St. John-Bullhead-Blairmore groups from 0.85 to 1.85, and for the minnes 0.70 to 1.00.

The locations of representative sections of both northern and southern groups for which reflectance data are available are shown in Figure 1. Table 2 summarizes the reflectance data for these sections. In both the northern and southern groups, rapid lateral changes in rank are not uncommon. Within the Kootenay Group, the highest rank coal, semianthracite, is found in the Canmore and Barrier mountain areas. Reasons for the lateral changes in rank of these coals are not well understood. For the Kootenay, part of the explanation may be the complicated structure of the area, in which sections that were once widely

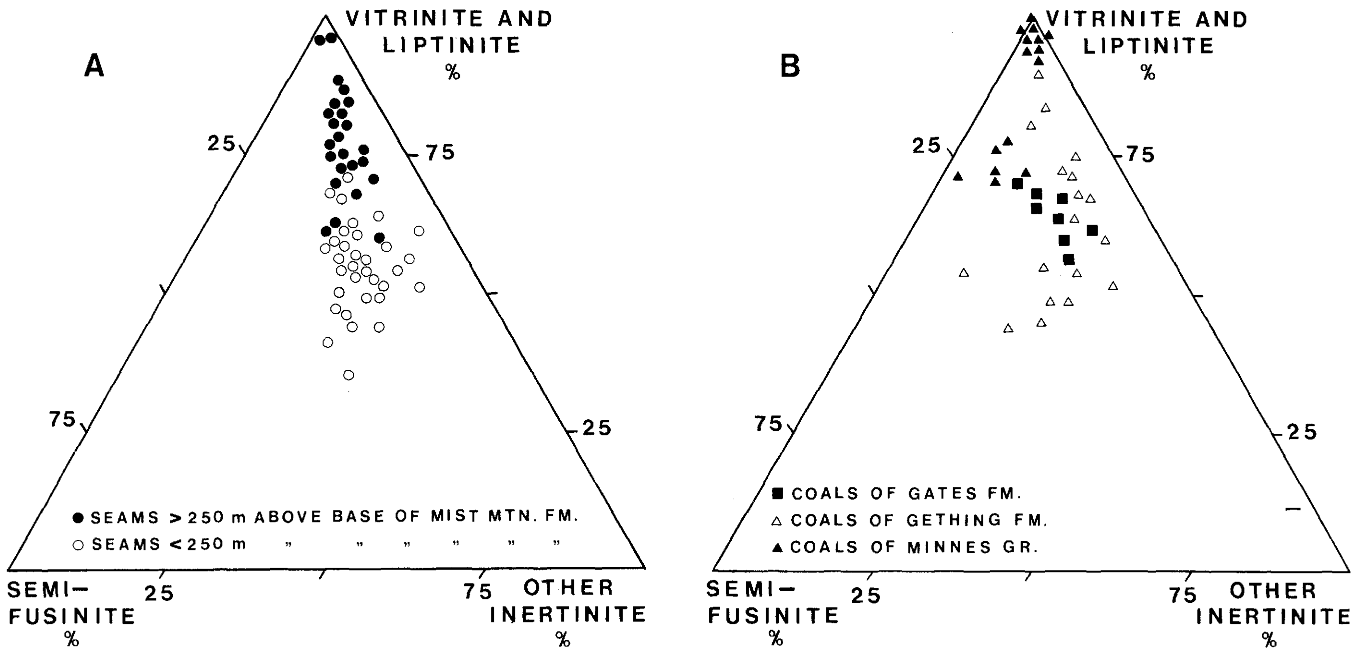

Figure 2. Maceral distributions for seams in Kootenay Group (A), and Minnes-Blairmore-Bullhead and Fort St. John groups (B).

Table 2. Representative sections with rank ranges.

No.[1]	Location Name	Stratigraphic Interval (m)	Formations in Stratigraphic Interval	Reflectance Range R_0 max.
1	Peace River Canyon	468	Gething	[2] 1.5 - 1.36
2	Rocky Creek	591	Gething-Cadomin Bickford	0.61 - 1.32
3	Mt. Minnes	1200	Gething-Gorman Creek	0.63 - 0.92
4	Smoky River	294	Gates	[2] 1.40 - 1.83
5	Mountain Park	369	Gates	[2] 0.85 - 1.27
6	Barrier Mtn.	700	Elk-Mist Mtn.	1.48 - 2.50
7	Canmore-Mt. Allan	873	Elk-Mist Mtn.	[3] 1.30 - 2.65
8	Upper Elk Valley	approx. 900	Elk-Mist Mtn.	[4] 0.64 - 1.16
9	Weary Ridge	498	Mist Mtn.	1.04 - 1.56
10	Sparwood	1090	Elk-Mist Mtn.	[3] 0.61 - 1.45
11	Cabin Creek	170	Mist Mtn.	1.10 - 1.19

[1] Geographic Position on Figure 1.
[2] Data from Hacquebard and Donaldson (1974).
[3] Data in part from Hacquebard and Donaldson (1974).
[4] Data from Graham et al (1977).

separated now lie in close proximity. Another possible explanation may be alternation due to localized sources of heat, such as suggested for the Canmore area by Norris (1971). Rank variations in the northern coals are equally difficult to explain. A complicating factor is the possible effect of substantial contents of alginite on reflectance as seems to be the case in some of the Minnes coals.

UTILIZATION POTENTIAL

Because of the high rank of many of the seams, and the low sulphur content of nearly all of them, a number of coals in both northern and southern groups are attractive for their coking potential and indeed at present about 14,300,000 tons annually (1980 figures) are being mined for this purpose. A review of the coking potential of these coals reveals: a) a wide range of maceral content, and much of the range suited to coking; b) coals range from oversaturated in inerts to oversaturated in reactives; c) many of the "inert oversaturated" coals produce better coke than might be expected so that it appears that a large part of the low-reflecting inertinite is reactive to the carbonization process (Koensler, 1980). In liquefaction potential: a number of the coals have "total reactive" contents of more than 70 percent and reflectances of 0.50 to 1.00; according to Davis et al (1976), these should be attractive prospects for this purpose.

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PETROGRAPHY OF THE MAMMOTH COAL SEAM, BULL MOUNTAIN BASIN, MUSSELSHELL COUNTY, MONTANA

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POSITION AND EXTENT

The Bull Mountain coal field is 40-50 mi north of Billings, Montana, along Highway 87. The coal field is mainly in Musselshell and Yellowstone counties, extending into portions of Golden Valley, Stillwater, Treasure, and Rosebud counties (Figure 1), and lies within the limits of 107°30'W to 108°50'W and 46°10'N to 46°40'N (Woolsey and others, 1917).

GENERAL GEOLOGY

The study area is commonly referred to as the Bull Mountain Basin (Woolsey and others, 1917). An asymmetrical syncline is the major structure, probably the result of sediments draped over a basement fault (Shurr, 1967). This syncline trends east-west, and has smaller synclines and anticlines superimposed on it; no beds dip more than 5 degrees.

The outcropping rock in the Bull Mountain area is the Fort Union Formation (Figure 2) which is underlain in sequence by the Lance and Bearpaw formations (Woolsey and others, 1917). An apparent unconformity exists between the Lance and Bearpaw here because of the missing Fox Hills Sandstone which is present in northern and central Montana. The Fort Union Formation is composed principally of sandstone, coal, and light to dark-gray shale. The lower 200 to 300 ft (Lebo Member) is mainly dark-colored shale, usually olive-green, drab, and gray, with thinly bedded arkosic sandstone containing little coal. Lithology of the Upper Fort Union member is principally massive sandstone, buff to yellowish-gray with interbedded light-colored shale and coal (Woolsey and others, 1917). Coals mined in the past were the Carpenter, Roundup and Mammoth seams; at the present, only the Mammoth is being mined.

RESULTS

Megascopic Description - The megascopic analysis of coal involves description of the coal stratification in terms of coal lithotypes, partings, and roof and floor rock. Megascopic descriptions in the past have been performed on different types of exposures such as mine walls, outcrops or on polished blocks of the coal seam.

In the strictest sense of the term megascopic description, that of a detailed description of the coal itself, very little has been done in North America (Cameron, 1976). Few coal geologist and petrologists think the data obtained from megascopic examination are worth the effort or are as reliable as microscopic analyses. These attitudes stem from poor reproducibility of results and from different methods of naming and defining the various lithotypes: vitrain, clarain, durain, and fusain. The ICCP Handbook (1971) and Stach and others (1975) describe these lithotypes and state that for vitrain, durain, and clarain, a thickness of 3 to 10 mm is needed for the lithotype to be noted, depending on the country. For instance, West German coal workers use a scale of 1:10 where 1 mm is the smallest unit for drawing (Stack and others, 1975). Cameron (1976) used the lithotypes of the ICCP Handbook, making a bright-dull division of the clarain in an attempt to categorize some of the differences in this abundant constituent. He used a thickness measurement of less than 10 mm to describe the lithotypes, especially

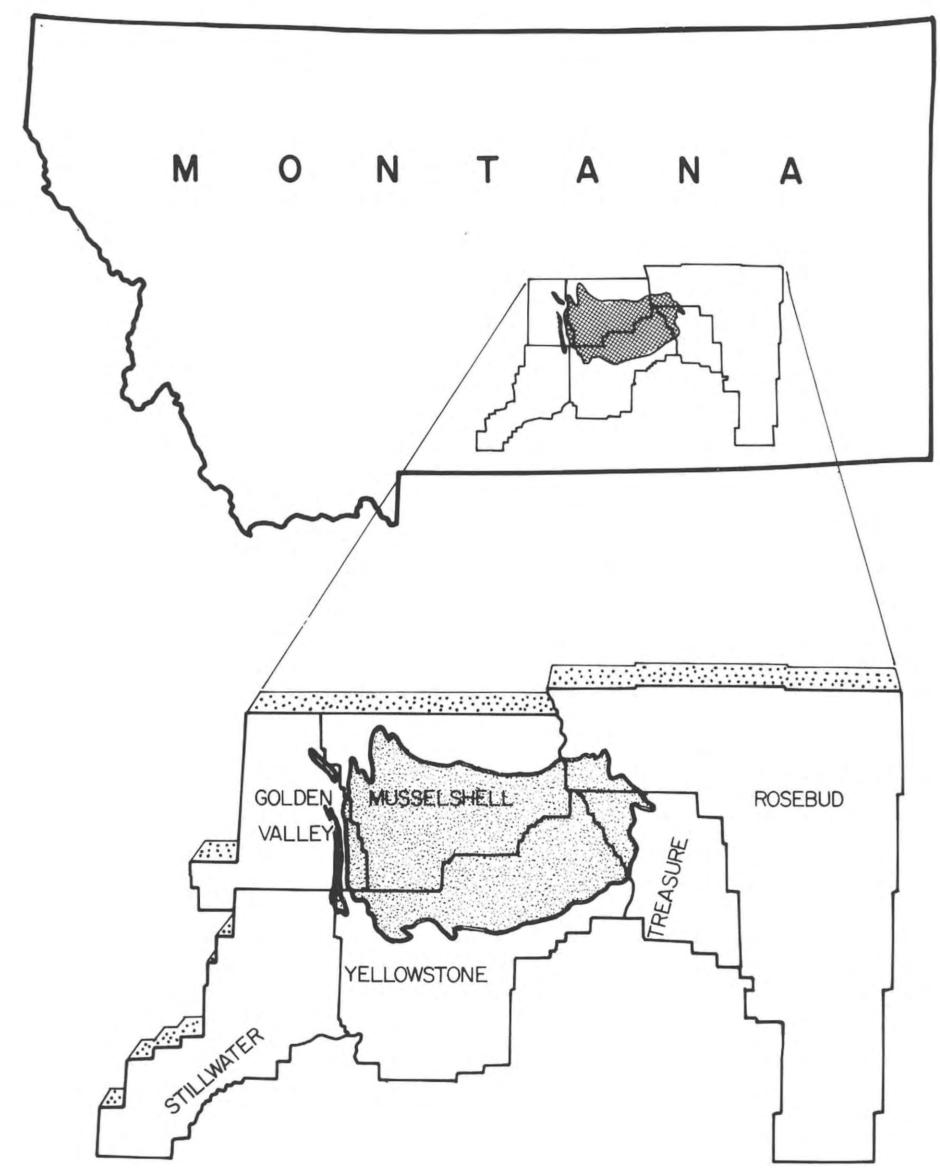

Figure 1. Position and extent of the Bull Mountain coal field.

vitrain and fusain, on a polished block. Schopf (1960) proposed the following terminology for the U. S. Geological Survey description of coal: vitrain, fusain, and attritus, with attritus divided into five groups ranging from bright to dull. Davis (1976) suggested using the terms bright and dull coal to describe the overall appearance of layers on a broad scale when convenient for a specific purpose.

Descriptions of the different lithotypes in coal are as follows (ICCP, 1971; Stach and others, 1975):

1. Vitrain: very bright black bands or lenses, frequently brittle and crossed by fine cracks. In

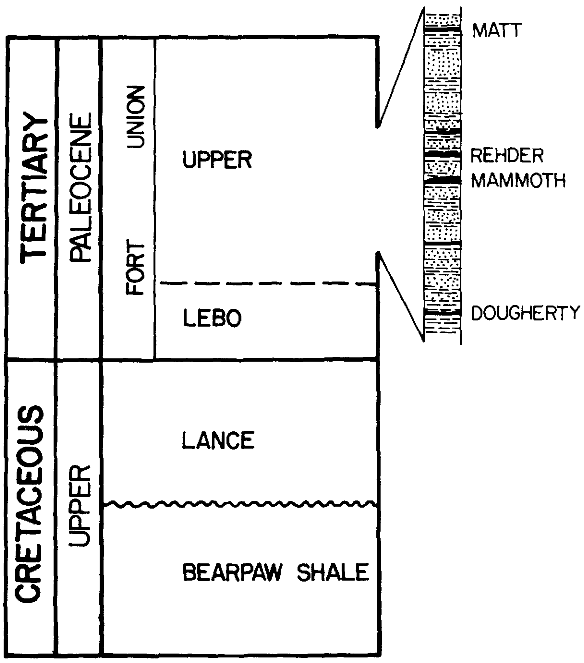

Figure 2. Stratigraphy of the Bull Mountain area (from Woolsey, Lupton, and Richards, 1917).

humic coals, vitrain is widely distributed and the second most abundant lithotype after clarain;

2. Clarain: very finely stratified coal layers having an overall luster between that of vitrain and durain. Clarain consists of alternating layers of vitrain, duraine and some fusain and is the most abundant lithotype in humic coal;

3. Durain: gray to brownish-black, dull, sometimes with a greasy luster. It is very hard with rough surfaces and usually breaks into large lumps. In humic coals, durain occurs in bands up to many centimeters in thickness but is not widely distributed;

4. Fusain: resembles wood charcoal and is black, soft, friable (distintegrates to black powder when roughly handled), and has a silky luster. Occasionally a hard fusain occurs as fusain impregnated with mineral matter, recognizable under the microscope. Fusain usually occurs as microscopically fine inclusions, but sometimes as bands or lenses up to 20 mm thick.

To show the stratification of alternating lithotypes, a megascopic description of the Mammoth coal bed was made on a seam section of polished blocks. Figure 3 is the profile of the megascopic description of the upper bench of the Mammoth coal and Figure 4 is the profile of the lower bench. These two benches are separated by a shale parting 7.5 cm thick. This profiles were drawn to the scale of 1:10 (Stach and others, 1975), and bands of vitrain, clarain, and durain 10 mm or more in thickness were recorded. Other lithotypes noted in these profiles were fusain, impure coal, shale or clay partings, pyrite, the roof rock and the floor rock (underclay).

Figures 3 and 4 are intended as a general megascopic description for field comparison purposes. For example, from the profile of upper bench is quickly summarized as a bright coal with the top 8 cm being dull and pyrite-rich, and the interval from 20 to 30 cm being vitrain-rich and very bright. The lower bench is a more consistent coal, except for the top 5 to 6 cm which are duller than the rest of the bed.

Figures 5 and 6 show megascopic profiles of the upper and lower benches of the Mammoth coal using the lithotypes and method of Cameron (1976). Clarain is divided into bright and dull fractions and lithotypes are recorded if they are greater than 1 mm in thickness. These two figures show a more detailed megascopic description of the seam than do Figures 3 and 4 which follow Stach and others (1975). For example, in Figure 5, the top of the coal (0-10 cm) is more accurately described than in Figure 3 because of the division of the clarain lithotype. In further comparison of the two profiles, Cameron's (1976) method shows greater percentages of vitrain and of the duller fractions of coal. Overall, Figures 3 and 4 show the coal as bright in nature throughout the profile but Figures 5 and 6 show the coal as having a duller appearance towards roof and floor and a very bright appearance towards the center of the seam. The advantage of more detailed profiles (Figures 5 and 6) is that they can be of assistance in correlations as more data become available.

Microscopic Examination - The use of reflected-light microscopy for analyzing coal is a technique to determine the differences in the average composition in a seam (Stach and others, 1975). Microscopic examination of coal is conducted on coal particle pellets, each forming a representative sample of an increment. The coal pellet is made by crushing the sample to -20 mesh, mixing it with epoxide resin,

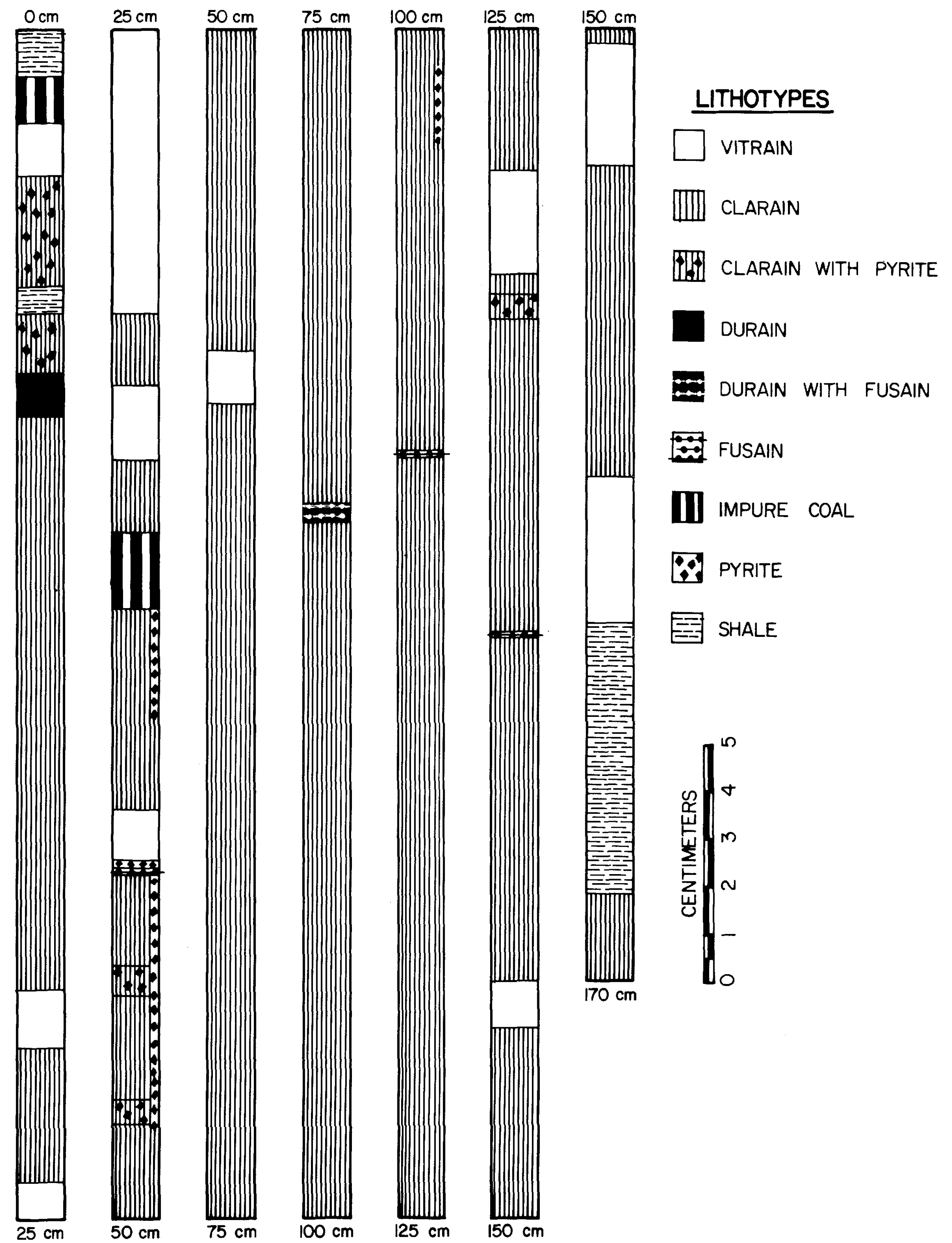

Figure 3. Strip log of the Mammoth coal master column.

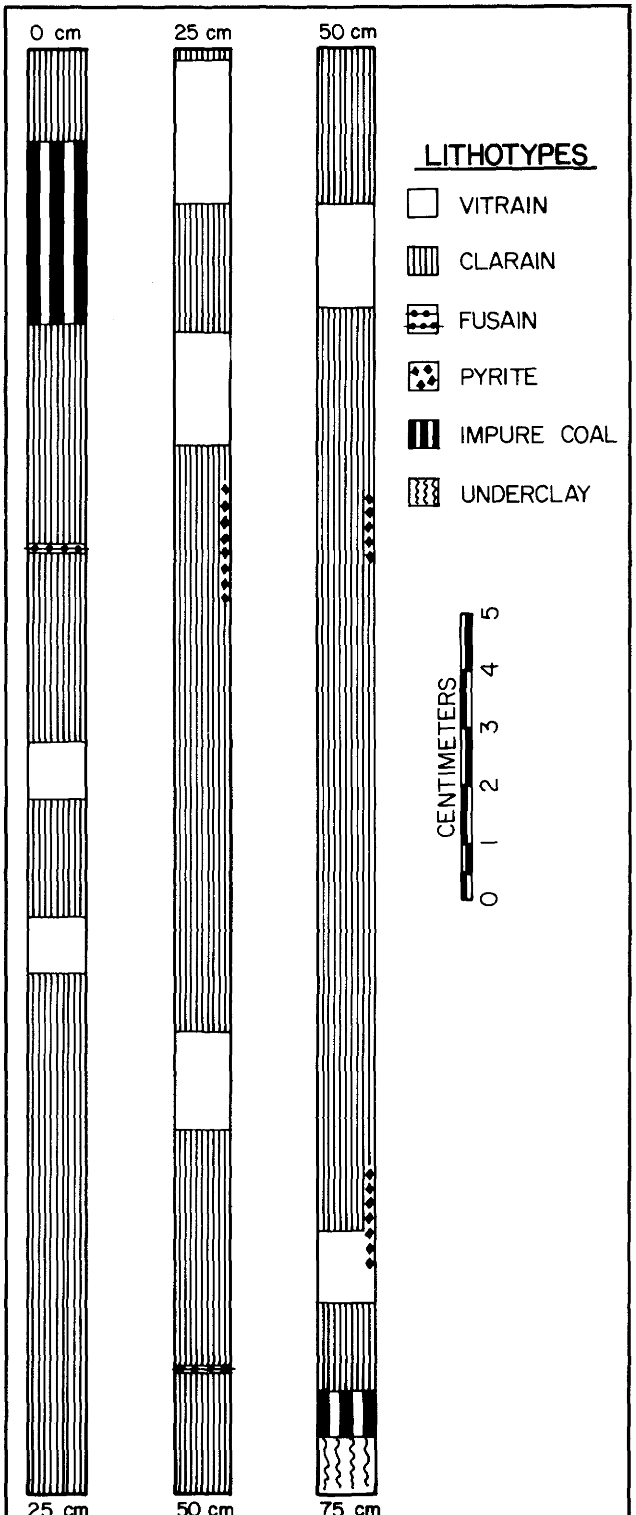

Figure 4. Strip log of the Mammoth coal master column.

and pressing it into a pellet (Weidman and Kopp, 1978; ASTM, 1981). The pellet is then ground and polished to a high luster. Macerals are point-counted to determine the composition of the coal. By analyzing the Mammoth coal in one foot increments, a general idea can be presented about the variation of maceral content due to the subsidence of the coal swamp.

The nomenclature used to describe the maceral species is listed in Table 1. The vitrinite group is the most common maceral group identified in the mammoth coal seam. Vitrinite is a medium gray-colored maceral formed by the alteration and gelification of humic material (lignin and cellulose) (Flaig, 1968). Rapid subsidence of the coal swamp (enough to keep the organic material submerged) promotes formation of vitrinite.

Table 1. Nomenclature used in anlayzing the coal pellets (ICCP Handbook).

Vitrinite group	Vitrinite
Inertinite group	Fusinite Semi-fusinite Inertodetrinite
Exinite group	Resinite Sporinite Cutinite

The inertinite group is present throughout the Mammoth coal seam although not very plentiful. Fusinite, semi-fusinite, and inertodetrinite have a higher reflectance than vitrinite because of the higher concentration of carbon in the inertinite maceral. Inertinite macerals are formed by oxidation of the peat when the water level of the swamp lowered, exposing the organic material. Part of the oxidation process includes burning of the peat by occasional fires in the swamp (Spackman and others, 1976).

The exinite group is comprised of the remains of spores, pollen, resins and waxes. Sporinite is the remains of the spores and pollen, resinite the remains of plant resins, and cutinite the remains of the cuticles or waxy parts of leaves. The exinite group has a lower reflectance than the vitrinite group.

The results from microscopic examination of the Mammoth coal seam are shown in Figure 7. With values ranging from 66 to 93 percent, vitrinite is the most abundant maceral group present in the Mammoth coal seam. Abundance of the inertinite and exinite groups are much less, with values ranging

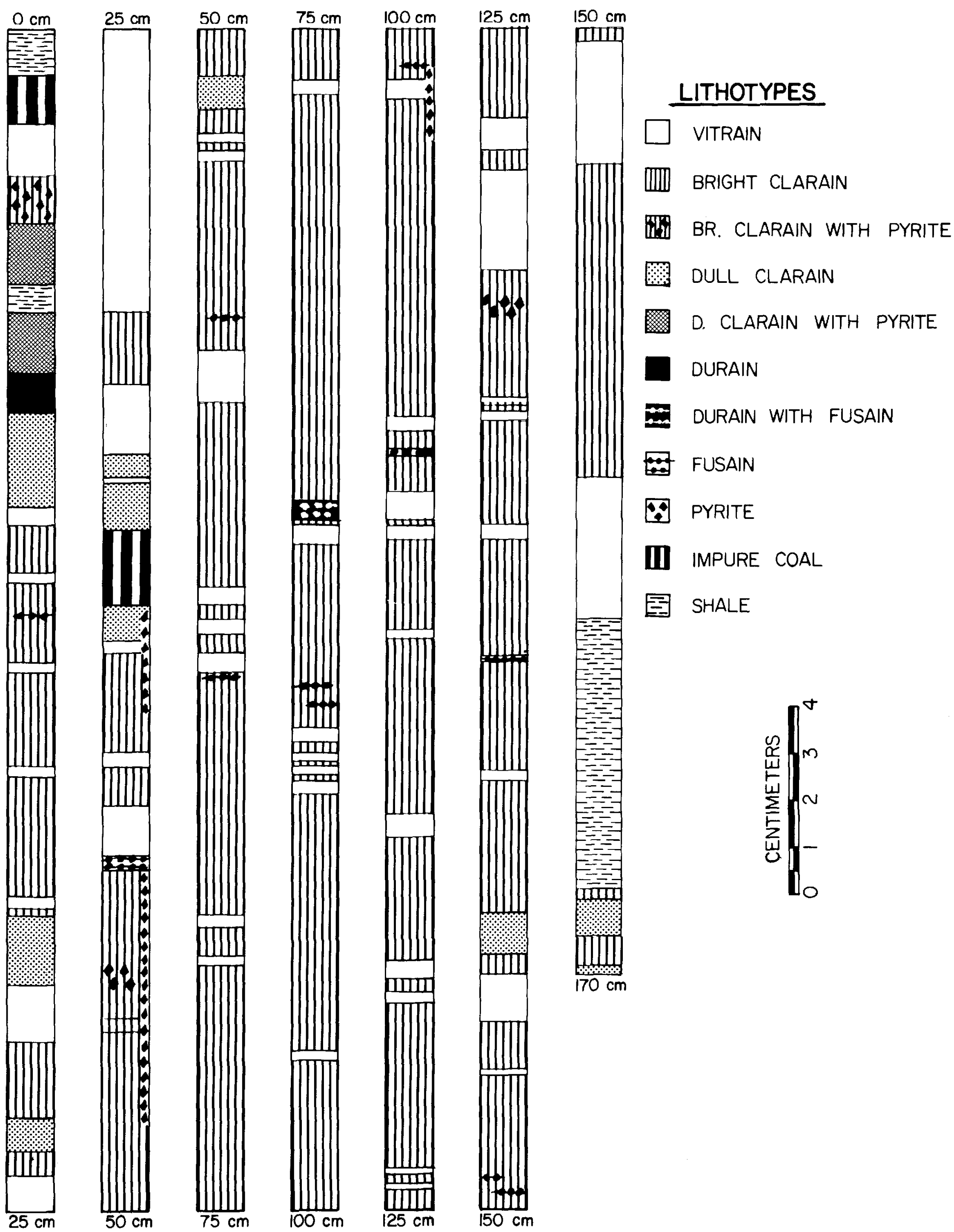

Figure 5. Strip log of the Mammoth coal master column.

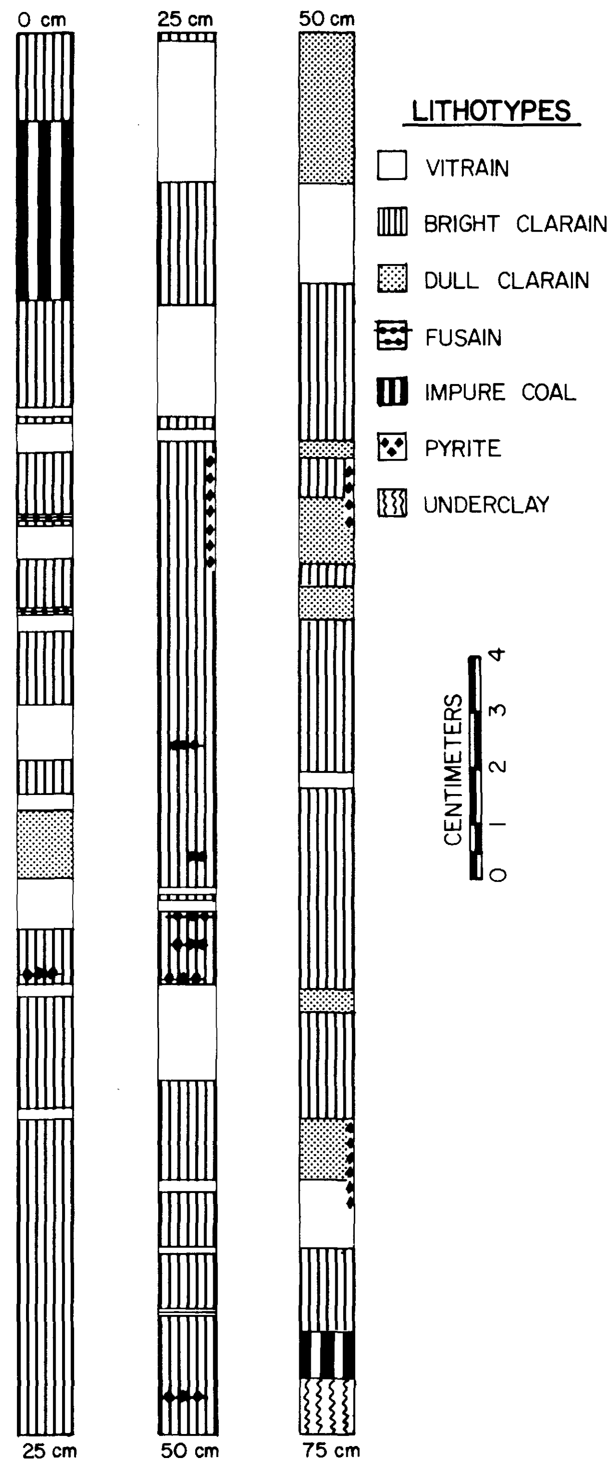

Figure 6. Strip log of the Mammoth coal master column.

from 2.8 to 28.7 percent and 1.6 to 11.1 percent, respectively.

Individual macerals in the three groups were also analyzed but not necessarily point-counted because of their scarcity. Macerals counted through point-counting were: vitrinite (non-delineated), resinite, sporinite, cutinite, fusinite, semi-fusinite, and inertodetrinite. Specific macerals observed were telinite and collinite, telocollinite, gelocollinite, corppocollinite of the vitrinite group and liptodetrinite of the exinite group. Reflectance ranged from 0.4 to 0.5 percent throughout the coal.

Low Temperature Ash Mineralogy - To determine the amount of mineral matter in the Mammoth coal seam, a low temperature asher (LTA) was used. An LTA oxidizes a coal sample at low temperature (100-110°C), leaving a whitish-gray powder containing the mineral phases in the sample. Because the coal is heated at low temperature, the minerals are relatively unaffected. Reactions that do occur are the dehydration of $CaSO_4\ nH_2O$ and, possibly, formation of reaction rims on the surface of the iron-sulfides. Given and Yarzab (1975) and Renton and Hidalgo (1975) have examined the use of an LTA for mineral matter determination in coal analyses and conluded that the LTA method is valid for mineral matter studies. Problems mentioned in these studies are the oxidation of some pyrite, loss of some carbonates by the formation of sulfuric acid from sulfates, and the transformation of some organic sulfur into sulfates.

Coal ash prepared by LTA methods is a complex mixture of minerals that vary in origin, size and orders of crystallinity. Analyzing the ash with X-ray diffraction can give quantitative results. Quartz and kaolinite are the two major phases evident from the XRD analysis with values ranging from 12.8 to 55.0 percent of the ash and 9.9 to 57.7 percent of the ash, respectively. Other minerals include varying amounts of calcite, anhydrite, gypsum, pyrite, siderite, plagioclase, illite and possibly other clays.

Distribution of the minerals determined by XRD of LT ash are shown in Figure 8. This graph is presented as a cross-section to show mineral distribution with varying thicknesses of coal. This diagram indicates the association of the mineral matter quantity and the proximity of sediments of over- and under-lying rocks and partings. In the increments near to the sediments, larger amounts of mineral matter were determined by LT ash, probably the effect of closeness to detrital sources. As the

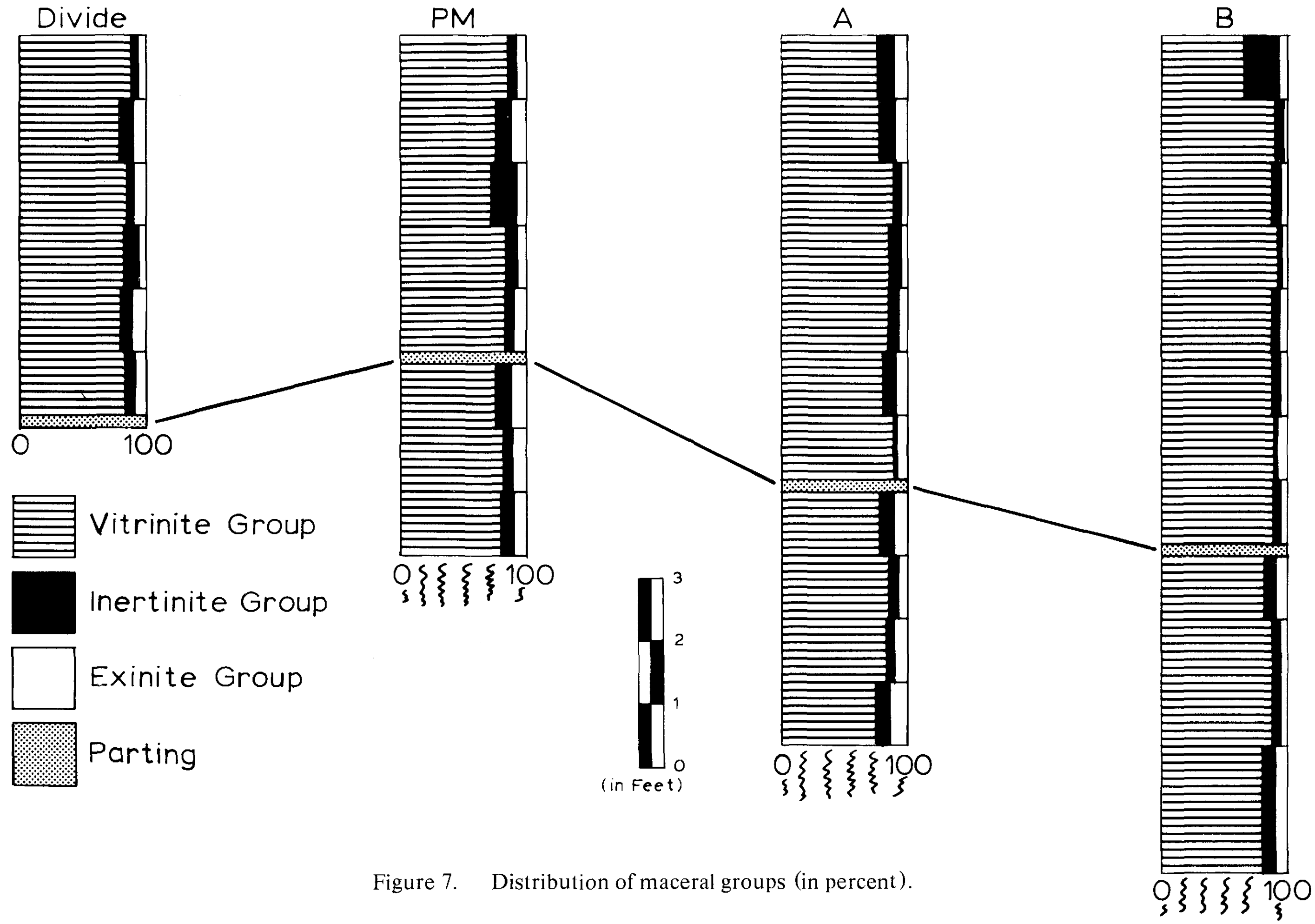

Figure 7. Distribution of maceral groups (in percent).

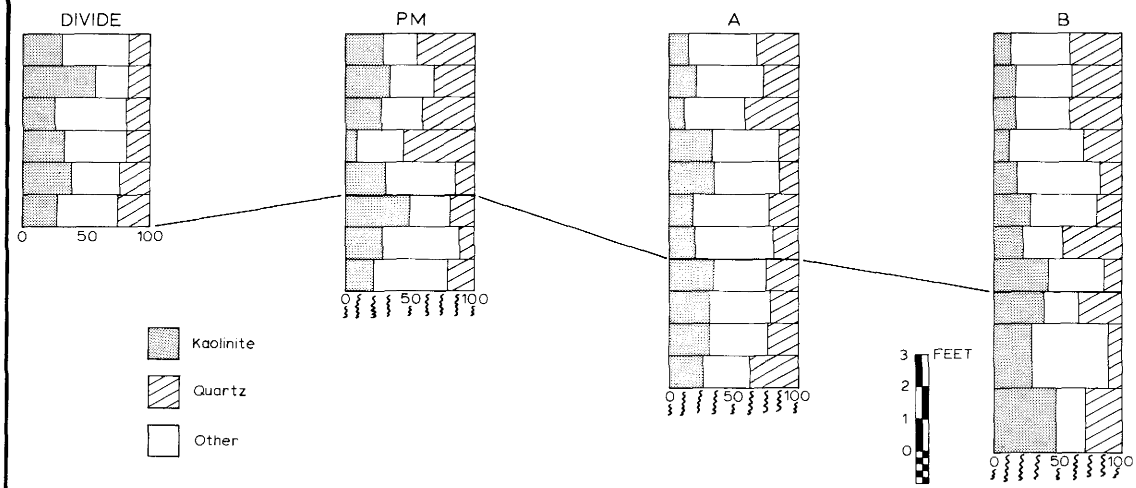

Figure 8. LTA mineralogy (in percent).

source migrated further away, the effects diminished, i.e., cleaner coal. The amount of mineral ash determined by LTA ranges from 4.76 to 28.30 percent.

INTERPRETATIONS AND CONCLUSIONS

1. Megascopic and microscopic analyses of various sections of the Mammoth coal show that the coal was deposited in a constantly subsiding environment indicated by the large amount of vitrinite. The inertinite and exinite groups are evenly distributed throughout the coal, except for an occasional sample interval (Figure 7), and the variations in the inertinite concentration suggest a change in the subsidence rate, which exposed peat, increasing the inertinite concentration.

   More detailed work is needed in the maceral distributions to delineate the subtle facies changes in the peat swamp. One method of analysis would be more extensive use of blocks instead of particle pellets. The preliminary work of this study has shown that this type of procedure may be worthwhile in determining subtle changes in maceral facies throughout the coal seam.

2. In past studies, the amounts and ratios of certain minerals to each other in the low temperature ash have been used to determine influences in the environment of deposition either during deposition or immediately following deposition. Kemezys and Taylor (1964), Gluskoter (1967), Hidalgo (1969) and Renton (1979) showed that coals more influenced by fresh water have higher ratios of kaolinite to illite and lower pyrite content. The occurrence of siderite also indicates fresh water influences.

The LTA mineralogy reinforces the fresh water origin for the Mammoth coal because of the extremely high kaolinite to illinite ratios (illite was not even detected in most samples, a high siderite content (as high as 16 percent in some cases), and a low total sulfur and low syngenetic pyrite content (most of the pyrite is epigenetic, occurring as cleat-fill).

The abundant kaolinite and siderite and the low sulfur content found in the Mammoth coal seam indicate the coal swamp formed in a fresh-water environment. Sedimentological evidence (Shurr, 1967) shows the coal formed in the flood plain of a low sinuosity fluvial system. The fluvial system left crevasse splay deposits that covered parts of the flood plain and plant material. The parting that runs through the lower third of the Mammoth coal seam probably represents the distal portions of a crevasse splay. Observation of Figure 9 shows zones of high mineral content (greater than 20 percent); these

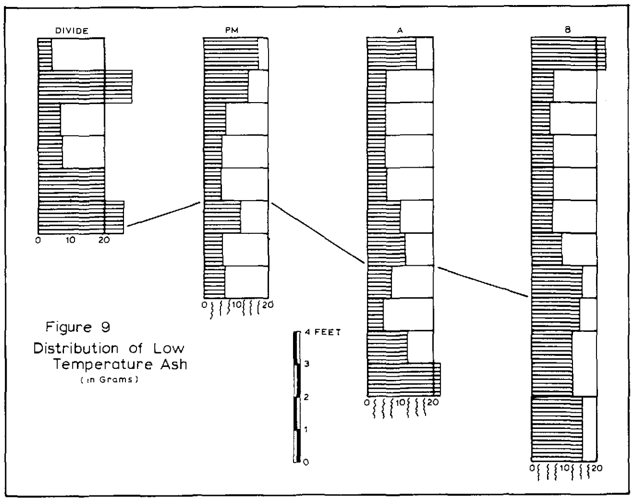

Figure 9. Distribution of low temperature ash (in grams).

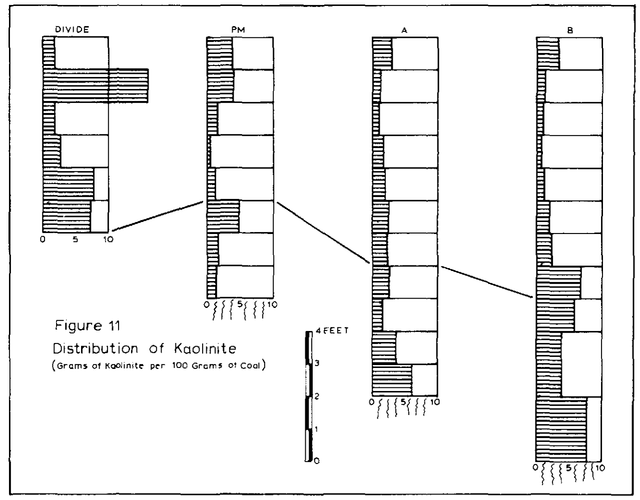

Figure 11. Distribution of kaolinite (grams of koalinite per 100 grams of coal).

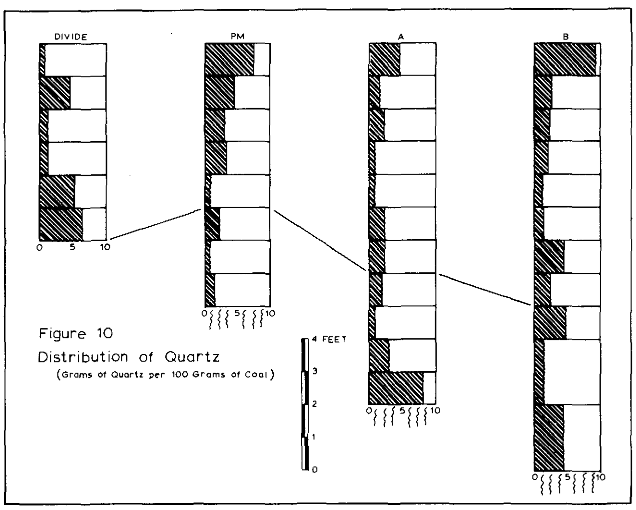

Figure 10. Distribution of quartz (grams of quarts per 100 grams of coal).

zones indicate high levels of detrital quartz that were left by splay deposits.

One zone in the Divide channel sample has a high mineral content but only a moderate level of quartz as compared to the corresponding interval in Figure 10. However, the amount of kaolinite in Figure 11 is extremely large, suggesting detrital kaolinite was deposited or other detritus deposited was altered into kaolinite from the acidic swamp water (Millot, 1970).

This study gives a general interpretation of the conditions in the coal swamp that formed the Mammoth coal seam; it was a flood plain of a low sinuosity fluvial system that was subsiding due to basement faulting. The sediment influx of the fluvial system had a minimal effect at the coal sample locations. Additional research is needed to give a complete understanding of the formation of coal in the Bull Mountain Basin.

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PETROGRAPHY AND FLUORESCENCE PROPERTIES OF BITUMINOUS COALS OF THE SPANISH PEAKS REGION, COLORADO

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INTRODUCTION

All coals studied are from the Trinidad coal field in south central Colorado. The ten samples were from drill cores, mines, and outcrops, all in Las Animas County. Figure 1 gives the location of the study area and outlines the boundaries of the coal field. The work reported here presents a portion of the results of a cooperative agreement between the Colorado Geological Survey and the Department of Geology at Southern Illinois University-Carbondale.

Rocks exposed at the surface in the area are Upper Cretaceous and Tertiary in age and occur in the northern part of the Raton structural basin. Commercial coals occur mainly in the Upper Cretaceous Vermejo Formation, in the Raton Formation which spans the Cretaceous-Tertiary boundary and in the lower few hundred feet of the Poison Canyon Formation which overlies the Raton. These coals in the lower portions of the Poison Canyon Formation are local in extent. Coals from the Trinidad coal field are considered as coking coals and some are utilized as blending coals for the production of metallurgical coke.

In the late Paleocene or early Eocene, the Sangre de Cristo mountains to the west were uplifted causing tilting and folding of strata in the sample area (Baltz, 1965). In this area the Raton structural basin is asymmetric to the west with the strata adjacent to the mountains vertical to overturned. The sediments on the eastern edge of the Trinidad coal field dip gently to the west. Further details on the geology of the region and the geology of the coals in particular are presented by Johnson and Wood (1956), and Johnson (1961, 1968, 1969).

During the Eocene or early Oligocene, the sediments of the region were intruded by magmas that formed sills, dikes, plugs, stocks, sole injections, and lacoliths (Johnson, 1968). Many of these intrusions locally altered the coal and some of the enclosing sedimentary rocks.

The effect and extent of the alteration, primarily by dikes and sills, has been reported upon extensively by Johnson (1961), Campbell and Dutcher (1964), Dutcher, Campbell, and Thornton (1966), Crelling and Dutcher (1968), and Podwysocki and Dutcher (1971). Coal seams have been virtually replaced in some local areas by sills, extensive natural coke has been formed by dikes and sills and some coals have been increased in rank by the proximity of intrusives even though actual contact may not exist.

OBJECTIVES

There are three primary objectives of this ongoing study. The first is to learn more about the poorly understood petrology of these coals with maceral and reflectance analyses. The second objective is to study the qualitative and quantitative properties of the fluorescent macerals in these coals as a continuation of work reported by Crelling and Dutcher (1980). The third objective is to investigate the effects of increasing rank on the petrographic properties of these coals.

REFLECTANCE ANALYSIS

To determine the rank of the coal reflectance, measurements were determined utilizing a Leitz Orthoplan MPV II microscope at 500X magnification using a 50X oil immersion objective. In general the procedure outlined in ASTM Standard 2798-79 were followed except that additional readings were recorded for pseudovitrinite.

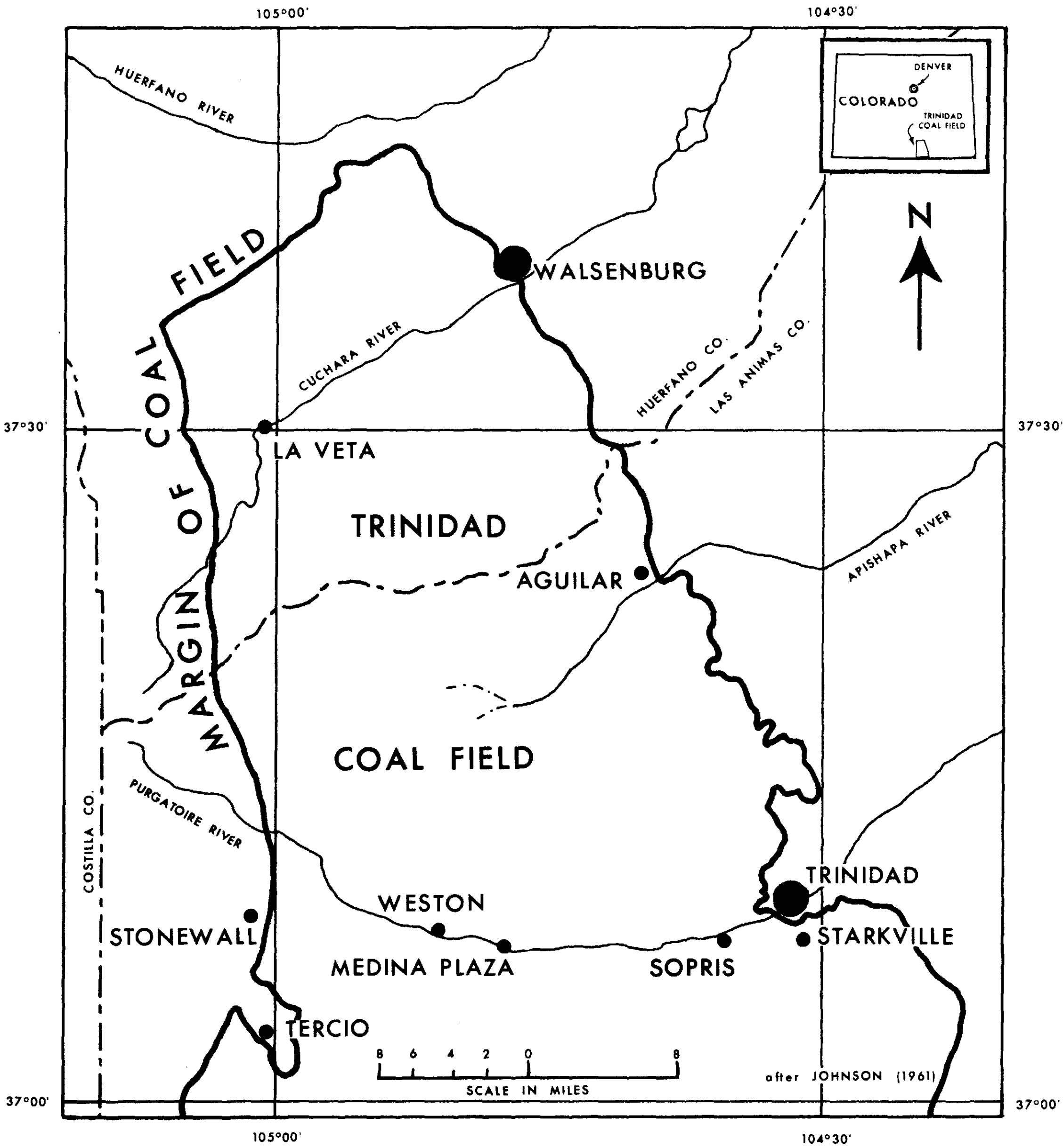

Figure 1. Index map of sample area.

The results of reflectance analyses given in Table 1 are the averages from measurements taken on "normal" vitrinite and pseudovitrinite, combined on a proportional basis. The reflectance values for these coals increase to the south along the eastern edge of the coal field. This regional trend in rank is illustrated, using other rank parameters, in a report by Goolsby et al (1979). An interesting result of the reflectance analyses is that the difference in percent reflectance between pseudovitrinite and vitrinite decreases as the mean maximum reflectance of the samples increases. At 0.92 percent mean maximum reflectance, Benedict et al (1968) indicated that in their studies of Appalachian coking coals a similar trend occurred. They state that the magnitude of this difference in reflectance diminished above 1.4 percent mean maximum reflectance. However, their diminished values do not decrease to the point of going below the limits of reproducibility, even at a sample reflectance of 1.79 percent. This indicates that

Table 1. Results of maceral analyses in white light.

SIU-C No.	575C	580C	573C	660	661	570	567C	666	664	665	663
Formation Seam	Vermejo Unnamed	Vermejo Unnamed	Raton Delagua	Raton Boncarbo	Raton Boncarbo	Raton Allen	Raton Apache	Vermejo Unnamed	Raton Primero	Raton Frederick-Martinez	Vermejo Unnamed
Reflectance, % (mean-max in oil)	0.70	0.72	0.76	0.76	0.76	0.77	0.87	0.92	0.93	1.05	1.21
Maceral Composition, % (white-light)											
Vitrinite	63.1	69.2	56.3	68.3	65.5	67.7	67.6	74.7	80.2	78.6	75.1
Pseudovitrinite	22.2	12.3	19.3	18.4	18.0	14.8	10.6	3.0	14.8	15.2	8.6
Semi-fusinite	4.9	8.9	8.7	5.1	6.2	5.9	8.4	11.9	1.3	3.4	9.8
Semi-macrinite	2.0	2.2	5.7	2.1	3.1	2.9	4.9	2.8	0.7	0.4	1.3
Fusinite	2.2	2.3	2.8	1.7	1.9	2.1	2.1	4.7	1.4	1.1	3.8
Macrinite	1.3	2.0	2.8	1.1	1.1	1.6	2.8	1.7	0.2	0.6	0.7
Micrinite	0.5	0.2	0.6	0.4	0.3	0.5	1.7	1.2	0.2	0.7	0.7
Exinite	3.1	2.4	2.8	2.1	3.6	3.8	0.8	0.0	1.0	0.0	0.0
Resinite	0.7	0.5	1.0	0.8	0.3	0.7	1.1	0.0	0.2	0.0	0.0
Total (Group)											
Vitrinite	85.3	81.5	75.6	86.7	83.5	82.5	78.2	77.7	95.0	93.8	83.7
Liptinite	3.8	2.9	3.8	2.9	3.9	4.5	1.9	0.0	1.2	0.0	0.0
Inertinite	10.9	15.6	20.6	10.4	12.6	13.0	19.9	22.3	3.8	6.2	16.3

there is a difference between the reflectance trends of the vitrinitic macerals from these two regions.

MACERAL ANALYSIS

White Light Analysis — Maceral composition was determined using an E. Leitz SM Lux microscope. Crushed-particle pellets were read at 500X using 10X occulars and a 50X oil immersion objective with oil of refractive index of 1.5180. The following macerals were counted: Vitrinite, pseudovitrinite, semifusinite, semimacrinite, fusinite, macrinite, micrinite, exinite and resinite. The occurrence of pyrite, mineral matter, voids and epoxy under any of the counting points was not included in the total.

The total volume percentage of each maceral was counted and recorded for each pellet. A comparison of the average difference of the values between two pellets of the same sample had to match to within 2.0 percent according to ASTM Standard D-2799-72. The only variations from this standard were that only 500 points were counted on each pellet and that pseudovitrinite, semimacrinite and macrinite were included. If agreement was not obtained, the pellets were recounted, which in all cases gave acceptable results. The volume percentages of each maceral from matching pellets were averaged to obtain the composition of that sample.

The white light maceral composition of the samples is reported in Table 1. The samples are listed according to increasing mean maximum reflectance of the seam so that trends in maceral composition that follow changes in rank will be apparent. The inertinite component varies between 3.8 - 22.3 percent showing no apparent trend with increasing mean maximum reflectance. The vitrinitic macerals vary between 75.6 - 95.0 percent, also showing no trend with increasing rank. The liptinite component varies between 0.0 percent for the samples with the greatest mean maximum reflectance (0.92, 1.05, 1.21 percent) to 4.5 percent for a sample with 0.77 percent mean maximum reflectance. There is a definite trend towards decreasing amounts of liptinites with increased rank.

Pseudovitrinite in these samples was identified primarily by its reflectance which is slightly higher than that of the associated vitrinite. Pseudovitrinite also appeared as "clean" particles devoid of other macerals, often showing slitted structures, brecciated edges and remnant cell structure. All of these characteristics conform to those described by Benedict et al (1968), who defined pseudovitrinite in Appalachian coking coals. It is noted, that particles having the morphology of vitrinite and/or pseudovitrinite, yet the reflectance of semifusinite were observed. Because of their significantly higher reflectance they were counted as semifusinite.

Two types of sclerotia, single celled and multicelled, were observed in these coals. The reflectance of the sclerotia varied between those of fusinite and semifusinite.

Sporinite, cutinite, and resinite were the macerals identified and counted as liptinites. Particles composed of sporinite, cutinite, resinite, and "inerts" within a mass of vitrinite were commonly encountered. Cutinite was present as very thin and long bodies, difficult to detect. Rounded or globular masses that had a reflectance slightly lower than the associated vitrinite, along with a distinctly different luster were identified as resinite. Pyrite, although not abundant, was observed as grains, predominantly framboidal in nature. No weathering was detected in any of the coal samples.

Harvey et al (1979) reported the average maceral composition for coals from the Illinois basin and some Appalachian seams. It is recognized that portions of the three maceral groups vary with rank level and therefore, a comparison of average maceral composition between basins across a wide spectrum of rank levels could be misleading.

The closest similarity to these Trinidad coals is seen in the coals of the Illinois basin which are slightly lower in rank. The percentage of vitrinitic macerals reported for coals from the Illinois basin is 83 percent compared to 82.9 percent for coals of this study. The Trinidad coal field inertinite average (14.3 percent) is similar to that of the Illinois Basin (9 percent) and 50 percent lower than that given for Appalachian seams (28.5 percent) (Harvey et al, 1979). The liptinite value is at least 70 percent less for coals of the Trinidad coal field (2.8 percent) than for both of the other basins (Illinois, 8.5 percent, Appalachian, 8.7 percent). Benedict et al (1968) stated that pseudovitrinite comprises 20-30 percent of the vitrinitic macerals of the Appalachian coking coals in their study. Compositions reported in Table 1 show pseudovitrinite to comprise an average of 14.3 percent of the vitrinitic macerals of the coals studied from the Trinidad coal field. Pseudovitrinite does not form as large a percentage of the coals from the Trinidad coal field as it does in the Appalachian coking coals.

Fluorescent maceral analysis — The fluorescent maceral analysis was run on a Leitz Orthoplan MPV II microscope at 500X magnification. A 100 watt Hg lamp with a BG 23 filter and a BG 12 blue-light filter were used. The light was passed to a vertical illuminator adapted with a TK 400 mirror. Light to the occulars was filtered through a K510 barrier filter. Because blue light excitation reveals additional maceral types and aids in the identification of all liptinites, it was possible to count the following: sporinite, cutinite, resinite, fluorinite, exudatinite and amorphous liptinite. In this analysis non-fluorescing macerals were also counted in such a way that the results were directly comparable to those previously described for the white light maceral analysis. Care was taken to examine the pellets within 24 hours of polishing to insure fresh, oil free surfaces.

The fluorescent maceral composition of the different samples is reported in Table 2. The samples are grouped according to increasing mean maximum reflectance so that changes in volume percentage at different rank levels will be apparent. There are percentage increases in liptinites ranging from 17 to 135 when the coal samples are evaluated utilizing fluorescence techniques. The two main reasons for these increases are: 1) exinite and sporinite are easier to detect when they fluoresce, and 2) some organic entities not noted at all in routine white light analysis are seen because they fluoresce. Prior to the use of fluorescence microscopy these might have been recorded as voids or mineral matter.

Sporinite shows diminishing intensity and a change in color towards red with an increase in rank level. In samples of mean maximum reflectance 0.70 and 0.72 percent, sporinite is bright yellow and yellow-orange. In sample of 0.76 percent mean maximum reflectance sporinite is bright orange. Sporinite is dark orange to a faint orange in samples of mean maximum reflectance of 0.87 percent. Sporinite was counted in sample SIU 664 which has a mean maximum reflectance of 0.93 percent. This

Table 2. Results of maceral analyses in blue light.

SIU-C No.	575C	580C	573C	660	661	570	567C	666	664	665	663
Seam	Vermejo Unnamed	Vermejo Unnamed	Raton Delagua	Raton Boncarbo	Raton Boncarbo	Raton Allen	Raton Apache	Vermejo Unnamed	Raton Primero	Raton Frederick-Martinez	Vermejo Unnamed
Reflectance, % (mean-max in oil)	0.70	0.72	0.76	0.76	0.76	0.77	0.87	0.92	0.93	1.05	1.21
Maceral Composition, % (blue-light)											
Sporinite	3.4	2.5	2.8	2.8	3.4	3.3	1.8	0.0	0.7	0.0	0.0
Cutinite	1.1	1.0	1.1	0.7	0.5	0.5	0.1	0.0	0.1	0.0	0.0
Resinite	0.7	0.6	1.2	0.5	0.4	0.4	0.2	0.0	0.3	0.0	0.0
Fluorinite	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Exudatinite	1.0	1.4	2.4	0.5	0.6	0.7	0.4	1.2	0.1	0.3	0.0
Amorphous Liptinite	1.0	1.2	1.4	1.1	1.3	0.7	0.6	0.4	0.2	0.7	0.0
"Other" macerals	92.7	93.3	91.0	94.4	93.8	94.4	96.9	98.4	98.6	99.0	100.0
Total Liptinite (blue-light)	7.3	6.7	9.0	5.6	6.2	5.6	3.1	1.6	1.4	1.0	0.0
Total Liptinite (white-light)	3.8	2.9	3.8	2.9	3.9	4.5	1.9	0.0	1.2	0.0	0.0
Increase	92%	131%	137%	93%	59%	24%	63%	—	17%	—	—

sporinite was dark orange and very dull, with less distinct morphology, making it less prominent than those in coals of lower rank levels. No sporinite was observed in the two highest rank level samples.

Cutinite also showed parallel changes in color intensity with increasing rank level. The cutinite of rank levels lower than 0.87 percent was dull orange and faint in intensity. Only one point in a thousand was counted as cutinite at mean maximum reflectance 0.93 percent and none at higher rank levels.

Following changes in color in resinite across rank levels is complicated by the occurrence of two resinites of different color. In samples with a mean maximum reflectance of 0.70 percent, a bright yellow and an orange resinite are present. The bright yellow resinite is the more common of the two and was most often observed associated with semi-inerts in grains of vitrinite. Samples with mean reflectance of 0.76 percent had only orange resinite present. This resinite was less bright than that of the samples of 0.70 percent mean maximum reflectance. However, at 0.87 percent reflectance a very low intensity orange resinite was observed as was a two-tone, circular resinite that has a khaki-green perimeter and a yellow center. This resinite occurs as small pods and is scarce. The orange resinite of these samples was fainter than in all previous samples. It is assumed by a comparison of the similar morphology of these three more common resinites that they are the same original maceral, the difference in color and intensity the outcome of different degrees of coalification or oxidation. And, therefore, it can be said that, as with sporinite and cutinite, resinites show a shift in color toward the red end of the spectrum with an associated decrease in intensity. No resinite was observed in the two highest rank samples.

Although our planned fluorescence spectral studies are not yet completed, initial results on the resinite macerals illustrated in Figure 2 show a strong spectral shift in the wavelength of maximum intensity on similar types of resinite macerals in coals of 0.70 and 0.77 percent reflectance.

Exudatinite and amorphous liptinite are the only fluorescent macerals that were counted in the samples of mean maximum reflectance of 1.05

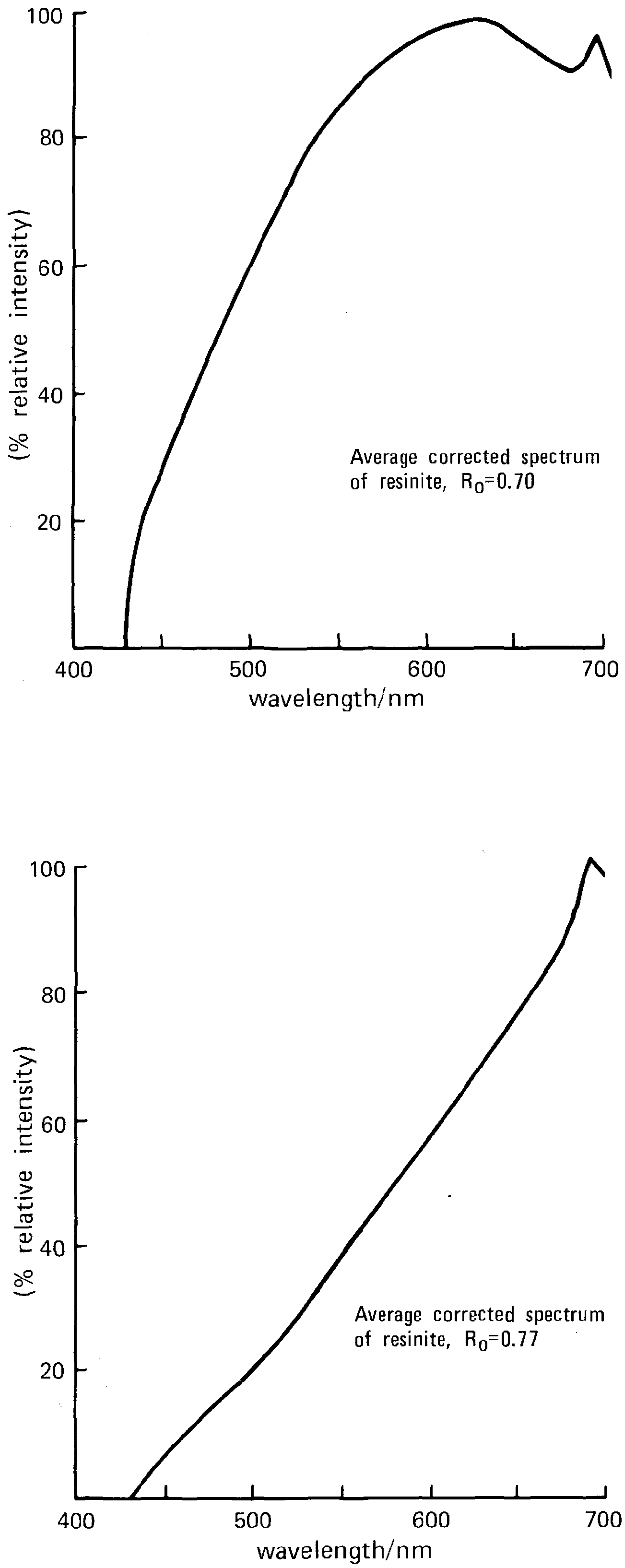

Figure 2. Average corrected spectra of resinite showing effects of increasing rank.

percent. At rank levels above 0.87 percent mean maximum reflectance, the exudatinite is dark, dull orange, and progressively fainter. It generally occurred as a filling in cracks within vitrinite grains and cell lumens of inertinite macerals.

Fluorinite was counted only in samples SIU 575C and SIU 573C, which have a mean maximum reflectance of 0.70 and 0.76 percent, respectively. It occurred as small lenses within vitrinite particles and in some cases was associated with cutinite. This maceral appears to be the most sensitive to changes in rank.

Any vitrinitic maceral that did not appear black, in the same way that inert macerals appear under UV light, was counted as fluorescing vitrinite, and in all of the samples examined well over 50 percent of the vitrinite was fluoresced. Because the intensity of fluorescence and the luster of the fluorescing vitrinitic macerals varies within samples and through rank levels, this was judged to be the most objective method of differentiating a fluorescing vitrinitic maceral from a non-fluorescing one. An example of this can be best illustrated in sample SIU 567C. In this sample, the orange color of the fluorescing vitrinite maceral appeared to cover an entire particle with a velvet-like luster. This is in contrast to lower rank level samples which display an easily discernible dull-orange color that shows less depth, and higher rank level samples in which the fluorescing vitrinitic macerals are a subdued brown. It is important to note that only the normal vitrinite macerals fluoresced. Pseudovitrinite was not observed to fluoresce.

