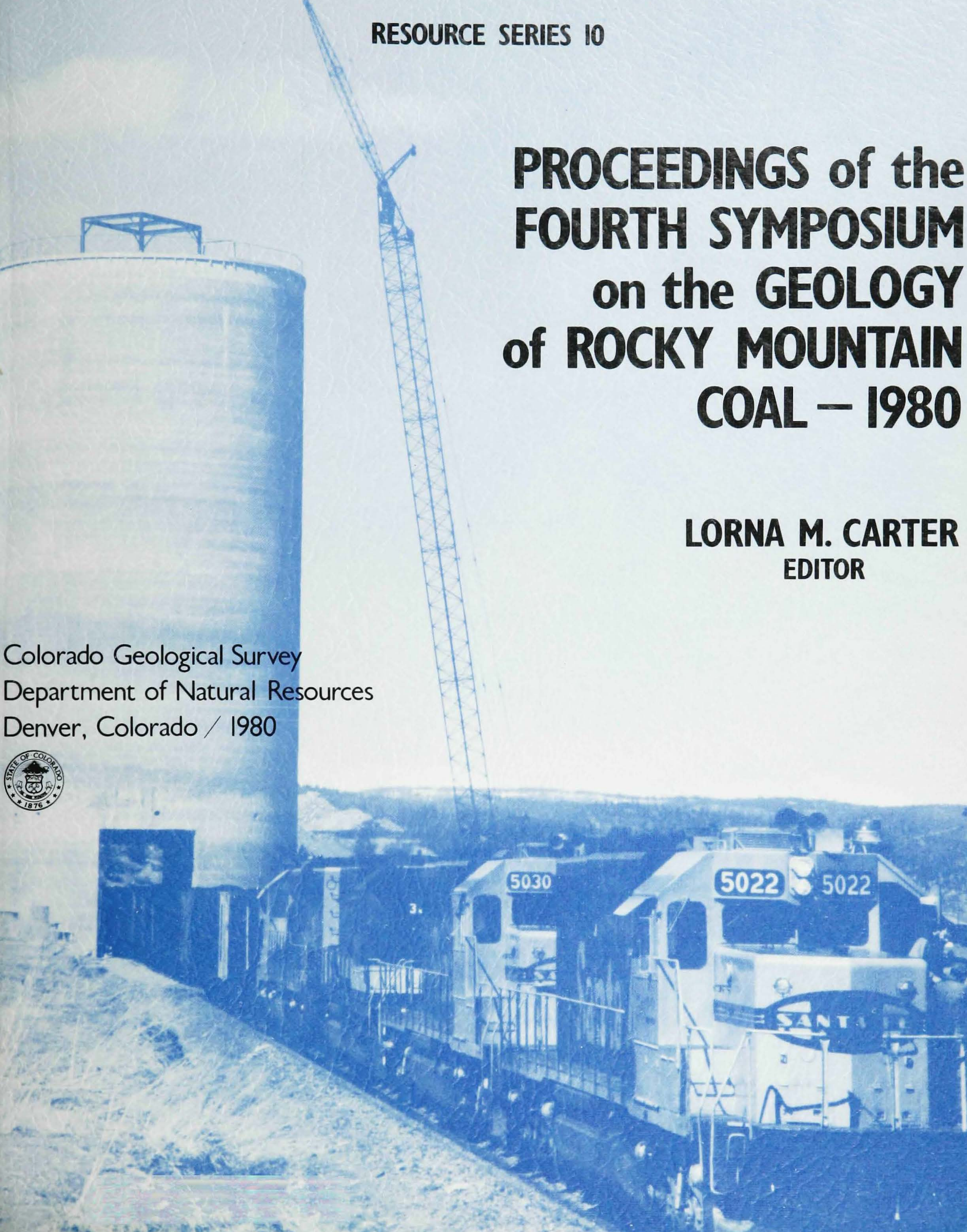

RESOURCE SERIES 10

PROCEEDINGS of the FOURTH SYMPOSIUM on the GEOLOGY of ROCKY MOUNTAIN COAL — 1980

LORNA M. CARTER
EDITOR

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado / 1980

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DOI: https://doi.org/10.58783/cgs.rs10.sogs7814

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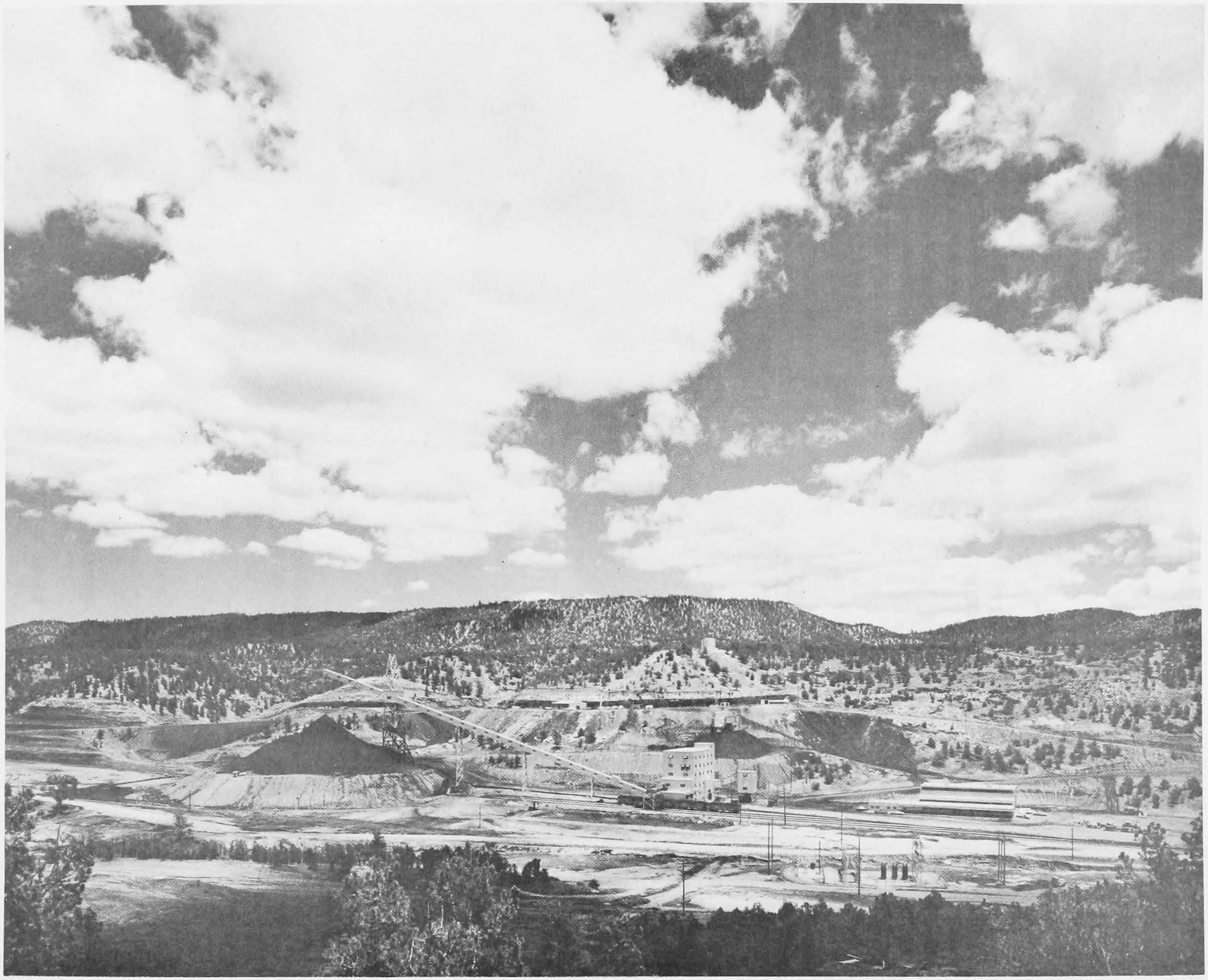

Frontispiece.--York Canyon mine showing outcrop of the coal, wash plant, and unit train loading facility. Raton coal field, northeastern New Mexico. Photograph courtesy of Kaiser Steel Corporation.

Cover photograph.--Loaded unit train exiting silo strip-coal loading facility, York Canyon mine, Raton coal field, New Mexico. Photography courtesy of Kaiser Steel Corporation.

FOREWORD

The 1980 Symposium on the Geology of Rocky Mountain Coal is to be held April 28-29, 1980, on the campus of the Colorado School of Mines in Golden, Colorado. This symposium, the fourth in a series, is sponsored by the Colorado Geological Survey, the U.S. Geological Survey, the Colorado School of Mines, and the Colorado School of Mines Research Institute, and supported by the Energy Minerals Division / American Association of Petroleum Geologists. The symposium will be followed by a 2-day field trip (April 29-May 1, 1980) to the Raton Mesa coal region, northeastern New Mexico and southeastern Colorado.

Since the last Rocky Mountain Coal Symposium, held in 1978 in Billings, Mont., the price of oil has gone through the roof and we've seen long lines at the gas pumps; the increased costs and scarcity of petroleum have affected the lives of all Americans. An obvious alternative to part of our fossil fuel needs involves this country's vast coal resources—in particular the almost 3 trillion tons estimated by the U.S. Geological Survey to lie in the Rocky Mountain and Northern Great Plains coal provinces. The purpose of this and previous symposiums in the series has been to promote an exchange of ideas and technical information so that informed decisions involving these resources can be made.

The technical sessions, the special addresses, and the field trip were all designed to provide geologists involved in exploration, development, and reclamation with information on recent work and thinking on a number of different aspects of the geology of coal and coal-related rocks. In this respect, this year's emphasis is similar to that of the first Rocky Mountain Coal Symposium held in 1976. The 1977 symposium emphasized depositional models, while the emphasis of the 1978 symposium was on geology and coal resources of the Powder River Basin, Montana and Wyoming.

Abstracts or extended abstracts of the 30 papers to be presented at the symposium are included in this volume. Also included herein is a paper by Tom Wollenzien, "Geology of the Decker Coal Area," which was presented at the 1978 Symposium. Proceedings of the 1976 and 1977 symposiums have been published by the Colorado Geological Survey as Resource Series numbers 1 and 4 respectively. This volume, a companion to the two earlier proceedings volumes, should add significantly to the information available on the geology of Rocky Mountain coals.

Joseph R. Hatch
General Co-Chairman
March 21, 1980

THE RO MO COAL FIELD TRIP

The RoMo Coal field trip for 1980 will travel to New Mexico and tour part of the Raton coal field in northern New Mexico, and the Trinidad coal field in southern Colorado. Highlights of the trip will be a tour of Kaiser Steel Corporation's York Canyon coal mine near Raton, and a visit to the Delagua mine northwest of Trinidad.

The field trip will leave the Green Center by bus following the final session of the Symposium on Tuesday afternoon, and travel south to Raton, New Mexico. A gourmet box banquet will be provided en route in addition to necessary liquid accompaniments. Bus leaders will give a running commentary on the geology until darkness overtakes us. The Holiday Inn in Raton will be field trip headquarters; in the event that the trip is fully subscribed, overflow will be lodged at the nearby Sands Motel.

Breakfast will be served from 6:00 to 7:00 A.M. Wednesday morning at the Holiday and Sands restaurants, and the buses will depart at 8:00 A.M. The route will take us west from Raton, through the eastern part of the Raton coal field, past York Canyon mine, to Vermejo Park, headquarters of Pennzoil's Vermejo Ranch. An opportunity to tour the grounds of the Bartlett mansion will be provided and a barbecue-style lunch will be served on the grounds. Following lunch, we will return to York Canyon mine, where mine officials will describe the mining operation.

Following the mine tour, we will return to Raton where, after removal of dust and grime, Teton Drilling will host a cocktail party at the Holiday Inn, which will be followed by a prime-rib dinner served at the Raton Elks club. Thursday breakfast will again be at the motel restaurants, with departure time at 7:30 A.M.

We will proceed over Raton Pass and will make one or two stops, where Henry Roehler of the USGS will discuss intraformational structures and sedimentation in the Raton Formation. Near Starkville, we leave the Interstate for a stop at new railroad cuts, where Romeo Flores, also of the USGS, will present his ideas regarding deltaic depositional environments of the Trinidad Sandstone. We will then proceed to Cokedale, Colo., where residents of the town will serve a Mexican-style lunch and discuss the mining history. Follwing lunch, we will continue on to the Delagua mine west of Ludlow for a tour of the surface-mining operation. Following the Delagua tour, the buses will return to the Green Center in Golden.

Appreciation is extended to the New Mexico Geological Society for authorizing use of the 1976 Vermejo Park Guidebook second and third day road logs and reprinting of the articles on "History of Verjemo Park," and "Underground and Surface Operations at the York Canyon mine." Copies of the 1976 NMGS Vermejo Park Guidebook, which contains much additional information on the areas of the field trip, will be available for purchase during the Symposium.

Bus and field trip leaders will be Glenn Scott, Glen Izett, Henry Roehler, and Romeo Flores, all of the U.S. Geological Survey; others may also be involved. Thanks are also extended to Roger Carlson and the exploration staff of Kaiser Steel Corporation for making arrangements for lodging and the banquets in Raton and for presenting a discussion of the exploration program. Thanks also to Ed Moore, superintendent of the York Canyon mine and his staff for arranging the mine tour and describing the operation at York Canyon and Potato Canyon. Access to the Ranch and lunch at Vermejo Park, arranged by Lewis Kestenbaugh of Pennzoil, is also much appreciated. Thanks also to the residents of Cokedale for arranging lunch at their historic townsite. Thanks are also extended to Al Wiggins of the Delagua mine for leading us through his operation.

Special appreciation is extended to our editorial assistants Sherri Iannacito and Sara Keehnen of the USGS for enabling us to make the deadline and include the road logs in the Proceedings Volume.

Charles L. Pillmore
Field Trip Chairman
April 1, 1980

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MAJOR FACTORS INFLUENCING THE DISTRIBUTION OF CRETACEOUS COAL IN THE WESTERN INTERIOR UNITED STATES

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The great epicontinental seaway that flooded the Western Interior of the United States from late Albian through Maastrichtian time fluctuated broadly in response to large-scale eustatic, tectonic, sedimentologic, and climatic cycles. Dynamic shifts in marine and marginal marine facies and biotas resulted, including those associated with major coal deposits. These changes are largely reflected in a succession of five marine megacyclothems formed during widespread transgressive-regressive (tectono-eustatic) events, which are well defined by vertical offshore stratigraphic successions, and by major migrations of strandline facies. Across the center of the Western Interior Basin, these comprise (fig. 1):

1. The Kiowa-Skull Creek Cyclothem (late Albian) within the upper part of the Dakota Group along the basin axis;
2. The Greenhorn Cyclothem (latest Albian-middle or earliest late Turonian) including, for example, the upper part of the Dakota Group, the Mowry and Graneros Shales, the Greenhorn Formation, and the Carlile Shale or their equivalents, through regressive sandy facies of the Codell, Turner, and Ferron Members;
3. The Niobrara Cyclothem (late Turonian-earliest Campanian) including, for example, the Juana Lopez and Sage Breaks Members of the Carlile Shale, the Niobrara Group, and the "transition member" through the regressive part of the Apache Creek Sandstone Member, Pierre Shale, in Colorado, or the upper part of the Ferron Sandstone, the Blue Gate Shale and the lower Emery Sandstone Members of the Mancos Shale in Utah;
4. The Clagget Cyclothem (early to early late Campanian) including, for example, the Eagle Sandstone-Clagget Shale-Parkman Sandstone sequence in Montana; the Blair-Rock Springs-lower Ericson sequence in southern Wyoming; the Point Lookout Sandstone-Menefee Formation-lower Cliff House Sandstone sequence in New Mexico; and the upper Emery Sandstone-Masuk Shale-basal Mesaverde Group sequence in Utah; and
5. The Bearpaw Cyclothem (middle late Campanian-Maastrichtian) including, for example, the upper Judith River-Bearpaw Shale-Fox Hills Sandstone-Hell Creek sequence of Montana, or the Cliff House Sandstone-Lewis Shale-Pictured Cliffs Sandstone-Fruitland-Kirtland sequence of New Mexico.

Major coal deposits are found associated with each megacyclothem (fig. 1).

Primary eustatic control on the development of these cyclothems is evidenced by rather precise correlation of points of initial transgression, peak transgression, and terminal regression throughout the Western Interior seaway with equivalent events in the

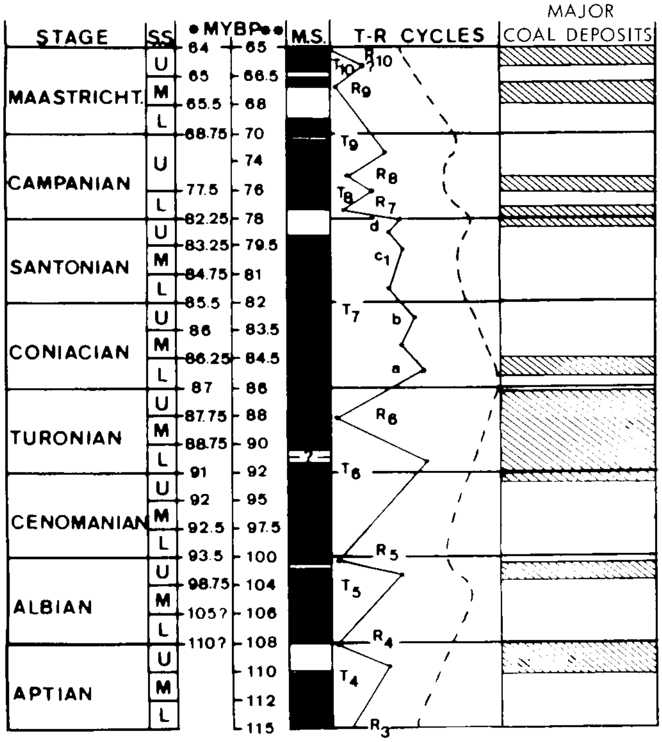

Figure 1.--Generalized diagram showing Aptian through Maastrichtian history of eustacy and coal deposition in the Western Interior of North America. From left to right columns show stages, substages (L, lower; M, middle; U, upper), radiometry based on Western Interior K-Ar dates on bentonites (from Kauffman, 1977), the van Hinte standard time scale for the Cretaceous (van Hinte, 1976), standard Cretaceous magnetostratigraphy, the sealevel curve of Kaufmann (1977) based on worldwide transgressions and regressions with synchronous peaks (T_4 occurs in Canada, T_5-R_9 occur in the interior United States), a generalization of this curve, and (cross-hatched) the stratigraphic levels where coals are common and of commercial grade in the Western Interior Basin.

coastal plain sequences of North America and many other parts of the world. These correlations depend upon a highly detailed, fully integrated system of biostratigraphy and geochronology; the Western Interior Cretaceous is unparalleled in this respect. These sedimentation events have been modeled as simply symmetrical cyclothems with uninterrupted transgressive-regressive migrations of the strand, inferring continuity in the rise and fall of sealevel. Detailed analysis of the rock record, however, depicts a much more variable history. Only in the depositional center of the basin are the cyclothems fully preserved, suggesting rates of tectonic subsidence that periodically exceeded rates of subsidence caused by sediment loading. Regional paraconformities and subtle disconformities cut the midbasin sequence and may reflect offshore sediment starvation during episodes of rapid transgression. Toward the margins of the Western Interior Basin, the broad transgressive and regressive events were frequently interrupted by major reversals in strand migration and sedimentation patterns; these are mainly expressed as widespread progradational events that were most commonly developed along the tectonically active western margin of the seaway. Thick Cretaceous coals are most extensively developed in association with these progradational events. Toward the east, on the stable cratonic platform, the cyclothems are thinner and more asymmetrical due to shortening of the transgressive sedimentary sequences by numerous widespread disconformities.

Despite the different development of these cyclothems in depositional sites along the western margin, in the depositional axis of the basin, and on the eastern platform, the major transgressive peaks are essentially synchronous (within 1-2 faunal zones) throughout the Western Interior; in nearly every area, these peaks effectively overprint regional and local tectonic or sedimentologic events. The erosional transgressive and regressive surfaces, however, are regionally diachronous across the basin, so that only the oldest age of a transgression and the youngest age of a regression are useful for interregional correlation of eustatic events.

Dating of the various interruptions or reversals in the development of these Western Interior cyclothems suggests that many of them may be basinwide; that is, a progradational event may be synchronous at various places along the entire basin margin, rather than being purely a local phenomenon. Thus episodes of coal formation associated with major progradational events may be predictable. The sharp transgressive disconformities that characteristically develop on top of progradational sequences may also be widely correlative. Similarly, major disconformities that cut the cyclothems on the stable eastern platform seem to have regional extent, and many of them are precisely correlative with disconformities, bypass surfaces, and hardgrounds developed in rocks of the same age in Europe. All of these factors suggest that major progradational events and disconformities or paraconformities in the Cretaceous marine sequence reflect eustatic events—minor stillstands or small-scale reversals superimposed upon the large-scale variations in sealevel. Attempts are now being made to relate transgressive events along the western strand margin with disconformities on the eastern platform as a test for eustatic control on their development. Dating of the large-scale eustatic cycles suggests that, on the average, the transgressive events (eustatic rise) were longer in duration (average 4.9 m.y.) than were the regressive events (eustatic fall), which average 3.5 m.y.

The timing of eustatic events in the Western Interior, as reflected in sedimentary megacyclothems, also shows a strong relationship to tectonic processes. For example, maximum subsidence rates within the basin, active thrusting and mountain building along the western margin of the seaway, rapid clastic sedimentation along this margin, and the greatest number and magnitude of volcanic events (as reflected by ash falls) seem to be associated with eustatic rise and regional transgression. In general, these were also times of more rapid plate spreading, suggesting a megatectonic link between the processes. Conversely, eustatic fall and regression were times of relative tectonic and volcanic quiescence in the basin, reduced rates of subsidence caused by sediment loading, and infilling of the basin. These last two factors have important connotations to coal geology, as do the physiographic consequences of transgression and regression. Transgressive events produced dissected landscapes and relatively narrow coastal plains as a result of continuous encroachment of the sea. During regression, broad, flat, wet coastal lowlands were left behind by the retreating strand, and these were ideal sites for peat accumulation.

Finally, the climatic and biological changes that resulted from major fluctuations in sealevel are an important consideration in attempting to model the environments that were conducive to massive peat accumulation in the Western Interior Cretaceous Basin. Widespread transgression of warm, shallow seas must have produced an amelioration of the regional climate, leading to a maritime climate characterized by low seasonality, high levels of moisture in the atmosphere, and relative warming of regional temperatures. As these conditions developed, biotic productivity in both marine and continental environments would have increased significantly. Regression must have resulted in decline of the maritime effect, greater seasonality, and somewhat lower temperatures in the Western Interior region. Isotopic and floral data support these interpretations. But since most of the Western Interior region remained within warm to mid-temperate climatic zones during the Cretaceous, and since all but the terminal Cretaceous regression were only partial withdrawals of the epicontinental sea, these climatic fluctuations would have been superimposed upon what remained basically a maritime climate with high atmospheric moisture levels. Biotic productivity remained high throughout the broad coastal lowlands that surrounded the Cretaceous seaway. The stage was thus set for massive peat accumulation leading to the development of the great Western Interior coal fields.

How do these diverse effects of major eustatic (transgressive-regressive) and tectonic cycles explain the observation that most of the thick coal accumulations in the Western Interior Cretaceous basin are associated with regressive deposits, and especially with major progradational events along the western margin of the seaway? The answer is complex but allows construction of a model that may enhance our ability to predict the occurrence of important coal deposits in sedimentary basins on the craton.

Despite climatic amelioration and high biotic productivity associated with transgressive episodes, representing significant eustatic rise in sealevel, the physiographic and tectonic setting of the Western Interior Basin was not conducive to large-scale peat accumulation at these times. Dissection of the marine margin produced relatively narrow coastal plains with well-drained uplands adjacent to them. Basinal subsidence was relatively rapid and exceeded downwarping due to sediment load; the delicate balance between subsidence and sedimentation that characterizes major peat-forming swamps today was not generally maintained during Cretaceous transgression. Further, the strata that directly underlay the deposits of a new transgression had already undergone compaction. This situation was not conducive to further compaction and subsidence necessary to maintain conditions for peat accumulation in coastal swamps. Active tectonic uplift along the western margin of the seaway during transgression resulted in rapid clastic sedimentation and dilution of organic deposits in coastal plain sites. Progradational events during transgression were relatively few and short lived, compared with their development during regression; the upper surfaces of these progradational sequences were deeply eroded by subsequent transgressive pulses, in some cases exposing peats to the influence of saline waters. There are many indications that this set of conditions produced poorer quality coals—higher in sulfur and ash content—than did environmental conditions that prevailed during regression. As a consequence of these factors, transgressive coals are normally thin, laterally discontinuous, few in number, and of relatively poor quality. Only those coals associated with major progradational events that interrupted a transgressive trend regionally should be of commercial quality.

In contrast, conditions for widespread peat accumulation were optimal during regressive phases of the Western Interior epicontinental seaway, especially along its western margin. Tectonic processes waned so that basin subsidence was balanced with sediment loading, and clastic sedimentation rates generally declined along the western margin of the basin. Broad, low coastal wetlands left behind by the retreating sea became the sites of extensive peat accumulation. These sites were floored by sediments still undergoing compaction and consequently subsided in response to sediment loading. Climates were mild and wet, and productivity was high. The ultimate demise of peat-forming basins was more commonly a result of fresh-water fluvial processes, and thus the peats were largely protected from infiltration and contamination by saline waters. The best quality coals, and virtually all of the major coal deposits of the Western Interior Cretaceous, formed during major regressive phases of the Western Interior seaway (for example, the Ferron, Frontier, Gallup, Mesaverde, Rock Springs, Adaville, Trinidad-Vermejo, and some of the Dakota coal deposits).

Recognition of coal formation and coal quality as the product of a dynamic environmental system in the Western Interior, driven by tectonic and eustatic cycles, allows establishment of generalized models useful in the prediction of and exploration for coal resources of the Cretaceous.

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DELTAIC COALS OF THE FERRON SANDSTONE MEMBER OF THE MANCOS SHALE: PREDICTIVE MODEL FOR CRETACEOUS COALS OF THE WESTERN INTERIOR

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Study of the Upper Cretaceous Ferron Sandstone Member of the Mancos Shale in the Emery coal field, central Utah, has led to development of a predictive model for deltaic coals in the Western Interior United States. The Ferron records the activity of a moderate- to high-constructional delta that repeatedly prograded in a northeasterly direction onto the western shelf of the Interior Cretaceous seaway during late Turonian time. On outcrops in southern Castle Valley, the Ferron consists of five major delta cycles (fig. 1). Each cycle contains one coal "zone"—a major coal bed plus associated splits and rider coal beds—except for the first delta cycle, which contains only thin coal beds. A clear relationship exists between the geometries of the thick coal bodies of the Emery coal field and the geometries of their associated delta-front sandstone units. In each cycle, the thickest coal occurs in a belt about 10 km wide that is situated just landward of the landward pinchout of the associated delta-front sandstone. This relationship constitutes the predictable element of the coal model. Superimposed is an unpredictable element—the effects of distributary channels that existed contemporaneously with the peat-accumulating swamps. The deposits of these distributaries divide the "belt" of thick coal into bodies whose long axes are generally oriented at a high angle to the paleoshoreline.

The C coal bed of the Emery coal field (fig. 1) illustrates these relationships well. Figure 2, an isopachous map, shows the geometry of the thick part of

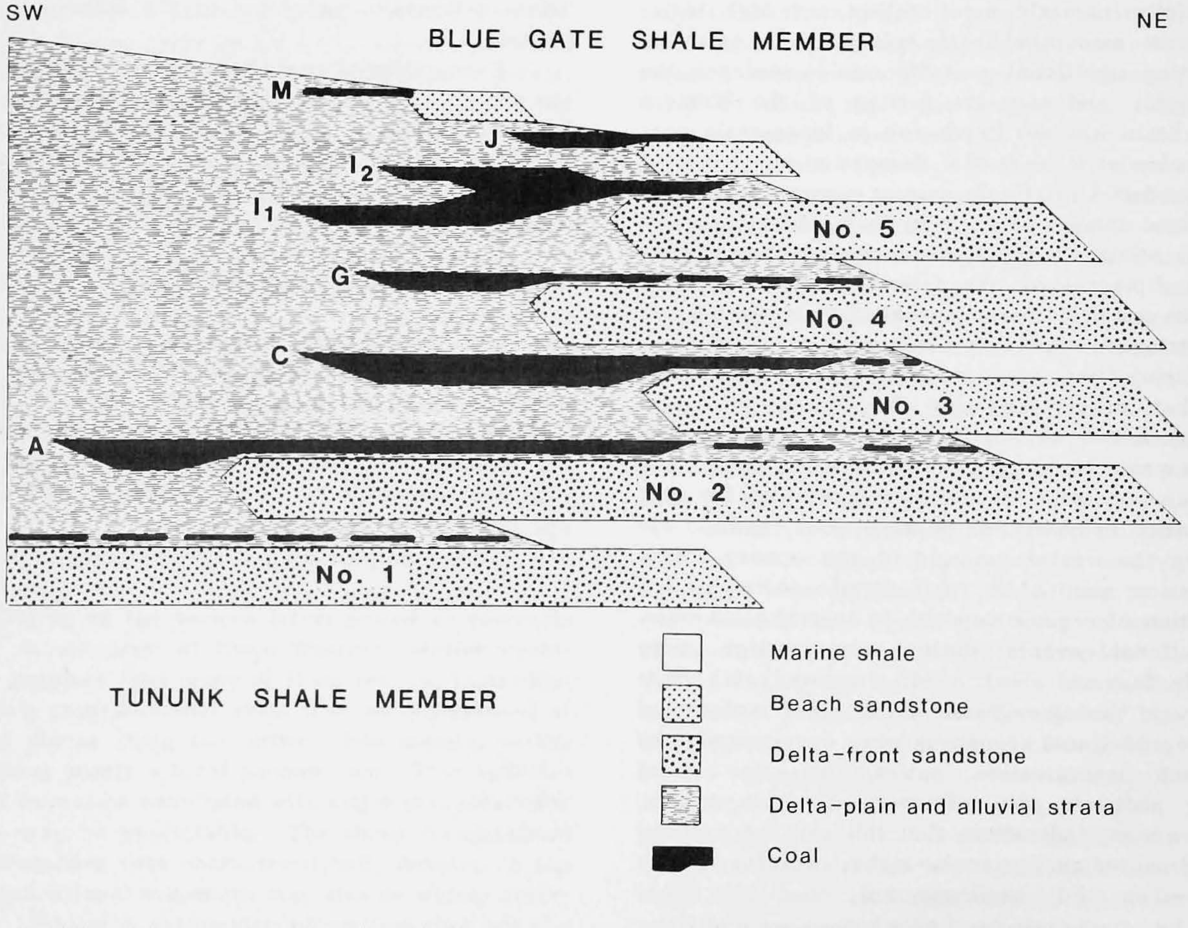

Figure 1.--Schematic cross section through the Ferron Sandstone Member of the Mancos Shale in the area of the Emery coal field, Emery and Sevier Counties, central Utah. Major coal beds of the Emery coal field carry letter designations; major delta-front sandstones of the Ferron carry number designations.

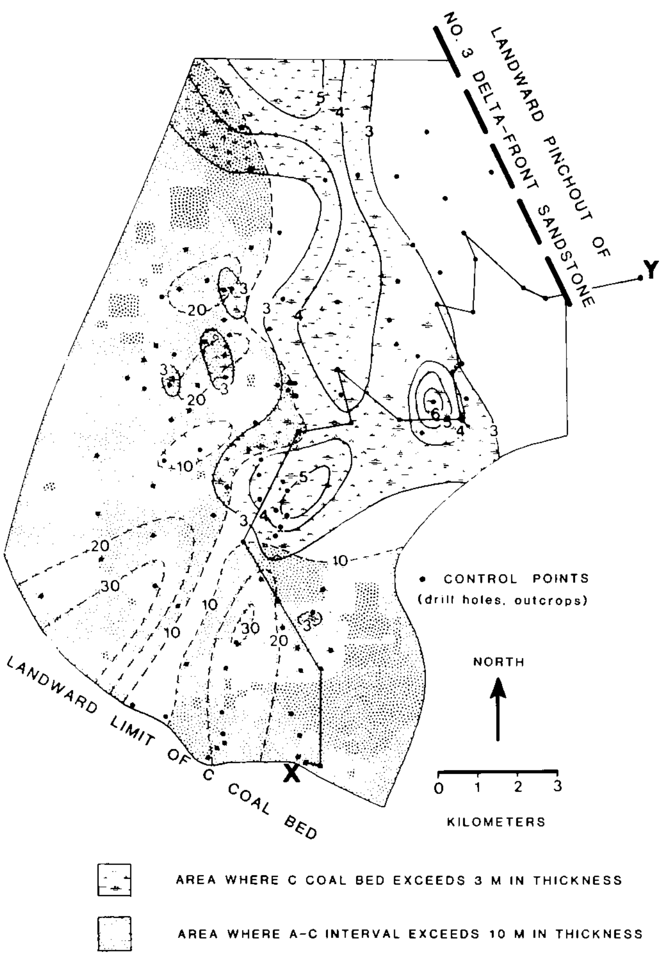

Figure 2.—Isopachous map showing thicknesses of the C coal bed (solid lines) and the A-C interval (dashed lines), and the position of the landward pinchout of the No. 3 delta-front sandstone unit. Landward to SW, seaward to NE.

the C coal bed, "thick" being arbitrarily defined here as 3 m or greater. All of the thick coal occurs within about 10 km of the pinchout of the associated No. 3 delta-front sandstone unit. Also isopached in figure 2 is the thickness of the interval between the top of the A coal bed and the base of the C coal bed. Two thick bodies are apparent within the A-C interval. The eastern one can be examined on the outcrop—it is a fluvial unit consisting of crossbedded channel sandstone plus associated overbank deposits. The western body, present only in the subsurface, is also believed to be a fluvial unit.