EFFECTS OF INCREASING RANK

One of the major petrographic effects of increasing coal rank is that the liptinite macerals disappear in higher rank coals. Teichmüller (1975) calls this disappearance the second coalification jump and places it at a reflectance of about 1.30 percent at the boundary between medium and low volatile rank coal. Thompson and Benedict (1974) also note a discontinuity in the metamorphic series corresponding to the disappearance of the liptinite macerals and they place it at a reflectance of 1.35 to 1.40 percent. The results of this study show that no liptinite macerals were observed in white light at or above the reflectance 1.05 percent. This observation is in fair agreement with that of Ting and Sitler (1979) who reported the disappearance of liptinite macerals at 1.10 percent. However, the results of the fluorescence analysis in this study indicate that most of the liptinite macerals start to disappear well below 1.05 percent reflectance. For example, fluorescence intensity noticeably decreases in the 0.7 to 0.8 percent reflectance range and gets very weak in the 0.8 to 0.9 percent reflectance range. The fluorescence colors shift toward the red end of the spectrum and this is also confirmed by spectral measurements which show an increase in the wavelength of maximum intensity in the same reflectance range.

The persistance of exudatinite in the coal sample with a reflectance of 1.05 percent is probably due to its nature as a secondary maceral. It appears to be a material exuded from other coal macerals during the coalification process (Teichmüller, 1974) and its persistance in coals after the other liptinite macerals have dissappeared is not surprising.

Both the alteration and disappearance of the liptinite macerals and the lack of any reflectance difference between vitrinite and pseudovitrinite indicate that the coals studied from the Spanish Peaks area have responded to the increase in rank in a different way than the coal of other basins. These coals are also different from the coals of many other basins in that their rank is higher than expected for their age. The high volatile to medium volatile bituminous rank and the Cretaceous-Tertiary age of the coals of the Spanish Peaks region contrast with many of the coals of the Appalachian basin which have a similar rank but are of Carboniferous age.

Although reasons for the different responses to coalification of these coals are not completely clear at this time, more rapid coalification had to be a major factor. The abundance of ingnious intrusions, which often produce natural coke, may well be a related factor. An alternate and less likely reason is that the macerals in the coals of this region may be fundamentally different in some way that caused them to react differently to coalification.

CONCLUSIONS

There are anomalies in rank in the coals examined from the Trinidad coal field. The reflectance difference between vitrinite and pseudovitrinite becomes statistically insignificant at much lower reflectance values than in Appalachian coals. In Appalachian coals this difference is still significant as high as the upper end of the low-volatile rank range and with the coals studied it becomes insignificant at the upper end of the high-volatile rank range. The primary liptinites disappear at a lower level in these coals when they are compared to those in the Appalachian region. There are spectral shifts for the liptinites which also occur at lower reflectance levels. All of these changes may be caused by locally high temperature gradients caused by the well documented igneous activity in the area which has caused the formation of natural coke encountered in one of the samples.

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PETROGRAPHIC AND FLUORESCENCE PROPERTIES OF RESINITE MACERALS FROM WESTERN U.S. COALS

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INTRODUCTION

Although resinite macerals occur in almost all U. S. coals, they are particularly abundant in some western U. S. coals, especially in coals from Utah as reported by Spieker and Baker (1928), Thiessen and Sprunk (1937), Tomlinson (1932), and Buranek and Crawford (1952). The latter authors report concentrations of resinite varying from trace amounts to 14.9 percent by volume. It is also commonly observed, that the resinite in the western coals of Cretaceous and Tertiary age tends to commonly occur in cleats and fissures where it is observable megascopically, (Thiessen and Sprunk, 1937; Buranek and Crawford, 1952). Cleat and fissure-filling resinite in coals from England has been reported by Jones and Murchison (1963) and by Murchison and Jones (1964). They conclude that the increased temperature and pressure of coalification in the bituminous range was sufficient to gently mobilize some of the resinite macerals to coalesce into globules and veins without increasing the reflectance or causing vesiculation of the resinite. On the basis of infrared spectral properties and carbonization behavior Murchison (1966) was able to divide the resinite macerals into two types — one type occurring only in coals of subbituminous rank or lower and the other type occurring in bituminous coals. Murchison (1976) also noted that much of the resinite in bituminous coals occurred as interconnected globules and veins and he concluded that this was of secondary origin. In this, he agreed with Teichmuller (1974a,b) who concluded that based on their petrographic and fluorescence properties, these mobilized substances should be classified as separate macerals which she called both exudatinite and secondary resinite. Teichmuller observed that these substances seemed to be exuded from other macerals during the subituminous to bituminous coalification range and that they varied widely in their fluorescence properties. A study by Crelling and Dutcher (1979) using fluorescence microscopy showed that at least two forms of resinite, primary and secondary were present in bituminous coals from Utah.

OBJECTIVES

The objectives of the ongoing study reported here are to define the nature of the resinite macerals in western U. S. coals by:

1. Classifying the various types of resinite macerals on the basis of their petrographic and fluorescence properties;

2. Separating the various types of resinite macerals by methods ranging from hand-picking to density-gradient separation; and

3. Characterizing the separated resinite macerals on the basis of their chemical, physical, and technological properties.

This paper reports on preliminary results of the classification phase of this study.

PROCEDURES

Based on their high resinite content and general availability, samples of five coal seams listed in Table 1 were collected. Each sample was characterized petrographically with a maceral analysis in white light and a reflectance analysis (mean-maximum reflectance in oil). These analyses generally conform to the ASTM standard procedures. A maceral

Table 1. Results of petrographic analysis.

SIU No.	Seam	Location	Combined Maceral Analysis: Vitrinite	Pseudovitrinite	Semifusinite	Semimacrinite	Fusinite	Macrinite	Micrinite	Sporinite	Resinite	Cutinite	Alginite	Fluorinite	Bituminite	Exudatinite	Amorphous Organic Matter	Reflectance % mean max. in oil
507 B	Blind Canyon	Utah	61.4	9.1	10.6	0.8	2.6	0.3	3.8	1.4	8.1	0.6	0.0	0.0	0.0	0.8	0.5	0.56
558	Hiawatha	Utah	73.7	7.8	3.4	0.8	1.2	0.1	3.8	0.5	6.9	0.8	0.0	0.0	0.0	0.3	0.7	0.52
1132	Subseam #3	Utah	70.2	12.2	3.9	0.8	1.7	0.3	4.3	0.3	5.2	0.7	0.0	0.2	0.0	0.3	0.0	0.51
1133	Castle-gate A	Utah	58.7	9.8	9.1	0.5	3.8	0.4	3.1	2.0	8.5	1.8	0.0	0.3	0.0	1.2	0.8	0.50
1134	San Juan	New Mexico	64.2	11.6	6.8	0.8	2.3	0.2	6.6	1.3	3.9	1.0	0.0	0.0	0.0	0.7	0.6	0.46

analysis in fluorescent light was also performed on each sample and the two maceral analyses were combined as shown in Table 1. The maceral analysis in fluorescent light was run with a Leitz MPVII Orthoplan microscope equipped with an HG 100-watt light source with a BG 23 heat-filter, a BG 12 blue-light filter, a TK 400 dichroic mirror and a K510 barrier filter. Fluorescence spectral measurements covering the range of 450 to 700 nm on resinite macerals were taken with the same instrumentation except that the BG 12 filter was replaced with a UG 1 filter and the barrier filter was replaced with a K 430 filter. The spectral measurements were corrected for background and system effects following procedures described by van Gijzel (1979). The spectra were also reduced to eight parameters:

1. λmax - the wavelength of maximum intensity;

2. red/green quotient - the relative intensity at 650 nm divided by the relative intensity of 500 nm;

3. area blue - percent area under the curve between 400 to 500 nm;

4. area green - percent area under the curve between 500 to 570 nm;

5. area yellow - percent area under the curve between 570 to 630 nm;

6. area red - percent area under the curve between 630 to 700 nm;

7. area < λ max - area under the curve less than the wavelength of maximum intensity;

8. area > λ - area under the curve greater than the wavelength of maximum intensity.

RESULTS

The results of the reflectance analyses and combined maceral analyses given in Table 1, show that all of the coals are near the rank boundary between subbituminous and bituminous and that they contain a large amount of resinite — between 3.9 and 8.5 percent of the whole coal by volume. During the analysis it was observed that many of the fluorescing macerals including resinite were often difficult to see and identify in white light. This observation is borne out in Table 2 which shows that there was an increase in observed liptinite macerals in fluorescent light that ranged between 63 and 224 percent. Table 3 shows the distribution of the liptinite

Table 2. Comparison of analyses of total liptinite group macerals in white light and blue light.

Sample No.	Seam	% Liptinite Macerals White Light	% Liptinite Macerals Blue Light	% Increase
SIU-507B	Blind Canyon	3.7	11.4	208
SIU-558	Hiawatha	4.8	9.2	92
SIU-1132	Subseam # 3	4.1	6.7	63
SIU-1133	Castlegate A	4.5	14.6	224
SIU-1134	San Juan	4.5	7.5	67

Table 3. Distribution of liptinite macerals in resinite-rich Rocky Mountain coals.

Sample No.	Seam	Sporinite (%)	Resinite (%)	Cutinite (%)	Fluorinite (%)	Exudatinite (%)	Amorphous Liptinite (%)
SIU-507B	Blind Canyon	12.3	71.0	5.3	0	7.0	4.4
SIU-558	Hiawatha	5.4	75.0	8.7	0	3.3	7.6
SIU-1132	Subseam # 3	4.5	77.6	10.4	3.0	4.5	0
SIU-1133	Castlegate A	13.7	58.2	12.3	2.1	8.2	5.5
SIU-1134	San Juan	17.3	52.1	13.3	0	9.3	8.0

Table 4. Distribution of resinite types in resinite-rich Rocky Mountain coals.

Resinite Type		"Green" Resinite Type 1		"Yellow" Resinite Type 2		"Orange" Resinite Type 3		"Red-brown" Resinite Type 4
Sample No.	Seam	Fracture filling (%)	Ovoid (%)	Fracture filling (%)	Ovoid (%)	Fracture filling (%)	Ovoid (%)	Fracture filling (%)
SIU-507B	Blind Canyon	57.5	1.0	5.3	9.8	16.5	4.6	5.3
SIU-558	Hiawatha	86.0	1.9	2.6	4.3	0.8	0.7	3.7
SIU-1132	Subseam # 3	55.2	0.3	5.0	7.1	6.4	12.1	13.9
SIU-1133	Castlegate A	58.6	1.6	6.5	15.6	2.4	3.5	11.8
SIU-1134	San Juan	56.7	7.9	0	8.7	2.2	7.7	16.8

macerals and the fact that these five coals are different from most U. S. coals in that resinite and not sporinite is the most abundant liptinite maceral. In fact, resinite macerals make up between 52.1 to 77.6 percent of the liptinite macerals in these five coals.

Based on both the qualitative and quantitative (spectral) fluorescence analysis, the resinite macerals in these five coal samples can be classified into the four types described below:

Type 1 (Green-fluorescing resinite) — as seen in Table 4 this is the most abundant type of resinite and it makes up from 55.5 to 87.9 percent of the resinite in the coals studied. It occurs mainly as a fracture-filling material, although small amounts do occur as oval to irregularly shaped masses. In fluorescent light this material appears as a clear to translucent solid with angular fractures. However, much of it has a cloudy texture and some has a granular texture. Occasionally particles with a peculiar droplet texture (intensely fluorescing droplets in a cloudy to granular matrix) are seen. A few occurrences of a vesiculated texture are also observed. In addition flow structures and coal inclusions in the fracture-fillings are common. This

Table 5. Parameters of average resinite spectra.

Parameter	"Green" Resinite Type 1	"Yellow" Resinite Type 2	"Orange" Resinite Type 3	"Red-brown" Resinite Type 4
λ max (nm)	460	540	580	690
Red/Green Quotient	0.19	0.82	1.32	2.24
Area Blue (440-500 nm) (%)	34	21	12	8
Area Green (500-570 nm) (%)	42	42	31	25
Area Yellow (570-630 nm) (%)	15	21	27	27
Area Red (630-700 nm) (%)	9	16	30	37
Area < λ max	25	37	53	92
Area > λ max	75	63	47	6

type of resinite fluoresces with a very high intensity in colors ranging from a deep green to a lime-green. The average spectral properties, given in Table 5, show a spectral maximum well below 500 nm and a low red/green quotient of 0.19.

Type 2 (Yellow-fluorescing resinite) — as shown in Table 4, this is the only type of resinite that occurs mainly as oval to irregularly shaped masses, although it does also sometimes occur as fracture-fillings. Most of this type of resinite appears in fluorescent light as a clear to translucent solid with angular fractures. However, some granular and cloudy textures are observed as are flow, vesicular and brecciated textures. This resinite type fluoresces moderately with a yellow color. The average spectral properties, given in Table 5, show a spectral maximum at 540 nm and a red/green quotient of 0.82.

Type 3 (Orange-fluorescing resinite) — as noted in Table 4 this type of resinite occurs as both fracture-fillings and as oval to irregularly-shaped masses. In fluorescent light it appears as a clear to translucent solid material with angular fractures, although it occasionally has granular, cloudy, and flow textures. It fluoresces weakly with a yellow-orange to red-orange color. The average spectral properties of this resinite type, given in Table 5, show a spectral maximum at 580 nm and a red/green quotient of 1.32.

Type 4 (red-brown-fluorescing resinite) — as shown in Table 4 this resinite type occurs only as a void filling. It is found mainly in cell lumens of the semi-fusinite, fusinite and sclerotinite macerals and in small fractures. It is not found in the cleats and large fractures like the other three types. This material has no shape of its own and never appears as a solid material with fractures. It is seen to dissolve and mix with the immersion oil after very short exposure to ultra-violet excitation. This type of resinite fluoresces moderately to weakly with a red-brown color. The average spectral parameters, given in Table 5, show a spectral maximum at 690 nm and a very high red/green quotient of 2.24.

DISCUSSION

From the results of the petrographic study, it is clear that resinite types 1, 2, and 3 are similar to each other in that they all occur as both fracture-fillings and oval to irregular masses and in that they all appear as solid particles with angular fractures. Although the three types separate nicely on the basis of their fluorescence properties, some transitional types are present, especially between types 1 and 2. Additional work needs to be done to determine if there is, indeed, a continuous series from type 1 to type 3. Although the oval to irregular shaped masses are usually considered to be of primary origin — that is, deposited in that form in the original peat precursor of the coal — no significant difference in the fluorescence properties between the ovoids and fracture-filling forms of each resinite type has been found in this initial study. However, the fracture-filling forms of all the types are obviously the result of mobilization of the original resinite macerals. The occurrence in fracture-fillings, flow

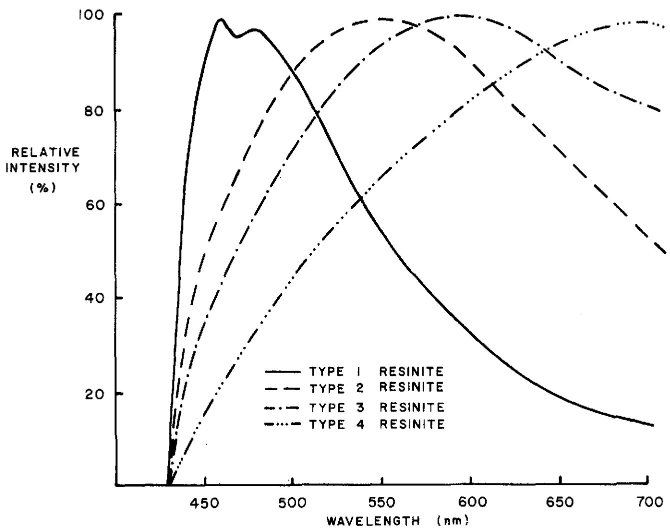

Figure 1. Spectral curves for four resinite types.

textures, coal inclusions, and vesiculated textures all support this conclusion. Thus, at least the fracture-filling forms of resinite types 1, 2, and 3, are secondary resinites resulting from mobilization of pre-existing resins.

The type 4 resinite is quite different from the other three types. It has no shape of its own and it fills cell lumens and small fractures. It reacts with the immersion oil and in general appears to be a substance exuded from other macerals during the coalification process, very similar to the material described as exudatinite by Teichmüller (1974a,b). As shown in Table 5 and in Figure 1, its spectral properties are also different from the other three types of resinite. Thus, type 4 is also a secondary resinite but quite different in its mode of occurrence and its petrographic and fluorescence properties.

Regarding the nomenclature of these secondary resinites, it is clear that Teichmüller's description of exudatinite — "its (exudatinite) fluorescence intensity and fluorenscence color vary widely, even in a single crack-filling and its appendices" (Teichmüller, 1974b, p. 382) — is broad enough to encompass the four types studied here. These four types of resinite could also be considered as exudatinite based on Murchison's agreement with Teichmüller that any mobilized resinite is exudatinite (Murchison 1976). However, additional work, particularly chemical analysis, is needed to further characterize the various types of resinite.

CONCLUSIONS

The results of this study show that the resinites in western U. S. coals fall into four distinctive types based on their petrographic and fluorescence properties. Most, if not all of the resinite macerals in these coals have been mobilized during coalification and are, therefore, of secondary origin. These may also be classified as exudatinite if it is necessary to utilize a maceral name as opposed to the group term liptinite. It may prove necessary to establish other names or some type of subdivision based on differences detected in this work.

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CURIE-POINT PYROLYSIS MASS SPECTROMETRY OF ROCKY MOUNTAIN COALS

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INTRODUCTION

Even the most seasoned coal scientist probably remembers his or her first confrontation with the coal characterization literature. The sometimes baroque nomenclature, the sheer number of tests used, the often ambiguous interpretation of the test results and the surprising heterogeneity of coals of different type and origin all combine to confuse the newcomer to the field. Of course, the problem described here is not unique to the field of coal science but appears to be the hallmark of a highly empirical scientific discipline in a relatively early stage of development. The time-honored strategy in such fields is to reduce the bewildering variety of phenomena to manageable proportions by means of classification methods. Not surprisingly, the art of classifying complex phenomena into correlating subsets ("classes") has been developed to high perfection in such fields as sociology, psychology, biology, and medicine. In contrast, chemists have long been rather reluctant to use empirical data reduction and analysis techniques.

More recently, however, the field of chemometrics has experienced rapid growth and development and now provides invaluable aid to chemists faced with highly complex analytical data. Application of chemometric techniques, such as factor analysis, to conventional coal characterization data has helped to reveal the major underlying correlated tendencies in these data as reported by Abdel-Baset et al 1978, and Waddell et al 1978. Nevertheless, collection of a sufficiently large conventional data base for coal characterization studies remains an extremely costly and time consuming endeavor. Moreover, most coal scientists feel the need for characterization methods which provide more information on the elusive "structure" of coal, or at least, on "key structural features" (Committee on Chemical Sciences of the National Research Council, 1979).

As a result, rapid physiochemical coal characterization techniques capable of providing multiple parameters in a single experiment are being developed by different groups around the world. Such techniques include chromatographic methods such as LC (Welsh et al, 1978) and GC (Philp and Saxby, 1980), spectrometric methods such as IR (Painter et al, 1981), and MS (Meuzelaar et al, 1981) and NMR (Zilm et al, 1981), as well as combined "hyphenated" techniques such as GC/MS (Van Graas et al, 1979), MS/MS (Meuzelaar et al, 1981) and LC/MS (Dark, 1977).

One of the most rapid techniques for coal characterization appears to be Curie-point pyrolysis MS, in which the sample is pyrolyzed directly in front of the ion source of a mass spectrometer. Promising results have already been reported by several different groups (Van Graas, 1980; Meuzelaar et al, 1981). Apart from the high speed, one of the strongest advantages of this approach is its compatability with computerized data processing methods (Windig et al, 1980). Furthermore, the high sensitivity of the Py-MS technique requires sample amounts in the microgram range, thus enabling the analysis of hand picked maceral samples, as reported by Larter et al (1980) and Van Graas et al (1979).

In an effort to investigate the full potentials of the Curie-point Py-MS approach we undertook a

Table 1. Conventional parameters used in correlation studies with pyrolysis mass spectra.

1. Total Vitrinites (Vitrinities and Pseudovitrinties)	14. Phosphorous, Percent of HTA (reported as oxide)
2. Fusinite	15. Percent Moisture (as received)
3. Semifusinite	16. Percent pyritic Sulfur (dry basis)
4. Total Macrinite (Macrinite, Micrinite, and Sclerotinite)	17. Percent Organic Sulfur (dry basis)
5. Total Liptinites (Sporinite, Resinite, Aliginite and Cutinite)	18. Percent Mineral Matter
6. Vitrinite	19. Percent Volatiles (dmmf*)
7. Silicon, Percent of HTA (reported as oxide)	20. Calorific Value (dmmf*)
8. Aluminum, Percent of HTA (reported as oxide)	21. Percent Organic Carbon (dmmf*)
9. Titanium, Percent of HTA (reported as oxide)	22. Percent Organic Hydrogen (dmmf*)
10. Magnesium, Percent of HTA (reported as oxide)	23. Percent Organic Nitrogen (dmmf*)
11. Calcium, Percent of HTA (reported as oxide)	24. Percent Organic Sulfur (dmmf*)
12. Sodium, Percent of HTA (reported as oxide)	25. Percent Organic Oxygen (dmmf*)
13. Potassium, Percent of HTA (reported as oxide)	

*dry, mineral matter, as determined by a modified Parr method.

study of over 100 Rocky Mountain coals and of some 25 conventional parameters on these coals. The results of this study will be reported here.

EXPERIMENTAL

A total of 102 coals from the Rocky Mountain province were selected from the Penn State Coal Sample Bank. Fine suspensions in methanol were prepared from each coal by grinding under liquid nitrogen and subaliquotting in a nitrogen atmosphere. Fifty microgram coal samples were coated on ferromagnetic wires and analyzed with the Extranuclear 5000-1 Curie-point pyrolysis MS system. The Curie-point pyrolysis mass spectrometry technique used has been described elsewhere (Meuzelaar et al, 1981). Analysis conditions were as follows: Curie-point temperature-610; temperature rise time-5 s; total heating time-10 s; electron impact energy-15 eV (Low Voltage EI); mass range-m/z 25-240, scanning rate- 10 spectra/s; total number of scans integrated: 200. Each coal sample was represented by two duplicate suspensions each of which was again analyzed in duplicate, thus resulting in 4 spectra per sample. Univariate statistical analysis methods using the interactive NORMA program (Meuzelaar et al, 1980) were used to eliminate badly reproducing spectra. Of a total of 408 coal spectra obtained on four consecutive days, only 8 spectra had to be deleted because of poor reproducibility. The remaining duplicate spectra were averaged. The residual mean peak height uncertainty in relative peak height in the averaged spectra was estimated to be 7.6 ($\pm$2.5) percent when including 25 of the most prominent and characteristic peaks. The averaged spectra representing the 102 coal samples were further analyzed by multivariate statistical analysis ("pattern recognition") techniques using the ARTHUR (Harper et al, 1977) program package.

Typically the data were autoscaled followed by principal component analysis. To enable correlation of the Py-MS results with conventional coal parameters on the Rocky Mountain coal set, 25 such parameters (Table 1) were selected from the Penn State Coal Data Bank and analyzed with the ARTHUR progam. Principal component analysis was followed by direct comparison between major factors as well as selected individual features of the Py-MS data matrix and the matrix of conventional parameters, using least squares (Target) rotation (Malinowski et al, 1980) or stepwise regression methods.

RESULTS AND DISCUSSION

The pyrolysis mass spectra in Figures 1 and 2 were selected to demonstrate the influence of differences in rank (Figure 1) and in depositional environment (Figure 2). The spectra are dominated by prominent homologous ion series believed to represent aliphatic and aromatic heteroatomic as well as hydrocarbon compounds in addition to a series of sulfur containing ion signals, as indicated in Figure 1. Nitrogen compound series (odd mass numbers) are difficult to identify because of interference with residual electron impact fragment ions. The most prominent effect of increase in rank appears to be a rapid decrease in heteroatomic compound series intensities, accompanied by a strong increase in aliphatic and aromatic hydrocarbon series. It should be noted that the pyrolysis mass spectra appear to offer a relatively broad view on coal structure since types and quantities of the observed building blocks

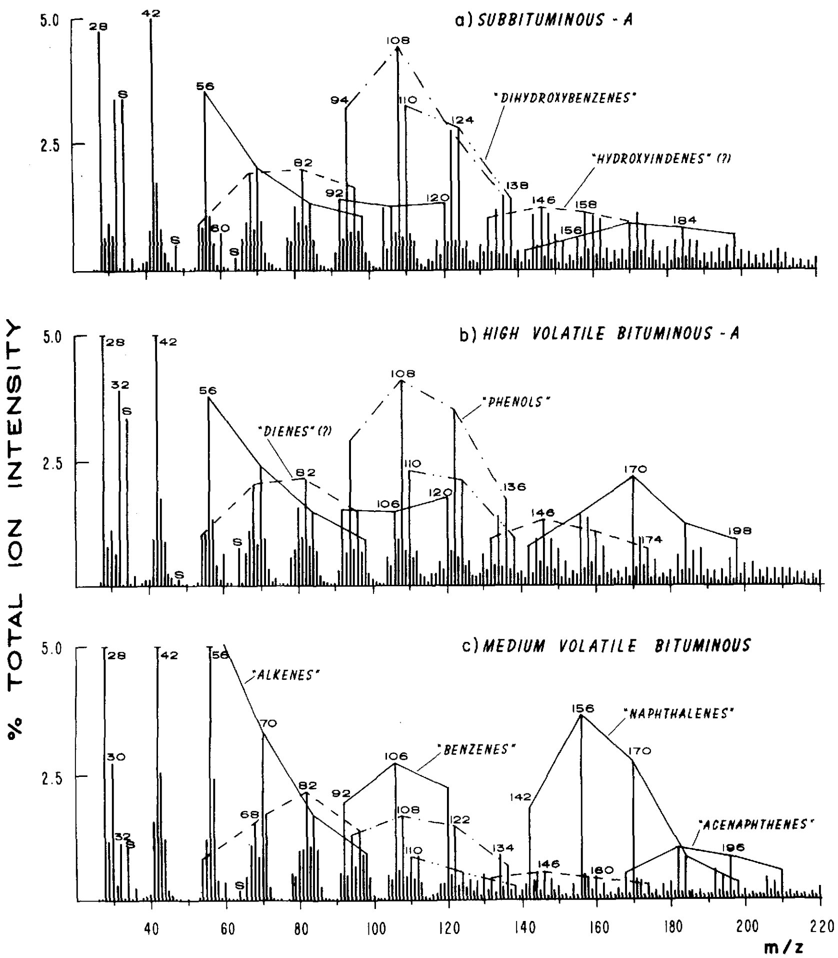


Figure 1. Low voltage pyrolysis mass spectra of UINTA region samples showing effects of rank differences.

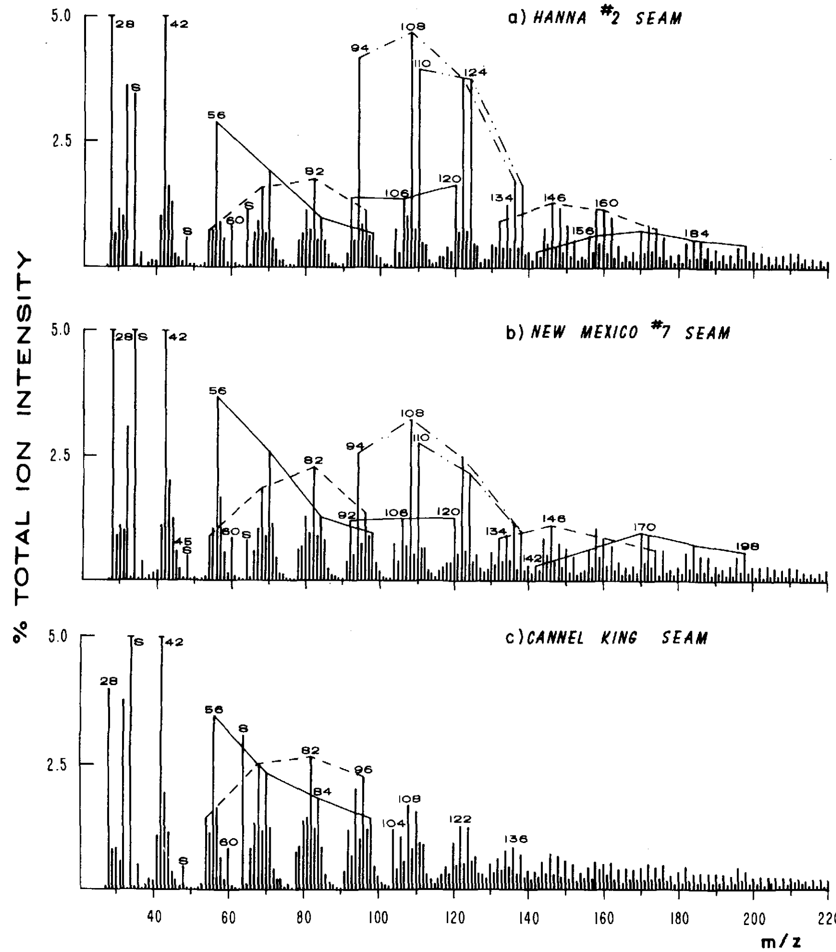


Figure 2. Low voltage pyrolysis mass spectra of three seams showing effects of depositional differences.

agree well with currently accepted coal structure models (Given, 1960; Wiser, 1977). The detectable pyrolysis yields of the sample, representing subbituminous through medium volatile bituminous ranks (the semianthracite from Crested Butte was eliminated because of low intensities caused by char formation), were roughly comparable and probably represent between 20-40 percent of the total sample mass pyrolyzed.

Upon evaluation of the pyrolysis patterns by computerized numerical methods the following specific problems were addressed and are discussed in chronological order below:

1. How representative are the spectra for the corresponding coal seams?
2. What is the chemical nature of the rank related differences in the spectra?
3. What information can be obtained on depositional environment and geological history?
4. What type of correlations exist between the spectral data and conventional coal parameters?
5. Can important technological parameters such as calorific value or liquefaction yield be predicted from the pyrolysis patterns?

Representativity of the spectra for the coal seams - Figure 3 shows a plot of the first two principal components [the Karhunen Loeve (KL) projection] of the Py-MS data matrix, together explaining approximately 35 percent of the total variance. The tendency of spectra from the same seams, e.g. Cannel King, Upper Sunnyside, Dakota, Colorado B, to cluster together is quite apparent. This is even more remarkable when taking into account that two of the Cannel King samples were collected ten years before the other samples; that the Colorado B samples were also collected at intervals of several years and that the Upper Sunnyside seam samples represent two different locations several miles apart. Since the heterogeneity of coal seams with regard to macro-and microlithotypes is well established, this supports the idea of a rather tenuous link between coal morphology and coal chemistry(Neavel et al, 1981).

Chemical nature of rank-related differences - Major clustering tendencies in Figure 3 appear to correlate with rank. A marked separation is seen between the three MVB coal samples and the lower rank coals. Moreover, a nearly perfect separation is found to exist between the HVCB coals and higher rank coals. These discontinuities in our data correlate with the two coalification "breaks" observed in conventional data (Waddell et al, 1978).

The chemical nature of the rank-related differences in the Py-MS data matrix can be investigated by interpreting the peak series loading on both principal components, as illustrated in Table 3. Because of the strong correlations between the peak series and the absence of noticeable overlap between the two components, the data in Table 2 can be further reduced to the representations in Figures 4a and 4b. Comparison of Figure 4b with Figure 3 shows that increase in rank coincides with a loss of heteroatomic compounds and an increase in hydrocarbon constituents. Supervised classification of Py-MS data into known ASTM rank classes (Table 3) by means of SIMCA, a principal component modeling technique (Wold, 1976), shows dihydroxybenzenes and naphthalenes to be most useful in predicting ASTM rank. This is illustrated by the bivariate plots in Figures 5 and 6. Combination of the best of two peaks of each series (m/z 110 and 156), produces the interesting plot in Figure 7. The apparent coalification track in Figure 7 bears a strong resemblance to a Van Krevelen plot (1961) with the dihydroxybenzene peak at m/z 110 representing O/C ratio's and the C_2 alkylnaphthalene peak at m/z 156 representing reciprocal H/C ratio's. This is further illustrated by the existence of a strong positive correlation between the instensity of the C_2 alkylnaphthalene peak at m/z 156 and calorific value, as shown in Figure 8.

Effects of depositional environments and geological history - The pyrolysis patterns of Cannel King coal, a boghead coal deposited in a predominantly fresh water or brackish environment, are easily distinguished from the other coals as shown in Figures 2 and 3. Figure 4b indicates these coals to have a strongly aliphatic character, in agreement with their high alginite and bituminite content and current views on the composition of these macerals (Teichmuller et al, 1975). Also the position of these coals outside the apparent coalification tracks of the other coals in Figures 7 and 8 is completely in line with Van Krevelen's original observations on "exinite" rich coals (Van Krevelen, 1961). Whereas Cannel King coals are rich in alginite, the Dakota seam coals have unusually high concentrations of fusinite. This probably causes the shift observed in

Table 2. Twenty mass peaks with highest total variance contribution to Factors I and II from complete coal pyrolysis MS data matrix.

	K-L I (21%)			K-L II (15%)		
Sequence number	m/z	loading	Tenative Identity of Ions	m/z	loading	Tenative Identity of Ions
1.	146	+.137	? (see text)	170	−.158	C_3-naphthalenes
2.	138	+.136	C_2-dihydroxbenzenes	60	+.150	acetic acid
3.	124	+.136	methyldihydroxbenzenes	50	+.147	$C_2H_3O_2^+$
4.	158	+.135	methylnaphthols	156	−.146	C_2-naphthalenes
5.	162	+.135	C_2-hydroxyindanes	72	+.135	C_4-ketones/aldehydes
6.	148	+.134	naphtols	184	−.142	C_4-naphthalenes
7.	132	+.133	? (see text)	58	+.142	C_3-ketones/aldehydes
8.	83	−.131	$C_6H_{11}^+$	73	+.140	$C_3H_5O_2^+$
9.	160	+.130	? (see text)	171	−.139	C_3-naphthalenes (m + 1)
10.	84	−.129	$C_6H_{12}^+$	182	−.133	C_2-acenaphthenes
11.	172	+.128	C_2-naphthols	157	−.133	C_2-naphthalenes
12.	110	+.127	dihydroxybenzenes	142	−.124	methylnaphthalenes
13.	150	+.125	C_4-alkylphenols	101	+.125	$C_5h_9O_2^+$
14.	108	+.125	methylphenols	78	+.124	benzene
15.	57	−.122	$C_4H_9^+$	120	−.123	C_3-benzenes
16.	71	−.120	$C_5H_{11}^+$	48	+.122	methanethiol
17.	85	−.120	$C_6H_{13}^+$	125	+.122	$C_9H_{17}^+$
18.	70	−.119	$C_5H_{10}^+$	47	+.121	CH_3S^+
19.	94	+.119	phenol	115	+.120	$C_6H_{11}O_2^+$
20.	112	−.118	$C_8H_{16}^+$	74	+.119	propionic acid

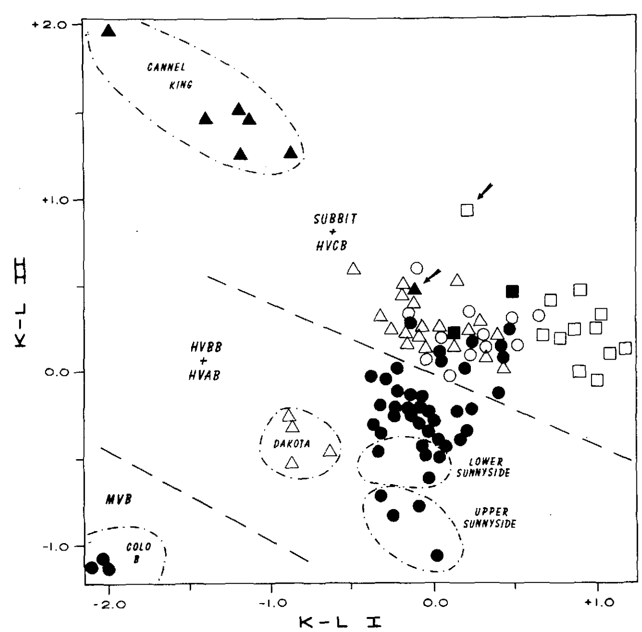
* % total variance explained by factor

Table 3. SIMCA misclassification matrix.

	Calculated Class			
True Class	SUB	HVCB	HVBB	HVAB
SUB	$10^{83.3}$	$2^{16.7}$	0	0
HVCB	$1^{2.2}$	$44^{95.7}$	$1^{2.2}$	0
HVBB	0	0	$17^{85.0}$	$3^{13.5}$
HVAB	0	0	$3^{17.6}$	$14^{82.4}$

Numbers in italics indicate % of true class.

Figure 6 since pyrolysis mass spectra of purified fusinite macerals, as published by Larter (1978) and Van Graas et al (1979), are dominated by aromatic hydrocarbon series with a relatively low average degree of alkylsubstitution. An interesting speculation would be to explain this shift towards lower degrees of alkylsubstitution (e.g., from C_3 alkened to C_2 alkened in Figure 6) by exposure of fusinite macerals to relatively high temperatures, as also indicated by ESR studies (Given, 1966). This would support a possible origin of fusinites as wood char from forest fires (Given, 1980).



Symbols Used:
● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region.

Figure 3. First two factors obtained from average spectra of all 102 Rocky Mountain coals.

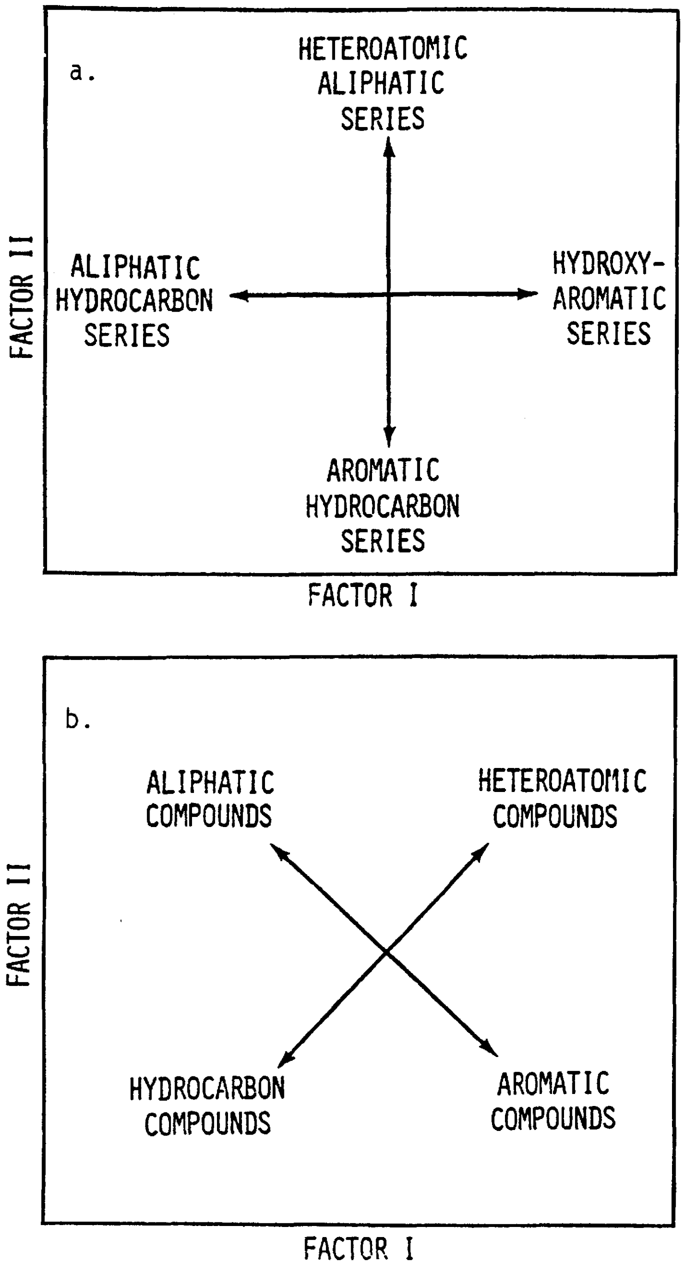
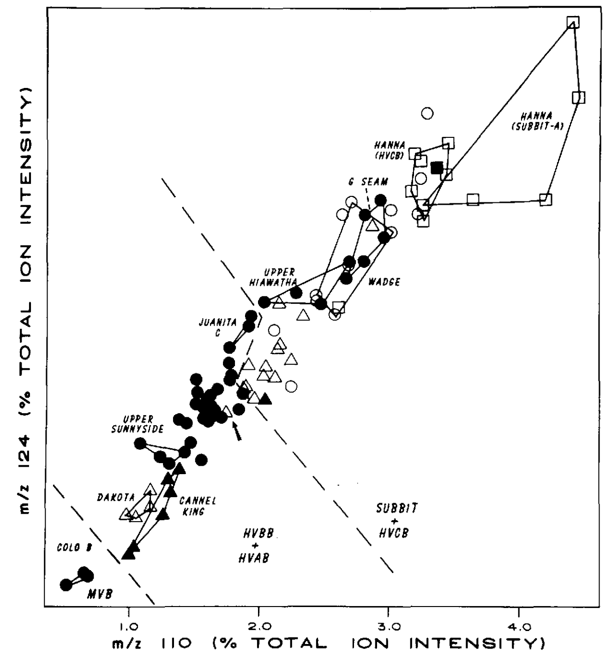


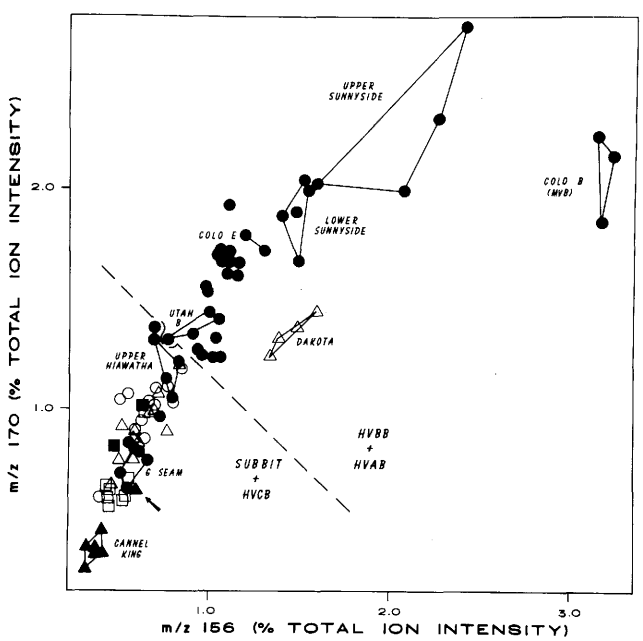
Figure 4. a) Main series of compounds represented by Factors I and II in Figure 3. b) Generalized interpretation showing underlying chemical tendencies obtained by a 45° rotation of a).

In Figure 6, a similar shift toward lower alkylsubstitution is observed for the Colorado B seam. Because of the low inertinite content a different explanation must be sought. This is a readily found in the accelerated coalification of this seam by exposure to high geothermal gradients resulting in the relatively high rank (MVB) of these coals



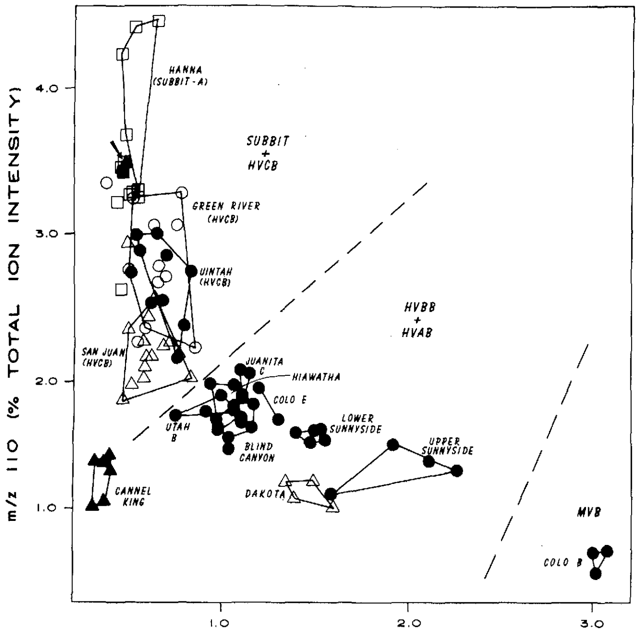
Symbols Used:
● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region.

Figure 5. Ion intensity distributions at m/z 110 (dihydroxybenzenes) versus m/z 124 (methyldihydroxybenzenes).



Symbols Used:
● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region

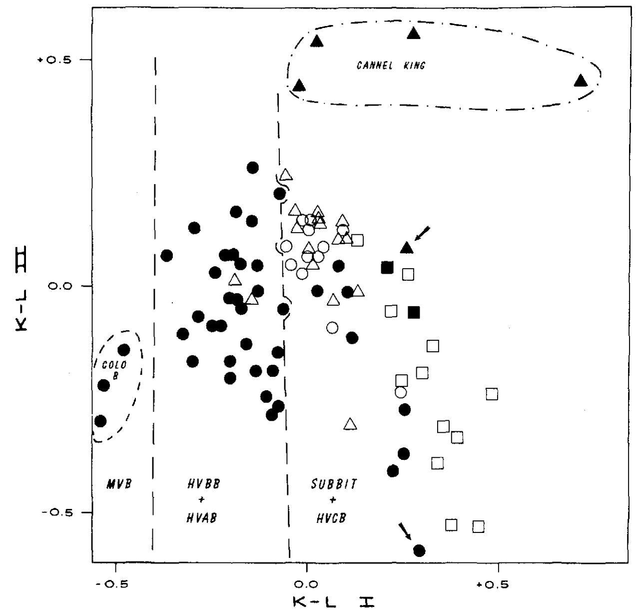
Figure 6. Ion intensity distributions at m/z 156 (C_2-alkylnaphthalenes) versus m/z 170 (C_3-alkylnaphthalenses).



Symbols Used:

● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region

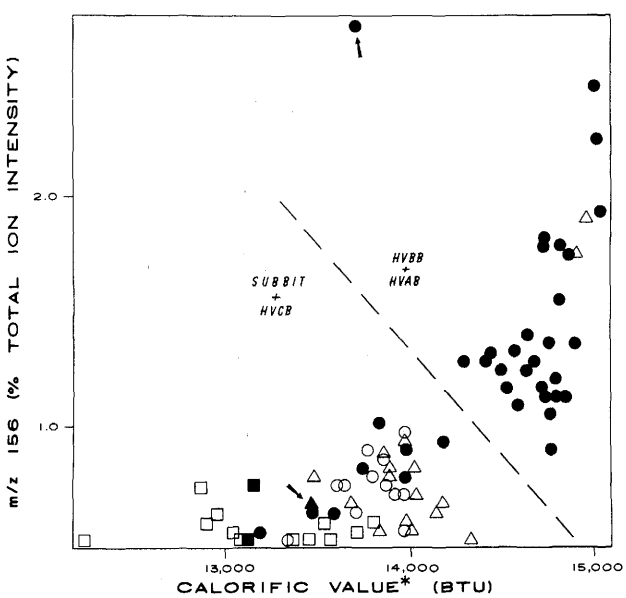
Figure 7. Ion intensity distributions at m/z 156 (C_2-alkylnaphthalenes) versus m/z 110 (dihydroxybenzenes).



Symbols Used:

● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region. Arrow points to HVAB rank coal (PSOC 1118, Upper Sunnyside seam) showing anomalous clustering behavior, probably as a result of a wrong c.v. value (see Figure 8).

Figure 9. First two factors obtained from conventional coal parameters.



*as received, modified Parr

Symbols Used:

● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region. Arrow points to a coal (PSOC 1118, Upper Sunnyside seam) with possibly erroneous c.v. value.

Figure 8. Calorific value versus ion intensity distribution at m/z 156 (C_2-alkylnaphthalenes).

(Collins, 1976). If the above interpretations can be confirmed by observations on other coals, analysis of alkylsubstitution patterns in coal pyrolyzates may provide a new and powerful tool to determine the temperature history of coals and coal macerals.

Correlations between Py-MS data and conventional coal parameters - Computerized numerical analysis of 25 selected conventional coal parameters (Table 1) representing the same coal samples as used in the Py-MS study reveals strong correlations between both data sets. This is illustrated by a strong comparison of the K-L plot in Figure 9 (conventional data) with the corresponding plot in Figure 3 (Py-MS data). Again, the first two principal components appear to be dominated by rank effects (Colorado B seam!) as well as depositional effects (Cannel King seam!). However, heterogeneity within seams plays a more important role in the conventional data in Figure 9 resulting in the disappearance of several clusters observed in Figure 3. Several studies were undertaken to investigate the nature and strength of the correlations between the two data matrices, namely (1) factor analysis of each matrix followed by least squares or stepwise regressions of factors from one set versus the other

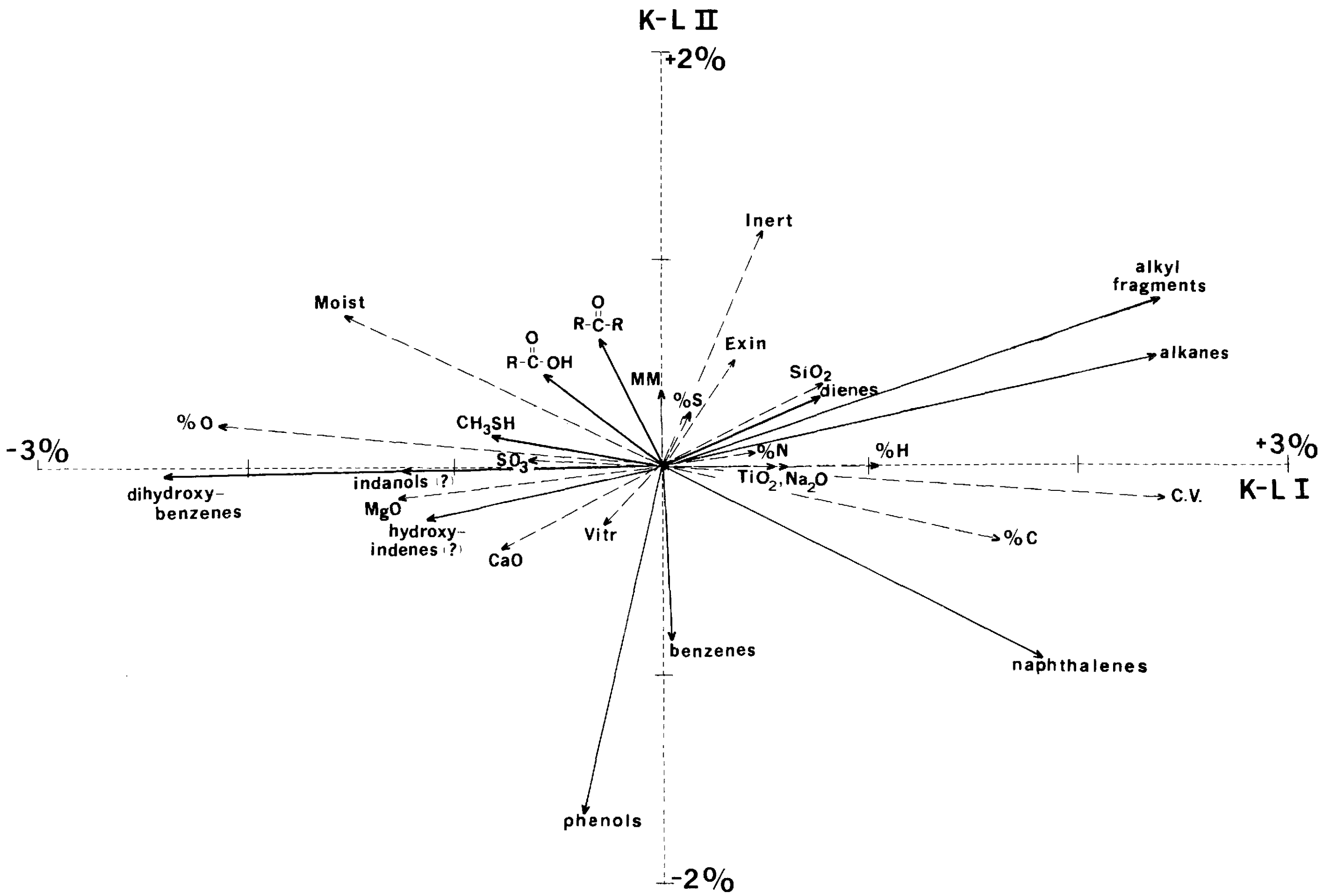
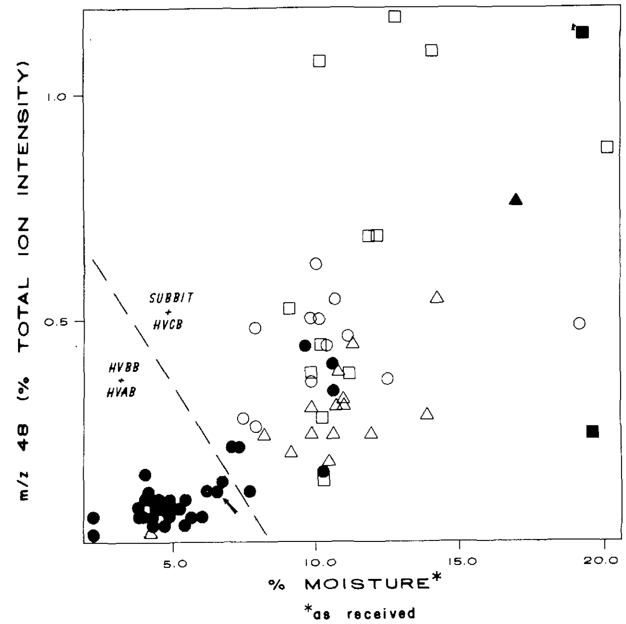


Figure 10. Variance contributions of conventional parameters and homologous ion series to the first two factors obtained from the combined data matrix.

set; (2) factor analysis of combined data matrices and; (3) univariate analysis of correlations between individual features. The results are discussed in detail elsewhere (Harper et al, 1982). Figure 10 shows a two dimensional plot of data vectors representing the variance observed in the first two components of a combined matrix (Cannel King and Colorado B seam samples were eliminated).

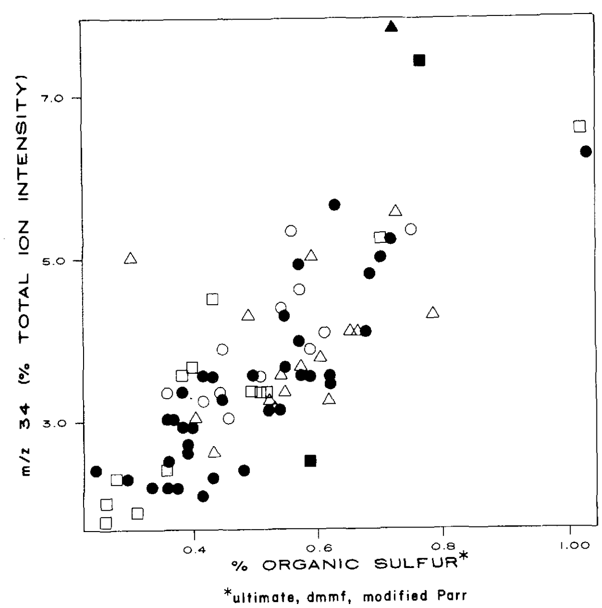
The correlations observed between the conventional variables are similar to those described by Waddell et al (1978) for a different subset of Rocky Mountain coals. The correlations between the conventional variables and the homologous ion series confirm the presence of strong rank related as well as depositional effects in both data sets. Examples of correlations between individual parameters in each set are shown in Figures 11 and 12 and illustrate the different nature of the sulfur signals observed in pyrolysis mass spectra. Whereas methanethiol (m/z 48) shows a strong positive correlation with moisture content (and thus a negative correlation with ASTM rank) the peak at m/z 34 ($H_2S^{+\circ}$) correlates strongly with organic sulfur content (and thus with depositional environment).

Prediction of important technological parameters from Py-MS data - As shown in Table 3, ASTM rank classes can be predicted from Py-MS data with 87 percent accuracy. In view of the widely recognized inadequacies of the ASTM Rank classification systems, especially when applied to non-Carboniferous coals such as the primarily Cretaceous Rocky Mountain coals, it might be argued that Py-MS parameters could perhaps provide a better estimate of the degree of coalification ("rank") than afforded by the ASTM procedure. Such a Py-MS rank parameter might take the form of a factor score, e.g., using the rotated "heteroatomic compound/hydrocarbon compound" factor in Figure 4b. Similarly, the "aliphatic compound/aromatic



Symbols Used:
● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region. Arrow indicates single HVCB coal on "wrong" side of dotted line.

Figure 11. Moisture content versus ion intensity distributions at m/z 48 (CH_3SH^+).



Symbols Used:
● Uinta Region, ○ Green River Region, □ Hanna Field, ■ Ham's Fork Region, ▲ South Western Utah Region, △ San Juan River Region

Figure 12. Organic sulfur versus ion intensity distributions at m/z 34 (H_2S^+).

Table 4. Representative least squares predictions of calorific value from pyrolysis mass spectra factors.

PSOC #	Actual C. V. (Btu)	Predicted C. V. (Btu)
152	13,950	13,760
233	13,790	14,160
235	14,510	14,680
238	14,640	14,740
313	14,540	14,440
462	14,670	15,010
468	13,260	13,410
493	13,520	13,220
517	13,040	13,250
542	13,600	13,740
546	13,710	13,710
860	14,910	14,810
863	13,540	13,510
916	13,640	13,790
934	13,440	13,700
939	13,830	13,850

compound" factor would provide an interesting "aromaticity" (fa) parameter largely independent from rank effects. Because of the importance of fa for coal technology (Davis, 1978) and the absence of a reliable direct determination method apart from ^{13}C NMR (Zilm, 1981), this may be a promising new approach.

Another technologically important parameter is calorific value. Table 4 shows that calorific value can be predicted relatively accurately (average error of all prediction experiments was $\pm$165 Btu) from Py-MS data using least squares rotation of principal components. This prediction error is not too far from the ASTM norm of $\pm$100 Btu for duplicate determination in different laboratories (Annual Book of ASTM Standards, 1981).

CONCLUSIONS

It has long been standard practice among geologists to classify the coal basins of the United States into seven provinces. The significance of the classifications is that the basins differ in the nature of the plants from which the coals were formed, in the paleosalinity and sulfur content, and in postburial geologic history (Given, 1966). The statistical analyses of Waddell et al (1978) show that the coals of the United States must indeed be classified into a number of subsets on the basis of their conventional chemical analytical characteristics, and this more chemical classification clearly has a geological rationale. Given et al (1980), in a similar study, which added liquefaction conversion to the chemical parameters considered, further emphasized these points, and stressed that the different subsets of coals had separate trends of developement with increasing rank.

These studies, as noted, relied on gross chemical and petrographic characteristics of coals. Obviously a much clearer understanding of the nature of the subsets and of their distinctive metamorphic trends would be obtained if data characterizing important aspects of the chemical structures of at least the vitrinitic macerals were available and could be incorporated into the statistical analyses. A start with achieving this was made by Yarzab et al (1979), in their study of the hydroxyl contents of 53 coals from three provinces, but the effort was of limited scope.

It is submitted that the approach discussed here is valuable because a considerable amount of structural information emerges simply and rapidly, and the information is acquired in a form such that it is readily interfaced with conventional data similarly stored. Moreover, the combinations of data can then be interfaced with any desired statistical program, such as principal components analysis. The work reported in this paper represents a first attempt to examine in detail the systematic trends of structural and basic compositional data for a reasonably large set of coals from a single province.

ACKNOWLEDGEMENTS

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USE OF SHEAR-WAVE SEISMICS IN EVALUATION OF STRIPPABLE COAL RESOURCES

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INTRODUCTION

In 1980, the U.S. Geological Survey and the U.K. National Coal Board began a cooperative research program to further the development of geophysical methods for strippable-depth coals. Three targets were selected: near-surface structure concealed by overburden, coal subcrops, and old mines. The principal method of investigation was to be shallow, shear-wave seismics. This paper discusses the first findings of the joint study.

Data were taken with the U.S. Geological Survey's shallow-coal seismic system — a portable, 12-channel, signal-enhancement seismograph with digital tape recording. Shear waves were generated by horizontally striking a metal-plate assembly with a 9.2 kg hammer, shear-wave arrivals were detected with 40-Hz horizontal seismometers, and data were processed on a desk-top computer. All field operations were performed with a two-person crew.

SHEAR-WAVE SEARCH FOR SHALLOW STRUCTURE

For any new prospect, to determine if seismic reflections exist and to guide selection of their data acquisition and processing procedures, a series of wave tests is conducted. An example of one such test is shown in Figure 1. Here, transverse seismometers at 3 m intervals were deployed along a straight line southeasterly for a distance of 135 m, and a shear-wave source was first struck to the northeast and then to the southwest. Results of striking to the northeast are shown with a variable-area presentation; inverted results striking to the southwest are plotted as wiggle traces. Thus, seismic arrivals 180° out of phase (as an ideal shear pair would be) appear to be in phase on the display.

In the wave test area, the surface is flat and blanketed by a half meter of spoil-pile material. The geologic section is known from foundation engineering studies to be laterally uniform, with 17 m of clay overlying siltstones and mudstones containing lenticular sandstones.

Wave test arrivals (Figure 1) that fall along straight lines are SH (shear-horizontal) refractions; arrivals that lie along the curve lines are SH reflections. The group of arrivals blocked between times of 20 to 50 milliseconds at offset distances of 12 and 30 m have the phase velocity of longitudinal (P) waves, but the phase coherence of shear (S) waves.

From analysis of P-wave and S-wave travel-time curves, the P-wave velocity is at least seven times faster within the first major layer than is the S-wave velocity. What this implies is that across an horizon displayed by a 0.35-m fault, the S-wave reflections at a velocity of 200 m/s would have a time difference of 3.5 ms (an amount readily seen on a seismic section), whereas the P-wave reflection time difference would be 0.5 ms.

Figure 2 shows a shear-pair seismic record section using the same data as for Figure 1. In preparing the section, a NMO (normal moveout) velocity of 0.21 m/ms was used and a 20-ms cosine-taper mute was applied. Total depth of the section assuming a constant velocity equal to the NMO velocity is 52.5.m, and subsurface distance between the traces is 1.5 m.

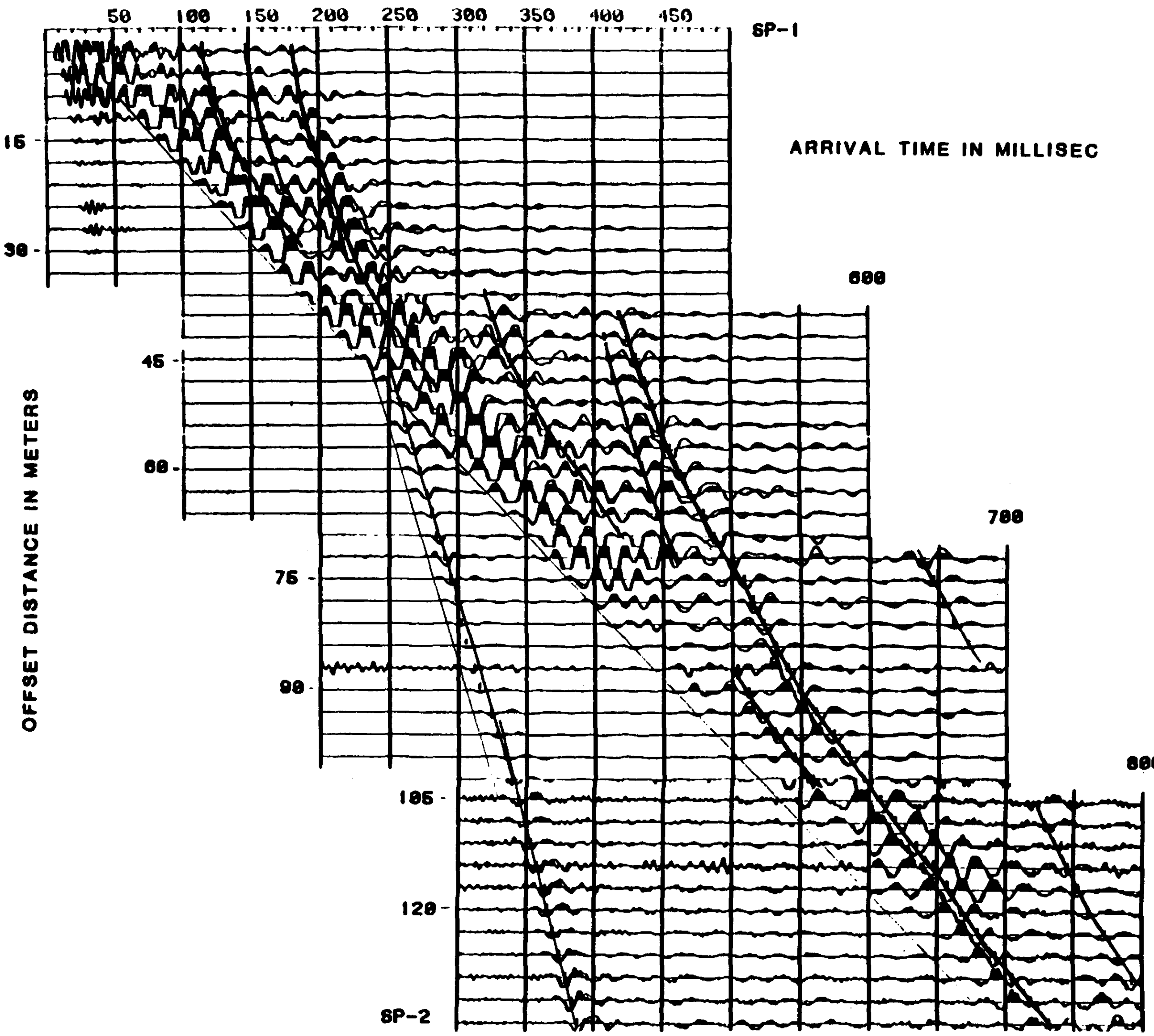

Figure 1. Results of wave test using a transverse shear-wave source and transverse seismometers.

An initial interpretation is that the section indicates flat-lying horizons within and near the base of the clay layer beneath which groups of reflections with characteristics of discontinous horizons appear. Some of the reflection-arrival alinements suggest a lenticular form. No drilling has been done in the immediate area of the wave test.

SHEAR-WAVE SEARCH FOR COAL SUBCROP

The target of the investigation is a commercial, strippable-depth coal seam roofed by a 10- to 12- m thick competent sandstone dipping approximately 8° northeasterly. The area of the target has been farmed extensively for centuries and outcrop of the coal can be seen only in stream and road cuts.

The basic approach to the subcrop-location problem is illustrated in Figure 3. Key to the procedure is the selection of a seismic line such that at least two of its source points (SP's) fall to either side of the suspected subcrop position. First arrivals from SP-A detected on spread A (Figure 3) should

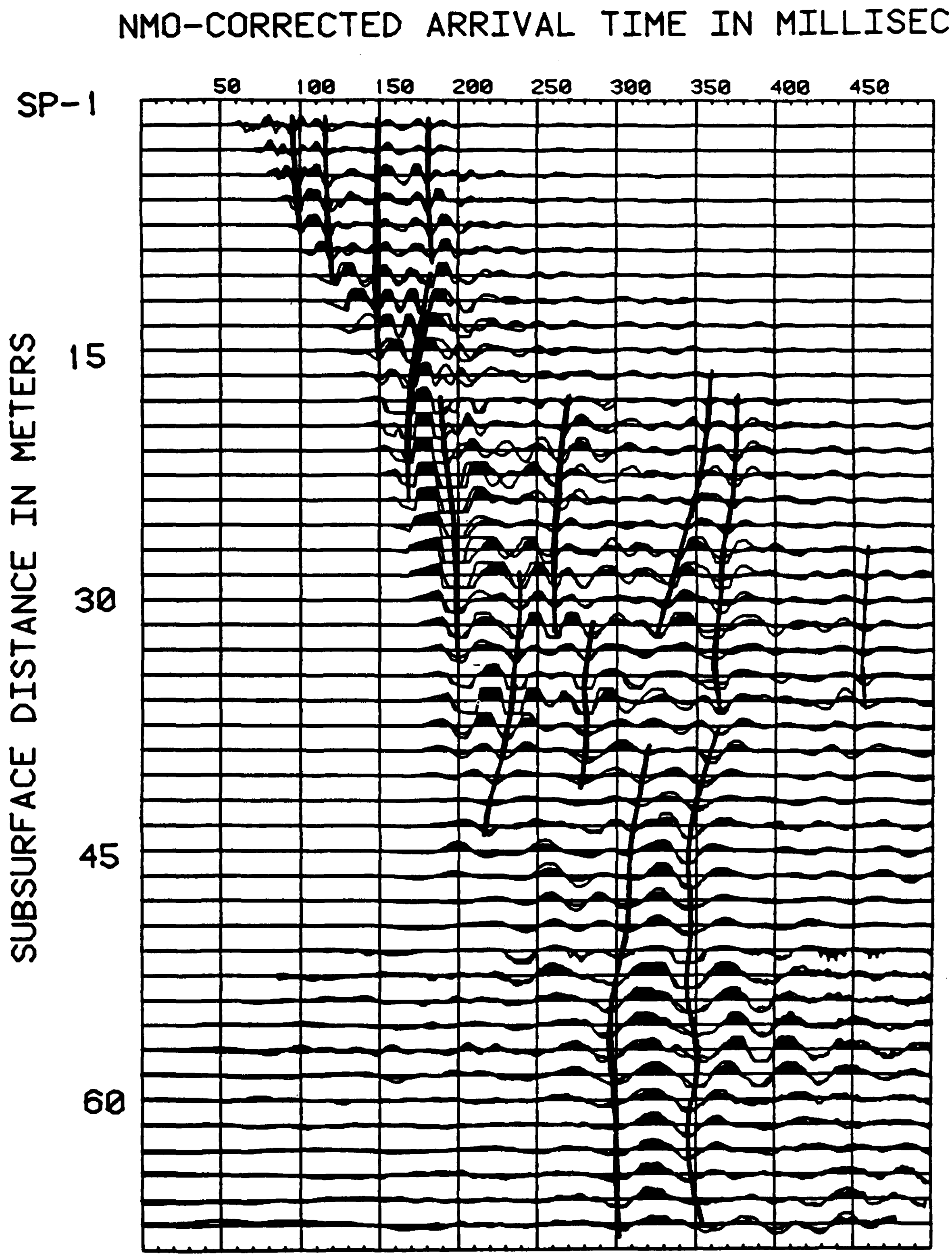

Figure 2. Shear-pair seismic record section derived from the transverse-source, transverse-seismometer data displayed on Figure 1.

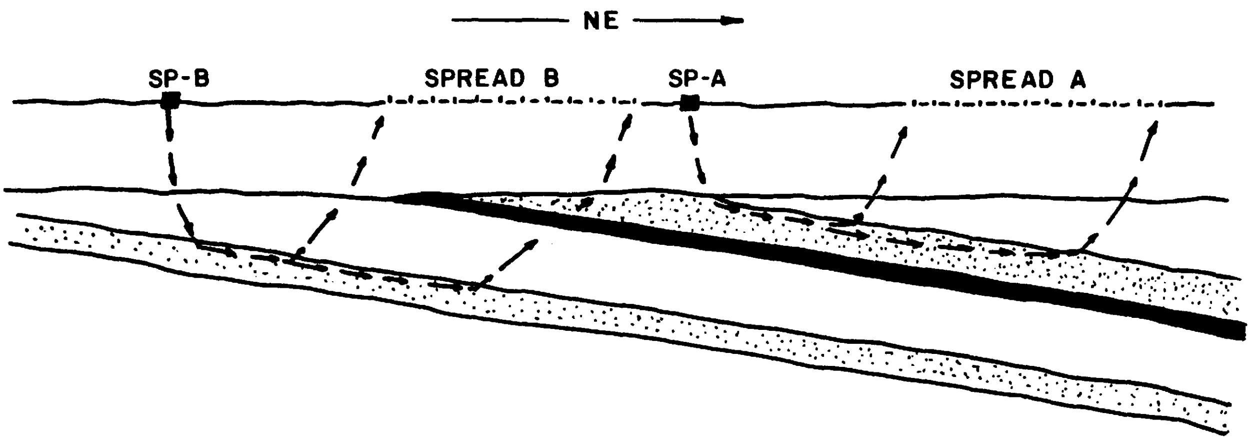

Figure 3. Schematic representation of coal subcrop and source points and spreads used to determine its location (not drawn to scale).

refract along the top of the sandstone roof, whereas first arrivals from SP-B detected on spread B should refract along the lower sandstone. Because the refraction-event path is longer for the B array than for the A array, first-arrival times from SP-B should be greater than from SP-A if both sandstones have about the same velocity.

Two shear-pair records (transverse source, transverse detector) that straddled a suspected subcrop position are shown in Figure 4. Clearly, the first-arrival times on the upper record are considerably less than the first-arrival times on the lower record. If the records of Figure 4 result from a condition such as that sketched in Figure 3, then the subcrop postition of the sandstone roof lies somewhere between the two source points. The coal subcrop, therefore should be located southwest of the source point of the upper record. Using refraction data from these records and from other records taken in the opposite direction and knowing the thickness of the roof rock, one should be able to locate the coal subcrop to within a few meters.

On the lower record of Figure 4, note the break in slope of the first arrivals at an offset distance of 48 m and observe that the first-break velocity is definitely lower for the upper six traces than for the lower six traces. The upper six traces depict arrivals from seismometers deployed over an abandoned mine.

SHEAR-WAVE SEARCH FOR AN OLD MINE

A schematic representation of the old-mine target is shown in Figure 5. A packed-wall entry is suspected under position 169 and a subsided surface is evident from position 172 to 197. At scattered sites within the subsided area, drilling encountered no voids, only occasionally a half meter or less of broken ground at coal-seam depths. Coal from this mine, last operated in the 1920s, was taken by the longwall-face tub method. In this procedure, sets of parallel entries from the main entry was dug and stowed, and then each miner worked his own stall along the advancing, sometimes stepped, longwall. Stalls varied in length from 10 to 15 m depending on the strength of the roof rock. Many old-time miners were skilled stonemasons, and it is likely that remnants of the old entries still stand.

Transverse-source, transverse-detector wave-test results from SP-166 and SP-201 are shown in Figures 6 and 7, respectively; seismometer interval is 3 m.

The sixth and seventh traces of the upper record in Figure 6 exhibit an oscillatory character much as would be expected from cavity resonance. Detectors for traces 6 and 7 were positioned at locations 172 and 173 (Figure 5), a position not far from the anticipated location of the main entry.

A glance at the upper record of Figure 6 shows that the bottom five and upper five traces have a different appearance—a different character. Seismometers for the upper set of five traces lie on undisturbed ground; detectors for the lower set of five traces lie over the mined area. The limits of

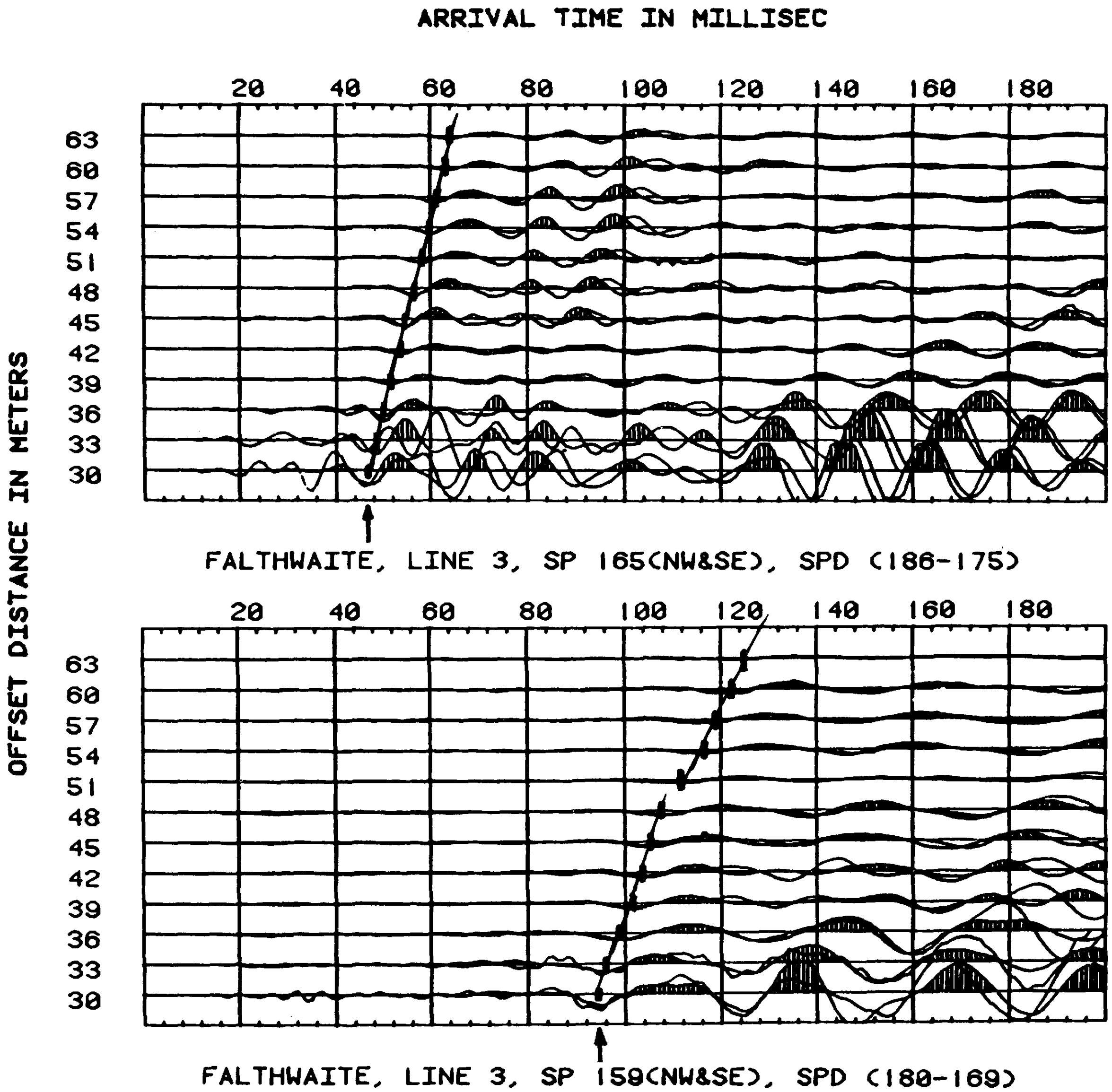

Figure 4. Transverse-source, transverse-detector, shear-pair records taken across a subcrop.

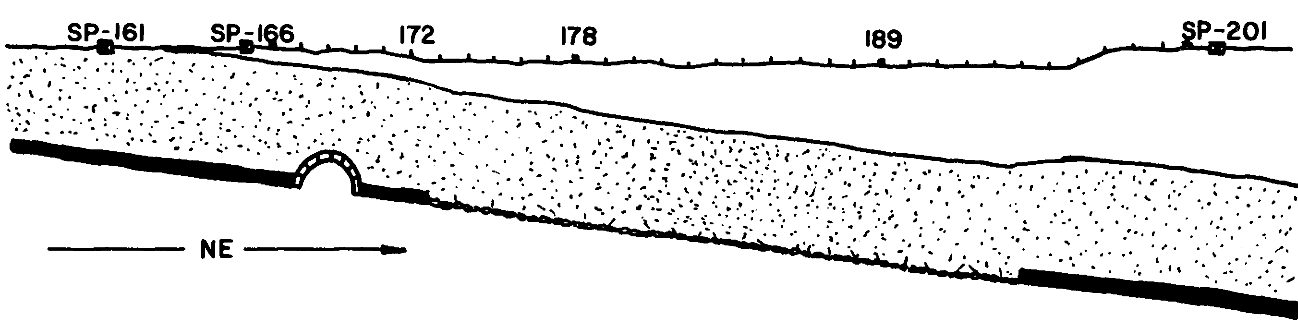

Figure 5. Schematic representation of the old-mine target. Maximum subsidence is 2 m, and distance from SP-161 to SP-201 is 120 m.

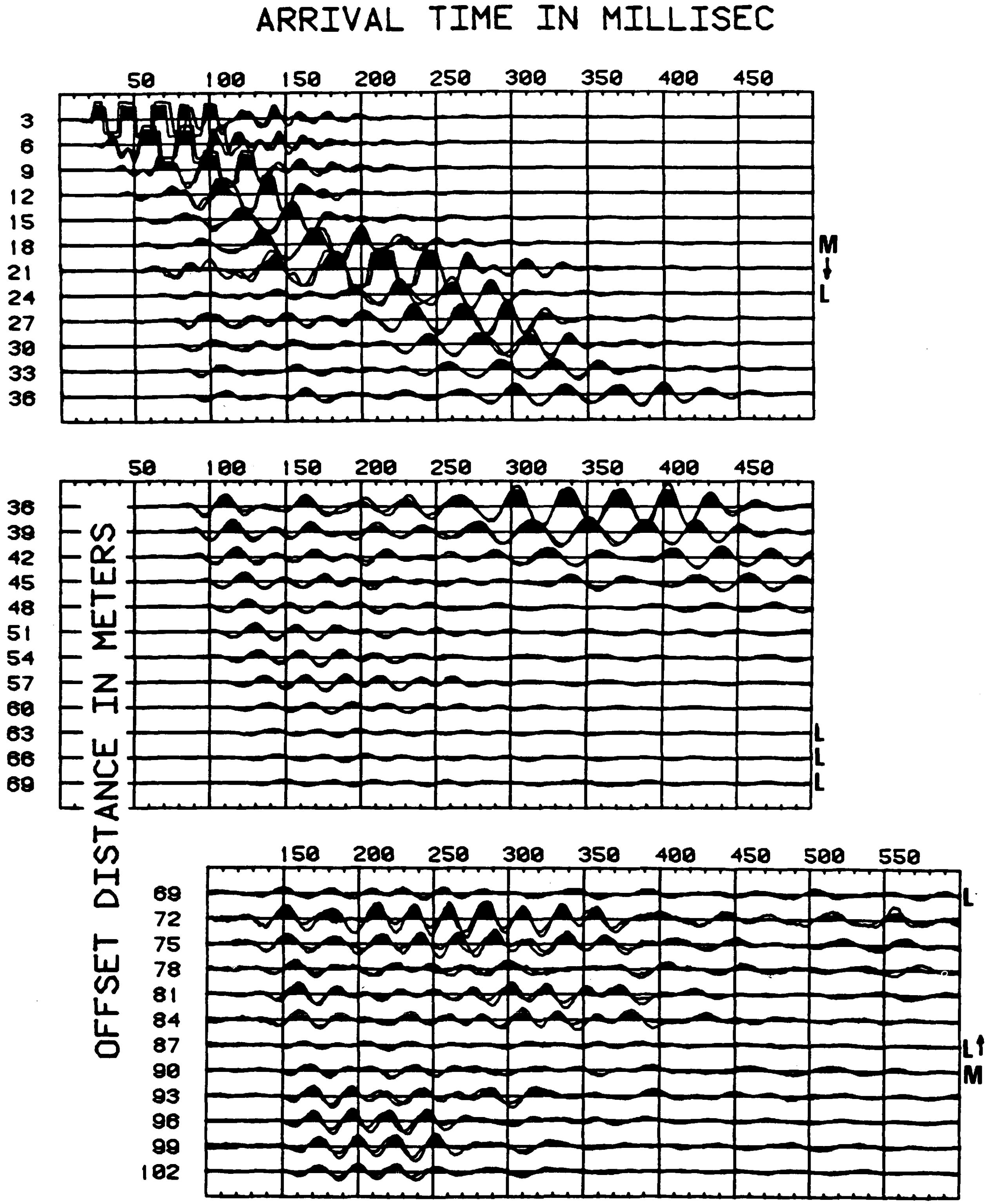

Figure 6. Transverse-source, transverse-detector, shear-pair seismic records from SP-166 to detectors whose offsets range from 3 to 102 m.

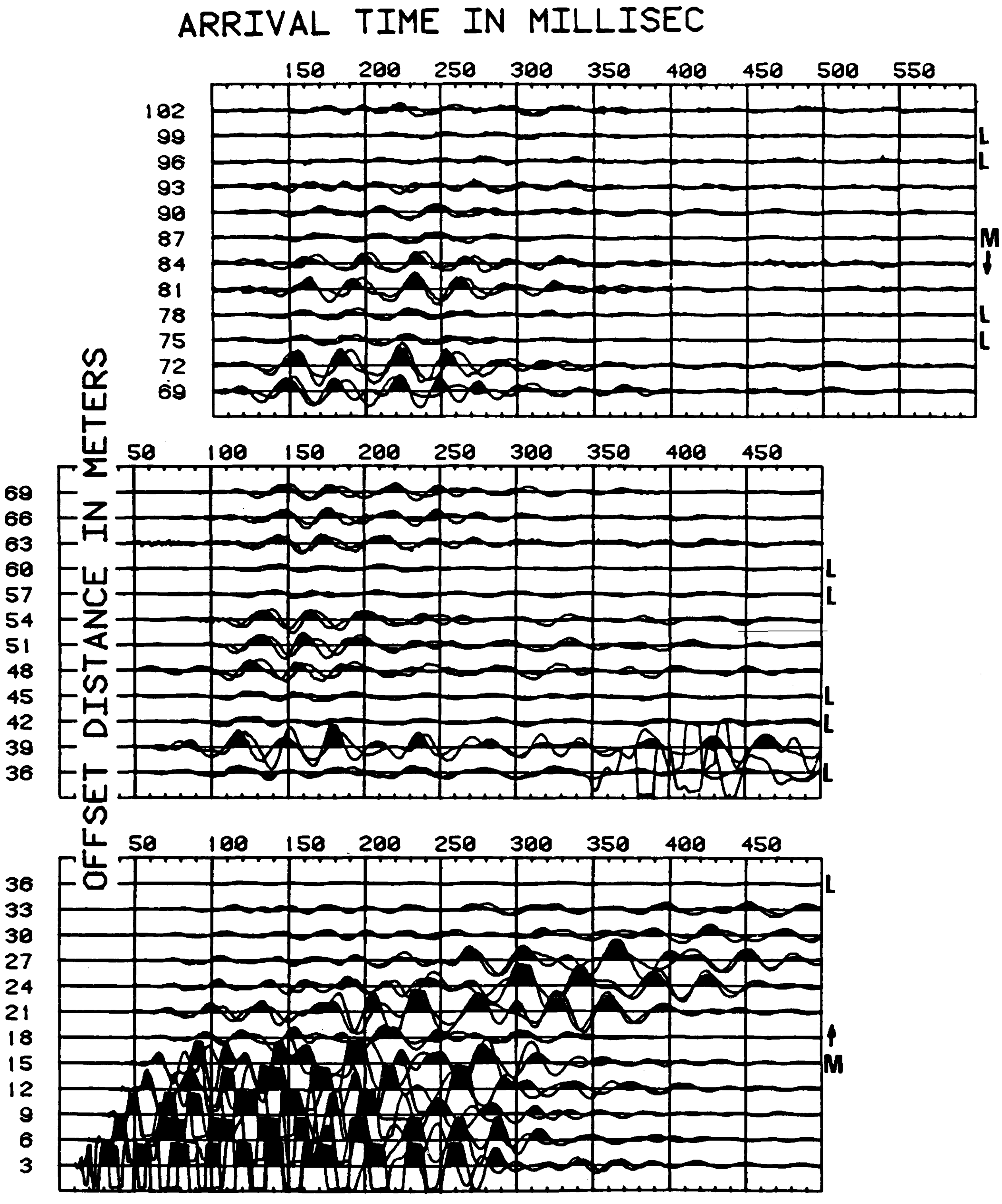

Figure 7. Transverse-source, transverse-detector, shear-pair seismic records from SP-201 to detectors whose offsets range from 3 to 102 m.

mining are shown in Figures 6 and 7 by a capital M. Note that in Figure 7, the traces below the M do not have the same general appearance, or character, as those above the M. This is scant evidence that could not stand by itself as an indicator of the presence of an old mine. However, when the observation made in Figure 4 relative to the marked decrease in apparent velocity that occurs at the same ground postitions is coupled with the results shown on the upper record of Figure 6, then the suspicion of the presence of an old mine is reinforced.

Another piece of evidence that might be significant, but of itself not conclusive, is the grouped low-amplitude traces shown in both Figures 6 and 7. In these figures, those traces whose amplitudes are lower than nearby traces are labeled with an L. An optimistic interpretation is that the low amplitude shear-wave arrivals are produced by still-open drifts through which shear waves will not pass. Although we are not that optimistic, we think it worthwhile to point out these occurrences.

CONCLUSIONS

From the first findings of the joint U. S. Geological Survey-U. K. National Coal Board studies on the geophysics of strippable-depth coals, the following conclusions can be drawn:

1. it is possible with a low-cost procedure to obtain shear-wave reflections from shallow depths;
2. it is possible by use of a common-offset shear-wave method to locate subcrops at shallow depth;
3. it is possible that shear-wave technology can increase the likelihood of detecting the extent of abandoned mines.

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HIGH-RESOLUTION SEISMIC: A PRACTICAL APPROACH TO COAL EXPLORATION

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INTRODUCTION

The use of high-resolution seismic survey has been extremely effective in defining the geologic structure and stratigraphy of a developed coal property located within the Wasatch Plateau Coal Field, Emery County, Utah (Figure 1). The coal property, which is the East Mountain property owned by Utah Power and Light Company, contains five underground coal mines that collectively produce about 4 million tons of coal annually.

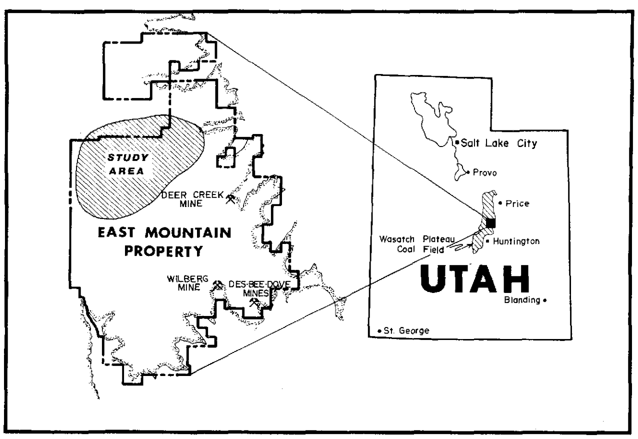

Figure 1. Location of study area.

The high-resolution seismic surveys were conducted in 1980 and 1981 to define the geologic structure in areas where data collected by geologic mapping and drilling resulted in questionable interpretations regarding the geologic structure. These surveys produced data which allow the identification of the geologic structure, the continuity and thickness trends of the coal seams present, and the location of fluvial channel sandstones superimposed on these coal seams.

GENERAL GEOLOGY

The coal seams present within the East Mountain property are located within the deltaic upper Cretaceous Blackhawk Formation. Two minable coal seams have been identified by mapping and drilling. These seams are the Hiawatha, which rests on the Starpoint Sandstone, and the Blind Canyon, which is located about 80 ft above the Hiawatha seam (Figure 2).

The coal seams within the property are covered by a regressive continental sedimentary sequence which is about 2,200 ft thick. The strata immediately above the coal zone consists of interbedded mud, silt and sandstones. The Blackhawk Formation is approximately 700 ft thick and generally coarsens upward. The fluvial Castlegate sandstones rests sharply on top of the Blackhawk Formation. This unit consists of fine to medium-grained well-sorted sandstone and is 200 ft thick. The Price River Formation which conformably overlies the Castlegate Sandstone is comprised of medium to coarse-grained sandstones with subordinate amounts of pebble conglomerates and mudstones. This unit averages approximately 500 ft in thickness. The Price River Formation is overlain by the North Horn Formation. Mudstones and siltstones comprise the majority of the North Horn strata but sandstones and limestones are also present, particularly near the top of the formation. The thickness of the North Horn Formation averages 700 ft. The youngest formation found within the property is the Flagstaff Limestone.

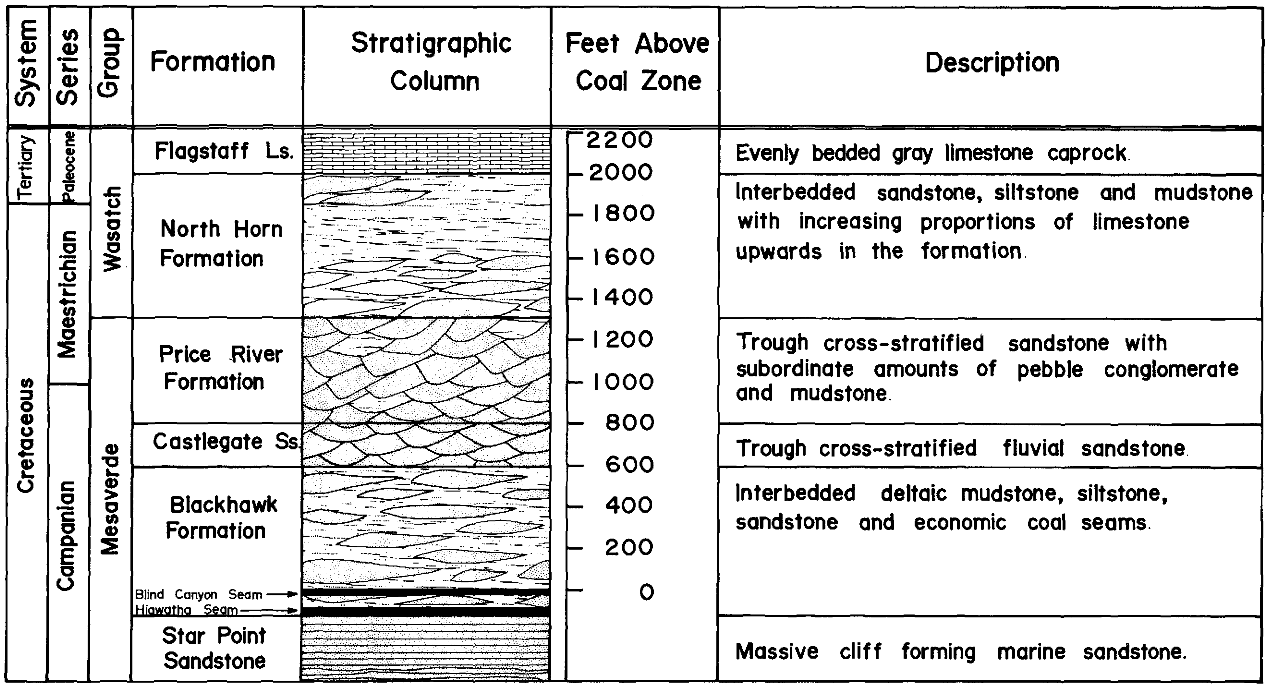

Figure 2. Stratigraphic section-east mountain.

An erosional remant of the lower 200 ft of the limestone caps the top of the East Mountain area.

The sedimentary rocks present have been cut by a series of north-south trending faults. An early investigation of the area documented the location and extent of these faults and is now considered to be a classic work of the stratigraphy and structure of the Wasatch Plateau Coal Field (Speiker, 1931). Generally, the faults mapped by Speiker are easily recognized on outcrop, particularly where they intersect the steep cliff escarpments flanking the eastern edge of the Wasatch Plateau.

A fault trending in a northeast direction has been identified in the northern portion of the property. Geologic mapping failed to produce data regarding the fault's displacement or lateral extent because of the lack of outcrops in that area.

The Straight Canyon syncline, a northwest trending structural feature, crosses the northern portion of the East Mountain property. The axis of the syncline roughly coincides with the north-east trending fault previously mentioned.

Prior to conducting the seismic surveys, the geologic structure was interpreted as shown in Figure 3. Although the interpretation was based on data collected from drill holes spaced roughly on .5 mi centers, aerial photo interpretation, and geologic mapping, many questions were left unanswered in the area of the syncline. The lack of outcrops in this area plus the fact that a fault was identified but its displacement could not be determined from the available data forced the Utah Power and Light Company to investigate this area using high-resolution seismic techniques.

SEISMIC SURVEYS

The primary objectives of the seismic surveys were to: 1) identify the displacement of the northeast trending fault at the depth of the coal seams, 2) locate any additional faulting present, and 3) substantiate the continuity of the coal seams adjacent to the fault zone. To accomplish these objectives, seismic data

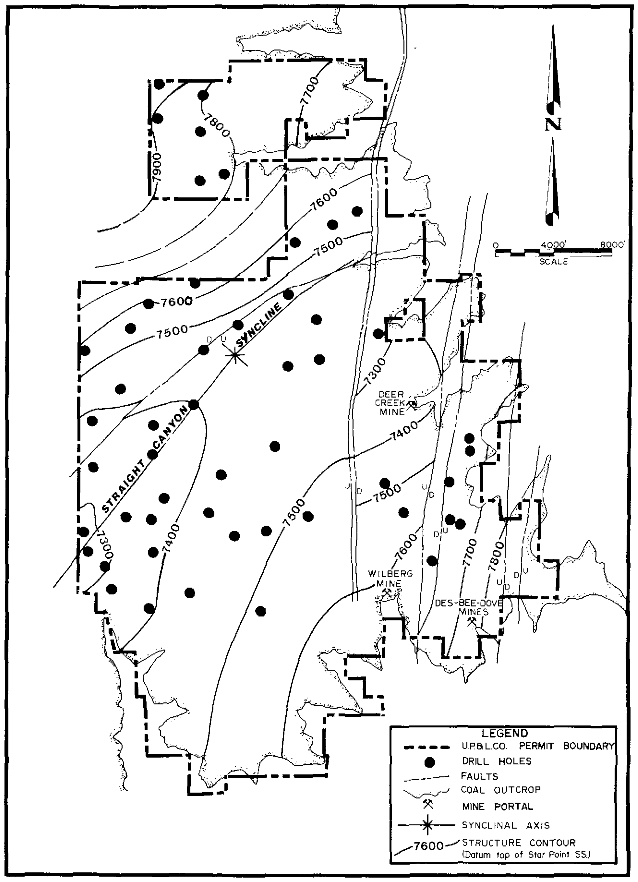

Figure 3. Preseismic structural interpretation.

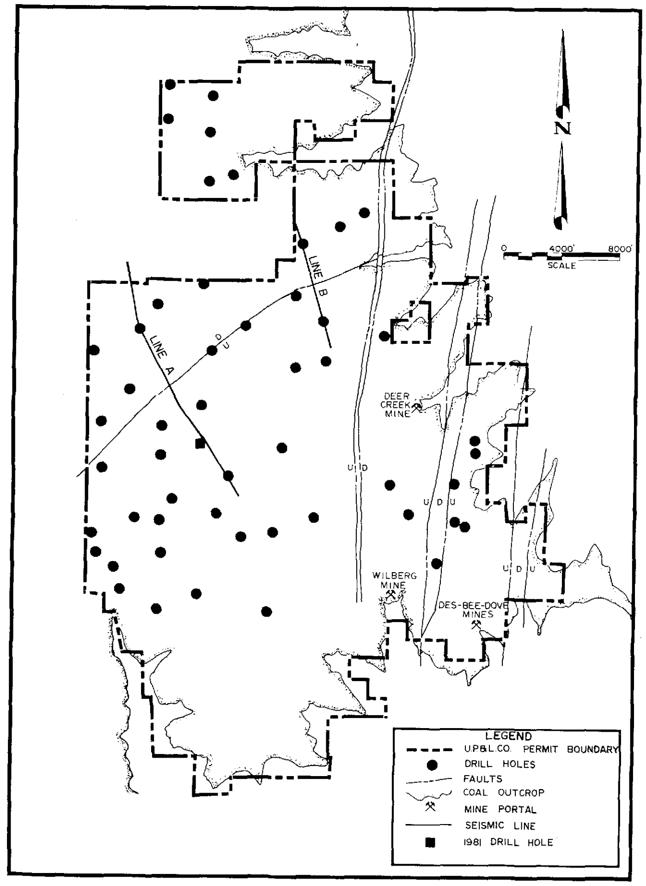

Figure 4. Location map-seismic lines.

were collected on two lines (Figure 4): one in 1980 (Line A), and in 1981 an extension made to that line as well as the implacement of a second line (Line B). The location of these lines was chosen based on the presence of coal exploration drill holes (used for interpretation control points) located at each end of the lines and viable access routes along the lines.

The seismic work was performed by Engineering Specialties, Inc., Conroe, Texas, under the direction of Emerald Exploration Consultants, Inc. The data processing was performed by Applied Research Concepts, Houston , Texas. These companies were chosen because of their proven expertise in high-resolution seismic data collection, processing and interpretation.

Data collection - The seismic data was collected using a Texas Instrument DFS-V seismic recorder which was mounted in a four-wheel drive vehicle. This system was capable of recording on 48 channels simultaneously. Each channel was connected to a series of six or twelve high-resolution Mark Product MP-L-28E geophones. These instruments were used to collect seismic data using the common depth point "CDP" method.

Prior to collecting the seismic data the energy source parameters had to established. To do this, shot holes four inches in diameter and 160 ft deep were drilled at each end of the Lines A and B. Tests were performed on both lines due to the variation in near surface rock characteristics. Line A was located stratigraphically on top of the Flagstaff Limestone while Line B was located in the upper part of the Price River Formation and lower part of the North Horn Formation. After drilling the holes, several one and five pound explosive charges were then placed at various intervals within the holes. As these charges were fired one at a time, data were recorded by the spread of geophones placed on the ground. This work demonstrated that a five pound explosive charge located at a depth of 60 ft would provide optimum results on both lines. However, on Line B it was determined that a three pound charge located at a depth of six feet would also produce adequate data. The shallow holes would not work on Line A because the Flagstaff Limestone on the surface required a deeper energy source to achieve acceptable reflected signals.

In addition to establishing the source parameters, measurements were also taken of the time required for the direct arrival of acoustic waves from the shot to a geophone on the surface immediately above the shot point. This information, termed the uphole time, relates to the velocity of the near surface strata, and was utilized in the data processing and interpretation stages.

After establishing the source parameters shot holes were drilled on the various lines. The shot holes on Line A were drilled on 100 ft intervals to a depth of 60 ft over the south half of this line and loaded with five pound charges (after initial data were collected on this line it was determined that the shot hole interval could be increased to 200 ft without sacrificing the quality of the data). Shot holes on the north half of Line A were completed at 200 ft intervals. These shot holes were drilled with a truck mounted Garner-Denver 1,000 drill rig.

On Line B shot holes were drilled in groups of three, with each hole spaced 25 ft apart. The center hole in each group was located at the surveyed shot point stations which were located at 100 ft intervals. These holes were drilled six feet deep and loaded with a one pound explosive charge. Much of this line was located in areas of rugged, roadless terrain. The shot hole drilling was done using an all-terrain vehicle mounted auger drill, where access permitted, and a hand-held gas-powered auger in the more rugged terrain.

Following the completion of the shot holes the seismic data were collected on the various lines using 50 ft trace spacing with a geophone array spread over 25 ft. On the south half of Line A the array consisted of six geophones. On the north half of Line A and all of Line B, 12 geophones made up the array. This array pattern was selected as a compromise between the desire for a long array or traces for noise reduction (by cancelling waves traveling along the surface) and a short array which provides maximum resolution. As the shots were fired the geophone arrays, 24 on each side of the shot point, spaced 50 ft apart, sensed the incoming acoustic wave and transmitted the data to the recorder where it was stored on magnetic tape. Before the next shot was fired some geophone arrays on one end of the line were dropped from the system and new arrays were added on the other end of the line. This was done from the recorder truck with the use of a roll-along switch and was necessary to maintain 24 geophone arrays on each side of the shot point. This procedure continued until all shot points had been fired.

Where the shot points were spaced on 100 ft intervals the data were collected twelve-fold, or in other words, events were recorded on each trace from twelve different shot locations. Where the shot points were located on 200 ft intervals the data were collected six-fold. The number of fold is a function of the number of traces being recorded, the shot point interval, and the trace spacing interval.

Data Processing - In recent years the seismic exploration industry has developed many computer software programs used to manipulate, mathematically adjust, and graphically plot seismic data. The processing of the quantity of data collected in this project would be impossible without the use of this computer technology. In all, ten processes were applied to the data collected which include: 1) demultiplexing, 2) CDP gathering, 3) filtering, 4) deconvolution 5) velocity analysis, 6) normal moveout correction, 7) mute, 8) stacking, 9) constant datum, and 10) equalization. A detailed description of the function performed by each individual step is beyond the scope of this report but can be found in other publications (Claerbout, 1976).

In the previous section on data collection, a discussion was made about the data being collected twelve and six-fold. In processing this data, many of the steps apply correction factors and manipulate the data so that when twelve or six traces are stacked together, the individual reflectors become superimposed. This produces reflectors that are amplified and the noise or meaningless data which stack randomly are cancelled.

Throughout the data processing the result of each intermediate step was examined carefully to ensure maximum data resolution at the depth of the coal seams. If a computer process is applied to the data incorrectly, the resolution of the data would be reduced. On the other hand, correct application of a process such as filtering can increase data resolution significantly. The higher frequency energy yields better resolution at shallow depths than do lower frequencies. The converse is true for deeper reflectors. By using filters to enchance the correct frequencies of recorded data, a high degree of resolution can be achieved at the depth of interest.

After all the data processing had been completed a final seismic profile can be made (Figure 5). The seismic profile is a graphical representation of processed data with the various traces plotted on the x-axis and the function of time plotted on the y-axis. Because the vertical position of a reflector is a funtion of its depth and the velocity the acoustic wave travels through the strata, the profile should not be interpreted the same way as a geologic cross-section.

Synthetic Seismograms - Unless the reflections shown on a seismic profile can be correlated to the various strata they represent, the profile is useless. An effective method to correlate the two data sets is to generate synthetic seismograms of control points, such as drill holes, located along the line. In this study, synthetic seismograms were developed using data from drill holes located at each end of both lines in addition to sonic velocity logs from nearby drill holes.

In compiling a synthetic seismogram of a drill hole, it is best to have a detailed lithologic log and a full suite of geophysical logs including sonic velocity and density. The synthetic seismogram is developed by a computer process that determines the reflection coefficient of the interface between the lithologies having different sonic velocities. This coefficient is further processed to generate a synthetic seismogram which should resemble the traces on the seismic profile at the drill hole location.

If hypothetical data are incorporated in a synthetic seismogram, for example, changing the thickness of the coal seam, the effect of that change can be observed. This procedure, synthetic seismogram modeling, was found useful in estimating coal thickness trends during the data interpretation phase of this study.

Data Interpretation -The data collected from the seismic surveys of the two lines produced profiles which show several reflectors: some are laterally continuous and some are intermittent. Figure 6 is the seismic profile in the central portion of Line A. The synthetic seismogram indicates that the reflectors shown at 0.35 and 0.37 seconds on the profile are the Blind Canyon and Hiawatha seams respectively.

The lateral termination of reflectors representing coal seams is interpreted as fault locations (Figure 6). Other reflectors are also useful in locating the faults such as the ones at 0.30, 0.64 and 1.15 which are interpreted as the tops of the Blackhawk Formation, Emery Sandstone and Ferron Sandstone, respectively. Similar interpretations can be made from the remaining portions of Line A and B.

A depression on the reflection representing the Blind Canyon seam on Figure 6 between traces 285 and 295 can be observed. This depression which coincides with an overlying lens-shaped reflector is interpreted as a fluvial sandstone channel. Data from adjacent drill holes support this interpretation.

By incorporating the seismic data with the data supporting the pre-seismic structural interpretation (Figure 3), a significantly different interpretation was made (Figure 7). The seismic study identified eight faults with displacements ranging from 20-180 ft. These faults were part of two graben systems not previously identified. In the pre-seismic structural interpretation the variation in coal seam elevation detected in drill hole data was assumed to be the effect of the Straight Canyon syncline. The seismic data proved this theory incorrect.

Synthetic seismogram models which represent different scenarios of coal thickness for the Blind Canyon and Hiawatha seam are shown in Figure 8. By carefully comparing changes in the character of the hypothetical reflections (Figure 8) with the Blind Canyon and Hiawatha seams (Figure 6), a general estimate of coal thickness trends can be made. The only significant discrepency found between the thickness estimations based on seimsic and drill hole data was at a point located in the southern portion of Line A. The seismic data indicated a thickness of 7.5 ft for the Hiawatha seam, but the drill hole data indicated a thickness of 2.5 ft. This point was centered between three drill holes located approximately one-half mile away. In the fall of 1981, a drill hole was completed in that area (Figure 4). The Hiawatha seam in that hole was measured to be 6.5 ft thick, one foot less than the seismic estimation.

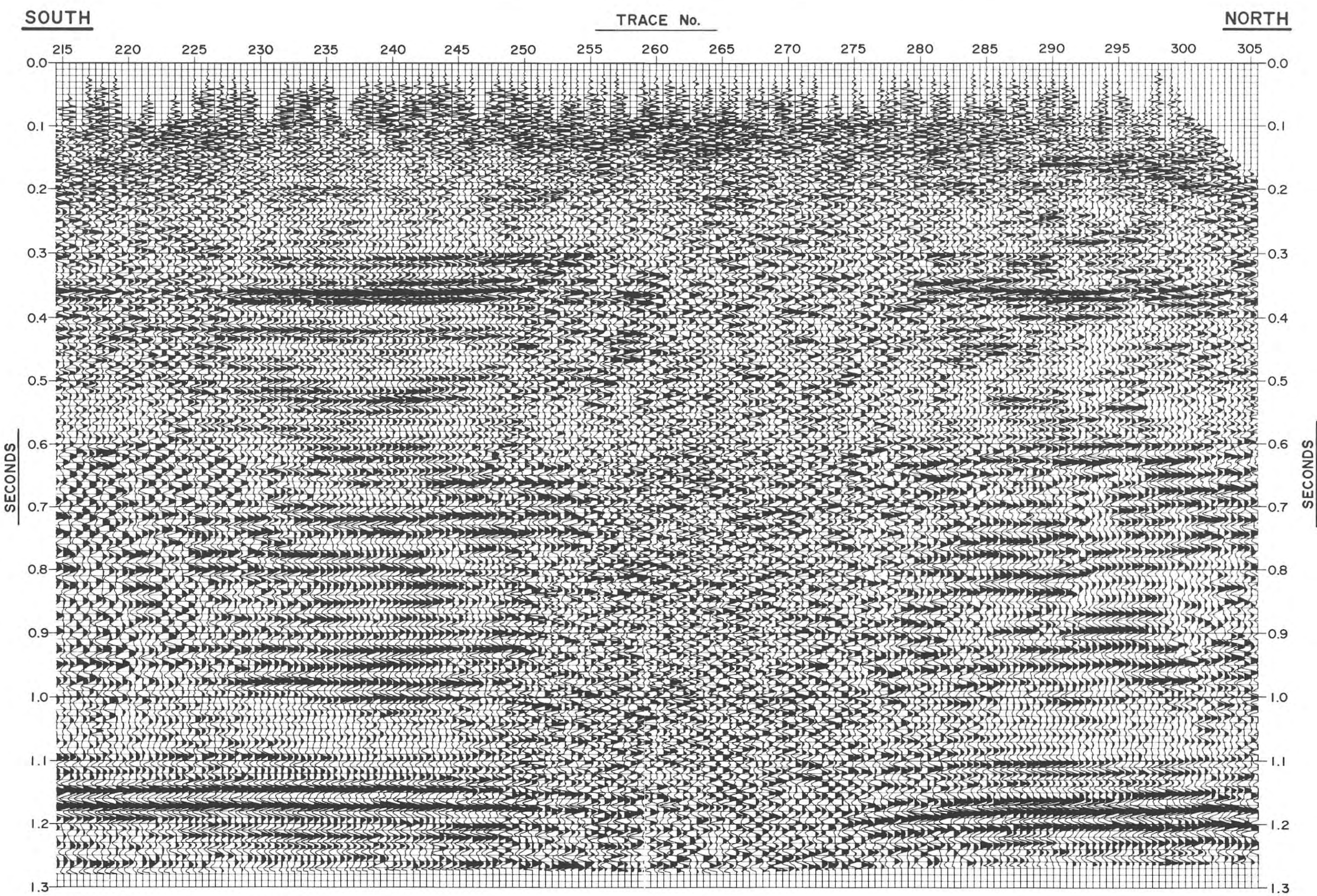

Figure 5. Seismic profile (central portion of line "A").

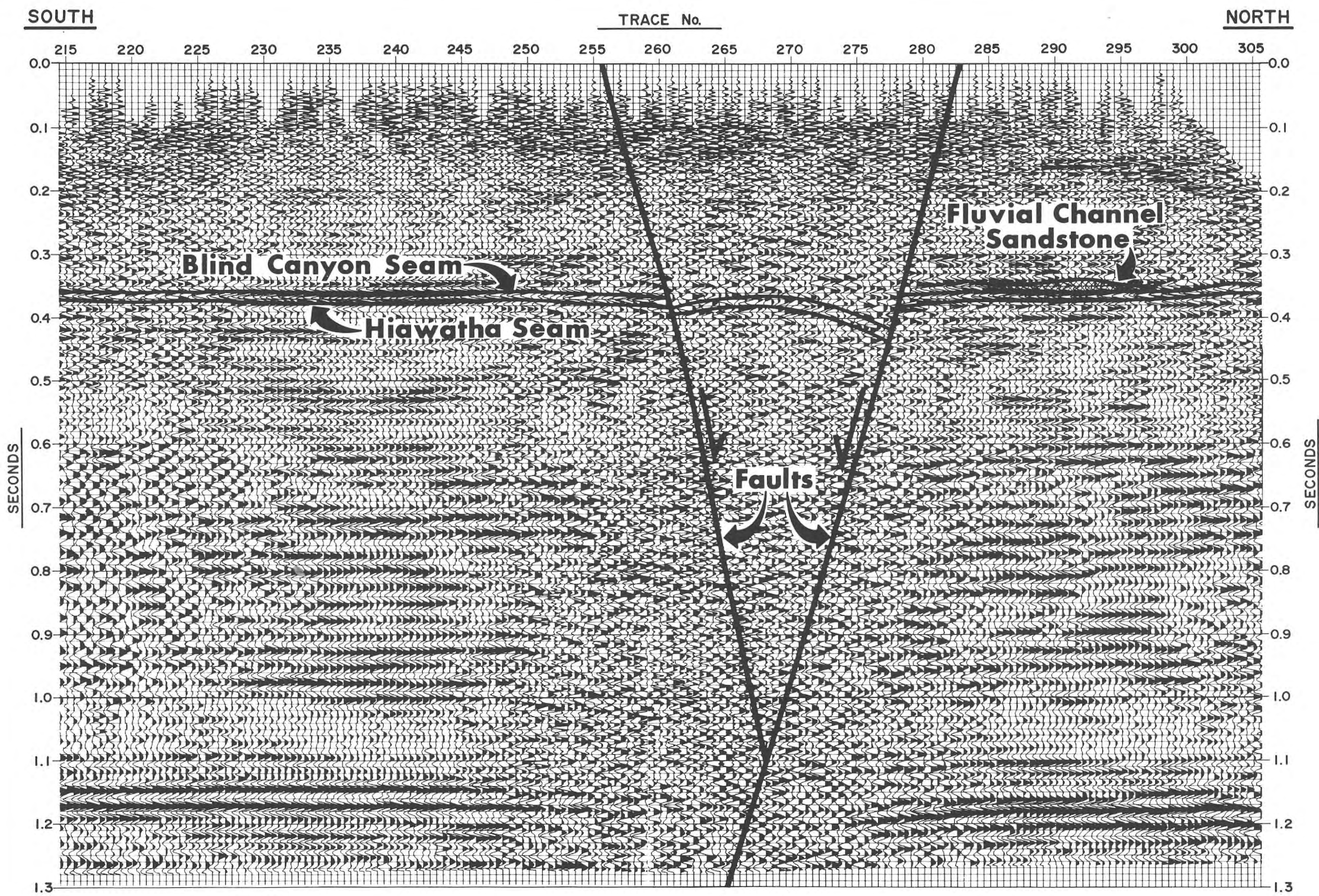

Figure 6. Interpreted seismic profile (central portion of line "A").

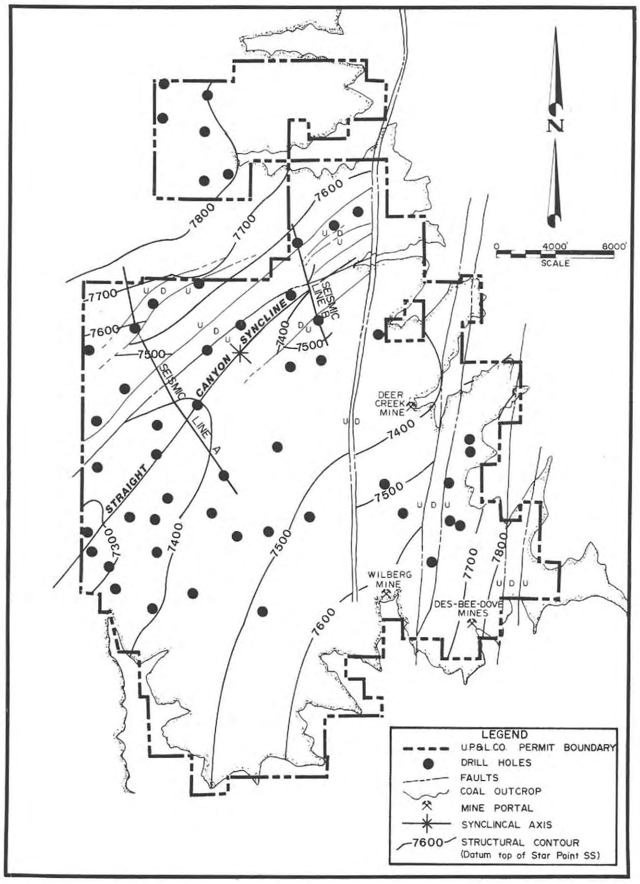

Figure 7. Postseismic structural interpretation.

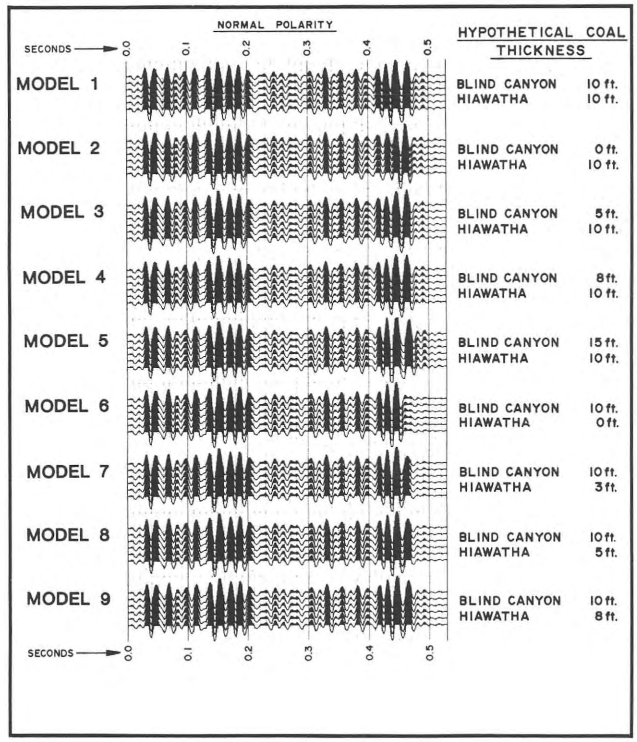

Figure 8. Synthetic seismogram models.

SUMMARY

High-resolution seismic surveys were effectively applied to the exploration of a coal property in central Utah. By utilizing this exploration method a better understanding of a complex geologic structure was accomplished. The method was also proven successful in the estimation of coal thickness trends and in identifying fluvial channel sandstones overlying the coal seam. These interpretations made an important contribution to mine planning.

ACKNOWLEDGEMENTS

The author wishes to thank the crews of Engineering Specialities, Inc., who collected the seismic data. Special thanks are given to the staff of Emerald Exploration Consultants, Inc. for their contributions in supervising the data collection and interpretation of the seismic information. It is through cooperation of the management of Utah Power and Light Company that the opportunity to publish this study is available. Appreciation is given to Robert Webster and Scott Child for preparation of the illustrations and editing suggestions made.

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IN-SEAM SEISMIC OF LONGWALL MINING PANELS

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ABSTRACT

When an explosion is forced inside a coal seam a portion of the seismic energy produced may be trapped inside the seam. The character of the signal seen by a distant geophone, also inside the seam, is strongly influenced by obstruction inside the coal. The objective of this paper is to encourage the practical utilization of such seismic surveys in U.S. mines by offering certain criteteria that must be met before obstruction in the seam can be mapped satisfactorily.

These criteria may be ordered as answers to four questions: (1) is the geologic environment suitable, (2) is the proposed target suitable, (3) what operational difficulties should be anticipated, and (4) what level of interpretive effort is appropriate?

The suitability of the enviroment and the target are best estimated after simultaneous onsite inspection of a sample target by both the client and the potential seismic contractor before the survey contract is negotiated.

All drilling of shot holes and recording holes, all underground logistics, and all handling of explosives are best conducted by employees of the mining company.

The time which the survey is to be conducted should be specified to the hour well in advance in order to minimize production losses.

The level of interpretation effort desired should be specified, if only in terms of a cost limit, before the survey is undertaken. The time lag envisioned between completion of underground work and presentation of a final report should be specified.

Utah Geological and Mineral Survey, Bulletin 118, 1982
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AUTOMATED LITHOLOGIC INTERPRETATION FROM GEOPHYSICAL WELL LOGS IN A COAL DEPOSITIONAL ENVIRONMENT, CARBON COUNTY, WYOMING

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INTRODUCTION

Density, gamma ray, and single point resistance well logs are now commonly used by geologists and engineers for identification of coal deposits and for lateral correlation of stratigraphic units associated with coal deposits. Authors of previous papers on well log analysis in coal depositional environments have limited their discussions to identifying coal seams and analysis of the economic and engineering parameters of the seams (Bond and others, 1969; Weltz, 1976; Kowalski and Fertl, 1976; Reeves, 1976; Brom and Driedonks, 1981). Many of these studies have utilized tools and techniques that were developed for the petroleum industry. Unfortunately, most well logging tools used in the petroleum industry require a minimum drill hole diameter of 6 inches, while most holes drilled for coal exploration and development are less than 5 inches in diameter. Recent developments in slimhole (less than 3-inch diameter probes) logging technology have provided the coal industry with a suit of geophysical tools to help the explorationist measure the physical properties of the coal depositional environment in an efficient and detailed manner. Simultaneous advances in digital data collection and processing now make it possible to interpret a complex suite of logs in a rapid and efficient manner.

No single type of well log can be used to completely interpret the lithology of rock surrounding a drill hole. However, detailed lithologic and stratigraphic interpretations of shallow sedimentary coal depositional environments can be made by using combinations of well logs that measure several different physical properties of the rocks. Gamma ray, density, neutron-neutron, self polarization (SP), single point resistance, resistivity, induced polarization (IP), and sonic velocity measurements can now be obtained with commercially available small-diameter probes. A computer-assisted interpretative technique is described for identifying lithologies intercepted by the drill hole. An earlier version of this interpretative technique applied to a coal depositional environment in Kentucky was described by Daniels and Scott (1980).

STUDY AREA

The four holes in this study were drilled in the Almond Formation in Carbon County, Wyoming. The location of these holes is shown in Figure 1. These four drill holes were chosen for the variety of geologic features that they represent. Drill holes DM-D12 and DM-D72 intersect many thick coal seams, with several thin sandstone and claystone layers present between the coal seams. Drill hole DM-D22 intersects thick sandstones that may represent channel deposits. Drill hole DM-D87 intersects only a few thick coal seams and many thin zones of calcareous sandstone. The study holes are part of an extensive coal-resource assessment of the region that is being conducted by the U. S. Geological Survey. Detailed lithologic descriptions of these holes are currently available, but specific information concerning the general lithology of the area and properties of the coals has been given to the authors by Venable Barclay (U. S. Geological Survey).

The coal depositional environment in the study area can generally be described as marginal-marine, with some localized fluvial channels. The dominant rock types include coal, sandstone, and claystone, with a few thin limestone layers. The sandstone-to-claystone ratio is highly variable throughout the logged interval, and is related to the

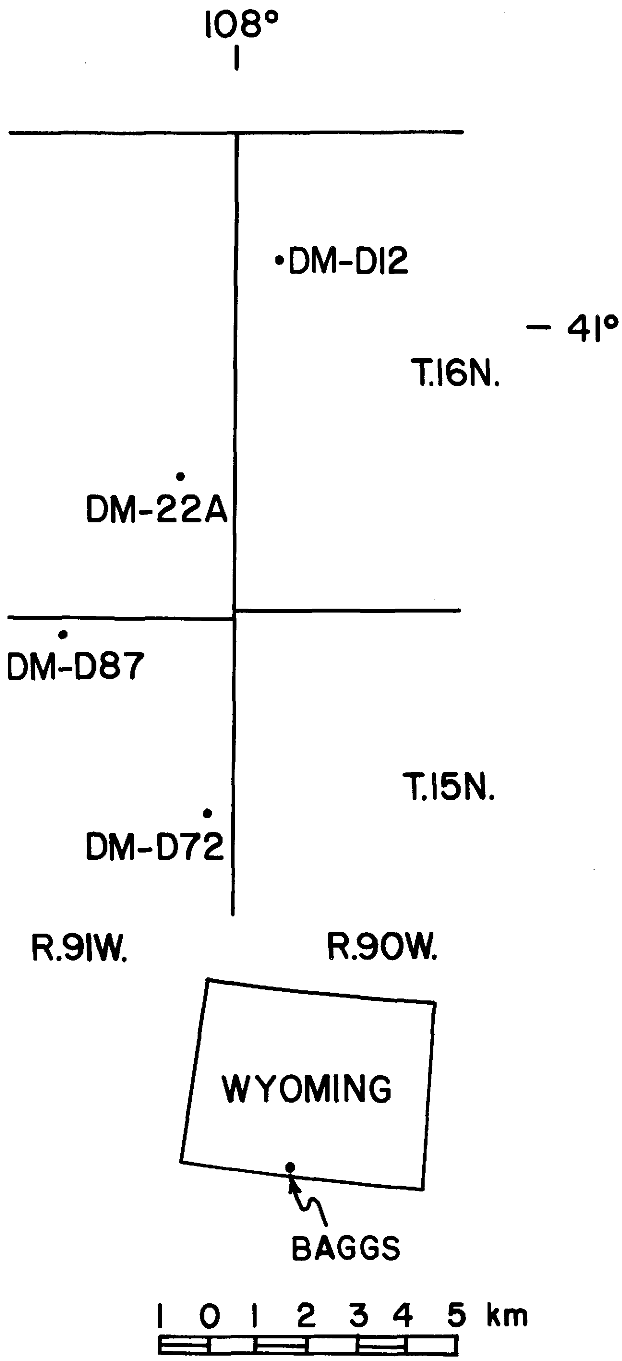

Figure 1. Location map of the four drill holes in Carbon County, Wyoming, considered in this study.

depositional environment. The sandstones are often cemented with calcareous material in varying degrees of induration. Highly indurated zones can also contain iron-stained nodules, that are interpreted as containing siderite with some associated pyrite. The thickness of the coal varies from a few centimeters to approximately three meters. The amount of pyrite contained in the coal is highly variable, and core analyses indicate that the pyrite content is not necessarily indicative of the total sulphur content (Venable Barclay, personal communication).

GEOPHYSICAL WELL LOGS

The geophysical well logs for drill holes DM-D12, -D22, -D72, and -D78 are shown in Figures 2, 3, 4, and 5, respectively. The logs considered in this study are only for that portion of the drill hole which is below the water table. These logs include "conventional" measurements (density, gamma ray, SP, and single point resistance), and measurements that are not usually made in a coal exploration program (neutron-neutron, resistivity, IP, and sonic velocity). The complete suite of geophysical well log measurements, shown in each of the figures, is called the "extended" logging suite throughout this paper.

Some detailed information concerning the nature of the coals and associated lithology can be obtained from the conventional geophysical well logs. The density log is usually the most reliable indicator of the presence of coal. A dual-detector, borehole compensated probe was used in this study. The dual-detector probe provides accurate density values, but is generally a low-resolution device. A single-detector, high resolution density probe (short spacing between the gamma ray source and the detector) should be used to accurately determine the thickness of the coal. The coals in each of the drill holes are readily identified by anomalously low density values.

The gamma ray measurement detects the presence of rocks containing elements that emit natural gamma radiation. The principal sources of natural gamma radiation in shallow sedimentary environments include the uranium and thorium decay series, and potassium-40. Gamma ray logs from the drill holes in this study principally indicate the presence of potassium-40 in some of the clay minerals (e.g., illite and smectite), and feldspar (e.g., orthoclase). Therefore, the gamma ray response, at a given depth, is roughly proportional to the amount of claystone. Coals in the study area are generally associated with a low gamma ray response, but equally low gamma ray values can be obtained in sandstone, calcareous sandstone, and limestone.

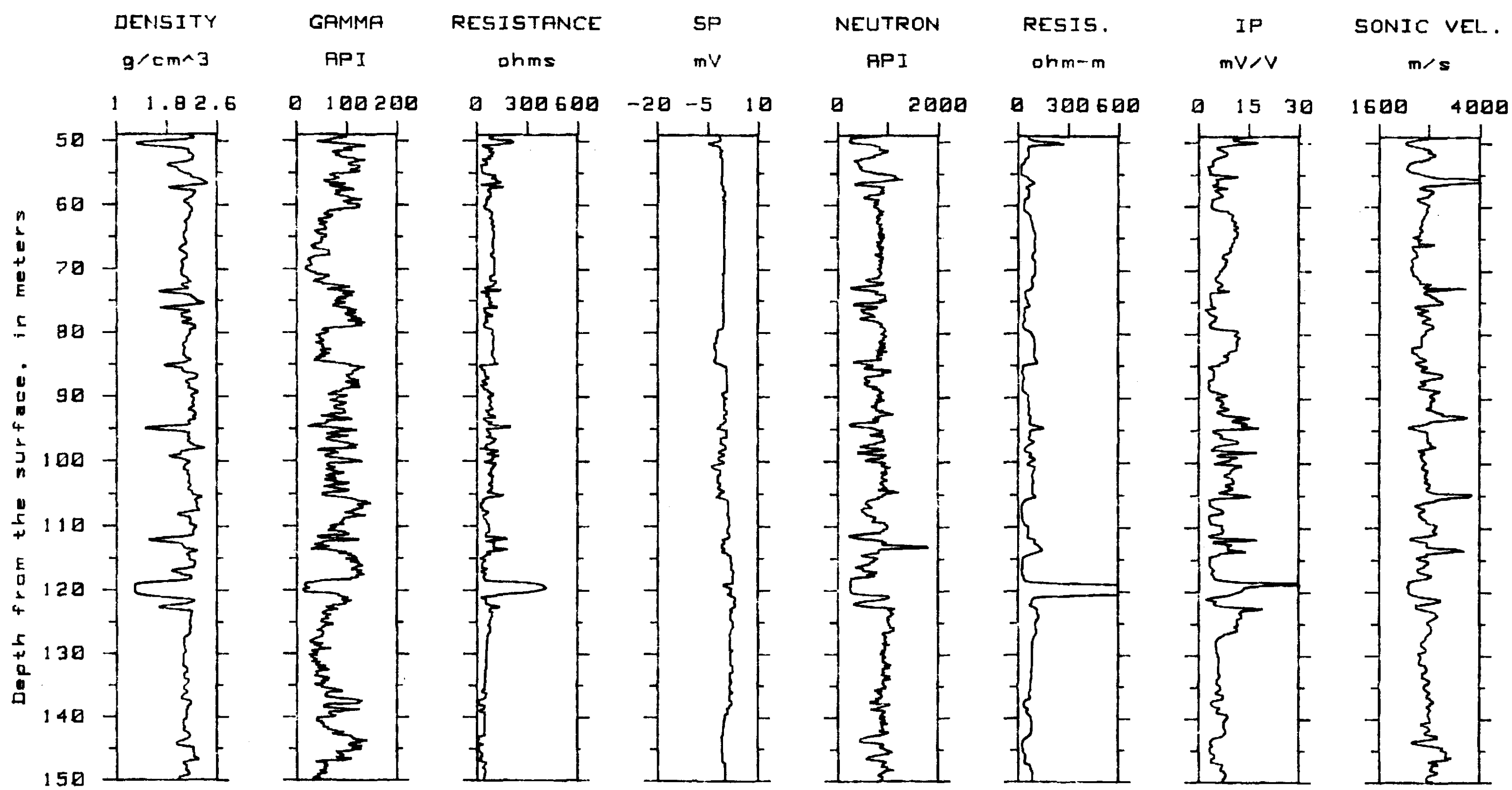

Figure 3. Geophysical well logs for drill hole DM-D22 (22). The resistivity log is abbreviated as Resis.

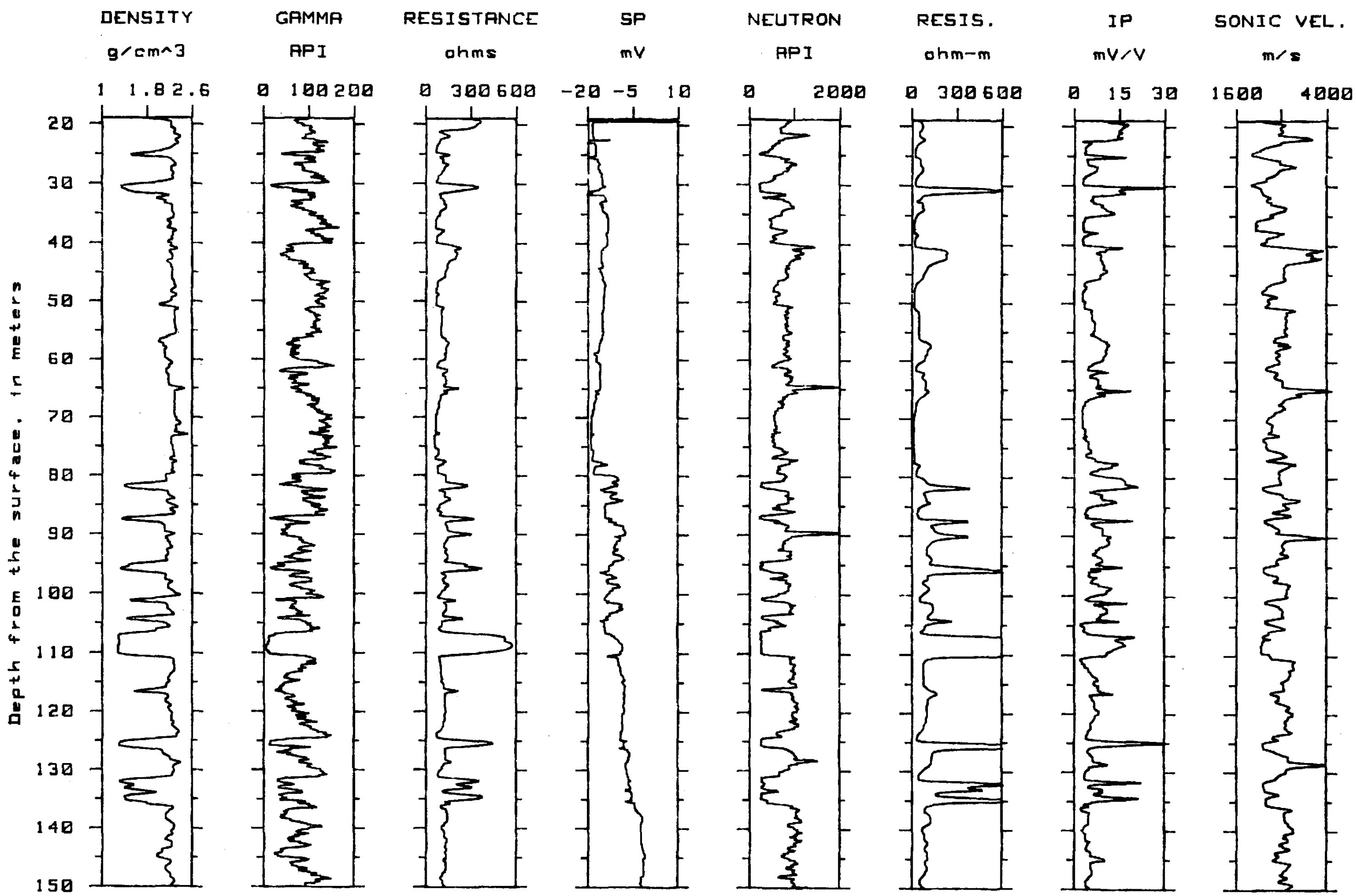

Figure 2. Geophysical well logs for drill hole DM-D12 (12). The resistivity log is abbreviated as Resis.

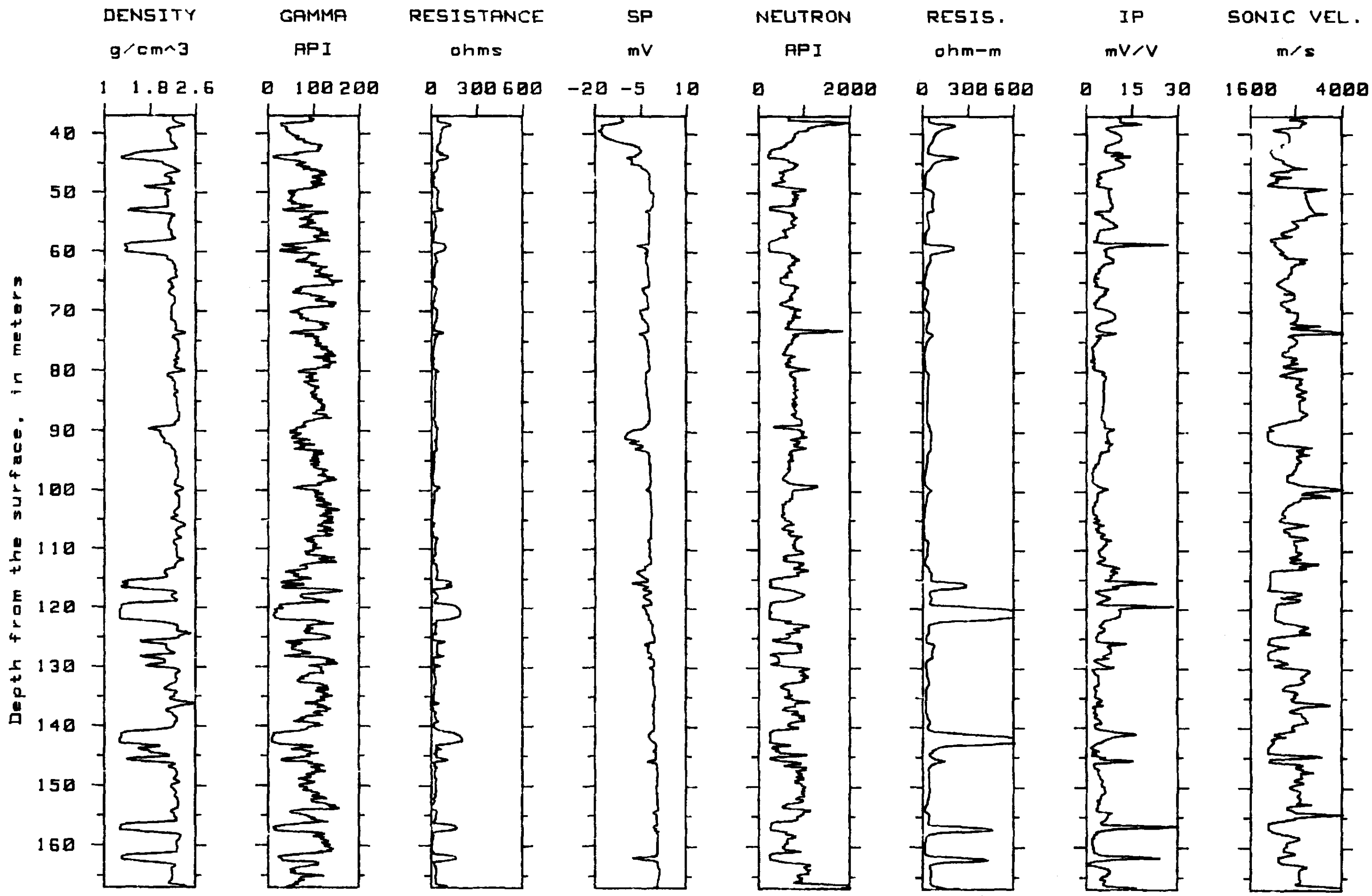

Figure 4. Geophysical well logs for drill hole DM-D72 (72). The resistivity log is abbreviated as Resis.