An inverse relationship is apparent between the thickness of the A-C interval and the thickness of the C coal bed, the thickest coal occurring where the interval is thinnest. Tracking of tonsteins—layers of volcanic ash altered to kaolinitic claystone and, therefore, time lines—along line X-Y, which approximates the outcrop of the Ferron, demonstrates that the body of peat from which the thick body of the C coal bed formed accumulated contemporaneously with parts of both the fluvial system near point X and the No. 3 delta-front sandstone near point Y. Clearly, a genetic relationship exists among these three units: the fluvial units were distributaries that fed the prograding No. 3 delta-front sand unit, while peat accumulated in the area between the distributaries.

It is anticipated that the predictive model developed for the Ferron will prove to be valuable in coal exploration in other deltaic units in the Western Interior. The landward pinchouts of delta-front sandstones and their trends can be established through outcrop studies and the 10-km-wide "belts" in which thick coal is most likely to occur thereby identified. Some fluvial channel systems can be identified on the outcrop and their trends projected into the subsurface. Others must be identified by drilling. Application of the predictive model could lead to exploratory drilling programs that are far more efficient than drilling programs laid out using a simple grid pattern or employing a "shotgun" approach.

STRATIGRAPHIC AND STRUCTURAL ASPECTS OF COAL IN UPPER CRETACEOUS MENEFEE AND FRUITLAND FORMATIONS AT DURANGO, COLORADO

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Upper Cretaceous formations that are well exposed along the Animas River at Durango include the Mancos Shale, Point Lookout Sandstone, Menefee Formation, Cliff House Sandstone, Lewis Shale, Pictured Cliffs Sandstone, and Fruitland Formation. The Menefee and Fruitland Formations contain coal formed in a variety of depositional settings along the Upper Cretaceous (Campanian Stage) coast. Interpretations of these settings are based on lithologic sequences, sedimentary structures, trace fossils, coal petrography, and palynomorph assemblages.

The upper Mancos, Point Lookout, and Menefee section represents a prograding delta lobe that eventually was submerged by the Cliff House-Lewis transgression. The sequence includes prodelta siltstones, delta-front sandstone, deltaic plain coal and shales, a major distributary channel sandstone, more deltaic plain coal, shale, and sandstone, and finally transgressive marine siltstone, sandstone, and shale. The Menefee coals are lenticular beds up to 8 ft (2.4 m) thick that formed between distributary channels on the deltaic plain.

The upper Lewis, Pictured Cliffs, and Fruitland section may represent a prograding interdeltaic barrier coastline with limited tidal influence at this locality. The sequence includes offshore claystone and siltstone, two barrier sandstones, thin brackish-water to freshwater lagoon and marsh beds, the thick Carbonero coal (freshwater swamp), and fluvial sandstones, shales, and coals. The Carbonero coal is an elongate bed as much as 73 ft (22.3 m) thick, trending northwest-southeast, that formed parallel to the stacked barrier sandstones.

Dominant fractures in shale and sandstone and the face cleats in coal have a remarkable uniform north-northwest orientation on and adjacent to the Hogback Monocline east and south of Durango. Orientations of the fractures and cleats are more variable west of Durango, but they trend mostly to the northwest. The overall fracture and cleat pattern suggests a basement-controlled regional system that varies mainly along certain folds and faults.

WAVE-DOMINATED DELTAS: AN IMPORTANT ECONOMIC DEPOSITIONAL MODEL FOR UPPER CRETACEOUS OF SOUTHWESTERN WYOMING

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INTRODUCTION

Wave-dominated deltaic deposits provide an economic model for exploration of laterally extensive economic coals in the Western Interior basin. Studies in the Upper Cretaceous Mesaverde Group (Rock Springs and Blair Formations of southwestern Wyoming) reported here give insights into the characteristics of wave-dominated deltaic environments. The widespread delta-front sheet sandstones associated with wave-dominated deltas produced substantial platforms upon which thick, laterally continuous coals could develop.

Components of wave-dominated deltas include thick prodelta deposits composed of graded-bedded siltstones and mudstones at the base of the sequence. Capping the prodelta deposits are distributary mouth bar sandstones at the mouths of distributary channels. Accumulations of delta-front sheet sandstones occur in interchannel areas due to high wave energies. Lateral continuity of these sandstones exists along depositional strike as well as dip. Coeval distributary channels tend to be straight or have low sinuosities with sediment fills varying from fine-grained mudstones to coarse-grained sandstones. Delta-plain deposits consist of lagoonal bayfill mudstones and small splay or bayhead delta sandstones formed in areas behind and marginal to the delta front. Multiple coarsening-upward sequences are capped by localized coals. Fluvial and upper delta plain areas consist of channel, levee, and backswamp materials that are laterally discontinuous. Backswamp coals that accumulated in this setting may be thick and low in sulfur but are laterally impersistent and often high in ash with multiple splits.

DEPOSITIONAL SETTING

In the Rock Springs Uplift, the Baxter Formation is comprised primarily of marine mudstones and some graded-bedded sandstones. It represents a tongue of the Mancos Shale that extends into the nearshore environments of the Mesaverde Group (Miller, 1977) and is part of the third major transgression of the Cretaceous of the Western Interior (Weimer, 1960).

The Airport Sandstone Member of the Baxter is predominantly marine sandstones with graded beds and mudstones. This unit was probably deposited in a delta front to prodelta depositional setting. In the subsurface to the northwest, the Airport Sandstone Member grades laterally to delta-front and delta-plain deposits from which there has been minor oil and gas production (Robert J. Weimer, oral commun.).

Gradationally overlying and interfingering with the upper portion of the Baxter Formation is the Blair Formation. The lower portion of the Blair is graded-bedded marine sandstones and mudstones that were deposited in subaqueous channels. These channels appear to have developed in deeper water at the base of the prodelta slope of the Rock Springs-Blair delta complex. The upper 1,900 ft of the Blair Formation is composed predominantly of marine mudstones with some intercalated graded-bedded sandstones with scoured bases and burrowed tops. The frequency and thickness of sandstone interbeds increases upward in the sequence.

Gradationally overlying and interfingering with the upper portion of the Blair Formation is the Chimney Rock Member of the Rock Springs Formation, composed of massive nearshore marine sandstones. In combination, the Rock Springs and the upper portion of the Blair were deposited in a wave-dominated delta system: the Blair accumulated in prodelta facies and the Rock Springs in delta-front, delta-plain, and fluvial environments. The delta-front deposits of the Rock Springs Formation are composed of some distributary mouth bar sandstones. Interdistributary areas were filled with reworked sandstone barriers formed as a result of high wave energies. Trend of the shoreline for these delta-front sandstones is N. 40° E.

In the lower portion, these delta-front marine sandstones are tan in color, commonly are calcareous cemented, and range from poorly to well sorted. Within the lower part of a sandstone unit, individual beds have a scoured base and are dominated by flat to hummocky bedding. The tops of these beds may be rippled and often contain some large, smooth-walled burrow structures. Generally, though, burrowing is sparse in these sandstones. This type of stratification may reflect periods of storm activity when diverse wave diffraction patterns are common in the nearshore environments. Similar bedding features have been observed in storm deposits of modern lower shoreface deposits of barrier systems (Kumar and Sanders, 1974), which would be equivalent to lower delta front deposits in a wave-dominated delta system.

The upper portions of the sandstone units are dominated by low-angle trough and planar cross-stratification. Southwesterly current orientations subparallel the N. 40° E. shoreline trend for this depositional system, indicating a longshore transport of sediment. Similar features to these have been observed in modern upper shoreface deposits of barrier systems (Kumar and Sanders, 1974; Barwis and Hayes, 1979), which would be equivalent to the upper delta front deposits in a wave-dominated delta system.

The sparseness of burrow structures within the Chimney Rock nearshore sandstones suggests that rapid sedimentation predominated in these delta-front sequences. This characteristic helps in distinguishing the delta-front deposits of a wave-dominated delta system from the shoreface sequences of a strandplain barrier system, where sedimentation rates are slower and burrowing is extensive.

To the north along the west flank of the uplift, these massive tan delta-front sandstones develop a series of three whitecaps in the vicinity of Reliance (fig. 1). Farther north in the Winton area, these whitecaps grade laterally into the delta-plain facies of the Rock Springs Formation comprised of coal swamp, salt marsh, lagoonal-bayfill and channel fill deposits. To the south, the massive sandstones of the Chimney Rock Member pass laterally into a series of graded-bedded sandstones and mudstones of the prodelta facies of the upper Blair.

Capping many of the delta-front marine sandstones of the Rock Springs Formation are white sandstones. The lower to middle parts of the whitecap sandstones are dominated by low- and high-angle trough cross-stratification that displays polymodal transport directions. This part of the whitecap represents the upper delta front environment and is comparable to the upper shoreface zone of barrier island deposits. The polymodal current directions may reflect a combination of onshore, offshore, and longshore transport. The upper portions of the whitecap sandstones represent the top of the upper delta front and are comparable to the foreshore zone of barrier island systems. This zone contains subparallel laminations indicating upper flow regime conditions produced by wave swash.

The whitecap sandstones are common, not only in the Rock Springs, but also in all the coal-bearing sequences of the Cretaceous of the Western Interior. These features are common in the Cretaceous coal-bearing sequences, but their origin is not well understood. Several theories and observations have been made.

One well-known theory on the origin of whitecaps suggests that they are leached zones of paleosols below the coals. The acid ground waters from the coal swamp leach the unstable minerals and put them in solution, the clays being altered to kaolinite. There is also a secondary solution and reprecipitation of quartz in the form of overgrowth. In support of this theory, alteration of clay minerals to kaolinite has been observed under modern peat swamps (Staub and Cohen, 1977), and the solution of unstable minerals and the reprecipitation of silica as quartz overgrowth have been reported under Carboniferous coals in the eastern United States (Horne and Ferm, 1976). However, in the Cretaceous whitecaps occur numerous areas of whitecaps but no overlying coals. In addition, the white sandstones often exhibit little silica overgrowth on the quartz grains and contain only minor amounts of clay minerals. The color of the whitecap sandstones is different on weathered and fresh exposures. Where black carbonaceous sandstones are weathered on outcrop, they take on a silver-white color. However, most whitecaps contain an organic-rich zone only in the upper few feet of the sandstone, which does not explain the origin of the entire whitecap.

In another theory, origin of the whitecaps is related to energy conditions of the depositional setting. The contact between the whitecap sandstones and the underlying tan-colored sandstones often occurs at the boundary between the lower energy lower delta front (lower shoreface) and the higher energy upper delta front (upper shoreface, foreshore) (John Balsley, oral commun.). Across this boundary, an abrupt increase in grain size usually occurs in the upper delta front, with most of the fine-grained constituents (biotites, micas, clays, and so on) being winnowed by the higher energy wave reworking and carried further offshore into the quieter lower delta front. Because of the lack of iron-bearing minerals in the upper delta front and their relative abundance in the lower delta front, the upper delta front sandstones remain white when weathered and their lower delta front equivalents are stained by the oxidation of the iron-bearing minerals. Although the contact between the whitecap and underlying tan sandstone often occurs at the boundary between the lower and upper delta front deposits, this is not always the case. Moreover, grain size does not always increase in the whitecapped sandstone at its contact with the underlying tan sandstone.

Another theory relates the origin of the whitecap sandstones to recent ground-water movements. Because the ground waters of coal-bearing strata tend to be acidic, it is theorized that these waters leach the unstable iron-bearing minerals from the whitecap. This theory predicts that the contact between the whitecapped sandstones and tan sandstones should occur at a permeability boundary, either due to a grain size change or to differential cementation. Since permeability boundaries often cross bedding planes, this theory is supported in instances where the boundary between whitecap and tan sandstone is askew to bedding. Although this has been observed occasionally, it is not commonly the case.

No single theory adequately describes the origin of the whitecap sandstones. However, an answer is of possible economic significance. For the oil and gas explorationist, the increased permeabilities of most whitecaps offer reservoir potential. For the uranium explorationist, the oxidizing effect of ground-water movements and the reducing environment of the black organic-rich sandstones may make a favorable climate for the accumulation of uranium minerals. In some coal drill holes where both core and geophysical logs exist, the gamma ray curve on the geophysical log will go off scale in zones of the black sandstone.

By observing the sequence of rock types and sedimentary structures in a vertical section through the delta front, the relative positions of the various facies within the delta-front sandstone can be determined. In a seaward direction, the upper portion of the sandstone sequence disappears progressively, with the rooted zones and flat beds of the whitecap the first to terminate, then the polymodal crossbedded sequence, and so forth downward. In a landward direction, the lower portion of the sequence disappears, the prodelta deposits being the first to die out, followed by the storm deposits of the lower delta front, and so forth upward.

Probably the most important economic component of the Rock Springs Formation is coal. Because of the high wave energies, most of the fine-grained sediment has been flushed offshore into the prodelta. However, some of the fine-grained sediment has been trapped behind the interdistributary barriers in lagoonal-bayfill deposits. The wave-dominated delta system provides an excellent platform on which thick, widespread coals can accumulate. In the Rock Springs Formation, the Nos. 3, 1, and 7 coal seams have been mined extensively throughout the northern and western portions of the uplift from Superior on the northeast to 10 mi south of Rock Springs on the west flank. To a

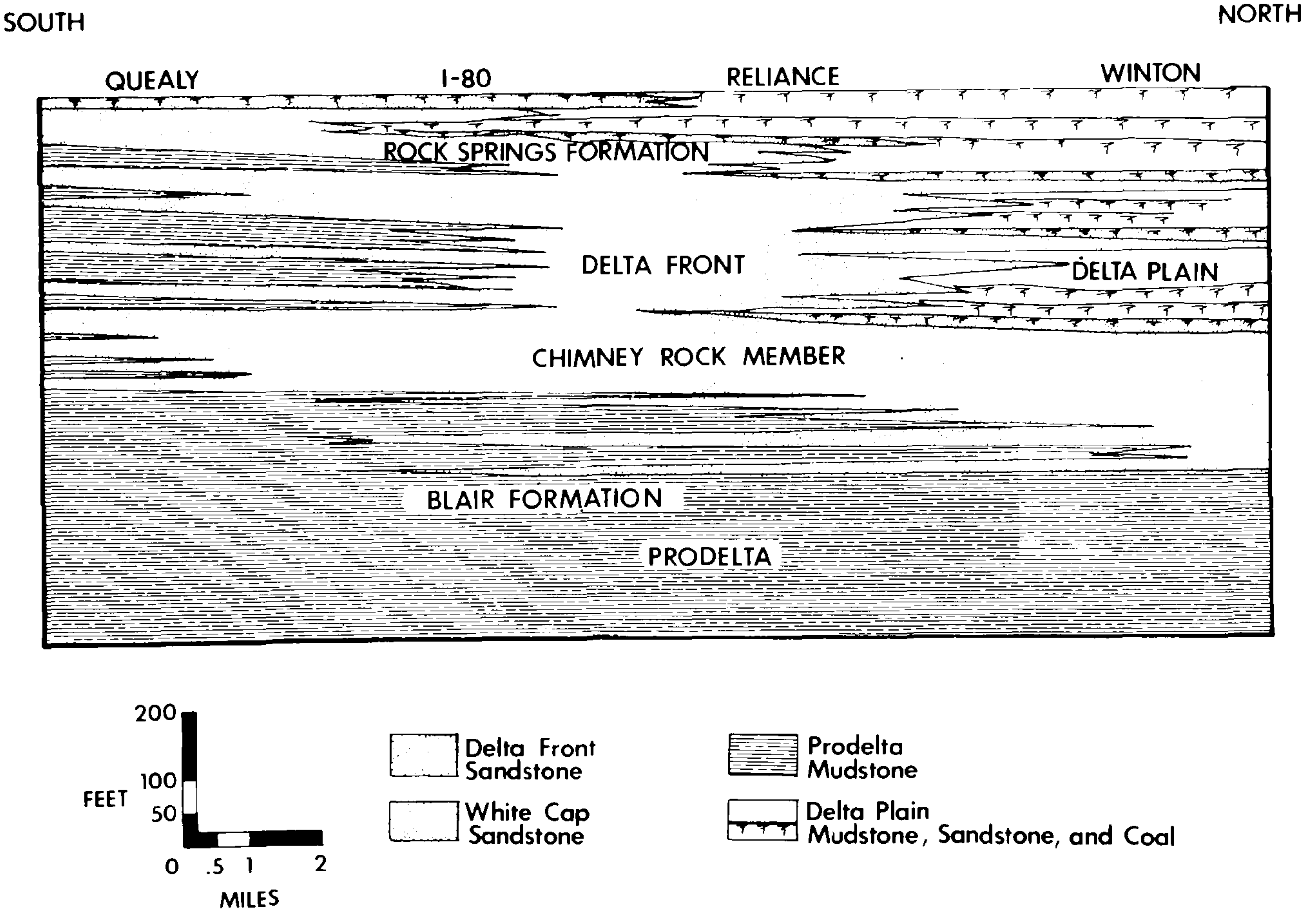

Figure 1.—Cross section along west flank of Rock Springs Uplift illustrating the Blair-Rock Springs relationships. (Modified from Roehler, 1978.)

lesser degree, the Nos. 7.5, 8, 9, 11, 13, and 15 coals have been mined locally in various areas in the northern portion of the Rock Springs Uplift.

Coals from the Rock Springs Formation are high volatile bituminous with Btu values ranging from 9,500 to 12,400, sulfur contents from 0.6 percent to 4.0 percent, and ash percentages as low as 2 percent.

Within this formation, there is a characteristic vertical sequence in the coal zones. In the lower part of the delta plain of the wave-dominated delta system, the coal zones are developed most commonly on sandstones. At the bases of the coal zones are predominantly black carbonaceous mudstones that are extensively root-penetrated. They contain noticeable amounts of resinous material and the remains of small plant fragments, usually a grassy or reed-type vegetation. (Similar characteristics to these have been described in the salt marsh deposits along the Delaware Coast by Allen (1977).) The carbonaceous mudstones grade upward into coals. This records the evolution of the salt marsh into a freshwater coal swamp. The coals are produced from the vegetation of swamp forests with large tree vegetation that is dominated by Sequoia but also contains ginkgoes and ferns (Lee Parker, oral commun.). In most cases, the coals are overlain abruptly by other black carbonaceous mudstones that reflect the drowning of the coal swamps. The drowning of the swamps occurred when plant growth could not keep up with the rate of subsidence (compactional or regional). As the swamps were transgressed, the upper portions of the peats were reworked. The resulting black carbonaceous mudstones contain abundant woody plant debris. The carbonaceous mudstones often contain a brackish-water fauna (Corbula, other pelecypods, and high-spired gastropods). These black mudstones grade upward into lighter colored mudstones that were deposited in more open water lagoonal bays.

Interruptions in coals and other delta-plain deposits of the Rock Springs Uplift are caused by distributary channels. Near the delta front, these channels have low sinuosity or are straight. Farther up the delta plain, the channels exhibit evidence of lateral migration (meandering). Paleocurrent directions indicate sediment transport generally to the southeast in these channels. The distributary channels range from 200 to 1,000 ft wide and 20 to 60 ft deep (fig. 2). Some of the channels are sandstone filled, but many are filled with fine-grained material.

Along the flanks of the distributary channels are coarse-grained levee and splay deposits. Thus, they differ from tidal channels becuse tidal channels have fine-grained levees and few splays. Maximum current velocities in tidal channels occur while the waters are confined to the channel; at channel overbank phase, the tidal currents are approaching a slack water stage when fine-grained suspended sediment is deposited. Distributary channels, by contrast, overbank during floods when the current velocities are at a maximum and coarse-grained material can be carried and deposited in levees and splays.

In the lower portion of the channels are lag deposits composed of clay and siderite pebbles as well as log debris, some of which contains Toredo-like borings, suggesting the presence of a salt water wedge in the lower portion--another indication that these channels are near the seaward edge of the delta plain. Grain size fines upward from 1.0 to 1.5 phi at channel base to 2.0 to 2.5 phi in the middle and 3.0 to 3.5 phi near the top. Bedding within the distributary channels consist of large trough crossbeds over the lag deposits with southeasterly transport directions. These grade upward into rippled beds with climbing ripples near the top of the channel sequence. The top of the sequence is extensively root penetrated. The upper portions of the channels grade laterally into sandy levee and splay deposits (fig. 2).

Offsetting these dipping sedimentary units of the Rock Springs Uplift are a series of northeast-southwest-trending faults (fig. 3). Some of these faults displace all the formations of the Upper Cretaceous Mesaverde Group (Baxter, Blair, Rock Springs, Ericson, Almond, Lewis, Fox Hills, and Lance Formations) and are definitely post-depositional. However, other faults die out at various levels in the stratigraphic sequence of the Upper Cretaceous and appear at least in part to be syn-sedimentary. Many of the major faults that offset the Mesaverde Group parallel the trend of a cross-basin arch that follows the trend of the Wamsutter Arch and is possibly a westerly extension of the arch or precursor to it. Because of the association of these faults with the cross-basin arch, they may be related to movements along this structure.However, many of the other northeast-southwest-trending faults die out in the Rock Springs Formation, suggesting they may be syn-sedimentary. In the vicinity of Dines (approximately 9 mi north of Rock Springs, Wyo.), one such fault ceases below the marine sandstone under the No. 3 seam. This fault parallels the general trend of the Rock Springs Formation paleoshoreline (N. 40° E.) and is downthrown on the side closer to the depositional basin (southeast). The coals, offset by the fault (Rock Springs Nos. 1, 7.5, 7, 8, 9, and 11), thicken dramatically on the downthrown side (southeast). The Rock Springs No. 3 coal, however, does not display this relationship. It appears that syn-sedimentary move-

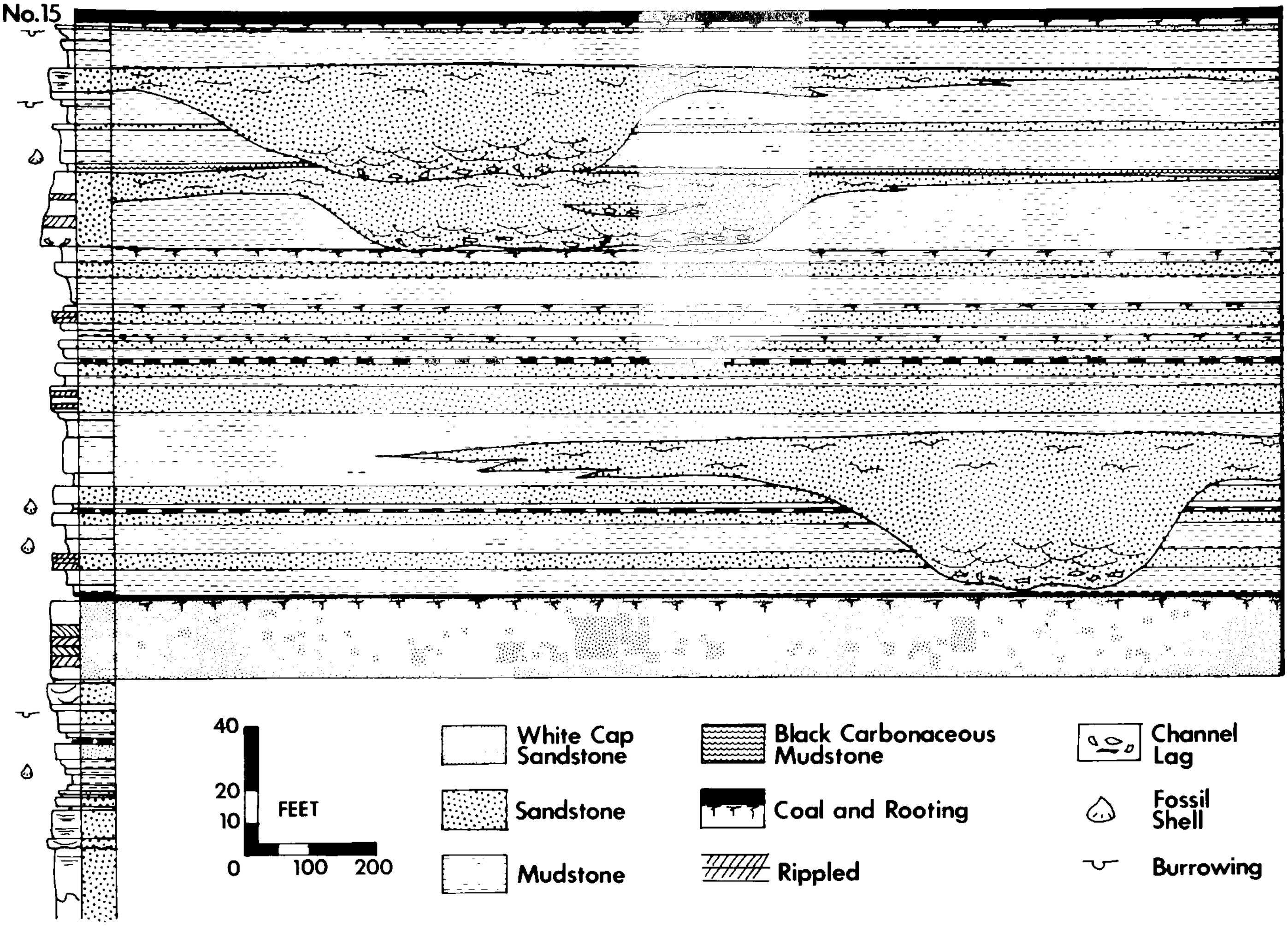

Figure 2.—Distributary channel-delta plain relationships in the Rock Springs Formation.

ments on this fault have helped to control the distribution of economically thick coals. Similar thickenings of various rock types on the downthrown side of faults that displace sediments of the Rock Springs Formation have been observed throughout the northern portion of the uplift.

CONCLUSIONS

1. The widespread delta-front sheet sandstones of wave-dominated deltas provide substantial platforms upon which thick, laterally continuous coals may develop.
2. Backswamp coals of the fluvial and upper delta plain portions of wave-dominated deltas may be locally thick and low in sulfur, but are laterally impersistent and often high in ash with multiple partings.
3. A predictable vertical sequence of sedimentary structures and rock types permits the relative position of facies within the delta-front sheet sandstone to be determined.

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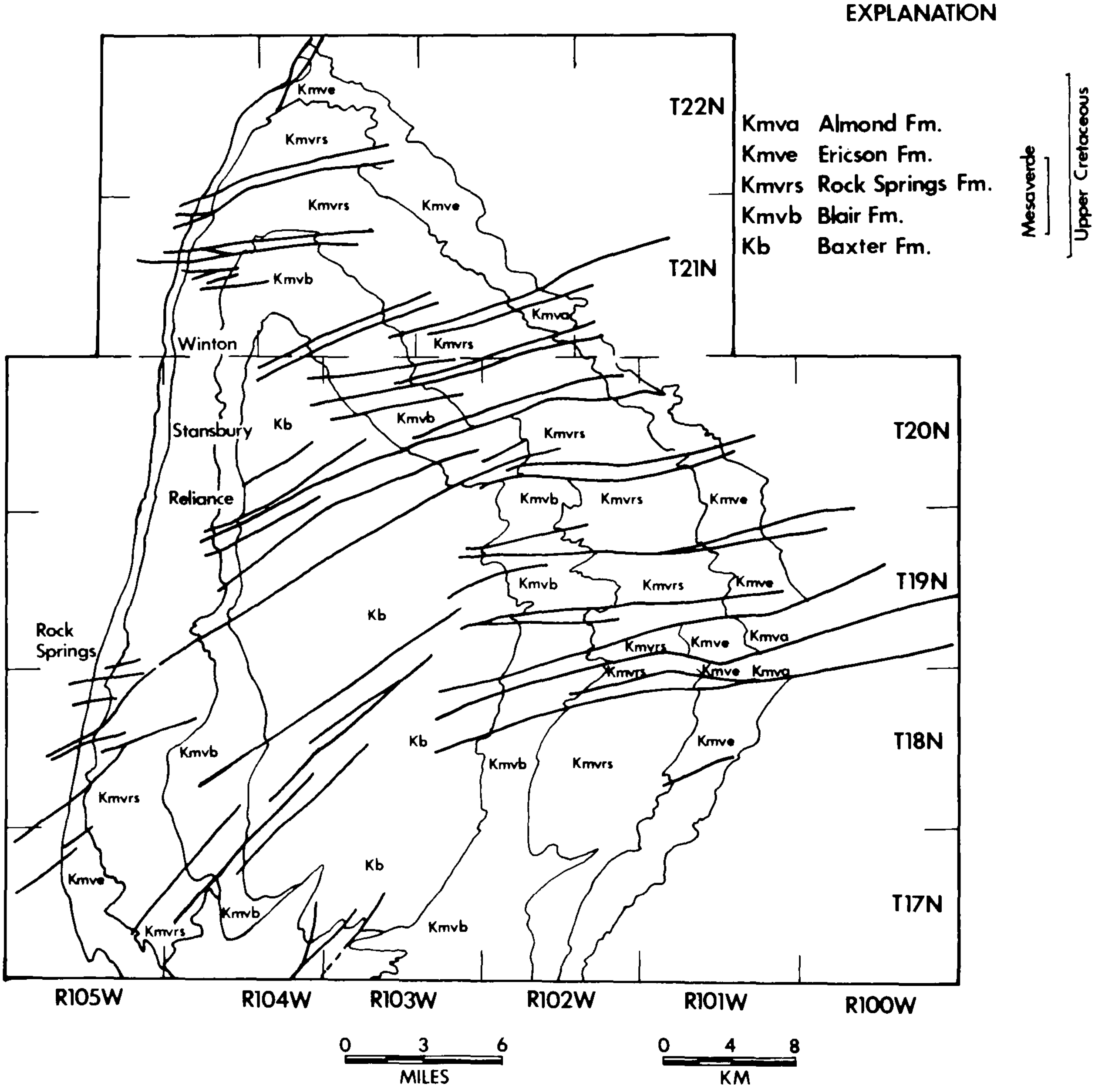

Figure 3.—Geologic map of northern 2/3 of the Rock Springs Uplift. Heavy lines, faults.

RELATION OF INTRAFORMATIONAL FAULTS TO FLUVIAL SEDIMENTATION AND COAL-BED DISCONTINUITY, RATON FORMATION, COLORADO AND NEW MEXICO

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The Raton Formation of Late Cretaceous and Paleocene age is more than 600 m thick. It is composed of interbedded gray and tan sandstone, mudstone, carbonaceous shale, and coal. Deposition occurred along the western margin of a broad coastal plain lying between the Rocky Mountains on the west and the Mississippi Embayment on the east.

Sandstones in the formation are mostly lenticular and crossbedded and are of fluvial origin. The sandstone lenses are commonly bounded by or truncate minor intraformational faults. The faults are believed to have resulted from the loading and differential compaction of the sands in thick enveloping muds at shallow subsurface depths during early stages of lithification. Faulting created linear depressions on the depositional surface that were subsequently occupied by streams. Fluvial scouring along the faults commonly resulted in channel superposition or sandstone stacking.

Coal-bed discontinuities in the Raton Formation result from compaction faults and the associated fluvial scouring. They constitute obstacles to underground coal mining.

Coal beds cut by stacked channel-fill sandstone deposits that appear controlled by intraformational faults (mile 6.9 on third day road log). Photograph by H. L. James.

DEPOSITIONAL ENVIRONMENTS OF QUATERNARY PEATS, YUKON DELTA, ALASKA

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The peats presently forming on the Yukon Delta in Alaska are strongly influenced by the geologic and climatic setting of the region. They therefore provide an opportunity to establish criteria by which high-latitude peats (and their resultant coals) might be distinguished from peats and coals formed in more temperate climates.

The Yukon River has formed a high-constructional lobate delta where it presently enters Norton Sound (fig. 1). This modern delta is part of the Yukon-Kuskokwim Delta complex which covers more than 54,000 km^2 in western Alaska. The delta complex is located within the Koyukuk volcanogenic province, which has been characterized by recurrent faulting and syntectonic volcanism throughout Mesozoic and Cenozoic time (Patton, 1973). The tectonic setting appears to be in part responsible for the shallowness of the depositional basin and the relatively low rates of tectonic subsidence of the shelf. This, in turn, strongly affects the geometry of the deltaic deposits.

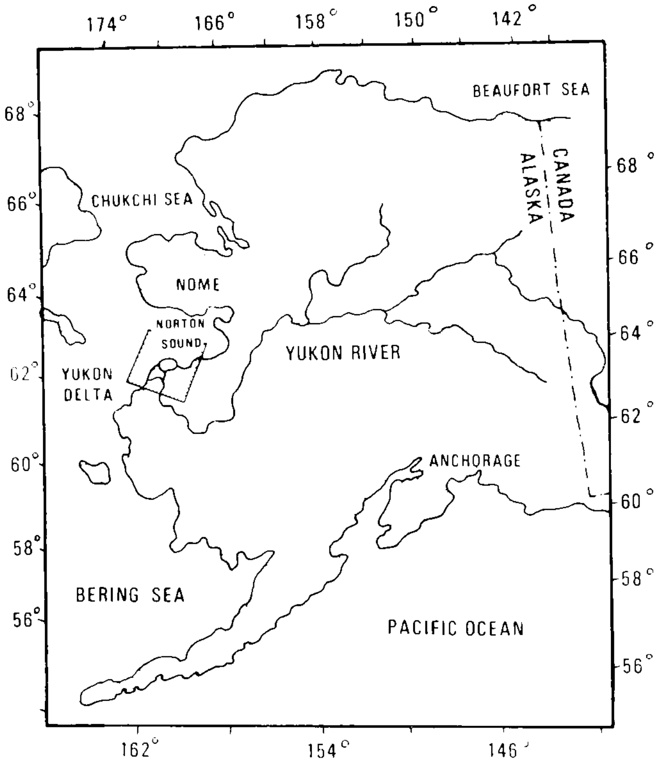

Figure 1.—Location of the Yukon Delta, west-central Alaska.