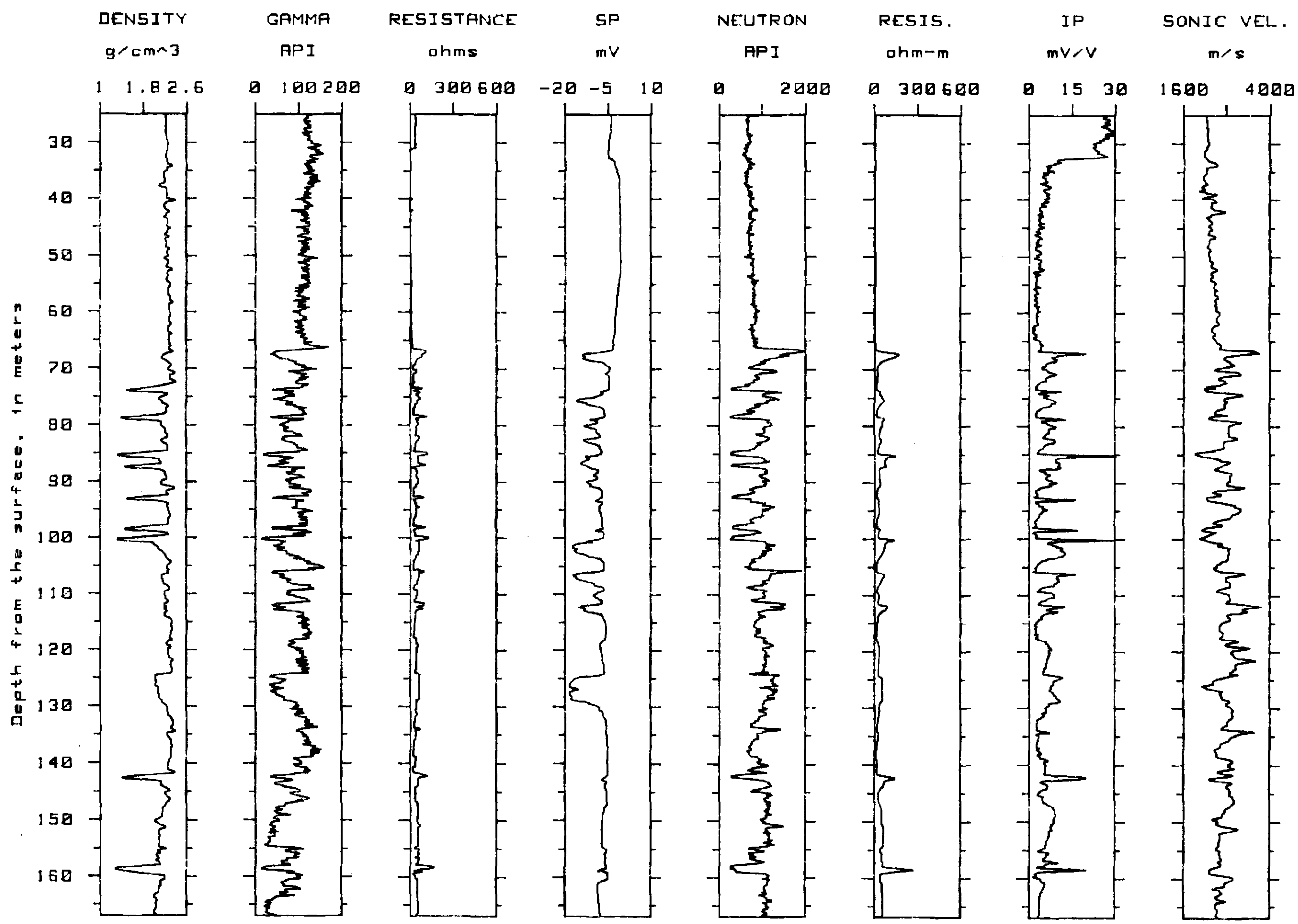

Figure 5. Geophysical well logs for drill hole DM-D87 (87). The resistivity log is abbreviated as Resis.

Single point resistance and SP measurements cannot be used quantitatively to interpret rock type. These measurements are strongly influenced by the electrical properties of the borehole fluid, which varies for each drill hole. SP values are usually low for coal, but do not provide reliable (or detailed) information on most other rock types. The low resolution of the SP log is illustrated by the well logs in Figures 2-5. The single point resistance log provides detailed information concerning "variations" of the rock type in a given hole, and resistance values can be qualitatively correlated between holes. However, resistance values cannot generally be quantitatively correlated between drill holes. SP and single point resistance logs should not be used in any interpretation scheme that requires values that are quantitatively consistent between drill holes.

Well log measurements in this study that are not normally made in coal-test holes include resistivity, IP, neutron-neutron, and sonic velocity. The resistivity logs shown in Figures 2-5 have not been corrected for the effect of the borehole fluid, and show influences from the borehole fluid that are similar to those on the single point resistance log. Previous experience has shown that if the conductivity of the borehole fluid and the borehole diameter do not change between drill holes, then the resistivity log is generally a good indicator of rock type in shallow sediments (Daniels and Scott, 1980). Accurate correction of the resistivity log for the influence of the borehole requires detailed numerical modeling of the borehole in the presence of thin sedimentary resistivity layers. This detailed modeling capability is not currently available.

The IP is measured by cording the decay voltage (emitted from an "on-off" current source) at a potential electrode that is positioned on the probe at a distance of 40 cm from an electrical current source. The rate of decay of the potential during the current off time is related to the electrical polarizability of the rock, and is called the induced polarization (IP) effect. The principal polarizable mineral associated with the Almond Formation coals is pyrite. The IP well logs in Figures 2-5 indicate the coal layers that contain an anomalously high pyrite content.

The neutron-neutron well logging prob consists of a neutron source and a neutron detector. Since hydrogen absorbs neutrons, the count rate of the neutron detector is inversely related to the hydrogen content of the rocks surrounding the borehole. Therefore, the neutron-neutron log is primarily a measure of the amount of water and hydrocarbons in the rocks. Boron, that is present in some western coals, and minerals containing chemically bound water (e.g., clays), will also yield an anomalously low neutron count rate. Coal has a low neutron count rate because of its high hydrocarbon content, whereas low-porosity limestones and calcareous (or silicified) sandstones have high neutron count rates because of their low water content. The highly indurated rocks in the study area are indicated by their high neutron-neutron log response. The coal layers in the study area are associated with low neutron-neutron response values. However, the coals are not always distinguishable on the neutron-neutron log from the claystones which have high apparent porosity caused in part by chemically bound water in the claystones.

The sonic velocity log is a commonly used logging device that measures the acoustic velocity of the rocks. Coal and claystone have low acoustic velocities, while limestone and calcareous (or silicified) sandstones have high acoustic velocities. Therefore, variations in the acoustic velocity for different rock types roughly correlate with variations on the neutron-neutron log. This relationship can be seen by comparing the neutron-neutron and sonic velocity well logs shown in Figures 2-5.

COMPOSITE INTERPRETATION OF WELL LOGS

Most explorationists have discovered that the interpretation parameters established from a particular drill hole do not necessarily apply to all of the drill holes in an area. Part of this problem can be alleviated by interpreting well logs that are minimally affected by variations in borehole fluid and borehole rugosity. These are the compensated density, and gamma ray for the conventional suite of logs. As stated previously, the SP and single point resistance logs are strongly influenced by variations in the borehole conditions, and are unreliable as quantitative interpretation parameters. In the extended logging suite, the IP and sonic velocity logs are relatively insensitive to changes in the borehole conditions. The neutron-neutron log is a good qualitative indicator of some rock types when the borehole diameter is nearly constant for each drill hole. In order to provide a consistent interpretation of a number of different types of well logs from several different drill holes in a given area, it is

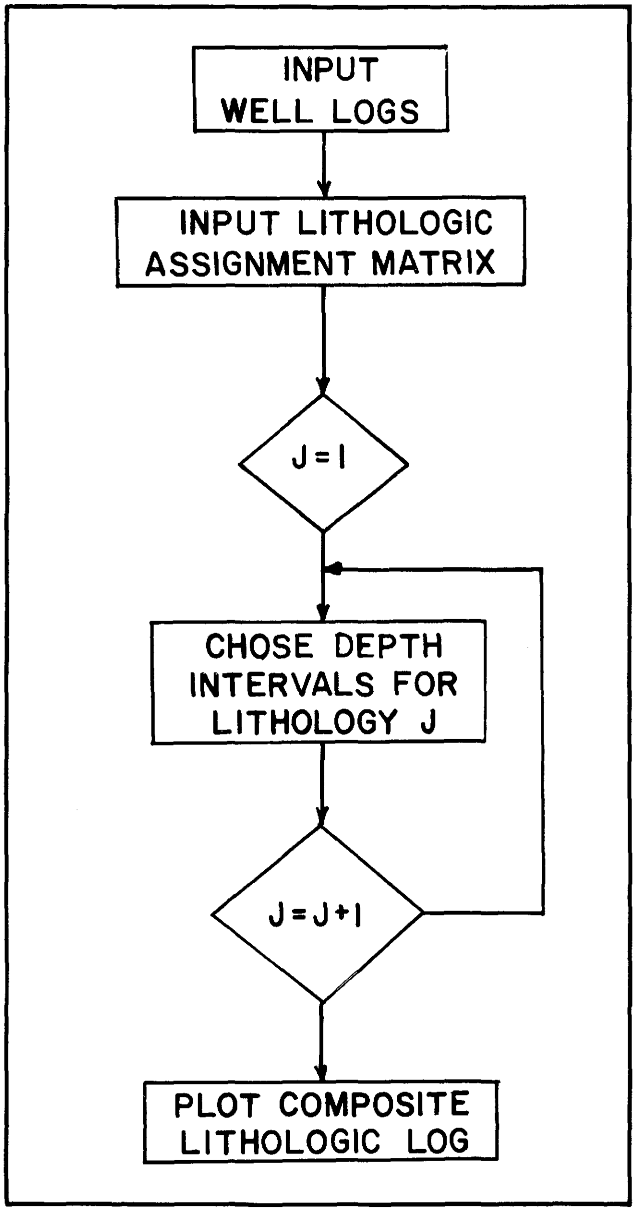

Figure 6. Flow chart for computer assignment of lithologies using a suite of geophysical well logs.

necessary to develop an interpretation strategy that can be easily applied to all of the drill holes. This can be accomplished most easily by interpreting digital well log data with the aid of a digital computer. The measurements from several different well logging probes allows a composite geologic interpretation based on simultaneous consideration of several physical properties.

The interpretation procedure that was followed in this study involves the following steps:

1. Visual inspection of the geophysical logs and the drilling log (cuttings-sample log) from a single test well to assign a geophysical well log response value range to each geologic parameter of interest;

2. computer-assisted assignment of a lithology for those depth intervals where the individual geophysical well log values for the test well are within the assigned value ranges;

3. comparison of the computer-assisted lithologic sequence with the drilling log and any other geologic information that is available;

4. adjustment of the assigned geologic parameters until a reasonable interpretation is obtained;

5. construction of a final composite geologic interpretation that is based on all of the geophysical well logs in the test well.

This final step in the interpretation is then applied to other drill holes in the area, and is summarized by the flow chart in Figure 6. The order of lithologic assignment in the automated interpretation procedure is important, because once a lithology has been assigned to a depth interval, the computer program does not consider that depth interval in future lithologic assignments. Therefore, lithologies that are most readily identified must be interpreted first. The final interpretation utilizes the well log response, or combination of well log responses, that best characterizes a particular lithology.

AUTOMATED INTERPRETATION EXAMPLE

The geophysical well logs for the study area were interpreted using the procedure outlined in the previous section. The specific value ranges for the conventional well logging suite and the extended well logging suite are given in Tables 1 and 2, respectively. Only the density and gamma ray logs were used for interpreting the lithologies from the conventional well logging suite. Since the single point resistance and the SP log are not quantitatively consitent between drill holes, they were not used for this interpetation.

The table of parameters for the extended logging

Table 1. Parameters for automated interpretation of the conventional well logs are given in Figures 2 through 5. Claystone and standstone are represented by the symbols cl, and ss, respectively.

Order of interpretation (J)	Lithology	Well log	Value range of well log
1	Coal	density	1.8
2	Sandstone	gamma ray	75
3	High ss, Low cl	gamma ray	75-90
4	Intermediate ss, Intermediate cl	gamma ray	90-105
5	High cl, Low ss	gamma ray	105-120
6	cl	gamma ray	120

Table 2. Parameters for automated interpretation of the extended logging suite. Units for the well logs are given in previous figures. The terms calcareous, sandstone and claystone are represented by the symbols calc, ss, and cl, respectively. Neutron-neutron, sonic velocity are abbreviated as nn, and sv, respectively.

Order of interpretation (J)	Lithology	Well log	Value range of well log
1	Coal	density	1.8
2	Coal, with	density	1.8
	pyrite	IP	10
3	Calc ss,	nn	1200
	with pyrite		
	(sideritic ?)	IP	10
4	Dense, calc ss	nn	1200
		sv	3000
5	Calc 33	nn	900
6	ss	gamma ray	75
7	Low cl, high ss	gamma ray	75-90
8	Intermediate cl,	gamma ray	90-105
9	Low ss, high cl	gamma ray	105-120
10	cl	gamma ray	120

suite (Table 2) shows the information that can be added to the final interpretation by considering geophysical well logs whose response is affected by the degree of induration of the rocks (sonic velocity, and neutron-neutron). It is assumed in this paper that calcareous cement is the principal cause of induration of the rocks, but it is possible for silicified rocks to yield a similar neutron-neutron and sonic velocity response. The IP well log provides information concerning the location of pyrite in coal, and the possible presence of pyrite in highly indurated sandstones. Pyrite in highly calcareous rocks may indicate the presence of iron carbonate in the form of siderite (Venable Barclay, personal communication).

Geologic well logs interpreted from geophysical well logs in the study area are shown in Figures 7 and 8 for both the conventional and extended logging suites. A comparison of the conventional and extended interpretation for each of the drill holes shows that there is no differences in the depths of the interpreted sandstone and claystone. This is to be expected, since the sandstones and claystones were

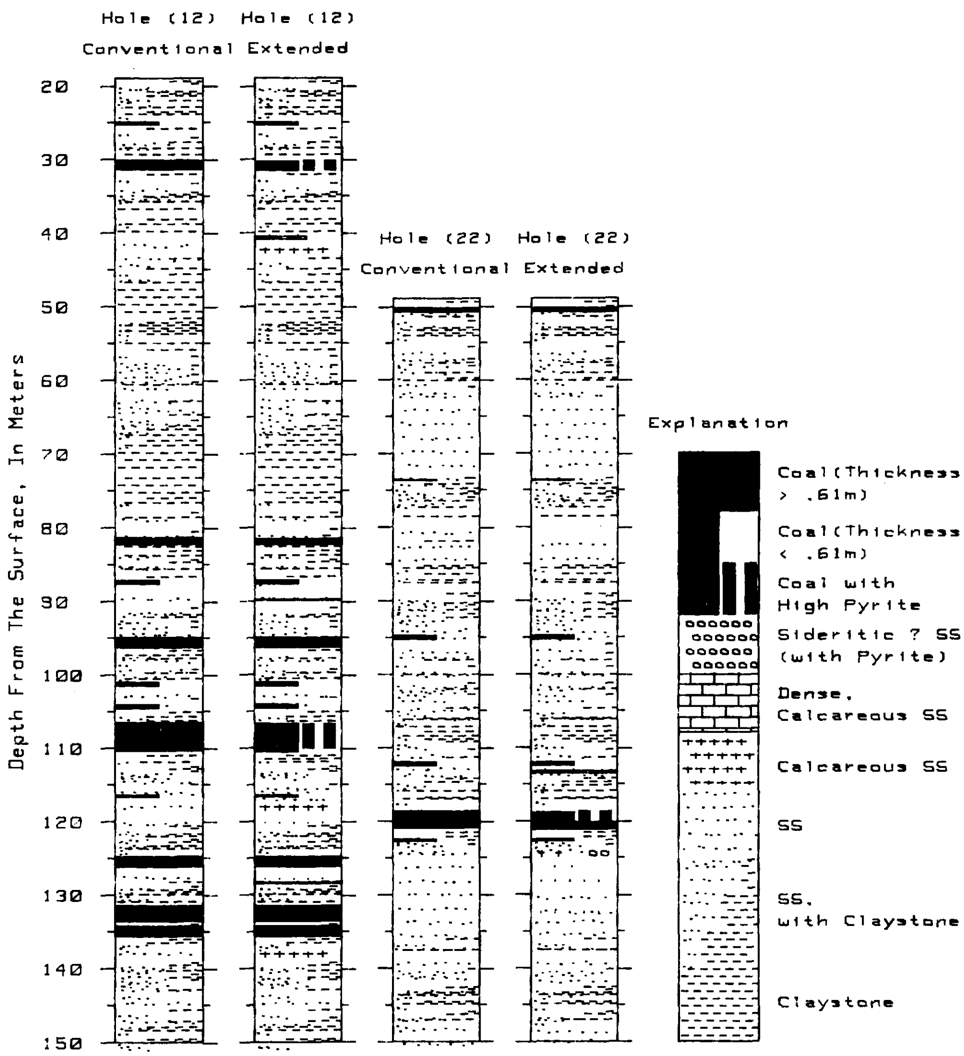

Figure 7. Geologic logs from computer assigned lithologies for conventional and extended geophysical logging suites in holes DM-D12 (12) and DM-D22 (22).

interpreted using the same criteria for each suite of well logs. Assignment of various amounts of sandstone and claystone provides information on grain size variations for individual sandstone-claystone layers. The coals in the extended interpretation indicate that several of the thicker seams (in drill holes 12, 22, and 78) may contain a significant amount of pyrite. The extended interpretation also indicates the presence of several calcareous zones. These zones are particularly noticeable near the bottom of drill hole 87.

Interpretations using the extended logging suites are also shown in Figure 9 for each of the drill holes, illustrating the variations in rock type that occur between each of the drill holes. Holes 12 and 72 contain the thickest coals within the interpreted interval, and also contain the least amount of calcareous material. There are two thick sandstones in drill hole DM-D22 between 60-72m, and 127-130.5m that may represent channel deposits. Hole 87 contains only very thin coal layers, and an anomalously large amount of calcareous material.

The depth and thickness resolution that can be obtained on the final interpreted logs is a function of the digital sample interval, and the scale at which the geologic logs are displayed. Figure 10 illustrates that

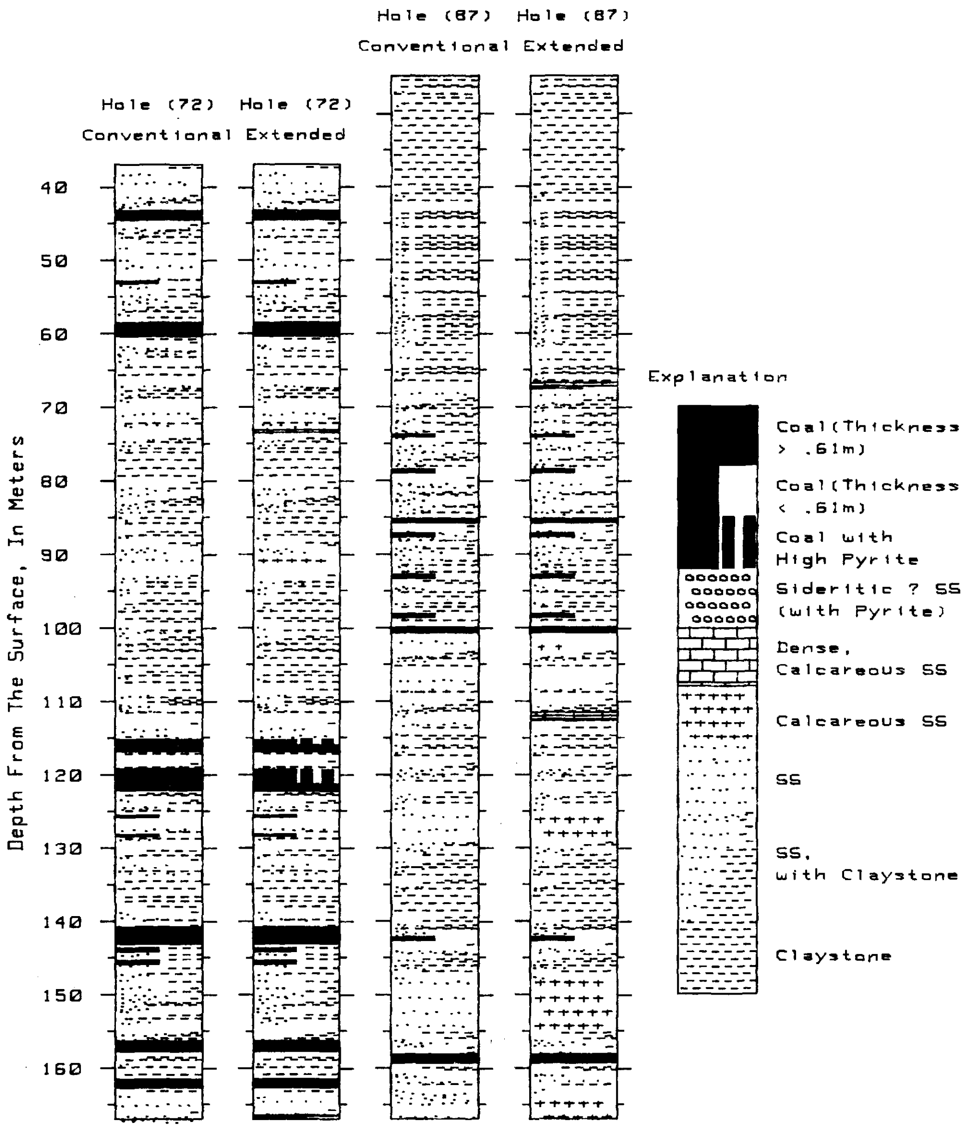

Figure 8. Geologic logs from computer assigned lithologies for conventional and extended geophysical logging suites in holes DM-D72 (72) and DM-D87 (87).

resolution can be enhanced by increasing the plotting scale. The inreased plotting scale is particularly useful for defining variations in sandstone-to-claystone content of individual layers. For example, the grain size and degree of induration in drill hole 72 increases from 88-92 meters and then decreases from 91-94 meters. The digital samples interval for the illustrations was 0.15 meters, and the resolution of the final interpreted log could be further enhanced by recording the data with a smaller digital sample interval in the field.

CONCLUSIONS

The interpretation of geologic features from geophysical well logs is necessarily subjective. This is particularly true when a single geophysical well log is interpreted without regard for the response of other types of well logs. Adequate interpretations must rely on combinations of geophysical well logs that best characterize each individual geologic feature of interest. Suites of geophysical well logs involving many different measurements can best be interpreted

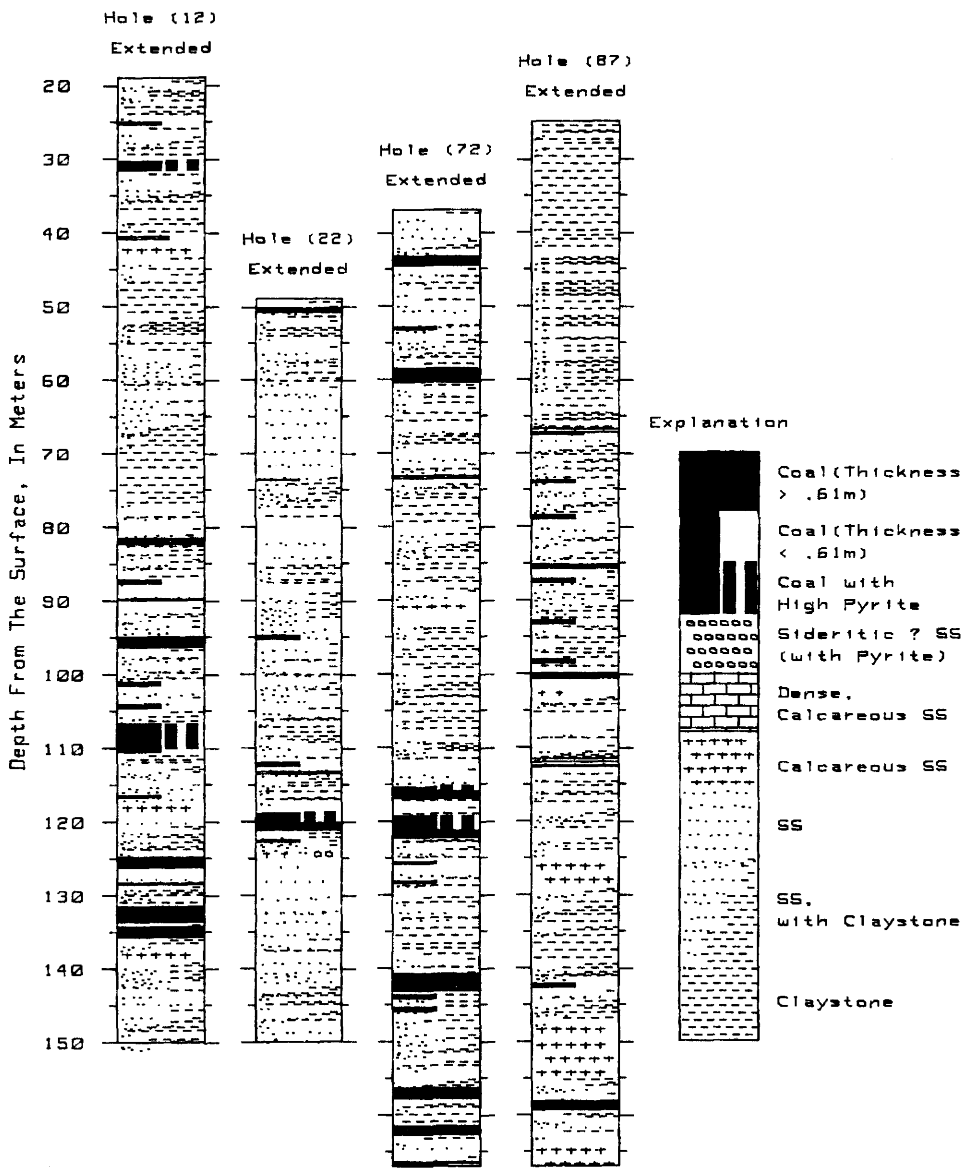

Figure 9. Geologic logs from computer assigned lithologies for conventional and extended geophysical logging suites in holes DM-D12 (12), DM-D22 (22), DM-D72 (72) and DM-D87 (87).

through an automated approach that assigns geologic features to depth intervals where digital well log response values fall within specified value ranges. Ths approach insures a consistent interpretation for all of the drill holes in a given area.

The examples given in this paper illustrate that even a simple suite of geophysical well logs (density and gamma ray) can provide valuable information concerning subtle variations in the lithologic and lithologic sequences when they are interpreted in a consistent manner. This information is essential for accurate coal correlations, for prediction and mining conditions, and in the study of depositional environments, especially in areas where the coal bearing sequences are poorly exposed. Subtle geologic features can be interpreted from a more extensive suite of geophysical well logs. Coals containing pyrite can be identified from IP log, and indurated zones can be interpreted using the

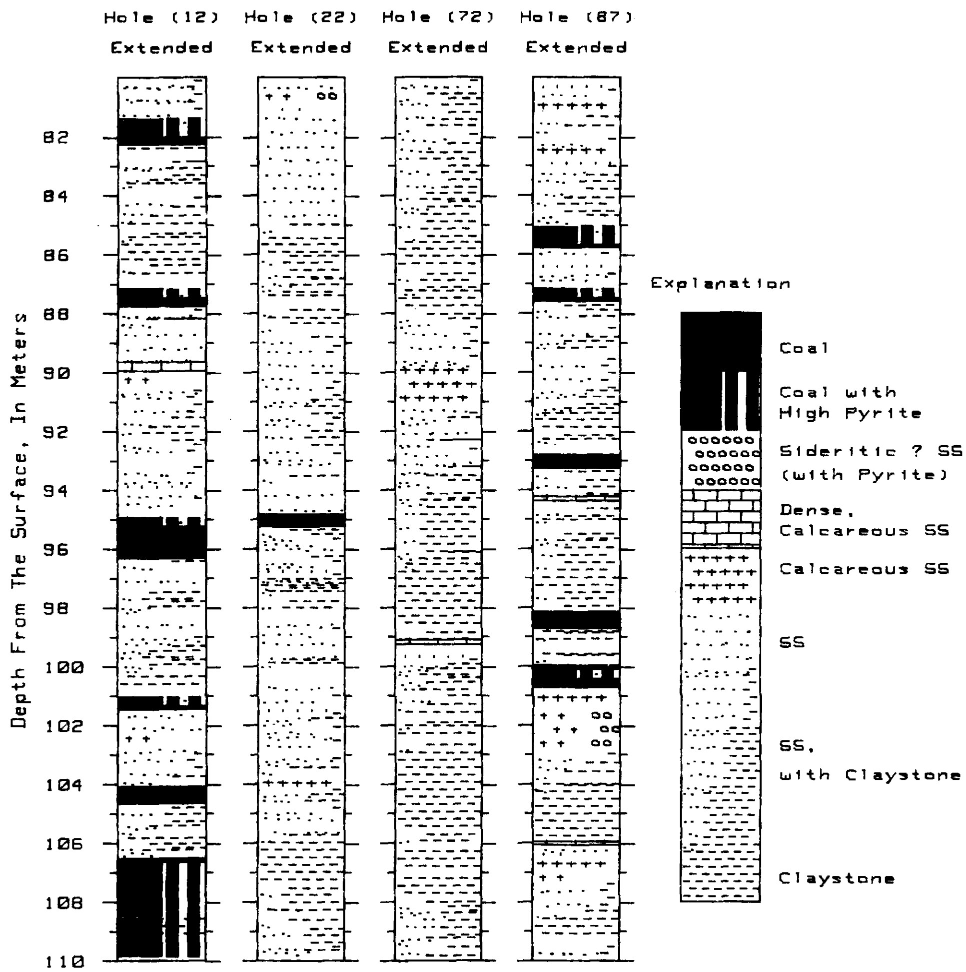

Figure 10. Expanded-scale geologic logs interpreted for the extended geophysical well logging suites in holes DM-D12 (12), DM-D22 (22), DM-D72 (72) and DM-D87 (87).

neutron-neutron and sonic velocity logs.

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COAL RESOURCE CLASSIFICATION SYSTEM OF THE UNITED STATES GEOLOGICAL SURVEY, 1982

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WHY ARE MOST COAL RESOURCE CLASSIFICATION SYSTEMS INADEQUATE?

Worldwide, many coal resource classification systems and accompanying instructional methodologies have been developed. Conceptually, most were designed to assist evaluations of the viability of mining coal, and hence, economic decisionmaking. In the past, economic pressures in many of these systems seem to have caused classifiers to ignore, to misunderstand, and not to utilize knowledge concerning 1) chemical and physical characteristics of coal, 2) geology of rocks enclosing coal deposits, 3) differences inherent in mining methods, 4) environmental changes accompanying extraction of coal by each mining method, and 5) the local to international impact on coal of competing sources of energy as to their extraction, transportation, preparation, demand, and use. The degree of understanding, consideration, and interrelating of these five factors by coal resource specialists, mining officials, and economists has commonly appeared to be the underlying reason for the success or failure of many mining enterprises. Therefore, a logical conclusion is that proper resource classification and methodology is basic to economic success.

Careful analysis has indicated to the authors that economic success in mining coal can be achieved only by: 1) understanding the chemical and physical attributes of the coal in each deposit; 2) careful geologic studies directed at ascertaining the three dimensional configuration of a deposit, deciphering the geologic history, and estimating quantities of coal available in relation to quality, thickness of coal, depth, and reliability of data; and 3) understanding surface, subsurface, hydrologic, and atmospheric environmental changes that inevitably accompany mining. After each of the foregoing has been considered, understood, and related, an economic analysis relating mining, processing, transportation, and marketing costs can be made with relative assurance that financial success will accompany coal extraction.

The preceding discussion emphasizes the necessity and desirability of careful classification of coal resources.

WHAT SHOULD A COAL RESOURCE CLASSIFICATION SYSTEM ACCOMPLISH?

The answer to this is complex and multi-faceted. From the authors' viewpoint, a satisfactory coal resource classification system and methodology should accomplish more than providing an answer to coal economics or amounts of coal. They should: 1) enhance communication, understanding, and discrimination of resource data. Ideally, a well-prepared and complete report derived from a properly designed classification system and methodology should be a resume of a large volume of coal resource data; a satisfactory coal resource classification system should also 2) quantify tonnage of coal underlying small areas to the entire nation, according to various quality, rank, thickness-of-coal, thickness-of-overburden, and reliability (distance-from-control) standards; 3) locate and distinguish where surface and subsurface information is adequate or inadequate for classification as to reliability and depth; 4) provide integration of resource data with existing land-classification networks; 5) provide data concerning minability, recovery potential, and possible end uses of coal; 6) highlight areas where the knowledge of resources is sufficient for future coal mining; and 7) be flexible and nonstatic so that new types of data can be added, integrated and analyzed, and the results compared with any system used by other coal resurce specialists for adjacent areas, counties, states, and Nations.

A well-designed coal resource classification system and methodology should utilize only objective, basic data and should eliminate or minimize personal and discipline-related judgements based on too little data and prejudices inherent to all classifiers of resources. The use of only objective data, the minimization of pesonal and discipline-related judgements (subjective data), and an adherence to relatively rigid standards, criteria, and parameters should result in different investigators classifying specified coal resources into the same categories with similar tonnage estimates. Failure to eliminate personal and discipline-related judgements and to use relatively rigid standards: 1) has hindered communication among classifiers; 2) has resulted in contradictory resource estimates for the same areas, in unnecessary re-estimation of resources in many areas, and in confusing classifiers, coal users, government agencies, legislatures, congress, and the public as to the precision and accuracy of estimates; and 3) has cast doubt on the abilities of classifiers and agencies charged with the responsibility of estimating, inventorying, and maintaining coal resource tonnage numbers.

The preceding discussion emphasizes the importance of flexible, nonstatic coal resource classification and methodology as the basis for correctly quantifying and categorizing resource estimates in small to international-size areas, for assuring similar results from the same data, and for adequately assessing coal tonnages as related to quality, thickness of coal, depth of burial, reliability, rank, economics, minability, and landownership.

EVOLUTION OF THE UNITED STATES GEOLOGICAL SURVEY'S COAL RESOURCE CLASSIFICATION SYSTEM AND METHODOLOGY

The U.S. Geological Survey (USGS) was directed by the 1879 Organic Act to map and to inventory the coal resources of the United States and all other mineral commodities. The act marked the inception of coal resource classification on a national basis. The initial period of coal investigations peaked between 1909 and 1913 with the publication of two reports (Campbell and Parker, 1909; Campbell, 1913). These reports discriminated the nation's coal resources by rank, depth of burial (easily accessible, easily accessible and available, accessible with difficulty), location (province, state, areas), and original versus presently available coal, and excluded coal of less than certain minimum thicknesses (workable or unworkable). Although vague criteria for five categories of resources were described, definitions accompanied by a written classification system were not delineated.

Study of a series of publications (Hendricks, 1939; Buch and others, 1947; USGS, 1951; and Averitt, 1961, 1969, and 1975) reveals a slow evolution of coal resource classification system that was climaxed by publication in 1976 of a bulletin, the "Coal Resource Classification System of the U.S. Bureau of Mines and U.S. Geological Survey" (USGS, 1976). The system as described in 1976 was successful in detailing a series of resource definitions and criteria that have been adopted by many coal resource estimators and that have evoked discussions directed towards state, national, and international compatibility of resource estimates. The discussions revealed that some of the 1976 definitions and criteria were ambiguous and were being variously interpreted by expert estimators. As a result, the Geological Survey decided (1977) to expand and revise the system.

Between 1909 and 1976, the coal resource classification system used by the Geological Survey gradually evolved from the five undefined general resource classes or categories used by Campbell and Parker (1909) to the thirteen defined categories recognized in the "Coal Resource Classification System of the U.S. Bureau of Mines and U.S. Geological Survey "(USGS, 1976). This evolution was relatively slow from 1909 to 1945.

In 1909, Campbell and Parker recognized five classes of resources and discriminated tonnages by: 1) rank; 2) location (coal field, coal province, and state); 3) depths of burial (distinguished by easily accessible versus accessible with difficulty); 4) original coal versus presently available coal; and 5) thickness of coal. During the period 1913-22 Campbell (1913, 1917) modified the five-category system by expanding the fifth category (thickness of coal) and refined and third category by recognizing depth of burial in terms of feet below the ground surface. In addition, he began the practice of generally relating quality of coal to proximate analyses. From 1922 to 1951, a series of coal resources reports (Hendricks, 1939; Buch and others, 1947; Combo and others, 1949; Reinemund, 1949; Cohee and others, 1950; Read and others, 1950; Berryhill and others, 1950; and USGS, 1951) gradually revised category 3 by recognizing three-ranges of depth of burial, refined category 5 by recognizing three ranges in thickness of coal for each rank of coal, and added category 6 (degree of reliability by recognizing three subcategories based on distance from points of measurement; these subcategories are the earliest recognition of measured, indicated, and inferred.

Averitt (1961, 1969, and 1975) greatly strengthened, refined, and expanded the coal resource classification system of the Geological Survey between 1960 and 1975. He published criteria for weight of coal or specific gravity, for existing reliability subcategories, for rank determination, for overburden, for depletion of resources, for percentages of coal recovery, and for methods of mining. In addition, he formalized category 4 — mined versus unmined by recognizing the terms "remaining resources" and "original resources;" category 7 — well-known versus poorly known resources by recognizing "identified" and "undiscovered;" category 8 — reserve base or the part of identified resources from which reserves are estimated and/or extracted; category 9 — quality of coal; and category 10 — specific location by township, range, and rarely section and location of unspecified areas and specified areas. Finally, Averitt (1975) formally published definitions for resource and reserve terms that are the basis for those used in 1982.

NEW COAL RESOURCE CLASSIFICATION SYSTEM OF THE U.S. GEOLOGICAL SURVEY

In late 1977, it was decided to rewrite the "Coal Resource Classification System of the U.S. Bureau of Mines and U.S. Geological Survey" (USGS, 1976). This decision was reached because of the ambiguity of some resource/reserve base/reserve definitions and criteria, and because it was evident that a compendium containing any more definitions, exact statements concerning criteria for each possible category, general and specific guidelines for applying the system, and a description of how to use geophysical data, all accompanied by illustrations, was required to meet the demands for disemination of coal resource information. The senior author of this paper was assigned the task of initially revising the 1976 system. In early 1978, the Geological Survey and Bureau of mines also decided to prepare a report on mineral resource classification, applying to all minerals which are in their areas of responsibility. The senior author of this paper was assigned to the committee preparing that report. Members of the staffs of the U.S. Geological Survey, U.S. Bureau of Mines, U.S. Department of Energy, and the U.S. Security Exchange Commission labored for two years to prepare "Principles of a Resource/Reserve Classification for Minerals," (USGS, 1980). This report recommended adoption of certain resource/reserve definitions and guidelines by those preparing classification systems for all mineral commodities.

The 1982 rewrite of the "Coal Resource Classification System of the U.S. Geological Survey," (USGS, 1976), which carefully follows the recommendations of the 1980 report on all commodities, has nearly been finished by a team of authors, has been reviewed technically, and is waiting for a decision about publication. This uncertainty is the result of: 1) the Minerals Management Service being created from the Conservation Division of the Geological Survey, and 2) a desire not to publish the rewrite until the roles and responsibilities of the new agency and the Geological Survey are clarified. Thus, the details of the Geological Survey's coal resource classification system and methodology cannot be spelled out herein.

The following paragraphs in the authors' opinion describe six concepts that control the system and methodology and summarize many details so that interested persons may form opinions as to the adequacy of the system.

First, the revised coal resource classification system is an expansion of the system adopted in 1976, by which a coal is classified into resource/reserve base/reserve categories and on the basis of geologic assurance of existence and on economic feasibility of recovery.

Second, all data used in determining the proper categorization of a coal for geologic assurance are to be objectively determined from field and laboratory investigations. Geologic assurance is determined by interrelating distance from points of control and other physical and chemical data about coal and associate rocks. Similarly, all data used in ascertaining economic feasibility are to be objective mining, transportation, and processing costs as related to demand, supply, and marketing data. These restrictions as to use of objective data are aimed at eliminating or minimizing the adverse effects of personal and discipline-related judgements upon ability to duplicate resource/reserve base/reserve estimates.

Third, resource and reserve base estimation is to be based upon the factors used to determining geologic assurance. In contrast, reserve estimation is to be based upon the factors for determing economic feasibility and is to be directed at specific bodies of coal designated as being parts of the reserve base.

Fourth, coal deposits designated as reserve base coal must have physical and chemical attributes similar to those of coal deposits currently being mined at a profit. Such similarity indicates the probability of mining at a profit without direct economic analysis.

Fifth, designation of a reserve within a body of coal categorized as reserve base is to be based only upon the factors used to determine economic feasibility. Reserves, therefore, are derived only from coal that has already been categorized as reserve base.

And sixth, total resource/reserve base/reserve tonnage estimates are to be recorded for all categories and areas that are separately estimated, so that local to international planning and decisionmaking are based on facts; such planning and decisionmaking should result in optimum use of coal.

These six controlling concepts clearly demarcate responsibilities that are discipline related. Resource/reserve base estimation is largely a geologic responsibility, reserve estimation is a responsibility shared largely by mining engineers, economists, process engineers, and marketing specialists, and to a small extent, by geologists and chemists.

The revised and rewritten coal resource classification system defines about 20 categories and subcategories of resources, 6 categories and subcategories of reserve base, and 7 categories and subcategories of reserves. These 33 categories and subcategories allow much greater flexibility and ease of resource/reserve base/reserve classification of tonnage amounts than do the 14 defined by the 1976 classification system. Approximately 150 coal resource related terms and coal terms are defined in the revision whereas only 4 were defined in the 1976 classification. These two comparisons indicate the magnitude of the revision. Each of these 33 resource/reserve base/reserve definitions is accompanied by criteria. Only 10 criteria ranges accompanied the definitions in the 1976 version.

The new system contains a chapter of specific instructions for use of the criteria, a chapter describing the estimating of hypothetical resources, a chapter on the use of geophysical logging of drill holes for determining the existence and thickness of coal beds, and an extensive series of illustrations showing the methodology of calculating coal resources under specified geologic conditions.

The discrimination of tonnages of coal resources by 4 ranks, 5 ranges of thickness of coal, 5 ranges of thickness of overburden, and 5 reliability categories allows the classification of coal resource tonnages into 500 categories for each township and range; county; state; coal bed and/or zone; coal field, basin, region, and province; and formation and member. Potentially, the number of categories is measurable in the thousands to millions, because of the possible inclusion of categories of ranges of sulfer, ash, and trace-element contents, and other measurable coal characteristics.

Generally, only a few categories are required to classify tonnages of coal in small areas. However, as the size of the area increases, or as more areas are investigated, recognition of additional coal characteristics may become desirable; the potential number of categories is, thus, greatly increased. The desirability of increasing the number of categories is based upon the principle of recognizing quantities of coal most suitable for particular requirements so as to minimize costs and manpower requirements.

The number of categories used by the U.S. Geological Survey's coal resource classification and methodology system is minimal at any specified time. However, when and if the system reaches full potential, the number of categories used to answer the inquiries of scientists, industrial and government planners and decisionmakers, the public, and academic institutions may be in the thousands.

The system has been designed so as to use basic data and samples collected at specific locations, that is geographic and depth data points. Analytical data from samples of coal collected at specific locations and other physical and chemical data are integrated into categories relating coal quality to coal tonnages, rank thickness of coal, depth of burial, and distance from the data points for any size area ranging from a land section to the nation. The criteria and definitions of resource categories are used to control assignment of coal tonnages into any resource/reserve base/reserve category. These criteria and definitions can be modified as knowledge increases and resource reporting requirements change. Thus, in the 1982 system, individual and currently undivided coal resource categories can be modified or completely changed as the objectives of scientists, planners, and dicisionmakers, and public needs evolve in coming decades.

In the authors' opinion, most currently used coal resource classification systems and methodologies are inflexible and static and will be nonresponsive to future resource/reserve base/reserve requirements because they cannot be enlarged, modified, or changed to accept and integrate new types of data into categories currently used or into new categories that are compatible with old categories. The Geological Survey's system was designed to be flexible and nonstatic so as to accept new types of data and new categories that can be integrated with older data and categories.

Realization of the full potential of the Geological Survey's coal resource classification and methodology system depends upon the continuing collection of pertinent geologic data and geochemical samples. The geologic data and the analytical results obtained from the geochemical samples must be integrated into coherent local to national estimates of coal resource tonnages as related to coai qualities, which is not limited only to quantity estimation, but these estimates must be reproducible regardless of the estimator and technique used.

COMPARISON OF RESULTS BETWEEN THE GEOLOGIC SURVEY'S COAL RESOURCE CLASSIFICATION SYSTEM AND THE KRIGING TECHNIQUE

During the decade since the Arab oil embargo, many coal resource classification systems and methodologies used in the United States and in the world have been investigated, criticized, and changed or abandoned. The Geological Survey's system and methodology have been widely investigated, have survived all criticisms, and have been modified or changed as needed.

The Geological Survey, in a continuing effort to base coal resource estimation on the most reliable methodology, has investigated the kriging technique. This technique has been successful in examining and predicting resources and reserves of metaliferous vein deposits. In the authors' opinion, the investigation has revealed, to date, that: 1) kriging statistical analysis of large coal-bearing areas yields total estimates similar to the total tonnage estimates of the Geological Survey classification and methodology system; 2) kriging is a statistical methodology designed to estimate mineral resource tonnages and to determine the statistical probability or confidence level of the estimates; 3) kriging methodology must be modified so as to categorize coal resources by man-made or natural constraints; such as depth limitations, thickness-of-coal criteria ranges, distance-from-points-of-control criteria (measured, indicated, inferred, and hypothetical), and faults, fold axes, erosion channels, lithologic and physical characteristics of rocks enclosing coal beds, and pre-existing mining; 4) kriging analysis, because of averaging of thickness data tends to de-emphasize areas of thick and thin coal, which are the areas of primary interest to the mining industry.

The Geological Survey's coal resource classification and methodology system, by contrast, is designed and capable of: 1) yielding tonnage estimates based on manmade and natural constraints (depth limitations, thickness-of-coal criteria, distance-from-points-of-control criteria, geologic and physical limitations); 2) accepting minimal to vast amounts of data on small to large areas and yielding tonnage estimates that emphasize areas of thick and thin coal and recognizing pre-existing mining, that effect resource estimates and on estimates of recoverable coal (reserves); and 3) adapting to changes of the man-made constraints and to changing resource requirements.

In our opinion, even through the kriging technique, as applied to coal, and the Geological Survey's coal resource system's methodology yield similar total resource estimates, the methodology of the USGS system is easier to use for small areas whose tonnages must be categorized according to manmade or natural constraints. Furthermore, because kriging tends to de-emphasize areas of thick and thin coal, and to emphasize the average thickness, we deem the systems' methodolgoy to be superior, despite kriging yielding statistical probability levels of confidence for total coal resources.

The methodology of the Survey's system has been used successfully for decades, and has an accompanying coal resource classification system and computer software, whereas the kriging technique, in our opinion, is still in the developmental stage when applied to coal resources.

It seems logical to the authors, in view of the comparative stages of development, to continue usage of the successful Geological Survey coal resource classification system and methodology and to add to it the kriging technique of statitistical probability determinations.

CONCLUSION

The lack of a commonly accepted national and worldwide coal resource classification system and methodology by coal resource specialists, governmental agencies, consultants, and the mining industry has hindered development of coal resources. Therefore, the need is great for adoption of a commonly accepted coal resource classification system that incorporates definitions, terminologies, criteria, guidelines, and methods of estimation. Adoption of a single system in the United States could enhance coal development, and perhaps, adoption of a single international system.

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COAL RESOURCES AND RESERVES ESTIMATES: SOME UNRESOLVED PROBLEMS

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By current estimates, the remaining coal resources of the United States of America exceed four trillion tons, and those of Canada are more than one-quarter trillion tons (Averitt, 1975; Canada Department of Energy, Mines and Resources, Report EP77-5, 1976). "Enough and to spare," an expression that was used in the recent past to describe American's oil and gas resources, comes easily to mind when one considers the enormity of these tonnage figures. It is the purpose of this paper that follow to report, analyze, and describe the multitude of inconsistencies, procedural disparities, and problems of nomenclature and methodology that lie within these simple and reassuring tonnage figures for North America.

It is perhaps surprising to note that many geologists and engineers today do not fully understand the critical distinction between the terms "resource" and "reserve;" that distinction provides simple discrimination between those coal deposits that *may* be mineable (now or in the future) and those that are now economically and legally mineable. These terms are often used interchangeably (incorrectly) today in reports that have been utilized in developing estimates for coal resources of the United States, and in studies of future energy needs.

Specific point of observation spacing standards for degrees of assurance for the terms "measured" and "indicated" have been defined and assigned individually for the major coal fields of Canada. Point of observation spacings of 0.5 mi, 1.5 mi, and 6.0 mi for measured, indicated, and inferred coal have been used by the U. S. Geological Survey and some state surveys for many coal fields of the United States, without consideration of the varying degrees of continuity of individual coal beds.

As a replacement for such inflexible procedures, a required level of accuracy for the categories of measured and indicated appears needed that would serve as a guide in the determination of spacing of points of observation for various coal fields. The required level of accuracy for each category might be expressed as a maximum allowable percentage of error.

Standards or guidelines are needed for the use of drill-hole data and geophysical logs in coal identification and thickness determinations. One major coal-producing state has significantly increased its reserve/resource tonnage by the utilization of data from oil test hole logs. Other states that have refrained from using such data report disproportionately lower resource/reserve tonnages.

Data from water wells are selectively used for coal resource/reserve estimates in some coal fields and are sometimes ignored in others. In some cases, water-well data are used, but only for determination of indicated or inferred reserves.

Special training or instructions are required to accurately determine coal thickness from the response curves of various geophysical logs. Quite often such logs are indiscriminantly used without consideration of boundary-determination problems which are unique for each type of geophysical log. Geophysical logs are now being used to make *in situ* coal rank and quality determinations. Should such data be incorporated, with or without qualification, into coal resource reserve estimates?

Both the U.S. Geological Survey and the U.S. Bureau of Mines figures for coal reserves and resources incorporate only the parameters of thickness and depth of coal, and are "blind" to many other geologic constraints on mining and recoverability. The most important of these constraints include the following:

1. Coal seams too thin or too thick for conventional mining methods.
2. Coal seams that cannot be mined due to insufficient separation from underlying or overlying previously mined beds.
3. Unstable or otherwise unfavorable roof strata.
4. Soft or heaving floor strata.
5. Coal seams that are too lenticular or discontinuous for conventional coal mining methods.
6. Coal seams in intensively faulted areas.
7. Coal seams having high angles of dip precluding the use of conventional coal mining methods.
8. Coal seams that cannot be mined due to proximity of water-bearing strata.
9. Coal quality problems such as excessive ash, sulphur, chlorine, or sodium.

The present USGS-Bureau of Mines classification for reserve base includes bituminous coal beds more than 28 in and subbituminous beds more than 60 in thick to depths to 1,000 ft. Both of these thicknesses are less than thicknesses now considered mineable in the western United States. The lower limit for bituminous seam coal in deep mines is about five feet. For subbituminous coal a thickness of at least eight feet is generally required. Accordingly, our current reserve estimates include many thinner coal seams that cannot or will not be mined in the foreseeable future.

Within the Powder River Basin many seams (Wall, Upper Pawnee, Lower Pawnee, Cache, Manning, etc.) ranging in thickness from 25 to more than 100 ft that occur at depths to 1,000 ft have been included in United States reserve estimates. However, the mining technology required to mine these thick seams does not exist, and will require many years for development. What the ultimate recoverability from these thick seams will be is unknown, but could be as low as 25 percent or less.

Many relatively thick coal seams in the western United States occur in stratigraphic sequences in which there is relatively little separation between individual beds. Because of the many constraints on multiple seam mining, it is likely that less than half of the seams that are present in many areas will be mineable, unless extraordinary precautions are used in mining that will add substantially to mining costs. .Recoverability will be considerably lower than normal even under the most favorable conditions.

Very little is known concerning prevailing roof and floor conditions for many western coals. It appears that many of the recognized seams in the Powder River Basin are overlain by soft shales that may not be of sufficient strength to permit conventional room and pillar coal mining. Whether longwall mining techniques can be developed for these thick seams remains questionable.

In strong contrast to the eastern and midcontinent coal fields of the United States, the western coal fields are commonly faulted and often contain seams having high dips. The occurrence of faults within a coal field may or may not preclude mining, but the problem must be fully considered in mine planning.

Shuttle cars and continuous miners become considerably less efficient when operating in coal seams that dip at angles greater than 10°. Dips of less than 8° are needed for efficient usage of longwall equipment. Large areas in some western coal fields contain strata that dip at angles of 20° or more. Until technology is developed to economically mine seams having high dips, the resources contained in such seams should not be included in reserve base figures.

Porous and permeable sandstones commonly occur in association with coal beds in many western coal fields. Where these sandstones are aquifers, serious water problems may result that could preclude the mining of adjacent coal seams. No systematic data are now available concerning the magnitude of this problem in western coal fields.

According to specifications listed in USGS Bulletin 1450-B, coal "containing more than 33 percent ash is excluded from resource and reserve estimates." In major areas of the Western United States, little or no data are available concerning ash content of coal included in reserve estimates. Available evidence indicates that many high-ash coals have been indiscriminently included in reserve estimates because details of ash content were not available. The sulfur content of western coals has been given considerable attention in recent years, but only relatively sparse information is available in most coal fields for even this important parameter. Only very limited data are available on objectionable impurities in coal such as sodium and chlorine. Whether coals high in sodium and chlorine should be included in the reserve base is questionable.

At least one geological survey has developed procedures to eliminate from its reserve estimates coal in those areas that are deemed unmineable due to environmental or geographic constraints. Again, no guidelines are presently available that would permit standardization.

Coal parameters such as amount of contained sulfur, chlorine, sodium, and so on, are often not identified in the reporting of coal resources and reserves. Guidelines for the incorporation of such data are needed.

We are, in the latter part of the Twentieth Century, commencing the intensive utilization of our second great fossil fuel resource—coal. If reliable procedures are developed and utilized in this generation for the accurate assessment of our coal resources, future generations may hope to avoid such an energy crisis as we are now experiencing.

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IMPACT OF GEOLOGIC CONCEPTS ON RESOURCE AND RESERVE ESTIMATES

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INTRODUCTION

Official estimates of the amount of remaining United States coal published during the past 15 years vary greatly. These differences imply that a high degree of uncertainty exists in coal resource and reserve assessment. Methods and procedures for the development of resource and reserve estimates are examined using examples from the Texas gulf coast and Appalachian coal fields. Uncertainties in resource and reserve evaluation are identified, especially with the official United States Geological Survey/United States Bureau of Mines system (USGS/USBM) (Averitt, 1974).

Uncertainty surrounds the definition of concepts such as reserves and resources. The term resource refers to a total amount of coal in the ground, whereas, reserves refer to coal that is technically, legally and economically minable at the time of evaluation. Resource numbers should be used for long-term policy planning (plus 20 years) at the regional scale (about 200 x 200 mi). Reserves are numbers upon which coal mines are planned and utility procurement contracts are based.

RESERVE ESTIMATES—METHODS AND USEFULNESS

By definition, reserves are those resources that are legally, technically, and economically minable at the time of evaluation. Although coal thickness, interburden between coal seams, depth of cover are fixed, but difficult to measure, reserves also imply minability which means costs and technology. This has led Van Rensburg and Bambrick (1978) to state that "Coal reserves are dynamic; therefore, our information is, by definition, incomplete. Higher prices and improved technology may permit the exploitation of deposits which previously may not have been considered as reserves. Higher prices and improved technology tend to increase the coal reserves of an area, whereas, inflation, increases in taxation, freight and power rates, excessive regulation and unrealistic environmental standards tend to decrease reserves." Therefore, in assessing the transferability of resources into reserves, consideration should be given to such factors as the political system, the availability and cost of capital, inflation, taxation and competition from other energy sources. The factors to be considered here, however, are those that comprise fixed elements in reserve assessment, i.e., tonnage existing in thickness categories that are now widely used in acquisition and procurement contracts in the utility industry.

USGS method and classification of coal reserves - The USGS system is based on a Joint U.S. Geological Survey-Bureau of Mines Resource Classification Agreement of November 21, 1973 (Averitt, 1974). The system employs a concept by which coal beds are classified in terms of their degree of geologic assurance of existence and economic and technologic feasibility of recovery (Figure 1). In the system reserves are categorized by:

1. Thickness, rank and quality of coal;
2. depth of coal bed beneath overburden materials;
3. the proximity of the data upon which the estimate was based.

Coal thinner than 14 in for antracite and

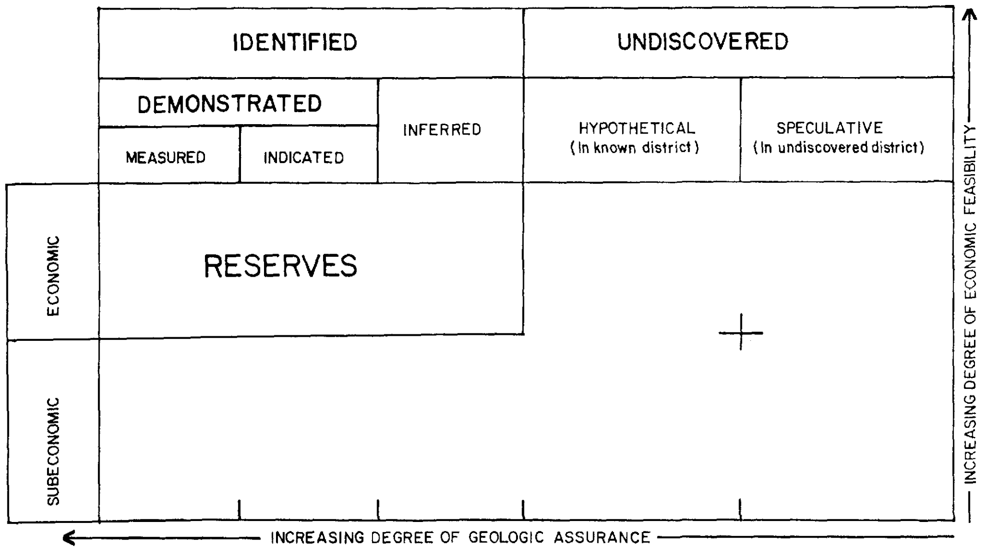

Figure 1. USGS - Classification of coal resources.

bituminous coal, and 30 in for subbituminous and lignite and all coal deeper than 6,000 ft is excluded. Coal containing more than 33 percent ash is also excluded from reserve estimation. Reserves, according to the USGS/USBM system, are broken down into **measured, indicated,** and **inferred** categories based on increasing distances from observation points.

Although the USGS recognizes that the spacing of observation points needed to demonstrate the continuity of a coal bed varies from region to region, in most cases, points of observation are on the order of .5 mi apart. Therefore, the outer limit of a block of **measured** coal will be one-fourth mile from the last observation point. **Indicated** coal is computed partly from specific measurements and partly from geologic projection. If the **measured** coal blocks appear to have good bed continuity, **indicated** coal will extend one-half mile out from measured coal. **Inferred** coal is calcuated only where geologic evidence seems to warrant projection from the indicated coal, where there are few, if any, actual bed measurements. **Inferred** coal extends as much as 2.25 mi out from **indicated** coal. Hypothetical coal can extend beyond inferred coal areas if geologic evidence warrants projection.

Problems with standard USGS method - Although the procedures for reserve estimates devised by the USGS/USBM are widely applied, there are serious problems inherent in the methods which limit their viability as an estimate of minable tonnage. These problems include assumptions of seam continuity and rate of coal thickness variability, the amount and character of interburden rock and the amount and variability of seam inclination — clearly properties that directly affect minability. The USGS/USBM system is also overly simplistic, with vague, qualitative definitions of most of the parameters and categories. The system does not have the capability of evaluating coal quality data like ash, sulfur and Btu values which are important for coal procurement contracts.

The assumption of seam continuity is the crux of estimation of minable reserves, yet determination of this factor as currently applied, is purely subjective. What one observer judges to be ample evidence of continuity, another may regard as totally unsuitable. Hence, the validity of any particular estimate for a specific seam becomes a function of experience and temperament of the estimator. As a consequence, those persons or agencies requiring estimates for procurement or investment seek "well-established" or "well-known" institutions as the best source of information, although, the term "well-established" or "well-known" are ambiguous in themselves. The exact rationale for establishment of continuity (called correlation) has not been precisely stated but consists of two basic factors. These are proximity of data points (horizontal and vertical) and similarity in

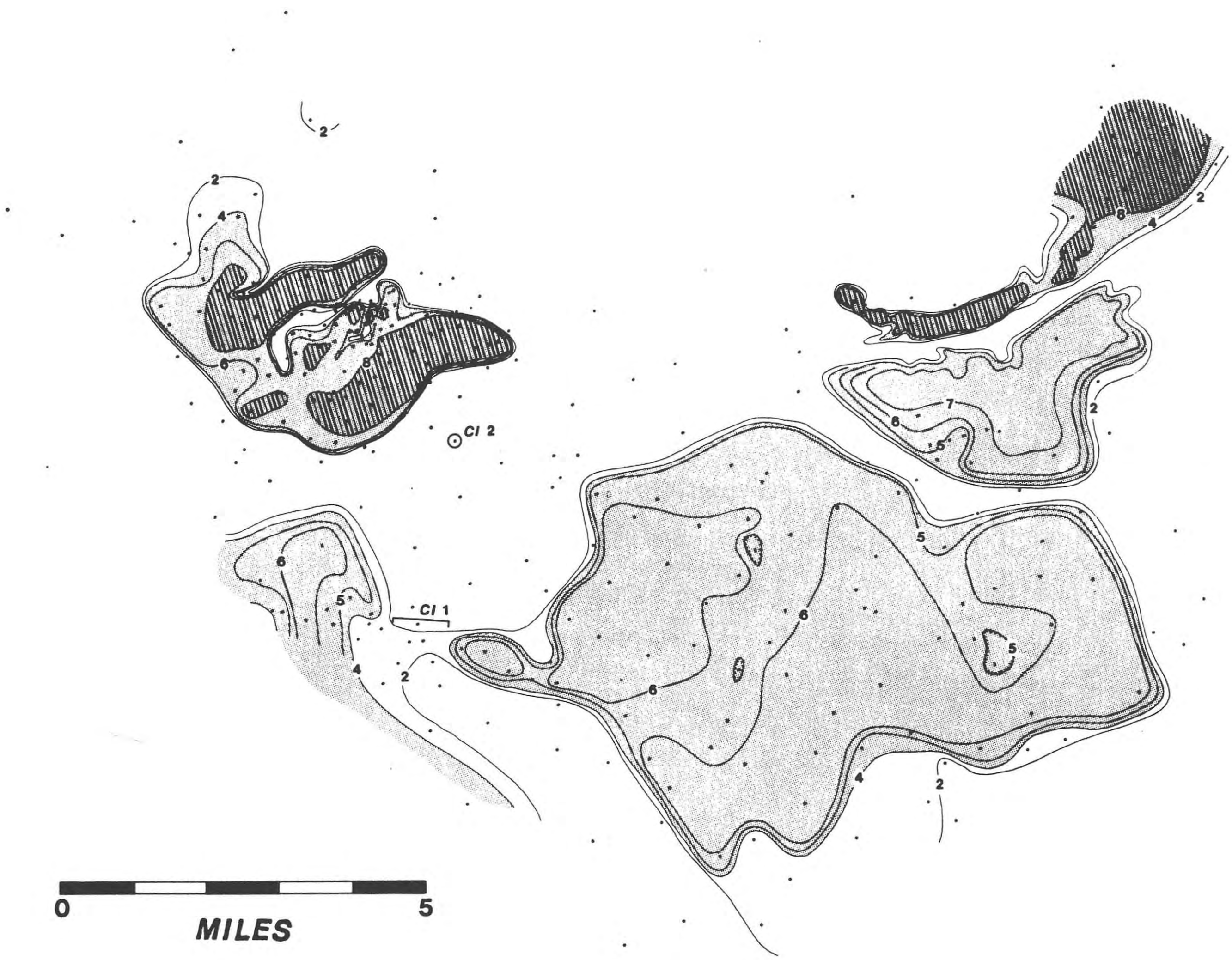

Figure 2. Isopach map of the Upper Freeport Coal Seam in western Pennsylvania (after Pedlow, 1977).

stratigraphic sequence. Construction of a mathematically based probability model for the solution of seam correlation is the greatest single problem in preparing reserve estimators.

Assuming that seam continuity can be established or reasonably inferred, a second major problem arises with rate of variation in seam thickness. Clearly the rate of variation in seam thickness must be known if reserve tonnages are expected to have a realistic meaning.

Finally, there is the question of interburden thickness and quality and inclination of the seams — factors that have a direct effect on minability yet are not included in standard reserve reports. The primary importance of interburden in minability arises when two potentially minable seams occur in such close proximity (one above the other) or where interburden strata are so weak that mining of one seam precludes the possibility of mining the other. In some cases, although reserves are reported for both seams, only one, in fact can be considered minable. Similarly, seam inclination which is highly variable or too great for currently used machinery can preclude the possiblity of mining, yet such data are not included in some standard reserve reports.

TEST OF ASSUMPTIONS IN USGS/USBM RESERVE CALCULATION

The question is whether the problems with the USGS/USBM system described above arise in the

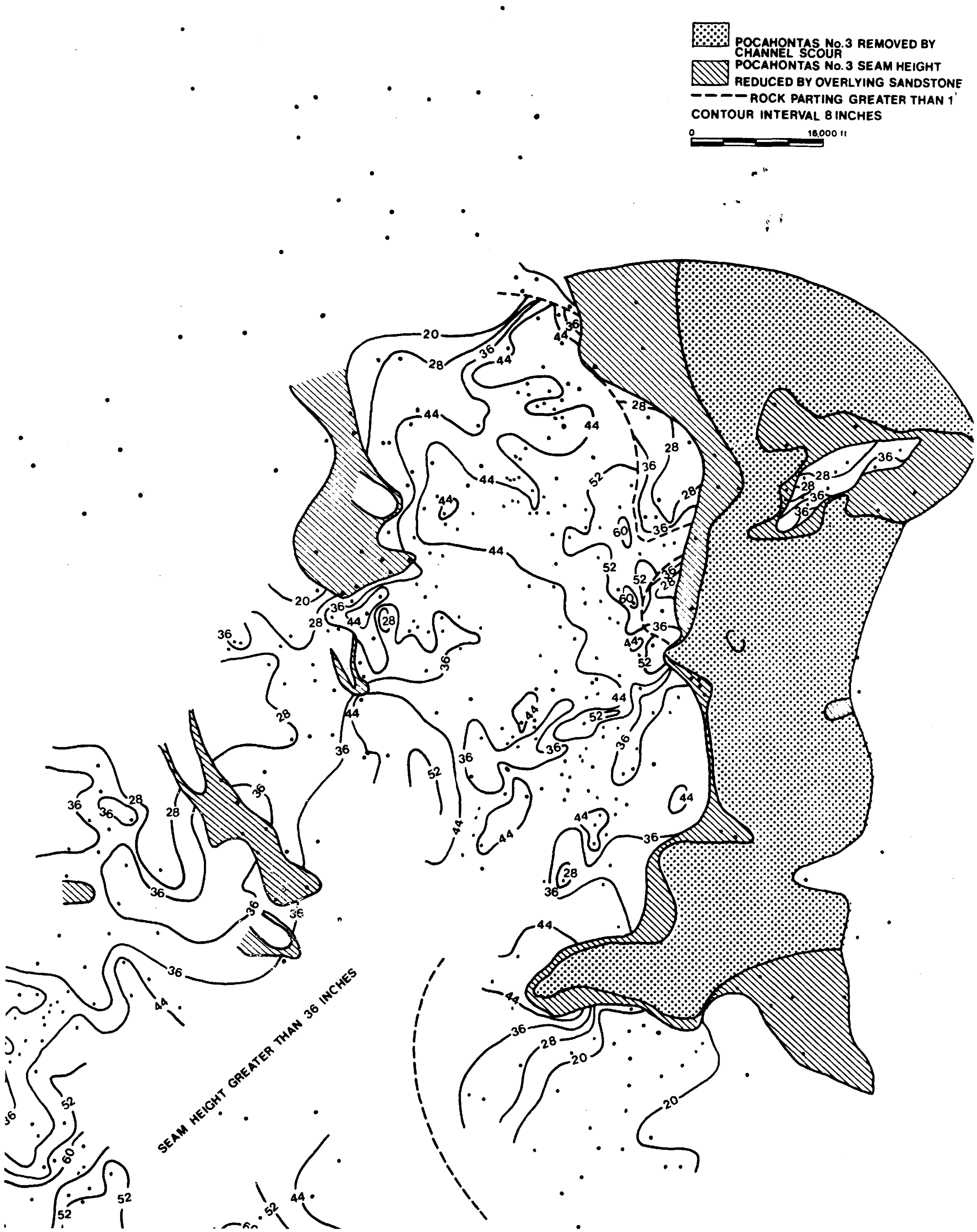

Figure 3. Isopach map of the Pocahontas No. 3 Seam in southern West Virginia (after Baganz, 1979).

course of a practical reserve estimation and to what degree these problems affect results? Four examples are given below. The first two examples are from work in the Appalachian coal fields by Ferm and his students at the University of South Carolina, and the second two examples are from work on Texas lignites undertaken at the Texas Bureau of Economic Geology.

Rate of variation of seam thickness in the Appalachian coal fields - The two examples presented here, the Upper Freeport Coal Seam (Figure 2) and the Pocahontas No. 3 Seam (Figure 3) are a small part of the work conducted over the past seven years in the Appalachian coal fields with the objective of determing the plan view (map) shape and thickness characteristics of minable coal bodies and seeking genetic explanations for them by associating coal body characteristics with those of overlying, underlying and laterally equivalent rocks (Jones, 1975; Pedlow, 1977; Mathew, 1978; Clark, 1979; Baganz, 1979; Howell, 1979; Buswell, 1980; and Bedford, 1980).

The basic data are derived from boreholes with spacing ranging from about 500 ft to 2 mi. Hence, most of the data pertaining to lateral variation are within the spacing of "measured" and "indicated" reserves, according to standard methods of reserve calculation, and all lie within the range of "inferred" reserves. It is assumed that mining of a seam is prima facie evidence of its continuity and that drill hole spacing up to 2 mi supported by ample sequence data found in boreholes comprises sufficient evidence for correct seam correlation. The primary concern here is that of lateral variation in minable seams.

The striking difference between the two seams (Figure 2 and 3) lies in continuity and thickness variation. In the Upper Freeport a "patchy" distribution of minable coal is evident, with thick coal areas being separated by linear no coal areas ("wants"), whereas the Pocahontas No. 3 is continuous over a large area, with only one major interruption on the eastern margin of the map and a few minor interruptions along its northeastern boundary. Both these maps show that over areas of minable coal, the seam displays little variation in thickness or varies in a more or less random pattern. These areas are surrounded (or interrupted) by zones of rapid thickness reduction.

Rate of variation of seam thickness in the Texas lignites - The two lignite seams, Seam No. 6 (Figure 4) and Seam No. 3 (Figure 5) presented here represent a small part of the work conducted on Texas lignites to investigate variability in resource estimates in areas of different ancient depositional environments. The two seams are interpreted as being deposited in different depositional environments, Seam No. 6, from an alluvial-plain setting, and Seam No. 3 from a delta-plain setting (Tewalt et al, 1981). Seam No. 6 and Seam No. 3 have similar variations in continuity and thickness that were observed in the Upper Freeport and Pocahontas seams described above.

Studying these four seams, it is easy to document if the linear distance of .25, .75, and 3 mi used to define measured, indicated and inferred reserves by the standard USGS/USBM method would encapsulate the range of variation of thickness recorded. Table 1 shows the linear distance required to affect a thickness change of 14 in (14 in represents the range of thickness category in standard reserve calculations, i.e., 14-28 in, 28-42 in). Since most of the seams are linear in shape, both width and length measurements are given. Measurements on each seam were also grouped into two categories, one category where the seam appears to change thickness drastically and rapidly ("Transition Category"), and the other where the thickness appears reasonably constant or changes gradually ("Platform Category"). Table 1 shows that in about half the cases the actual distance to affect a 14 in rate of change is less than the standard distances of the USGS for measured, indicated, and inferred categories.

In summary, there is a distinct disparity in seam thickness and continuity among seams, and to apply a single standard to all seams as the USGS /USBM's system does, can only lead to unrealistic reserve estimates. It is the contention of all the above mentioned studies, and many more, that seam continuity and seam thickness variability are mainly a function of the depositional history of the ancient coal environment in which they were formed. To generalize, for example, "alluvial plain" and "back barrier" coals are more variable in thickness and less laterally extensive than "delta plain" coals and are thus more difficult to characterize, i.e., require closer spaced drilling.

Quantitative (Tonnage) Investigation of the two Texas Lignite Seams - Quantitative studies were undertaken to investigate the effect lignite seam

Table 1. Comparison of measured rates of variation in two Appalachian seams and two Texas lignites with confidence categories used in reserve calculation.

			Distance required to effect thickness change of 14 in		Distance to effect rate of change is less than that distance used for defining degrees of confidence in standard reserve calculations					
					Measured		Indicated		Inferred	
Seam	Kind of category	Thickness range (inches)	In width of area (feet)	In lengthwise direction of area (feet)	width	length	width	length	width	length
Upper Freeport 1	platform	120-96	2,900	9,200			*	*	*	*
Upper Freeport 1	platform	96-72	3,080	1,850		*	*	*	*	*
Upper Freeport 1	transition	72-24	145,290	9,250	*		*	*	*	*
Pocy 3	platform	60-52	14,000	35,000					*	*
Pocy 3	platform	52-36	21,000, 21,000	56,000					*	
Pocy 3	transition	36-28	875, 1,400 1,750, 7,000, 10,500	112,000	*		* *		* *	
Seam 6	platform	96-36	5,000, 2,500 3,000	7,500, 8,000			*		*	*
Seam 6	transition	84-0	150, 200 175	4,000 1,000	*		*	*	*	*
Seam 3	platform	125-46	4,800, 8,100						*	*

variability had on tonnage estimation. The techniques for tonnage determination included:

1. standard statistical methods using hand contoured and machine generated maps;
2. geostatistical techniques utilizing the kriging method.

To test the degree of uncertainty in reserve estimates caused by variations in seam thickness and the amount of control available, the numbers of boreholes used in calculating the reserves in each seam were progressively reduced and reserves were calculated for each reduction in data. Various techniques of resource calculation (manual, computer, and geostatistical) were used.

Isopach (equal thickness) lines were hand drawn on maps that included all of the available data points, a random selection of half of the points and a similar selection of one quarter on the points. Isopaching in each case took into account the alluvial and delta plain characteristics of the setting.

The hand-drawn isopach map for Seam No. 6, using 100 percent of the data (Figure 4) documents all irregularities of the lignite seam which occur between horizontal distances of 1,000 ft. The map resulting from using 50 percent of the data shows the general trend of the thickest lignite, but, many of the minor irregularities in seam thickness are omitted, and the boundary between the lignite body and barren area is not so sharply defined. Reducing the data set by 75 percent produces a map that still documents the north-east-southwest-trending thick lignite, but the boundary line between lignite and barren areas is very vague, and its position has changed somewhat from previous maps. In addition, very few of the thickness irregularities within the lignite body are documented. The impact of this variation in seam geometry on total tonnage estimates was tested by comparing the reserves calculted from each of the maps. The tonnage figures are remarkably similar, with less than a 10 percent difference between the values (Table 2).

Figure 5 represents the isopach map of Seam No. 3 of the delta plain setting using 100 percent of

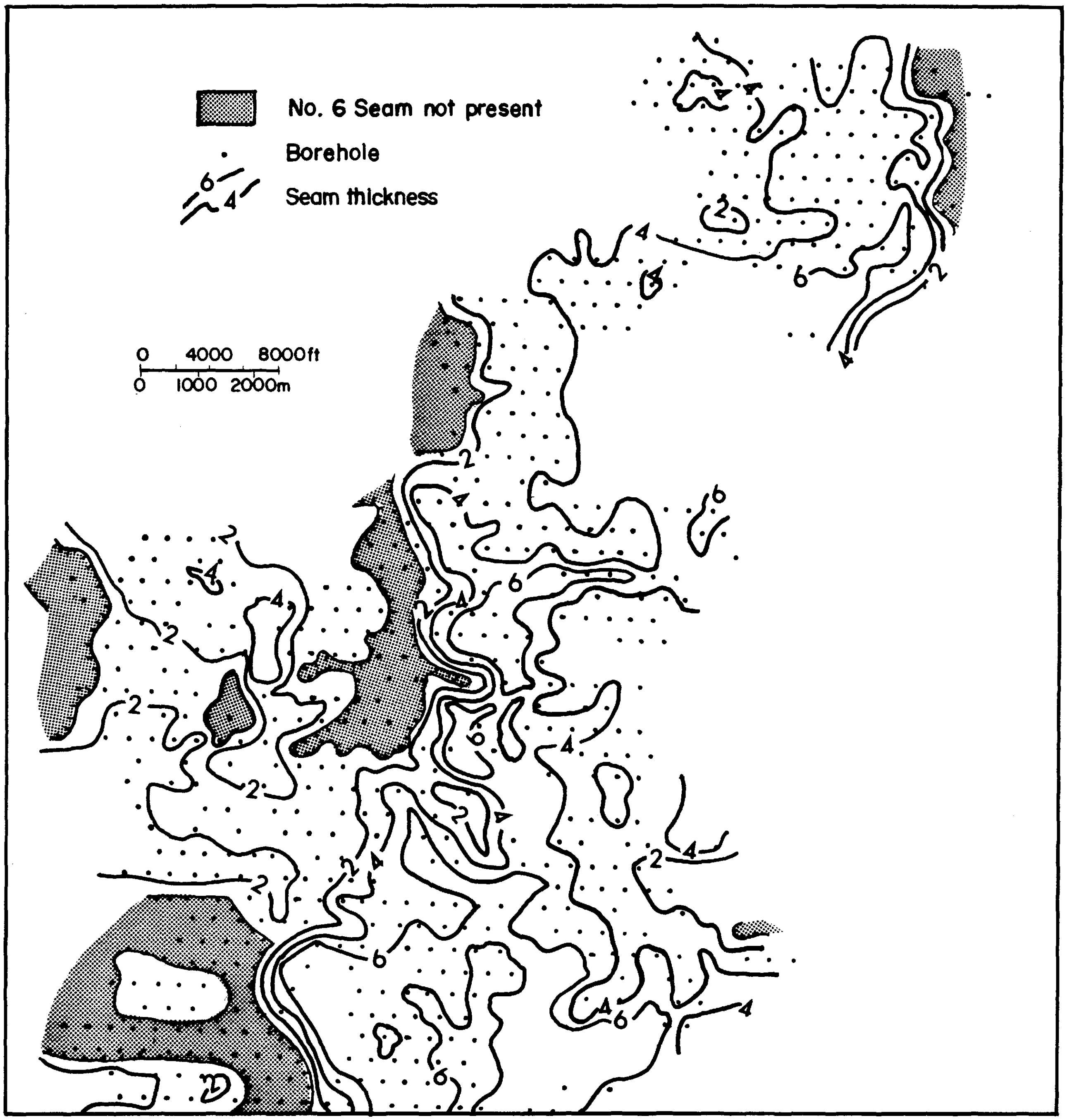

Figure 4. Isopach map of Seam No. 6, alluvial plain deposit, Wilcox Group of east Texas.

the data. A roughly dip-oriented lobate pattern is apparent from the contouring.

A 50 percent reduction in the data still preserves the lobate trend; but, localized thickenings and thinnings become poorly defined and there is a smoothing or averaging effect. The isopach map constructed with 25 percent of the available data preserves a generalized lobate trend, but delineation of isolated patches of thinner and thicker lignite has been lost. Estimates of tonnage decreased with use of fewer data points because of the omission of isolated patches of thicker lignite (Table 2), but differences in estimates did not exceed five percent.

In order to compare the results of computer generated vs. manually generated thickness contour-

Table 2. Comparison of resource tonnages using different methods of calculation (short tons x 10^6 "tonnage factor 1,750 short tons/acre ft").

Method	Alluvial plain (Wilcox) Seam 6	Lower delta plain (Jackson) Seam 3
Hand-calculated tonnage (% of data set)		
100	276.8	111.2
50	269.3	105.1
25	274.3	104.8
Computer-calculated tonnage (% of data set)		
100	261.1	118.8
50	259.0	115.9
25	229.4	109.4
Kriging-calculated tonnage (% of data set)		
100	260.1	123.1
50	265.9	127.1
25	270.9	–

ing, the same two data sets that were hand contoured were used to generate maps using CPS-1 mapping programs (Radian Corp., 1979). Each data set utilized 100 percent, 50 percent, and 25 percent of the data points as was done in the hand contour experiment. Hand-calculated and computer-generated tonnages are compared in Table 2. The difference between manually calculated and machine-calculated reserves were found to be no more than 10 percent overall.

Geostatistics, the statistical theory that describes and utilizes the spatial dependency structure relating data points and kriging was used to calculate the tonnage of Seam No. 6 and Seam No. 3. The tonnage estimates are again very similar to those generated by hand and computer methods (Table 2).

In summary, these quantitative studies have shown:

1. Similar reserve estimates can be derived from data points spaced as far as 8,000 ft or as little as 1,000 ft apart.
2. Similar reserve estimates can be derived from machine or manually contoured data sets.
3. Variations of thickness within a lignite seam have little effect on the overall resources of that seam, given the level of data usually available.
4. Minor irregularities in the definition of the boundary between a seam and a barren area have little effect on the overall resources of that seam.

SUMMARY

It should be emphasized that resources and reserves are two quite different concepts: Resources are broadly defined as the total amount of coal that occurs in large areas of the earth's surface, whereas, reserves are those amounts that are legally, technically and economically minable.

The four seam studies present here, two from Appalachia and two from Texas, suggest that the lack of rigorous methodology for establishment of seam continuity and the inadequate relationship between confidence statements and seam thickness variability preclude precise reserves obtained by the USGS/USBM's method. These studies suggest that linear measurements used to define measured, indicated, and inferred reserves by the USGS/USBM method be adjusted on a seam-by-seam basis.

The quantitative studies on the two Texas lignites indicate that hand or computer contouring (CPS-1 and kriging) of thickness yield similar tonnage estimates. Also, stable tonnage figures can be obtained using a lot less control than normally available.

The subject of resources and reserves has received little concentrated research effort in the past with most of the energies devoted to number generation (tons). It is suggested that if these numbers are to have meaning, considerable effort must be devoted to establishing sound theoretical premises and procedures that will lead to stable meaningful estimates.

ACKNOWLEDGEMENTS

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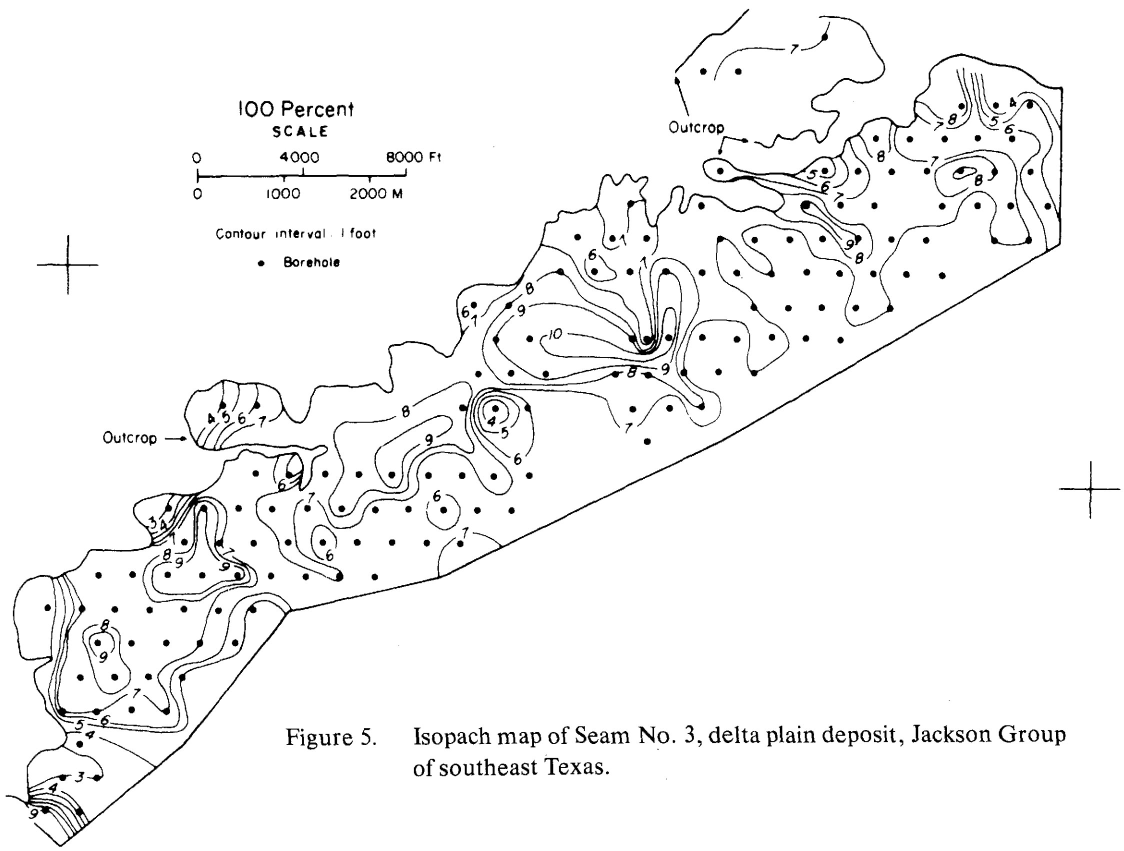

Figure 5. Isopach map of Seam No. 3, delta plain deposit, Jackson Group of southeast Texas.

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APPLICATION OF GEOSTATISTICS TO COAL EVALUATION

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INTRODUCTION

A number of geostatistical methods have been developed during the last three decades which can be applied to the evaluation of coal deposits. These methods can assist in the detection of sampling and assaying errors, the development of geologic hypotheses, the optimization of exploration programs, and the estimation of reserves. Geostatistics can also help to examine the impact of mining selectivity on dilution, to improve quality control, and to define stockpiling and blending parameters.

Some statistical methods are relatively simple and well accepted, including the calculation of mean, confidence intervals, frequency distributions, and scatter diagrams. Considerable information can be obtained from the use of these techniques, but they do not take into account the spatial distribution of the sample values and in this respect have limited application.

When analyzing a deposit, the qualities (Btu, ash, sulfur, etc.) measured in two drill holes located next to each other can be expected to be similar and a greater dissimilarity should be observed as the spacing between holes increases. Geostatistical methods, including semivariogram analysis and kriging, take this fundamental property of all mineral deposits into account. They have been applied extensively to the study of metal deposits and are now routinely performed for all new projects by a continuously increasing number of mining companies. Application to coal deposits has, however, been limited.

The purpose of this paper is to give a general introduction to those geostatistical methods of data analysis which are most applicable to coal deposits. It is addressed to geologists and mining engineers who wish to gain some familiarity with geostatistical terminology and basic knowledge of what geostatistics can do to help them in their daily task. The emphasis is on the simpler, easier to use method of analysis and their practical application. Prior to a discussion of spatial geostatistical techniques, an introduction to classical non-spatial statistics is given to illustrate the value of such analyses in gaining an initial understanding of the deposits characteristics.

NON-SPATIAL STATISTICS

Histograms and Scatter Diagrams - A statistical analysis of coal data will usually begin with visual displays such as frequency distributions and scatter diagrams. These displays are valuable as they help in detecting anomalous data; sampling, assaying or reporting errors, mixture of geologic zones, and other anomalies which may influence the validity of later studies.

Typical frequency distributions are shown on Figure 1 for heat, ash, and sulfur content. The frequency distribution of heat content is negatively skewed possibly reflecting the presence of two zones within the seam. If this does indeed prove to be the case, it is a very valuable piece of information as separate evaluation of the distinct zones will usually produce more accurate tonnage and quality estimates.

The frequency distribution of ash content and sulfur content are, on the other hand, positively skewed. Such distributions are commonly observed with elements like these which appear in small proportions. A positively skewed distribution is indicative of the presence of a small number of exceptionally high drill hole values, which may create problems in an evaluation of the deposit.

Cumulative frequency distributions can also be plotted on normal probability paper and, in such a

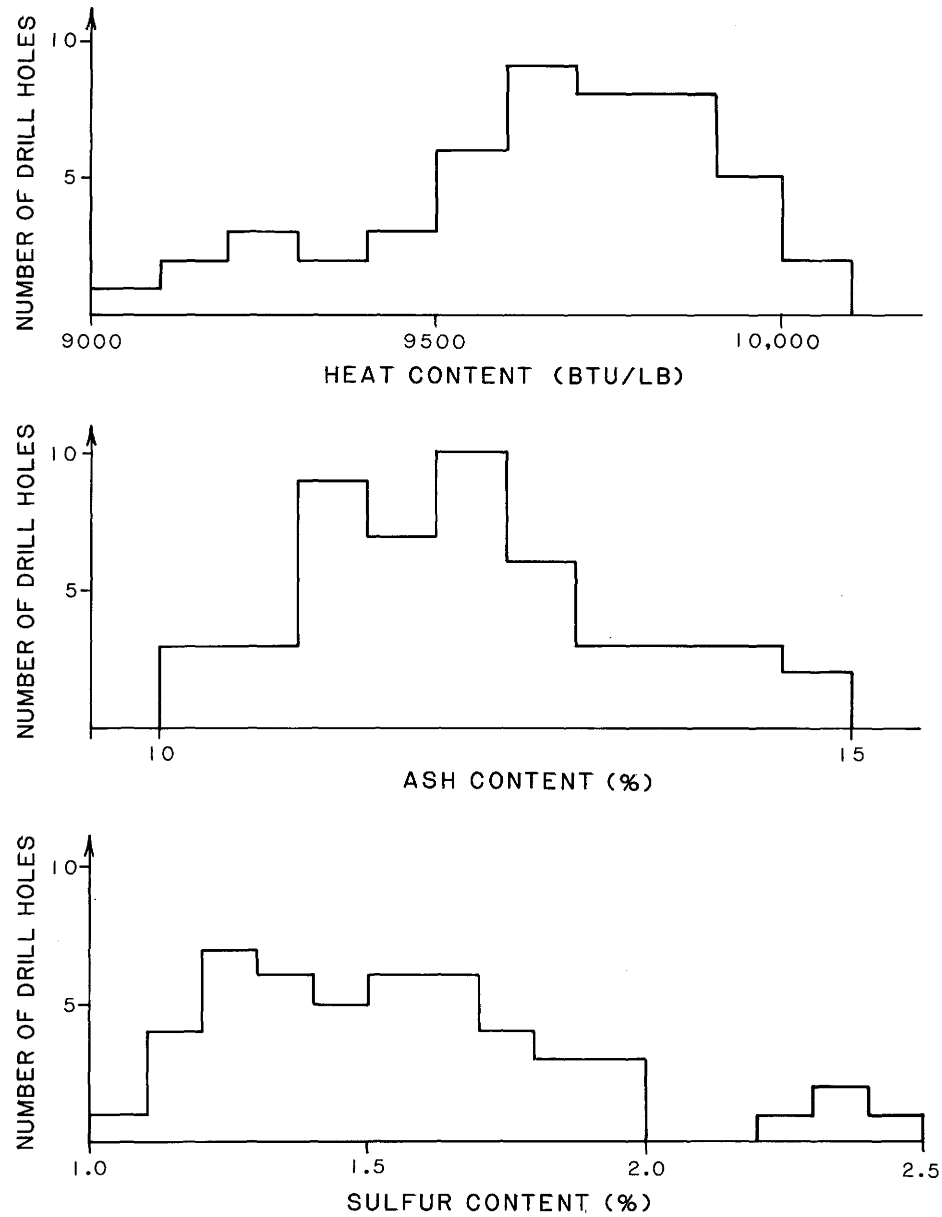


Figure 1. Examples of frequency distribution.

plot, a normally distributed variable will be represented by a straight line. Significant departure from normality may indicate the presence of more than one geologic zone or show the need for special geostatistical analyses. The cumulative distribution of the heat content of the samples studied on Figure 1 is shown on Figure 2. The sharp change of curvature observed between 9,300 and 9,500 Btu per pound may provide further indication of the presence of two distinct zones within the seam.

Scatter diagrams are shown on Figure 3 and indicate for this deposit, a positive correlation between ash and sulfur contents, no correlation between heat content and thickness, and negative correlation between heat content and both ash and sulfur contents. As this figure suggests, scatter diagrams can be extremely useful in gaining a visual understanding of the variability in, and the relationship between, coal quality parameters. Anomalous values are also visible, which may be

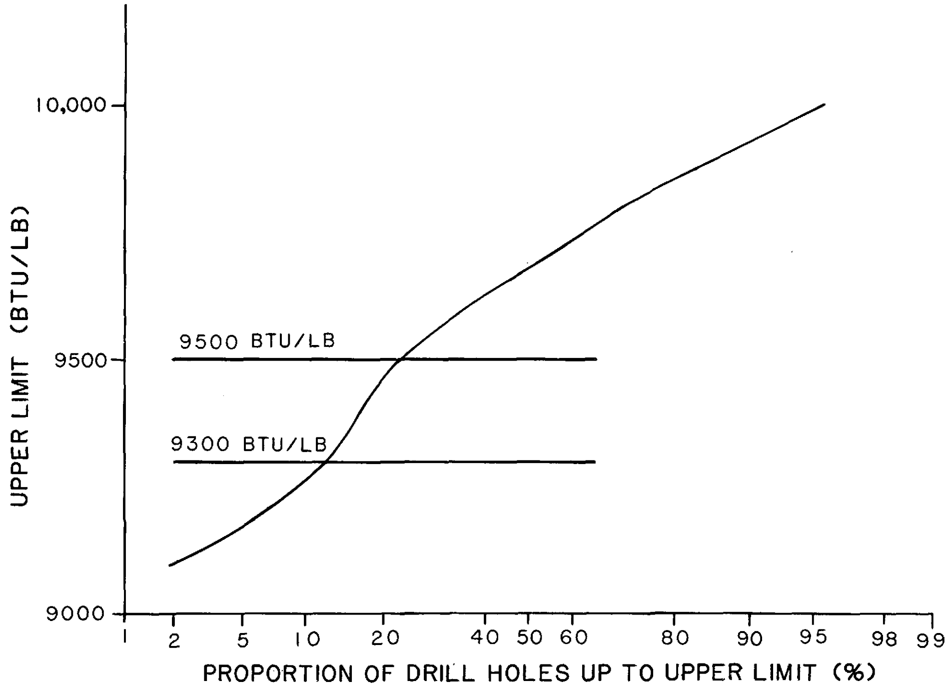


Figure 2. Cumulative frequency distribution of heat content.

indicative of errors.

Such plots are simple and inexpensive to produce, particularly when the data are held on a computerized data base. Although more sophisticated statistical methods are available for analyses of this type and can offer improved interpretations in skilled hands, the simple presentation and comparision of values illustrated here will serve the basic purposes of differentiating between geologic environments or zones, detecting anomalous and potentially erroneous samples and providing some basis for later analysis. No substantial body of data should be used without being first subjected to such checks.

Mean and Confidence Intervals - The simplest statistical estimate involves calculating the mean of a series of values and assigning some measure of confidence limit to that calculation. When using these simple non-spatial statistical methods, it must be kept in mind that they are based on the assumption of random sampling and that the results obtained may be biased if the drill hole locations are chosen according to some assumption or knowledge of the coal properties. Highly variable sample densities may also bias estimated values and results may well be meaningless if geologically distinct areas are mixed.

The mean and the variance of the sample values are calculated using the following formulae:

$$\text{mean } m = (x^1 + \ldots + x_n)/n \quad (1)$$

$$\text{variance } s^2 = [(x_1 - m)^2 + \ldots + (x_n - m)^2]/(n-1) \quad (2)$$

n = number of drill hole intercepts
x_i = value of i-th intercept

The variance of estimation of the mean is calculated as follows:

$$S^2 = s^2/n \quad (3)$$

S is known as the standard error of the mean and provides a first estimate of the precision with which the average value of a particular seam quality is known. In first approximation, there is 68 percent probability (2 chances in 3) that the average value will be greater than $(x-S)$ and less than $(x+S)$ There is 95 percent probability that it will be greater than $(x-2S)$ and less than $(x+2S)$.

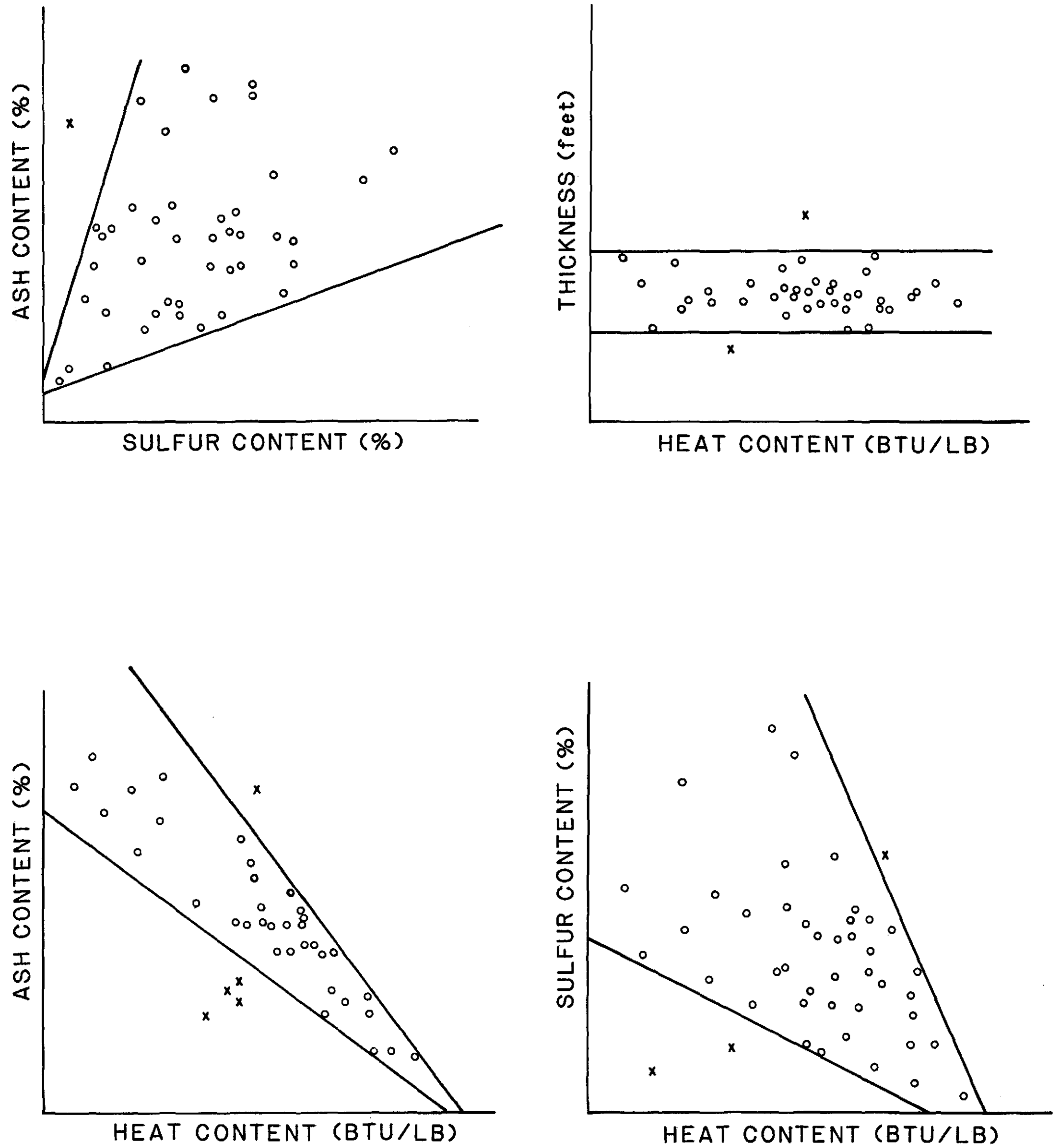


Figure 3. Examples of scatter diagrams.

An example of the application of non-spatial statistics to the estimation of coal thickness and qualities is given on Figure 4. The mathematical formulae used in these calculations are also shown. In this case, the best estimate of the thickness is 10.80 ft and there is 95 percent probability that the true thickness will be greater than 8.32 ft and less than 13.28 ft. The average heat content of the seam is expected to be 11, 007 Btu per pound, but could be as low as 9,579 Btu per pound or as high as 12,435 Btu per pound.

SPATIAL STATISTICS

The statistics discussed earlier do not take into account the relative positions or spatial arrangement of the samples with respect to each other. They are also of limited use for interpolation between drill holes when evaluation of individual panels of coal is required within which very few drill holes, if any, may be located. These methods also do not give any indication concerning the continuity of the deposits, and cannot, therefore be used to optimize a drilling program. Other statistical methods must be used to

Drill Hole n^{o}	Seam Thickness T (feet)	Heat Content Q (BTU/1b)	Heat Content x Thickness A = Q.T (feet x BTU/1b)
1	10	10,000	100,000
2	9	9,800	88,200
3	15	13,000	195,000
4	8	9,900	79,200
5	12	11,000	132,000

Drill hole mean: $\bar{T} = 10.80$ feet, $\bar{A} = 118{,}880$ feet x BTU/1b

Drill hole variance: $s_T^2 = 7.70$, $s_A^2 = 2{,}210 \times 10^6$

Standard error: $s_T = 1.24$ feet, $s_A = 21{,}022$ feet x BTU/1b

Covariance between thickness and QT:

$$cv = \frac{1}{n-1} \Sigma (T_i - \bar{T})(A_i - \bar{A}) = 129{,}220$$

Correlation coefficient between thickness and QT:

$$r = cv/s_T s_A = 0.991$$

Estimated average heat content:

$$Q^* = \bar{A}/\bar{T} = 11{,}007 \text{ BTU/1b}$$

Relative error variance:

$$\left\{\frac{s_Q}{Q^*}\right\}^2 = \left\{\frac{s_T}{\bar{T}}\right\}^2 + \left\{\frac{s_A}{\bar{A}}\right\}^2 - 2r \frac{s_T}{\bar{T}} \frac{s_A}{\bar{A}} = 0.421 \times 10^{-2}$$

$$s_Q = 714 \text{ BTU/1b}$$

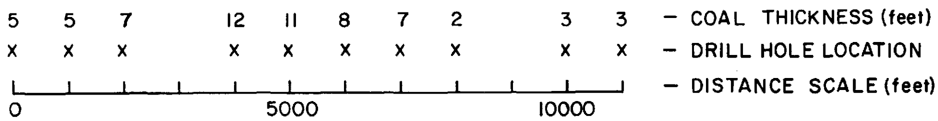
	Expected Value	95% Central Confidence Limits	
		Lower Limit	Upper Limit
Seam thickness (feet)	$\bar{T} = 10.80$	$\bar{T} - 2s_T = 8.32$	$\bar{T} + 2s_T = 13.28$
Heat content (BTU/1b)	$Q^* = 11{,}007$	$Q^* - 2s_Q = 9{,}579$	$Q^* + 2s_Q = 12.435$

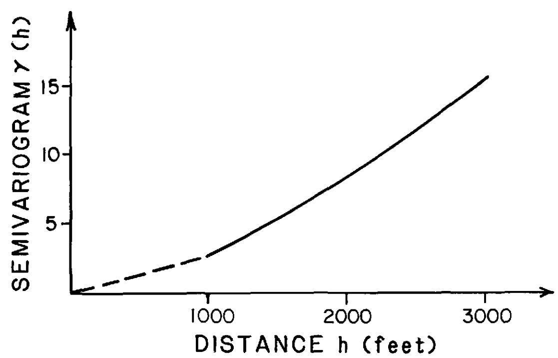
Figure 4. Estimation of average value and confidence limits.

answer these questions, which are better adapted to the analysis of mineral deposits.

The Semivariogram - Drill holes located a few feet apart are likely to indicate similar coal qualities, and this similarity will decrease when the distance between holes increases. It may, however, be possible to define a distance of influence beyond which the similarity between sample values becomes negligible. This distance may vary significantly between deposits, between different parts of the same deposit, or even between different directions at the same point in the deposit. The degree of similarity or dissimilarity between values can be quantified and this can be of great assistance in understanding the properties of the deposit and optimizing its evaluation.

The geostatistical tool used to quantify the dissimilarity between drill hole values as a function of the distance between holes is called the semivariogram. By definition, the value of the





h (feet)	1000	2000	3000
γ (h)	2.86	8.17	15.67

Figure 5. Calculation of semivariogram.

semivariogram g (h) for a distance h between drill holes is equal to "one half the mean squared difference between sample values located a distance h apart."

The general formula for calculation of the semivariogram is:

$$g\,(h) = [(x_1 - x'_1)^2 \ldots + (x_n - x'_n)^2]/2n \qquad (4)$$

n = number of pairs of drill holes a distance h apart
x_i = value at first drill hole in i-th pair
x'_i = value at second drill hole in i-th pair

This definition is best explained through an example:

Consider 10 drill holes located on a straight line as shown in Figure 5. Most drill holes are 1,000 ft apart and the coal thickness has been measured at each point. The semivariogram value for a distance of 1,000 ft between holes is calculated as follows:

$$g(1000) = [(5-5)^2 + (5-7)^2 + (12-11)^2 + (11-8)^2 + (8-7)^2 + (7-2)^2 + (3-3)^2]/2x7 = 2.86$$

For a distance of 2,000 ft between holes the following results are obtained:

$$g(2000) = [(5-7)^2 + (7-12)^2 + (12-8)^2 + (11-7)^2 + (8-2)^2 + (2-3)^2]/2x6 = 8.17$$

A similar calculation for 3,000 ft gives a result of 15.67. These results are plotted on Figure 5.

Equation 4 can be modified to calculate the semivariogram in different directions and to take into account variations in drill hole spacing. Other methods of calculation of the semivariogram are applicable when the distribution of the sample values is significantly different from a normal distribution, hence, the need for the non-spatial statistical analysis discussed earlier.

Once a semivariogram has been calculated, it must be interpreted by fitting to it a mathematical formula or "model" which will help to identify the characteristics of the deposit and yield numerical parameters which describe the deposit's continuity. Examples of such models are shown in Figure 6 and each has, to the practiced eye, a particular significance.

The "general model" in Figure 6 shows the main parameters derived from a semivariogram model, namely:

- The *sill*, which shows the highest level of variability measured by the semivariogram.

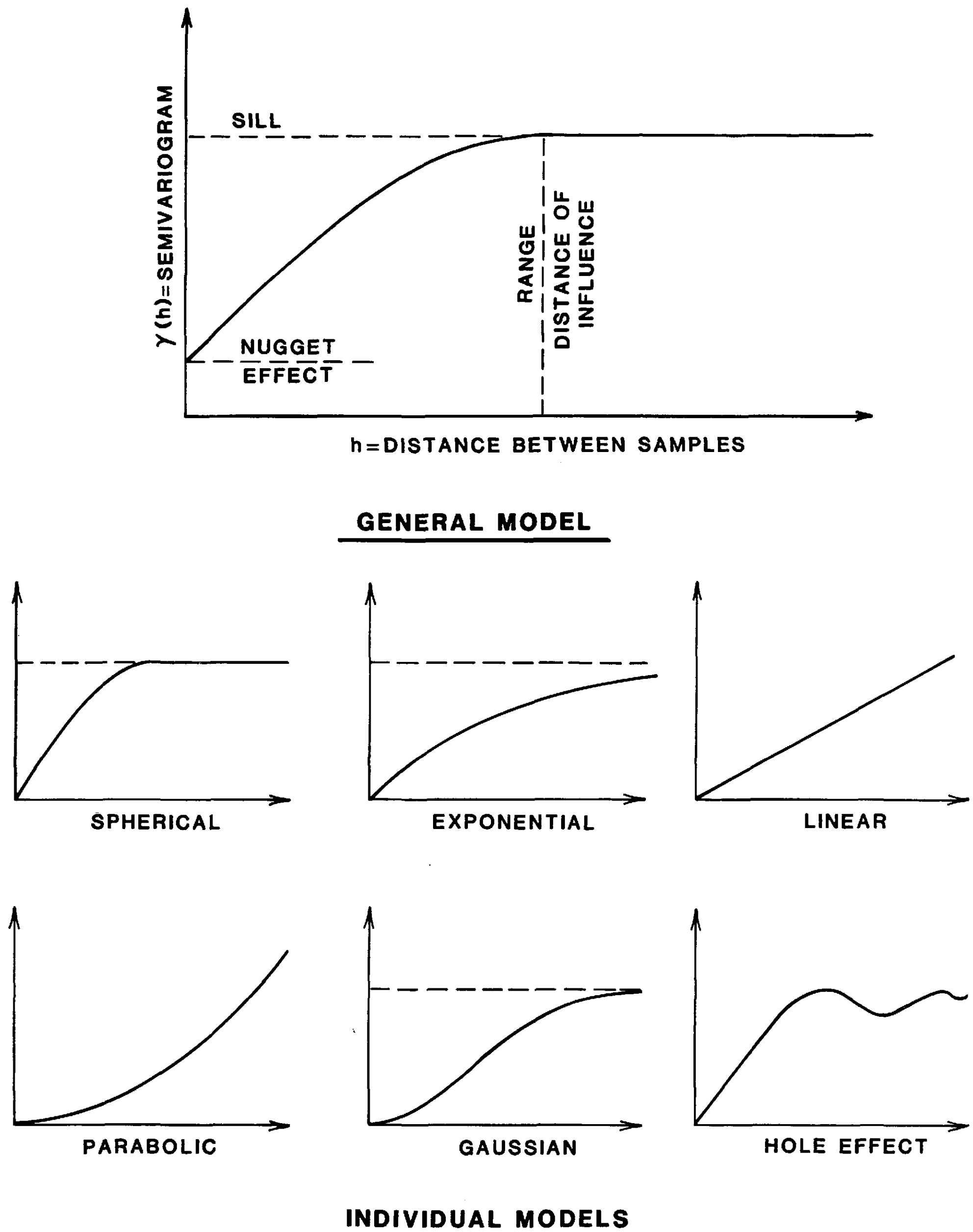


Figure 6. Models of semivariograms.

- The *range* is the distance at which the semivariogram plateaus or reaches the sill value and represents a measure of the maximum distance of influence of a drill hole in the direction concerned. Beyond this distance, sample values are independent of one another.

- The *nugget effect* is the value of the semivariogram at zero distance. It represents the sample variability at small distance caused by such factors as erosion channels. It also gives an important indication of the presence and magnitude of sampling, assaying, and reporting errors.

Semivariograms of the thickness of a coal seam

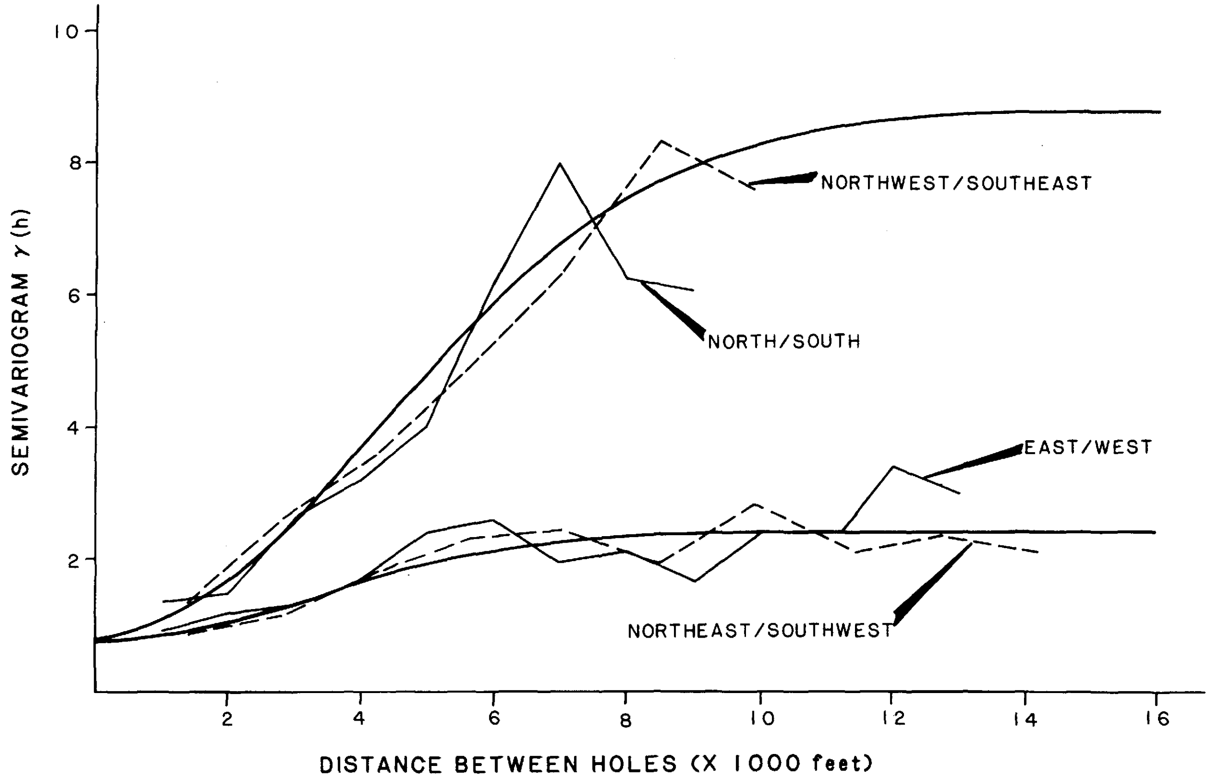


Figure 7. Semivariogram of coal thickness.

in four directions are shown in Figure 7. The east-west and northeast-southwest directions show very low variability in thickness, while the north-south and northwest-southeast directions show a very high level of variability.

If drilling of the deposit analyzed on Figure 7 was pursued for the sole purpose of defining the seam thickness, the drill hole spacing should be shortest in the general north-northwest direction and largest in the east-northeast direction. The spacing should not exceed 6,000 ft in the east-northeast direction. A spacing of 4,000 ft in the east-northeast direction and 2,000 ft in the north-northwest direction could be considered.

A nugget effect with value 0.80 square foot is observed which indicates that the precision with which the coal thickness is known at the point where a drill hole is located is 0.9 foot (at the 68 percent confidence level). This relatively high nugget effect can be explained by geologic features or by measurement errors and could be taken as an indication that logging accuracy should be carefully reviewed.

Error of Estimation - Errors are always made in estimating the properties of a coal seam from sample data and it can be very valuable to have some measure of the potential size of such errors. Consider a panel of size 2,000 by 4,000 ft. The true average thickness of the coal in this panel is obviously unknown (let Z be this unknown value), but can be estimated by drilling a hole in the center of the panel (let Z^* be the thickness measured in this hole, say 20 ft). The expected squared differences between Z and Z^* is known as the variance of estimation of the panel.

$$S_E^2 = \text{expected value of } (Z-Z^*)^2 \qquad (5)$$

The square root S_E of the estimation variance is the standard error of estimation and there is an approximate 68 percent probability that the true average thickness of the seam in the panel is greater than Z^*-S_E. Obviously, the main objective in any estimation method is to minimize the error of estimation.

The precision which can be attached to any estimate of the tonnage of coal in a panel will vary depending on the method used to estimate it and the variability of the coal seam. Although the true value of the panel is unknown, the variance of estimation for a particular estimation method can be calculated

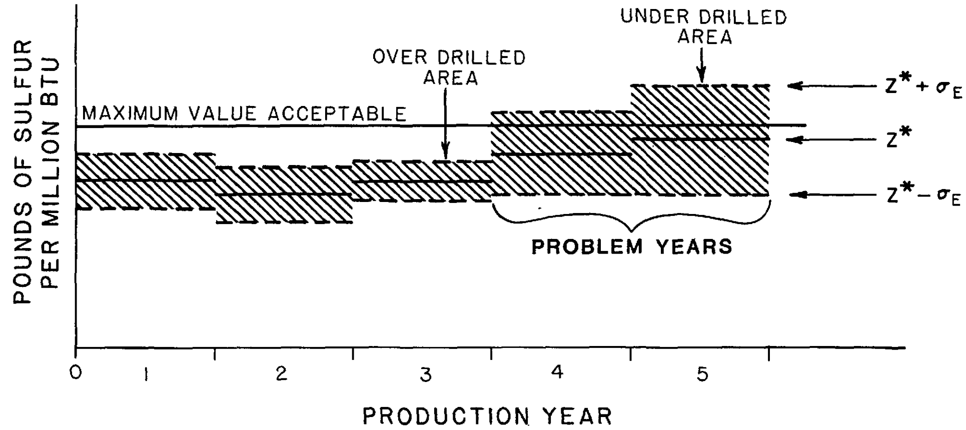


Figure 8. Estimation error and quality control.

as a function only of the semivariogram, the location of the samples with respect to the panel, and the size and orientation of the panel.

Given the semivariogram shown on Figure 7, consider a panel of size 2,000 by 4,000 ft oriented in an east-northeast direction. If the panel was estimated by only one sample located at its center (i.e., polygonal method) it would be known with a standard error of 1.3 ft. If the same panel was estimated as the arithmetic average of the four corner samples, the standard error would be reduced to 0.5 ft.

The error of estimation is extremely useful for estimating the risk involved in opening a new mine. The need for additional drilling can be quantified by comparing the cost of drilling with the expected resulting decrease in estimation error. The optimal location of additional drill holes can also be determined.

The error of estimation can be used to determine, on a yearly basis, the precision with which the properties of the coal to be produced are known. Confidence limits for critical parameters, such as pounds of sulfur per million Btu, can be obtained. The potential for unacceptable variations in these parameters can be detected, and might lead to a decision for additional drilling, a change in mining strategy, and/or an increase in storage and blending capacity (Figure 8).

Dispersion Variance - When designing storage and blending facilities for a new coal deposit, it is necessary to have some indication of the variability in coal qualities which can be expected on a daily, weekly, or monthly basis. Typically, the drill hole spacing is not sufficient to form a basis for accurate individual estimation of qualities of the relatively small tonnages of coal which will be mined during such short time periods. An answer is therefore sought to the following type of question:

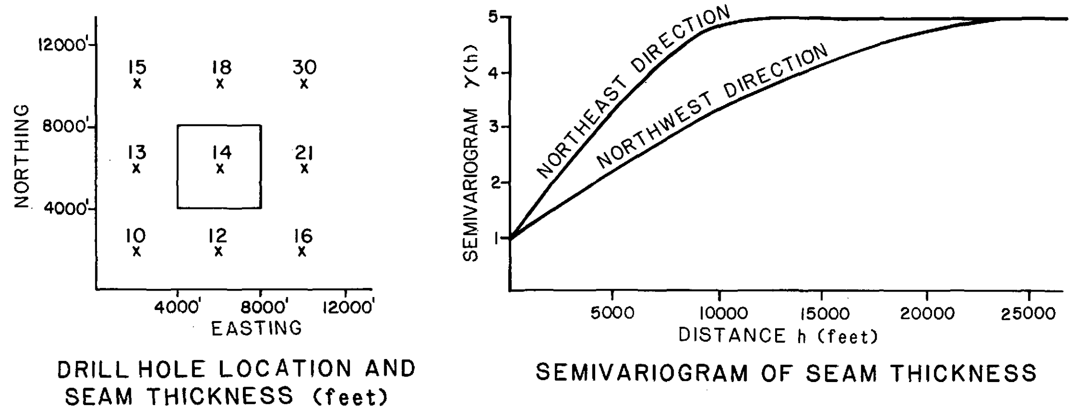
> Given that the sulfur content of the coal to be produced in year 1 is estimated to average 1.1 pounds per million Btu, what range of monthly sulfur contents can be expected?

Based on a knowledge of the area to be mined during the year, the degree of mining selectivity envisaged, the shape and size of the area to be mined in a typical month, and with the semivariogram, it is possible to use geostatistics to produce a dispersion variance on sulfur content of one month's production within 1 year to help solve this problem. This variance is a measure of the sulfur grade fluctuation characteristics and, in the example given above, might have a calculated value of 0.04. From this, the following answer can be given to the question:

> There is a 68 percent probability that the monthly sulfur content will remain between 0.9 and 1.3 pounds per million Btu and a 95 percent probability that it will remain between 0.7 and 1.5 pounds per million Btu. It is likely that the sulfur content will exceed 1.3 pounds per million Btu for one month during the year, but very unlikely that it will exceed 1.5 pounds per million Btu.

OPTIMAL EVALUATION—KRIGING

Intuitively, when estimating a panel of coal, the closer samples should be given more weight than the farther ones. Also, the directions showing the best continuity should be considered in assigning a weight to a sample. The relative position of the drill holes



DRILL HOLE WEIGHTS	METHOD USED AND RESULTS OBTAINED
0 0 0 0 1 0 0 0 0	POLYGON METHOD ESTIMATED THICKNESS: 14 feet ERROR OF ESTIMATION: 1.20 feet
0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11 0.11	MEAN OF ALL SAMPLES ME IN VICINITY ESTIMATED THICKNESS: 16.56 feet ERROR OF ESTIMATION: 0.72 feet
0.15 0.10 0 0.10 0.30 0.10 0 0.10 0.15	KRIGING METHOD ESTIMATED THICKNESS: 15.25 feet ERROR OF ESTIMATION: 0.52 feet

Figure 9. Comparison of estimation methods.

with respect to each other should be taken into account. The size of the block to be estimated is also an important factor. Most important is the fact that the optimal method of reserve estimation should be a function of the specific properties of the deposit or part of deposit within which the block is located. The geostatistical method of reserve estimation takes all these factors into account.

As indicated earlier, the precision with which a block of coal is estimated can be quantified using the semivariogram. The error of estimation is a function of the estimation method or, more specifically, of the weight given to each sample in estimating the block. Instead of calculating the error of estimation which corresponds to a given set of sample weights, it is possible to calculate the weights which will result in the minimum error by solving a system of linear equations, known as the kriging system, which makes extensive use of the semivariogram. The resultant weights then form the basis for estimation of thickness, qualities, etc. An illustration of a simple kriging problem is given in Figure 9.

Nine drill holes are available to estimate a block of 4,000 by 4,000 ft. The seam thicknessess measured at each hole are shown on Figure 9 as well as the semivariogram calculated from all the drill holes in the deposit. If the polygon method is used, the block is estimated by the central sample, with value 14 ft and an error of 1.20 ft (8.6 percent) is made. If the mean of nine samples is used, an average of 16.56 ft is calculated with an error of 0.72 ft (4.3 percent). If kriging is used, the central sample is given most of the weight and the outside samples are given weights which reflect the anisotropy shown by the semivariogram. The block estimated average thickness is 15.25 ft with an error of estimation of 0.52 ft (3.4 percent).

Kriging can be used to estimate the coal reserves within an entire deposit, to estimate the reserves on a yearly basis, or to estimate a regular grid of blocks. If a regular grid is estimated, the corresponding errors of estimation can be contoured, as well as the estimated block values. Areas with relatively high errors can be analyzed to determine whether additional drilling is required. The block values estimated by kriging can also be used for computerized or manual mine design.

The kriging method of coal evaluation is the only method which optimally uses the statistical and geological properties of the deposit as represented by the semivariogram. Solving a kriging system of equations can be extremely cumbersome if done by hand or with a pocket calculator. For this reason, optimal estimation by kriging is usually done by computer. Recent progresses made in computer hardware, communications, and software and significant reductions in computing costs have brought this technique within the reach of most coal companies.

CONCLUSIONS

This brief overview of the possible applications of geostatistics to the evaluation of coal deposits illustrates the variety of tools available and the numerous practical problems which these tools can help resolve. There are strong indications that geostatistics is going to play an increasing role in the evaluation of coal projects.

Geostatistical studies can help coal suppliers to better evaluate their product and reduce the probability that they will enter into long term contracts with which they might not be able to comply. These studies can also help the utilities in their effort to obtain reliable sources of coal.

There are many ways of using geostatistics incorrectly, but if it is well understood and properly applied it can only benefit the coal industry as a whole.

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GEOSTATISTICAL ANALYSIS OF A 113-BILLION-TON COAL DEPOSIT, CENTRAL PART OF THE POWDER RIVER BASIN, NORTHEASTERN WYOMING

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INTRODUCTION

As part of the U.S. Geological Survey's program of research and development of computerized methods for estimating resources, computer programs employing the geostatistical method known as kriging currently are being used to portray and estimate coal resources in selected areas. This work is done on an experimental basis to determine whether it is desirable to use the kriging technique along with other methods of assessing coal resources.

A routine survey of gamma-ray logs of oil and gas test holes in the central part of the Powder River Basin called attention to the presence of a single bed of coal, as much as 182 ft thick, about 1,100 ft below the level of the Powder River and about 30 mi southwest of Gillette, Wyoming. This occurrence appears to be a coal deposit of unusual thickness and extent: it is defined as a single bed of coal 46 to 182 ft thick and underlies an elongate area of about 950 sq mi (Figure 1). Computer programs for kriging were used to portray the coal deposit and to generate estimates of the tonnages involved; the estimates are summarized in Table 1.

THE DATA BASE

Coal data used in this study were interpreted from publicly available geophysical logs of oil and gas wells. Logs from approximately 300 holes were used to outline the deposit; 193 of these holes are within the boundary shown on Figure 1.

Tertiary coal in the Powder River Basin has extremely low radioactivity compared to other Tertiary rocks, making it easy to recognize on gamma-ray logs. Because these logs have proved to be reliable indicators of coal in other parts of the basin, they were used almost exclusively to outline the coal deposit described here. Cored coal thickness information was not available.

For nearly all drillholes in the region underlain by the coal deposit, gamma-ray logs were available for the interval containing the single thick bed of coal; the existence of these logs may indicate that the deposit has been known to the oil and gas industry for some time. The location of our "discovery" well, in which the coal is 182 ft thick, is shown on Figure 1.

THE COAL DEPOSIT

Tertiary coal beds in the Powder River Basin of Wyoming and Montana are the nation's largest resource of low-sulfur subbituminous coal. Throughout the basin, resources are commonly concentrated in definable subareas where several named coal beds merge locally to form thick deposits of combined coal. The well-known Wyodak coal bed east of Gillette, Wyoming, illustrates this feature of coal deposition. The Wyodak is a combination of five named coal beds (Kent and others, 1980).

One or more of the upper beds forming the Wyodak merge westward with several overlying coal beds to form the coal deposit described here. The deposit is defined as a single bed of coal, and the boundary of the subarea containing the deposit is placed at the approximate locations were the single bed splits. For convenience, the single bed is identified collectively as Anderson coal, because that name identifies one of the principal coal beds included.

The deposit is assessed as a unit resource containing about 113 billion tons of coal (Table 1). By comparison, in-place coal resources in the entire Wyoming part of the Powder River Basin are

Table 1. Amount of in-place coal by township. (In millions of short tons.[1] The coal is assumed to weigh 1,770 short tons per acre-foot.[2])

Township north	Range west	Area (acres)[3]	Kriged thickness (ft.)[3]	In-place coal (megatons)	0.95 error limits (percent)
T 50 N	R 79 W	12084	101.5	2172	±19
T 50 N	R 78 W	9507	104.9	1766	±11
T 50 N	R 77 W	10018	123.3	2185	±15
T 50 N	R 76 W	7767	105.0	1444	±14
T 49 N	R 79 W	8669	98.9	1518	±26
T 49 N	R 78 W	16669	109.7	3237	±13
T 49 N	R 77 W	21056	135.1	5035	±14
T 49 N	R 76 W	23020	135.7	5530	±12
T 49 N	R 75 W	273	130.8	63	±18
T 48 N	R 79 W	5051	87.8	785	±17
T 48 N	R 78 W	23041	106.7	4353	± 7
T 48 N	R 77 W	23189	148.9	6113	± 9
T 48 N	R 76 W	21703	125.6	4826	±12
T 47 N	R 78 W	8912	92.9	1466	±20
T 47 N	R 77 W	22489	121.1	4821	±12
T 47 N	R 76 W	21614	110.5	4228	± 8
T 47 N	R 75 W	3103	87.6	481	±23
T 46 N	R 77 W	4607	105.4	860	±10
T 46 N	R 76 W	22617	105.8	4235	± 9
T 46 N	R 75 W	19416	88.1	3026	±12
T 45 N	R 77 W	7486	116.5	1543	±15
T 45 N	R 76 W	23344	113.7	4698	± 9
T 45 N	R 75 W	22610	101.2	4052	±10
T 45 N	R 74 W	2953	80.2	419	±24
T 44 N	R 77 W	10323	115.7	2114	±14
T 44 N	R 76 W	22545	126.5	5046	±10
T 44 N	R 75 W	23639	104.5	4374	±10
T 44 N	R 74 W	11556	82.4	1686	±29
T 43 N	R 77 W	15833	107.8	3020	±16
T 43 N	R 76 W	23675	122.8	5148	±12
T 43 N	R 75 W	23667	104.4	4375	±22
T 43 N	R 74 W	11551	77.4	1583	±20
T 42 N	R 77 W	13818	87.2	2132	±26
T 42 N	R 76 W	23706	93.5	3923	±27
T 42 N	R 75 W	23567	82.0	3422	±31
T 42 N	R 74 W	22091	70.7	2765	±18
T 42 N	R 73 W	410	72.0	52	±30
T 41 N	R 77 W	535	82.5	78	±50
T 41 N	R 76 W	12697	72.4	1627	±38
T 41 N	R 75 W	16328	64.8	1874	±24
T 41 N	R 74 W	4903	71.1	617	±35
TOTAL (or average)		**602042**	**[4](105.7)**	**112700±4%**	

[1]One short tone equals 0.907 metric ton.
[2]1.30 metric tons per metric meter.
[3]Values rounded for inclusion in table, but not for calculations.
[4]Average thickness value for deposit.

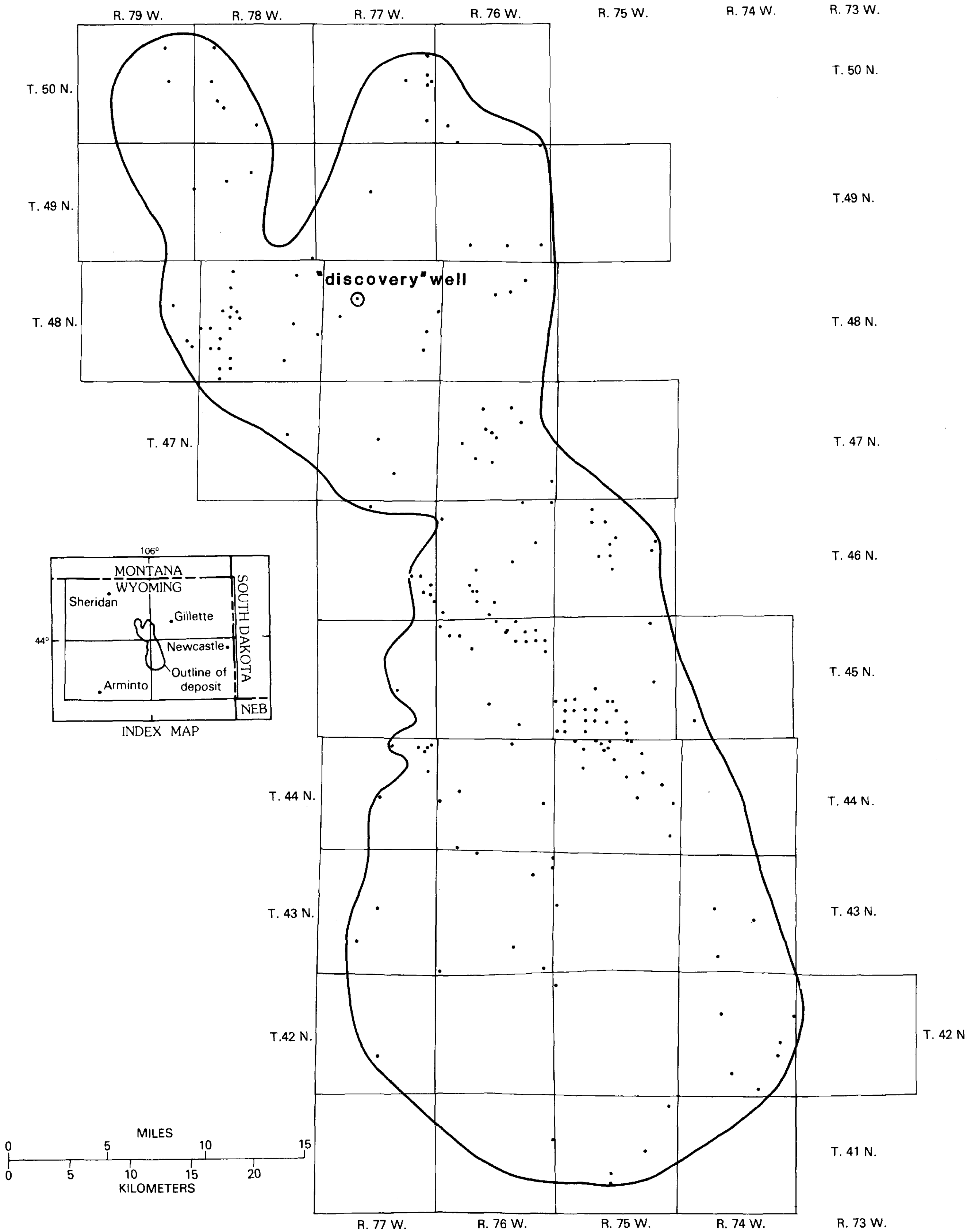

Figure 1. Land net and distribution of drillholes within deposit boundary.

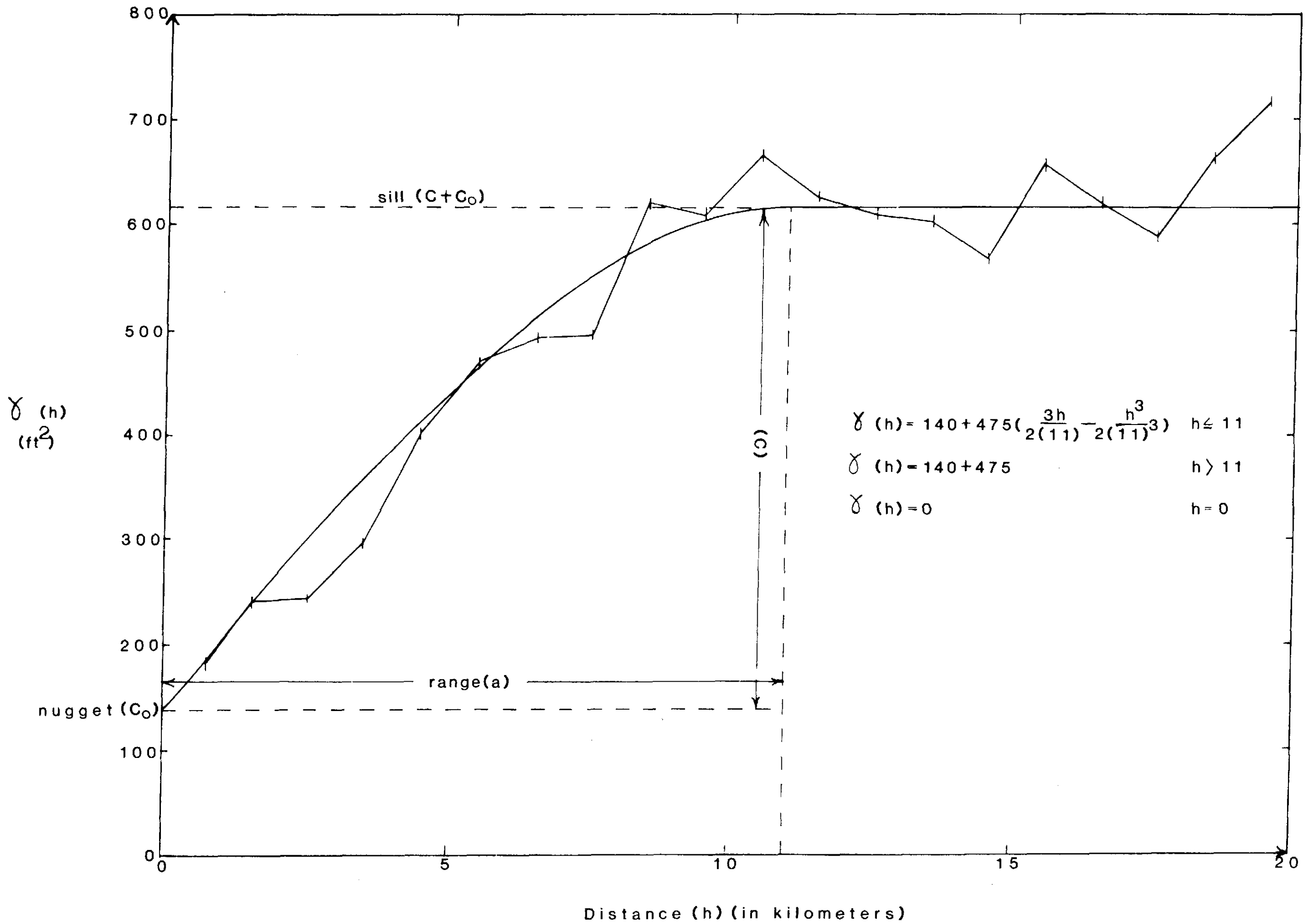

Figure 2. Experimental and fitted semi-variograms of thickness. The theoretical curve was chosen by visual fit and cross-validation. Cross-validation results: Kriged average error = −0.28 ft; kriged root mean square error = 19.21 ft; kriged reduced mean square error = 1.07.

reported to be about 110 billion tons by Glass (1978, Table 6, p. 80).