The climatic setting is also significant as it affects not only the type and amount of peat accumulation, but also the type of minerogenic sediments, the patterns of sedimentation, and the degree of cryogenic alteration of sediments. The subarctic Yukon Delta is located approximately lat 63° N., with a mean annual temperature of approximately 27.5°F (-2.5°C). Summer temperatures may range as high as 70°F (21.5°C) (thereby allowing some seasonal addition to the peat biomass), but the net primary productivity is still low due to the low mean annual temperature and the reduced photoperiod. Thus the rate of peat accumulation is relatively small.

The relative lack of chemical weathering at high latitudes results in a sediment rich in silt with a paucity of clays (Hill and Tedrow, 1961). The lack of clay significantly reduces the amount of post-depositional compaction and subsidence, thereby further reducing the potential thickness of the peats formed on the delta plain. In addition, ice plays a key role in controlling the patterns of sediment dispersion and deposition, especially during breakup, both on the delta plain and in adjacent nearshore regions. In fact, some of the depositional environments of the Yukon Delta appear to be unique to ice-dominated deltas (Dupre' and Thompson, 1979). The development of ground ice (permafrost) is also important, as it affects both the microtopography and dominant plant assemblages in the area.

The modern Yukon Delta can be divided into a variety of depositional environments, including the delta plain, delta margin, delta front, and prodelta. The delta plain can be further subdivided into a complex assemblage of active and abandoned distributary channels and channel bars, natural levees, interdistributary marshes and lakes, and coastal marshes and distributary mouth bars. Shallow (0.5-2 m) cores were obtained from the various peat-forming environments of the delta plain using a modified piston coring device. (See Cohen and Spackman, 1972.) Megascopic description of the peat cores, combined with microscopic examination of peat thin sections, provided the means to document the stratigraphy of the peats and their petrology, as well as distinguish between various peat types formed in different environments (Klein, 1980).

The peats in the Yukon Delta region can be conveniently classified according to their proximity to the coastline, their dominant plant assemblages, and the extent to which permafrost has developed. The peats are classified as follows:

1. Lower delta plain peats: accumulating in prograding coastal marshes, abandoned beach ridges (storm washovers), abandoned channels and associated bars near the coast; composed of sedge/grass remains; characterized by abundant dispersed sediment, thin bedding (less than 1 m), and allochthonous origin; permafrost absent or poorly developed.
2. Upper delta plain peats: accumulating in interdistributary marshes and in abandoned channels and associated levees; composed of a heterogeneous assemblage of sedge/grass, willow, alder, and Sphagnum remains; characterized by abundant sediment partings, relatively thin bedding (1-2 m), and autochthonous origin; incipient permafrost development.
3. "Dry tundra" peats: accumulating on Pleistocene uplands in the interior regions of the abandoned delta complex; composed of Sphagnum, willow, alder, lichen, and heath remains; characterized by little or no sediment inclusion, relatively thick bedding (2 m or greater), and autochthonous origin; well-developed permafrost; may be laterally discontinuous due to interfingering thaw lake deposits.

The geometry of each peat type is controlled by the depositional environment (as, lenticular bodies filling abandoned channels), whereas the composition of the peat types is controlled largely by the dominant plant contributor. The dominance of particular plant assemblages is a function of ecological succession reflecting the age of the deposits, the permeability of the substratum, and the degree of permafrost development.

In general, Yukon Delta peats contain abundant roots, altered plant tissues, cells/cell fragments, opaque debris (inertodetrinite), fungal hyphae, huminite (pre-vitrinite), and dispersed minerogenic sediment. Freshwater diatoms are particularly conspicuous in thin section. Few woody fragments are present in any of the peats, attributable to the general lack of woody plants on the delta. Pyrite is also absent from the peats, probably as a result of the dominance of freshwater deposition. Although present, spores and pollen occur only occasionally, attributable to inhibition of infiltration into the dense, fibrous peat mass. Pyrofusinite (charcoal) is confined to the dry tundra peats—the lower and upper delta plain peats are too wet during summer months to burn.

Comparisons with peats forming in more temperate regions reveal unique properties of high-latitude peats (and resulting coal). The peats of the Yukon Delta are of a rather homogeneous botanical composition, primarily marsh grasses and sedges. This contrasts sharply with the Florida Everglades (Cohen, 1968) and the Mississippi Delta (Frazier and Osanik, 1969), where the peats are composed of a diverse assemblage of both woody swamp and marsh plants. In addition, the peats of the Yukon Delta appear to be deposited under relatively aerobic conditions, as is evidenced by the abundance of fungal hyphae and the abundance of inertodetrinite (derived by oxidation during surface exposure and transport). This does not appear to be the case in all facies of peats formed in more temperate climates (Cohen, 1968).

The paucity of clays formed by pedogenic processes in high latitudes results in little prodelta clay underlying the delta plain. This in turn results in little compaction and subsidence of the delta plain; thus the rates of peat deposition are relatively slow (typically 0.01 cm/yr), and total peat thickness is generally low (typically less than 2 m). This is in contrast to peats formed on the Mississippi Delta plain where compaction and subsidence of underlying clays has resulted in relatively rapid rates of peat deposition (approximately 0.7 cm/yr) and relatively thick peat deposits (approximately 10 m). The lack of subsidence on the Yukon Delta is also related to the very shallow nature of the depositional basin.

Formation of permafrost and associated cryogenic processes cause considerable distortion of the strata deposited in high latitudes. Contortions and involutions associated with frost heaving and ice formation are common in the Yukon Delta region, and their recognition in outcrop should be considered a reliable indicator of formation in high latitudes.

The resulting coal may be a trimaceral coal type, containing abundant inertodetrinite, vitrinite, and minor exinite. Megascopically the coal will probably be dull (durainic) because of the maceral content and abundance of minerogenic sediment. The coal will be relatively thin, although some thick coal seams may develop in abandoned channels of the upper delta plain and in some regions of dry tundra. The strata are likely to be disrupted locally by cryogenic processes, with originally stratified seams broken up into convoluted lenses and chips. Lastly, the lack of pedogenic clay formation in these latitudes will probably preclude the formation of underclays beneath the coal seams.

In summary, the stratigraphy and composition of the peats on the Yukon Delta are strongly affected by their formation in a high-latitude deltaic environment. These properties may be used to recognize coals formed under similar depositional and climatic conditions.

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COMPARISON OF DEPOSITIONAL MODELS OF TERTIARY AND UPPER CRETACEOUS COAL-BEARING ROCKS IN SOME WESTERN INTERIOR BASINS OF THE UNITED STATES

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Stratigraphic-environmental and paleo-depositional modeling of representative Tertiary and Upper Cretaceous coal-bearing strata in selected Western Interior basins of the United States (fig. 1) has demonstrated a dependency of coal characteristics on subenvironments. The stratigraphic units and areas studied to date include: (1) the Tongue River Member of the Fort Union Formation of the Powder River Basin in Wyoming and Montana; (2) the Blackhawk Formation of the Wasatch Plateau in Utah; (3) the Fruitland Formation of the San Juan Basin in New Mexico; (4) the Vermejo Formation of the Raton Basin in Colorado; and (5) the Almond Formation of the Rock Springs Uplift in Wyoming. In each case, paleodepositional models, diagrammatically shown in figure 2, were developed on the basis of closely spaced stratigraphic sections and drill-hole data from small representative areas. The resultant field identification of specific ancient depositional settings provided a key to understanding variations in thickness, lateral extent, sulfur and ash contents, and areal distribution of individual coal beds or coal zones, and also suggested areas of potentially productive coal accumulation.

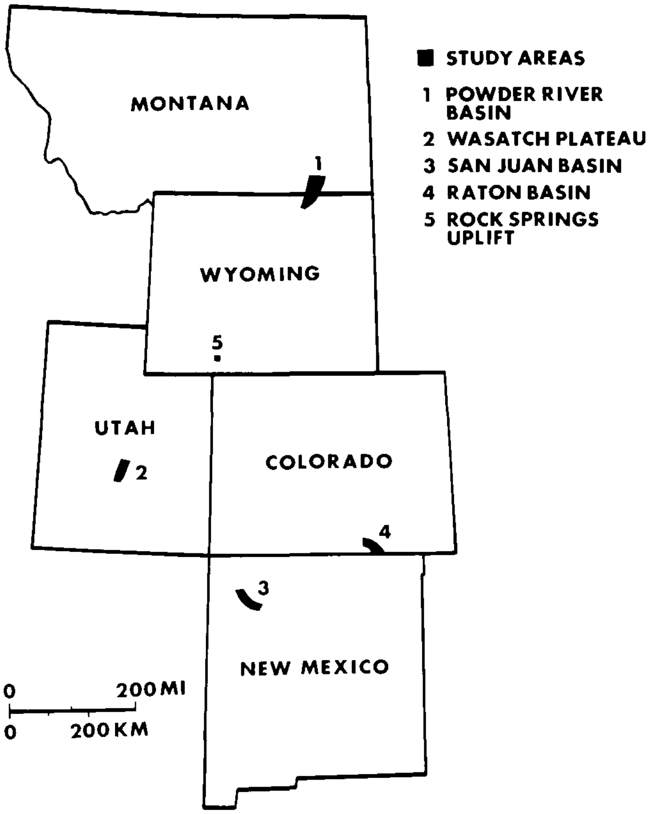


Figure 1.--Selected Western Interior basins of the United States.

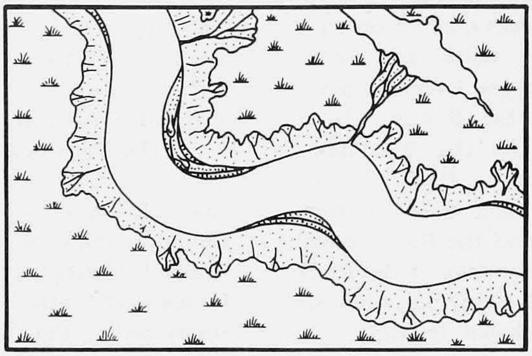
The Paleocene Tongue River Member of the Fort Union Formation in the Powder River area, Powder River Basin in Wyoming and Montana, represents a fluvial or alluvial sequence characterized by a fluvial channel-dominated facies and a fluvial lake-dominated facies. Potentially economic coal accumulations are restricted to the fluvial channel-dominated facies that contains very thick, lenticular coal beds with low sulfur and ash contents. Three minable coals (Anderson, Canyon, and Pawnee), as thick as 30 ft, occur in the fluvial channel-dominated facies. These coals occur as thick beds for 3.5 to 6 mi along lines of sections between areas of splitting or merging caused by overbank-crevasse splay deposits. Sulfur and ash contents of these coals average 0.71 and 6.8 percent, respectively. Carbonaceous shale partings in these coals are moderately few. Three-dimensional study of these coals shows uniform thickness subparallel to the length of contemporaneous channel sandstones.

It is suggested that in the fluvial channel-dominated facies, isolated, broad interchannel floodbasins formed poorly drained, freshwater backswamps in which thick peat deposits of alternating hummocks and hollows accumulated by a doming mechanism and were sustained by a gradual and continuous rise of the ground-water table. These floodbasins, protected from frequent incursions of flood waters by well-developed levees, provided stable and long-lived areas of peat generation and regeneration. Autocyclic shifts of channels and local overbank-crevasse splay sedimentation into the backswamps occasionally interrupted peat accumulations.

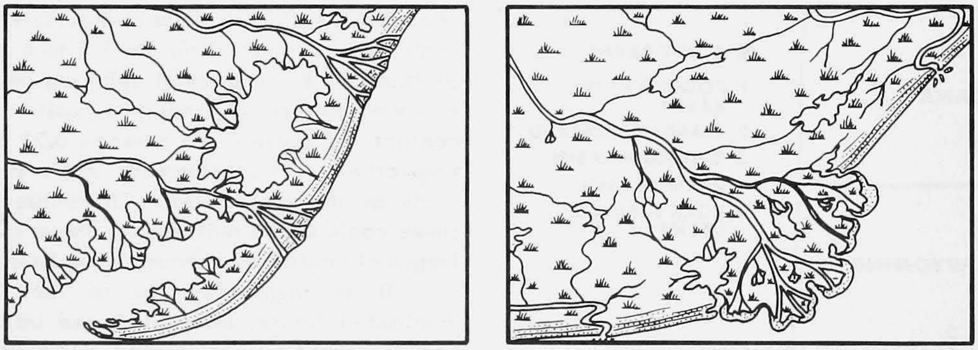
The Upper Cretaceous Blackhawk Formation in the southern Wasatch Plateau, Utah, contains two discrete coal populations formed in lower delta plain and distributary mouth bar-accretion ridge swamps. These coal-forming subenvironments are genetically related to the intertonguing of the Blackhawk Formation and underlying Star Point Sandstone. Two Star Point tongues, 12 mi apart, are each 55 ft thick and 1 mi wide and rise stratigraphically northward.

They represent accretion ridge sands formed by reworking of mouth-bar sands of distributary channels and by transportation along the paleoshoreline by longshore currents. These marginal sand complexes were deposits of wave-dominated deltas. The accretion ridge sands were built landward by local storm washover deposits and acted as physical barriers to the sea. The Blackhawk deposits that merge with the Star Point tongues represent bay or lagoon deposits formed immediately behind the accretion ridges. The lagoon deposits in turn pass landward into lower delta plain deposits.

The two coal populations in the Blackhawk Formation accumulated in swamps formed on washover platforms of the accretion ridge sands and on crevasse splay-crevasse channel deposits of the lower delta plain. Individual coal beds are not physically continuous across the bay or lagoon deposits that were

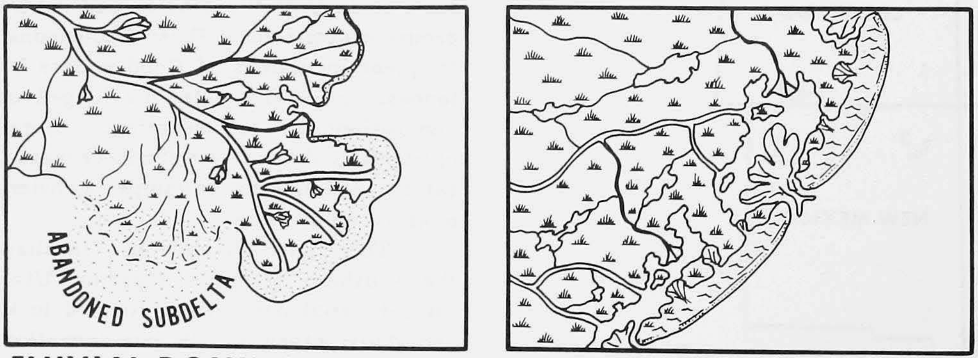


FLUVIAL (ALLUVIAL) MODEL



WAVE-DOMINATED DELTA MODEL

FLUVIAL-INFLUENCED DELTA AND STRANDPLAIN MODEL



FLUVIAL-DOMINATED DELTA MODEL

BARRIER-ISLAND AND BACK-BARRIER MODEL

Figure 2.--Paleodepositional models. No scale.

formed in open brackish-water conditions. However, where the bay or lagoon deposits formed in a partly to completely closed subenvironment, coals are traceable across these deposits. The coals formed behind the accretion ridge sands range from a few inches to 11 ft thick and show a uniform thickness subparallel to paleoshoreline (that is, at a high angle to the paleoshoreline). In contrast, the coals formed on the lower delta plain vary from a few inches to 14 ft thick and show a uniform thickness subparallel to paleochannels. The accretion ridge coals tend to be less well developed than the coals of the lower delta plain. Analysis of a coal zone immediately above the accretion ridge sandstone shows sulfur content ranging from 0.7 to 1.6 percent and ash content from 9.3 to 10.1 percent. In a laterally equivalent coal zone in the lower delta plain deposits, sulfur content ranges from 0.4 to 0.45 percent and ash content ranges from 5 to 10 percent.

The Upper Cretaceous Fruitland Formation in the San Juan Basin, N. Mex., contains deposits of fluvially influenced delta plain and adjoining back-beach bar or strandplain subenvironment. Identification of subenvironments of coal deposition was made possible by study of the underlying Pictured Cliffs Sandstone. This sandstone consists of two contemporaneous facies: distributary channel-delta front sandstones and beach bar-shoreface sandstones. The delta-front facies contains ball-and-pillow and slumped structures; the shoreface facies contains heavily bioturbated zones separated by crossbeds, ripples, and horizontal lamination. Thus, the overlying coal-bearing Fruitland Formation represents delta-plain and back beach-bar deposits that prograded over the coastal-sand complex of the Pictured Cliffs Sandstone.

The delta-plain coal beds range from a few inches to 12 ft thick and are laterally traceable in lines of sections for at least 6 mi. The thick delta-plain coals are concentrated in the lower part of the formation. The coals show a high degree of lateral variability caused by frequent splitting or merging by overbank-crevasse splay deposits and distributary channel sandstones. Isopach mapping of some of the coals shows uniform thickness subparallel to the lengths of contemporaneous channel sandstones. The areal distribution of the coals with respect to the distributary channel deposits indicates that they were formed in interchannel backswamps. Commonly, as the distributary channels were filled, adjoining backswamps spread and overrode the abandoned channel deposits. Predominance of freshwater over brackish-water conditions in these backswamps is indicated by the rarity of oyster shells in associated overbank-crevasse splay deposits. Limited updip invasions of brackish water in the interchannel lows permitted widespread accumulation of peat in freshwater backswamps of the lower delta plain.

The back beach-bar coals vary from a few inches to 11 ft thick and are laterally traceable along lines of sections for at least 8 mi. Thick coal beds in the back beach-bar facies occur in the upper part of the formation. The lowermost back beach-bar coal bed, lying immediately above the Pictured Cliffs beach-bar sandstone, contains abundant carbonaceous shale interbeds and laterally merges with thick carbonaceous shale. This "dirty" coal probably represents accumulation in a marsh formed immediately behind the beach-bar sands. That the marsh was choked by widespread influx of flocculated clays brought in by tidal currents is indicated by the presence of well-developed carbonaceous shales in this zone. The thick coals that occur above this dirty coal bed probably represent accumulations in freshwater swamps formed farther landward and far removed from the influence of tidal processes.

Analyses of the sulfur and ash contents of these two coal populations do not show a significant difference. The delta-plain coals show average sulfur and ash contents of 0.65 and 24 percent, respectively. The back beach-bar coals show average sulfur and ash contents of 0.55 and 21.2 percent, respectively.

The Upper Cretaceous Vermejo Formation in the Raton Basin, Colo., contains coal deposits that formed in swamps of a fluvial-dominated delta plain. This formation is underlain by the Trinidad Sandstone, which consists of distributary channel, distributary mouth bar, and distal bar deposits. The distributary mouth bar deposits consist of several sandstone beds separated by at least two destructional units. The destructional unit consists of sandstone and siltstone that is heavily burrowed by Ophiomorpha. The unit ranges from a few inches to 6 ft thick and is laterally traceable for at least 4 mi. The lowermost beds of the distal bar deposits, which are transitional to underlying prodelta sediments, contain slump and load structures, sole marks, and graded beds.

Coal beds in the Vermejo Formation generally occur throughout a 220-ft-thick interval; however, at some localities the coal-bearing interval has thinned to 120 ft. These intervals are overlain by sequences of thick, multistory channel sandstones interbedded with siltstones, shales, and a few thin coals and carbonaceous shales. The major coal-bearing intervals of the formation are interpreted to have developed in lower delta plain subenvironments, and the overlying multistory channel sandstones and associated sediments represent deposits of alluviated upper delta plain subenvironments. The occurrence of alluviated upper delta plain deposits in the upper part of the Vermejo Formation may reflect rapid progradation of subdelta lobes. The presence of pod-like deposits of quartzose sandstones distributed in the transitional zone between the lower delta plain and the alluviated upper delta plain deposits, and oriented subparallel to the paleoshoreline, suggests that proliferation of subdelta lobes by avulsion may have been accompanied by reworking of detritus of earlier abandoned subdelta lobes. The quartzose sandstones may represent updip counterparts of the destructional units observed in the distributary mouth bar deposits of the underlying Trinidad Sandstone.

The coal beds in the Vermejo Formation range from a few inches to 11 ft thick. They can be traced laterally along lines of sections for at least 3 mi before they split. Three-dimensional study shows that coal zones separated by overbank-crevasse splay deposits occur in interchannel lows between distributary channels and were built on abandoned distributary channel-sandstone platforms. Isopach mapping of some coal beds shows uniform thickness subparallel to the long dimensions of contemporaneous channel sandstones. The general absence of remains of brackish-water faunas in interchannel deposits suggests that the coals were formed mainly in freshwater swamps. However, the presence of some Teredo-like borings in wood imprints in the distributary channel sandstones indicates at least limited development of brackish-water conditions in the lower delta plain. Perhaps the freshwater condition of the coal swamps is reflected by the low sulfur content of the coals, which ranges from 0.5 to 0.9 percent. The ash content ranges from 8 to 17.7 percent.

The Upper Cretaceous Almond Formation in the southeastern part of the Rock Springs Uplift contains back-barrier and barrier-island coal deposits. The interval studied in the Almond Formation is one in a succession of barrier-island and back-barrier sequences that were deposited in an overall transgressive setting. The study centered in an upward-coarsening interval, 120 ft thick, sandwiched between an older and a younger deposit of barrier complexes.

The two-dimensional stratigraphic-environmental study of the interval shows three major facies: a lower facies consisting of a coal zone interbedded with shale, siltstone, and channel sandstone; a middle facies of upward-coarsening shale, siltstone, and sandstone with thin coal beds and brackish-water oyster shells and burrows; and an upper facies of upward-coarsening bleached sandstone and a scour-base, upward-fining sandstone that grades laterally into and is underlain by burrowed, lenticular sandstone. The upper facies is locally capped by coal, carbonaceous shale, and oyster shell beds.

The lower facies represents back-barrier swamp and river channel deposits. These deposits are succeeded upward by bay-fill deposits of the middle facies, which in turn are overlain by barrier island, tidal inlet, flood-tidal delta, and barrier-island marsh deposits of the upper facies. The coal beds in the lower facies formed in swamps protected by a stable, older barrier-island complex. They range from a few inches to 7 ft thick and are laterally traceable, before merging along lines of sections, for as much as 3 mi. The thin coals associated with the bay-fill deposits were formed in isolated marshes built on raised bay-fill platforms. The barrier-island coals range from a few inches to 5 ft thick and are laterally traceable for as much as 2.25 mi prior to merging. These coals contain abundant carbonaceous shale interbeds and laterally merge at their margins with carbonaceous shale as much as 4 ft thick. Coal analyses show a wide range of sulfur content, from 0.3 to 1.5 percent; the ash content ranges from 5.2 to 31.3 percent.

MINE PLAN OPTIMIZATION THROUGH THE USE OF GEOLOGIC AND FUEL QUALITY CONTROL PROGRAMS

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INTRODUCTION

The exploration and development of a large coal property (approximately 20,000 acres) in central Utah have afforded excellent opportunities to initiate both geologic investigations and fuel quality control programs and then to monitor their usefulness to the continuing development of the property (fig. 1). These programs have evolved along with the mining process with the support of Utah Power & Light Company and Emery Mining Corporation, and their successful application has resulted in the efficient development of the largest underground mining complex in the Western United States, which in 1980 will produce more than 4 million tons of coal.

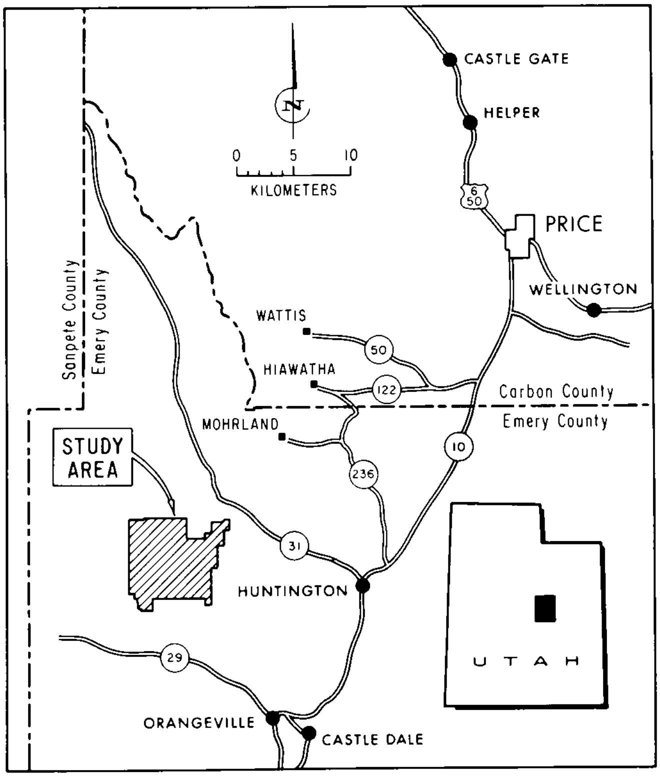


Figure 1.--Location map of coal property study area, Utah.

GEOLOGIC PROGRAMS

Geologic investigations useful in the development of the property have proceeded from general to specific: initial evaluations were for purposes of reserve evaluation and acquisition; later programs evolved to develop mine plans and ascertain reserve quantities. More recent geologic programs have concentrated on obtaining detailed information for use in mine planning, prediction of roof conditions, and determination of hydrologic conditions and fault offsets.

Initial Geologic Program

Early geologic workers in the area located coal seams having a potential for economic development (Spieker, 1931). Spieker's classic analysis of the Wasatch Plateau coal field defined the geology, stratigraphy, structure, and the characteristics of the numerous coal seams exposed in the region. Spieker defined the presence of two major coal seams in the area investigated here. These seams, the Hiawatha seam (basal) and the Blind Canyon seam (upper), are located in the lower 150 ft of the Blackhawk Formation (Upper Cretaceous) and are separated by about 100 ft of interburden (fig. 2).

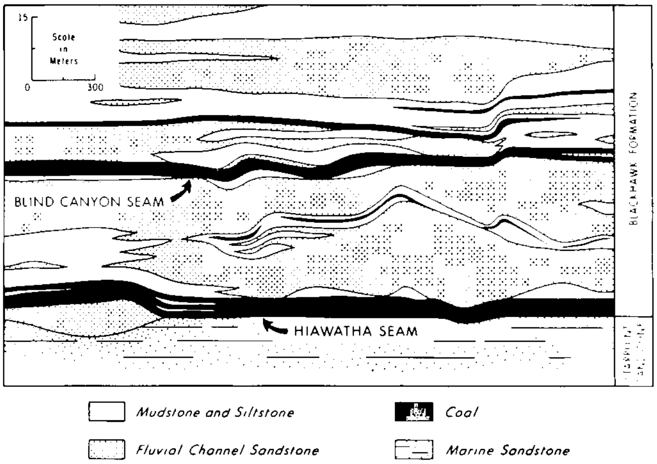


Figure 2.—Partial stratigraphic cross section illustrating general relationship of principal coal seams and enclosing strata.

Initial investigations on the property focused on defining the continuity and presence of both seams; mapping activities supplemented the information presented in Spieker (1931). Outcrops were measured to determine coal seam thicknesses, roof partings, roof and floor rock types, seam continuities, interburden thicknesses, burn areas, and inferred depositional environments. Some results of the mapping program are shown in figure 3. The outcrop data were used in the initial stages of property acquisition and evaluation. The coal seam continuities and thicknesses delineated a major coal reserve with great potential for underground mining. These data were then used to prepare a recoverable reserve estimate, which was the basis of the justification for proceeding with acquisition negotiations.

Drilling Programs

The second phase of geologic activities was motivated by the need to know in more detail where coal seams of minable thickness were distributed in the subsurface.Drilling programs were thus conducted, proceeding from a general to a specific understanding of coal seam geometries. The first drill holes were completed on wide spacing patterns of 1 or 2 mi between holes. Later programs closed the spacing to about 3/4 mi in those areas seen to contain seams of minable thickness. All drill holes were geophysically logged, and about one in six was cored for coal quality and rock mechanics data.

The derived data were used to develop mine plans and estimate recoverable reserves. Isopach maps of the two seams were prepared to show the geometry of the coal of minable thickness in each seam so that efficient extraction could be planned. Acquisition of reserve was based on the amount of reserve estimated to be recoverable.

Mine Mapping Program

The latest geologic program to evolve for the property consists of underground mapping and drilling activities, which permit refinement of isopach maps, preparation of roof control maps, evaluation of the hydrology of the coal-bearing strata, identification and prediction of rock splits, and documentation of the lenticularity of minable seams. All of these data are used to refine mine plans so that they are consistent with the geology of the deposit.

Isopach maps show, in addition to the typical contour lines, the roof, floor, and rock splits that characterize the seam at a given locality (figs. 4A and 4B). The graphic representation of drill-hole data on isopach maps has proved useful to mining engineers.

Mine mapping activities and literature studies (McCabe and Pasco, 1978; Hylbert, 1978) indicate a definite relationship between roof lithologies and roof conditions. Roof conditions have commonly been unstable in areas where a minable seam is overlain by a zone along the margins of a paleochannel sandstone where mudstones and siltstones interfinger with the

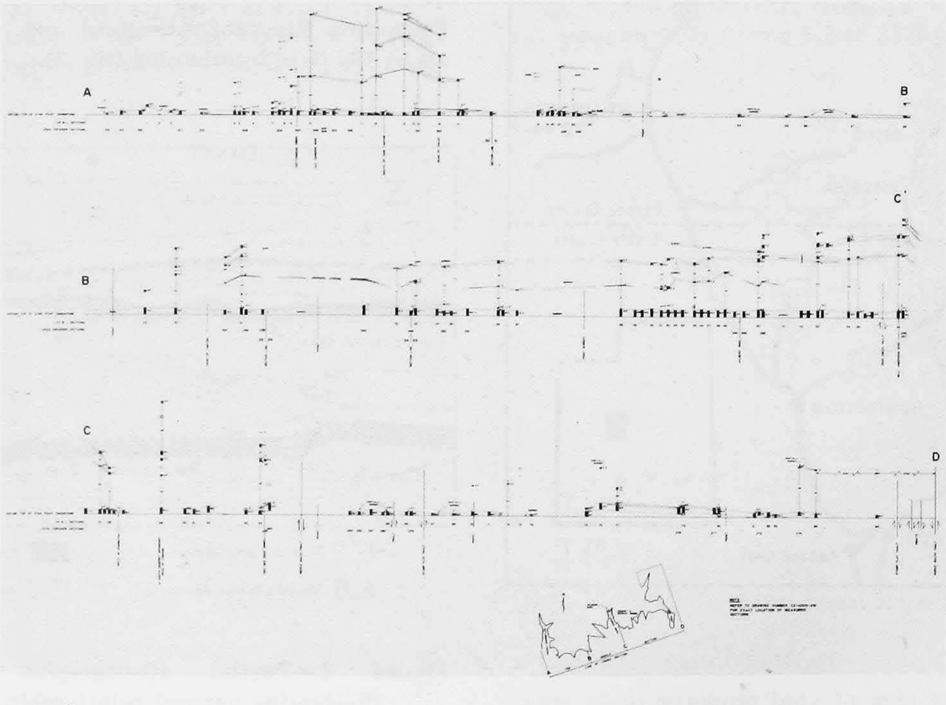


Figure 3.—Outcrop coal seam measurements.

sandstone. These areas of instability are probably caused by slickensides that have developed in response to differential compaction of sediments with different grain sizes, pore spaces, and water contents.

Coal seams immediately below paleochannel sandstones are commonly compacted into what miners call "rolls." Sometimes the channels have scoured into the underlying coal seam and have created "wants." Water is commonly concentrated in sandstones because of greater porosity and permeability than adjacent

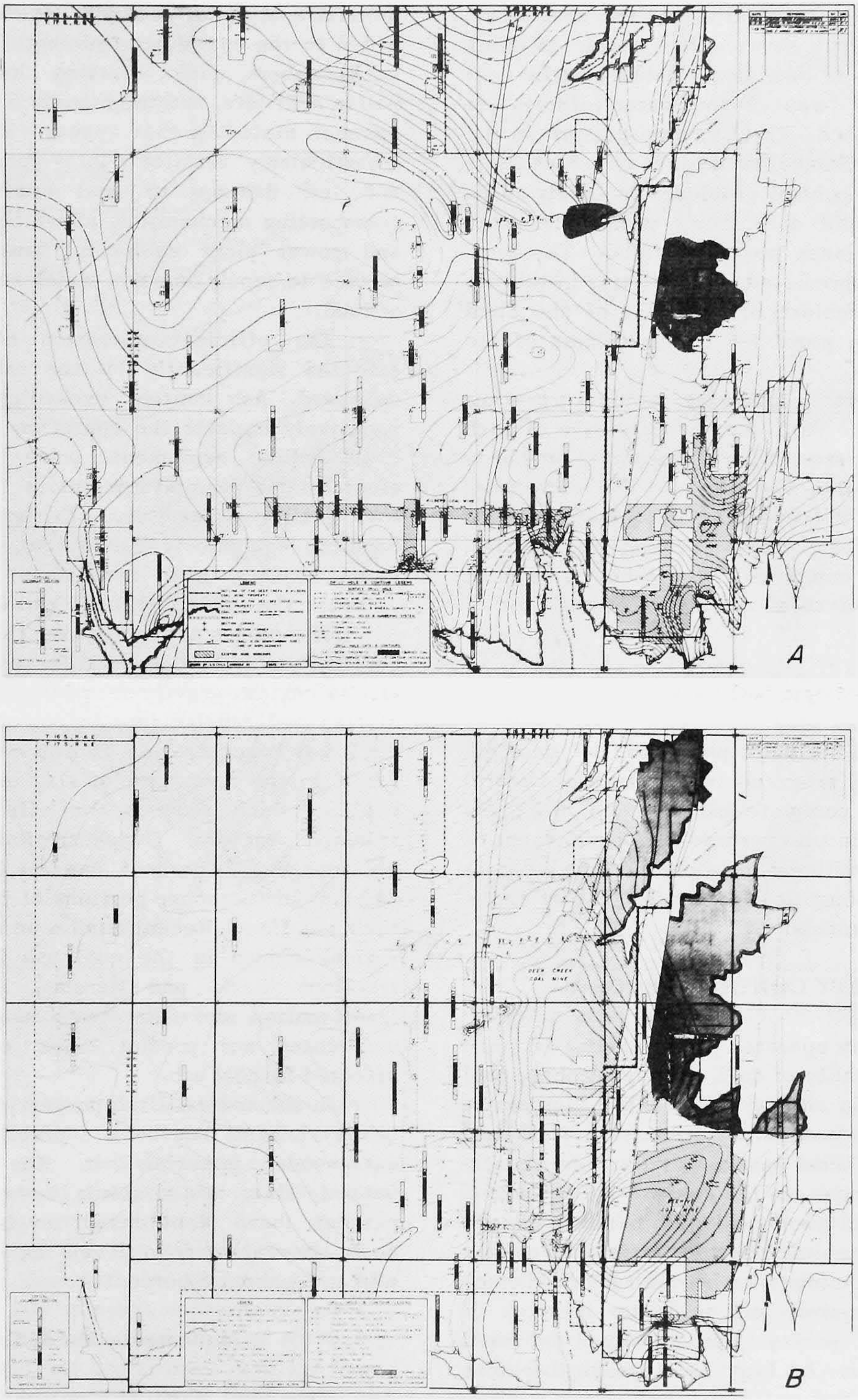


Figure 4.--Isopach maps. A, Hiawatha; B, Blind Canyon.

sediments. The disruption of sandstones by the mining process usually results in water flows that approach 30 gal/min in a given area. The maps presented in figures 5A and 5B indicate the distribution of sandstone in the immediate roof of the two minable coal seams on the property. The contour lines show the percent of sandstone in the 10-ft interval above the coal seam. The stippled pattern shows the areas in which paleochannel sandstone beds immediately overlie coal seams where "rolls," "wants," and water influxes are likely to be in evidence. The hachured pattern on the margins of the paleochannel sandstones indicates those areas in which roof control problems are likely to be present, and the solid dots shown within the mine workings on these maps are roof falls. The good correlation between predicted zones of roof instability and roof falls, particularly in the case of the Blind Canyon seam, is the proof for the usefulness of the mapping program.

Our experiences in collating and interpreting underground drill-hole data have proven to be of such value that drill holes are regularly completed on 400-ft spacing patterns within the mines. The data from these holes permit the preparation of isopach and roof control maps that aid mine planning capabilities. These holes can be completed from seam to seam in underground applications at a fraction of the cost of surface drill holes.

Geologic Summary

Data obtained in each phase of the geologic mapping and drilling programs in this area of central Utah permit a more complete understanding of a given coal deposit, which in turn permits the development of more accurate and efficient mine plans. Such geologic programs are now thought to be an intrinsic part of the mine development process.

FUEL QUALITY CONTROL PROGRAM

Utility company operated power plants, designed to burn a specific quality of coal, usually purchase coal on a contract basis, where fuel quality limits are defined and benefit and penalty clauses are invoked when the delivered coal quality varies significantly from established norms. In the case of Utah Power & Light Company, coal produced from company-owned mines fuels company-owned power plants, and quality variations are not administered by contract. This lack of a contract requires an in-house method of maintaining the fuel quality of produced and delivered coal: Utah Power & Light Company therefore initiated their Fuel Quality Control Program.

Definition of Problem

Fuel quality-related problems that hamper the efficient operation of power plants include extraneous materials in the coal, high ash content, and the abnormal concentration of certain oxides in the mineral analysis of coal ash. Extraneous materials are added to the coal during mining. Roof bolts, tin cans, mine timbers, chain, brattice cloth, miner bits, roof bolter drill bits, and mine spads are some of the more common materials that appear. Extraneous materials —particularly brattice cloth—cause the pluggage of and (or) damage to coal crushing, grinding, and transporting mechanisms, at which time coal handling and power plant equipment must be taken out of service to repair damage, which results in curtailment of load.

The efficient operation of power plants is affected significantly by the ash content of coals delivered. Ash content exceeding equipment design negatively impacts the operation and maintenance of coal-handling equipment, power plant boilers, and electrostatic precipitators more than does any other fuel quality parameter. Excessive loading on ash handling equipment, pulverizers, and coal transport piping causes load reductions and outages that decrease the overall efficiency of a power plant.

The oxides that comprise the mineral matter in coal ash can, if concentrated at certain percentages and in certain gravity fractions, cause the formation of slag and ash buildups in power plant boilers. An abnormal concentration of iron oxide in coal ash can result in the formation of slag in the lower parts of boilers, which reduces the efficiency of the heat transfer process. Concentrations of sodium oxide greater than 3 percent can result in excessive ash buildups in the upper portions of boilers and constrict their gas flow. Recent studies on the concentration of various oxides in the coal ash in different gravity fractions (Borio and Narciso, 1978) indicate that fractionation sink-float tests must be performed to understand and predict boiler operations that are affected by coal ash.

In the central Utah property discussed here, fuel quality control has been a problem: the amount of extraneous materials in the coal has been unacceptable; ash contents have been from 3 to 8 percent above plant design levels; sodium oxide has been concentrated to levels as high as 10 percent, averaging about 5 percent.

Implementation of Program

The Fuel Quality Control Program mentioned previously was designed to quantify fuel quality data

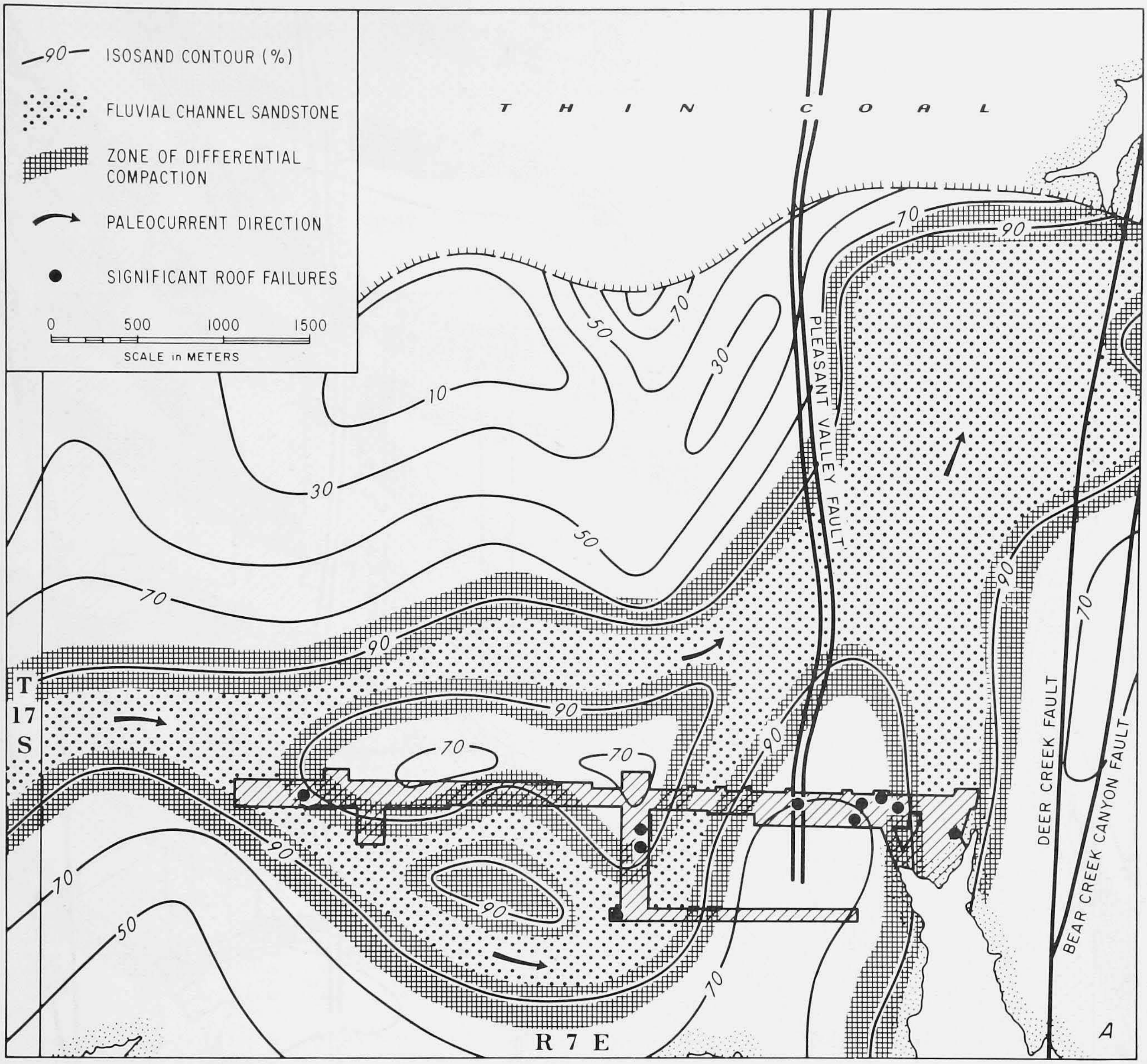
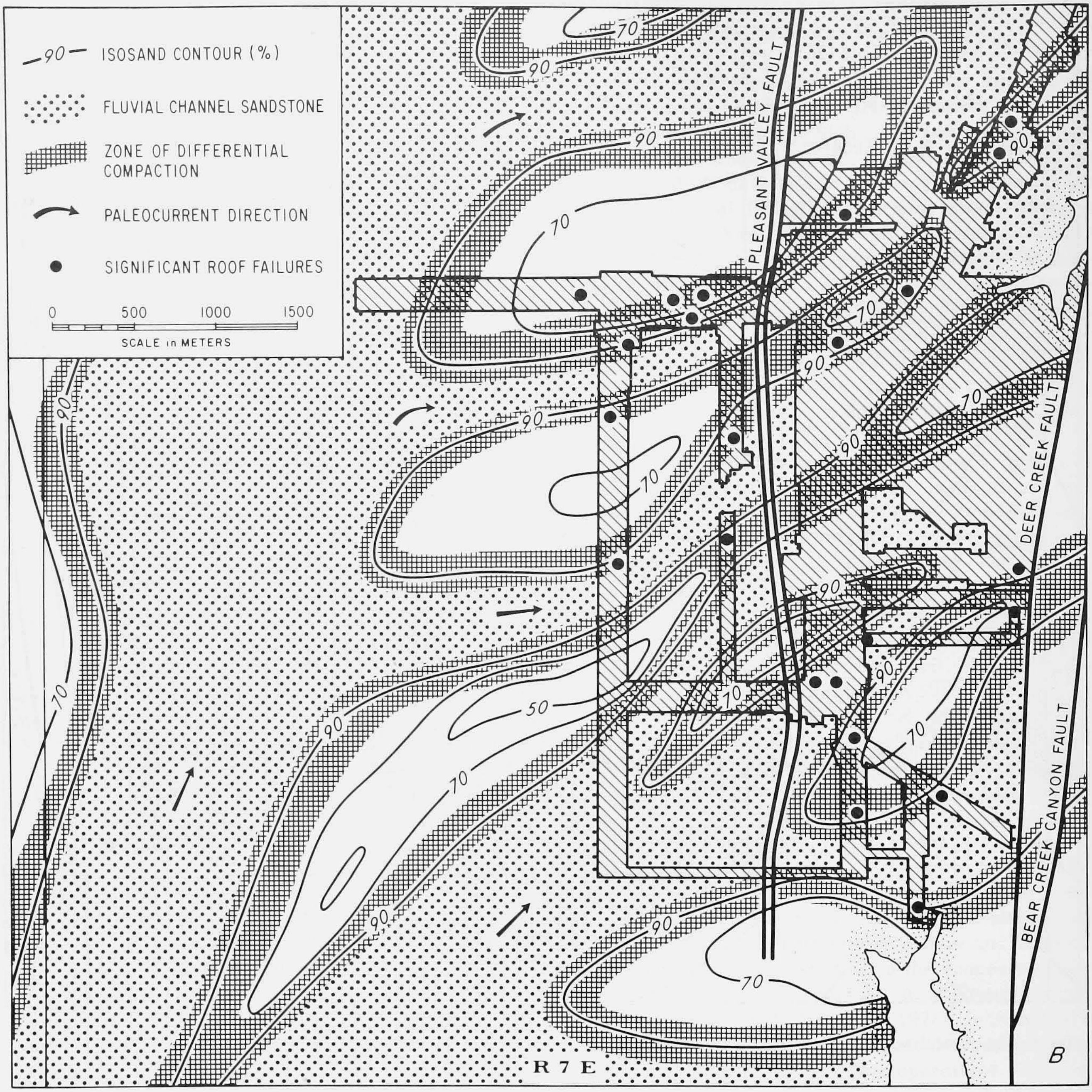


Figure 5 (above and next page).—Roof prediction maps for A, the Hiawatha seam, and B, the Blind Canyon seam.

from samples collected at various locations throughout the coal mine/power plant system so that decisions could be made on the basis of hard data. The cornerstone, therefore, of the program is the central coal testing laboratory, constructed by Utah Power & Light Company and operated by an independent third party. The lab is designed to accommodate 600 proximate analyses, 100 mineral analyses of ash and ash fusion temperature tests, and various screening, grindability, and sink-float tests, on a monthly basis. The data produced are stored in a computer, and weekly printouts of fuel quality data in the form of statistical information for week, month, and year-to-date for various sample sites are prepared (table 1).

Samples are collected at three major types of locations throughout the coal supply system: as channel samples within coal mines, at the portals of mines, and at power plants (table 2). A total of eight regular sample locations at portals and power plants are supplemented by about 20 in-mine sample sites in areas where mine workings are advancing.

Samples are collected in accordance with ASTM (American Society for Testing and Materials) standards when possible, although some grab samples are



collected at power plants and mine portals. Mechanical samplers have been installed at several sites in order to provide representative sample data.

Other activities of the Fuel Quality Control Program are to maintain close relationships with and provide input to research departments of boiler manufacturers who study fuel quality and boiler design and operation, to update coal preparation techniques to improve the quality of coals, and to train persons who mine and transport coal.

Results

Analytical data from samples collected throughout the system permit the identification of sites that contribute inordinate amounts of ash, sodium oxide, or other fuel quality constituents detrimental to power plant operations. Analyses of samples collected at power plant sites can be compared with operational experiences at the plants to determine the impact of certain fuel quality parameters on plant operation.

The quantitative information that is available concerning the fuel utilized in the Utah Power & Light

Table 1.—Fuel quality data; format for computer tabulation

```
                                                STANDARD LABORATORIES INC
  LAB NOS. FOR WEEK                                UTAH POWER & LIGHT CO.                        DATE WEEK ENDING   1/13/80
  -----------------
 9811  9812  9813  9814
 9815  9816  9850  9851
 9852  9853  9854  9855

SAMPLE ID WILBERG BELT SAMPLE

MATERIAL--STEAM COAL
                                                                    % VOLATAL     % FIXED    ASH FUSION TEMP-REC        ASH FUSION TEMP-OXD
SPECIFICATIONS      % ASH     % SULFUR      BTU/LB  % MOISTURE     MATTER       CARBON    ID    ST    HT  FLUID      ID    ST    HT  FLUID
                    -----     --------      ------  ----------    -------      ------    ----  ----  ---- -----      ----  ----  ---- -----
  AS RECEIVED
  -----------
    WEEK-MEAN       11.10        0.46        11568        9.09      38.61        41.20   2390  2422  2450  2535
        -# SMPL        12          12           12          12         12           12
        -SD          0.93        0.02          116        0.81       0.91         0.98     49    15    22    20
    MTD -MEAN       10.91        0.48        11565        9.23      38.64        41.22   2398  2425  2451  2529
        -# SMPL        24          24           24          24         24           24      4     4     4     4
        -SD          1.07        0.04          130        0.80       0.88         0.70     43    14    18    20
    YTD -MEAN       13.44        0.49        11129        9.23      38.09        39.28   2311  2361  2403  2473
        -# SMPL       480         480          480         480        480          480    111   111   111   111
        -SD          3.24        0.06          600        1.51       1.80         2.39     55    49    54    65
  DRY BASIS
  ---------
    WEEK-MEAN       12.21        0.51        12724                  42.47        45.32
        -# SMPL        12          12           12                     12           12
        -SD          0.96        0.03          145                   0.99         1.11

    MTD -MEAN       12.01        0.53        12742                  42.57        45.42
        -# SMPL        24          24           24                     24           24
        -SD          1.12        0.05          176                   1.05         0.82

    YTD -MEAN       14.82        0.54        12260                  41.94        43.23
        -# SMPL       480         480          480                    480          480
        -SD          3.59        0.07          600                   1.66         2.44

                                                ELEMENTAL MINERAL ANALYSIS OF ASH
             BASE/ACID   FE/CA   SI/AL   % SIO2  % AL2O3  % FE2O3   % CAO2   % MGO2   %NA2O    % K2O   % TIO2   % P2O5    % SO3

             ---------   -----   -----   ------  -------  -------   ------   ------   ------   -----   ------   ------    -----
WEEK-MEAN        0.18    0.66    2.52    54.13    21.56     4.44     6.66     0.60     1.74     0.37     1.23     0.17     4.41
    -SD          0.01    0.04    0.12     1.26     0.58     0.22     0.54     0.03     0.15     0.12     0.08     0.03     0.21

MTD -MEAN        0.18    0.64    2.51    54.60    21.81     4.34     6.76     0.60     2.11     0.35     1.28     0.17     4.33
    -# SMPL         4       4       4        4        4        4        4        4        4        4        4        4        4
    -SD          0.01    0.05    0.10     1.39     0.69     0.26     0.48     0.03     0.75     0.10     0.12     0.02     0.24

YTD -MEAN        0.21    0.63    2.55    55.37    22.19     3.95     6.50     1.41     3.41     0.83     1.18     0.16     3.48
    -# SMPL       111     111     111      111      111      111      111      111      111      111      111      111      111
    -SD          0.04    0.17    0.46     4.30     2.33     0.68     1.50     0.88     1.32     0.37     0.28     0.05     1.17
```

Table 2.--Mean averages and changes in fuel quality in various locations within a coal utilization system for a 2-month period

	In-Mine	Change (+ or -)	Mine Portal	Change (+ or -)	Power Plants	Total Change
Long Proximate						
No. of Samples	34		167		234	
Moisture (%)	5.33	+1.98	7.31	+0.35	7.66	+ 2.33
Ash (%)	7.33	+2.26	9.59	+2.34	11.93	+ 4.60
BTU/Lb.	12,785	- 891	11,894	- 310	11,584	-1,201
Sulfur (%)	0.54	+0.12	0.66	-0.08	0.58	+ 0.04
Ash Fusion Temp. (°F)						
No. of Samples	33		115		38	
Initial Def.	2,119	+ 93	2,212	+ 41	2,253	+ 134
Softening	2,215	+ 38	2,253	+ 65	2,318	+ 103
Hemis.	2,275	+ 31	2,306	+ 96	2,402	+ 127
Fluid	2,402	- 46	2,356	+ 112	2,468	+ 66
Mineral Analysis of Ash						
No. of Samples	25		116		34	
SiO_2	49.61	+4.24	53.85	+3.35	57.20	+ 7.59
Al_2O_3	20.45	-2.01	18.44	+1.68	20.12	- 0.33
Fe_2O_3	5.23	0.00	5.23	-1.25	3.98	- 1.25
CaO	9.08	+0.26	9.34	-2.84	6.50	- 2.58
MgO	0.97	+0.60	1.57	-0.15	1.42	0.45
Na_2O	6.74	-3.64	3.10	-0.34	2.76	- 3.98
K_2O	0.39	+0.74	1.13	+0.20	1.33	+ 0.94
TiO_2	0.25	+0.74	0.99	-0.06	0.93	+ 0.68
P_2O_5	0.14	-0.03	0.11	-0.01	0.10	- 0.04
SO_3	5.58	-0.35	5.23	-1.27	3.96	- 1.62
Si/Al	2.63	+0.42	3.05	-0.32	2.73	+ 0.10
Fe/Ca	0.59	+0.18	0.77	-0.18	0.59	0.00
Base/Acid	0.32	-0.04	0.28	-0.08	0.20	- 0.12

Company system allows a much fuller understanding of the nature and degree of contamination that occurs as a result of mining. These data have been used to modify mining plans, initiate training programs for mining personnel on maximizing fuel quality, install new magnets and other devices for removing extraneous material from coal, and justify the purchase of thin-seam mining equipment.

Fuel quality data collected as a result of the Fuel Quality Control Program have also been utilized by power plant designers to help justify the modification of plant equipment, the purchase of new equipment, changes in coal handling procedures, and changes in the design of new power plants. Blending systems and the purchase of blend coal has also been justified on the basis of fuel quality information.

The success of the Utah Power & Light Company Fuel Quality Control Program is illustrated for 1978 in figure 6. Total ash contamination at the start of the program was about 4.0 percent, but by year's end the contamination was reduced to about 2.5 percent. The sodium oxide content of coals delivered to power plants with tight design specifications (Gadsby and Carbon) was reduced to minimize slagging and fouling problems.

SUMMARY

The development of a major coal deposit in central Utah has necessitated the evaluation of geologic and fuel quality control programs as intrinsic components of the mining process. Geologic information collected as a result of the development of a coal property can be used to optimize mine plans. Fuel quality information, when collected systematically, can be used to justify modifications in power plant, coal handling, and mining practices that will result in the most efficient use of the fuel.

ACKNOWLEDGMENTS

The authors wish to thank the management of Utah Power & Light Company for the opportunity to publish the results of these studies. We particularly wish to thank John Mercier, who was instrumental in organizing and implementing the mine mapping program, as well as J. Steven Castleberry, Edward Agoston, and C. F. Busch for their contributions in compiling the information presented in this report. An expanded discussion of the mine geology portion of this report is available from a preprint of a talk given by Mercier and Lloyd at the 1979 meeting of the ASME.

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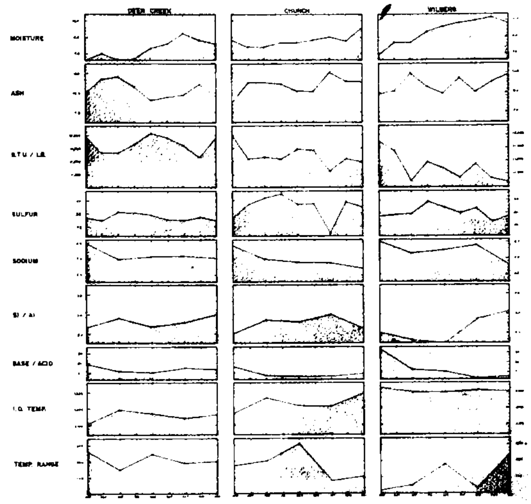

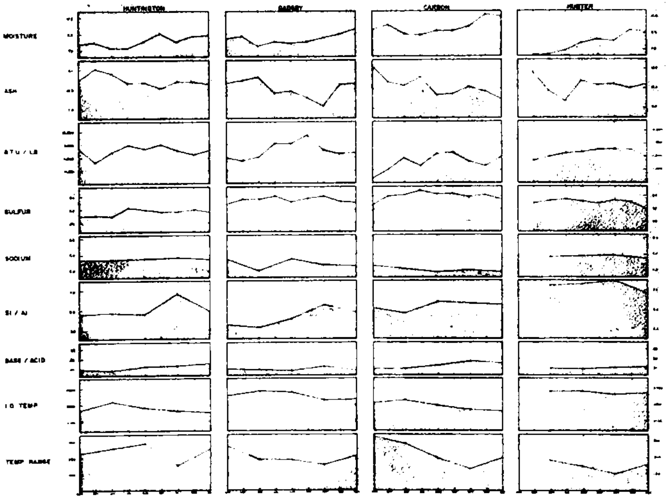

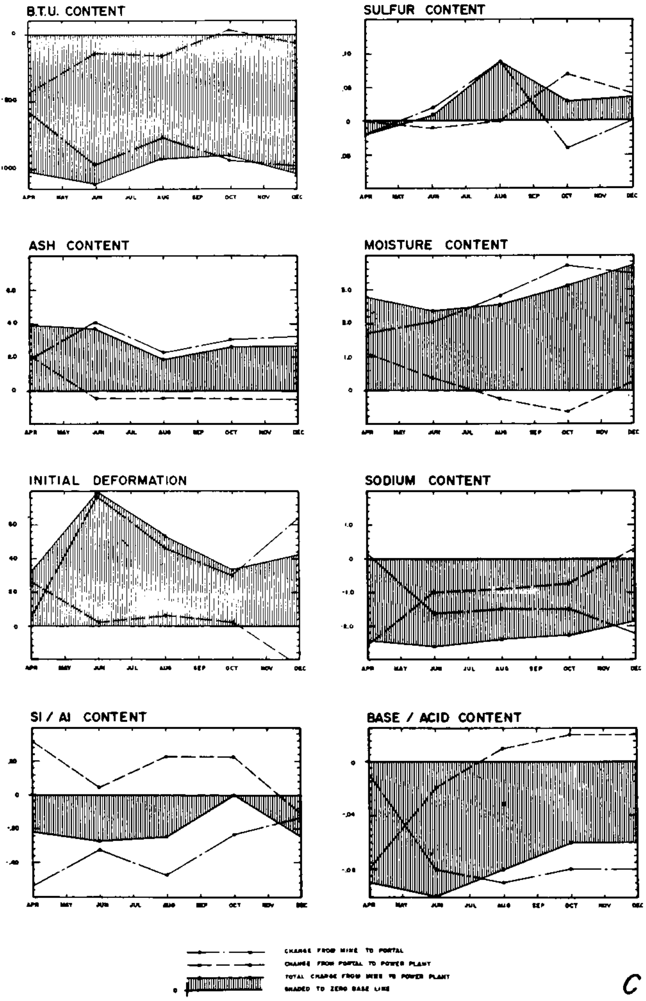

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Figure 6.—Quality data of A, mine portal (1978), and B, power plant (1978); C, total fuel quality changes (1978).

THE EFFECTS OF A RIDER COAL AND SPLAY DEPOSITS ON ROOF CONDITIONS IN THE STANSBURY MINE

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INTRODUCTION

The Stansbury Mine is located in T. 20 N., Rs. 104-105 W., Sweetwater County, Wyo. Rock Springs, population 23,000 and county seat for Sweetwater County, is located approximately 6 mi south of the property. The mine is an underground operation producing coal with continuous miners and roof and pillar panel development.

The coal measures of the Stansbury area are located in the Rock Springs Formation of the Upper Cretaceous Mesaverde Group. The Rock Springs is part of a wave-dominated deltaic system and consists of an alternating sequence of sandstone, shale, and coal. In the Stansbury area the Rock Springs Formation includes from top to bottom the following defined seams: #5, #3, #1, #7.5, #7, #8, #9, #11, #13, #15, #17, #19, #21, and #23. The mine itself is currently operating in the #3 seam with future development to occur in the #7 seam and perhaps the #7.5 and #8 seams.

This report will focus on the geologic evaluation of roof conditions above the #3 seam and in particular the effect of a rider coal and splay deposits upon those roof conditions.

METHOD OF APPROACH

Geologic evaluation of Stansbury began with the review of available data for the mine area, including in-mine mapping of roof and coal exposures, reevaluation of drilling data, outcrop mapping, and use of old mine maps. Discussions with engineers and miners involved in day-to-day operation of the mine provided insight into the effect of geologic conditions on mining procedures. In-mine mapping involved detailed description of roof exposures in the main incline of the #3 seam and the developing portions of the #1 seam. Individual rock types encountered during the mapping were given a three-digit code based upon a system developed at the University of South Carolina. Roof exposures near recent roof falls were studied to determine the relationship between rock types, depositional setting, and roof problems.

In order to extend our predicting capabilities into unmined portions of the mine tract, in-mine mapping was followed by evaluation of drilling data. Available spot core from 14 holes on the mine tract was cleaned and described using a photographic core book containing the three-digit code numbers, which produced a standardized logging technique, consistent between drill holes. In addition, some rock mechanics testing was conducted on selected roof cores to determine potential strengths of rock types.

For uncored holes, it was necessary to relate a three-digit code to characteristic geophysical log signatures. For this purpose core lithologies were correlated with the curves produced on geophysical logs run in the cored holes. This permitted the identification of the various rock types by their characteristic association of curves (log signature) on the geophysical logs.

Once the log signatures of the various rock types were calibrated by the cored sections of the bore holes, these "signatures" were used for lithologic interpretations in the sections of the drill holes where only geophysical logs and cuttings samples were present. These data for the entire hole were then loaded into the computer drill-hole data base, and a plotting program produced strip logs at a 1 in=10 ft scale, from which correlations were made.

Outcrop mapping began with the study of aerial photographs to trace key coal and sandstone units. Coal zones are generally easy to establish in the Stansbury area because of the high degree of "burning" of the coal, which oxidizes the surrounding lithologies and gives them a reddish color. Where coals are burned, it is not possible to measure a stratigraphic section; however, when these were traced laterally along strike, fresh exposures were discovered.

Finally, data were collected from maps of the mine workings. Available data consisted of measured coal sections, occasional elevations on the base of the coal, and some idea of seam geometry. The mine map data were especially useful, though, in the creation of the isopach maps (and hence reserve calculations) due

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to the addition of needed data points. Using all the lithologic data from outcrop and in-mine mapping, core, and geophysical logs, roof maps were prepared for the roof types that overlie the #3, #1, #7.5, and #7 seams in the Stansbury Mine tract.

Roof quality in underground mines is dependent on the interrelationship of rock types, syndepositional structures, early post-depositional compactional traits, and later tectonic features. Because most of the deposits of the coal measures in the Rock Springs region are terrigenous clastics, rock types are contingent upon grain size and degree of cementation. Most commonly, the syndepositional features are burrow and root structures, bedding, and slickensided surfaces in clayey rooted zones. Where less compactible rock types such as sandstones are surrounded by more compactible rock types such as shales and siltstones, differential compactional features occur. Superimposed on these characteristics are later tectonic structures such as jointing and fracturing. Thus most of the features of roof conditions can be related to depositional or early-stage compactional processes. It appears probable that later tectonic events have accentuated these early-formed traits, but the basic characteristics seem to be established during or shortly after the sediments were deposited. Therefore, by depicting the depositional sequence, potential roof conditions can be anticipated.

In the Stansbury Mine tract, six basic depositional sequences have been established. They have been related to observed roof conditions in the active workings in the #3 and #1 seams of the Stansbury tract and from there to other active underground mines in both the western and eastern United States. The six roof sequences overlying the coals in the Stansbury tract have been arranged according to potential roof quality (table 1) from good (1) to bad (6).

Table 1.--Roof sequences

Roof No.	Roof type	Roof quality
1	Coarsening-upward grain size--	Excellent.
2	Shale sequences---------------	Good.
3	Fining-upward grain size------	Do.
4	Slump structures--------------	Poor-good.
5	Rider seam within 6 ft of main seam--------------------	Fair.
6	Rider seam within 6-10 ft of main seam-------------------	Poor.

The best quality roof conditions in this mine tract occur in coarsening-upward rock sequences (1) that grade from shale upward through shales with sandstone streaks to sandstone and shale interbedded and are capped by sandstones. These sequences provide few roof support problems. However, separations can take place at sandstone/shale bedding planes, producing roof falls; hence, roof bolting is an essential precaution.

Although not quite as good as the coarsening-upward sequences, thick sequences of shales and sandy shales (2) and fining-upward sandstone sequences (3) also can provide stable roof conditions. The shales and sandy shales provide suitable roof quality for conventional mining with roof bolting and excellent roof for longwall mining. Fining-upward sandstone sequences (channels) in excess of 10 ft can provide excellent roof conditions. These sandstone bodies are occasionally crossbedded near the base and will grade upward into a shaly sandstone. However, lag deposits composed of shale and coal pebbles may occur at the base of the sandstone channels and can weaken the sandstones and cause local roof problems. In areas where the less compactible sandstones are present as discrete bodies adjacent to more compatible shales and sandy shales, slickensided surfaces form at the contact between the lithologies due to differential compaction. Zones of weakness are developed along these surfaces, and separations may take place, causing roof falls.

Another circumstance where roof problems may develop occurs where slump structures (4) are present in the roof over the coal. The slickensided planes found with these disturbed blocks are analogous to slicked surfaces observed in association with modern channel bank slumps. Because of numerous slickensided surfaces, roof problems can be anticipated whenever these slumps are encountered, and roof bolting and bracing may be of little use. To date, no serious slump features have affected mining at Stansbury.

Finally, roof problems arise where rider coals have formed within 10 ft over the main seams, and the intervening rock type is dominantly fine grained material such as shale and sandy shale. Because the rider coals and underlying root-penetrated clays have little strength, they provide zones of weakness along which separations can take place. When these separations develop, severe roof falls may evolve, encompassing all the material up to the rider seam.