KRIGING

Kriging addresses two fundamental problems of the mining industry: First, the need to estimate the "global" resources of a deposit, (i.e., the average quality or thickness and the total tonnage), and second, the need to know the average grade and tonnage of each of the blocks into which the deposit has been divided. Kriging was named for D. G. Krige, a pioneer in the application of geostatistical methods to ore reserve problems of South African gold mines. The method was generalized as an engineering evaluation tool by Georges Matheron of France. Works by Rendu (1978), Skrivan and Karlinger (1980), Knudsen and Kim (1977), Journel and Huijbregts (1978), and David (1977) were used in developing the geostatistical programs used for this study. Clark (1979) provides a good general introduction to geostatistics.

In this study, the total tonnage of the Anderson coal deposit was computed using the theoretical semi-variogram of thickness shown on Figure 2. Cross-validation of the semi-variogram yielded satisfactory results, according to criteria described by Karlinger and Skrivan (1981, p. 5).

Estimates of the amount of in-place coal by township are summarized in Table 1. Error limits in excess of ±20 percent identify either townships that

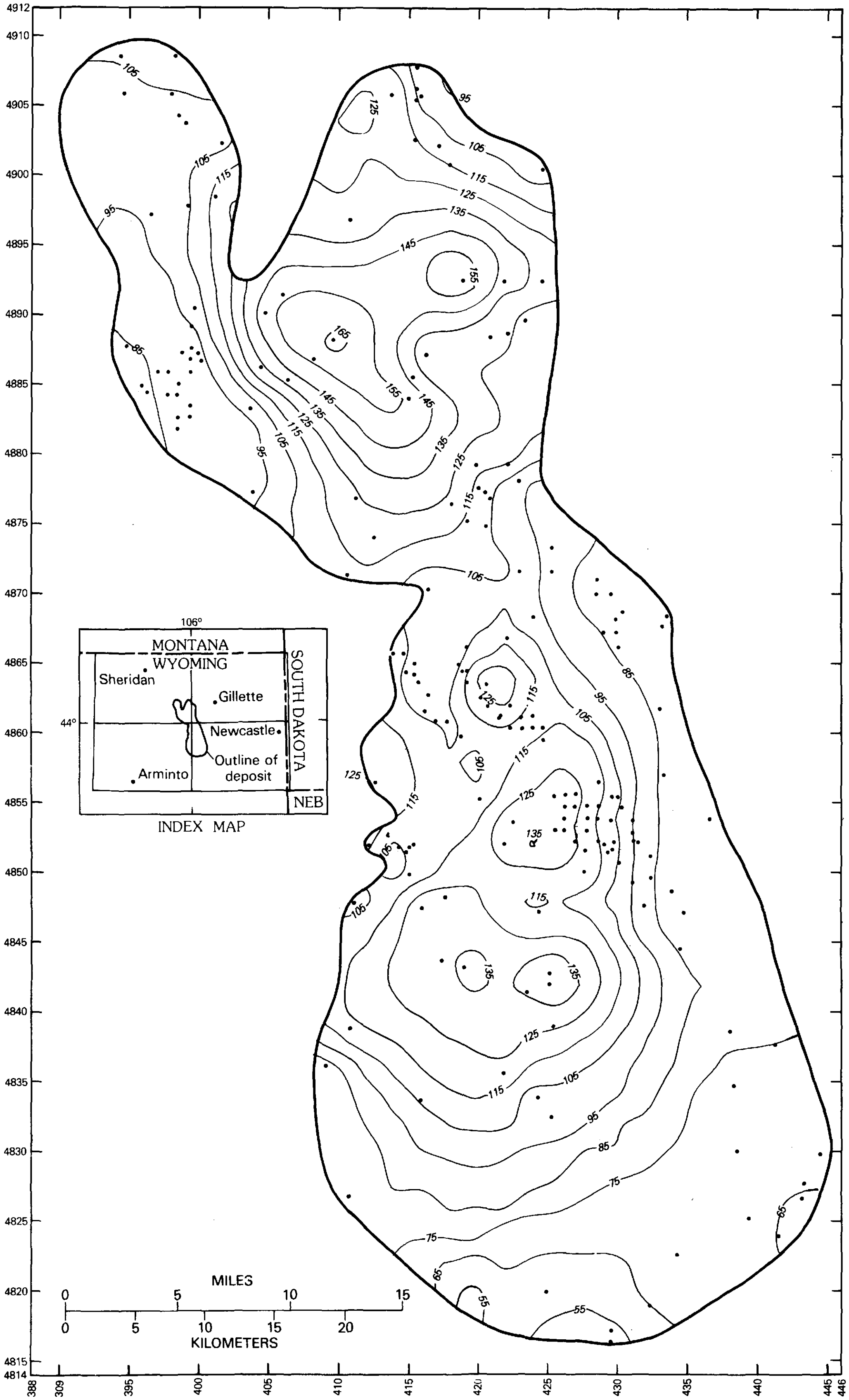

Figure 3. Thickness map of the Anderson coal deposit. Contour interval is 10 ft; marginal grid is in kilometers based on the UTM grid, zone 13.

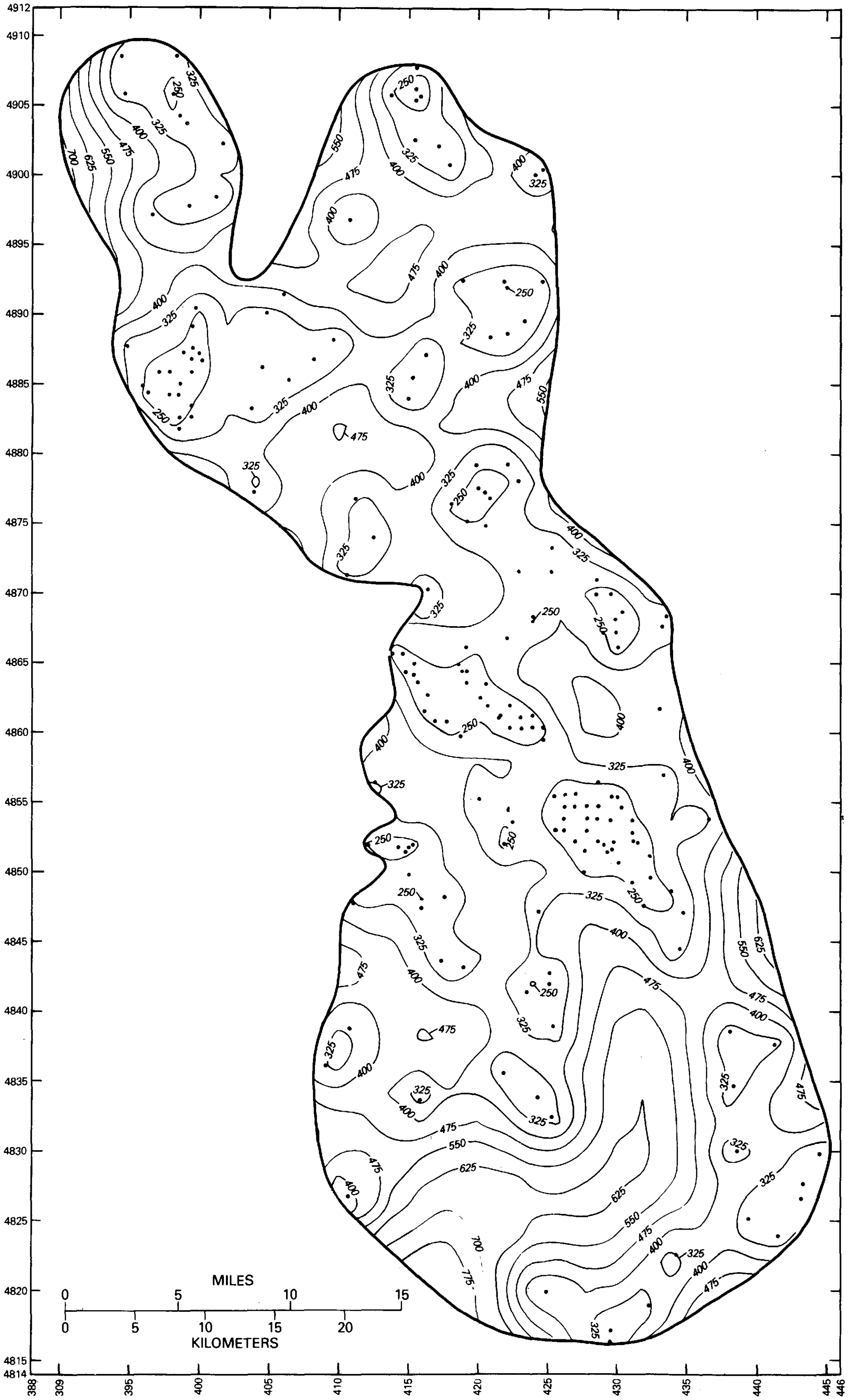

Figure 4. Map showing the kriging variances associated with the thickness map of the Anderson coal deposit. Contour interval is 75 ft^2; marginal grid is in kilometers based on the UTM grid, zone 13.

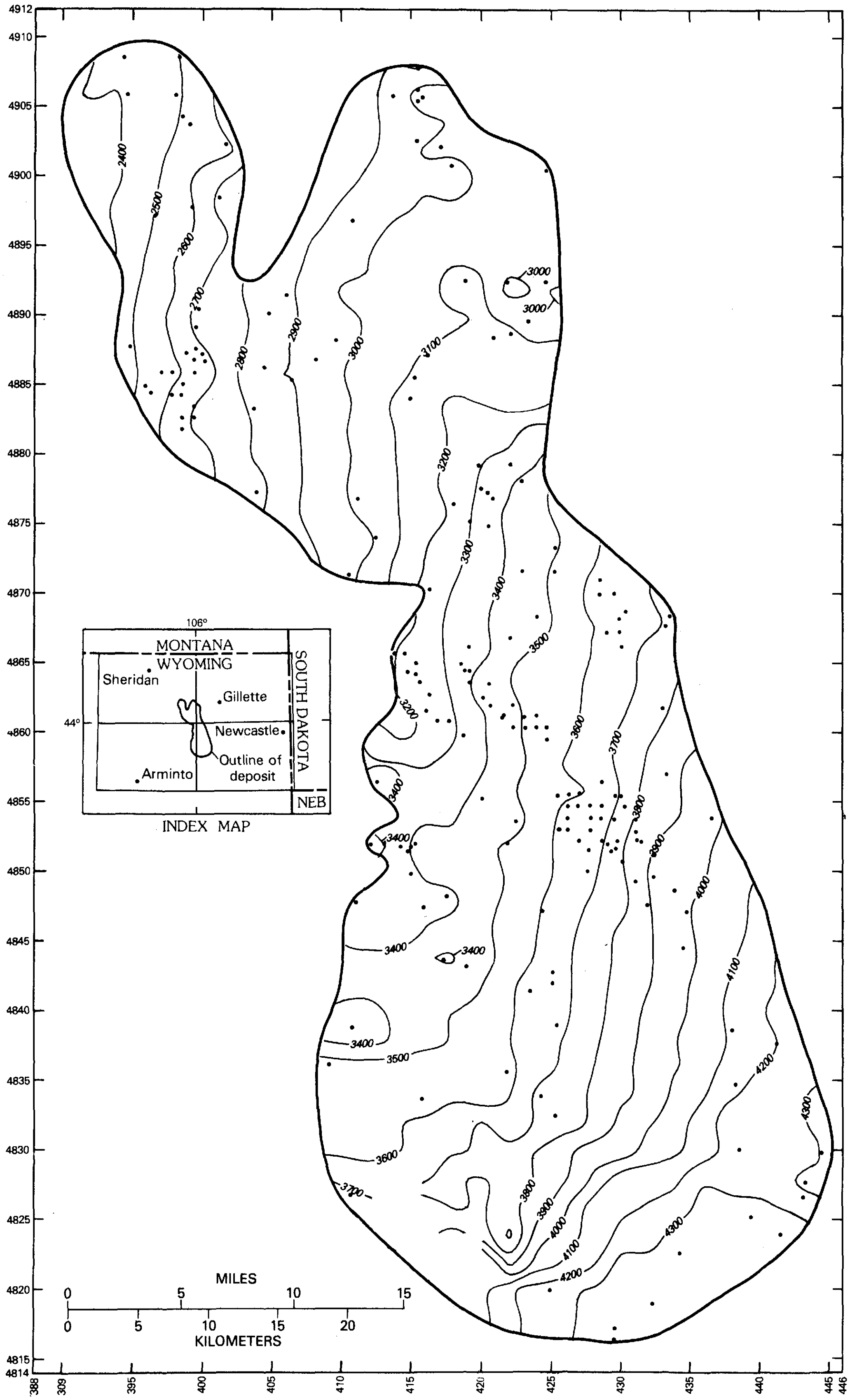

Figure 5. Structure contour map of the top of the Anderson coal deposit. Contour interval is 100 ft; marginal grid is in kilometers based on the UTM grid, zone 13.

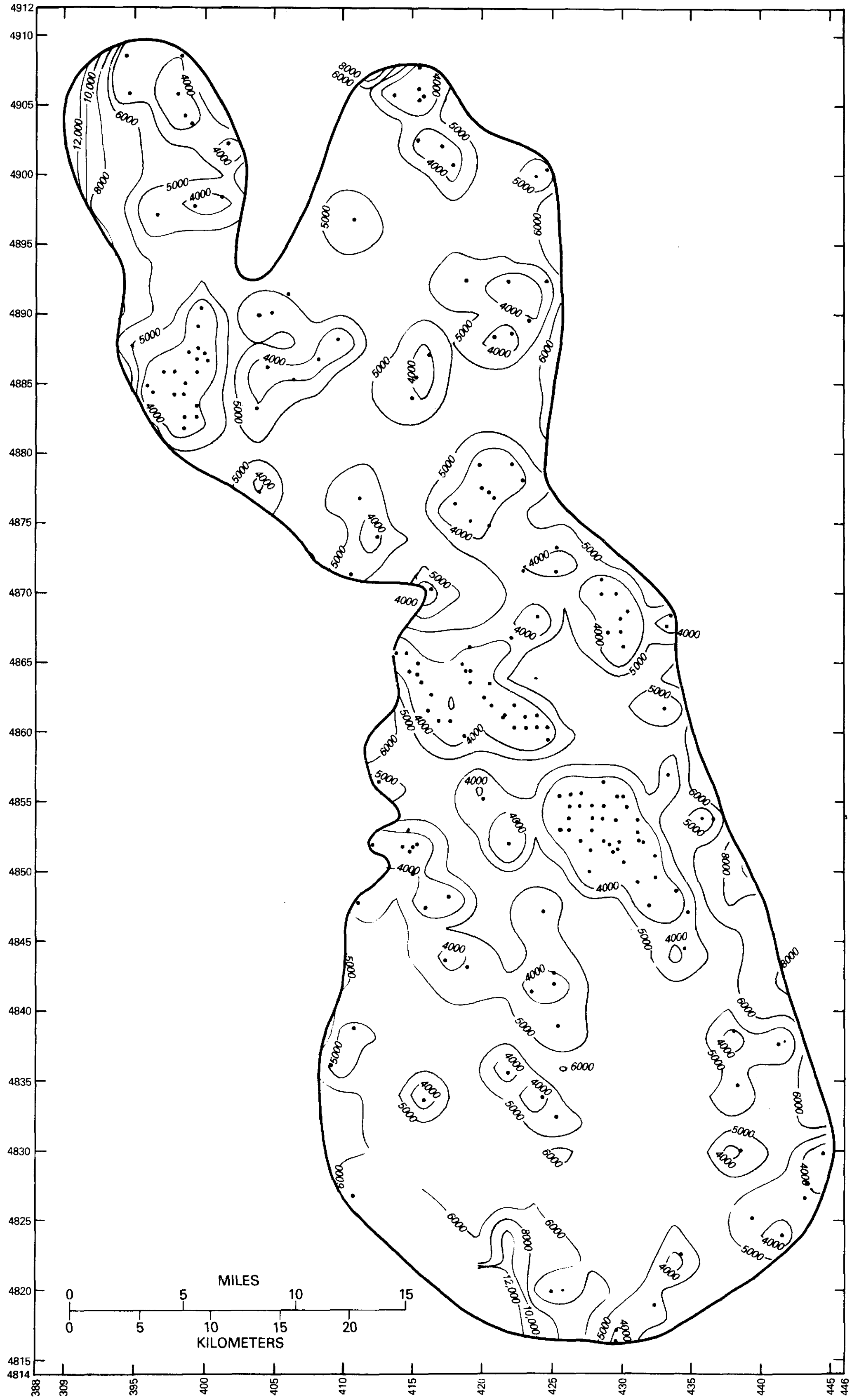

Figure 6. Map showing the kriging variances associated with the structure contour map of the top of the Anderson coal deposit. Contour interval is 1000 ft^2 for values less than 6000 ft^2, and 2000 ft^2 for greater values; marginal grid is in kilometers based on the UTM grid, zone 13.

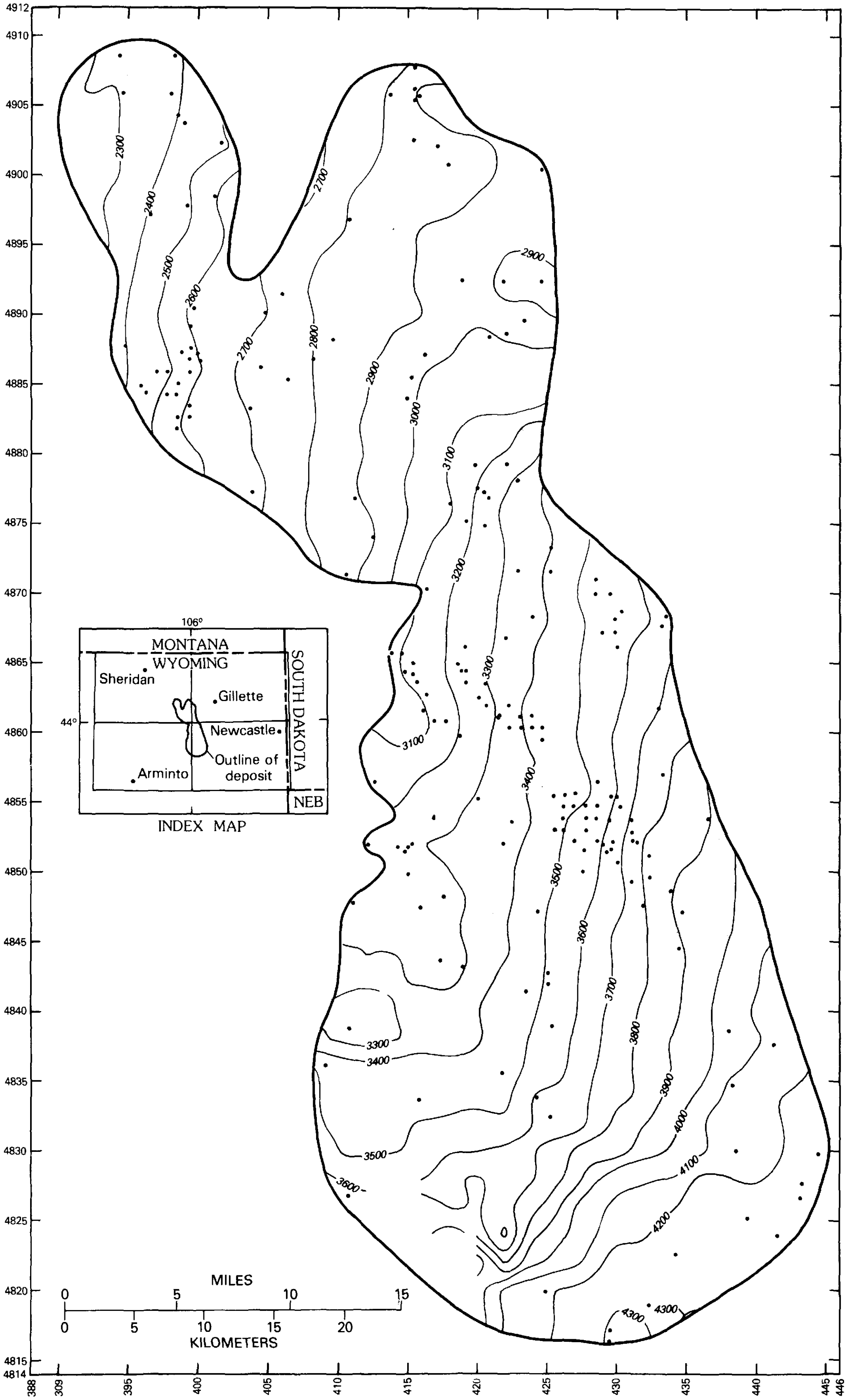

Figure 7. Structure contour map of the bottom of the Anderson coal deposit. Contour interval is 100 ft; marginal grid is in kilometers based on the UTM grid, zone 13.

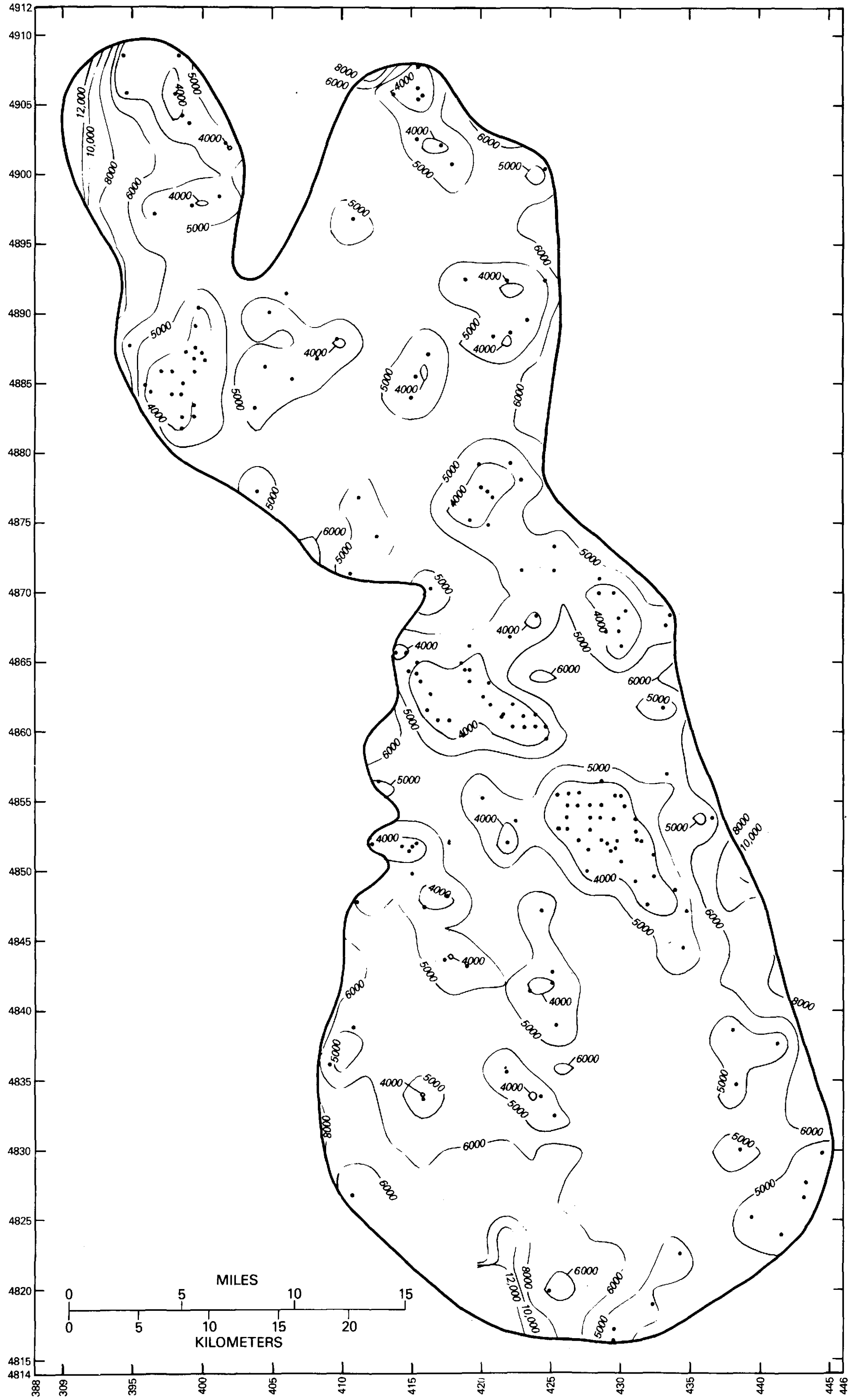

Figure 8. Map showing the kriging variances associated with the structure contour map of the bottom of the Anderson coal deposit. Contour interval is 1000 ft^2 for values less than 6000 ft^2, and 2000 ft^2 for greater values; marginal grid is in kilometers based on the UTM grid, zone 13.

have fewer than two data points (Figure 1) or townships in which coal is considerably thinner than the reset of the deposit (as in T. 41 N., R. 75 W., Table 1). The ±4 percent kriging error for the entire deposit was determined by a single kriging of the deposit using all the data.

The same variogram parameters used to compute the deposit tonnage were used to create the grid of points for the thickness map (Figure 3). The thickness map of the coal deposit shows that the thickest coal is in the northern part of the subarea. The associated kriging variance map (Figure 4) indicates the precision of the thickness estimates.

On the kriging variance maps (Figures 4, 6, and 8), higher values indicate lower precision; lowest values enclose clusters of closely spaced data points. In the southern and northwestern parts of the deposit where data points are sparse, isovariance lines have the highest values. In this way, kriging graphically calls attention to areas that require more sampling. Because kriging variance is a function of the number and arrangement of data points and is independent of the actual values at the data points, hypothetical sample points can be introduced for the purpose of determining the potential reduction in kriging error. In this way, the effect of data from drillholes can be assessed before actual drilling is begun (Kim and others, 1981, p. 1478). If drilling funds are limited, such an assessment assures that the optimum results will be obtained.

To create the grid of points for the structure contour maps, universal kriging was required because of the westerly dip of the bed. A theoretical, spherical semi-variogram of the drift residuals was used, along with a linear form of drift. As for thickness, the semi-variogram model was fully validated. the sparsity of data in the southern part prevented gridding by universal kriging in that area. The contouring program was instructed not to contour through empty cells.

Structure contour maps of the top and base of the Anderson coal deposit are shown on Figures 5 and 7. Associated viariance maps are shown on Figures 6 and 8.

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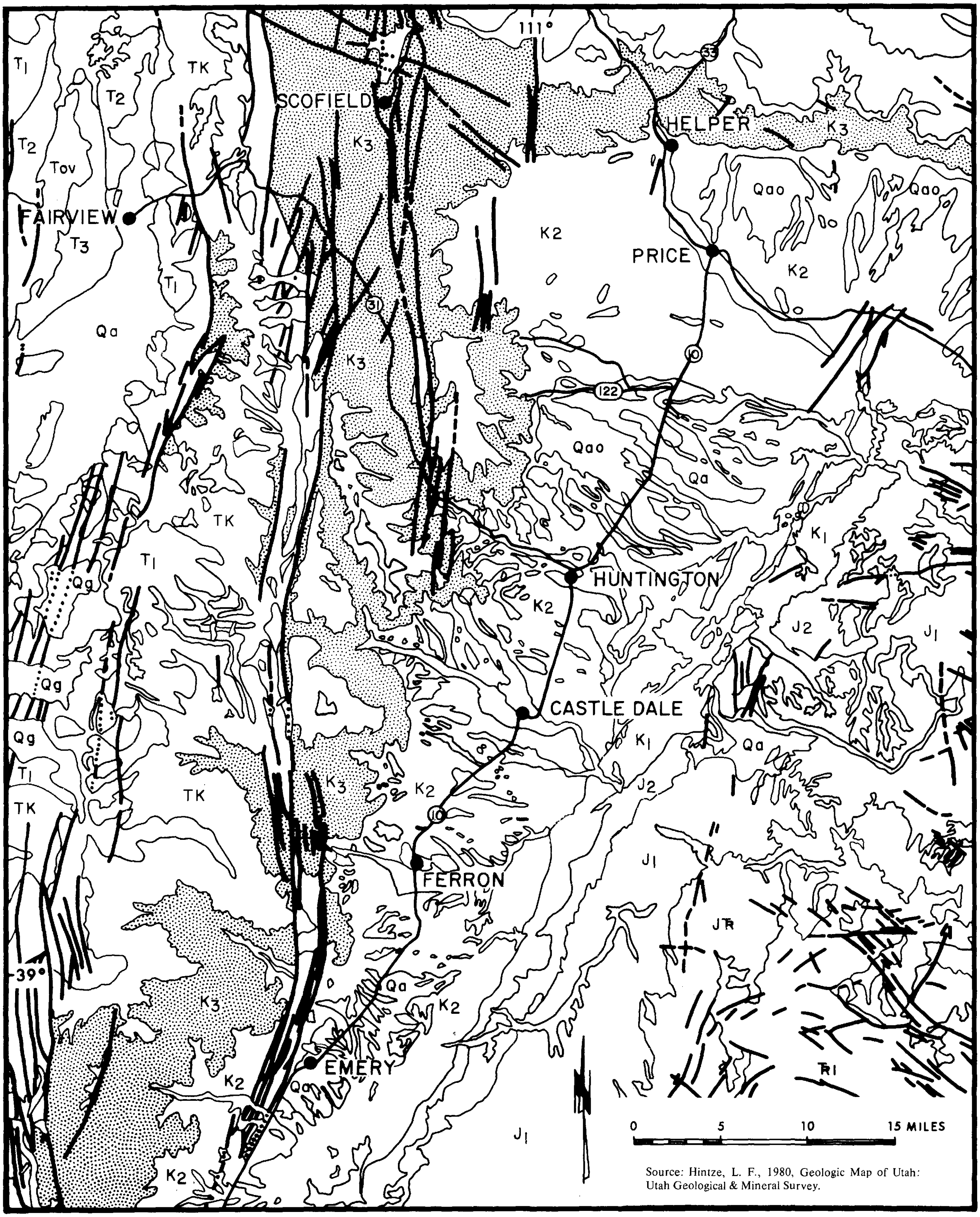
ROMOCOCOAL FIELD TRIP, 1982
UTAH



Source: Hintze, L. F., 1980, Geologic Map of Utah: Utah Geological & Mineral Survey.

Utah Geological and Mineral Survey, Bulletin 118, 1982
Proceedings — 5th ROMOCO Symposium, 1982

1982 ROCKY MOUNTAIN COAL SYMPOSIUM FIELD TRIP FIRST DAY ROAD LOG: Ferron Sandstone Member

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Research Planning Institute, Boulder, CO 80302

The Upper Cretaceous Ferron Sandstone Member of the Mancos Shale offers some of the finest exposures of coal-bearing strata to be found in the western United States. Because of the rugged nature of the terrain, however, only a small number of Ferron outcrops are accessible to a large field trip party traveling by bus. Rather than attempt to overview the regional stratigraphy of the Ferron, the group will examine just one small part of the Ferron deltaic system in considerable detail.

The buses will drop the field party off approximately one-and-a-half miles east of the town of Emery. From this spot, it will be about a 1 mi walk to the head of Muddy Creek Canyon, where exposures of the Ferron begin. During the course of the day, the group will work its way southward along the western wall of the Canyon, a distance of about 2 mi. The relief of the walls of the canyon increases gradually to about 400 ft in the southern part of the canyon, where almost the entire Ferron section is beautifully exposed. A 1 mi walk westward across the dip slope of the Ferron will take the group back to the buses, which will be waiting near the head of Miller Canyon. The route to be followed is shown on Figure 1.

Included at the end of this article is a paper reprinted from the American Association of Petroleum Geologists Bulletin. The paper describes the depositional setting and the stratigraphy of the Ferron Sandstone Member, plus the various facies that will be examined. Supplemented by information presented here, the paper forms the basis for the first day of the field trip.

Figure 2 is a cross section showing the stratigraphy of the Ferron in the southern part of Castle Valley. The locations of the measured sections incorporated in the cross section are shown in Figure 3. Sections 18-21 were measured in Muddy Creek Canyon. Figure 4 delineates the facies that can be recognized in exposures along the west wall of the canyon. It has been prepared from a complete set of photo mosaics controlled by a large number of measured sections, the locations of which are indicated across the top of the panel.

The units that will be examined in the greatest detail during the trip are the J coal bed, the marine sandstone unit that occurs beneath the J coal bed near the head of the canyon, the marine shale and sandstone unit that overlies the J in the middle part of the canyon, and the delta plain deposits that underlie the J. These delta plain deposits are laterally equivalent to the I coal bed, which exceeds 25 ft in thickness in the vicinity of the Consolidation Coal Company's Emery Mine, several miles to the southwest. The relationships between the I coal bed and the strata exposed in Muddy Creek Canyon are shown in Figure 5; these relationships will be discussed in detail during the course of the trip. The locations of the measured sections (S-1 to S-6) and holes drilled as part of the Muddy Project of the U. S. Geological Survey (M-1 to M-10) are shown in Figure 6. Additional drill hole data provided by Consol are also shown but, because of the proprietary nature of the data, exact locations of the drill holes are not shown. The southwesternmost hole was drilled in the immediate vicinity of the Emery Mine.

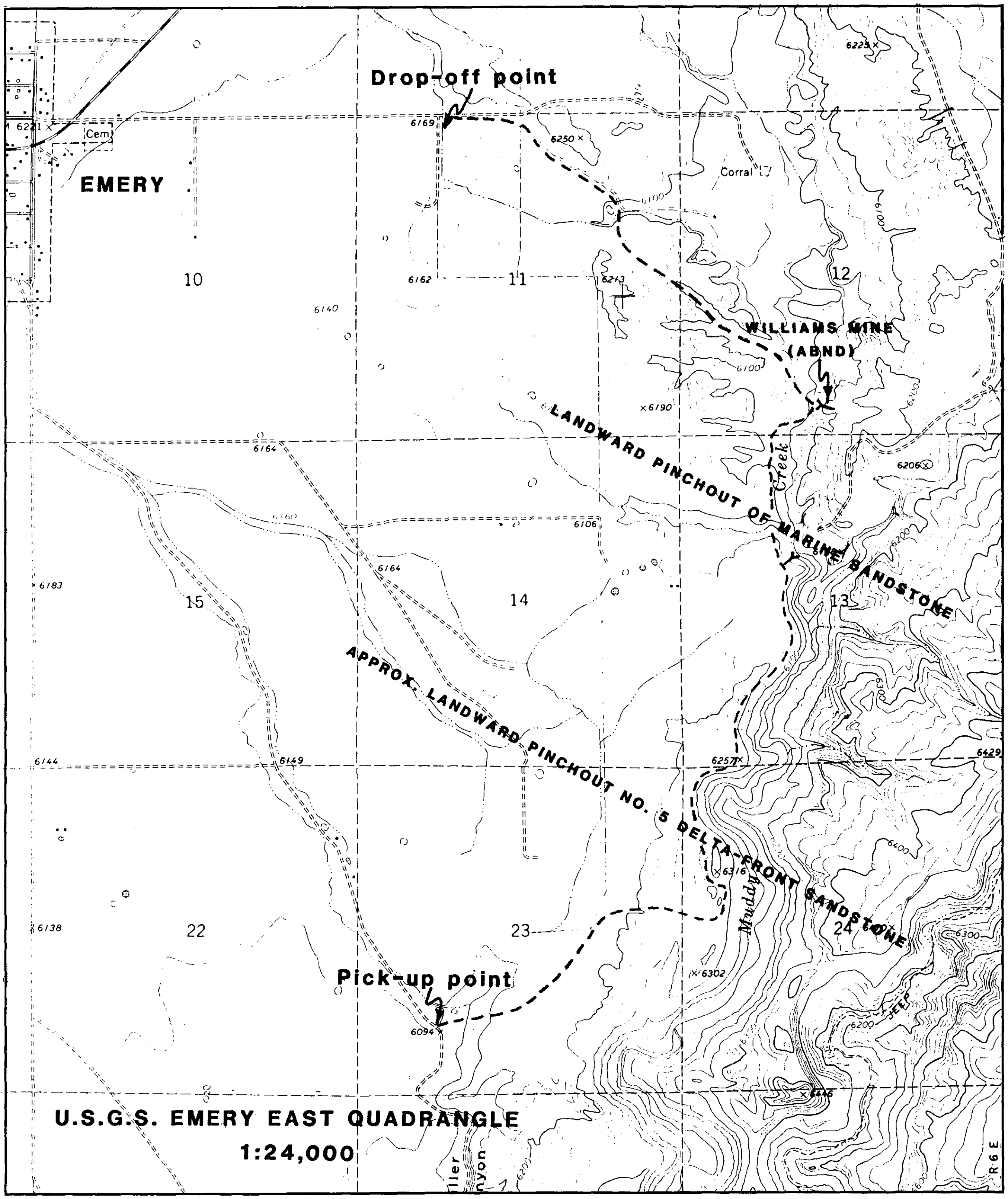


Figure 1. U.S.G.S. Emery East Quadrangle 1:24,000

Figure 2. Cross section showing the stratigraphy of the Ferron Sandstone Member of the Mancos Shale in the southern part of Castle Valley. Seaward to right; landward to left.

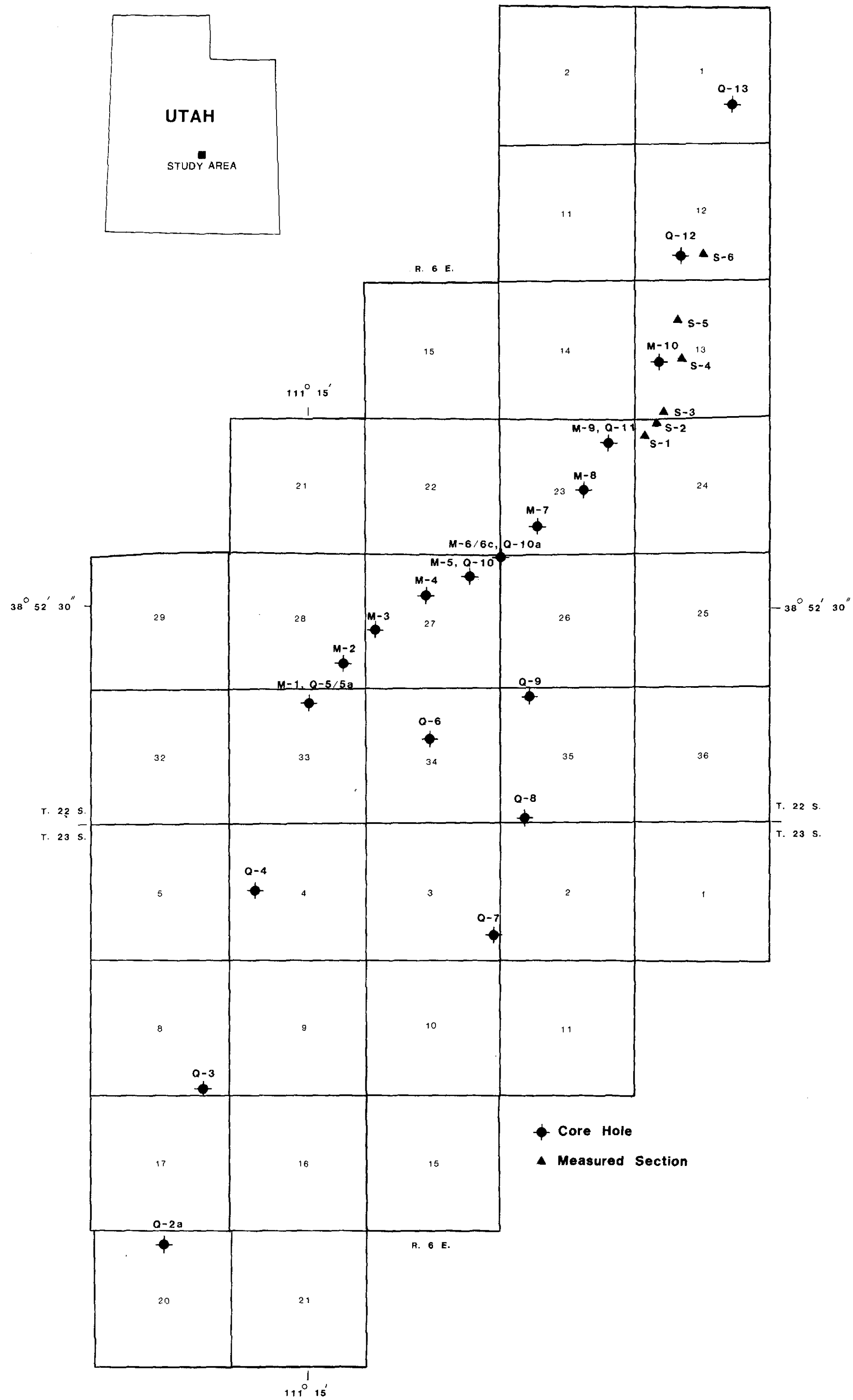
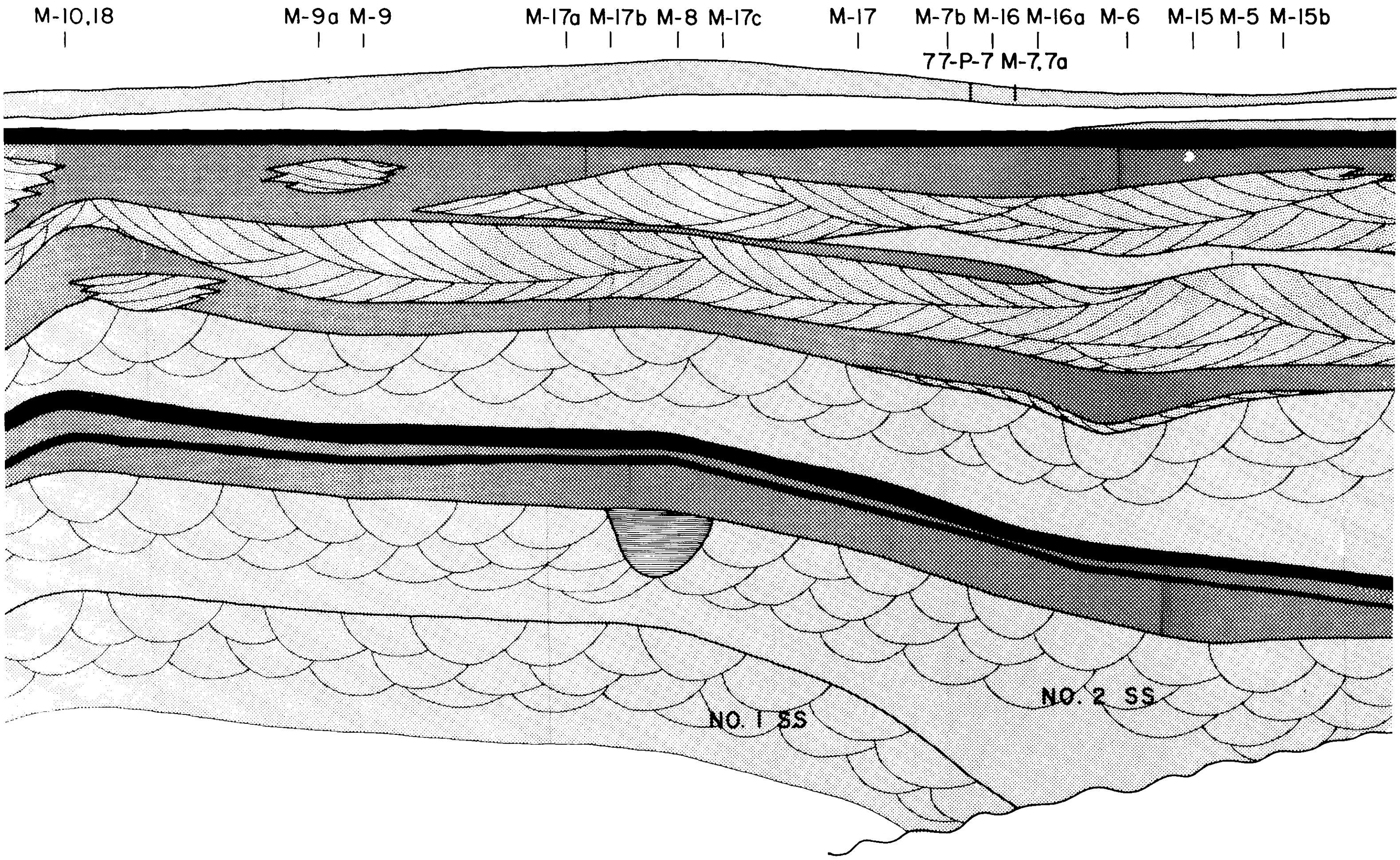


Figure 3. Index map showing locations of measured sections (25), and outcrop of the Ferron Sandstone Member of the Mancos Shale (Kfe).


M-10,18
M-9a M-9
M-17a M-17b M-8 M-17c
M-17
M-7b M-16 M-16a M-6
M-15 M-5 M-15b
77-P-7 M-7,7a
NO. 1 SS
NO. 2 SS

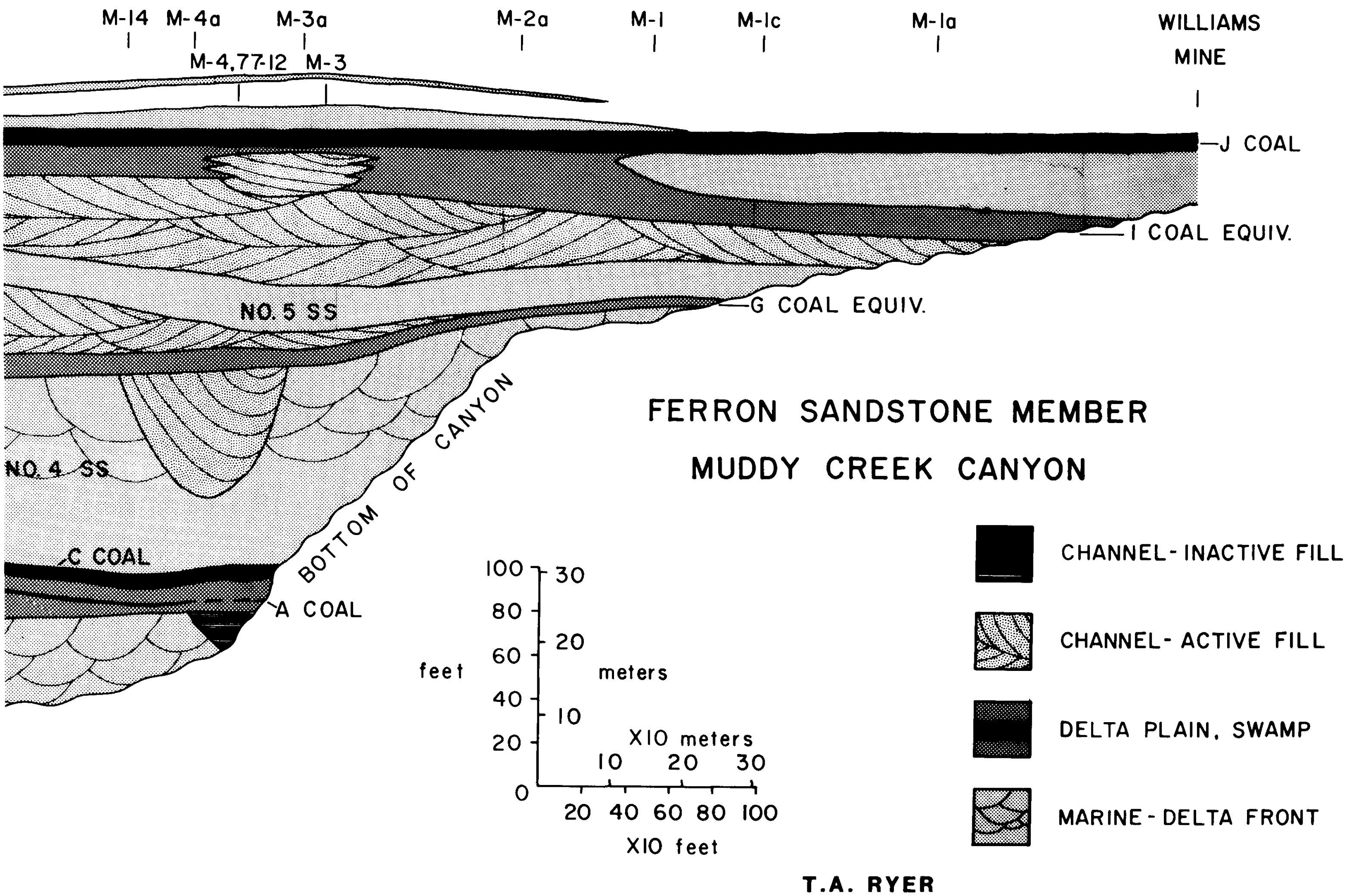
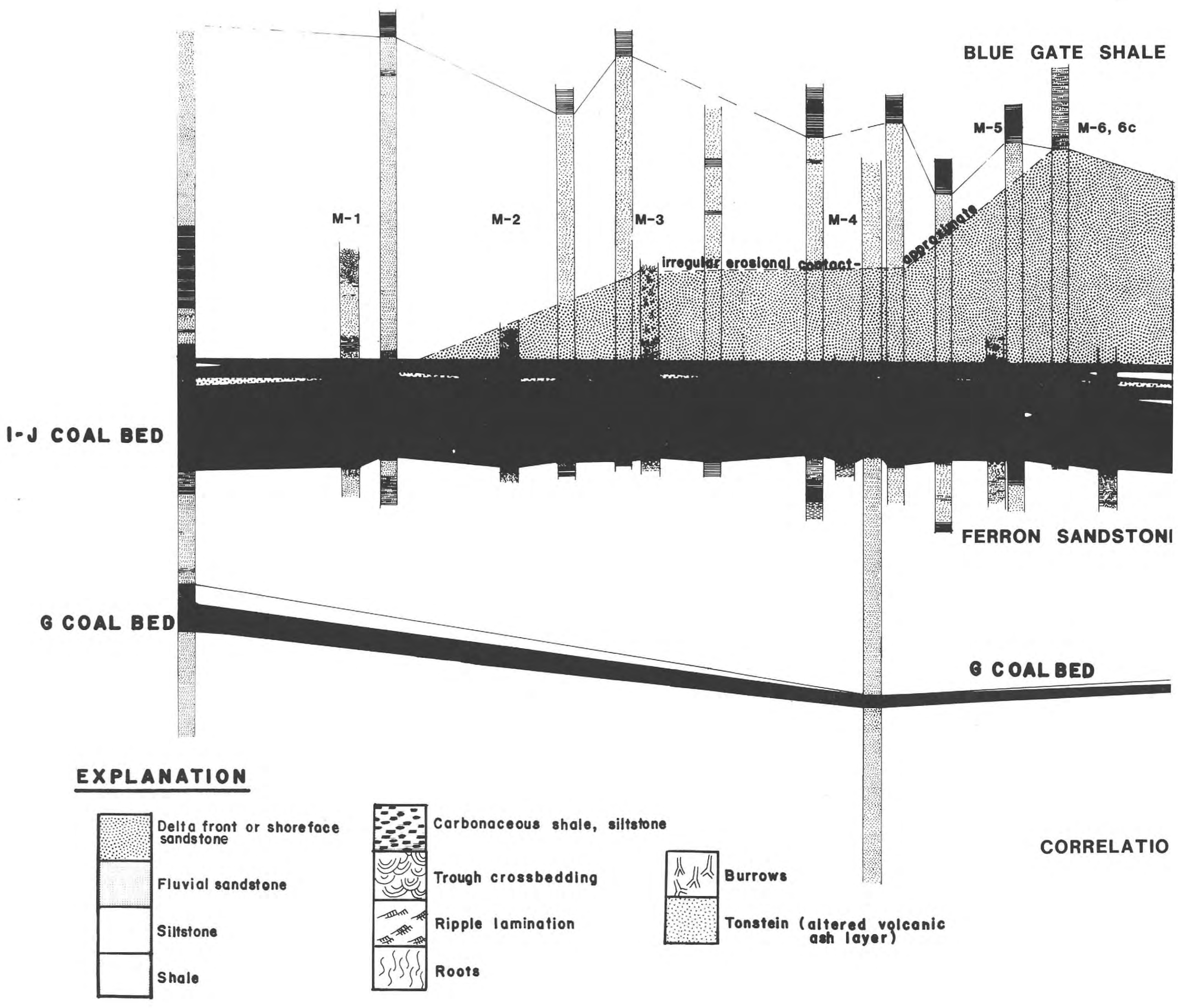


Figure 4. Stratigraphy and facies of the Ferron Sandstone Member in Muddy Creek Canyon.


BLUE GATE SHALE
M-1
M-2
M-3
M-4
M-5
M-6, 6c
irregular erosional contact- approximate
I-J COAL BED
FERRON SANDSTONE
G COAL BED
G COAL BED
EXPLANATION
Delta front or shoreface sandstone
Fluvial sandstone
Siltstone
Shale
Carbonaceous shale, siltstone
Trough crossbedding
Ripple lamination
Roots
Burrows
Tonstein (altered volcanic ash layer)
CORRELATIO

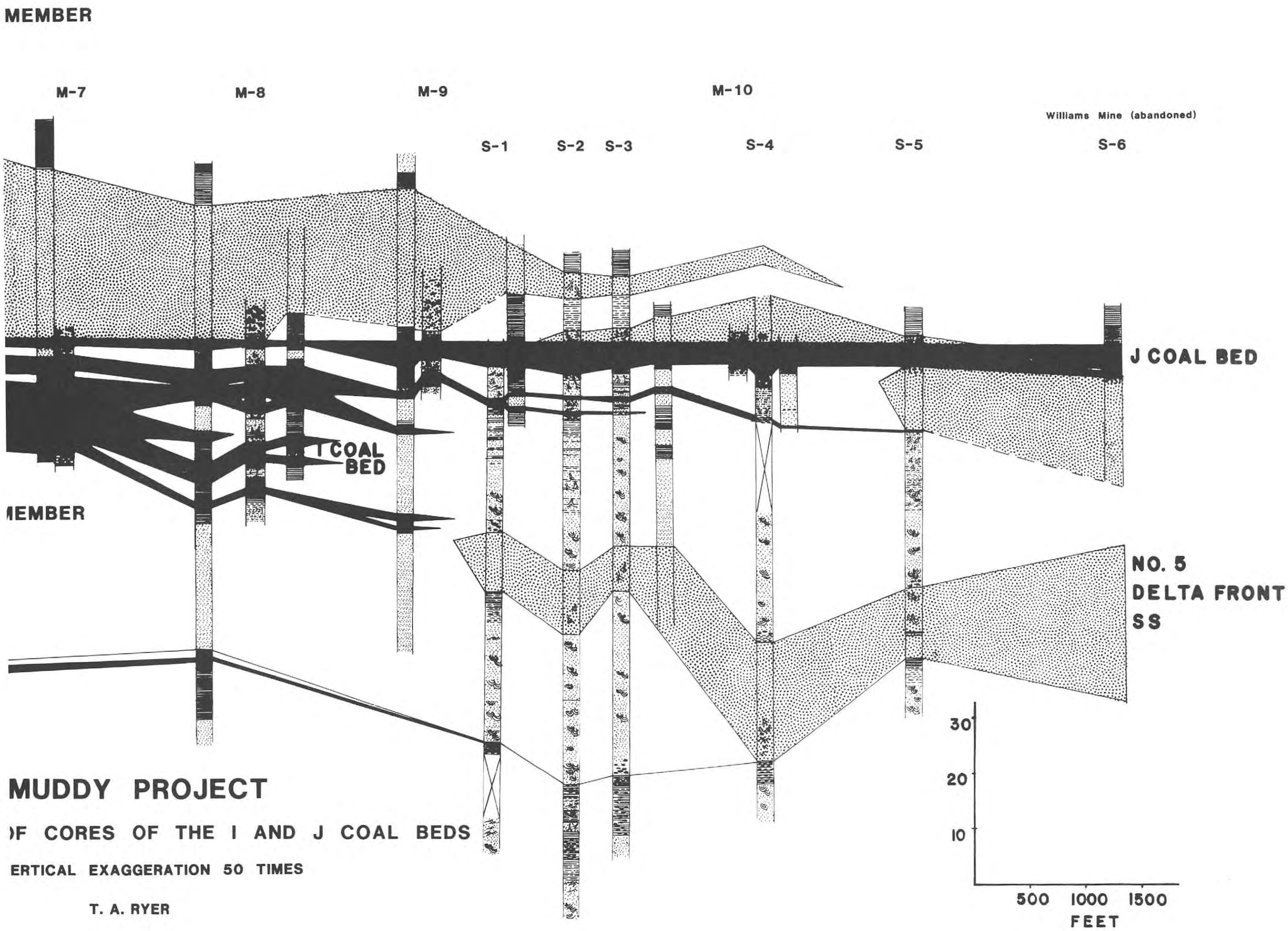


Figure 5. Stratigraphy of the upper part of the Ferron between Consolidation Coal Company's Emery Mine (left) and the head of Muddy Creek Canyon (right) as determined from drillhole and outcrop sections.

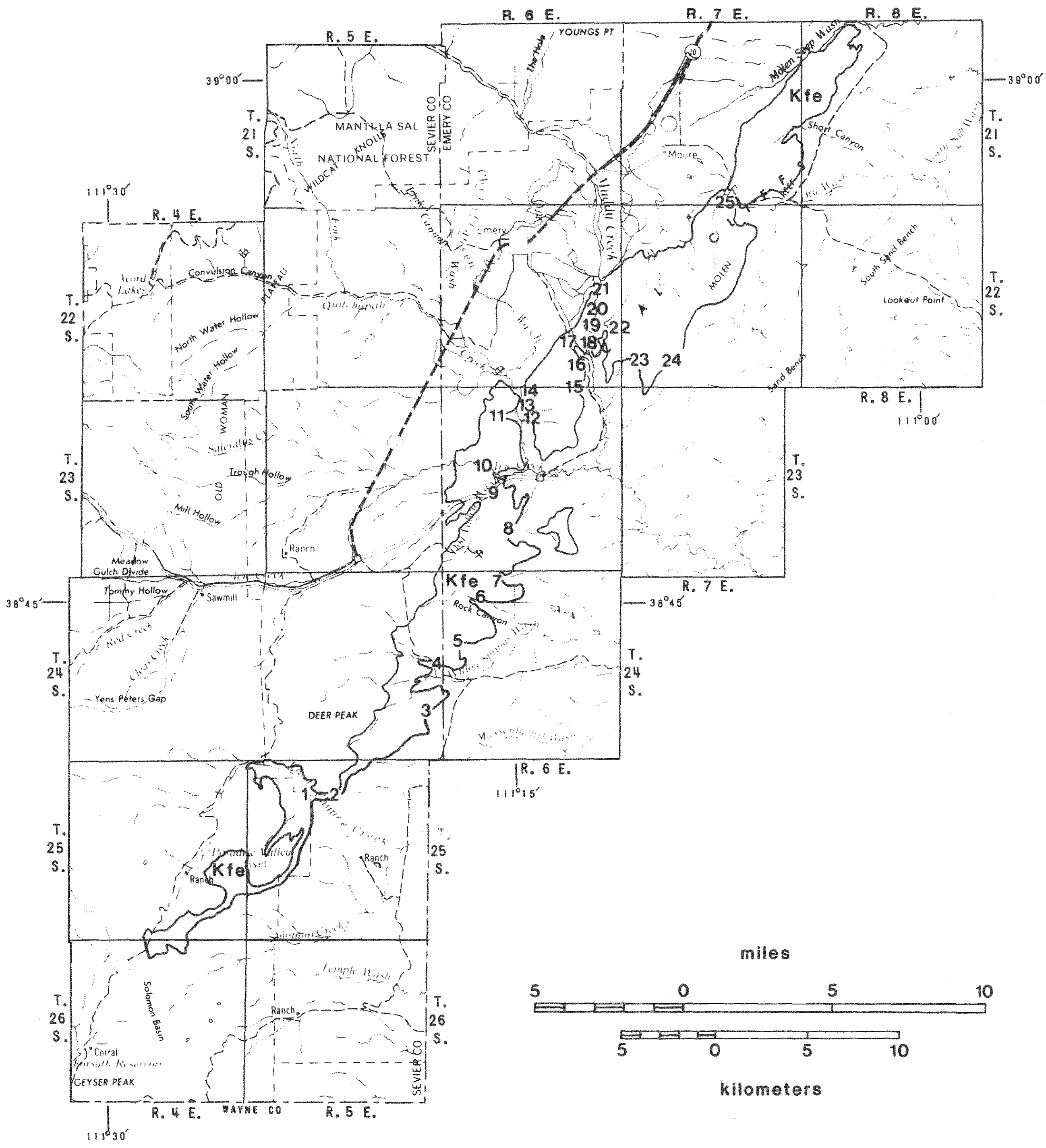


Figure 6. Muddy and Quitchupah projects, locations of core holes.

Reprinted with permission from: The American Association of Petroleum Geologists Bulletin, v. 65, no. 11 (November 1981), p. 2323-2340, 23 Figs.

Deltaic Coals of Ferron Sandstone Member of Mancos Shale: Predictive Model for Cretaceous Coal-Bearing Strata of Western Interior[1]

THOMAS A. RYER[2]

ABSTRACT

The Upper Cretaceous Ferron Sandstone Member of the Mancos Shale, the coal-bearing unit of the Emery coalfield in central Utah, shows accumulation of clastic sediments in a lobate, river-dominated deltaic system that existed along the western shoreline of the Interior Cretaceous seaway during late Turonian time. Five cycles of deltaic sedimentation, each containing one major coal bed or coal zone, are represented. A clear genetic relationship exists between the geometries of the major coal beds of the Emery field and the geometries of the delta-front sandstone units with which they are associated. The thicker part of each coal bed extends from the vicinity of the landward pinch-out of the associated delta-front sandstone landward to a distance of about 10 km. This genetic relation forms the basis of a predictive model that can be used in designing more cost-effective exploration programs in coal-bearing strata of Cretaceous age in the Western Interior.

INTRODUCTION

A substantial gap exists between capabilities and common practices in the science of coal geology. The basic tasks of the coal geologist typically are (1) to design drilling and coring programs that, in combination with existing data, adequately evaluate areas of interest; (2) to supervise the drilling programs and the collection of data and coal samples; (3) to compile and interpret data to establish coal bed continuity, thickness, coal quality, and minable reserves; and (4), when a particular area warrants, to cooperate with mining engineers in the planning of a mine. This procedure has been applied effectively for many years, but it has one major shortcoming—little or no attention is paid to the relations between the coal beds and their enclosing strata. If the strata are studied at all, it is to determine physical properties that affect mining. A great deal of valuable information has remained unutilized.

In recent years, depositional models relating the paleoenvironmental histories of coal beds and associated strata have been effectively and profitably applied in mine planning (Horne et al, 1978). The principal value of the models is that they are predictive. Areas of potentially dangerous roof conditions, areas where coal beds are likely to thin or split, and, to a lesser extent, coal quality and chemistry all can often be predicted with even a limited amount of drill hole data. These predictions can be utilized in both advanced-stage drilling and mine planning. Unfortunately, most tract evaluation and mine-planning programs do not include development and application of depositional models. This will undoubtedly change in coming years, as increasing demand for coal, wider use of multiple seam mining methods, mining to greater depths as shallow reserves are depleted, and increasing concern for mine safety all increase the desirability of more efficient and cost-effective methods in tract evaluation and mine planning.

It is the premise of this paper that depositional models can also be effectively applied in coal exploration. The predictive model presented here has been developed for the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale, the coal-bearing unit of the Emery coalfield in central Utah. I believe that the model will prove to be applicable to much of the coal-bearing strata of Cretaceous age in the Western Interior United States, although modification will be necessary for its application to areas characterized by different styles of sedimentation. Some possible modifications are discussed.

EMERY COALFIELD, UTAH

The Emery coalfield (Fig. 1), with total coal resources

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The results of this study were first presented at the AAPG annual meeting, Houston, Texas, in 1979.

Stratigraphic studies of the Ferron Sandstone Member and its coal beds were conducted primarily during the summers of 1976-78. Michael Hannigan, Debra Hannigan, Richard Phillips, and Steven Goolsby all rendered capable assistance in the field.

A large quantity of subsurface data from the Emery coalfield was made available by The Consolidation Coal Co. The conclusions drawn here would not have been possible without access to these data; special thanks to William Eastwood and Edwin Kuhn for their help in its acquisition. Additional subsurface data were provided by Gerald Vaninetti, Utah Power and Light Co., Salt Lake City, and Mark Wilkerson, Atlantic Richfield, Denver. Anna Langer compiled much of the subsurface data and assisted in its interpretation.

of approximately 1.3 billion metric tons (Lupton, 1916; Doelling, 1972), is one of the smaller coalfields in the Rocky Mountain region. It combines various characteristics that make it ideally suited for a study relating the geometries of coal beds to their paleoenvironmental settings: (1) natural exposures of the Ferron Sandstone Member in the Emery area are superb (Fig. 2), permitting detailed stratigraphic study and paleoenvironmental reconstruction; (2) the structural strike of the area is at a high angle to the depositional strike of the Ferron, making it possible to describe complex interfingering of marine and nonmarine facies in the direction of depositional dip; (3) all major coal beds and some associated rocks contain layers of altered volcanic ash that can be correlated and used as isochronous surfaces in paleoenvironmental reconstructions; and (4) the area has been extensively drilled by the coal industry.

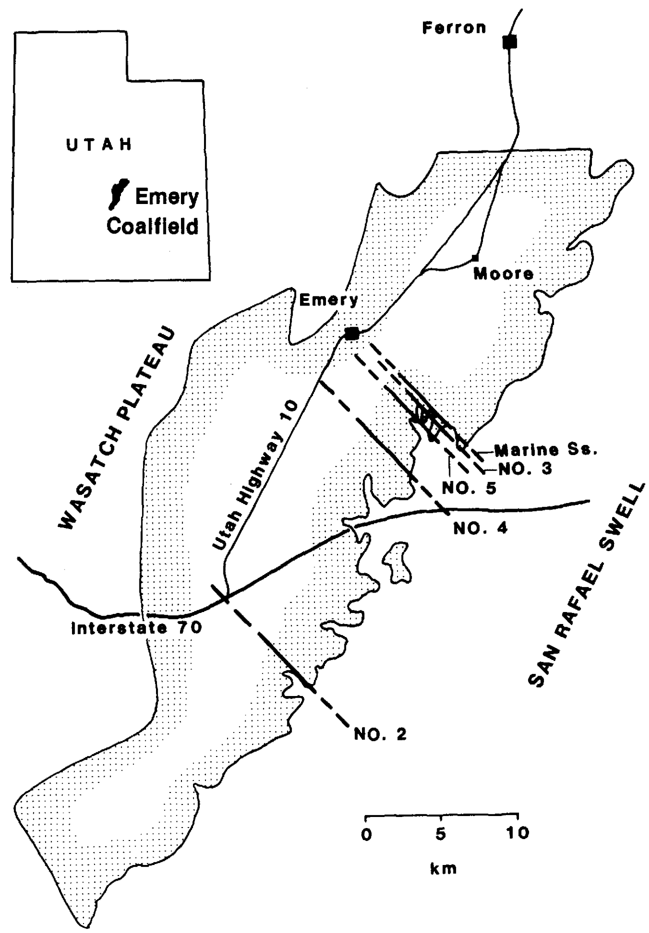


FIG. 1—Outline of Emery coalfield. Southeast edge of coalfield is outcrop of Ferron Sandstone Member; northwest edge approximately coincides with eastern escarpment of Wasatch Plateau. The coalfield is defined at its northeast edge by approximate seaward limit of coal in Ferron and at its southwest edge by covering of Ferron by Tertiary volcanic rocks. Also shown are locations of landward pinch-outs of delta-front and marine sandstones discussed in text. (Outline of coalfield from Doelling, 1972.)