Where these rider coals are within 6 ft of the main seam (5), conventional 6-ft roof bolts may be sufficient to prevent falls. Experience with bolting in the #3 seam at Stansbury indicates that this is normally the case where the bolt can be anchored into competent sandy shales that overlie the rider coal. Obsevations in the eastern United States suggest that when the shales between the rider and the main seam are extensively root penetrated, slickensides are developed in the fine-grained seat earths. These root-penetrated shales possess little strength and roof falls may occur even when the area is heavily bolted.

The poorest roof conditions in the Stansbury tract develop where the rider seams are 6-10 ft above the main seam (6). Here, conventional roof bolts do not penetrate the rider seam and are anchored into weak, root-penetrated shales. In this situation, falls can occur encompassing all the material up to the rider seam. Most of the falls in the #3 seam at Stansbury have been the result of this condition.

#3 SEAM ROOF CONDITIONS

The #3 seam at Stansbury ranges in thickness from 4 to 8 ft, with an average of 6.5 ft. The seam dips to the west at 10°-15°. A typical sequence above the #3 seam is as follows:

Immediately above the #3 seam is a rooted gray shale overlain by a thin rooted black carbonaceous shale with coal streaks. Overlying the carbonaceous shale is another rooted gray shale with siderite nodules that grades upward into a second rooted black carbonaceous shale with coal streaks. Capping the sequence is a thin brown band of siderite overlain by the #3 rider coal. The interval between the top of the #3 seam and the top of the #3 rider is generally within the range of 3 to 5 ft. Six-foot rock bolts anchor, in competent strata, above the rider coal in these situations, and the roof is adequately supported. Unfortunately, the rider coal frequently climbs into the roof above the #3 seam, and the standard 6-ft bolts anchor in the underlying weak rooted shale lithologies. In a few cases these poorly anchored bolts have failed and roof falls have resulted.

The ability to predict variations in the interval between the #3 seam and the #3 seam rider would assist mine engineers in augmenting the roof support system by using longer bolts, employing resin bolts, or, in severe situations, cribbing. Careful evaluation of the #3/#3 rider interval from in-mine mapping and drill-hole analysis resulted in an interesting discovery. The preceding data were combined with previous roof fall information to produce an isopach map of the parting between the #3 seam and the #3 rider (fig. 1). The similarity in shape to splay deposits found in modern peat-forming environments is striking. The mine mapping revealed a change in parting lithology from rooted shale, to sandy shale, and finally sandstone, as the parting between the #3 and the #3 rider increased. Paleocurrent directions obtained from these splay sands indicate a sediment source to the west. Recent drilling data collected to the north of Stanbury point to a north-south-trending channel system that passes west of the current mine boundary.

A roof lithology sequence map for the #3 seam was produced by integrating the parting map with lithology data from drill-hole strip logs and cross sections. The resulting map (fig. 2) displays those areas of potentially poor roof (type 6) to be encountered during development of the three-seam mine. The splay deposit has influenced roof conditions by producing a sinuous digitate pattern of type 6 roof. Near the interior of the splay, roof conditions improve to type 3 and type 1 conditions. Of particular importance, however, is the lateral variability in roof conditions. The form of the splay results in rapid changes from type 6 to type 3 and 1 conditions. The average drill-hole spacings of greater than 1,500 ft are inadequate to accurately predict these changes, which occur over distances as short as 200 ft. It is, therefore, necessary to monitor the distance to the rider coal during roof bolting operations. This process helps to further define the geometry of the splay and aids in planning roof support for further panel development.

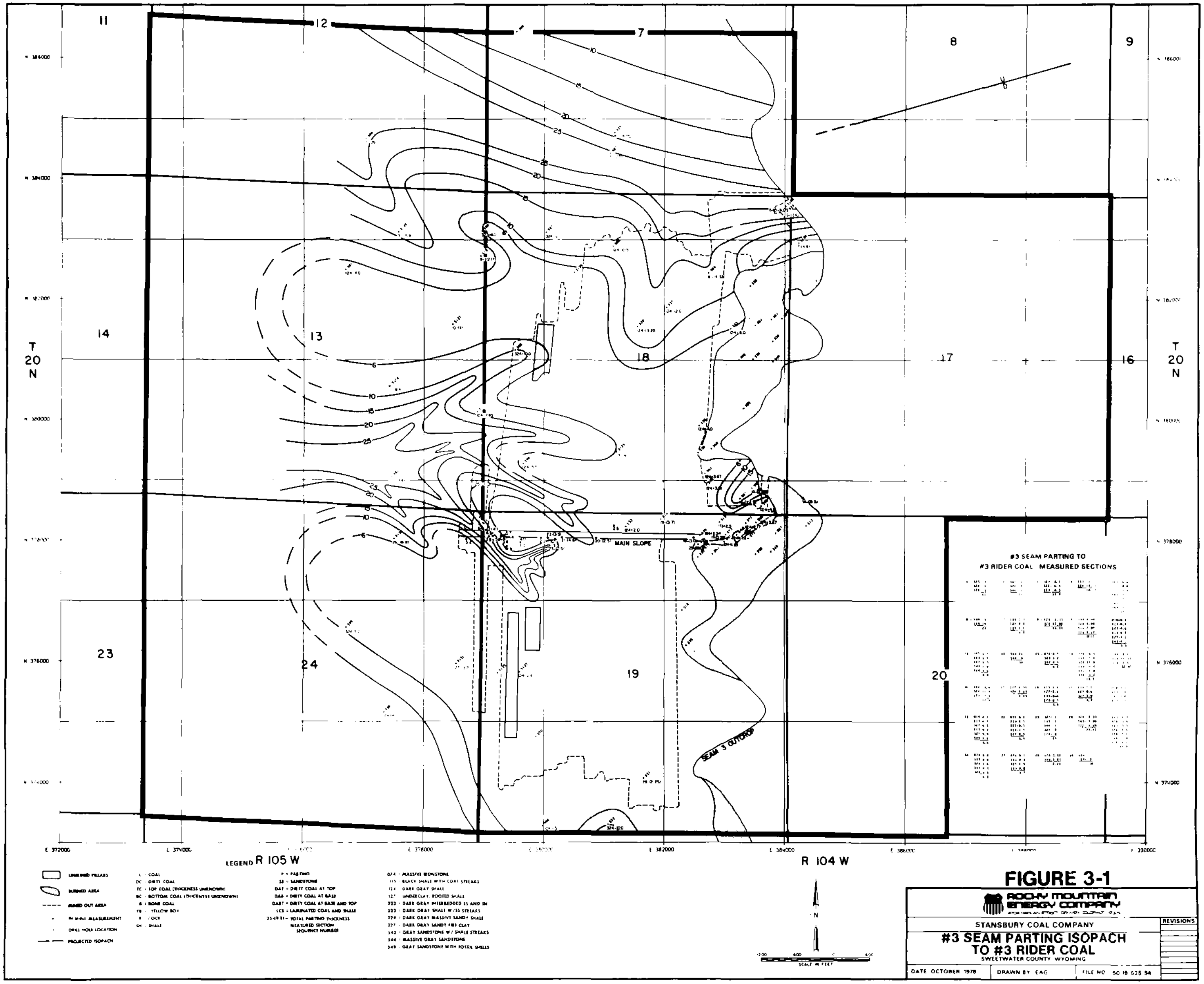

Figure 1.—Isopach #3 seam parting to #3 rider coal.

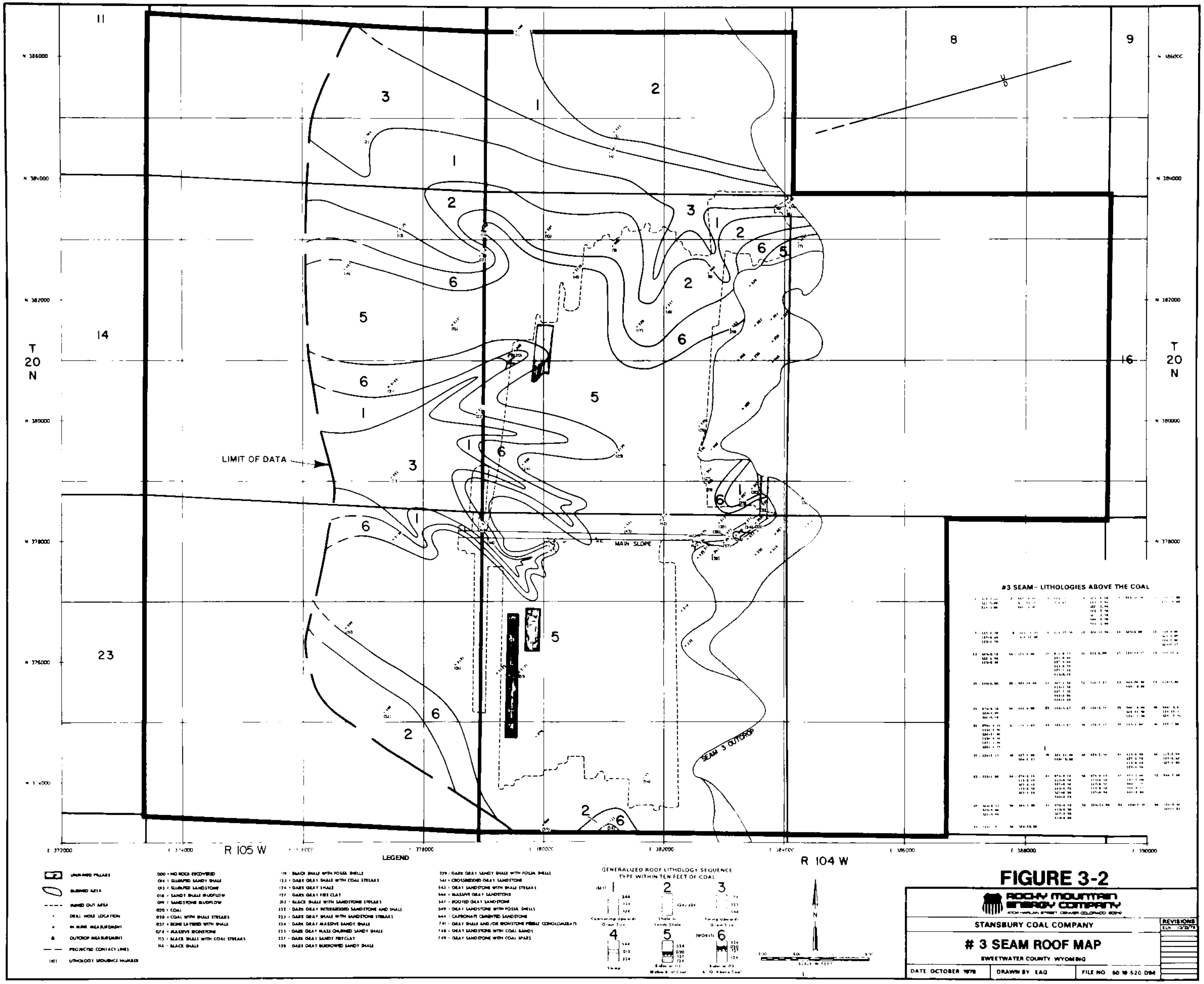

Figure 2.—#3 seam roof map, Stansbury Coal Company.

COAL MINE SUBSIDENCE AND FIRES IN THE SHERIDAN, WYOMING, AREA

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INTRODUCTION

Coal mine subsidence and fires in the Sheridan, Wyo., area are hazards to people, animals, and property; fires also waste large amounts of coal. Subsidence and fires occur in underground mines in the area, such as the New Monarch and nearby Acme mines, even though most were closed 40-70 years ago (Dunrud and Osterwald, 1980) and the last one was closed nearly 30 years ago. It is estimated that 25-30 million tons of coal have burned in abandoned underground mines in the Sheridan area since mining began in the late 1800's. Although pits, cracks, and depressions are in themselves hazards, a greater hazard exists where subsidence pits suddenly form to expose underground fires and emit noxious gases (Dunrud and Osterwald, 1980). Noxious and toxic chemicals produced by the fires also can pollute the air and contaminate surface and ground water.

Knowledge of the long-term effects of underground and surface mining is essential in planning the safest and most efficient methods of mining the hundreds of billions of tons of subbituminous coal in the Fort Union (Paleocene) and Wasatch (Eocene) Formations in the Powder River Basin, with a maximum yield and with a minimum of long-term environmental damage.

SUBSIDENCE

Subsidence depressions, cracks, and pits are common above the mines and continue to form, even in areas where mining ceased over 50 yr ago. New subsidence pits form among old, revegetated pits, as sections of mine roofs and overlying rocks and surficial material collapse into mine voids. Pits also develop locally in surficial material above subsidence cracks in the underlying bedrock. The surficial material can deform without failing above cracks in the underlying bedrock, until the activities of man or animals create holes, particularly during wet periods. The holes enlarge by erosion, mass wasting, and mass-gravity movement to form pits that look much like subsidence pits caused by successive collapse of mine roofs above individual mine openings (Dunrud and Osterwald, 1978, p. 26-31). Subsidence pits can occur suddenly and without warning where surface collapse above near-surface cavities or cracks in bedrock occurs due to the added weight of persons, animals, or vehicles.

Depressions, pits, tension cracks, and compression bulges or ridges, caused by stretching and shortening of the ground surface near the margins of the depression, can damage structures and utility lines and trigger landslides on landslide-prone slopes. These subsidence features also can disrupt and alter the natural flow of surface and ground water and therefore may adversely affect water rights. All these effects of subsidence reduce or limit the value of the land above abandoned underground coal mines for agricultural, residential, or industrial development.

Subsidence also can occur in surface mining areas. Downward vertical and lateral movement of the surface is locally common as the reclaimed mine spoil undergoes compaction, particularly when the spoil is saturated (Charles and others, 1978). Such subsidence may only amount to a small fraction of the thickness of coal mined and usually can be further reduced by proper grading and compaction procedures that are designed with respect to the geologic and geotechnical properties of the bedrock and surficial material.

Subsidence amounting to 50-90 percent of the thickness of coal mined is common above underground mines where longwall or room-and-pillar methods were used, the pillars were removed, and the mine workings were not backfilled. Also the surface area affected by subsidence commonly is greater than the mine area (Dunrud, 1976, p. 7-26; Dunrud and Osterwald, 1978, p. 42; National Coal Board, 1966; Shadbolt, 1978). Subsidence pits above room-and-pillar mines can be even deeper than the thickness of coal mined, where pillars are not extracted, the overburden is less than about 10-15 times the thickness of coal mined, and the collapsed roof and overburden material is moved laterally into adjacent mine openings by water (Dunrud and Osterwald, 1980).

FIRES

Fires are locally common in underground and surface mines in the Sheridan area. The coal is susceptible to spontaneous combustion where air and water come in contact with coal dust or fine coal (Kim, 1977). Fires in coal exposed in highway cuts or surface mines are usually much more easily controlled than those in underground mines because they are visible and accessible. Underground fires also may ignite by spontaneous combustion where air and water reach exposed coal through subsidence cracks, pits, or poorly sealed mine portals. Subsidence commonly continues as the fires burn and create more void space, which in turn creates more subsidence cracks and pits, allows more air to the fire, and accelerates the burning process (Dunrud and Osterwald, 1978, p. 48). Such fires are difficult to control or extinguish. Fires may spread to large areas of abandoned mines or abandoned parts of active mines before flames, smoke, steam, and other noxious pollutants are seen or smelled at the surface. It is difficult, perhaps impossible, to use large earthmoving equipment to control a fire in underground mines without risk to personnel and equipment, unless the mine is first exposed by removing the overburden.

A fire started by spontaneous combustion in the northwest corner of the New Monarch mine (operated from 1950-53) in November 1978, after a subsidence pit had formed about a year earlier. By mid-December a second flaming and smoking pit had developed above the mine in the fire area; two explosions occurred in early January 1979. Flames reaching as high as 30 m above ground and columns of smoke, steam, and noxious gases as much as 600 m high were emitted from the pit after the explosion (fig. 1).

Within a week after the explosions, a total of six smoking and steaming pits had developed, when fire control measures began. The pits were bulldozed full of local surficial material and bedrock. The filling operations were not without pitfalls, however: a bulldozer became trapped when one track broke through into an underground cavity near a pit being filled. New steaming and smoking pits have continued to form at or near the filled pits (several within a few days of filling); the fire has spread and the overburden continues to collapse into the mine workings. The heat and steam produced by underground fires, particularly where the mines contain some water, weaken the 30-m-thick soft claystones, shales, coal, and surficial overburden and promote rapid collapse of mine roofs and ultimate surface subsidence (fig. 1). In November 1979, the author observed a steaming pit about 3.5 m deep and 4 m in diameter form during a 30-minute period. The burning rate and amount of air pollutants emitted to the atmosphere commonly are sporadic because collapse of the overburden temporarily retards the rate of burning until new pits or cracks again ventilate the fire.

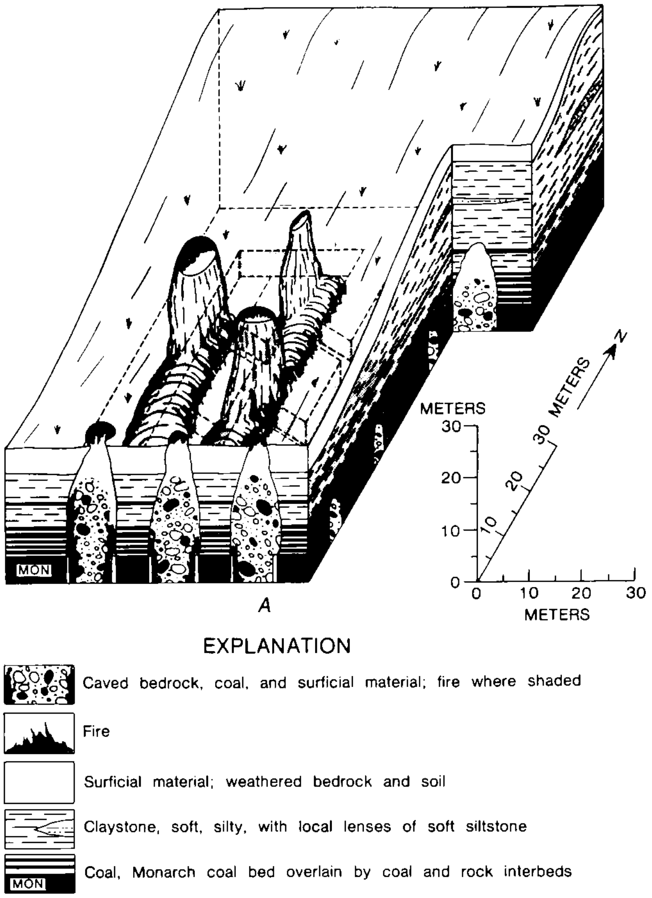

Figure 1.—Conceptual block diagram of northwest corner of New Monarch mine. Diagram shows relationships between subsidence pits, underground collapse, underground mine workings, and fire, as of early January 1979, a few days after explosions occurred in the mine and smoke and fire were visible above ground level.

SUBSIDENCE AND FIRE-MONITORING STUDIES

The breaking and caving of rocks above the mine and movement of air, steam, and (or) water through the mine workings cause pressure waves and small earth tremors in the mine workings and adjacent bedrock and surficial material. As many as 2,500 earth tremors per day have been monitored in the New Monarch mine by U.S. Geological Survey personnel with the use of sensitive seismometers placed near the fire area. Subaudible earth tremors and noises within the mine are recorded on visible charts and on magnetic tape in a recording van and also are amplified and connected to a low-frequency loudspeaker in order to hear the noises. Crackling, rumbling, and hissing sounds from the loudspeaker are similar to the sounds that sometimes accompany overburden breakage and collapse and emission of smoke, steam, and sulfurous gases.

Periodic mapping and studies of aerial photographs showed that surface depressions with peripheral cracks began to develop about 6 weeks after the smoke and fire were visible above ground level. Some of the initial pits began to enlarge into north-south-trending troughs after the depressions and cracks formed. As of January 1980, the fire continues to spread and to cause more subsidence pits, troughs, cracks, and air pollution.

Surface tilt above the fire area at New Monarch is being monitored by tiltmeters and periodic surveys of bench marks. Results of the studies show that the ground surface is subsiding as the coal pillars that support the overburden are burned or weakened.

CONCLUSIONS AND RECOMMENDATIONS

Subsidence and fire studies in the Sheridan, Wyo., area show that the economic and safety consequences of coal mine subsidence and fires should be considered in planning future mining operations and also in planning the use of lands underlain by coal mines. Where lands above underground coal mines are to be developed for residential or industrial use, steps should be taken either to locate the mine voids, stabilize them by backfilling (Whaite and Allen, 1975) or grouting or to design surface structures to withstand deformations caused by subsidence (Geddes, 1978a, b). Steps must be taken to insure that underground fires cannot occur whether either method is used.

Construction of a strip mine firebreak or isolation trench is proposed as the best method to control large underground fires such as those burning in the New Monarch and Acme mines in the Sheridan area. The fires can be stopped from spreading by these methods and the coal mined could help defray the costs of fire control. Backfilling or grouting the mine workings, although workable alternatives where fly ash or mine tailings are abundant, would be very expensive in the Sheridan area and would not recover any coal.

Coal mine subsidence and fire studies in the Sheridan area by the USGS (Dunrud and Osterwald, 1980) also indicate that surface mining with adequate reclamation practices commonly is less hazardous, less damaging to the environment, and produces a greater percentage of coal than does underground mining, where either method is economical.

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FORMATION OF CLINKER BY NATURAL BURNING OF COAL BEDS IN THE POWDER RIVER BASIN, WYOMING

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INTRODUCTION

Large areas in several coal basins in the Western United States are dominated by red and orange outcrops of erosion-resistant, fractured rocks that resemble porcelain or brick. These rocks have been baked by coal beds burning in place. This widespread phenomenon was noticed and correctly interpreted by Lewis and Clark (1814) and has been commented on in many studies since then, but since Rogers (1918) little work has been directed at detailed study of these rocks. Collectively the baked and fused rocks commonly are referred to as "clinker," which originally meant the ash of coal, especially if it was scoriaceous or glassy; but in the context of burned coal beds the term has come to mean the baked rocks, and the coal ash is referred to simply as ash.

Clinker is extensively developed in the Western United States in the Powder River Basin, the Williston Basin, the Piceance Creek Basin, and the San Juan Basin, and it occurs in lesser quantities in other areas where coal crops out. The U.S. Geological Survey is currently examining the origin, distribution, structure, geochemistry, petrology, and geophysical properties of clinker, and its use as a tool to interpret erosion rates and perhaps burning rates.

STRUCTURE OF CLINKER

In the eastern Powder River Basin in northeastern Wyoming (fig. 1), the bulk of the clinker is baked siltstone, sandy siltstone, and shaly siltstone; sandstone generally makes up no more than 5 percent of clinker. Although the rock commonly is moderately to highly fractured, bedding is preserved on a gross scale in most exposures. Bedding may be disrupted by high-angle faulting as well as by gentle to abrupt folds and brecciated zones.

Irregular to tabular bodies of slightly to greatly fused black to iron-gray open breccia locally extend upward through the clinker from a meter or two above the ash to the ground surface. The breccia is composed of angular unfused fragments, slightly fused fragments, rocks that have undergone simultaneous fracturing and plastic deformation, angular fragments covered with a fused rind and welded together at points of contact, and black, vesicular, cryptocrystalline to glassy fused rock that has flowed like low-viscosity lava. These rocks clearly have been hotter than underlying and surrounding rocks.

Rogers (1918) attributed the near-vertical "chimneys" of fused rocks to the combustion of coal gas that was driven off during combustion of the coal; the gas burns at high temperature when it has risen high enough in a vent to mix with sufficient oxygen. Probably for this reason, fused rock is very rarely found at the level of the coal ash but may occur as much as 25 m above the ash in chimneys that rise through less altered rocks.

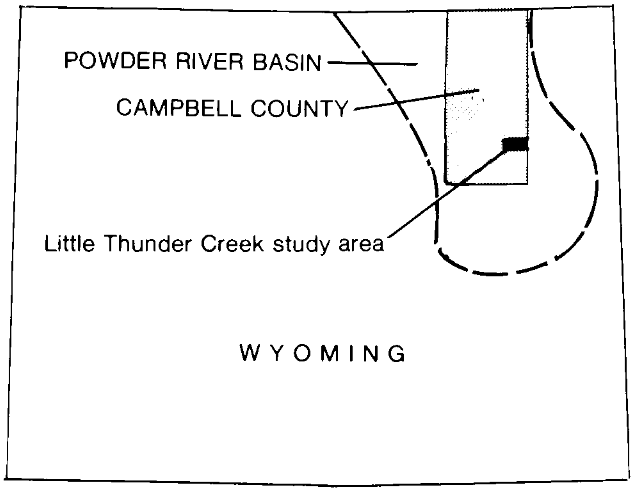

Figure 1.—Index map showing the location of clinker study area in the eastern Powder River Basin, Campbell County, Wyo.

After a fire has started, it generally advances in the top part of the coal bed and then burns downward. Support for the overburden is removed slowly, and the overburden is lowered more by settling than by disruptive collapse. That collapse may occur is shown by open breccia at the base of the clinker in some areas, but this generally is no more than a few meters thick and is overlain by fractured clinker in which bedding is little disrupted. In some cases a near-vertical burned face of coal as much as 4 m high is preserved, showing that the advancing burn face may be steep. Near this front, fractures are opened to the surface by flexing of the body of overburden. Combustion gases and combustible coal gas burn as they are vented along these cracks toward the surface, creating the fused chimneys. In some areas settling takes place along discrete high-angle faults, which may coincide with tabular chimneys of fused breccia.

Exposures of extinguished burn fronts show that alteration propagated upward from the last burning so slowly that only part of the overburden shows signs of baking. The top of the zone of altered rock slopes or curves from the burned area down to the burn front. Because of this, the edge of the discolored rock at the ground surface in many cases does not indicate the farthest advance of the burn in the subsurface.

Changes in mineralogy of the iron in the rock caused by burning, and perhaps addition of iron (O'Connell, 1979) cause the clinker to be more strongly magnetic than equivalent unbaked rock (Watson, 1979). Because of this, a ground magnetic survey generally can determine the edge of the burned area in the subsurface. This method, however, cannot detect the presence of economic coal beneath clinker.

CAUSE OF BURNING

Clinker has formed in the Western States almost everywhere that beds of coal are exposed. Lightning and range fires were long considered the main causes of ignition. Rogers (1918) concluded that spontaneous ignition probably accounted for most coal fires in the Powder River Basin. The opening of large coal mines in this region has exposed large amounts of coal to the air, and the abundance of spontaneous mine fires, mostly in finely comminuted coal, is dramatic confirmation of Rogers ' ideas. Some of the factors that control spontaneous ignition are chemistry of the coal, water content, grain size and reactive surface area, freshness of the coal, and microclimate and the ability of the fractured coal to retain heat.

In considering the circumstances for spontaneous ignition in nature, Rogers thought that an ideal site would be where a stream cuts into a coal bed so that the outcrop slacks and forms a bank of finely comminuted coal below the face. He suggested that this coal would ignite most efficiently if the bank were facing south so that solar heat would provide an initial rise in temperature, but I have not confirmed the role of solar heat.

Presently we cannot establish why fires go out: surely the water table is involved in some instances, although a furiously burning coal fire with ample air probably could drive out a good deal of water ahead of it. Snuffing of the fire by collapse of overburden probably is the dominant mechanism, although this is not a direct function of overburden thickness; burning of the Wyodak coal in the Powder River Basin has baked as much as 35 m of overburden in some places. Some other fires have been extinguished beneath as little as 10 m of overburden in topographic situations suggesting that ground water was not a major factor.

EASTERN POWDER RIVER BASIN

On the eastern flank of the Powder River Basin in Campbell County, Wyo. (fig. 1), clinker is significantly more resistant to erosion than any other rock abundant in the area. Clinker, therefore, caps most of the high points of topography and controls the shape of the landscape as a whole. The thickest coal bed in the region is the Wyodak coal in the Paleocene Fort Union Formation, which dips westward at a few meters per kilometer. Streams that drain this area flow eastward into the Cheyenne, Belle Fourche, and Little Powder Rivers. As streams cut deeper they intersect the Wyodak coal progressively down dip. The coal so exposed is susceptible to burning, which progresses down dip (upstream in the east-flowing main drainages), and across strike (upstream in the minor drainages north and south of the main streams). Thus a major east-facing, dissected escarpment is formed, consisting of flat-topped promontories and ridges rising gently eastward to stand some 200 m above the main drainages (fig. 2).

Within this dissected escarpment, known as the Rochelle Hills, the major promontory north of Little Thunder Creek was selected for study. Near the end of the promontory, all coal has apparently burned, and the clinker-capped promontory is a narrow flat-topped ridge. Farther west where the promontory broadens, it remains rimmed by clinker but has unburned areas in the central part (fig. 2). At the western limit of the Wyodak clinker, where Little Thunder Creek and the coal converge, the coal has burned only along the main stream and a major tributary, Burning Coal Draw; the intervening land is underlain by shallow economic coal. The Kerr-McGee Jacobs Ranch Mine,located here, typifies the position of many of the mines along the west side of the Rochelle Hills.

Clearly the clinker forming the escarpment here is older on the east or high side than on the west, and the whole escarpment is migrating westward. But at what rate is this process proceeding? C. W. Naeser, U.S. Geological Survey, has found that detrital zircons in the baked sediments were completely annealed during burning, thus resetting the clock for this radiometric dating method (Coates and Naeser, in press). Naeser has determined the age of clinker from the tip of the subject promontory and from the next major promontory to the south to be about 0.7 m.y. In the study area, he found ages of the clinker on the tips of spurs north of Little Thunder Creek to be progressively younger westward (upstream). He also found ages to be consistently about 200,000 yr younger in the heads of valleys between spurs than on the tips

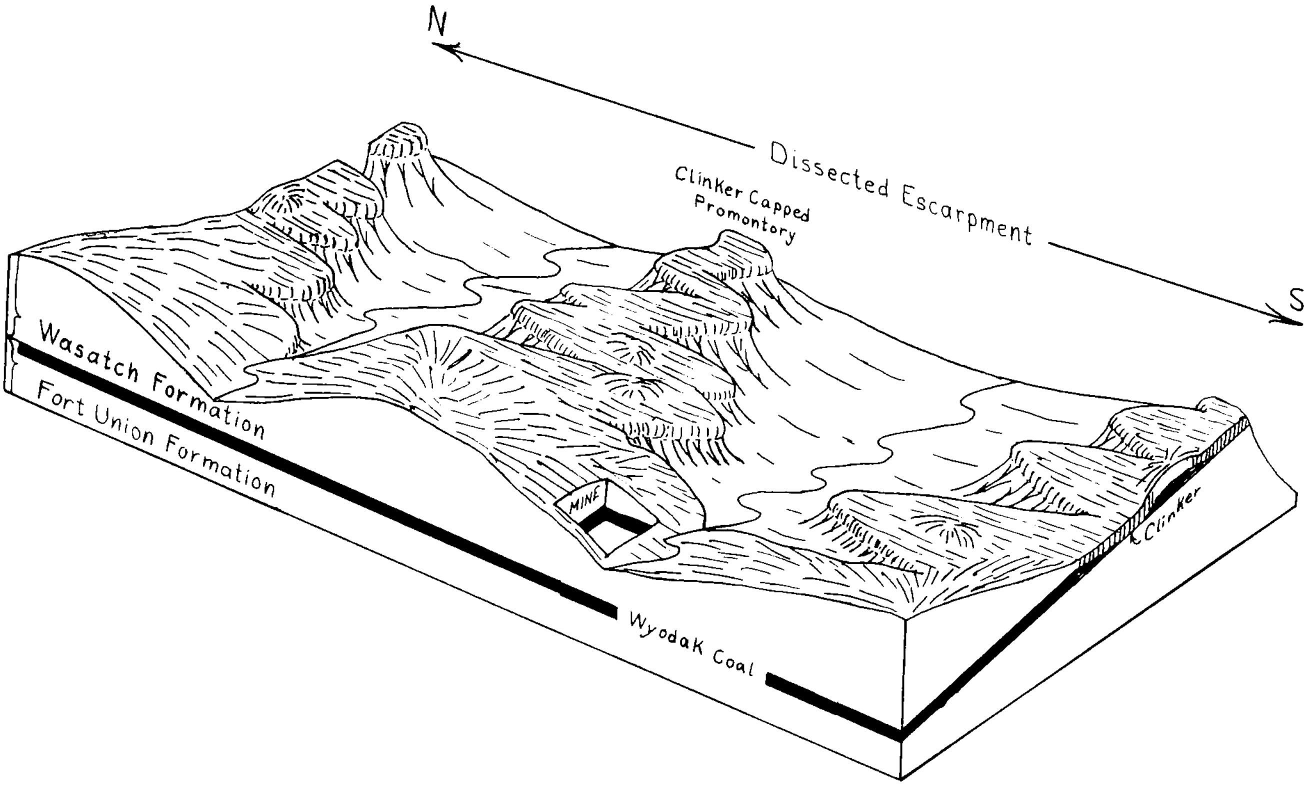

Figure 2.—Schematic diagram showing the relationships of coal, clinker, topography, and drainage in valley of Little Thunder Creek in the Rochelle Hills, southern Campbell County, Wyo. The Rochelle Hills form an eastward-facing escarpment crossed by Little Thunder Creek and other eastward-flowing streams, and further dissected by tributaries to these streams.

of the spurs. Using these figures we have calculated that burning along the middle of the promontory has progressed about 8 km in the last 0.7 m.y., or about 10 m per thousand years. Further dating is expected to refine the rate of landscape development.

The diversity and orderly progression of dates forces another conclusion regarding the progression of burning: despite the large areas of total burn and the long expanses of cliffs topped entirely by clinker, the clinker has been formed by many localized fires rather than by one or a few major fires. The youngest clinker, formed by a number of small burns, occurs farthest downdip; updip, a large number of small burns merge to form a complete cover of clinker on the promontory and its spurs.

We cannot assume that the presence of clinker in a given spot means that all of a coal bed beneath it has burned. In many places in Campbell County, drilling and mining have demonstrated the presence of economic coal beneath clinker, showing that only part of the thickness of a bed has burned. Yet toward the east side of the Rochelle Hills, little if any coal seems to be left beneath the Wyodak clinker. If the sequence of events in the East was similar to what has happened more recently in the West, then surely parts of the clinker have been baked more than once.

The next major coal bed above the Wyodak is the Felix coal, in the Wasatch Formation (Eocene). Because the Felix is not as thick as the Wyodak, and perhaps because of lithologic differences in overburden, the Felix clinker does not form a continuous escarpment but instead caps small groups of hills and buttes in a strip some 10 km wide lying west of and parallel to the Rochelle Hills. The easternmost of these buttes generally are the highest, being farthest updip. The west edge of this belt is marked by a low discontinuous ridge dominated by Felix clinker.

CLINKER BASINS

The forming of clinker on a hillside produces a band of resistant rocks along the hillside. As erosion proceeds, the hillside above the clinker generally becomes graded to the top of the clinker, and in the Fort Union and Wasatch Formations this generally produces slopes of low gradient. Streams ultimately cut into the clinker and expose more coal. Subsequent burning causes subsidence and produces a second generation of clinker the top of which is lower than the top of the first generation (fig. 3). The "clinker basin" thus formed is a direct result of coal burning and the associated series of events. Such clinker basins form in sizes from 1 ha or smaller to several square kilometers, depending on thickness of the coal bed, slope and size of the hillside or mountainside, erosional resistance of the overlying rocks, rate of downcutting of streams, and other factors. Clinker basins were first recognized and defined on the Northern Cheyenne Reservation in Montana (Woesner and others, in press; Heffern, this volume), where burning of the Anderson coal has produced basins as much as 5 km across. A new clinker basin of about 1 ha was formed in Theodore Roosevelt National Park, where a 3-4-m-thick coal bed burned from 1951-1977.

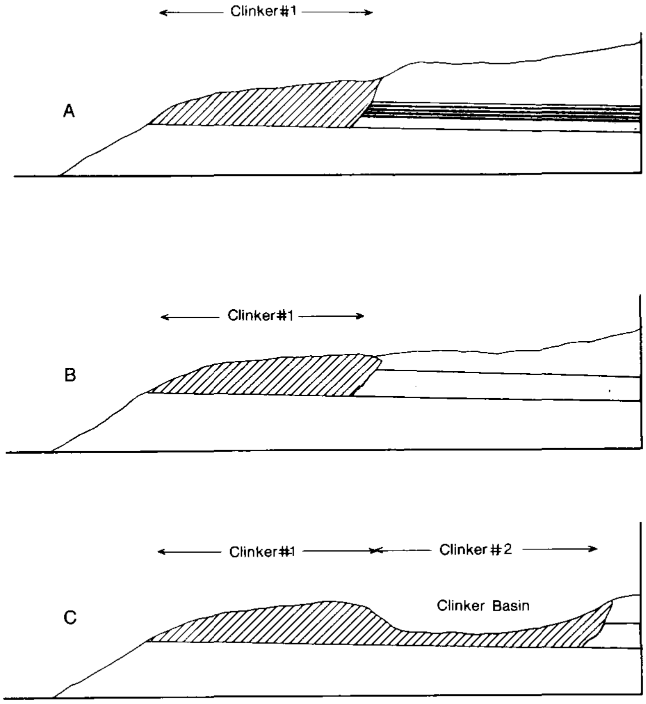

Figure 3.—Sketch of clinker basin formation by two or more generations of burning separated by periods of erosion. *A*, Burning of coal bed forms clinker, which is more resistant to erosion than unbaked bedrock upslope from it. *B*, Erosion grades slope above clinker to top of clinker so that overburden above coal is thinner than clinker. *C*, Second generation of burning removes coal from beneath thin overburden so that surface of new clinker is below surface of old clinker.

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GEOCHEMISTRY OF CLINKER, NATURALLY BURNING COAL, AND MINE FIRES

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INTRODUCTION

Large amounts of coal have combusted naturally in the western United States, both in place, either in undisturbed seams or in mines, and in spoil piles in mines. Natural combustion of undisturbed coal seams has occurred during the past 750,000 years (Coates and Naeser, 1980); a few current natural burns still exist in the United States. Mine fires have occurred over the past two centuries; many are active today. This report examines the nature of the fires, reasons for combustion, geochemistry of the heated and altered rock, and the effects of fires in releasing volatile compounds.

NATURE OF BURNING COAL SEAMS AND MINE FIRES

Coal will burn if spontaneously ignited and burning will continue until limited by a lack of fuel (coal) or air. Shallow coal seams have burned through extensive areas of the western coal-producing States, as evidenced by large amounts of associated altered rock (clinker). When coal burns, heat is vented upwards through fractures in the overlying rocks and the rocks near the heat source are metamorphosed. The fire front probably is inclined forward in the direction of burning. The width of the fire front need not be more than several meters; its rate of advance will depend on the rate at which air is supplied to the burn. One natural fire, near Bowman, N. Dak., has been burning at a rate of approximately 3 m/yr for the past 100 yr.

As the fire front advances into the unburned coal, the void left to the rear fills with overlying rocks that slowly collapse. Such slumping probably is neither instantaneous nor chaotic. The burning coal is reduced to an ash whose thickness is typically 5-10 percent of the original thickness of the coal; thus, approximately 90 percent of the original thickness of the seam is gradually filled by the collapse of the overlying rock. Disturbance of the overlying rocks is minimal: small blocks may cant slightly as they slump, but the final orientation of the overlying rocks is not grossly disturbed. Bedding may thus appear intact over distances of tens of meters.

Fractures in the collapsing rock may serve as air ducts to sustain combustion of the coal, while fractures near the fire front serve as chimneys for the conveyance of heat and gases.

A burning coal mine differs from a naturally burning coal seam. The nature of a burning coal mine depends on whether the mine is surface or underground. In active strip mines, fires are quickly detected and usually remain small. Burning or smoldering parts of a coal seam or burning spoil piles at a mine are excised by bulldozer and left to burn out. Explosions or small fires in active shaft mines will not be considered, because ignition is usually human caused. In an abandoned underground mine, fuel consists of coal remaining on the mine floor or ceiling, or in pillars, if room and pillar mining was used, poor-grade coal, or coal in seams too thin to mine. Fire seals between galleries are of little use once a fire is established: subsidence can permit the fire to circumvent a fire seal or it may simply be blown out by explosions in the mine. Combustion continues slowly, probably as a result of air limitation: slow burn rates are suggested by the several months to years that it can take a fire to move through a mine or gallery.

The results of fire in an abandoned mine include subsidence of overlying rocks, explosions, and emission of flames, heat, or gases, the latter usually including noxious and toxic compounds. Dunrud and Osterwald (1980) discussed some of the effects and hazards caused by burning coal mines near Sheridan, Wyo. Fires in abandoned coal mines are particularly common in two regions: bituminous and lower grade coal mines in Colorado, Utah, and Wyoming; and bituminous and anthracite coal mines in eastern States, especially Pennsylvania.

IGNITION AND COMBUSTION OF COAL

In the vast extents of clinker in the western United States, researchers have proposed exotic forms of original ignition, such as prairie fires, lightning strikes, or the heat of the summer sun on south-facing slopes (Rogers; 1918). Such exotic ignitions seem unnecessary; chemical reactions could also produce sufficient temperatures to start burning. Once the coal is burning, the reaction becomes self sustaining.

Ignition and combustion are of concern in the mining industry because of coal loss due to pit fires, ignition of spoil piles, and the combustion of stockpiles of coal at a mine, under shipment, or at power plants. Various factors that influence the ignition of coal include the following: coal rank, moisture content, heat of wetting or oxidation, surface area, air flow, rate of hydration over time, availability of water, source of initial heat, exothermic nature of initially oxidizing compounds, wind, air pressure, external water source (such as rain, snow, or water table changes), and perhaps the presence of bacteria or sulfur compounds. Kim (1977) has compiled the literature of these potential ignition sources. Based on laboratory studies, the three most important factors in spontaneous heating in coal are air flow rate, change in moisture content of the coal, and coal rank. Coal rank seems to be inversely correlated with combustion potential, although this may be more strictly related to association of coal deposits of certain rank with particular geologic and hydrologic settings. Higher rank coals in the eastern United States have not undergone extensive natural combustion; however, when these coals are mined or spoil piles are stored, fires frequently occur. This suggests that ignition and combustion are air limited.

Water may be important to ignition; surprisingly, it may be the presence of water, not the absence, that is important to initiating combustion. Moisture may be important in enhancing exothermic reactions that otherwise would be kinetically too slow to permit ignition. The presence of water has been shown to cause ignition in such systems as baled grasses or grains, where the temperature is initially raised by thermophilic bacteria to around 80°-90°C. (Above this temperature the bacteria are no longer viable, and other inorganic reactions must occur to raise the temperature to the point of ignition and sustained combustion.) A similar mechanism could occur in the ignition of coal, perhaps water-mediated and accelerated by the presence of bacteria. Similar processes could occur with the sulfur system, as the exothermic oxidation of reduced sulfur compounds in the coal could be kinetically accelerated by the presence of bacteria.

A clue to spontaneous ignition is found in active strip mines, where ignition can be closely observed. Fires occasionally start on actively worked faces of the highwall of a coal seam. Exposure to air seems necessary; the fire can start quickly—within a day or so of the exposure of the highwall surface to air. There is no apparent seasonality in fire incidence. A few operators have noticed fires in conjunction with puddles of water or mounds of melting snow. Again, the presence of water may increase the possibility of ignition. Another clue to the cause of natural coal ignition comes from operators of coal-fired power plants where large stockpiles of combustion-grade coal are stored. To reduce porosity, coal stockpiles are intentionally sloped, the slope edges packed, and mixed-sized coal particles are used on the outside of the pile. Voids are filled, reducing porosity and reducing the amount of contained air. These techniques have been found to reduce fire incidence. The coal stockpiles at power plants show no seasonal ignition tendency; however, a strong correlation exists between ignition of coal and strong winds. Winds are able to induce more circulation of air into the interior of the pile, where the heat evolved from spontaneous oxidative processes is contained. Ignition tendency will also increase if small particle sizes of the coal exist: more surface area exists per unit mass, and oxygen will be in contact with more of the coal.

The temperatures of coal combustion and the nature of the product gases depend chiefly on the amount of oxygen supplied to the heated coal,[1] but also on coal rank; particle size; water content; and the presence of elements or compounds that can change the rate of burn. Iron or sodium, for example, tends to slow combustion by lowering the combustion eutectic. A well-oxygenated fire can produce temperatures on the order of 2,000°C. Carbon dioxide, the product of complete oxidation of carbon, is the principal combustion product, and sulfur from the coal will be well oxidized.

Conversely, a fire that is starved for oxygen will smolder at temperatures of a few hundred degrees. Hydrogen and carbon monoxide, products of incomplete combustion, will be discharged along with reduced compounds of sulfur from the coal, such as elemental sulfur, carbon disulfide, and sulfur carbonyl.

GEOCHEMISTRY OF CLINKER

The western coal-producing States contain extensive surficial and subsurface deposits of clinker, baked rocks formed from the in-place burning of underlying coal seams. A summary of previous work on mineralogy and petrology of clinker in the western States is in Bauer (1972). Changes in resulting mineralogy and petrology in strata that overlie burning coal are alterations due to low pressure and low to extremely high temperature. Clinker studied so far in western coal regions occurs in rocks of the Tongue River Member of the Fort Union Formation (Paleocene) and from the lower part of the Wasatch Formation (Eocene). These rocks are sequences of alternating and interbedded claystones, siltstones, and sandstones. The altered rock reflects the texture and mineralogy of the original rock, except where temperatures were sufficient to fuse or melt the rock. Remnant sandstone or siltstone textures are often easily recognized in the clinker; the only apparent change from the original rock is color change, usually to a shade ranging from subtle pink to

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[1] The oxygen is probably furnished by air, but it could be entirely furnished by the disassociation of natural ground water into gaseous hydrogen and reactive oxygen. This situation would be similar to the process of underground coal gasification, where steam is used as the oxidant (Campbell and others, 1978). Combustion products in this process are CO and H_2.

intense red. If the original rock is predominantly fine grained, such as a claystone, sufficient heat will produce buchite—a vitrified, fused rock similar to hornfels. The buchite is extremely hard and fractures conchoidally. Color will range from yellow-beige to intense red and texture from extremely fine grained to glassy. Color in the altered rocks usually depends on the local geochemistry of iron: abundant iron and strongly oxidizing conditions produce intensely red rocks; low abundance of iron results in more subdued hues.

Mineralogy of the clinker primarily depends on the unaltered minerals and the degree of heating, but other variables include duration of heating, rate of quenching, amount of moisture available to the system, and the availability of elements, especially iron, that may be introduced into or removed from the system. Silica polymorphs commonly compose a significant part of the rock. Depending on the degree of thermal alteration, the original quartz will recrystallize into tridymite or, given sufficiently high temperature, into alpha or beta cristobalite. Across an outcrop face, the total amount of silica remains more or less constant while the particular polymorph abundance reflects the degree of heating. Thus, quartz generally will inversely correlate with the sum of cristobalites plus tridymite.

Mineralogy of iron is variable. The variety of iron-containing minerals produces the unique and highly variable magnetic properties of clinker (Watson, 1978). Iron geochemistry and mineralogy in clinker are of interest to mining companies using magnetics as a tool to detect localities or extent of clinker at a prospective mine site. Iron-containing minerals with low magnetic susceptibilities are usually produced by oxidizing conditions, and these minerals frequently compose the bulk of iron-containing clinker. Less oxidizing conditions are required to produce lower oxidation state iron minerals with high magnetic susceptibilities, typically including ilmenite and magnetite. A paradox arises from the magnetic properties of the clinker: while the clinker usually produces an intense magnetic anomaly, the mineralogy, as determined by X-ray diffraction, suggests that the majority of iron-containing minerals are those with low magnetic susceptibilities. The resolution of this paradox demands that reduced-iron minerals with extremely high magnetic susceptibilities must exist in trace quantities or that higher than normal concentrations of iron, possibly in combination with order elements such as Mn or Ti, may radically increase the magnetic susceptibilities of some otherwise nonmagnetic minerals.

The minerals indicative of the highest temperature so far identified included mullite, indialite, and hercynite. Mullite is an orthosilicate that usually is composed of silicon and aluminum oxides, although minor amounts of iron and titanium can substitute. Indialite and hercynite are the iron-rich end members of the cordierite and spinel series, respectively.

ELEMENTAL RELATIONSHIPS OF BURNING COAL

Two classes of chemical elements or compounds, the volatiles and the refractories, are of interest in considering the effects of coal burning to ash and in the heating of overlying rocks; they reflect the phases that are respectively most and least mobile due to heating. Volatiles include any of the elements or compounds distilled out of the coal or overlying rocks and lost to the coal-ash-rock system because of high vapor pressures. These elements or compounds later may recondense depending on their reactivity and the ambient temperature. A discussion of mineral condensates and trace-element release resulting from burning coal in the eastern United States, especially Pennsylvania, is provided by Finkelman (1978) and by Finkelman and others (1974). The elements most commonly released include elemental or oxidized compounds of C, S, Se, As, F, and N; Hg is probably also released but has not yet been studied. Refractory compounds, on the other hand, remain behind after combustion of the coal and are concentrated in the ash. Elements with especially high boiling points, such as V, U, and W, should be among these. Iron should also behave as a refractory phase, although it may be removed locally from the rocks by flow as a dark-gray magnetic slag of lower oxidation state iron minerals. Other residual phases include high-temperature minerals such as mullite.

Among the volatile compounds are several potential toxic pollutants. Around mine fires the following gases or gaseous compounds have been noted: F, As, Se, reduced sulfur compounds (CS_2 and COS), oxides of carbon, oxides of nitrogen, oxides of sulfur, steam, and hydrocarbons. A suite of as-yet undetected organic compounds probably also exists. Those most likely to be of concern include polycyclic aromatic hydrocarbons and the chlorinated dioxins, both classes known for their extreme toxicity and known to occur during the industrial burning of coal. The odor around several mine fires suggests the existence of mercaptans.

The amounts and fluxes of these compounds released from burning coal need to be quantified, both in conjunction with present mine fires and also for their implications on natural burning of coal throughout the world. Fission-track dating of detrital zircons in clinker from the western United States shows that combustion has occurred within the past several hundred thousand years and is still occurring. During this geologically brief interval, substantial quantities of volatile elements have been mobilized and released into ground waters or the atmosphere.

The compounds of greatest concern include those previously mentioned and also carbon dioxide. A knowledge of the flux of toxic compounds helps to define the amounts that have been released into the environment. For example, what is the total amount and rate of release of selenium into the Powder River Basin and could this be a major source of the selenium in rocks, soils, and plants of this region? Carbon dioxide is of interest because it may contribute to atmospheric heating and possible worldwide climatic change. As more data become available on the dating of natural coal burns, it will be possible to see whether a significant amount of fossil carbon has entered the atmosphere as carbon dioxide from burning coal, over recent geologic time. For example, a small area of the Powder River Basin contains clinker from a coal seam that has burned during the past 750,000 yr (Coates and Naeser, 1980; written commun., 1980). The amount of carbon introduced into the atmosphere from this single burn is roughly equal to the present mass of carbon in the atmosphere. While the input from this single source has been very low compared to other carbon input rates, the burning of coals could become an important source of atmospheric carbon if the amount of worldwide, naturally burned coal increases.

A final concern about naturally burning coal is its effect on ground-water quality. The effects of several potentially toxic species on ground water are unknown, as are the broader effects of clinker on the quality of ground water. Local consideration of the effects may be important to reclamation procedures at strip mine sites. Clinker aquifers generally seem to produce water of good quality, with relatively small amounts of dissolved and suspended solids (Osborne, 1979). However, ash from coal burn or the concentration of the combustion products in sediments or clinker beds may adversely affect ground-water quality.

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CHEMICAL CHARACTER AND PRACTICAL PRE-MINING SAMPLING NEEDS, FORT UNION FORMATION COAL OVERBURDEN ROCK

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Rocks in the overburden column disturbed during surface mining and subsequent land reclamation may have undesirable effects on plants and on the animals that eat them, or on the chemistry of the ground waters which they contact.

A sampling and analysis program was undertaken in the part of the Western Energy Regions where surface-minable coal is in the Paleocene Fort Union Formation, in order to answer these questions:

1. Is there any rock material that has potentially undesirable qualities in the Fort Union Formation rock overlying coal?
2. Are the potentially undesirable and the benign materials identifiable and distinguishable in some clear and simple way?
3. Is the nature of the material consistent throughout the region?
4. How densely must we sample at a potential mining site in the region to be reasonably confident that we are not overlooking some undesirable material in the overburden?

SAMPLING SCHEME

Samples of cored overburden were collected at the following sites, spaced a few tens or hundreds of kilometers apart:

1. Otter Creek, Montana
2. Bear Creek, Montana
3. Dunn Center, North Dakota
4. Dengate, North Dakota
5. Estevan, Saskatchewan
6. Hanging Woman Creek, Big Horn County, Montana

At the first five sites above, samples were collected from a pair of cored drill holes spaced about 1-2 km apart. More core holes were sampled at the Hanging Woman Creek site, but the spatial separation of the holes was still 1-2 km. Additional samples in other parts of the region were collected from outcrops on a similar spatial array. Analytical and sample preparation methods are summarized in Hinkley and others (1978).

VARIATION INFORMATION FROM SAMPLING ARRAY

Such a spatial array allows us to assign portions of the variability in the chemical and mineralogical data to the following distinct distance scales:

1. tens or hundreds of kilometers: the distance between sites;
2. about 1 km: the distance between the two or more holes (or outcrops) at each site;
3. meters or tens of meters: the distance between samples taken from the core of a single hole.

The question is the following: do the high and low concentrations of elements in the rocks become more or less extreme the farther away one looks, or do samples from nearly any small area contain element concentrations that are close to the extremes for the larger area?

SAMPLING BY ROCK TYPE

Samples were classified by lithic type, as identifiable by quick, simple tests and by appearance in hand specimens. This classification was done to determine whether the different rock types had distinctive chemistry; if so, it might be possible to predict the chemistry from hand specimen observation in future work, thereby avoiding considerable delay and analytical expense.

The samples were classified into the following groups:

1. sandstone
2. fine-grained rock: siltstone and shale
3. very dark colored or black shale
4. "special" samples of unusual appearance or anticipated anomalous chemistry or mineralogy.

RESULTS AND ANALYSIS

The largest portion of the total variance for most elements is between the samples taken within a single hole. This observation may be associated with the fact that Fort Union Formation rocks alternate in their lithic type over small vertical distances (tens of centimeters to a few meters), and that the same rock types are found throughout the region.

The small fractions of total variance between holes (at approximately 1 km spacing) observed for most elements indicate that the total spread of values was increased very little by sampling from multiple holes compared to what it would have been if samples had been taken from only one hole. Only a few elements have variation across a site (1 km) greater than variation within a single hole (Cu in the fine-grained rocks and Mg and Ge in the sandstones at Hanging Woman Creek).

At the largest scale, across the region underlain by the Fort Union Formation that was sampled, the concentrations of some elements do show a significant amount of variation, although never as much as the portion of the total variation within a single hole. The elements Mg, Ca, Na, Ba, and Ti vary significantly at this highest level; the minerals plagioclase, calcite, dolomite, and chlorite also vary at this same scale, and this variation corresponds with that of Mg, Ca, and Na.

The trace elements B, Co, Cr, Cu, Ge, Ni, Sc, Th, V, Y, Zr, and Yb exhibit statistically significant regional variation. They are less clearly associated with the mineralogy of the rocks, but the fact that so many of these elements, especially the minor and trace elements, are clay-related suggests that the regional effect reflects variation in the amount of one or more clay minerals. Some of the more prominent of the potentially toxic trace elements (As, Hg, and perhaps Se) do not vary significantly in overburden at regional scales.

The distribution of the total variance between the three spatial scales shows the following: (1) Almost as much information about the range in composition of the rocks could have been obtained if only a single hole had been sampled at each of the sites. (2) Only a very slight risk of missing rocks of undesirable properties would have occurred if the nearby hole had not been drilled. (3) The local compositional variation at a new proposed mine site may be assessed by limited sampling.

Because of the lack of variation on a regional scale (distances of hundreds of kilometers), for most elements other than those listed above, it is possible to make useful inferences about chemistry at new, unsampled sites in the region underlain by the Fort Union Formation, based on a knowledge of chemistry at many distant sites separated by hundreds of kilometers. Dollhopf and others (1978) have taken a divergent view of the problem and its solution. Montana Department of State Lands (1978) discussed sampling and analysis procedures in current use in that State.

CHEMICAL DISTINCTIVENESS OF DIFFERENT ROCK TYPES

The Fort Union Formation shows a general relationship between chemistry and rock types. Coarse- and fine-grained rocks have distinct chemical properties, but considerable overlap in chemical character occurs. Suites of trace elements, of known and potential concern in reclamation of mined land, tend to be more abundant in the fine-grained rocks (siltstone and shale) than in sandstone. Dark shale generally has slightly higher concentrations of these elements than the other fine-grained rocks. A plot showing the separation (and overlap) of rock types by elemental content for some rocks of this suite is presented in figure 1.

The overlap in chemical composition between rock types is consistent with the observation that the two types of shale (and to a lesser extent sandstone) exist both in the form of continuously mixed types and in fine-scale alternation in the Fort Union Formation.

ROCKS FROM WIDELY SEPARATED SITES: SIMILARITY TO EACH OTHER AND TO SOILS OF THE REGION

Table 1 presents geometric mean concentrations of selected elements in three suites of rocks from the Fort Union region (the intensely drilled Hanging Woman Creek site, the other five sites with pairs of core holes at each, and the samples from outcrop) and from three suites of soils collected in the region. Comparison of data among the three rock suites shows that the rocks are, for a given rock type, homogeneous across the region.

In addition to having similar averages of element concentrations, the three rock suites also have similar degrees of spread (total variance) about their average values and a similar pattern of chemical variation with respect to spatial location of the samples. These features indicate that a satisfactory amount of the chemical information about rocks at any new site in the Fort Union Formation could be assessed from a modest sampling program, certainly no more extensive than that followed at sites for this study where only a pair of holes was cored for sampling at each site.

The similarity of chemical compositions of sandstone and shale samples collected from outcrop to those from samples collected from drill cores across the region indicates that in potential mining sites where the overburden material is exposed as outcrop within or near the area to be disturbed, at least some samples may be collected from outcrop with confidence that the results will be similar to results obtained from core samples, which cost much more to obtain.

From the data of the table, sandstone of the Fort Union Formation is chemically similar to a large number of subsoils from the same region. In fact the subsoils have concentrations of many elements that fall midway between the concentrations of these elements in sandstones (lower values) and those in finer-grained rocks (higher values) of the region. This similarity to soils is perhaps the single most important statement to be made about the lack of potential chemical harmfulness of a potential soil-replacement material (overburden rock). Based on bulk chemistry, it appears that much of the overburden rock could be used to replace soils.

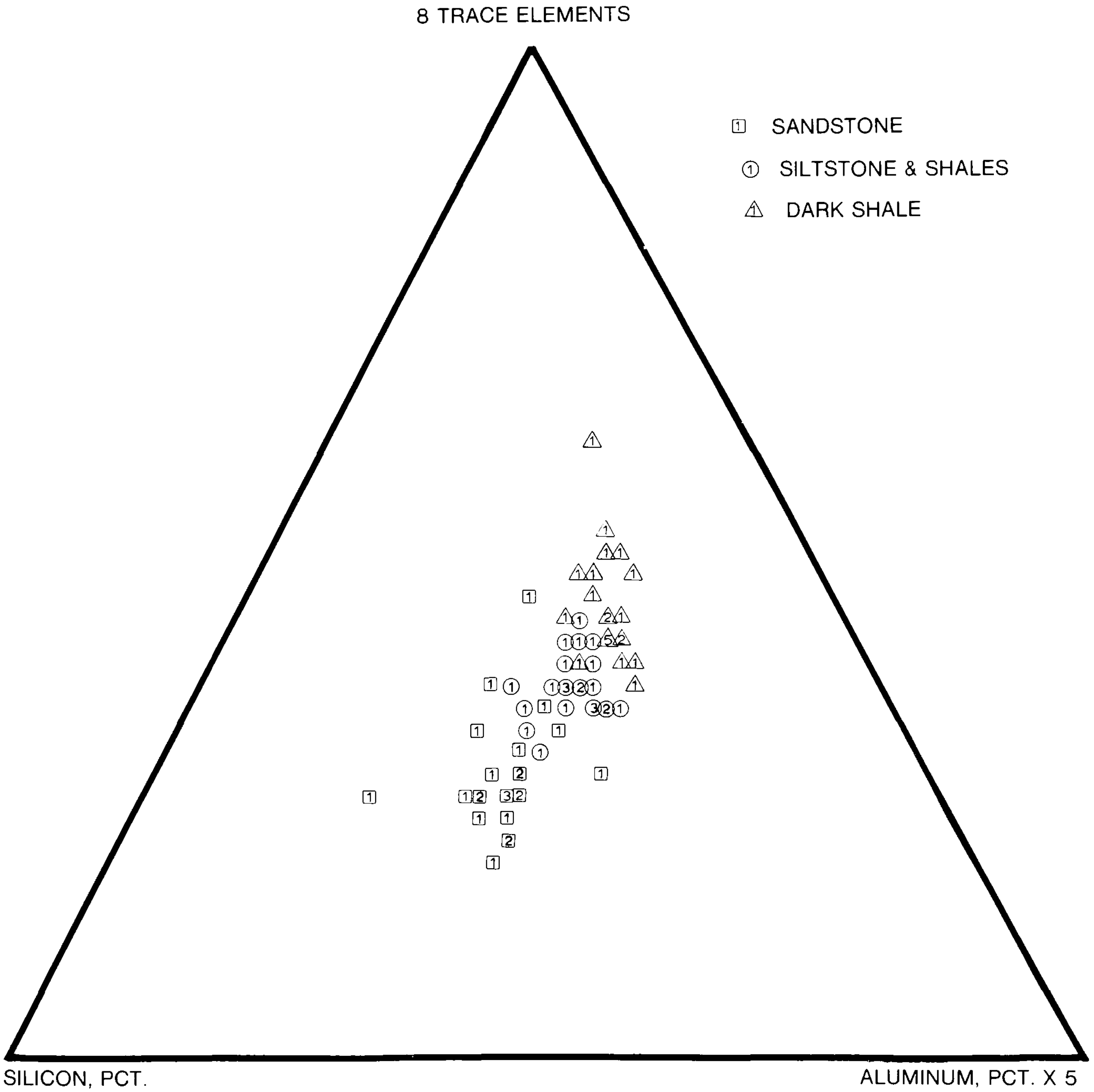

Figure 1.—Compositional relationships of the samples of the three rock types with respect to silicon, aluminum, and a suite of eight trace elements. The digits indicate the number of samples that plot at that point. The trace elements (beryllium, copper, lanthanum, lead, mercury, nickel, sulfur, and yttrium) have been normalized by factors proportional to their typical individual concentrations, so that each will have an equal effect on the plot.

CHEMICAL-LEACH AVAILABILITY STUDY

It is probable that the pulverized overburden material will not make the elements available to growing plants in the same amounts as they are available in the soils of the Northern Great Plains. Preliminary studies for the availability of certain minor or trace elements to aqueous leaching solutions have been performed on a limited number of samples of the Fort Union rocks. The purpose was to determine whether the rocks release elements in proportions different from their proportions in the bulk

Table 1.--Selected elements in Fort Union overburden rocks, compared to soils in and near the Fort Union coal region

Element	Hanging Woman Creek			Rocks from cores, five sites (Hinkley & Ebens, 1977) (50 samples each type)		Rocks from outcrop (Ebens & McNeal, 1977) (80 samples each type)		C-horizon soils, Hanging Woman Site (Tidball, 1978)	C-horizon soils, Powder River Basin (Tidball, 1978)	Subsoils of Powder River Basin (Connor, Keith & Anderson, 1976)
	Sand-stone	Silt-stone	Dark shale	Sand-stone	Shale	Sand-stone	Shale			
As-----	3.8	6.1	7.6	5.4	3.6	4.4	5.1	7.3	N.R.	N.R.
B------	26	58	64	42	59	51	98	41	[1]24	26
Co-----	6.9	13	16	11	8.7	5.4	9.1	[1] 9.5	7.3	6.3
Cr-----	59	96	109	46	72	45	84	[1] 59	46	49
Cu-----	13	51	54	14	38	13	34	[1] 35	17	16
Hg-----	.031	.063	.11	.08	.10	.032	.060	.03	N.R.	.023
Mo-----	5.0	8.7	8.5	[2]1.8	6.1	5.0	8.1	N.R.	N.R.	<3
Na-----	.84	.64	.54	.68	.64	.49	.42	.72	.47	N.R.
Pb-----	3.3	13.9	22	12	11	5.2	15	N.R.	N.R.	17
Se-----	.042	.21	.30	.31	.16	.19	N.R.[3]	N.R.	N.R.	N.R.
V------	59	131	148	75	86	46	97	N.R.	N.R.	87
Zn-----	60	110	125	62	100	44	80	N.R.	N.R.	61

[1] Averaged from values for distinct soil types or regions.

[2] Used less reliable method than for other Mo determinations.

[3] N. R., not reported.

rock. Some results are as follows: sandstone averaged higher releases of water-soluble $SO_4^=$, Na^+, K^+, and Ca^{+2}, and it had higher specific conductance than siltstone-plus-shale or dark shale; dark shale released most DTPA-complexed Cu, Zn, Co, Mn, and B, and had the lowest pH. Dark shale also released the most exchangeable Mg, K, Ca, and Na. Thus, the sandstone released the greatest amounts of water-soluble minor ions, whereas dark shale released the most exchangeable minor ions and chelatable trace elements. The ratios of release for total exchangeable cations were as follows: dark shale:siltstone-plus-shale:sandstone were 2:2:1. For cation exchange capacity the ratios were 4:3:2.

The availability information gives us a strong preliminary suggestion that the distinct rock types in the Fort Union Formation behave fundamentally differently in the way they would release chemical elements in a soil environment. The sandstones release their contents of major element salts rapidly and easily and probably become relatively inert over the longer term; they are relatively barren of a large suite of trace elements. The finer grained rocks have higher concentrations of the trace element suite, many of which are necessary nutrients to plants and animals, and a few of which are toxic if present in high natural concentrations. As is seen in the availability information, the finer grained rocks hold elements in more tightly bound forms (exchangeable and complexable, rather than water soluble), from which they could be released in a slow and even manner over very long periods of time. It might be anticipated that it would be necessary to mix the major rock types of the Fort Union Formation to make satisfactory soil substitutes. Soils formed from mixtures of rock types should be superior in texture to those from one type alone.