METHODOLOGY

Of primary importance in this study was the delineation of the stratigraphic framework of the Ferron Sandstone Member in the Emery coalfield, specifically, the recognition and mapping of the major cycles of sedimentation. The nearly continuous outcrops of the Ferron were studied along a distance of 40 km parallel with the structural strike. The actual outcrop distance studied, considering the numerous canyons and smaller irregularities of the outcrop, totals about 70 km. Smaller areas within the coalfield and selected stratigraphic intervals within the Ferron were chosen for more detailed stratigraphic study. The purpose of these studies was to relate, in as much detail as the outcrops would afford, several major coal bodies to their paleoenvironmental settings within the depositional cycles. The results of these studies are reported elsewhere (Ryer and Langer, 1980; Ryer et al, 1980; Ryer, 1981a). A large amount of proprietary drill hole and corehole data was made available by the coal industry. These data were interpreted and combined with the general and specific stratigraphic models to provide a sound, three-dimensional picture of the Ferron Sandstone Member and its coal beds. Finally, all data were integrated to produce the predictive model.

FERRON SANDSTONE MEMBER

Stratigraphic Setting

The Ferron Sandstone Member accumulated during late Turonian time in a suite of deltaic paleoenvironments along the western shoreline of the vast Interior Cretaceous epeiric seaway. The seaway (Fig. 3), which occupied the interior of the North American continent during latest Early Cretaceous and most of Late Cretaceous time, connected waters of the proto-Caribbean on the south with those of the Circumboreal sea on the north and, at times of maximum development, stretched from western and central Utah eastward to Missouri and Iowa (Williams and Stelck, 1975). West of the Interior Cretaceous seaway, in southeastern Nevada, western Utah, and southern Idaho, a mountainous region, the Sevier orogenic belt, was repeatedly thrust-faulted and uplifted throughout Cretaceous time (Armstrong, 1968). Erosion of Paleozoic strata and, later, granitic basement rocks in the Sevier orogenic belt during Late Cretaceous time produced immense quantities of clastic sediments, which were shed eastward to accumulate in the Rocky Mountain geosyncline. The thickest Upper Cretaceous sections occur in a pronounced foreland basin that extended from central Utah northward into southwestern Wyoming (McGookey, 1972). The Emery area lies on the southeastern flank of this foreland basin.

The western shoreline of the Interior Cretaceous seaway underwent a series of major transgressions and regressions during Late Cretaceous time (Kauffman, 1977). The regressions are represented by eastward-thinning and generally eastward-fining wedges of clastic

FIG. 2—Exposures of Ferron Sandstone Member east of Emery, Utah. Delta-front sandstone units form prominent ledges.

sediments from the Sevier orogenic belt; the transgressions are represented by westward-thinning tongues of marine mudstone and shale. The Ferron Sandstone Member constitutes the earliest of these major Upper Cretaceous clastic wedges in central Utah (Fig. 4). The Emery coalfield is situated at the distal end of the wedge, where the Ferron interfingers with and pinches out eastward into mudstones of the Mancos Shale.

Stratigraphy and Paleoenvironments

The stratigraphy of the Ferron Sandstone Member was first described by Lupton (1916) in his comprehensive study of the coal resources of the Emery field. Lupton's coal resource data have been updated and revised by Doelling (1972). Davis (1954) and Katich (1954) recognized the Ferron as a deltaic deposit, recording accumulation of sediment derived from an area located southwest of the Emery coalfield. They also noted that the Ferron Sandstone Member in central Utah is not a single genetic unit. In addition to the deltaic complex, typified by exposures in the Emery coalfield, the Ferron includes a slightly older, stratigraphically lower sequence of intensely bioturbated, predominantly horizontal planar-laminated sandstone and siltstone that is best developed north of the Emery field. Cotter (1975a, b, 1976) has elucidated this relation. Hale

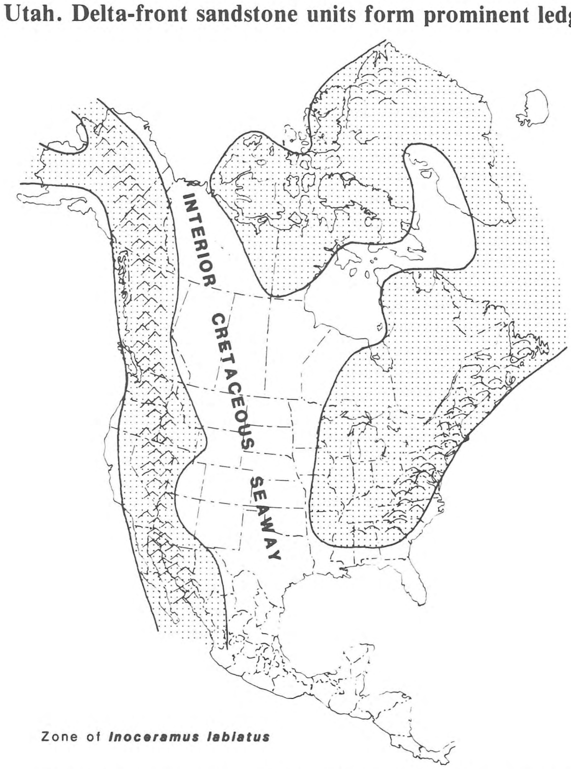


FIG. 3—Paleogeography of Interior Cretaceous seaway of western North America at peak transgression in early Turonian time. (Modified from Williams and Stelck, 1975.)

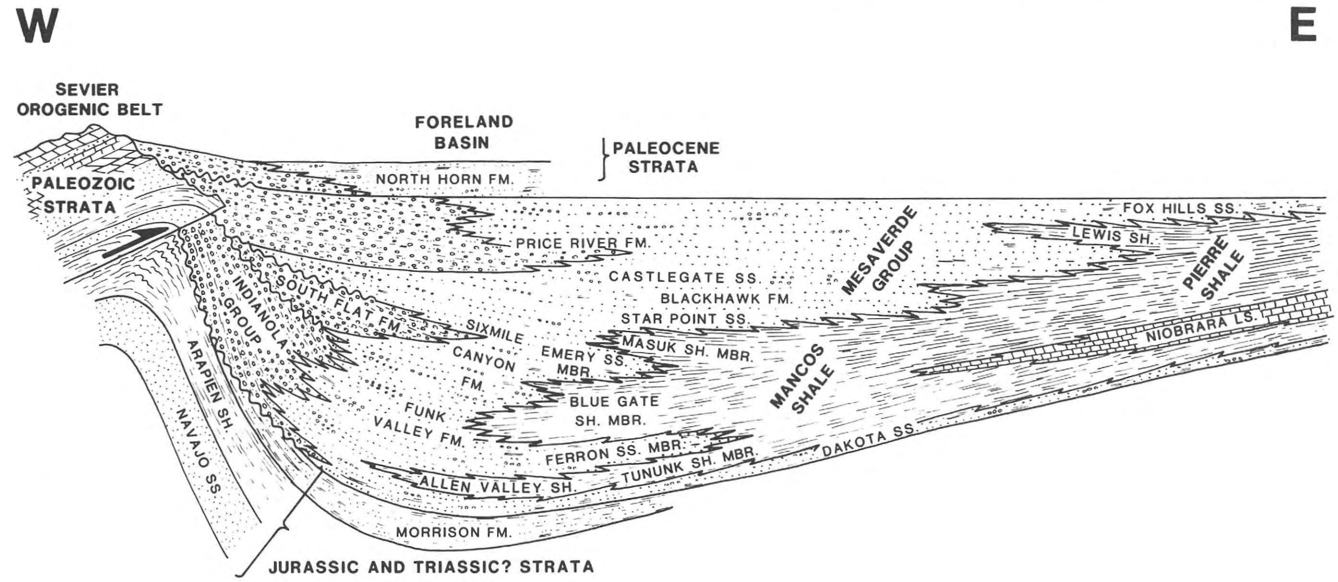


FIG. 4—Diagrammatic, restored west-east cross section of Cretaceous strata extending from western Utah to western Colorado. (Modified from Armstrong, 1968.)

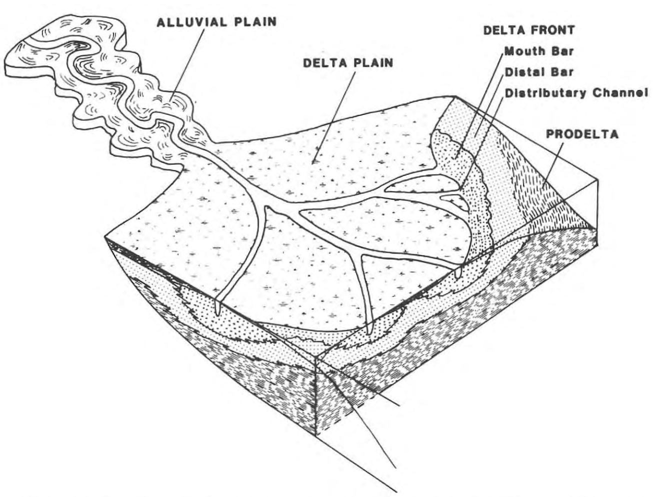


FIG. 5—Facies of lobate, river-dominated delta. (Modified from Fisher et al, 1969.)

(1972), utilizing subsurface data from oil and gas tests, published a regional interpretation of the depositional history of the Ferron Sandstone Member. The Emery coalfield is in the southernmost part of Hale's study area.

The Ferron Sandstone Member in the Emery coalfield is the product of episodic northeastward progradation of a lobate, river-dominated deltaic system. Broadly defined facies in a deltaic system of this type are shown in Figure 5. As a delta progrades seaward, the more landward facies come to overlie the more seaward facies in a progradation sequence. An idealized progradational sequence for the Ferron Sandstone Member is shown in Figure 6.

Cotter (1975a) described the deltaic facies of the Ferron Sandstone Member in considerable detail and compared them with analogous facies of several modern deltas. Inasmuch as my observations and interpretations agree with Cotter's, a detailed redescription of the facies of the Ferron here is unwarranted. The following is a brief description of facies (Fig. 6), emphasizing those features that substantiate the interpretation of the Ferron as a river-dominated, lobate deltaic system.

Prodelta—Prodelta deposits of the Ferron consist of interbedded mudstone and very fine to fine-grained sandstone (Fig. 7). The number and thickness of sandstone beds increase upsection. The sandstone beds are generally planar laminated and have abrupt lower contacts that commonly display evidence of minor erosion. Long-crested oscillation ripples and ripple drift lamination are commonly present in the upper parts. Bioturbation in the prodelta facies is generally sparse. The most common burrow types are *Ophiomorpha* and *Thalassinoides.*

Delta front—The laterally continuous, cliff-forming sandstone units of the Ferron Sandstone Member (Fig. 2) accumulated in the delta-front environment. The units consist of very fine to medium-grained sandstone with minor interbeds of mudstone and typically range from about 15 to 25 m in thickness. Though the thickness of a particular delta-front sandstone changes only gradually along the outcrop, the sequence of sedimentary structures in the sandstone may change dramatically over short distances. These rapid lateral changes are related to the proximity of contemporaneous distributary channels within the deltaic system.

At most localities, the delta-front sandstones can be divided into distal bar and distributary mouth bar subfacies. Deposits of the distal bar consist of very fine to fine-grained, planar-laminated sandstone with minor interbeds of mudstone. Some hummocky cross-stratifi-

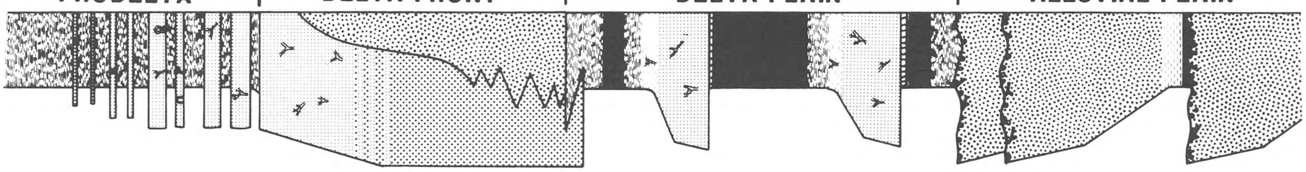


FIG. 6—Idealized progradational sequence for Ferron Sandstone Member.

FIG. 7—Interbedded sandstone and mudstone of prodelta facies. Sandstone bed at middle of photo displays oscillation ripples.

cation is present; bioturbation is sparse. Bedding planes dip gently seaward. Very fine to medium-grained sandstones of the distributary mouth bar are characterized by trough cross-stratification. Transport directions are variable but are generally seaward. Biogenic structures are rare. Just seaward of active distributary channels, the distributary mouth bar deposits are thicker than normal and display large, complicated cut and fill structures (Fig. 8). The delta-front sandstones are locally cut by distributary channels (Fig. 9). The largest distributary channel observed on the outcrop was 15 m deep and about 100 m wide. Following abandonment, the distributaries were filled with trough cross-stratified sandstone, interbedded sandstone and mudstone, or carbonaceous mudstone.

Delta plain—The delta-plain facies of the Ferron includes a variety of subfacies. Most distinctive are extensively bioturbated mudstones and siltstones deposited in brackish water bays. These deposits commonly contain oysters, corbiculid, corbulid, and mytilid bivalves, and a variety of gastropods. The bay deposits are commonly capped by upward coarsening crevasse splay sequences of laminated siltstone and ripple drift cross-laminated sandstone. The tops of the splay sequences are commonly root penetrated and overlain by carbonaceous shale or coal. The major coal beds of the Emery coalfield are associated with the delta-plain facies though, as discussed later, the areas of peat accumulation may later have become isolated between river channels of the alluvial plain as the deltaic system prograded. Abandoned fills of nonsinuous distributary channels are common in the delta-plain facies. The channel fills are plano-convex lens shaped in section perpendicular to the direction of flow and may be filled with sandstone, siltstone, or shale. Flanking the channels are levee deposits consisting of bioturbated, very fine-grained sandstone and siltstone.

Alluvial plain—The alluvial-plain facies is characterized by fining-upward sequences of coarse to very fine-grained sandstone that record accumulation of sediment on the point bars of meandering river channels (Fig. 10). The sandstones of the point bar sequences are trough cross-bedded. At the bases of the channels are lag deposits composed of chips and pebbles of claystone and some carbonized logs. The size of the bed load material becomes coarser in the most landward part of the deltaic system, where the channels commonly contain coarse sandstone with granules of quartz and chert. The point bar sequences range up to about 12 m in thickness. Thicker fluvial sandstone units, up to about 30 m thick, are the result of vertical stacking of point bar sequences. Laterally migrating channels have eroded much or all of the preexisting delta-plain facies in some areas. There, alluvial channel sequences may rest erosionally upon a delta-front sandstone unit. Also present in the alluvial facies are levee deposits and beds of mudstone, carbonaceous shale, and coal deposited in flood basins. The coal beds of the alluvial facies are generally thin and laterally discontinuous.

Transgressive deposits—Progradation of the Ferron deltaic system was interrupted several times by transgressions of the shoreline. Associated with the erosional surfaces developed during these transgressive episodes are transgressive lag deposits. These deposits vary greatly in character and are thin or absent at most localities. The thickest transgressive unit observed on the outcrop reaches 2 m in thickness and is shown in Figure 11. It directly overlies the C coal bed of the Emery coalfield and is overlain by prodelta deposits of the next delta cycle. The unit consists of intensively bioturbated, poorly sorted, silty sandstone. Fragments of coalified peat, eroded from the underlying C coal bed, are abundant in the lower part. Logs bored by *Teredo*-like bivalves are also present. Numerous sand-filled burrows extend downward from the base of the deposit into the top of the coal bed. Locally, the erosional surface beneath the transgressive deposit descends to the level of a layer of altered volcanic ash contained in the C coal bed (the "thick" parting described by Ryer et al (1980). Here, rotated and partly rounded blocks of kaolinitic claystone from the altered ash layer are incorporated into the base of the transgressive lag. Other transgressive deposits consist of planar laminated, moderately bioturbated, very fine to medium-grained sandstone. In most places, the transgressive deposits consist of only a few centimeters of poorly sorted, intensely bioturbated sandstone. Volumetrically, they form an insignificant part of the Ferron Sandstone Member.

The outcrop of the Ferron Sandstone Member is approximately parallel with the depositional dip; the width of the outcrop belt, parallel with the depositional strike, reaches a maximum of only about 4 km. As a result, it is impossible to distinguish the shapes of individual delta lobes within the Ferron deltaic system. A variety of evidence, however, can be used to determine the basic geometry of the deltas.

1. Bioturbation within the prodelta and delta-front facies is generally sparse, indicating that rates of sediment accumulation were sufficiently rapid to preclude complete homogenization of sediment by the burrowing infauna.

2. Shoreface sequences (Clifton et al, 1971; Howard and Reineck, 1972, 1981), the result of sedimentation along wave-dominated coastlines, are rare in the Ferron, being only locally present in the southernmost part of the Emery coalfield. Wave energy, however, was sufficient to produce laterally continuous delta-front sheet sands.

3. The delta-front sandstones of the Ferron consist primarily of distal bar and mouth bar deposits and are

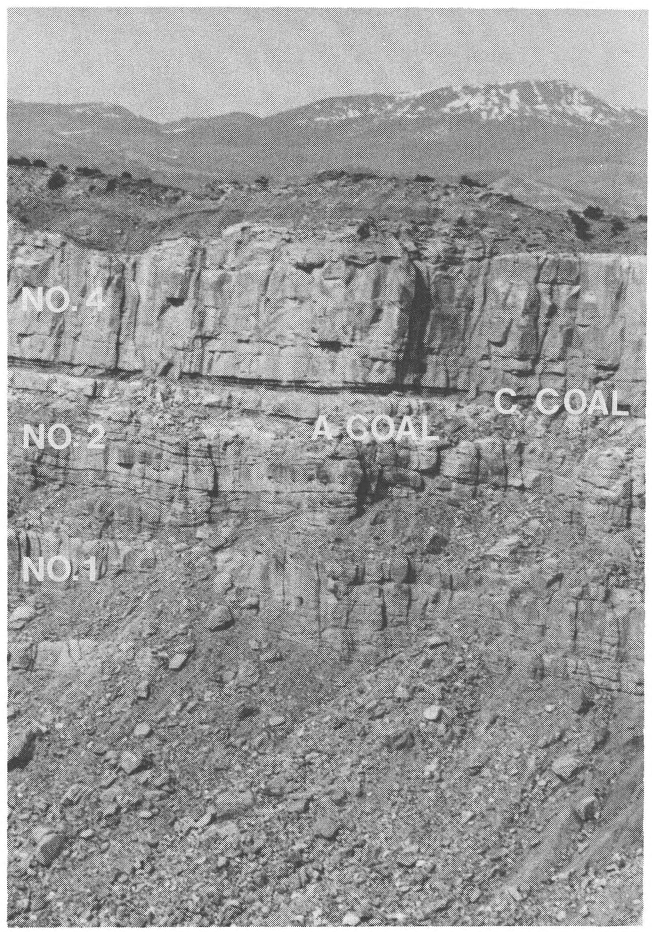


FIG. 8—Exposure of Ferron Sandstone Member southeast of Emery shows Nos. 1, 2, and 4 delta-front sandstones, plus A and C coal beds of Emery coalfield. No. 2 delta-front sandstone displays complicated cut and fill structures characteristic of mouth bar deposits seaward of active distributaries. Small distributary channel filled with mudstone cuts top of No. 4 delta-front sandstone.

cut by nonsinuous distributary channels.

4. The delta-plain facies contains many nonsinuous distributary channels and the deposits of brackish water bays. Though the development of brackish water bays suggests tidal exchange of water, there is no evidence for strong tidal influence.

5. The alluvial-plain facies consists primarily of the deposits of meandering river channels.

These criteria are all consistent with those of modern lobate, river-dominated delta systems (Galloway, 1975; Coleman, 1976).

As is evident from the preceding discussion, the Ferron Sandstone Member consists not of a single prograded delta but of a series of deltaic systems stacked one above another. The basic cross-sectional geometry of each of the deltaic systems in the direction of depositional dip is shown in Figure 12. With the exception of the earliest system, which gradationally overlies the Tununk Shale Member, each deltaic system is underlain and overlain by erosional surfaces associated with preceding and succeeding transgressions. These prograded deltaic systems, each consisting of a series of coalesced delta lobes, plus their associated transgressive disconformities, define cycles of deltaic sedimentation. Cyclicity may be the result of autocyclic (Beerbower, 1964) processes within the fluvial-deltaic system, chief among them being the processes of river avulsion and delta switching. Cotter (1975a) cited the cyclic nature of progradation as further evidence that the delta was lobate and river dominated, thereby implying autocyclic control. Another possibility is that the transgressions are responses to episodic subsidence within the foreland basin.

Figure 13, a diagrammatic cross section of the Ferron Sandstone Member in the vicinity of the Emery coalfield, shows the basic stratigraphic framework of the Ferron (Ryer, 1981a, b). The Ferron consists of five major cycles of deltaic sedimentation. The delta-front sandstone units, which serve to define the cycles, are labeled numerically in ascending stratigraphic order. Each cycle includes one major coal bed or coal zone. Minor coal beds, most of which are locally developed rider coal beds associated with the major beds, are not shown in Figure 13. The coal beds are labeled alphabetically, in ascending stratigraphic order according to the scheme proposed by Lupton (1916). The I coal bed is split in a landward direction by a wedge of predominantly alluvial strata. The lower and upper

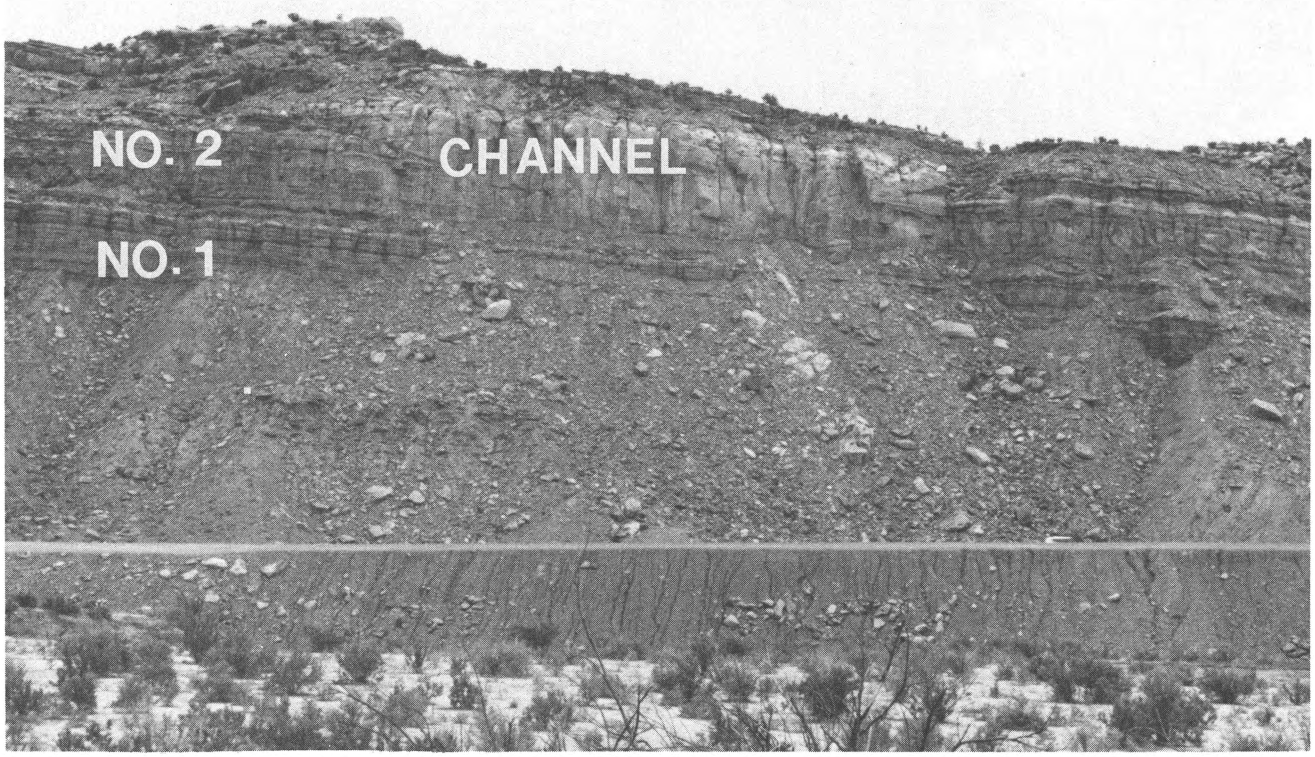


FIG. 9—Sandstone-filled distributary channel cutting No. 2 delta-front sandstone. Thin coal zone lies between No. 1 and No. 2 delta-front sandstones at this locality just south of Interstate 70.

subseams of the coal bed are designated I_1 and I_2, respectively.

Southwestward transgression of the sea across the top of the deltaic complex at the close of Ferron deposition was rapid but was interrupted by several brief periods of northeastward progradation of the shoreline. The progradational, shallow-marine sandstone units that accumulated at these times extend only a few kilometers seaward. Coal, generally in thin, localized beds, and carbonaceous shale are associated with these minor progradational events. One of these, the J coal bed (Fig. 13), is thick enough to be of economic value.

LANDWARD PINCH-OUTS OF DELTA-FRONT SANDSTONES AND ESTABLISHMENT OF SHORELINE TRENDS

Each delta-front sandstone of the Ferron, together with its associated prodelta deposits, may be regarded as a unit having the general configuration of a parallelogram in a section parallel with the depositional dip (Fig. 12). Tracked in a landward direction, the prodelta, distal bar, and mouth bar deposits successively thin and pinch out against the erosional, disconformable surface that defines the base of the unit. The landward pinch-out of the delta-front sandstone against delta-plain or alluvial-plain deposits of the previous cycle marks the point of maximum transgression of the shoreline during the transgressive or delta-destructive phase that separated the two phases of deltaic progradation. Where the pinch-out of an individual delta-front sandstone unit can be observed at two or more localities along depositional strike on outcrops or recognized in the subsurface, the trend of the shoreline at maximum transgression can be established. The shoreline trends of the Ferron deltaic sandstones, recognized in this way, are approximately northwest, which agrees with the shoreline trend established for the area by regional study of the Ferron Sandstone Member and its lateral equivalents (Hale, 1972; paleogeographic maps, McGookey, 1972). The landward pinch-out of the No. 2 delta-front sandstone on an exposure in the southern part of the Emery coalfield (Fig. 1) is shown in Figure 14.

In areas where channels of the alluvial facies have eroded the upper parts of the delta-front sandstones, it is not possible to observe the landward pinch-outs, and their positions must be estimated. The landward pinch-out of the No. 4 sandstone on the outcrop is obscured in this way, and it was necessary to locate it approximate-

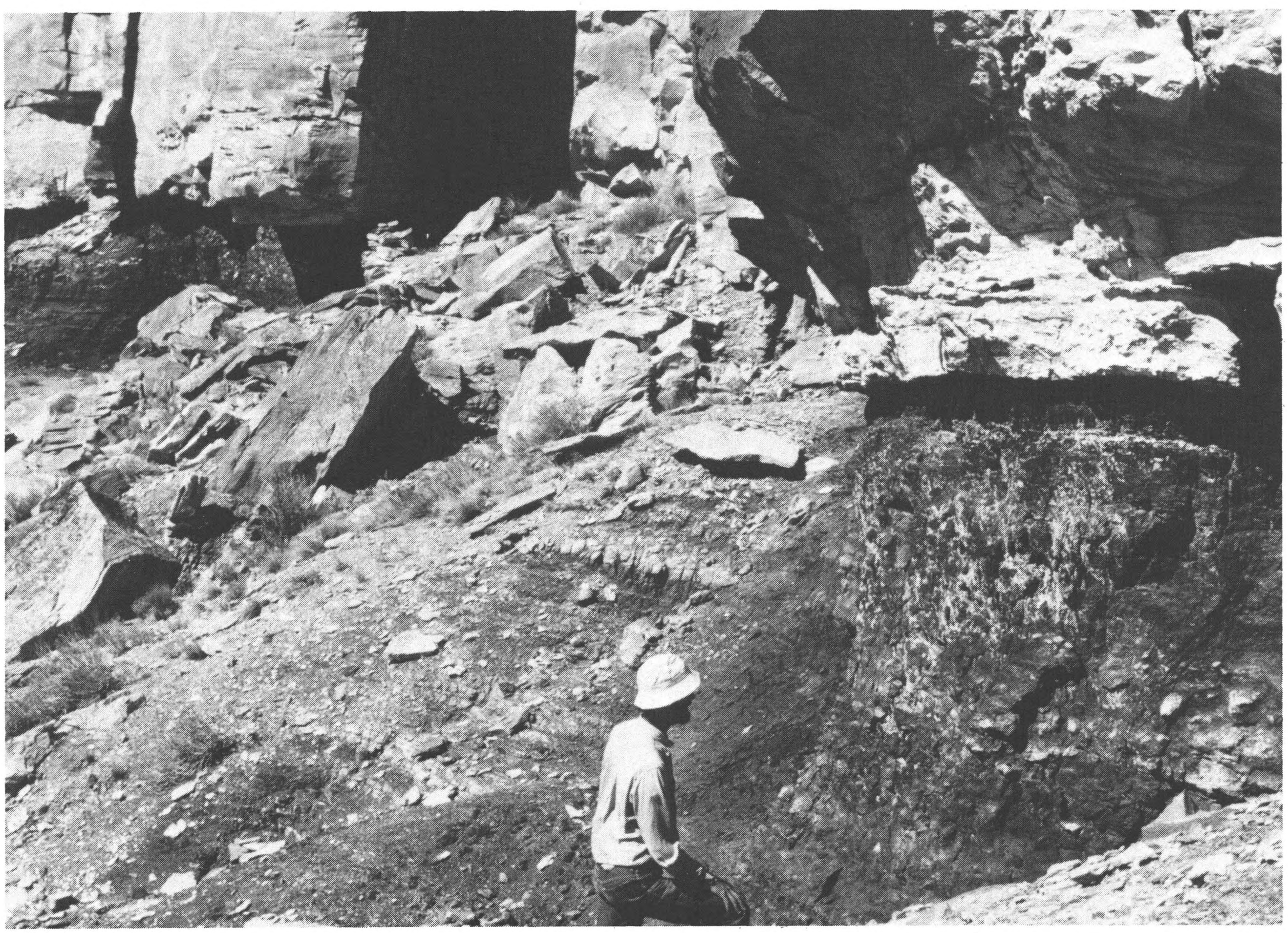


FIG. 10—Sandstone, representing active filling of meandering channel of alluvial facies, erosionally overlies bioturbated, carbonaceous siltstone of delta-plain facies.

ly. Fortunately, the trend of this pinch-out downdip from the outcrop could be defined using subsurface data.

MAJOR COAL BEDS OF EMERY COALFIELD

A clear genetic relation exists between the geometries of the major coal beds of the Emery coalfield and the geometries of their associated delta-front sandstones. This relation is illustrated in Figures 15-19. The isopach maps in these figures were constructed using proprietary subsurface data augmented by outcrop measurements. To protect the confidentiality of the subsurface data, no information is shown that could be used to precisely locate the data points. These are total coal isopach maps, showing the thicknesses of the major coal beds, less any rock splits, plus the thicknesses of rider seams; they do not show minable seam thicknesses. Several thin, localized coal beds in the Ferron could not be related to any major coal bed with certainty, and therefore have not been included in the analysis. Their inclusion would not significantly alter the picture presented here. The coal beds are discussed individually in descending stratigraphic order. Though opposite to the order of deposition of the coal beds, this order of discussion allows progression from simpler to more complex situations.

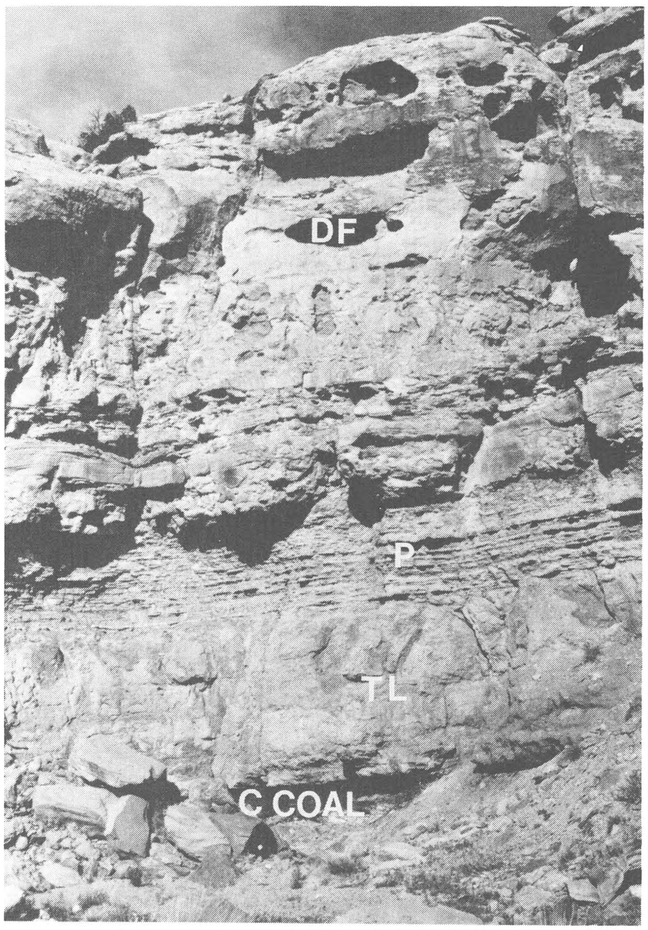


FIG. 11—Transgressive lag deposit (TL) overlies C coal bed with erosional contact. Prodelta (P) and delta-front (DF) deposits of No. 4 delta cycle overlie transgressive lag.

The J coal bed (Fig. 15) is the product of peat accumulation during one of the minor progradational events that interrupted the southwestward transgression of the sea across the Ferron deltaic complex. The coal bed only locally exceeds 2 m in thickness. The thicker part of the bed, "thicker" being arbitrarily defined as equaling or exceeding half the value of the greatest isopach line mapped on the bed, extends from a position approximately 3 km seaward of the landward pinch-out of the associated marine sandstone to a position approximately 11 km landward of the pinch-out. The body of thicker coal is elongate, the direction of elongation being nearly normal to the trend of the pinch-out of the marine sandstone.

The I coal bed (Fig. 16) is, economically, the most important bed in the Emery coalfield. It attains a maximum thickness of about 10 m. The thicker coal (greater than 5 m) occurs in an elongate body that extends from a distance of approximately 2 km to a distance of approximately 11 km landward of the landward pinch-out of the No. 5 delta-front sandstone. The elongation of the coal body, like that of the body of thicker J coal, is nearly normal to the trend of the pinch-out. The relation of the channel system that is indicated in the northeastern part of the area is unclear because the outcrops in the vicinity of the channel deposits have been disturb-

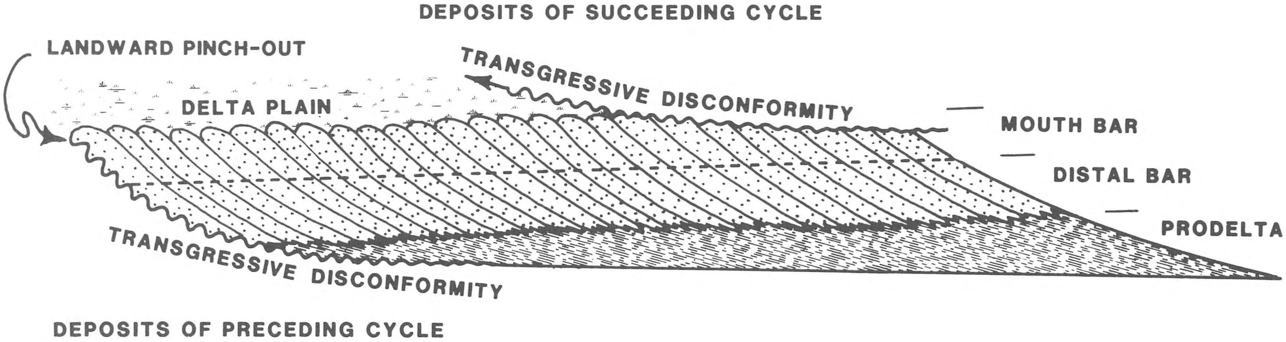


FIG. 12—Diagrammatic section, parallel with depositional dip, through deposits of deltaic cycle showing bounding transgressive disconformities and landward pinch-out of delta-front sandstone unit.

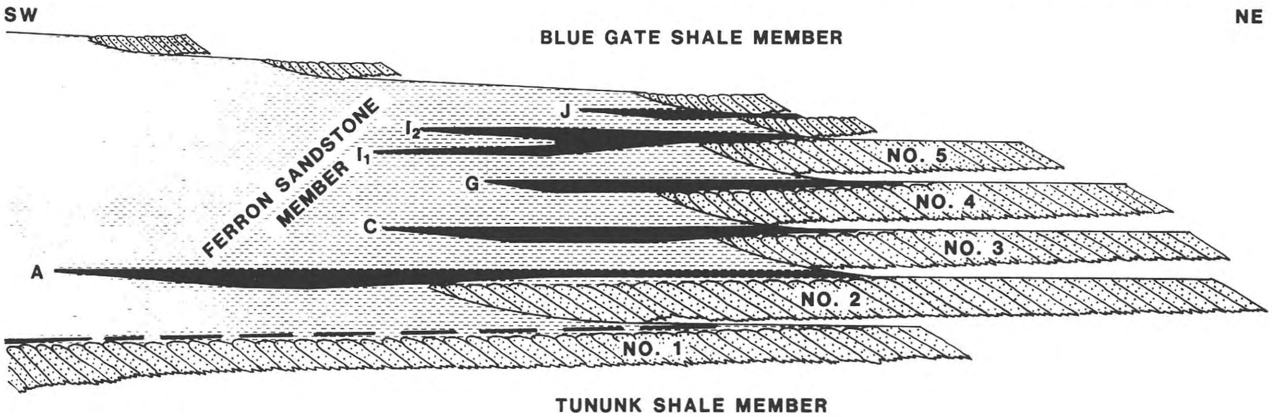


FIG. 13—Diagrammatic cross section of Ferron Sandstone Member in vicinity of the Emery coalfield. Delta-front sandstone units are labeled numerically, major coal beds alphabetically. Undivided alluvial- and delta-plain deposits are indicated by horizontal dashed pattern.

ed by natural burning of the I coal bed. It is probable that the channel system, which is represented by a series of stacked point bar sequences totaling 25 to 30 m in thickness, was at least partly contemporaneous with the swamp that produced the I coal bed. The channel system was abandoned prior to accumulation of the J coal bed.

The G coal bed (Fig. 17) only locally exceeds 2 m in thickness. The thicker (greater than 1 m) part of the coal bed extends from approximately 2 km seaward of the landward pinch-out of the No. 4 delta-front sandstone to at least 11 km landward of the pinch-out. If the thicker coal body has a direction of elongation, it is not apparent from the available data.

The C coal bed (Fig. 18) locally exceeds 6 m in thickness. The thicker part of the coal bed (greater than 3 m) extends from approximately 1 km landward of the landward pinch-out of the No. 3 sandstone to approximately 10 km landward of the pinch-out. The area of thicker coal parallels the trend of the pinch-out of the No. 3 sandstone but can be subdivided into two bodies by the convergence of the 3-m isopach lines in the north-central part of the mapped area. The shape of the northwesternmost of these two bodies cannot be clearly discerned because of the small number of drill holes that have penetrated it. Coal exceeds 5 m in thickness in two small areas within the well-defined southeasterly body. A line passing through these two areas of thickest coal intersects the trend of the pinch-out of the No. 3 sandstone at approximately a right angle.

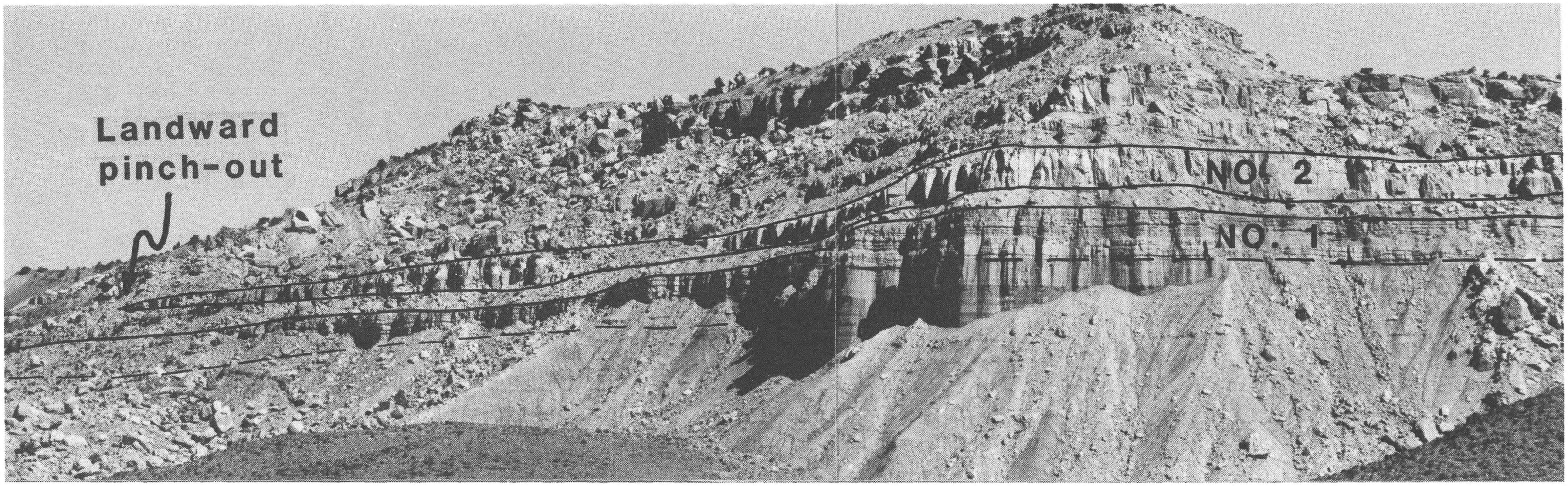
The A coal bed (Fig. 19) is, by far, the most widespread of the coal beds in the Emery coalfield. This reflects the fact that the No. 2 delta-front sandstone, with which it is associated, has a much greater lateral extent parallel with the depositional dip than do the succeeding delta-front sandstones (Fig. 13). The coal bed locally exceeds 5 m in thickness. The thicker coal (shown in Figure 19 as coal exceeding 2 m in thickness, no 2.5-m contour having been mapped) occurs in three larger and one smaller bodies. One of the larger bodies is associated with the landward pinch-out of the No. 2 delta-front sandstone, following the pattern of the stratigraphically higher coal beds. This coal body extends from approximately 2 km seaward of the pinch-out to approximately 8 km landward of the pinch-out. As mapped in Figure 19, it is elongate perpendicular to the trend of the pinch-out of the No. 2 sandstone. The distribution of control points, however, is such that a different configuration is possible. The other two of the larger bodies of thicker coal occur between approximately 2 and 9 km seaward of the landward pinch-out of the No. 2 sandstone. The northernmost of these bodies is elongate at a high angle to the trend of the pinch-out; the other shows no elongation.

A zone containing carbonaceous shale and thin beds of coal is associated with the No. 1 delta-front sandstone. A maximum observed coal thickness of about 1 meter occurs in a bed in the southernmost part of the Emery coalfield. Lupton (1916) miscorrelated this coal bed with the A coal bed, which pinches out several kilometers to the north. The thin, localized coal beds of this zone were not isopached. No landward pinch-out of the No. 1 sandstone can be observed, the No. 1 sandstone being covered by Tertiary volcanic rocks at the south end of the outcrop of the Ferron Sandstone Member (Williams and Hackman, 1971).

PREDICTIVE MODEL

A body of thicker coal is associated with each of the landward pinch-outs of the delta-front sandstones of the Ferron Sandstone Member in the Emery coalfield. The coal bodies extend about 10 km landward from the vicinities of the pinch-outs. This is also true for the minor marine sandstone unit associated with the J coal bed. This relation was used to construct the simple model shown in Figure 20. The model has predictive value in coal exploration: landward pinch-outs of the major delta-front sandstones within a deltaic complex can be located and their trends established; the probability is high that bodies of thicker coal will occur within belts that parallel these pinch-outs, each belt be-

(Left half)



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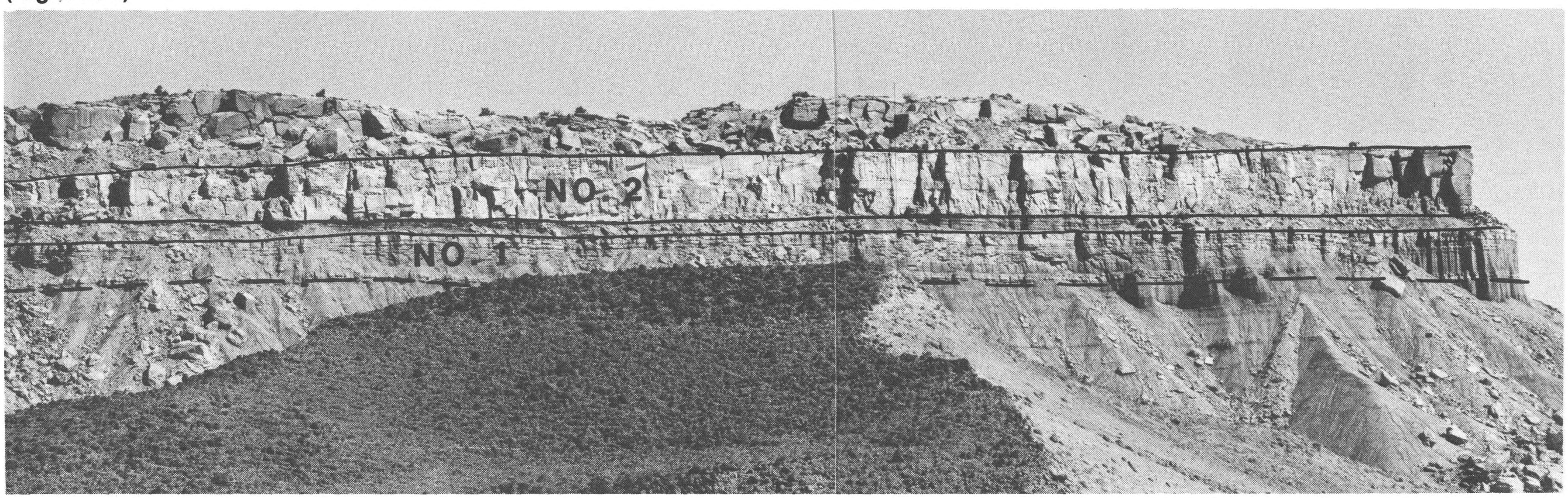

FIG. 14—Landward pinch-out of No. 2 delta-front sandstone of Ferron in southern part of Emery coalfield. Basal contact of No. 2 sandstone is erosional, resting on coal zone associated with No. 1 sandstone. Contact between No. 1 sandstone and underlying Tununk Shale Member is transitional.

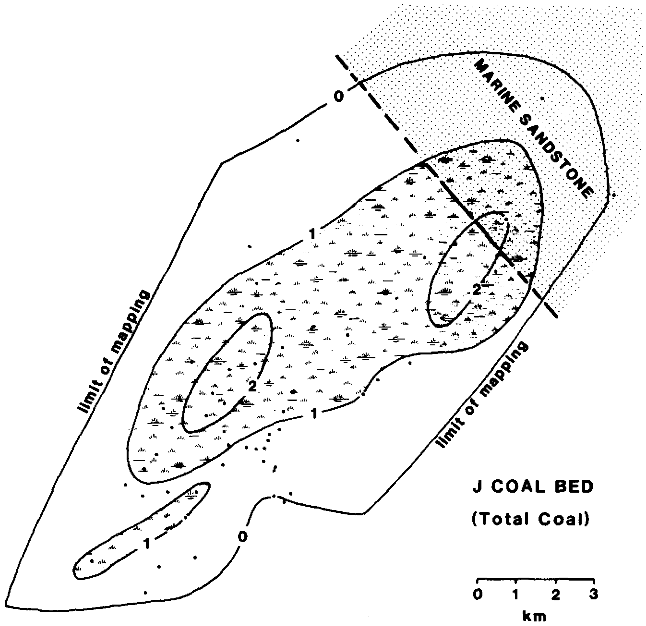

FIG. 15—Isopach map of J coal bed of Emery coalfield. In this and following figures: isopach lines are at 1-m intervals; north is toward top of figure, areas of thicker coal are indicated by swamp pattern, and landward pinch-out of associated marine sandstone or delta-front sandstone is indicated by northwest-trending line, which is solid in vicinity of outcrop. (Refer to Figure 1 for locations of pinch-outs.)

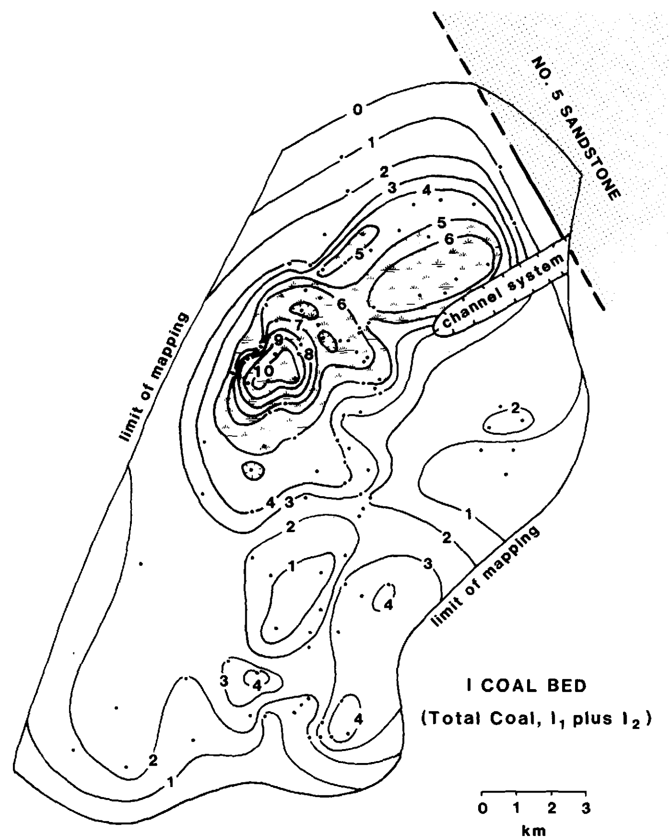

FIG. 16—Isopach map of I coal bed, the most economically important coal bed of Emery coalfield.

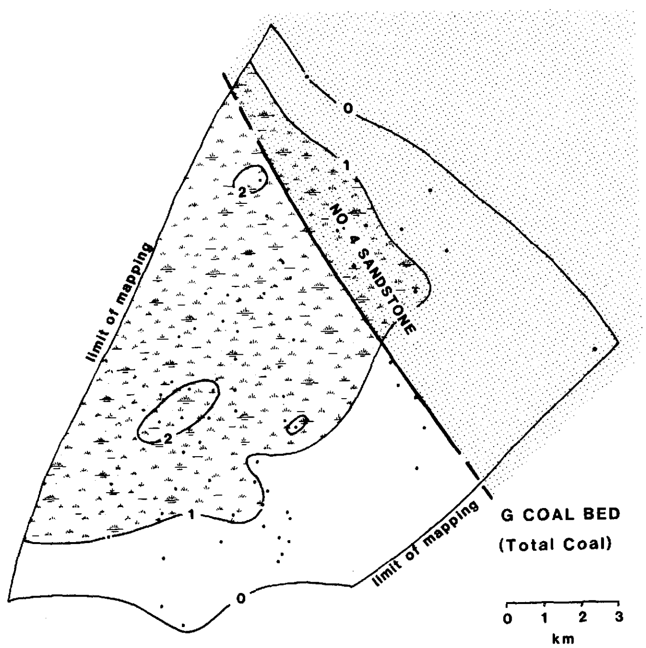

FIG. 17—Isopach map of G coal bed of Emery coalfield.

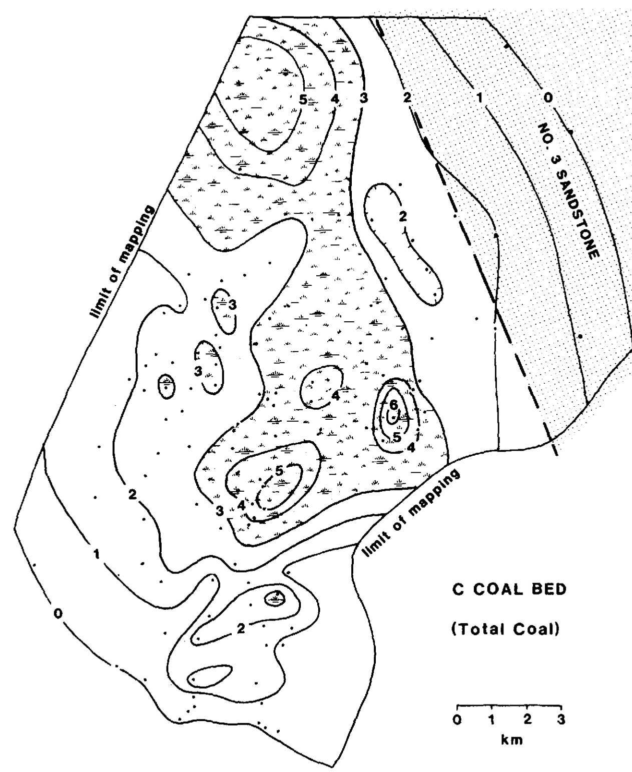

FIG. 18—Isopach map of C coal bed of Emery coalfield.

ing about 10 km in width and extending landward from its associated pinch-out.

Why does this relation between coal thickness and location of pinch-outs exist? The reasons are not entirely clear, though two contributing factors may be (1) the fact that the delta-front sandstones show evidence of stratigraphic rise during progradation, and (2) the effects of early compaction of fine-grained and organic-rich sediments.

Stratigraphic Rise

Units consisting of the combined prodelta and delta-front facies of the Ferron Sandstone Member thicken seaward from their landward pinch-outs by progressive addition of strata at the bottom of each unit (Fig. 12). On outcrops, this is most easily discerned as seaward thickening of the prodelta facies. The rate of thickening exceeds that which would be expected had the deltas simply prograded, at constant relative sea level, across the gently seaward-dipping to horizontal surfaces developed during the preceding transgressions. The uppermost parts of the delta-front sandstones commonly interfinger, on a small scale, with strata of the delta plain facies (Fig. 6). The seaward thickening of the combined prodelta and delta-front units and their interfingering with delta-plain deposits indicate that relative sea level, or "base level," rose during the period of time represented by the progradational phase of each of the deltaic cycles. This rise of relative sea level, expressed as seaward stratigraphic rise of facies contacts within the progradational sequences, reflects continuous subsidence within the basin of deposition, local subsidence produced by loading and compaction of underlying sediments, or both.

Deposits of the delta plain accumulate at or near sea level. Unlike the delta-front strata, which record lateral accretion of sediment on the seaward-dipping delta front (Weimer, 1970), delta-plain deposits record principally vertical accumulation of sediment (splays and active channel fills being exceptions).

Because of these facts, the upper delta-plain facies thins seaward within a depositional cycle (Fig. 21a). The thickest delta-plain deposits tend to be associated with the landward pinch-outs of the delta-front sandstones. These were the areas where delta-plain sediments were initially deposited during the first stages of progradation and also the areas where vertical accumulation of these sediments could occur for the longest periods of time. The thicker coal bodies of the major coal beds of the Ferron occur primarily within the delta-plain facies. The same argument may be applied to them—the greatest thicknesses of peat (and therefore coal) would be expected in the areas just landward of the pinch-outs. However, delta-plain deposits in these areas are prone to erosion by meandering channels of the seaward advancing alluvial plain facies. Conversely, erosion of delta-plain deposits from the more distal parts of a delta system during the succeeding delta-destructive phase accentuates the seaward thinning of the delta-plain facies.

Compaction of Sediments

All sediments undergo compaction during their trans-

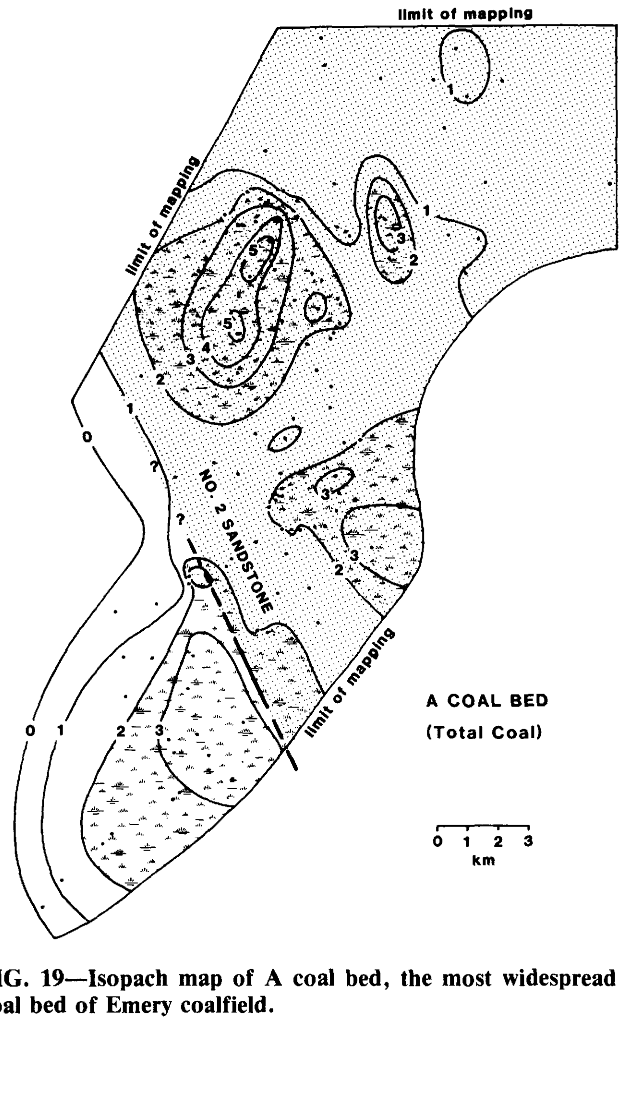

FIG. 19—Isopach map of A coal bed, the most widespread coal bed of Emery coalfield.

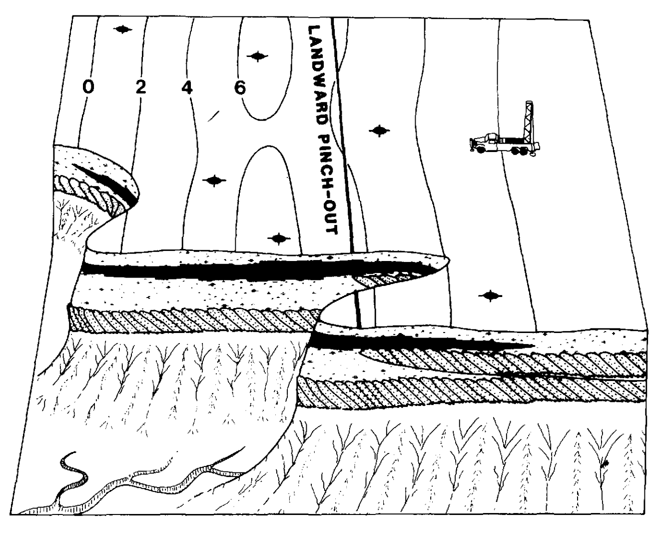

FIG. 20—Simple predictive model showing relation between coal thickness and location of pinch-out of delta-front sandstone.

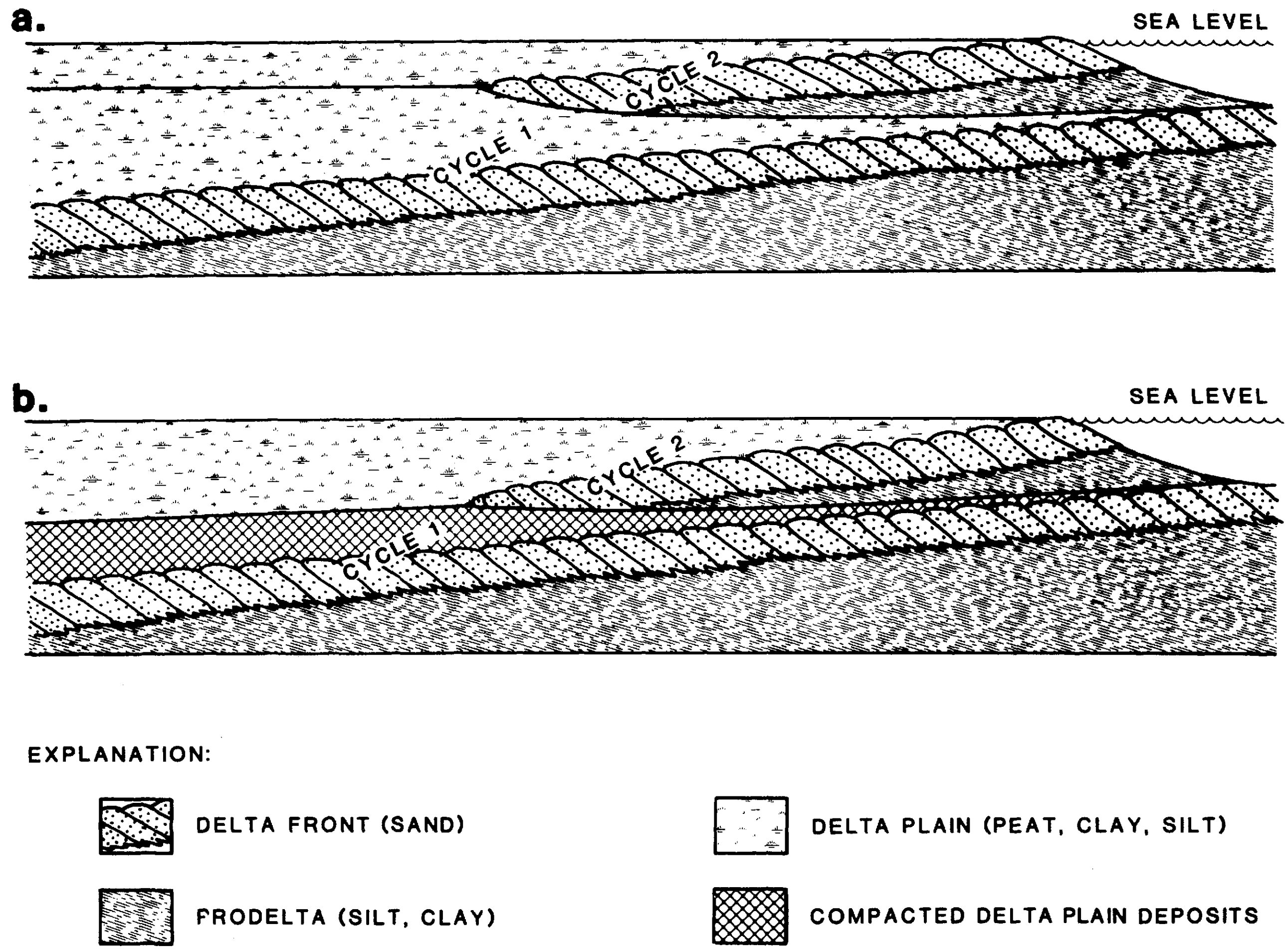

FIG. 21—Diagram showing effects of (a) stratigraphic rise during progradation, and (b) early compaction of fine-grained and organic-rich sediments.

formation to sedimentary rocks (Weller, 1959). The compaction begins early in the history of burial (Conybeare, 1967). Of the sediments present in a deltaic system like that represented by the Ferron, well-sorted sands and peat represent the minimum and maximum extremes in terms of compactibility. The sand-to-sandstone transformation involves little or no compaction; the peat-to-coal transformation involves a compaction ratio of about 10:1 (Ryer and Langer, 1980). Delta-plain deposits contain large amounts of peat, plus organic-rich clays and silts that are also susceptible to compaction.

The landward pinch-outs of the delta-front sandstones most commonly overlie, with erosional contacts, delta-plain strata of the preceding delta cycle. This provides another mechanism that can accentuate the thickening of delta-plain deposits in the vicinities of the pinch-outs (Fig. 21b). Deposits of two cycles are shown. The landward pinch-out of the second cycle occurs within delta-plain deposits of the first cycle. If, during the period of time represented by the second cycle, the fine-grained and organic-rich deposits of the first cycle undergo compaction, a greater-than-expected thickness of delta-plain sediments can accumulate in the vicinity of the landward pinch-out of the delta-front sandstone. Compaction of the delta-front sandstone seaward of the pinch-out is negligible.

These two mechanisms, stratigraphic rise during progradation and early compaction of sediments, both favor the accumulation of thick bodies of peat in the vicinities of and just landward of the landward pinch-outs of the delta-front sandstones. The former is probably the more important of the two mechanisms.

EFFECTS OF CHANNELS AND A MORE REFINED MODEL

The predictive model shown in Figure 20 is too simple; it does not provide for the elongation of the thicker coal bodies, as observed in Figures 15, 16, 18, and 19, parallel with depositional dip.

The C coal bed, because it is very well exposed on the outcrops and because it contains distinctive beds of altered volcanic ash that can be correlated over the lateral extent of the bed, is probably the best understood of the coal beds in the Emery coalfield. The depositional history of the C coal bed is described elsewhere (Ryer et al, 1980) and will only be summarized here.

The C coal bed (Fig. 18) illustrates the shortcomings of the simple model. As predicted by the model, an area of thicker coal is associated with, and generally parallels, the landward pinch-out of the No. 4 delta-front sandstone, but that area can be divided into two bodies of thicker coal. The shape of the southeasternmost body is controlled by channel systems that were partly contemporaneous with accumulation of the peat.

The depositional history of the C coal bed is shown in Figure 22. Two fluvial channel systems are shown feeding sediment to the delta front of the No. 3 delta (Fig. 22a-c). The southeasternmost (closer) channel system can be examined on the outcrops; the other is known only from subsurface data. Outcrops of the southeasternmost channel system display one or, more commonly, a series of stacked point bar sequences, indicating that these strata accumulated within the alluvial-plain facies, where the channels were highly sinuous and meandering. Because the two channel systems are separated by a distance of only a few kilometers, it is highly unlikely that they represent two different, contemporaneous rivers. It is believed, instead, that a single river repeatedly occupied these two systems, switching from one to the other, and probably to additional systems spaced along the depositional strike, by avulsion. Peat that would eventually produce the southeasternmost thicker coal body of the C coal bed accumulated in the area between the two channel systems. Peat, unlike sands and silts deposited by a meandering channel, is a fibrous, cohesive material that resists erosion. Once a bed of peat has accumulated, it is unlikely that a new channel system can be developed across it by river avulsion. Thus the placement of the channels controls the location of initial peat accumulation, and the peat then keeps the courses of the channel systems fixed. Channel systems that postdate peat accumulation can and do erode peat beds; they produce the sand rolls or cutouts that cause localized erosional thinning of coal beds, and which often create problems in mine planning and development. It is the channels that exist contemporaneously with peat accumulation, however, that exert the greatest influence upon the configurations of coal beds. Because the positions of channel systems along the depositional strike in an area like the Emery coalfield must, with few exceptions, be determined by drilling, only their general effects can be considered in the predictive model.

The predictive model, then, must be made to incorporate two elements: a predictable element—the location of areas of thicker coal relative to the landward pinch-outs of the delta-front sandstones; and, superimposed, a basically unpredictable element—the effects of channel systems, which isolate thicker bodies of coal. These two elements are shown in Figure 23. Figure 23b represents a more refined predictive model for deltaic coals of the Ferron Sandstone Member.

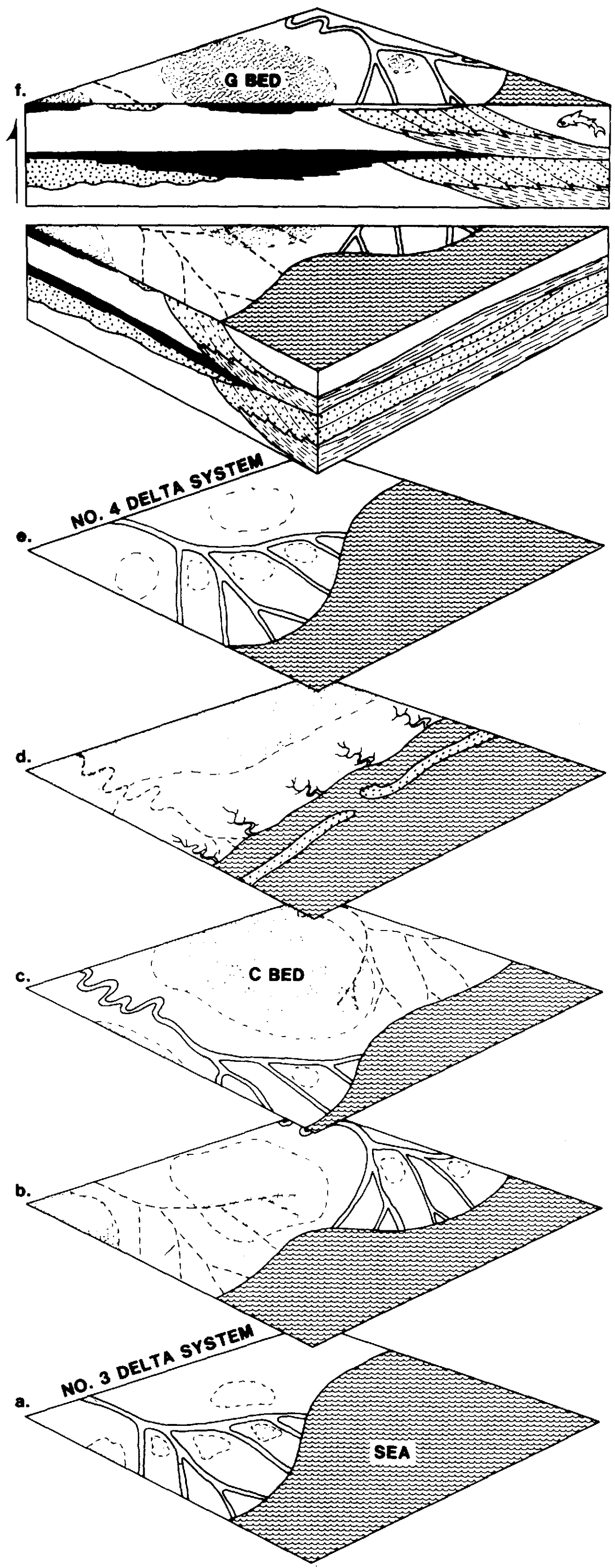

FIG. 22—Depositional history of C coal bed. View is toward west. Areas of most rapid peat accumulation are indicated by "scrub" pattern. Progradation of No. 3 deltaic system and accumulation of peat (a-c) in area between channel systems; (d) abandonment of No. 3 deltaic system and beginning of delta-destructive phase; (e-f) progradation of No. 4 deltaic system.