RELATIVE VOLUMES OF THE ROCK TYPES AND OPTIONS FOR USE IN RECLAMATION

In general, sandstone is sufficiently abundant (about one-third of the overburden rock) and is present in sufficiently thick, continuous, and recognizable units to allow it to be used as needed for plant growth medium on top of the refill column, and for the material most likely to contact ground water at the bottom of the refill column. Strata of siltstone are sufficiently thick in much of the overburden rock column to be utilized in the same way, if desired. Dark shale and other shale are more commonly interbedded with each other and with sandstone and siltstone over short vertical distances (tens of centimeters). However, the relative volumes of either pure or intermixed beds of shale are small enough that these rocks could practically be segregated into the middle part of the refill material and separated from both plant roots and the ground-water zone by a thickness of sandier rock at top and bottom.

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APPLICATION OF AUTOMATED IMAGE ANALYSIS TO COAL PETROGRAPHY

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INTRODUCTION

Detailed knowledge of the petrographic and chemical characteristics of the organic and inorganic components of a particular coal is required for the interpretation of its depositional environment, diagenetic and burial history, and degree of coalification or metamorphism. This information is also necessary to delineate lateral and vertical variations of a single coal bed or different coal beds. The same information may be useful for correlating coal beds, for mine planning, and for designing coal-preparation systems and other utilization processes.

One of the principal objectives of our research is to devise a rapid quantitative technique to produce detailed descriptions that are easy to visualize and comprehend. To achieve this goal, we have adopted a quantitative rather than qualitative nomenclature for the description of coal microlithotypes and lithotypes. For rapid quantitative analysis of compositional and textural characteristics of coal components as well as rapid rank determination, we are utilizing an automatic image-analysis system (AIAS). In this report we present the details of our AIAS, the petrographic terminology used, and our procedures for describing coal samples megascopically, microscopically, or both.

NOMENCLATURE FOR QUANTITATIVE PETROGRAPHIC ANALYSIS

A coal bed can be characterized in terms of its maceral and mineral composition or in terms of microlithotypes, lithotypes, and lithologic facies. In agreement with many other petrographers, we believe that qualitative microlithotype and lithotype terms currently approved by the International Committee for Coal Petrology (ICCP, 1963, 1971, 1975) are usually inadequate. A quantitative and less ambiguous system for easy visualization and comprehension of coal description is needed. Coal samples or units can be conveniently and definitively analyzed microscopically according to their maceral and mineral constituents in volume percentages of V for vitrinite group, E for exinite group, I for inertinite group, and M for mineral components. Combined megascopic and microscopic analyses describe the coal in terms of microlithotypes and (or) lithotypes. For the combined studies we suggest using (V) for vitrite or vitrain, (E) for liptite, (I) for inertinite or fusain, and (M) for layers of mineral matter. Volume percentages are indicated by subscripts. Thus, in the VEIM notation, a microlithotype analyzed microscopically as consisting of 80 volume percent vitrinite, 8 percent exinite, 6 percent inertinite and 6 percent mineral constituents is represented as $(V_{80}\ E_8\ I_6\ M_6)$. According to the present ICCP nomenclature guidelines, this microlithotype would be less precisely described as duroclarite. Similarly, for a combined megascopic-microscopic analysis, $(V)_{20}\ (V_{80}\ E_{10}\ I_5\ M_5)_{80}$ indicates an assemblage of 20 volume percent vitrite or vitrain and 80 percent of a microlithotype or lithotype having a bulk composition of $V_{80}\ E_{10}\ I_5\ M_5$. The ICCP designation for this assemblage would be the term "clarain." After extensive trials in our studies, we have adopted the VEIM nomenclature as best suited for quantitative coal description and analysis. (Further details on use of the VEIM scheme have been given by E. C. T. Chao, J. A. Minkin, and C. L. Thompson, unpub. data, 1980.)

THE AUTOMATED IMAGE ANALYSIS SYSTEM

In order to adequately describe and define coal microlithotypes, lithotypes, and lithologic facies and their vertical and lateral variations, many coal core or columnar samples must be studied in detail. Hence, any improved method for coal description and petrographic analysis must be not only quantitative but also rapid. The adoption of an AIAS seems to us to be the only choice. For coal research, an AIAS must be capable of: (1) maceral and (or) modal analysis on the basis of differences in reflectance, equivalent to gray-level resolution for the AIAS; (2) textural analysis, such as size distribution or shape analysis of a category of maceral or maceral group; (3) a combination of (1) and (2) as required; and (4) rapid determination of rank on the basis of vitrinite reflectance (gray level). To perform these functions as quickly and precisely as possible, the system must be easy to operate, must resolve as many shades or levels of gray as possible, must be able to monitor and optimize uniformity of illumination, must allow the operator to set or change gray level thresholds readily and quickly, and must be capable of editing or amending the image to correct imperfections due either to flaws in the sample or to improper segmentation. After thorough evaluation, we have acquired in our laboratory a completely software-based AIAS, the Joyce Loebl MAGISCAN,[1] because of its versatility, flexibility, and adaptability to new research requirements.

The software-controlled MAGISCAN is capable of resolving or differentiating 64 gray levels of the image under optimum illumination. The system consists of a television camera, an analog-to-digital converter, a microprocessor for analyzing the digitized image, a minicomputer and terminal for measurement and data-processing functions, a digital-to- analog converter, and a TV monitor screen (14 inch diagonal) and keypad. The minicomputer may also be used for stand-alone calculations.

For the megascopic analysis of hand-size samples or photographs a large (macro) viewer is provided. In the study of core or block coal samples partly polished to reduce extraneous reflection, a fluorescent 10-inch-diameter ring light is used to provide uniform and sufficiently intense illumination. If photographs of coal samples are to be analyzed, the floodlights that are attached to the large viewing table are adequate. A zoom lens is attached to the TV camera when the system is used in the macro mode.

Most coal macerals in polished mounts have less than 5 percent reflectance in oil of refractive index 1.518 when viewed in incident light of wavelength 546 nm. Hence, for microscopic study, the AIAS should be equipped with a TV tube sensitive in the low reflectance region. The manufacturer provided for our system a vidicon tube, which has greatest sensitivity and linear response characteristics in the low reflectance range. The video system is coupled with a research petrographic microscope equipped with a 150-watt Xenon light source to provide the necessary stable and intense illumination. This combination results in a high-quality TV image for microscopic analysis. Polished coal samples, either block or pellet mounts, or polished thin sections are used in the micro mode.

The image analyzer can be addressed via the computer terminal or via a lightpen and keypad on the instrument console. Three computer languages are provided for MAGISCAN operations: (1) SPEL, a simple language that does not require any prior knowledge of computer programming; (2) MAGIC, a straightforward conversational programming language that allows for more flexibility and complexity in operations and output than SPEL; and (3) FORTRAN, the most powerful of the available software languages, which allows the full range of scientific programming plus modification of instructions to the microprocessor and is therefore required for the larger and more intricate image analysis tasks. The fact that this AIAS is entirely software based provides us with almost unlimited flexibility for image-analysis applications and the solution of related problems.

APPLICATION TO COAL PETROGRAPHY

The application of AIAS to coal petrography has until now been limited (Harris and others, 1977; Harris and DeRoos, 1979; Zeiss, 1979). Several automated systems have been devised to obtain reflectograms by automated point count of polished pellet mounts (Gray and others, 1979; Kojima and others, 1979; Hoover and Davis, 1979; Ting and Klinkachorn, 1979); however, such systems clearly do not use the method of image analysis. We are not concerned with reflectograms or their interpretation, particularly in the study of coal blends. We are convinced that it is preferable to monitor the analysis of a single coal sample visually, as is done in phase segmentation by image analysis.

Modal and Textural Analyses using the AIAS

Organic (maceral) and inorganic (mineral) phases in coal can be classified either in terms of reflectance (gray levels in the AIAS) or by texture, or by a combination of both. By using the AIAS, most segmentation or separation of component phases of hard coals can be accomplished on the basis of gray-level thresholding alone. The term "thresholding" means the bracketing of gray-level intervals corresponding to the range of gray values shown by a particular phase. Once the phases are properly identified and classified by the operator in terms of gray levels, then the areal extent covered by each phase or group of phases in terms of number of picture points (pixels) on the TV screen is quickly analyzed by the minicomputer; the result is expressed in terms of volume percents of V, E, I and M components, as described previously.

Megascopic Description of Coal Core and Columnar Samples.-- The purpose of megascopic description of coal is to provide the maximum amount of useful data characterizing the variation of coal depositional units in terms of lithologic layers. Any method or procedure proposed must be rapid, consistent, and as objective as possible. Megascopic characterizations of coal core or block samples in the laboratory, based on examination by naked eye augmented by hand lens or binocular microscope, generally identify the lithologic layers or bands as vitrain, fusain, attrital coal, impure coal, and so on (ASTM, 1977a). The use of the AIAS produces more quantitative and objective descriptions.

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[1] The use of trade or brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

In the macro mode of operation, using illumination from the fluorescent ring light, the gray values of the image are related to the bulk light-scattering properties of the different bands in the coal (these gray tones do not correspond to the reflectance values of coal components in incident light). For this type of examination, samples are only partly polished by 800-grit abrasive, in order to produce a surface that reveals all megascopically resolvable details but does not reflect the fluorescent ring light.

To construct the columnar profile of part of a coal bed (fig. 1), distinctive lithotypes are first identified on the basis of binocular examination and specific gravity (S.G.) determinations. Layers of vitrite or vitrain, fusite or fusain (inertinite group), pyrite, and partings of other mineral material or shale are easily distinguishable. These recognizable layers 2 mm or more thick are entered on the columnar section. The thickness of 2 mm, arbitrarily chosen, is a convenient dimension that can be easily seen by the naked eye and plotted in a columnar section. The blank spaces left in the columnar section are the remaining lithologies of the coal bed. Such lithologies commonly consist of bimaceral and trimaceral microlithotypes interbedded with monomaceral microlithotypes (less than 2 mm thick). They are designated as mixed lithologies. The mixed lithologies are characterized not only by their bulk S.G.'s, but also by different gray level ranges (G.L.) on the TV screen under the macro mode. The vitrite, inertinite, and mineral components of these mixed lithologies are easily segmented in the AIAS megascopic procedure and designated in terms of their abundance as described above. The modal composition of the remaining individual microlithotypes is later determined microscopically.

Another aid to megascopic description of core or block samples is the use of an optical "logging" technique. Our AIAS can produce a G.L. profile or cross section across the layering or banding structure of the coal. Such a profile is plotted in figure 1. It may serve as a cross check of the lithotype demarcations determined as described above.

The correlation of the S.G.'s and G.L.'s of the mixed lithologies helps us to select those parts for which polished blocks and (or) polished thin sections should be prepared for microscopic study and analysis by AIAS. Clearly this procedure greatly reduces the number of samples required for microscopic study. The microscopic study of the selected samples (indicated by asterisks alongside the described columnar section in fig. 1) provides the quantitative description of the mixed phases.

Microscopic Characterization of Coal Polished Mounts and Polished Thin Sections.—Two major categories of information can be derived from microscopic studies: (1) the modal composition of the macerals or maceral groups and mineral components represented; and (2) the texture of the maceral particles or habit of the minerals that are generally distributed in the vitrinite-rich matrix.

Modal analysis of coal components in terms of percent exclusive area over total area and reported as volume percent is readily accomplished by using gray-level segmentation. Although analyses are most commonly performed on polished blocks, the use of polished thin sections of complex coal microlithotypes and lithotypes has certain advantages. For example, the relative abundance of alginite versus sporinite can be significant in interpretation of the depositional environment. The reflectances, and hence gray-level values, of sporinite and alginite are essentially the same and therefore cannot be segmented on the basis of gray-level difference in reflected light. The two can, however, be readily distinguished and segmented in transmitted light, because alginites are clear and sporinites are yellow (white and light gray, respectively, in the TV image). Furthermore, when transmitted light is used cutinite can be distinguished from resinite and sporinite for a specific rank of bituminous coal. In addition, cell walls and cell fillings of vitrinite can be distinguished much more readily in transmitted light than in reflected light.

The AIAS can also be utilized to rapidly evaluate size distributions of maceral particles. Such data may be significant for either distinguishing microlithotypes of different coal beds or as indication of the effects of transport and the nature of sites of deposition.

Correlation between Reflectance and Gray Levels for Coal Rank Investigations

In generally accepted practice, the rank of coal is determined on the basis of the mean maximum reflectance ($\bar{R}$ max) or mean random reflectance ($\bar{R}$e) of 100 or more points measured microscopically using a photometer on vitrinite (ASTM, 1977b). In image analysis, if a polished block normal to the layering or banding is used, the vibration direction having maximum reflectance or gray value can be easily checked by its extinction position in polarized light. The maximum gray value of each vitrinite band in such orientation then can be quickly determined by the use of the lightpen or from gray-value histograms of vitrinites. If pellet mounts are used, the coal particles are in random orientation. Analogous to an uniaxial crystal, the omega or the ordinary ray of any randomly oriented vitrinite lies in the plane of the microscope, parallel to the one of the two extinction positions having the larger gray value. This extinction position and corresponding gray value may be determined quickly by using the lightpen.

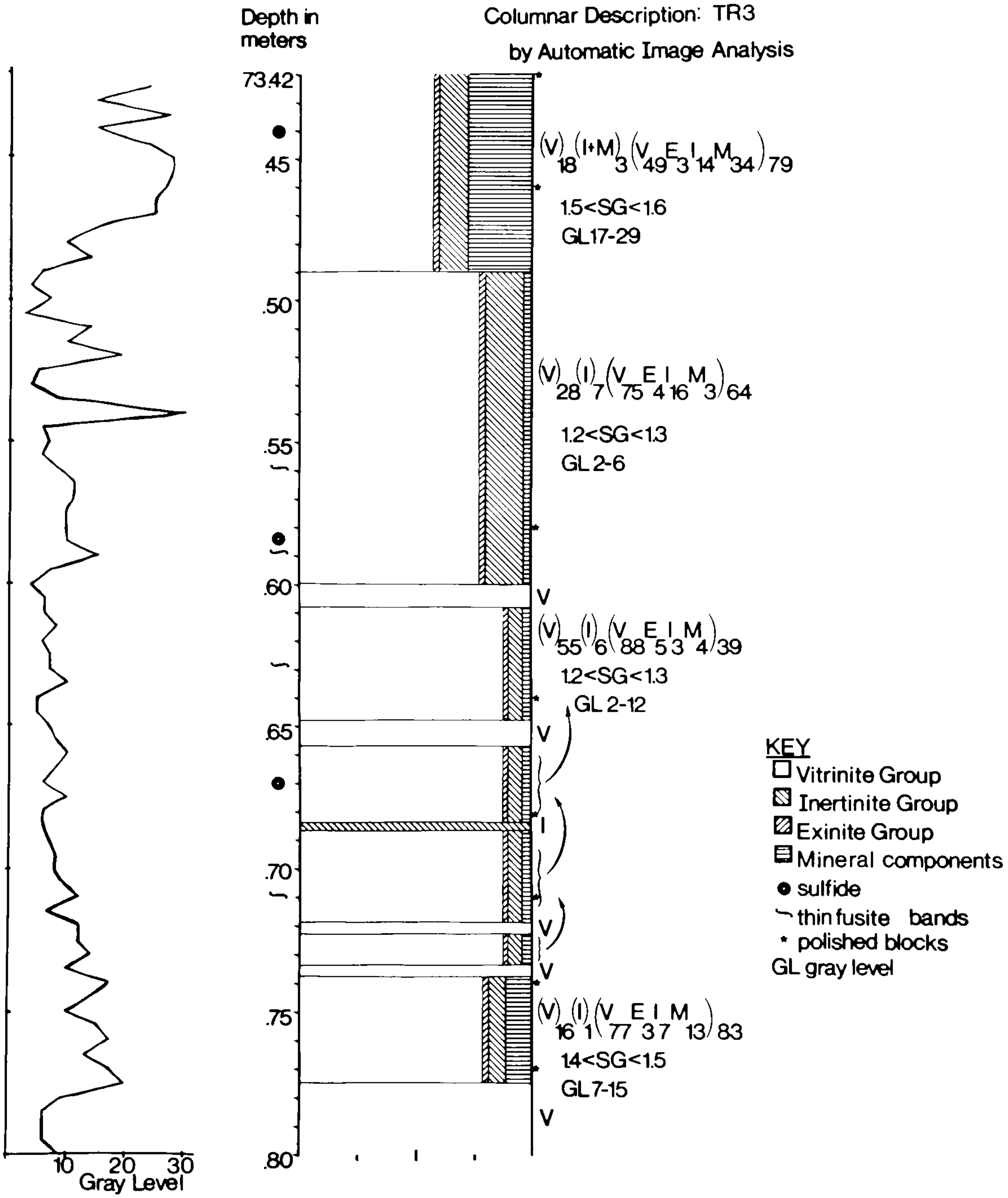

Figure 1.—Columnar profile (right) for a drill-core sample from part of a coal bed of Cretaceous age from the Ferron Sandstone Member of the Mancos Shale, Central Utah. AIAS gray-level profile (left) for same interval of column.

Alternatively, if the incident light is not polarized, one may determine the average reflectance ($\bar{R}$) on the basis of several gray-level determinations in vitrinite, where $\bar{R} = \bar{R}$ max/ 1.066 (Ting, 1978). A correlation curve of gray values with reflectance can be established using a set of calibrated glasses as standards. A large number of samples can then be quickly measured to estimate their rank of coalification. Rank determinations rapidly done by the AIAS compare favorably with those obtained by the standard reflectance method.

CONCLUSIONS

We have here introduced a new procedure and approach for the determination of the rank of coal and the description of drill core or block samples of coal in quantitative VEIM nomenclature by using the AIAS. This method combines megascopic and microscopic analyses supplemented by S.G. determinations to determine and describe coal lithotypes and microlithotype assemblages in terms of modal abundances and textural characteristics. The resultant columnar section can easily be visualized in terms of both the megascopic association of microlithotypes and lithotypes, and the microscopic organic (maceral) and inorganic (mineral) composition and distribution. We stress that the AIAS method is not operator free. It requires the judgment of a competent petrographer in determining gray-level thresholds, and so forth. On the basis of our experience, we feel that the AIAS provides the means to acquire a maximum amount of pertinent data rapidly and thus could be a key device in the advancement of coal petrography. We also suggest that for laboratories that do not have an AIAS, the above procedures can be used by substituting trained visual estimates for the quantitative AIAS data.

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PETROLOGY AND COKING POTENTIAL OF SELECTED COALS FROM THE PICEANCE CREEK BASIN, COLORADO

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Through a cooperative agreement with the Colorado Geological Survey, the petrography and coking potential of 10 coal seams from 11 active mines in the Piceance Creek coal region are being evaluated by the Coal Characterization Laboratories of the Department of Geology at Southern Illinois University-Carbondale. Initial results of this study are reported here. The samples studied are identified in table 1. The samples were collected in a variety of ways: (1) tipple samples; (2) channel samples, where the whole seam was collected as a single sample; (3) bench channel samples, where a whole seam was collected in a number of benches; and (4) bench samples, where only part of a seam was collected. For this report, when there was more than one sample for a single locality, the results of the various analyses were combined proportionally to represent the seam at that locality.

MACERAL ANALYSES

The maceral analyses of these samples were run on crushed particle pellets following ASTM Standard D-2799-72 with two modifications. First, only 500 points per pellet on two pellets were counted because it was found that the mean variation of this method produced results that were within acceptable limits. Second, two additional macerals, semi-macrinite and pseudovitrinite, were counted. The semi-macrinite was counted for completeness and the pseudo-vitrinite was counted because it was readily identifiable and present in significant quantities. The pseudovitrinite usually had a slightly higher reflectance than the rest of the vitrinite and tended to occur in larger particles that were homogeneous and free of other macerals and minerals. The pseudovitrinite also showed serrated edges, brecciation, and remnant cell textures. In fact, this material conforms to the original description of pseudovitrinite by Benedict and others (1968).

Table 1.--Sample Identification

SIU-C No.	Coalfield	County	Formation	Seam	Coal thickness and percent seams sampled	Sample type
535A	Grand Hogback	Garfield	Williams Fork	"E"	17.3; 100	Bench channel.
538	--do---------	--do----	--do-----------	Sunnyridge	6; 100	Channel.
526	Carbondale---	--do----	Lower Mesaverde	"A","C","D"	8; 100	Tipple.
541A	--do---------	Pitkin	Williams Fork	Coal Basin "B"	29.3; 62	Bench.
543	--do---------	--do----	--do-----------	Coal Basin "B"	26.75; 30	Do.
565A	--do---------	--do----	Lower Mesaverde	"B"	6.4; 100	Bench channel.
539A	--do---------	--do----	Williams Fork	Dutch Creek	6.7; 77	Bench.
530A	Somerset-----	Gunnison	Mesaverde	"E"	9.5; 100	Bench channel.
528A	--do---------	--do----	Lower Mesaverde	"C"	6; 100	Bench channel.
527	--do---------	--do----	Mesaverde	"B"	26; 24	Bench.
533A	Book Cliffs--	Mesa	Lower Mesaverde	Cameo "B"	7; 100	Bench channel.

The results of the maceral analyses are given in table 2 and show that all of these coals are bright coals. The total vitrinite-group maceral content ranges from 75 to 90 percent and averages 84 percent. This is comparable to Midwestern coals and greater than that of Appalachian coals, which range between 50 and 75 percent total vitrinite-group macerals. The maceral pseudovitrinite is present in all of the samples as part of the total vitrinite and ranges from 12 to 25 percent of the total coal. The liptinite macerals for the high-volatile coals average 4.5 percent and range from 3.5 to 7 percent, which is slightly lower than the range for Midwestern and Appalachian coals. It is significant that in the higher rank coals, with reflectance values ranging from 1.14 to 1.37 percent, the liptinite macerals are much less abundant and appear to be pitted and corroded. In some cases the liptinite macerals occur as fillings in cell lumen and other voids and appear to be of secondary origin. The inertinite maceral content of all of the coals is low, averaging about 14 percent compared to Appalachian coals, which commonly range from 15 to 40 percent inertinite. Most of the inertinite macerals are semifusinite (table 2). The reflectance of this semifusinite is notably low and even overlaps with the vitrinite macerals. The inertinite maceral sclerotinite is also present in small amounts. Data on the maceral compositions of the Midwestern and Appalachian coals are from Harvey and others (1979).

Table 2.--Results of Maceral Analyses

SIU-C No.	Vitrinite	Pseudo-vitrinite	Semi-fusinite	Semi-macrinite	Fus-inite	Mac-rinite	Mic-rinite	Ex-inite	Res-inite
535A	66.1	18.1	7.3	0.3	3.3	0.03	1.0	3.4	0.7
538	61.0	22.1	7.5	0.3	3.7	0.1	0.9	3.8	0.6
526	68.2	14.7	5.1	0.2	4.9	0.1	1.5	4.4	0.9
541A	65.2	18.3	10.5	0.4	3.8	0.03	1.0	0.2	0.6
543	69.6	15.6	10.3	0.1	2.8	0	0.7	0.3	0.6
565A	70.9	16.0	8.9	0.1	3.2	0	0.8	0	0.2
539A	65.2	24.7	6.6	0.1	2.6	0	0.8	0.1	0
530A	64.9	22.8	4.6	0.1	2.1	0	2.2	3.2	0.2
528A	68.1	13.1	10.3	0.3	2.3	0.10	1.2	4.7	0.2
527	70.3	10.6	7.4	0.4	4.1	0	2.2	3.0	0.4
533A	59.0	16.9	13.3	0.5	4.0	0	2.2	3.7	0.5

REFLECTANCE ANALYSES

The reflectance values for all of the samples were determined following the procedures outlined in ASTM Standard 2798-79. However, additional reflectance readings on pseudovitrinite were also taken. The results of these analyses, given in table 3, show that all of the samples except some of those from the Carbondale coalfield are in the 0.7-0.8 reflectance range and of high-volatile bituminous rank. Four of the samples from the Carbondale coalfield are in the reflectance range of 1.14-1.37 percent and of medium-volatile to low-volatile bituminous rank. This high rank is remarkable in North America for coals of Upper Cretaceous age and may be associated with igneous intrusions in the region.

Preliminary evaluation of the reflectance data also indicates that the reflectance differences between normal and pseudovitrinite may converge at a lower rank than in the Appalachian coals. While Thompson and Benedict (1974) reported this convergence at a reflectance of about 1.80 percent, the limited data from this study suggests a convergence at reflectances as low as 1.20-1.30 percent.

Table 3.--Results of Reflectance Analyses

SIU-C No.	Mean max. reflectance	Mean max. reflectance		Reflectance difference
		Normal vitrinite	Pseudo-vitrinite	
535A	.74	0.73	0.78	0.05
538	0.76	0.73	0.79	0.06
526	0.76	0.74	0.80	0.06
541A	1.26	1.25	1.27	0.02
543	1.35	1.35	1.36	0.01
565A	1.37	1.37	1.38	0.01
539A	1.14	1.12	1.16	0.04
530A	0.77	0.75	0.80	0.05
528A	0.74	0.72	0.77	0.05
527	0.70	0.69	0.74	0.05
533A	0.74	0.72	0.77	0.05

COKING POTENTIAL

The petrographic data were used to evaluate the coking potential of these coals using both the coke strength prediction methods both of the U.S. Steel Corporation as described by Schapiro and others, (1961) and of the Bethlehem Steel Corporation as described by Benedict, Thompson, and Wenger (1968). These predictions for the strength of coke made from single coals show that the higher rank coals, with a reflectance in the 1.14 to 1.37 percent range, should under normal conditions produce a coke with an ASTM stability of greater than 50. Although some extrapolations are necessary, the lower rank coals of this study will certainly produce cokes with lower stabilities. However, these coals should be suitable for use as the high-volatile coal components of coal blends used for coking and should be expected to perform at least as well as most Midwestern high-volatile coking coals. In blending these Colorado coals, it should be remembered that they are deficient in inert macerals when compared to Carboniferous coking coals.

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FLUORESCENT MACERALS IN COLORADO COKING COALS

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INTRODUCTION

Through a cooperative program with the Colorado Geological Survey, representative samples of Colorado coking coals are being petrographically characterized at the Coal Characterization Laboratory of Southern Illinois University at Carbondale. Both the qualitative and quantitative fluorescence properties of these coals are being evaluated. This report discusses the initial results of the evaluation of the types and abundance of fluorescent macerals present in these coals, and the manner in which the fluorescent macerals change with increasing coal rank.

Although it has long been known that a number of coal macerals will fluoresce when excited by ultraviolet light, and a number of quantitative studies on the fluorescent spectra of coal macerals have been reported (for example, Jacob (1964), van Gijzel (1967, 1971, 1975), Ottenjann and others (1975), and Teichmuller (1974a)), little has been reported on the systematic evaluation of the fluorescent macerals in coals of a given region, especially in North America. Spackman, Davis, and Mitchell (1976) surveyed United States coals, showed that a variety of fluorescent macerals are present, and demonstrated that normal maceral analyses in white light may result in an underestimate of the liptinite macerals by as much as 25 percent. They recommended using a combination of white light and fluorescent light analyses for coal containing greater than 5 percent liptinite macerals in a normal white light analysis. They also showed that fluorescent analysis is useful in studying residues from liquefaction tests and agreed with Teichmuller that fluorescent macerals may play an important role in determining coking properties of coal.

In other studies, Teichmuller (1974b) and Teichmuller and Wolf (1977) suggested that the precursors of petroleum also occur in coal in small amounts and indeed, produce a petroleum-like substance (exudatinite) and leave a micrinite residue when the coal is subjected to the same temperature and time conditions as petroleum source rocks. They also showed that the changes in the fluorescent spectra of some coal macerals, particularly sporinite, are good indicators of the degree of metamorphism (rank) of a coal and further that at least two discontinuities or jumps occur in the coalification series at a reflectance in oil of 0.6 and 1.3 percent. These discontinuities manifest themselves first with the sudden transformation of some liptinites into exudatinite and micrinite and later with the disappearance of all liptinite macerals. These two discontinuities also correspond respectively with the "birth line" and "death line" of petroleum source rocks, and the authors give examples of how fluorescence microscopy has been used in applied coal petrology and petroleum exploration. Similar discontinuities in the coal metamorphic series at a reflectance in oil of 0.7 and 1.35 percent have also been identified for Appalachian coals on the basis of chemical and coking properties by Thompson and Benedict (1974); they are generally thought to represent major changes in coal structure and composition.

In contrast, Ting and Sitler (1979) reported that in Upper Cretaceous to Tertiary coals of the western United States the second coalification jump at which the liptinite macerals disappear is much lower, at a value of 1.1-1.15 percent reflectance, ascribing this difference in the younger coals to differences in the composition of the original plant source material.

PROCEDURES

Each sample used in this study was characterized petrographically with a maceral analysis in normal white light and a reflectance analysis (mean-maximum reflectance in oil). These analyses generally conform to the ASTM standard procedures. The fluorescence analysis was run on a Leitz Orthoplan incident light microscope using a 100 watt Hg lamp. The light was filtered with a BG23 heat filter and a BG12 blue-light filter and then passed to a vertical illuminator adapted with a TK400 mirror, which allowed the incident light of less than 400 nm to be reflected to the sample and the fluorescent light of greater than 400 nm to be transmitted to the oculars after passing through a K510 nm barrier filter. The point-counts on the fluorescent macerals were run to be directly comparable to the white light counts.

FLUORESCENT MACERALS OBSERVED

All of the samples examined are listed in table 1, and the results of the fluorescent maceral analyses of selected samples are given in table 2.

Descriptions of the fluorescent macerals observed in the samples are based on observations in coals with reflectance values ranging from 0.7 to 0.8

Table 1.--Coal Samples Used in Fluorescence Analysis

SIU-C No.	Coal Field	County	Formation	Seam	Rank (Ro in oil)
		Raton Mesa			
575A	Trinidad	Las Animas	Vermejo	Unnamed	0.70
580A	--do----	--do------	--do---	--do---	0.72
582	--do----	--do------	--do---	--do---	0.74
573A	--do----	--do------	Raton	Delagua	0.76
570	--do----	--do------	--do-	Allen	0.77
567	--do----	--do------	--do-	Apache	0.87
		San Juan region			
590	Durango	La Plata	Menefee	Pueblo	0.71
592	Nucla-Naturita	Montrose	Dakota	Unnamed	0.73
583	Pagosa Springs	Archuleta	Upper Fruitland	"A"	0.95
584A	--do----------	--do-----	--do----------	"B"	0.96
587A	--do----------	--do-----	--do----------	"C"	0.99
		Uinta region			
535A	Grand Hogback	Garfield	Williams Fork	"E"	0.80
538	--do---------	--do----	--do---------	Sunnyridge	0.76
526	Carbondale	--do----	Lower Mesaverde	"A","C","D"	0.76
541A	--do------	Pitkin	Williams Fork	Coal Basin "B"	1.26
543	--do------	--do--	--do---------	Coal Basin "B"	1.35
565A	--do------	--do--	LowerMesaverde	"B"	1.37
539A	--do------	--do--	Williams Fork	Dutch Creek	1.14
530A	Somerset	--do----	Mesaverde	"E"	0.77
528A	--do----	--do----	Lower Mesaverde	"C"	0.74
527	--do----	--do----	Mesaverde	"B"	0.70
533A	Book Cliffs	Mesa	Lower Mesaverde	Cameo "B"	0.74

Table 2.--Results of Fluorescent Maceral Analysis on Selected Coal Samples

Region----	Raton Mesa		San Juan		Uinta			
Sample No.-	567	575A	584A	590	538	539A	565A	527
Rank (Ro)--	0.87	0.70	0.96	0.71	0.76	1.14	1.37	0.70
Fluorescent Analyses								
Sporinite	2.0	2.8	0.8	5.4	3.2	0.2	0	1.0
Cutinite	0	1.0	0.2	1.6	1.4	0	0	1.6
Resinite	1.2	0.6	0.2	0	0.6	0.6	0	1.0
Fluorinite	0	0.2	0	0	1.2	0	0	0.6
Exudatinite	0.2	0.8	1.4	0.2	0.2	1.6	4.8	1.6
Amorphous liptinite	0.2	0	3.2	3.0	2.4	0.8	0	1.8
Total liptinite	3.6	5.4	5.8	10.2	9.0	3.2	4.8	7.6
Fluorescing vitrinite	63.4	73.0	44.8	30.2	18.8	31.4	0	32.8
Total fluorescent macerals	67.0	78.4	50.6	40.4	27.8	37.8	4.8	40.4
White Light Analyses								
Total liptinite	2.4	3.8	0.1	2.8	4.4	0.1	0.2	3.4
Total vitrinite	78.6	87.1	93.3	78.6	83.1	89.9	86.9	80.9

percent, because in this reflectance range (the lowest studied) a greater variety of both fluorescent macerals and fluorescent colors occurred, and the intensity of the fluorescence was greatest. Also, even though they comprise only a small amount of the total coal, the fluorescing liptinite macerals (non-vitrinite) were seen in almost every field of view.

Fluorescing vitrinite.—A significant portion of the vitrinite fluoresces with a faint orange to brown color. The criterion used to count fluorescing vitrinite was that it had to fluoresce with an intensity sufficient to distinguish it from the other opaque nonfluorescing macerals in the same field of view. Fluorescing vitrinite is by far the most abundant fluorescing maceral present.Among the nonfluorescing portion of the vitrinite macerals, one type was never observed to fluoresce. This maceral usually has a slightly higher reflectance than the rest of the vitrinite and occurs in larger particles that are most often homogeneous and free of other macerals and mineral matter. It also shows some brecciation and serrated edges. This nonfluorescing maceral has the petrographic characteristics of the material that would be called pseudovitrinite in Carboniferous coals.