APPLICATION OF MODEL TO OTHER AREAS

The predictive model presented here and modifications of it should prove to be generally applicable to coal-bearing strata deposited along the western margin of the Interior Cretaceous seaway in North America and perhaps to similar rocks of other ages and in other areas.

The Ferron Sandstone Member in the vicinity of the Emery coalfield records stacking of the deposits of a lobate, river-dominated deltaic system under conditions of near balance between the rate of change of sea level and the rates of regional subsidence and sediment input (Ryer, 1981c). Speculations on modifications that might make the predictive model applicable to areas characterized by other sets of conditions follow.

Wave-Dominated Deposits

Most Cretaceous coal-bearing strata in the Western Interior represent wave-dominated paleoenvironments—wave-dominated deltas and strand-plain systems. The deposits of these paleoenvironments generally contain fewer channel systems than do the deposits of river-dominated deltas. This is particularly true of strand-plain deposits. In these deposits, segmentation of

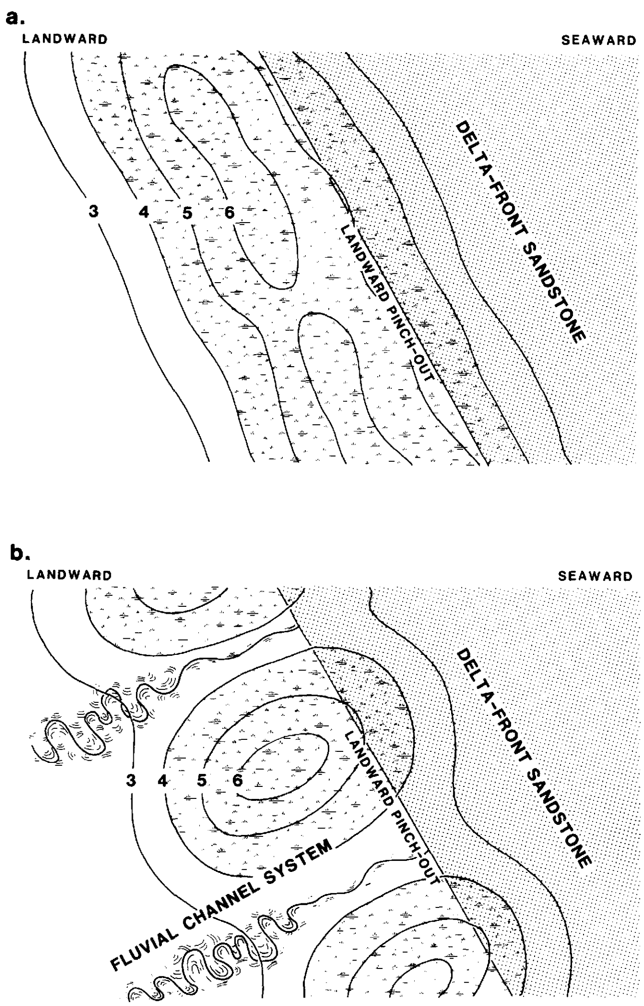

FIG. 23—Predictive model for Ferron Sandstone Member: (a) simple model as in Figure 20; (b) effects of fluvial channels; represents more refined model for Ferron.

the areas of thicker coal associated with landward pinch-outs into distinct coal bodies should be less pronounced or absent, and the simple model shown in Figures 20 and 23a should apply. An area that appears to conform to the simple model is the Kaiparowits coalfield of south-central Utah (Peterson, 1969; Vaninetti, 1979). Another possible example may be seen in the distribution of coals in the Rock Springs Formation in the Rock Springs coalfield of southwestern Wyoming (Roehler, 1978a, b).

Regressive Phase Deposits

Shoreline deposits of the regressive phases of the major Cretaceous transgressive-regressive cycles of the Western Interior (Kauffman, 1977), as exemplified by the Mesaverde Group in Utah (Fig. 4), locally display stacking of delta-front or shoreface units (Fassett and Hinds, 1971, p. 11) but are generally characterized by seaward shingling of units. As a result, individual progradational units generally have a much greater extent parallel with the depositional dip than do the delta-front sandstones of the Ferron. Coal beds are associated with the landward pinch-outs but also overlie the platforms provided by the prograded delta-front or shoreface sandstones. This pattern is exhibited by deposits of the No. 2 delta of the Ferron Sandstone Member. It has also been documented in the Wasatch Plateau and Book Cliffs coalfields, both in central Utah, by Marley et al (1979) and by Balsley (1980), respectively, and in the Rock Springs coalfield by Levey (1981). The model described here, though applicable to deposits of this type, cannot be used to predict the occurrences or locations of additional coal bodies that may overlie these shoreline sandstones. The occurrence of coal bodies in this stratigraphic position are expected in association with shoreline deposits that have prograded seaward a distance of 20 km or more.

Transgressive Phase Deposits

Strata deposited on the transgressive phases of the major transgressive-regressive cycles, as exemplified by the Dakota Sandstone in central and eastern Utah and western Colorado (Fig. 4), generally do not contain thick beds of coal, though there are exceptions: Almond Formation, Rock Springs coalfield, southwestern Wyoming (Roehler, 1976); Dry Hollow Member (Hale, 1960) of the Frontier Formation, Hams Fork coalfield, southwestern Wyoming (Veatch, 1907; Myers, 1977); Coalville Member (Hale, 1960) of the Frontier Formation, Coalville coalfield, north-central Utah (Doelling and Graham, 1972; Ryer, 1976); and the upper part of the Frontier Formation, Tabby Mountain coalfield, northeastern Utah (Doelling and Graham, 1972). When coal does occur, it is usually associated with minor episodes of progradation, like that represented by the J coal bed of the Emery coalfield and its associated marine sandstone. Such occurrences of coal bodies should conform to the predictions of the model. Coal beds in this stratigraphic position, though, were subject to erosion by landward advancing shorefaces during succeeding periods of transgression and, because they are commonly overlain by marine roof rocks, tend to be high in sulfur (Horne et al, 1978).

CONCLUSIONS

Depositional models have proven valuable in coal mine planning and development; they can also be valuable in coal exploration. In the Emery coalfield of central Utah, the thicker parts of the major coal beds are associated with the landward pinch-outs of the delta-front sandstones of the Ferron Sandstone Member, extending about 10 km landward from the vicinities of the pinch-outs (Figs. 15-19). This relation forms the basis of a predictive model (Figs. 20, 23) that may, with some modifications, be used in designing drilling programs to evaluate Cretaceous coal-bearing strata of the Western Interior. A coal exploration program utilizing the model should include the following: (1) analysis of outcrops and available subsurface data to reconstruct the basic stratigraphic framework of the coal-bearing unit; (2) delineation of the landward pinch-outs of the major delta-front or shoreface sandstone units and establishment of the trends of the pinch-outs; (3) delineation of 10-km-wide belts located just landward of and paralleling the trends of the pinch-outs, these belts being the areas most likely to contain thicker bodies of coal; (4) designing of drilling and coring programs to evaluate the belts. In river-dominated deltaic systems, the trends of thicker coal bodies within the belts may parallel the direction of depositional dip; in wave-dominated deltaic and strand-plain systems, the bodies are more likely to parallel depositional strike. In shoreline deposits that have prograded seaward a distance of 20 km or more, the possibility that additional bodies of coal will occur overlying the platforms formed by the shoreline deposits must be considered.

A coal exploration program employing these guidelines should be more cost-effective than one employing a hit-or-miss approach.

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1982 ROCKY MOUNTAIN COAL FIELD TRIP SECOND DAY ROAD LOG: Northern Wasatch Coal Field of Central Utah

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This one day field trip to the Northern Wasatch Plateau coal field of central Utah is designed to quickly acquaint visitors with a number of producing coal operations in the area and to give some insights into the geologic characteristics of the coal deposits. Like the Book Cliffs and Emery coal fields, the Wasatch Plateau coal field was formed along the western shoreline of the Upper Cretaceous Interior Seaway (Figure 1). Mine exposures and local outcrops display a variety of features characteristic of fluvial, wave-dominated delta, and strand-plain deposits. Repetitive cycles of transgression and regression are also identifiable and have played an important role in the coal/peat swamp development and geometry. Stratigraphic units viewed during the day (Table 1) will be noted in the Field Trip Log and include Mancos Shale exposures and the deltaic and lower coastal plain sediments of the lower Mesaverde Group (Star Point Sandstone and Blackhawk Formation).

At each of the stops, various aspects of coal depositional environments, coal seam geometries, exploration and mining operations, and mining development response to desireable and undesireable seam features will be discussed. Figure 2, shows the general areas which will be discussed and visited and the field trip route. The included cross section (Figure 3) illustrates the principal (minable) coal seams found in the Northern Wasatch coal field and

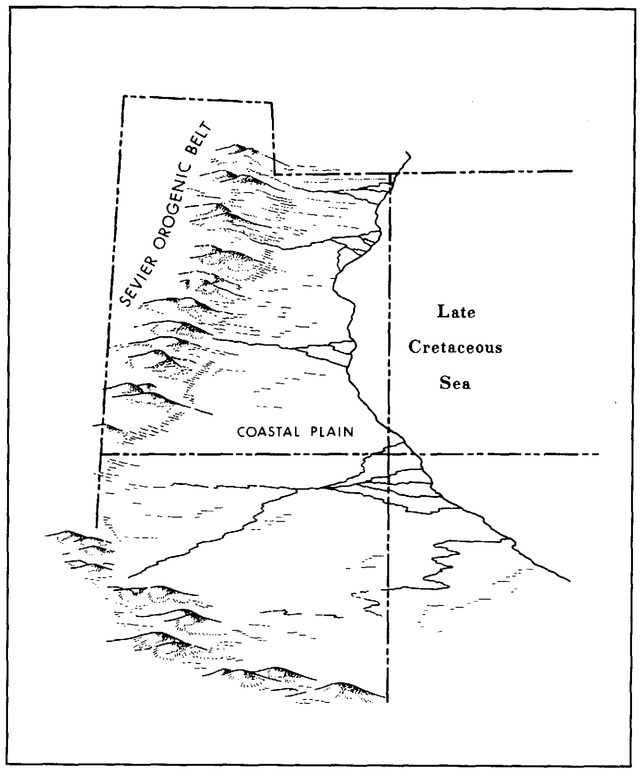

Figure 1. Generalized portion of western shoreline of Upper Cretaceous Sea (modified after Hunt, 1956).

[1]The release of information and participation by American Electric and Power Company (Price River Mining Company), Anaconda Minerals (Beaver Creek Mineral Co.), Coastal States Energy Company (Skyline), Getty Oil Company (Plateau Mining Company), United States Fuel Company (Hiawatha), and Utah Power and Light Company — so important in the construction of the cross-section as well as the mining operation presentations — is essential to the success of this field trip and is greatly appreciated.

System	Series	Stratigraphic Unit		Thickness (feet)	Description
TERTIARY	Eocene	Green River Formation		–	Chiefly greenish lacustrine shale and siltstone.
		Wasatch Group	Colton Formation	300-1,500	Varicolored shale with sandstone and limestone lenses, thickest to the north.
	Paleocene		Flagstaff Limestone	200-1,500	Dark yellow-gray to cream limestone, evenly bedded with minor amounts of sandstone, shale and volcanic ash, ledge former.
CRETACEOUS	?		North Horn Formation (Lower Wasatch)	500-2,500	Variegated shales with subordinate sandstone, conglomerate and freshwater limestone, thickens to north, slope former.
	Maestrichthian	Mesaverde Group	Price River Formation	600-1,000	Gray to white gritty sandstone interbedded with subordinate shale and conglomerate, ledge and slope former.
			Castlegate Sandstone Member	150- 500	White to gray, coarse-grained often conglomeratic sandstone, cliff former, weathers to shades of brown.
			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.
	Campanian		Star Point Sandstone Members	90-1,000	Yellow-gray massive cliff-forming sandstone, often in several tongues separated by Masuk Shale, thickens westward.
	Santonian	Mancos Shale	Masuk Shale	300-1,300	Yellow to blue-gray sandy shale, slope former, thick in north and central plateau area, thins southward.
			Emery Sandstone *COAL (?)*	50- 800	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.
	Coniacian		Blue Gate Member	1,500-2,400	Pale blue-gray, nodular and irregularly bedded marine mudstone and siltstone with several arenaceous beds, weathers into low rolling hills and badlands, thickens northerly.
	Turonian		Ferron Sandstone Member *MAJOR COAL SEAMS*	50- 950	Alternating yellow-gray sandstone, sandy shale and gray shale with important *coal* beds of Emery coal field, resistant cliff former, thickens to the south.
	Cenomanian		Tununk Shale Member	400- 650	Blue-gray to black sandy marine slope forming mudstone.
	Albian	Dakota Sandstone *MINOR COAL*		0- 60	Variable assemblages of yellow-gray sandstone, conglomerate shale and *coal*. Beds lenticular and discontinuous.

Table 1. Generalized stratigraphic column of cretaceous and tertiary rock of the northern Wasatch Plateau (after Doelling, 1972).

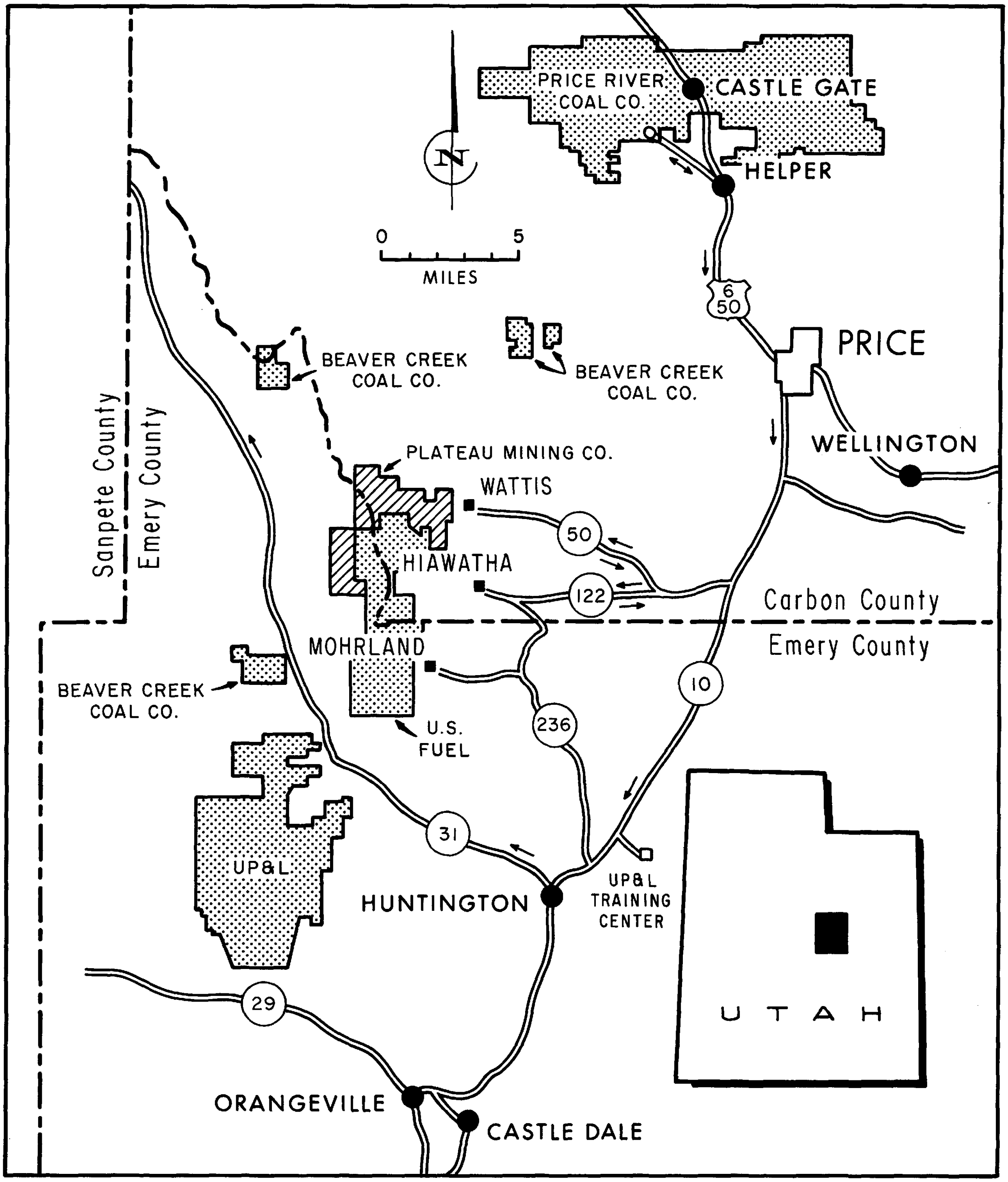

Figure 2. Location map of properties and field trip route.

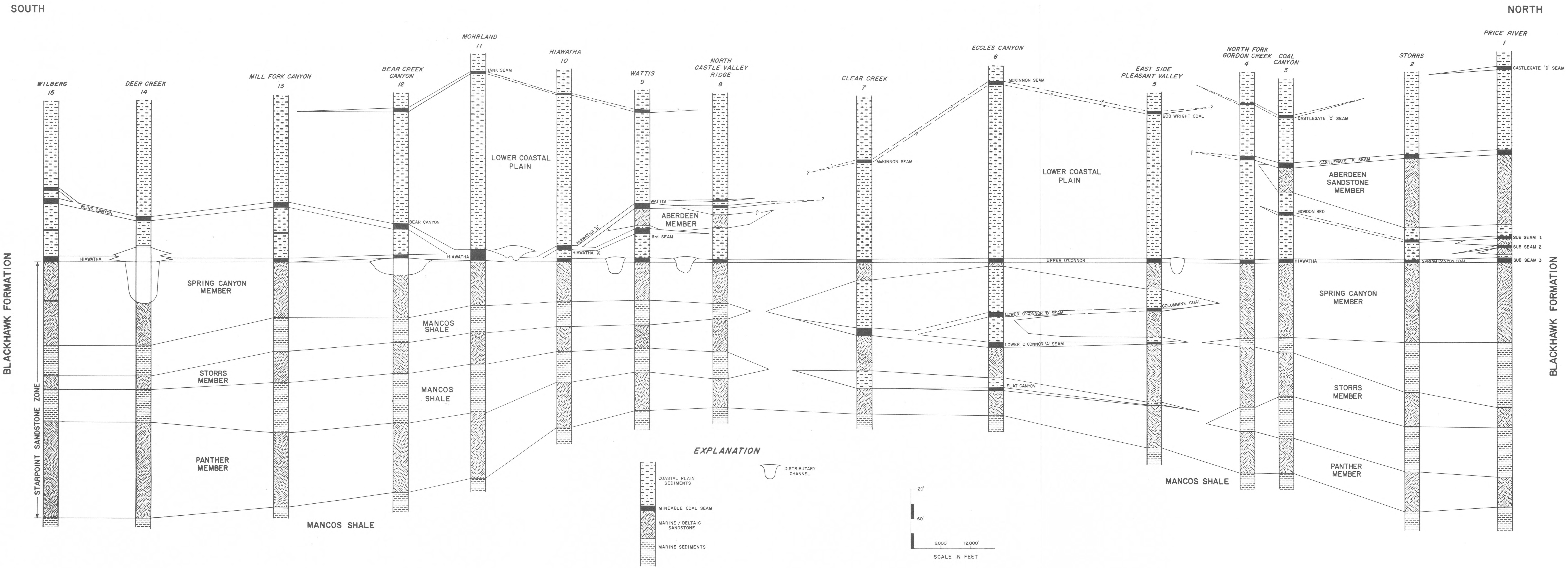

Figure 3. Generalized correlation cross section of minable coal seams in the northern Wasatch Plateau.

their relationship to associated deltaic sandstone units. Some minable seams of more localized extent may not be shown. Figure 4 shows the location of section points on the coal-seam cross-section.

PARTIAL STRATIGRAPHIC SECTION OF THE WASATCH PLATEAU COAL FIELD AND NORTHERN BOOK CLIFFS AND SOME SUGGESTED REVISIONS

Mancos Shale - The Mancos Shale, named by Cross (1899), forms the broad slope at the base of the Wasatch Cliffs, and the rounded hills and shallow dipping flanks of the San Rafael Swell. It consists largely of gray to bluish-gray to drab marine shale with occasional interbeds of sandstone and minor limestone. Only the uppermost portion of the Mancos is exposed in the area, and it grades upward into, and interfingers westward with, the three deltaic sandstone tongues of the Star Point Sandstone. Rocks at the contact between the Mancos Shale and the overlying tongues of the Star Point are reported to be early Campanian (Young, 1966).

About 1,000 ft of the upper Mancos Shale is exposed in the area (Young, 1966), and is the uppermost Masuk Member according to Young (1955). At the base of the Masuk Member is the ledge-forming Emery Sandstone Member of the Mancos. The Emery member is reported to contain three thin beds of sandstone (each up to 25 ft thick), separated from each other by about 50 ft of shale (Clark, 1928).

The westward-thinning wedges of Mancos Shale which interfinger the basal tongues of the Star Point Sandstone represent only a portion of the regional intertonguing of deltaic sandstones that occur in the contact zone of the Mancos Shale with the Mesaverde Group (Balsley, 1980; Young, 1955).

Mesaverde Group - Both the Star Point Sandstone and the Blackhawk Formation of the Mesaverde Group were named by Spieker and Reeside in 1925 and were subdivided into formations on the basis of their apparent facies relationships. Their study suggested a littoral marine origin for the Star Point Sandstone and distinguished the Blackhawk as a coal-bearing formation formed in a coastal swamp system. The Star Point Sandstone, which is a prominent cliff-former, consists of several eastward thinning marine sandstone tongues of medial Campanian age (Clark, 1928). The three members are the basal Panther Sandstone, the middle Storrs Sandstone, and the upper Spring Canyon Sandstone. Continued study of the deltaic sandstones of the Star Point and the interdeltaic and lower coastal plain sediments of the Blackhawk, however, has since greatly defined the origin and complex relationship of these two sedimentary facies (Blanchard, 1981). Young (1955) described the detailed intertonguing of the deltaic sandstones and coal bearing facies of the Book Cliffs and found it necessary to include six deltaic sandstone members into the Blackhawk Formation. The base of the Blackhawk Formation included the Spring Canyon Member of the Star Point Sandstone. Because drilling in the Wasatch Plateau indicates all of the deltaic sandstone members of the Star Point Sandstone are traceable landward (west) into lower coastal plain deposits, all of the sandstone members of the Star Point Sandstone are here considered to be seaward equivalent facies or members of the Blackhawk Formation (Figure 5).

For the sake of discussion, the Blackhawk Formation, as described, will be divided into two intervals: a seaward deltaic interval, and an upper or adjacent coal-bearing interval.

BLACKHAWK FORMATION

Deltaic Members ("Star Point Sandstone") - As noted, the three sandstone tongues of the Star Point are prominent cliff-formers and usually thicken rapidly to the west and then develop landward pinchouts in the Wasatch Plateau coal field. These sandstone units are generally separated from each other by westward projecting tongues of Mancos Shale (Figure 5). While the sandstone tongues reveal an overall regressive pattern of deposition, records of minor transgressive phases have been noted.

The basal Panther Sandstone is about 100 ft thick and consists of massive, well indurated, crossbedded delta-front sandstones which grade downward to a transitional, thin bedded sandy shale at the base.

The Storrs Sandstone is located about 120 ft above the top of the Panther Member and consists of 20-80 ft of soft, friable sandstone. The unit exhibits normal delta front sandstone development upwards from a thin-bedded sandy shale to a thick-bedded top.

The Spring Canyon Sandstone Member ranges from about 150 ft thick in the Price River mine area

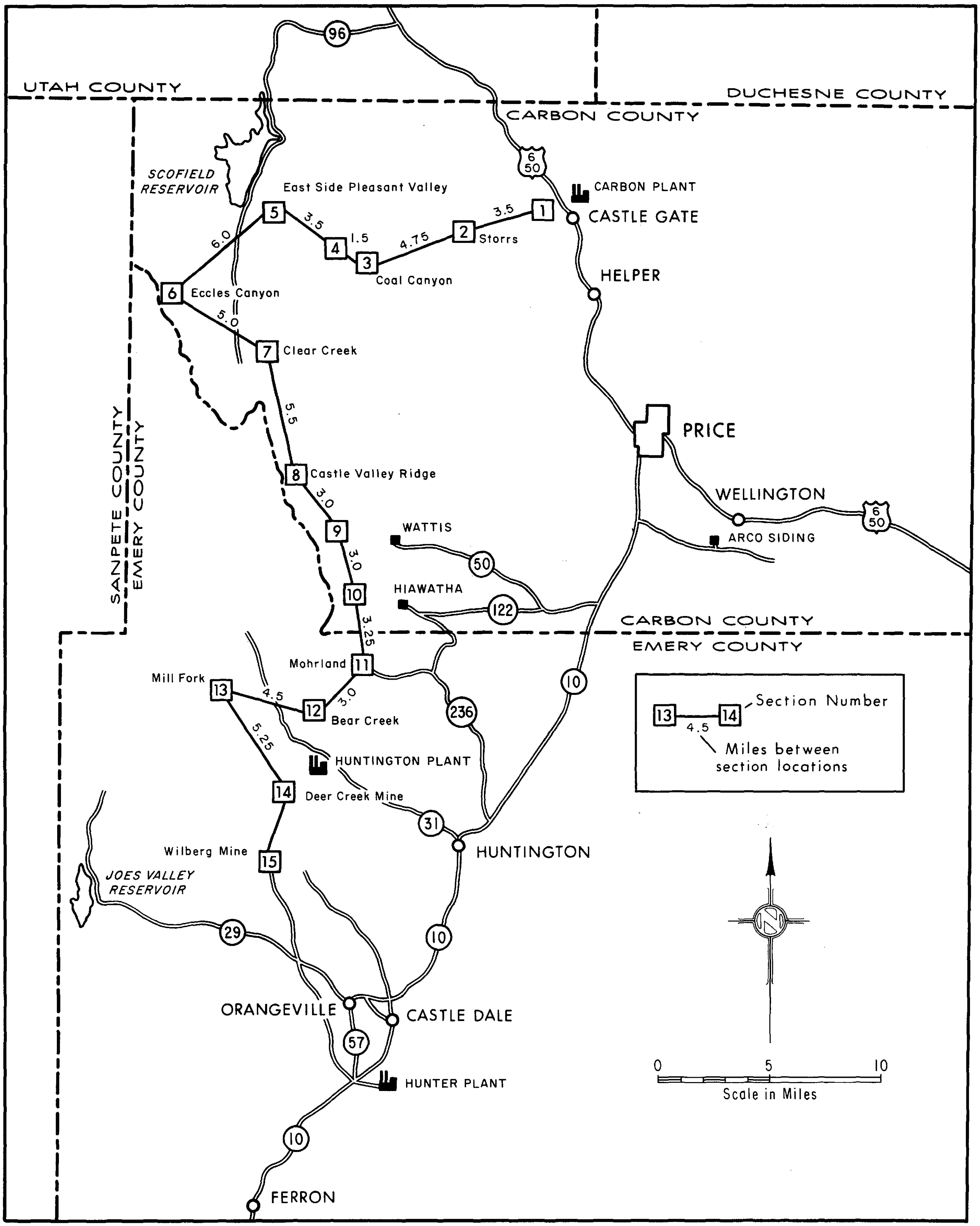

Figure 4. Index map showing location of cross section.

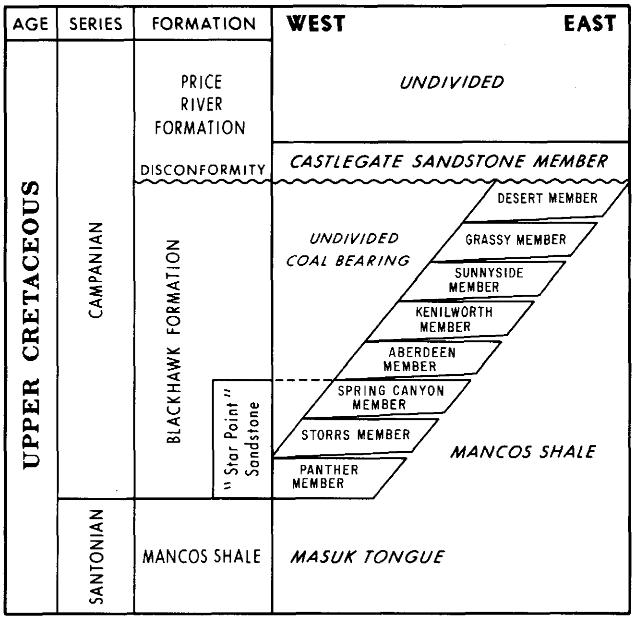

Figure 5. Diagrammatic selection illustrating overlapping and intertonguing of deltaic and marine facies in the Wasatch Plateau and Book Cliffs (modified from Young, 1955; Balsley, 1980).

to a landward pinch-out in the Pleasant Valley area. This unit also exhibits typical delta front sandstone features.

The stratigraphically highest delta front sandstone found in the area to be visited is the Aberdeen Sandstone Member. This rock unit is well developed in the Book Cliffs and exhibits a landward pinchout at several localities in the Wasatch Plateau Coal Field. In the areas visited, the base of the Aberdeen is transgressive over coal bearing coastal plain deposits. This member ranges from 0-150 ft thick (Figure 3).

Coal Bearing Interval (Undivided Blackhawk Formation) - The Blackhawk, as named by Spieker and Reeside (1925) and which includes the major coal bearing strata, consists of about 750-900 ft of sandstone, siltstone, mudstone, and coal.

Regionally, the base of the coal bearing Blackhawk Formation shifts with the eight overlapping deltaic sandstone tongues, with the lowest/oldest coals to the west and the stratigraphically highest/youngest coals appearing to the east (Figure 5). Because of limited exposures and faulting in the interior of the Wasatch Plateau coal field, identification and correlation of coal seams in the past was based on tenuous stratigraphic clues and patterns. As a result, a variety of seam names evolved over the plateau which often confused and disguised the true area extent and reserves of individual minable seams. However, recent drilling by various mining companies coupled with detailed depositional environment investigations has revealed a basic pattern of coal deposition and seam development controlled in large part, by adjacent delta processes. Major minable coal seams found in the area include: Flat Canyon seam on the Panther Sandstone; Lower O'Connor coals above the Storrs Sandstone (locally named the Aberdeen Sandstone); the Hiawatha/Upper O'Connor/Spring Canyon/Sub Seam coals resting on the Spring Canyon Sandstone or equivalent sediments; the Hiawatha A/Bear Canyon/3rd Seam/Blind Canyon seam splitting off the Hiawatha seam; the Castlegate A/Wattis/Hiawatha B seam stratigraphically above the Aberdeen Sandstone. The McKinnon seam and Bob Wright coal seam may also be equivalent to the Castlegate C horizon; and various other seams of lesser economic importance. Wave dominated deltaic environments give way to fluvial dominated coastal plain facies as one moves upward or laterally through the Blackhawk Formation.

PRICE RIVER FORMATION

Spieker and Reeside (1925) separated a series of non coal bearing-beds above the Blackhawk Formation as the Price River Formation. This unit forms the upper part of the Mesaverde Group. The lower part of the Price River Formation consist of a massive basal sandstone member (Castlegate Sandstone) about 400 ft thick overlain by the sandstones and minor mudstones of the upper Price River.

NORTHERN WASATCH PLATEAU FIELD TRIP LOG

The aridity and structural history of the Wasatch Plateau/San Rafael Swell area of central Utah have combined to allow for broad exposures of geologic facies and features which have influenced the formation of the coal seams. Because of the complex history of uplift, faulting, and erosion in the region, structural patterns and topography have figured importantly in the exposure and subsequent development of the coal deposits.

The general route of the road log is shown in Figure 2. The geology is described in the road log where appropriate. Three main stops will be made: 1) Price River Coal Company; 2) Plateau Mining Company and U.S. Fuel Mining Company; and 3) Emery Mining and Beaver Creek Mining companies. Various site stops will be made to view areas of interest. Because of the time constraints placed on the trip by distances to be covered, it is important that participants keep aware of trip progress and general stop time intervals.

General coal seam relationships can be followed on Figure 3.

Miles

0.0 Helper City. Helper City Auditorium.

*PRESENTATION OF PRICE RIVER COAL COMPANY OPERATION

PRICE RIVER COAL COMPANY

Don Stephens (Mine Geologist) and
Mark Bunnell (Coal Geologist)

Price River Coal Company was formed in December, 1979, as a wholly-owned subsidiary of the American Electric Power Service Corporation, the nation's largest privately owned (i.e., non-governmental) utility company. Coal produced by Price River Coal Company is shipped to the Indiana and Michigan Electric Company (another operating company within the AEP system) for use in their coal-fired generating plants.

Price River Coal Company's reserves extend over 26,500 acres in the vicinity of Helper, Utah (Figure 2). The ten potentially minable coal seams on the property occur in the Blackhawk Formation over an interval of approximately 500 ft. The two marine sandstone units occurring in this interval (the Aberdeen Sandstone and the Spring Canyon Sandstone) are easily recognized in outcrop by the white cap at the top of each unit.

Price River Coal Company currently operates mines in two seams (Figure 3). The no. 3 mine is located in the Sub-seam no. 3. This seam, which is the lowest seam on the property, lies directly above the Star Point Sandstone. The no. 5 mine is located in the D seam which is approximately 450 ft above the sub-seam no. 3. The low sulfur coal is classified high volatile "A" bituminous and there is little variation among the seams in rank or other quality characteristics.

Two methods of mining are used in PRCC's mines. Several continuous miner sections are deployed in both mines, while the longwall system operates in the no. 5 mine. (Future mine plans call on longwall production from both mines.)

The roof conditions in both mines are generally good. However, some localized areas of roof control problems are caused by sandstone channels and overbank deposits, plus deep cover (+2,000 ft). The roof geology of both mines continues to be examined and mapped. The objective of these programs is to establish a data base in order to predict areas of adverse roof, thereby allowing management the opportunity to assess and evaluate those mining plans best designed to maximize production and employee safety.

Miles

Hardscrabble Canyon Road Log

0.0 Start at Helper Auditorium. Drive northward on Main Street. Looking northward, you can see the following stratigraphic units:

1. Mancos Shale - forms the valley floor.
2. Sandstone unit - Panther Tongue of Star Point Sandstone.
3. Mancos Shale.
4. Sandstone unit - Storrs Tongue of Star Point Sandstone. Generally a softer, friable sandstone which becomes well indurated and massive to south and west. Locally supports the Lower O'Connor seams to southwest.
5. Mancos Shale
6. Balanced Rock is part of the Star Point Sandstone.
7. Lower white capped sandstone unit - top of the Star Point Sandstone (Spring Canyon Member). This unit is a prominent cliff-former of massive well indurated

marine/deltaic sandstones. The sub-seam coals developed on this unit are correlative to the Hiawatha seam farther South.

8. Upper white capped sandstone unit - top of Aberdeen Sandstone. This massive marine sandstone can be traced to a landward pinchout to the South and supports the important Castlegate "A" seam on its upper surface.

9. The uppermost cliffs are part of the Blackhawk Formation. The red coloration is due to burned coal seams. This formation is the major coal-leasing unit in the Wasatch Plateau coal field.

Miles

1.3 Turn right on Utah State Highway 50 and 6.

1.5 Turn left - straight ahead is the mouth of Hardscrabble Canyon. Panther Sandstone appears near the base of the canyon. Below Panther, note the Mancos Shale.

1.7 Cross Utah Railway tracks.

2.4 Entering Hardscrabble Canyon.

2.6 Panther Sandstone outcrop on the right side of the road.

2.9 Looking straight up the canyon, two sandstone units are visible. The uppermost white capped unit is the Aberdeen Sandstone. The lower white capped unit is the Star Point Sandstone (Spring Canyon Member).

3.3 Left hand side of road - Mancos Shale.

3.6 Both sides of the road are outcrops of the Star Point Sandstone (Spring Canyon Member). On the right side of the road on top of the Star Point Sandstone, the Price River Coal no. 3 mine portal is found. Above the mine portal can be found a sandstone channel with a channel bank slump deposit on the right hand side of the channel. Walking east from the portal along the outcrop, are found overbank deposits of sandstone which possibly represent splay deposition.

3.7 Aberdeen Sandstone outcrops on both sides of the road. Looking straight up the canyon, the Castlegate Sandstone can be seen forming a cliff several hundred feet high.

3.8 Top of the Aberdeen Sandstone - note the red coloration of the rocks caused by the burning of coal seams.

4.0 Turn left up side canyon. Ascended through coastal plain sediments.

6.3 A portal of the Price River Coal no. 5 mine in the D seam. Note the red coloration of the rock in places where the D seam was burned.

Start back down Hardscrabble Canyon.

8.0 Back at the mouth of Hardscrabble Canyon looking across Price River Canyon, several rock units are visible:

1. Aberdeen Sandstone;
2. Spring Canyon Tongue of Star Point Sandstone;
3. Mancos Shale;
4. Storrs Tongue of Star Point;
5. Mancos Shale;
6. Panther Tongue of Star Point Sandstone;
7. Mancos Shale.

Miles

10.7 North Helper Exit - Traveling towards Price.

The town became known as Helper in 1892 because, beginning that year, extra engines or "helpers" were stationed here to assist the coal trains up the grade to Soldier Summit. Note Mancose Shale exposed on bluff on both sides of the valley. Capping is a veneer of gravel pediments.

10.7 Gordon Creek turn off to Beaver Creek Mining Operations in Gordon Creek and Coal canyons. See Figure 2 and Beaver Creek Operation presentation at mile 72.3.

10.9 Price River Bridge. Garley Canyon Sandstone visible on both sides of road is thought to be a thin deltaic tongue from the west. A thin remnant of the Emery Sandstone lies about 400 ft higher in the section.

13.7 View to northwest of Book Cliffs. Note prominent deltaic units and reddening due to burned coals.

15.2 Turn left in to Price by Creek View shopping center. With a population of approximately 15,000, Price is the main community in the Castle Country area. While Price started out as a farming and ranching community, it now functions as a booming center for an expanding coal industry.

16.0 Turn south on Highway 10.

16.3 Past Commercial Testing and Engineering Co. laboratories on right. This organization is one of several in the area which handles coal quality testing and sampling for various coal companies in the Wasatch Plateau and Book Cliff coal fields. C. T. & E.'s Price office specializes in coal washability studies, coal sampling, and exploratory drill core analysis as well as quality testing of daily mine run samples for area mines.

16.9 Price city by-pass forming one major artery for coal transportation in area via truck haulage. Leaving Price City.

20.5 Turn off on right to the Beaver Creek coal handling facility. View to left of upper Mancos and Mesaverde Group which forms the cliffs of northern Wasatch Plateau coal field. Note deltaic tongues of Panther, Storrs, and Spring Canyon sandstones. Coal swamps of the Blackhawk generally hugged the coastline and are often found immediately overlying shoreline deltaic deposits.

23.9 Turn to left on Highway 122 (west) to old mining town sites of Hiawatha and Wattis.

26.4 Site of gas well recently drilled (Spring 1982) to left. Gas producing horizon probably Ferron Sandstone.

26.8 Wattis turnoff. The old Company town of Wattis, located near the Star Point Ridges of Gentry Mountain (the type section of the Star Point Sandstone) is now buried under the coal refuse of the current operation.

33.5 Cross railroad spur to Hiawatha and Mohrland. This rail line handles coal haulage from the Mohrland, Hiawatha, and Wattis sites.

34.2 Refuse Piles/Plateau property line. The reject material from the preparation plant illustrates the important of wash facility in maintaining an acceptable coal product.

34.6 Main office building on left and clean stockpile on right. The clean coal is a composite of three mined seams, (Wattis, 3rd, and Hiawatha seams) recovered from the Star Point no. 1 and no. 2 mines.

34.7 Wash plant, tipple complex, and train-loadout on right.

35.0 Stacking tube and intermediate storage transfer point on overland conveyor belt.

35.6 Panther Sandstone member visible across canyon to north (right). Note the old tramway access built about 1920. This tramway had a maximum grade of 36 percent and was about 1.3 mi long. Production during 1920-30 rose to about 1,500 short tons/day.

36.6 View point stop on top of Panther tongue. View of Castle Valley and San Rafael Swell to east and north. Note the planar top of the deltaic sands. View of coal handling set up at the no. 1 mine load-out to south and no. 2 mine portal to west. Note Mancos Shale exposed in the road cut. Beaver Creek preparation plant and Book Cliffs visible to northeast.

36.8 Storrs Sandstone member of the Star Point Sandstone. Note the stratigraphic progression from lower shoreface to foreshore sediments (coarsening upwards).

37.1 Spring Canyon Sandstone member on right. Note white cap of unit and the planar top diagnostic of delta front sandstone bodies. Hiawatha coal seam deposited on top.

37.3 Hiawatha coal seam. Visable in the seam is a crevasse splay split. Above the seam is an abandoned channel fill which was, in turn, buried by active channel fill.

37.4 Third seam coal zone replaced by sandstone channel and lagoonal deposits. This coal zone is overlain by the transgressive Aberdeen sandstone.

37.7 Arrive at the Star Point no. 2 mine portal. The bench area contains bathhouse, office, maintainance, and storage facilities. Note the burned Wattis seam on top of the Aberdeen sandstone.

*PRESENTATION OF PLATEAU MINE OPPERATION

PLATEAU MINING COMPANY

John M. Mercier (Mine Geologist)

Plateau Mining Company, situated at the old mine town of Wattis, is located approximately 12 mi (by air) southwest of Price, Utah (Figure 2). The mine site which first experienced development in 1916, began a new phase of development and operations in 1975 through the renovations of old workings and active exploration of virgin coal reserves to the west. The company was purchased by Getty Oil Company in mid-1980 and is aggressively developing and producing coal from reserves in three seams (from top to bottom these three seams are: Wattis Seam, Third Seam, and Hiawatha Seam). The Plateau Mining Company presently produces in excess of 1 million short tons of raw coal per year and is systematically expanding operations to increase this figure. Coal extraction is accomplished by continuous miners and belt haulage. Underground haulage and logistics are handled by diesel-powered rubber-tired equipment. An overland conveyor transports the coal from the cliff side mine site to a preparation plant utilizing an air/water jig separator. Mine portals are separated from the preparation and shipping facilities by over 1,000 ft of elevation. Coal quality is ranked as a low sulfur, low ash, high volatile bituminous-B with general markets in steam generation and cement manufacturing.

While mining has periodically taken place on the property for almost seventy years, a variety of geological conditions encountered during this time has had an occasional detrimental impact on operations profitability. Plateau successfully utilizes an active geologic program to help identify, predict, and evaluate features and conditions which might affect this cost-sensitive but profitable mine operation.

Reconstruction of depositional environments and structural deformation of the property's multi-seam coal deposit has revealed interfingering sequences of marine and non-marine sediments associated with a persistent lower delta plain coal swamp. Enclosing strata of the coal seams display features characteristic of regressive and transgressive sequences. The alternating regressive and transgressive paleoevironments created a complex pattern of seam geometries which has been further complicated by faults and intrusion of igneous dikes.

Some of the geologic features which directly affect mining operations are storm washover deposits (rock splits and splays); flood tidal inlet and tidal flat deposits (coal scouring, seam undulation, sulfur content variation); lagoon deposits (splitting and thinning of seams); distributary channel, levee, and splay deposits (differential compaction, seam splitting, undulation and scouring adjacent and beneath channels); drowning lower delta plain deposits (weak, slickensided roof rock); tectonic lineaments (jointing, faulting, and dikes).

Mining responses to the significant geologic features are: rock sloping between seams to by-pass thin coal and seam splits caused by distributary channels and lagoon embayments; selective mining where storm washovers have caused rock splits; roof or floor-rock removal in areas of channel scour or weak, clay-rich mudstone, extensive rock-work across faults or dikes; and appropriate roof support measures (resin and mechanical bolting, matting, cribbing, and timbering) to meet changing conditions.

Other mining responses to geologic features include orientation and placement of panels and selection of equipment to allow for the greatest flexibility and efficient recovery of minable reserves.

*PRESENTATION OF U.S.
FUEL OPERATION

UNITED STATES FUEL COMPANY

Jean Semborski (Mine Geologist)

The United States Fuel Company operating at Hiawatha, Utah represents one of Utah's historic mining sites which has continued to meet the challenge of changing energy demands nationwide and has emerged in the 1980s as a modern, progressive operation. From 1909-11, several pioneer mines were opened in Miller and Cedar Creek Canyons. They were organized into the Consolidated Fuel Company respectively. Soon after, the old Southern Utah Railroad from Price to Hiawatha was built.

In 1911, the Blackhawk Coal Company opened the Blackhawk mine 1,000 ft above the present town of Hiawatha in the side of the canyon.

During 1914, the Utah Railway was organized and by 1916, a line was completed which provides transportation for mined coal along the Wasatch Front. This line replaced the older, steeper railway which previously served Hiawatha.

The United States Fuel Company was organized in 1915 and took over the properties of Consolidated Fuel Company, Castle Valley Coal Company, Black Hawk Coal Company, and Panther Coal Company at Heiner, Utah, in 1916.

After the mid-1930s, the company began to mechanize their mines in order to compete with gas and oil in the marketplace. Loading, cutting and drilling machines were now employed in their mining operation. The coal was blasted, loaded with mechanical loaders into shuttle cars and hauled to the loader head. The fifteen-car train then relayed the coal down a 1-mi long incline to the preparation plant.

United States Fuel Company began construction of the preparation plant in 1937. It's completion in 1939 enabled the company to sort, wash, dry, and blend their coal thus meeting a wide variety of orders.

A resin plant, used up to 1979, sits adjacent to the tipple. Resin was extracted from the coal for a now defunct market in Salt Lake City.

Hiawatha today is one of the last company towns in the area. It's population has fallen from the 1940s and early 1950s when 1,500 people inhabited 200 apartments and homes. The town is now comprised of about 57 homes and one church. The schoolhouse and townhall have been torn down but a store, gas station and post office still provide their services for the town.

The United States Fuel Company presently operates three mines; King 4, 5, and King 6. Production is from three seams: the Hiawatha, Hiawatha A, and Hiawatha B (Figure 3). The latest mine to open, King 6, was started in late 1981 and is the only mine of the three presently working the Hiawatha seam. Production for the three mines totaled 860,000 short tons in 1981. All extraction is by continuous miners.

Plans for future coal mining in the Mohrland area are being developed. Longwall mining is proposed for extracting the coal reserves of this area.

In addition to underground mining, the company is also mining one of the old slurry ponds quite successfully. The mined product is shipped as it is removed from the pond bed.

Future considerations to upgrade their operation include a new preparation plant, conveyor system, and a unit train loadout.

Geologic activity in the Hiawatha area dates to the early part of the century. Because of a long history as well as encounters with changing conditions, underground diamond drilling has periodically been used to determine the geometry and relationships between the coal seams. Drilling became a necessity as major seam splitting created unusual and troublesome mining problems as entries were advanced into new areas.

Relationships between the Hiawatha A and B seams have proven to be quite interesting and complex in the mining areas. All three seams are found in very close proximity in one particular locality and from there diverge.

In several places the Hiawatha and A seam and/or the A and B seams combine to form one thick seam (Hiawatha). The seams appear to split in a rough NNW-SSE pattern. The close proximity of the tree seams in the center of the mining area suggests that a portion of the swamp was relatively unaffected by repeated marine and fluvial influences.

Outcrop mapping and surface drilling has also been implemented to better evaluate coal resources. Obtaining information through these methods is somewhat hindered by burned coal, alluvium obscuring coal seams in the outcrop and by steep slopes and cliffs covering much of the mining area thus preventing drill hole data from being obtained in some critical areas.

LUNCH BREAK

Miles

38.2 View point stop. Note the location of the three seams and the deltaic Panther, Storrs (mostly covered) and Spring Canyon (with Hiawatha coal above), and Aberdeen Sandstones.

38.4 Aberdeen Sandstone fractured by burning of Third and Wattis seams. The unit contains diagnostic *Ophiomorpha* and *Thalassinoides* burrow forms.

38.6 Top of Third seam - Notice abandoned channel fill deposits forming roof of seam.

38.7 Hiawatha Seam and portals of the Star Point no. 1 mine. Note the interval between seams has decreased. Splays and rock splits are visible in the Third seam about 12 ft above the Hiawatha Seam.

39.5 View of coal truck loadout for Star Point no. 1 mine.

40.6 Leave Plateau/Wattis area.

48.2 Turn right on Highway 122 and head west to Hiawatha/U.S. Fuel Company.

48.4 Gravel quarry on right in gravel pediment covering Mancos Shale.

53.3 View of U.S. Fuel's refuse piles and fine coal impoundments straight ahead. Coal "fines" are currently being mined and sold from the no. 5 slurry pond. The pond will resume its function as a slurry containment after mining.

53.5 Utah railroad crossing and turn off on left to Mohrland. Enter town of Hiawatha. Hiawatha, Utah is a company-owned town (U.S. Fuel) with many of the houses built in the early 1900s. The two story green and white building displaying the King Coal emblem is the main operations office. Mine portals are several miles to the west up Miller Creek Canyon. Across the street is the company store (U.S. currency) and next to the mine offices are the town jail and post office.

61.5 Return to Highway 10 and turn right (south) for Huntington.

65.6 Road again passing through Mancos Shale. Note the rather common buckling and heaving of the pavement as road cuts are approached and passed. A road cut at mile 65.6 has revealed a lamprophyre dike cutting vertically through the shale on a general east-west trend. Dikes of this type are relatively common to the north and west.

65.7 Intersection of Highway 155 connecting small towns of Elmo and Cleveland and gateway to the famous Cleveland-Lloyd Dinosaur Quarry. This Jurassic collecting locality in the Morrison Formation is noted for its prolific and diverse reptilian fossil fauna.

71.6 Mine Training Center Turnoff.

72.3 Mine Training Center. This facility is used by Utah Power and Light Company for training and certification of miners. Buildings located at the south end of the enclosed property are the area facilities of

Standard Laboratories, Inc. This organization specializes in complete coal and water quality analysis utilizing atomic absorption equipment and techniques. The facility also offers specialized sampling capabilities and size and washability studies for client coal operations.

*PRESENTATION OF UTAH POWER AND LIGHT

UTAH POWER AND LIGHT COMPANY

Tom Lloyd (Mine Geologist)

Utah Power and Light Company controls in excess of 22,000 acres of fee and assigned federal lease coal land in its East Mountain property which is located at the southern end of the Wasatch Plateau coal field. Within this property, there are two minable seams of upper Cretaceous coal, which are the Hiawatha and the Blind Canyon in ascending order.

Both seams are situated in the lower part of the Blackhawk Formation and were formed in a lower coastal plain environment. The Hiawatha seam, which directly overlies the deltaic Star Point Sandstone, is generally well developed but shows local variations in thickness, often due to channel cuts and splitting by crevasse splays. These variations directly affect mining operations. The interval between the Hiawatha and Blind Canyon seams varies from 40-140 ft and averages approximately 100 ft. This interburden consists of interbedded sandstones, siltstones, and mudstones. The Blind Canyon seam has little variation in thickness as compared to the Hiawatha. Coal in both seams is ranked as high volatile bituminous coal and is characteristically low in sulfur.

There are three active underground mine complexes situated on the property wich include the Des-Bee-Dove, Deer Creek, and Wilberg. These are operated by Emery Mining Corporation. Approximately 4.0 million short tons of coal is produced annually supply fuel for nearby power plants (Figure 4).

During the last six years, Utah Power and Light Company has designed and tested an exploration program utilizing a combination of various exploration tools. This system has worked well in gathering data to meet the specific needs of company geologists, engineers and those directly involved in producing electricity from the raw coal. Surface and in-mine drilling, outcrop and in-mine mapping and various geophysical techniques, including surface reflection and in-seam seismic, are all being used during the course of the program. In addition, hydrologic and coal quality data is continually being collected and interpreted. This combined exploration method approach has increased data reliability and proven to be excellent in predicting occurrences of many geologic features which will ultimately affect the mining and coal quality.

Geologic modeling through the use of various combinations of data collected by the different exploration methods is very effective. Modeling of depositional environments utilizing drilling and geophysical data incorporated with structural information gained from mapping faults, joints and cleat patterns has improved mine layout profoundly. Roof lithologic mapping serves to identify and predict areas influenced by fluvial channels, including possible scours and related zones of differential compaction in advance of mining. Hydrologic monitoring provides information for both mining engineers and those involved with environmental programs. In addition, fuel quality predictions based statistically on coal seam geology and dilution introduced by the mining process have proven reliable for short-term and long-term ash predictions. The combination of geologic models along with reliable ash projections has aided in production, planning and power plant utilization.

*PRESENTATION OF BEAVER CREEK OPERATIONS

BEAVER CREEK MINES

Alex R. Papp (Minesite Geologist)

Beaver Creek Coal Company, a subsidiary of Anaconda Minerals, currently operates three mines and one coal processing and loadout facility near Price, Utah. The coal is mined by room and pillar method with continuous miners and is transported by shuttle car, conveyors and then haul trucks to the preparation plant. A total of 700,000 tons was mined in 1981. Processed coal is transported by unit trains to Nevada and Mississippi for electrical generation.

The no 2 and 3 mines are located twenty miles west northwest of Price at Gordon Creek (Figure 2).

The area has a long history of production and at least nine mines have been opened. Operations commenced in 1925 and continued to the mid 1940s. In 1967, Swisher Coal Company reactivated the area, and in 1975, General Exploration acquired the properties. Atlantic Richfield purchased the properties in 1979 and established the Beaver Creek Coal Company.

The no. 2 mine is in Castlegate "A" seam which at the portal measures 14.0 ft thick (Figure 3). The average as received quality is 12,700 Btu/lb, 0.4 percent sulfur, and 5.9 percent ash. The no. 3 mine works the Hiawatha seam, which is the lowermost coal bed in the immediate area. This seam rests on the Star Point Sandstone and is separated from the Castlegate "A" seam by 150-230 ft of interburden. The average as received quality 12,200 Btu/lb, 0.6 percent sulfur, and 6.5 percent ash.

The complex structural geology of the area is dominated by high angle normal faults of the North Gordon fault zone and the eastern extension of the Fish Creek graben complex. The area is also influenced by the three to five degree dip of the Beaver Creek Syncline. The no. 3 mine is located at the intersection of these fault zones consequently forming four trending fault sets. The no. 2 mine is dominted by NW-SE trending faults of the Fish Creek Complex and mine panels parallel this trend. Igneous dikes, rock spar zones and channels compound the problem in mining this area.

The no. 4 mine is located in Mill Fork Canyon, twelve miles northwest of Huntington, Utah (Figure 2). The area of the Hiawatha NW quadrangle was actively mined from 1936 to 1964 and several small defunct operations are scattered through the canyons. The no. 4 mine tract was acquired from the General Exploration Company in 1979 and access into East Mountain was made through the old Leamaster mine. The mine works the Blind Canyon seam which measures 16 ft thick at the portal. The quality as received is 12,500 Btu/lb, 0.6 percent sulfur and 6.0 percent ash. The Blind Canyon seam is stratigraphically located 50-120 ft above the underlying Hiawatha seam. Access to this minable lower seam is presently underway by rock sloping from the mine. Faults within the area parallel the trends of the Pleasant Valley fault zones. Channeling and oxidation perimeters are rather extensive in the mine.

A minesite geologist was assigned to the properties in 1981. Abundant data have been generated as a result of in-mine drilling and mapping programs, surface drilling, aerial photography reconnaissance, surface mapping, and seismic activity. Acquistion of a new hydraulic diamond drill (500 ft of BW size rod) has stepped up the pace in underground fault and lower seam exploration. Geologic mine maps have been prepared for each mine and include data on drilling, faulting, oxidized and burn coal, channels, igenous dikes, rock spars and bad top. Projections of faults and channels into unmined areas were complimented by data accumulated from surface high velocity seismics, aerial photography reconnaissance and surface drilling. Geologic programs concerning coal quality prediction and hazardous mining conditions are well underway .

Miles

73.0 Leave Training Center and resume trip to Huntington. Turn south on Highway 10.

75.2 Past Mohrland turn on right (Highway 236). Mines in this area operated from 1912 until 1938 in the Hiawatha seam. Remains of old mine buildings and sealed portals dot the walls of narrow Mohrland (Cedar) Canyon.

77.0 Reach Huntington. Turn right (west) on Highway 31 and continue up to Huntington Canyon. East Mountain on the left and the southern end of Gentry Mountain visible on the right.

79.0 Red Point, the southeastern most ridge of East Mountain, visible on right. The coal bearing section of the Blackhawk Formation has experienced extensive outcrop burning on this end of the mountain. Note the top of the Star Point Sandstone and the occasional exposures of coal.

81.0 Exposure of upper tongue of Emery Sandstones.

83.0 Utah Power and Light research farm and Huntington Power Plant. The power plant is comprised of two 415 Megawatt coal-fired generators which utilize approximately 2.2 million tons of coal annually from the nearby Deer Creek

Mine. Experiments are conducted on the research farm to evaluate the effect of irrigating with excess cooling tower water from the power plant.

84.7 Make turn to left on Deer Creek Canyon road. View stop for power plant. Note the exposures of the Panther, Storrs, and Spring Canyon members of the Star Point Sandstone directly south. Above the deltaic sandstones are exposed the Blackhawk Formation and the overlying Castlegate Sandstone member of the Price River Formation.

85.6 Huntington Power Plant coal storage facility at the end of a 2.5 mi overland conveyor belt from the Deer Creek Mine up canyon.

87.1 View stop by canyon conveyor belt system of the Deer Creek/Bear Creek Canyon fault graben system. The fault system hinges about 2.5 mi south and displays about 310 ft of total displacement through three distinct step faults. Note also the works of the old American Mine work on the east (left) side of the canyon. On the west side of the canyon are exposures of distributary channeling in the top of the Spring Canyon Sandstone.

87.6 Deer Creek Mine parking lot with a view of the mine tipple system, conveyor belts and storage. Note the surface area restriction due to the narrow canyon. The Deer Creek Mine produces coal exclusively from the Blind Canyon seam.

90.5 Return down Deer Creek Canyon to Huntington Canyon Road (Highway 31).

91.1 Utah Power and Light Company's Huntington Creek water station on left.

91.3 Located on the right is an exposure of the Bear Canyon fault which is downthrown on the west approximately 100 ft. Note also the complete section of marine sandstone members.

92.2 The exposure on the left is a minor fault of the Pleasant Valley fault system. Note also the red iron oxide staining. On the right is Bear Canyon in which the Bear Canyon mine is located. The Bear Canyon (Blind Canyon) seam is being mined.

92.5 Straight ahead (north) is an excellent exposure of a 20-ft displacement fault which is downthrown on the west. Also note the three marine sandstone members and the white cap at the top. This white cap which underlies the Hiawatha seam represents foreshore and upper shoreface environments.

93.2 On the left and up the canyon is an excellent exposure of a lenticular fluvial sandstone body.

93.9 An exposure of the Hiawatha seam is located on the right.

94.0 On the right is Trail Canyon and the location of the Co-op mine. This mine works the Blind Canyon seam.

94.3 On the left is a canyon exposure of a channel overlying the Spring Canyon Member. Here, the Hiawatha seam has been scoured away.

94.4 Mill Fork Canyon is on the left. This is the location of the Beaver Creek Coal Company no. 4 mine. The Blind Canyon seam is being mined.

94.7 On the right is a sandstone block of the Panther member which was painted as a house.

96.4 On the left is Little Bear Canyon and site of a portion of Huntington City's water supply. Water is collected from springs in the Panther Member. Regular flow is estimated at 300 gal/min.

97.9 On the left is Crandall Canyon, the site of the new Genwall mine. To date, the only construction has been a bridge across Huntington Creek.

100.9 Forks of Huntington Creek.

109.7 Electric Lake. This resevoir serves as a water impoundment to assure steady supplies for Utah Power and Light's

Huntington Power Plant. The lake and surrounding area contains four coal seams of about five ft thick each. The coal stratigraphy closely approximates the Eccles Canyon section shown on Figure 3.

End of Field Trip Log. Return to Salt Lake City.

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HISTORY OF COAL MINING IN THE WASATCH PLATEAU AND BOOK CLIFFS COAL FIELDS

(Modified from Hauck and Weder, 1980)

Coal was first discovered in the Castle Valley area of Utah by Captain J.W. Gunnison of the U.S. Corps of Topographical Engineers in 1853. However, these deposits were ignored and forgotten during the subsequent settlement of the area by Mormon pioneers in the late 1860s and early 1879. Coal was rediscovered in the Wasatch Plateau in 1874. Mining began the following year in Huntington Canyon with the establishment of the Fairview Coal and Coke Company and a small mining town called Cannelsville.

By 1876, a number of mines had been developed in Coal and Huntington canyons. Plans for a railroad line connecting existing coal operation in the Sanpete Valley to mines in the Castle Valley were drawn up by the line was never built. The Fairview Coke and Coal Company failed in 1878 after only three years of operation due to haulage expenses and coke quality problems.

About the same time, the Pleasant Valley Coal Company, headed by Milan O. Packard, constructed a wagon road from Springville up to Spanish Fork Canyon to Pleasant Valley and in 1877 the no. 1 mine in Winter Quarters Canyon was opened. A narrow gauge rail line was completed from Springville through the Spanish Fork Canyon in October in 1879 by the Pleasant Valley Railroad Company (a haul to Springville by wagon road occupied four days in good weather while in winter the road was impassable). The Pleasant Valley area proved to be extremely productive and the first three large scale mines in eastern Utah were established in this area when the Mud Creek Mine was reopened in 1882 followed by the 1884 opening of the Union Pacific Mine at Scofield just east of Winter Quarters.

In their efforts to gain control of territorial coal supplies, the Denver and Rio Grande Railroad extended its lines from Colorado through Utah.

Although the line was originally graded through Castle Valley and Salina Canyon, the route of the railroad was altered, going through Price and Spanish Fork Canyon thereby accessing the rich coal areas of what was to become Carbon County.

Further expressing its interest in Utah coal, the Denver and Rio Grande Western (Denver and Rio Grande's Utah holdings) bought out the independently owned Pleasant Valley Railroad Company and Pleasnt Valley Coal Company in 1882. Shortly thereafter, the Union Pacific Railroad Company entered the Pleasant Valley area in order to protect its threatened hold of Utah coal. The Union Pacific then formed the Utah Central Coal Company in 1883 and opened the Union Pacific Mine near Scofield in 1884. As a result of this activity, the railroad companies almost totally dominated the ownership and production of the Utah mines until the early 1900s.

In 1888, a mine was opened at Castle Gate on the Price River near the mouth of Price Canyon. The next year, a new mine began operations at Sunnyside about 25 miles east of present-day Price at the base of the Book Cliffs. The Sunnyside no. 2 mine also began its production in 1889. Both the Sunnyside and the Castle Gate coals were utilized for coking purposes.

In 1906, the first of the coal operations which managed to remain free from railroad control began production at Kenliworth, 3 mi east of Helper. This enterprise was financially backed by James Wade and F.A. Sweet and was appropriately called the Independent Coal and Coke Company because of its unique onwership status. Sweet, one of Utah's most prominent coal authorities, also opened a mine on the middle fork of Miller Creek in 1908 and named the camp Hiawatha. This locality at the foot of Gentry Mountain was the scene of further coal mining development when the Black Hawk Mine was opened by Brown and Eccles in 1911. A few miles to the south in northern Emery County, a small wagon mine was purchased by the Castle Valley Fuel Company and the town, Mohrland, was named from the initials of the company's four major figures; Mays, Orem, Heiner, and Rice. In 1916, W.H. Wattis undertook the last development in this area at Wattis, several miles north of Hiawatha on the flanks of the Star Point ridge of Gentry Mountain.

The decade from 1911-20 saw an explosion of activity in the coal producing regions of central Utah with many new mines being opened in hitherto undeveloped area. In 1911, Frank Cameron prospected the region around Panther Canyon on the Price River, and in 1914, the first coal was shipped out by the Utah Fuel Company which had leased the properties to Cameron for development. Cameron also developed and opened a small camp at the base of Castle Rock located directly on the main line of the Denver and Rio Grande Western Railroad. The camp's name was changed many times as was its ownership. Originally known as Bear Canyon, the camp was soon called Cameron, for its developer, then Rolapp, and finally, Royal as ownership changed.

In 1912, Jesse Knight, one of the most prominent men in Utah mining history, bought 1,600 acres of coal land west of Helper to provide coal for his smelting operations in the Tintic District. His mine, located in Spring Canyon, began production in 1913 and was the first of many mines in the Spring Canyon District, which became known as one of the most prolific coal producing areas in eastern Utah. Soon after the establishment of Storrs (Spring Canyon), F.A. Sweet opened another mine in Spring Canyon at Standardville (so called because it was considered to be the standard for the development of future mining camps). The year 1914 saw the opening of the Latuda Mine and camp by Liberty Fuel Company. New mines were also opened in 1916 at Peerless and Rains. The last mining development undertaken in the Spring Canyon District was Mutual Coal Company's Mutual and Little Standard operations, begun in 1921 and 1925, respectively.

The final major coal producing area to be opened in east-central Utah was the Gordon Creek District. This region had first been prospected in 1908, but was finally brought to prominence in 1920 by A.E. Gibson, the superintendent of the Spring Canyon Mine. Mines were developed in this area up until 1925 by Consumers Mutual Coal Company, National Coal Company amd Sweet Coal Company. The operations of all three companies ceased by 1950.

After the development of the Gordon Creek area, areas previously developed experienced further interest and activity. In 1922, the Columbia Steel Company opened a mine at Columbia near the location of Sunnyside's in order to exploit the excellent coking coal obtainable from the region. A very late development of the same coal seams that supported the Columbia operation was initiated in Horse Canyon in 1942 by the United States government to support steel production activities at its Geneva plant near Provo, Utah. Both the mine and steel plant were purchased by U.S. Steel after World War II and have continued in operation to the present.

Most of the mines in east-central Utah continued production through the heavy demand years of World War II and the years of prosperity that followed. However, a combination of overdevelopment, increased use of other natural fuels, rising costs associated with expensive underground haulage and labor, and the Depression of the late 1920s and early 1930s caused several camps to be abandoned. Among the first mines to fail were the long exploited Pleasant Valley mines. Winter Quarters, near Scofield, was closed down in 1928 while Scofield and Clear Creek experienced reductions of operations during the 1920s and 1930s, respectively. The operation at Rains was also forced to cut back on activities in 1930. Despite these setbacks, in 1929, there were 22 coal mines operating in Carbon, Emery and Grand counties, with the production of these mines providing 98 percent of the state's output.

Economic and production difficulties continued to plague Utah's coal industry during the decade of the 1930's, forcing the closure of the Mutual and Mohrland mines in 1938. World War II brought a temporary respite to the general downward trend with many mines achieving their highest production levels the war years and immediately thereafter.

The 1950s signaled the end for most of the eastern Utah coal mining operations as the adaption of coal for new uses was insufficient to keep pace with this fuel's replacement in many of its traditional roles. The increasing use of natural gas for heating homes and heavy industry use and the railroad's switch to diesel power were among the developments which severly hurt the coal industry. This bleak picture has drastically changed with the advent of America's "energy shortage." New technologies and markets for coal have caused dramatic upswing in coal production in east-central Utah. Mines which were closed, or kept running with skelton crews, have begun to increase operations and an intense competitive spirit is present among organizations attempting to expand their reserve bases and corner lucrative markets.

REFERENCES

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UTAH GEOLOGICAL AND MINERAL SURVEY

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THE UTAH GEOLOGICAL AND MINERAL SURVEY is a Division of the Utah Deparment of Natural Resources and Energy and operates under the guidance of a Governing Board appointed by the Governor from industry and the public-at-large. The Survey is instructed by law to collect and distribute reliable information concerning the mineral resources, topography, and geology of the state, to investigate areas of geologic and topographic hazards that could affect the citizens of Utah, and to support development of natural resources within the state. The *Utah Code annotated, 1953 Replacement Volume 5, Chapter 36, 53-36-1 through 12,* describes the Survey and its functions.

The Survey publishes bulletins, maps, a quarterly newsletter, and other publications that describe the geology of the state. Write for the latest list of publications available.

THE SAMPLE LIBRARY is maintained to preserve well cuttings, drill cores, stratigraphic sections, and other geological samples. Files of lithologic, electrical, and mechanical logs of oil and gas wells drilled in the state are also maintained. The library's collections have been obtained by voluntary donation and are open to public use, free of charge.

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