Sporinite.—This is the most abundant liptinite maceral and shows the same form in fluorescent light as in white light viewing. It fluoresces with a mild to strong intensity with a yellow to orange color. Often, more details of the structure of this maceral can be observed in fluorescent light.

Cutinite.—Cutinite also shows the same forms in fluorescent light as in white light. It fluoresces with a mild to strong intensity in colors ranging from yellow to orange. In any given sample it tends to have its colors shifted more toward orange than the accompanying sporinite.

Resinite.--Resinite occurs as both a primary and secondary maceral. In its primary form it occurs as ovoid bodies that fluoresce with a mild to strong intensity and a yellow to yellow-orange color. Occasionally the ovoid bodies are zoned with the bright-yellow center being encircled with a much paler yellowish-gray rim. Also seen occasionally are resinite-like ovoids that fluoresce with a very intense lime-green color. These also sometimes show flow textures. The ones that show flow textures are certainly the secondary fracture-filling resinites discussed later. At this time the classification of the textureless green-fluorescing ovoids is uncertain. They may be primary resinite, secondary resinite, or large masses of fluorinite.

Secondary resinite occurs as obvious fracture fillings that fluoresce quite strongly with either a lime-green or yellow color. This secondary resinite is most common in the coals of the Uinta region and is the same material described by Crelling and Dutcher (1979) in coals from Utah.

Fluorinite.--Fluorinite occurs as lenses in stringers that fluoresce intensely with a yellowish-green to green color. The frequent occurrences of fluorinite between two layers of cutinite suggest some common botanical affinity between these two macerals.

Exudatinite.--Exudatinite is another secondary maceral that fills void spaces in the coal structure such as cell lumens in fusinite, semi-fusinite, and sclerotinite, and fractures in vitrinite. Exudatinite fluoresces weakly with a dull reddish-orange color.

Amorphous liptinite.—In this category were placed all occurrences of primary liptinite that had no clear affinity to the other macerals described above. Amorphous liptinite fluoresces weakly with an orange to reddish-orange color.

EFFECTS OF INCREASING RANK

In general, as the rank of the coals increased above the 0.7-0.8 percent reflectance range the variety of fluorescent macerals, the variety of fluorescent colors, and the intensity of fluorescence diminish. Fluorinite disappears in this range. In the 0.9-1.0 percent reflectance range, sporinite, cutinite, and resinite are scarce and, when present, have very weak fluorescent intensities. In white light, most of the fluorescent macerals present, except for exudatinite and fluorescing vitrinite, have a corroded, pitted, and degraded appearance. In the coals in the reflectance range of 1.0 to 1.37 percent, all of the liptinite macerals except exudatinite and scattered pieces of amorphous liptinite disappear. However, as the liptinite macerals diminish and finally disappear, no massive replacement by micrinite occurs. In fact, micrinite was fairly uncommon in all of the coals examined. These observations agree with those of Ting and Sitler (1979) that in white-light viewing most of the liptinite macerals disappear by a reflectance of about 1.10 percent. However, they disagree in that fluorescent light analysis reveals that exudatinite, amorphous liptinite, and fluorescing vitrinite continue to occur in these coals to the highest rank studied, 1.37 percent reflectance.

CONCLUSIONS

Based on the results of this study the following conclusions are made:

1. Fluorescence analyses show a high percentage of fluorescing vitrinite in Colorado coking coals as well as a greater variety and abundance of liptinite macerals than revealed in normal white-light compositional analysis.
2. Although most of the primary liptinite macerals disappear at a reflectance of about 1.1 percent, fluorescing vitrinite, exudatinite and amorphous liptinite remain in these coals to a reflectance of at least 1.38 percent.
3. No evidence exists for the replacement of liptinite macerals by micrinite.
4. The fluorescent macerals are extremely sensitive indicators of the degree of coalification up to a reflectance of at least 1.1 percent.

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METHANE IN COLORADO'S MINABLE COAL BEDS—AN OVERLOOKED ENERGY SOURCE

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INTRODUCTION

In 1978, a maximum of 11 million ft^3 of methane was emitted per day from Colorado's coal mines. Methane occurs in concentrations of less than 1 percent in the mine air; it is relased into the atmosphere from a mine's ventilation system.

In an effort to conserve gas that would otherwise be lost, as Colorado's coal production increases, the Colorado Oil & Gas Conservation Commission funded a joint project with the Colorado Geological Survey to study the feasibility of degasifying Colorado's coalbeds ahead of mining.

BACKGROUND

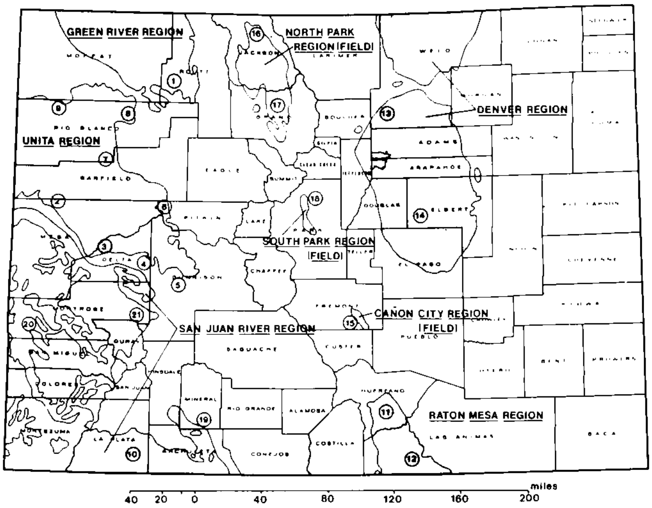
Methane is the main constituent of firedamp, an explosive mixture of gases well known to coal miners. Methane is an odorless and colorless gas which (at volume concentrations of 5-15 percent) in the presence of oxygen is readily combustible. To prevent ignitions, present mine safety laws in the United States require that the concentration of methane be kept below 1 percent in active underground workings.

In the past, high methane concentrations have been controlled mainly by adequate coal-mine ventilation. Research done by the principal coal-producing European countries and the United States has been directed toward alternate methods of controlling methane emission into mines. One of the most promising methods is the draining of methane by means of vertical, horizontal, or directional degasification holes from the coal prior to mining and (or) the gob after mining. (These methods have been described thoroughly in work done by the U.S. Bureau of Mines.)

This unconventional gas constitutes a resource that can be utilized on mine site, in nearby communities, or, if in sufficient quantity, fed into regional pipeline systems. Developing methane as an alternative energy source involves determining the geologic, mining, and economic controls on a potential degasification site.

METHANE RESOURCES IN COLORADO

Over the past 4 yr, the Colorado Geological Survey has delineated areas in the Green River, Raton Mesa, San Juan River, and Uinta coal regions that may be suitable for gas recovery (fig. 1). Preliminary figures show an estimated methane resource of 38.4 trillion ft^3 contained in mined and unminable coal beds in these regions, 20 percent of which may be recovered using present technology. Most gas is of pipeline quality with heating values ranging from 500-1,000 Btu/ft^3. Upon writing this report, H_2S has not been found in samples collected.



COAL REGIONS AND FIELDS IN COLORADO
(ROCKY MOUNTAIN COAL PROVINCE)

COAL FIELDS

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

Figure 1.—Coal-bearing regions in Colorado.

Although much of the resource is known to exist in potentially unminable coal beds, substantial amounts of methane are known to be present in four active coal fields in Colorado: the Book Cliffs, Carbondale, and Somerset fields of the southern Uinta region; and the Trinidad field of the Raton Mesa region (table 1).

Table 1.—Average methane contents for four Colorado coal fields

Coal region	Coal region	Methane content in ft^3/ton			
		Above 1000 feet overburden		Below 1000 feet overburden	
		Average	Range	Average	Range
Raton Mesa	Trinidad	79	2-254	159	38-492
Uinta	Book Cliffs	79	--	224	--
	Carbondale	--	--	458*	--
	Somerset	150	80-217	162	9-245

*Estimated using U.S. Bureau of Mines formula based on rank and depth of coal.

Methane content in the coal was determined using the Direct Method developed by the U.S. Bureau of Mines.

CONTROLS ON METHANE DEVELOPMENT

Geologic Controls

Geologic parameters influencing methane migration and the subsequent emission into the coal mine are (1) rank of the coal, (2) thickness and areal extent of the coal bed, (3) degree of cleat development in the coalbed and structure of the general area, (4) lithology of the roof and floor rock, (5) depth of the overburden, and (6) degree of water saturation.

Rank of the coal.--The volume of gas contained in a coal is a function of several factors. The adsorptive capacity of the coal is controlled mainly by the temperature and gas pressure; it is also related to the rank of the coal. Research done in Europe and in the United States demonstrates that the adsorptive capacity increases with increasing rank. In Colorado, the rank of coals associated with high gas concentrations ranges from high volatile A bituminous through medium-volatile bituminous. Most of the minable coals in this category are in areas where heat from igneous activity has upgraded the coals either locally or over a large area.

Thickness and areal extent of the coal bed.--The reserve base of methane in an area depends not only on the gas content of the coal but also on its thickness and areal extent. As the coal acts as the source of and (or) reservoir for the gas, the bulk volume is a variable that can be determined by exploration techniques.

Degree of cleat development in the coal bed and structure of the general area.--In coal, the flow of methane is determined by a two step process: (1) diffusion through the coal's micropore structure; (2) flow of free gas along natural fractures (cleats) in the coal. Two main sets of cleats are present in coal; the face or primary cleat, and the butt or secondary cleat (oriented at approximately 90° to the face cleat). The face cleat, the more continuous and well developed of the two, is the main migration path for fluids in the coalbed. The control on migration in the butt cleat direction is secondary.

The structure of the area is also important in determining the controls on methane migration. Work done by various authors has shown that the directions of both cleating and jointing tend to coincide with the main structural trends in the area. This, as well as the presence and degree of faulting and fracturing, influences the methane migration path.

Lithology of the roof and floor rock.--The methane content of a coalbed and the emission into mine workings are also determined in part by the lithology of the strata above and below the coal. In the roof, an unfractured shale lying directly above the coal may act as an impermeable layer restricting the flow of methane. A sandstone or other material exhibiting a higher permeability, by contrast, would allow methane to migrate away from the immediate roof and concentrate in higher strata. The floor lithology is important if the mined seam is underlain by coal stringers or carbonaceous shale. In cases where fracturing of the interburden between gas-bearing lower beds and the main bed has occurred, methane migrates upward into mine workings and is dispersed into the mine air.

Depth of overburden.--Another important factor in methane content is depth of overburden. Research done by the U.S. Bureau of Mines in eastern coals indicates that, in general, the amount of gas in a coal bed increases with increasing depth. In Colorado, an increase in gas content was noted with increased thickness of overburden. A complicating factor is that of high heat flow, that has locally upgraded the coal.

Degree of coal bed water saturation.--Moisture in coal both lowers its adsorptive capacity and restricts methane flow. Kissell (1972, U.S. Bureau of Mines,1972) noted that portions of a coal bed adjacent to older mined out areas were considerably more permeable than freshly mined areas. The probable cause of the phenomenon was a relative permeability effect in which the coal bed's permeablity to methane increased as water content decreased.

Mining Factors

The amount of methane emitted into a mine is controlled only in part by geologic factors. Parameters of a particular mine influence the methane emission into the mine as well as determine the most suitable degasification method. These parameters include: (1) the mine plan and mining method, (2) the rate of expected coal production, and (3) the presence of workings—both active and abandoned.

The mine plan and mining method.—The mine plan and mining method is important in determining the amount of methane emitted into the coal mine. This is related to the surface area exposed by the mine workings and the face area being worked. The mine plan also determines the placement of degasification holes.

The rate of expected production.--The amount of expected production is an important factor in the concentration of methane emitted into the air. As production increases, methane released increases proportionally. Thus, the amount of expected production may determine either the need for degasification in a new mining operation or introduction of degasification techniques in an expanding operation.

The presence of workings—both active and abandoned.—It was noted previously that the presence of active or abandoned workings helps decrease the water saturation in a coal bed, and, as a result, increases the gas flow by increasing the permeability. Placement of vertical holes near the workings may substantially cut down on the time necessary to dewater a coal bed.

Economic Factors

The economics of degasification are important in determining the feasibility of a drainage program on any given mining property. Of major importance is the amount of gas that can be recovered using available drainage techniques, and the income generated by the gas. The cost of placement and maintenance of pipelines, compressors, and generators must be balanced by a return to the company on the recovered gas.

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POTENTIAL FOR COAL-BED METHANE PRODUCTION FROM THE GREATER GREEN RIVER COAL REGION

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Methane, a natural byproduct of the coalification process, is retained by coal through absorption on its internal surfaces. It is present in all coal, in highly variable quantities dependent on factors including coal quality and depth of burial. Recent long-range energy analysis has considered this coal-bed methane as a potential energy resource; however, much predevelopment remains to be done in all areas including resource characterization. This report is a preliminary estimate of the potential coalbed methane resource in the Greater Green River Coal Region, an estimate is based on existing quantitative methane content data and present estimates on the quantity of the coal resource in this region. In addition, this report outlines an initial program for expanding the existing coal-bed methane data base.

The Greater Green River Coal Region occupies about 21,000 mi^2 in southeastern Wyoming and northwestern Colorado and includes the following structural units: the western Wyoming thrust belt, the Green River basin, the Rock Springs Uplift, the Great Divide basin and the Washakie basin. This coal region contains significant quantities of both bituminous and subbituminous coal with the total original in-place resource estimated at more than 82 billion short tons. This coal is found in both Upper Cretaceous and Tertiary units that crop out on the flanks of the uplifts and dip into the basinal areas. Very little is known about the quantity and stratigraphic distribution of coals in the deeper part of the basins; therefore, the estimate of the total quantity of coal in this region is bound to be conservative.

The coal outcrop area in the western Wyoming thrust belt is called the Hams Fork Coal Region; the major coal-bearing units include the Upper Cretaceous Frontier and Adaville Formations. Other formations containing coal are the Lower Cretaceous Bear River, the Upper Cretaceous Blind Bull, and the Paleocene Evanston. The two primary coal groups within the Frontier Formation are the Kemmerer and the Willow Creek. Kemmerer group coals are as thick as up to 20 ft and average 5-10 ft. The rank of the Kemmerer group coals ranges from high-volatile B to high-volatile C bituminous. Willow Creek coals range from about 2 to 11 feet in thickness and are generally high volatile B bituminous in rank. The Adaville Formation contains up to 32 subbituminous coal beds, many of which are the thickest Upper Cretaceous coals in Wyoming. The thickest bed in this unit is the Adaville No. 1 bed, which locally reaches a thickness of 118 ft. The total estimated original in-place coal resource, both bituminous and subbituminous, in the Hams Fork Coal Region is approximately 5 billion short tons.

The Green River basin which is located in southwestern Wyoming between the western Wyoming thrust belt and the Rock Springs Uplift, is a broad synclinal area of about 10,000 mi^2. Only minor coals crop out in the basin, but it is probable that substantial coal resources are present in the subsurface. Very little is presently known about the quantity and stratigraphic distribution of these coals; therefore, any estimate of the coal resource in this basin should be considered extremely conservative.

The Rock Springs Uplift is a north-south-trending anticlinal feature of Laramide age, in the center of Sweetwater County, Wyo. The principal coal-bearing units in this area are the Upper Cretaceous Rock Springs and Almond Formations of the Mesaverde Group, the Upper Cretaceous Lance Formation, and the Paleocene Fort Union Formation. The Rock Springs Formation contains at least 12 coal beds with an average thickness of about 6 ft. Coals from this formation are generally high volatile C bituminous in rank. The Almond Formation contains up to 30 ft of coal in beds thicker than 2 ft. Almond Formation coals range from subbituminous C to subbituminous B. Upper Cretaceous Lance Formation coals known locally as the Black Buttes coal group average about 5 to 6 ft in thickness and are generally subbituminous B in rank. The Paleocene Fort Union Formation coals known locally as the Black Rock coal group average about 6 ft in thickness and range in rank from subbituminous C to subbituminous B. The estimated total original in-place coal resource of this area, both bituminous and subbituminous, is approximately 14 billion short tons.

The Great Divide basin, located in northeastern Sweetwater County, Wyo., is a large synclinal basin modified by broad shallow folds and widespread small-scale faults. The major coal-bearing unit here is the Eocene Wasatch Formation. Coals in this formation are best developed in the southeastern and central parts of the basin where it is estimated that approximately 1.6 billion short tons of subbituminous coal lie within 3,000 ft of the surface.

The Washakie basin is a broad syncline covers an area of about 3,000 mi^2 in south-central Wyoming and northwestern Colorado. The essentially uniform synclinal structure is broken by a west-trending uplift area along the Wyoming-Colorado State line. This uplift is called the Cherokee Ridge Arch and separates the primary Washakie basin on the north from the subsidiary Sand Wash basin to the south. In the Washakie basin the major coal-bearing units are the Upper Cretaceous Mesaverde Group and the Eocene Wasatch Formation. Mesaverde Group coals range in thickness from about 3 ft to 12 ft and are generally high volatile C bituminous in rank. The Eocene Wasatch Formation coals are best developed in the northwestern part of the basin in the Cherokee coal district, where two beds range in thickness from 10 ft to 32 ft, and in quality from subbituminous B to lignite. The estimated total original in-place coal resource in this basin is approximately 23 million short tons of bituminous coal and 1.9 billion short tons of subbituminous coal.

The Sand Wash basin is a southeasterly trending synclinal prong of the Washakie basin. The major coal-bearing units are the Upper Cretaceous Williams Fork and Iles Formations of the Mesaverde Group, and the Paleocene Fort Union Formation. Mesaverde Group coals range in thickness from about 2 to 20 ft and are generally high volatile C bituminous in rank. The total estimated original in-place coal resource from this group is approximately 40 billion short tons. Fort Union Formation coal beds range from about 6 ft to 17 ft in thickness and are generally subbituminous B or C in rank. The total estimated original in-place coal resource from this formation is about 18 billion short tons.

Coal beds in the Greater Green River Coal Region have been sampled for methane content determination at widely spaced locations. The sampling and testing has been carried out by the U.S. Geological Survey, the Colorado Geological Survey, and by TRW Energy Systems Group as part of the U.S. Department of Energy's Methane Recovery From Coalbeds Project (MRCP). All sampling to date has been done on Upper Cretaceous Mesaverde Coals. Table 1 summarizes these data. To help put the methane content values in perspective, it should be pointed out that from a mining standpoint, coal with a methane content in excess of 200 ft^3/ton would be considered very gassy. Additionally, the methane content of 539 ft^3/ton exhibited by coal sampled at the Belco S-29-27 well in Sublette County, Wyo., is one of the highest observed to date. The only other quantitative methane content data is an estimate by the Colorado Geological Survey on methane content of coal being mined at Apex #2 (A) mine, Sec. 22, T.4.N., R. 96 W. At this mine the methane content of the Pinnacle coal bed was estimated to be 190 ft^3/ton.

In addition to this quantitative information, significant quantities of methane have been observed during coal exploratory drilling in shallow coal beds at various locations in the region. These include the Leucite Hills and other areas on the eastern flank of the Rock Springs Uplift where Rocky Mountain Energy Corporation (RMEC) has encountered several blowouts from shallow wells drilled for coal resource evaluation (T. Cox, RMEC, personal commun.). Table 2 details the location of these blowouts and the projected depth where the methane was encountered.

The specific types of data required to allow reasonable estimates of the methane resource include the methane content of coals from each coal-bearing formation and quantitative data on how these methane contents vary with coal quality and with depth of burial. To date, this type of data in the Greater Green River Coal Region is limited to those locations summarized in table 1. For resource estimation purposes a value of 2.9 ft^3/ton is chosen as the minimum methane content for bituminous coals. The chosen maximum value is 539 ft^3/ton. To date, subbituminous coals from the Greater Green River Coal Region have not been sampled for methane content determination. Therefore, to estimate the the potential coal bed methane resource in the subbituminous coals of this area, minimum and maximum methane contents of 0 to 100 ft^3/ton are assumed. Using these figures, the total coal-bed methane resource in the Greater Green River Coal Region is estimated to range from 150 billion ft^3 to more than 32 trillion ft^3. Table 3 summarizes the estimated coalbed methane resources in this region.

As previously mentioned, the Greater Green River Coal Region includes an area of approximately 21,000 mi^2. Within this region, smaller areas of about 5,000 mi^2 that contain major coal-bearing units in the upper 5,000 ft should be considered as primary target areas for detailed evaluation of the coal-bed methane resource and its production potential. Figure 1 outlines the general locations of these primary target areas.

Within these primary target areas, individual site selection should be based on local structure and existing direct indicators of potential coal-bed methane. Local structures that would be attractive are fold axes and intersections of linear structures. In both these cases, the stress on the coal-bearing units should provide fractures for the collection of desorbed methane. Direct indicators of potential coal-bed associated methane include shallow drill holes which flow methane, and methane emitted from artesian wells. An initial program, here recommended, for investigating the methane contents of the various coal-bearing formations and the potential methane recovery from these coals in the Greater Green River Coal Region include: (1) Construction of a lineation map of the basin, particularly in the primary target areas, utilizing satellite imagery and aerial photo-

Table 1.—Summary coal methane content data, Greater Green River Coal Region

Well I D	Location	Collecting Agency	Approximate Sample Depth (ft)	Coal Bed Thickness (ft)	Coal Rank	Estimated Methane Content (Ft^3/Ton)
C-IC-H	Section 23 T4N R91W Moffat County, Colorado	USGS/CGS	177.5 646.0 722.5 770.0 805.0	20.6 3.6 3.0 9.0 3.3	N/A[1] N/A N/A N/A N/A	3.6 2.9 0.0 16.1 5.7
Belco S-29-27	Section 28 T 30N R 113 W Sublette County, Wyoming	DOE/TRW	3480.0 3495.5 3527.0	4.0 5.0 2.2	hvAb[2] hvAb hvAb	485.0 539.0 513.0
Confidential	Confidential	DOE/TRW, CGS	3652.0 3675.0 4661.0 4705.0	1.0 1.5 14.0 1.4	hvBb[3] hvBb hvBb hvAb	251.0 256.0 269.0 - 322.0 376.0

Table 2.--Estimated coal-bed methane resources in the Greater Green River Coal Region

Well Location	Area	Depth To Methane (Ft)	Formation	Comments
Sec. 5 T21NR103W (SENW)	Long Canyon	300-320	Rock Springs	Hydrologic Observation Well
Sec. 5 T21NR103W (NESE)	Long Canyon	300-320	Rock Springs	—
Sec. 16 T19NR99W	Bitter Creek	240	Wasatch-Ft. Union	—
Sec. 15 T20NR101W (NWNW)	Leucite Hills	240	Almond	Burned the Rig Down
Sec. 15 T20NR101W (NESW)	Leucite Hills	500	Almond	Big blow-required 500 bags of cement to plug it.
Sec. 9 T17NR101W (NENW)	Salt Wells	100	Almond	—
Sec. 9 T17NR101W (SESW)	Salt Wells	220	Almond	Big Blow
Sec. 16 T17NR101W (SWSW)	Salt Wells	50-100	Almond	—

Table 3.--Estimated coal-bed methane resources, Greater Green River Coal Region

Coal Region	Coal Rank	Estimated Coal Resources (Millions Short Tons)	Methane Content of Coal		Total Estimated Methane Resource	
			Minimum (Ft^3/Ton)	Maximum (Ft^3/Ton)	Minimum (Ft^3)	Maximum (Ft^3)
Green River	Bituminous	49,581.67	2.9	539.0	.15 x 10^{12}	26.7 x 10^{12}
	Subbituminous	27,598.23	0.0	100.0	0	2.8 x 10^{12}
Hams Fork	Bituminous	3,197.68	2.9	539.0	.01 x 10^{12}	1.7 x 10^{12}
	Subbituminous	1,676.86	0.0	100.0	0	.17 x 10^{12}
Total		82,054.44	—	—	.16 x 10^{12}	31.4 x 10^{12}

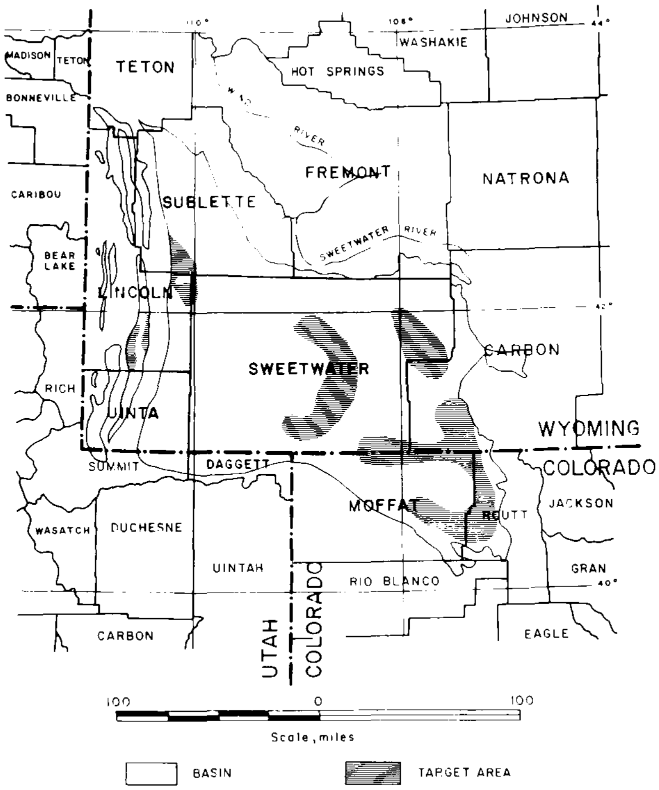

Figure 1.—Generalized locations of the primary target areas, Greater Green River Coal Region.

graphs; (2) Compilation and analyses of water-well data from the basin to determine methane content of the effluents; (3). Review of all geophysical logs available in the upper 5,000 ft of the primary target areas to analyze the stratigraphic distribution and cumulative thickness of coal beds. For those areas where logs are unavailable, development of cooperative agreements with private operators or government agencies drilling in these areas, to generate density logs, is recommended; (4) Entering into cooperative agreements with private operators or government agencies drilling in primary target areas for the collection of coal samples for desorption and for testing of the coal seams.

STRATIGRAPHY AND COAL RESOURCES OF DAKOTA SANDSTONE IN SAGE PLAIN, SOUTHWEST COLORADO AND SOUTHEAST UTAH

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INTRODUCTION

Sage Plain is a broad, rolling, upland surface covering about 1,000 mi^2 that extends 60 mi in a gentle northwest-southeast arc between Monticello, Utah, and Cortez, Colo (fig. 1). The plain lies in portions of San Juan County, Utah, and Dolores, Montezuma, and San Miguel Counties, Colorado. The northeast edge of the study area is bounded by the Dolores River Canyon. The southwest edge of the plain is extensively dissected by southwestward-draining canyons. The surface of the plain is formed on a gently warped dipslope of Dakota Sandstone (Cretaceous). Most of the surface is mantled by as much as 40 ft of reddish-brown loess. The Dakota Sandstone is poorly exposed even in canyons around the margin of the plain.

The discussion of Dakota Sandstone stratigraphy and coal resources presented here is based largely on new drill-hole information. Thirty-one holes, including 27 open holes and 4 core holes, were drilled by AMAX Coal Company as part of a regional exploration project that began in the fall of 1977. Such data have allowed AMAX to develop a considerably more refined understanding of Dakota Sandstone stratigraphy and depositional history than was available in the past. Most earlier descriptions of the Dakota were based on partial or poorly exposed outcrops and thus did not generally include data from the interior Sage Plain. The purpose of this paper is to present a more complete and detailed stratigraphy of the Dakota Sandstone and discuss the potential coal resources of the formation in the Sage Plain.

The authors express their gratitude to Dr. Charles Wier and Dr. John Sulima of AMAX Coal Company, who helped make possible the publication of this report.

DAKOTA SANDSTONE

In the Sage Plain area, a rough, tripartite, vertical succession in the Dakota Sandstone is recognized on the basis of gross lithology (fig. 2). The tripartite division agrees with observations made in other parts of the Colorado Plateaus by workers such as Coffin (1921), Repenning and Page (1956), Owen (1969) and Lamb (1968). The three divisions consist of: (1) a conglomeratic lower sandstone; (2) a carbonaceous middle shale: and (3) a littoral upper sandstone; together these average 138 ft thick across Sage Plain.

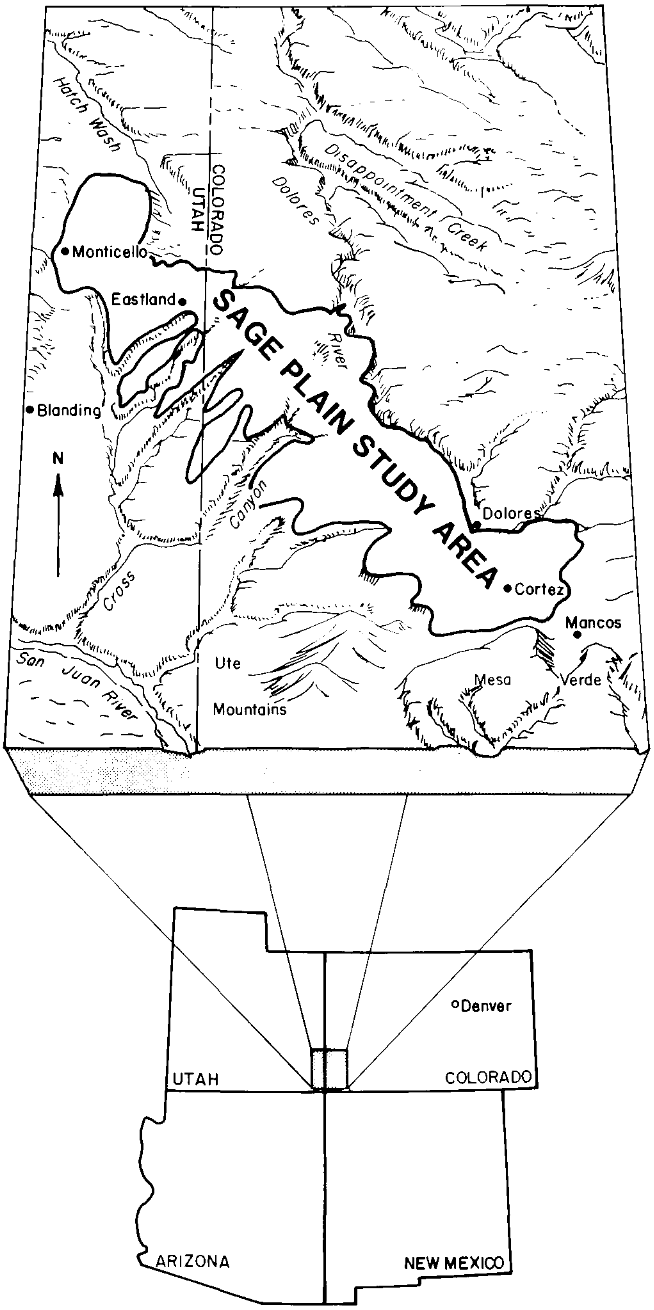

Figure 1.—Location of Sage Plain study area, Colorado and Utah.

"Lower Sandstone"

The Dakota unit informally known as the "Lower Sandstone" averages 44 ft thick but varies widely from 4 to 134 ft. It lies unconformably upon the Burro Canyon Formation, which was distinguished from the Dakota by the presence of bluish-green or reddish-brown shale. Thick sections of "Lower Sandstone" probably represent channel fill in ancient stream valleys that were cut into the Burro Canyon Formation. These thick sections may consist of as many as three individual sandstone units separated by siltstone beds usually less than several feet thick. The sandstone beds of the "Lower Sandstone" unit are light gray on fresh surfaces and weather to grayish orange or light brown; they are fine to medium grained, quartzose, and often pebbly or conglomeratic at the base. The lower siltstone is grayish green and sandy, and may be reworked Burro Canyon shale. The siltstone between the upper two sandstones is gray and sometimes carbonaceous. All three sandstones are hard, have noncarbonate cement, contain sparse chips and fragments of coalified wood, and have conspicuous cross-stratification. The sandstones fine upward and grade into the overlying "Middle Shale" unit of the Dakota. Along the edges of canyons that dissect Sage Plain, the Lower Sandstone unit forms ledges and rimrock cliffs.

The "Lower Sandstone" has been interpreted as a braided stream deposit by other workers such as Owen (1969; 1973) and Young (1973). AMAX's data support their interpretation. Young (1973, p. 12) explained the origin of the sandstone as orogenic detritus derived from major uplifts in the western source area and transported eastward by braided rivers.

"Middle Shale"

The informal Dakota unit known as the "Middle Shale" averages 73 ft thick and varies from 45 to 122 feet thick. It is distinguished from members above and below by its dominant lithologies of gray to dark-gray silty shale, carbonaceous shale, and coal.

The occurrence of impure or dirty coal in discontinuous beds in the Dakota is frequently mentioned in the literature. (See Shomaker and others, 1971, p. 31-37, and Doelling, 1972, p. 270-280.) Four important coal horizons are recognized in the "Middle Shale," based on AMAX's drill-hole data. They are informally named here the"A," "B," "C," and "D" coal seams in ascending order. Where they occur, the seams average from 2 to 8 ft thick. Locally, the seams are as much as 8 to 15 ft thick. The "D" coal occurs 0-5 ft below the top of the Middle Shale. The intervals between the coal seams average 12-15 ft thick. All of the seams are discontinuous and impure, and they grade laterally into carbonaceous shale. The "C" and "D" seams are most continuous and thickest in the southeast half of the plain, whereas the"B" seam is the most important in the northwest half of the plain.

Two fairly persistent sandstone horizons are recognized in the "Middle Shale." They occur interbedded with the coals in the middle or lower part of the Middle Shale. The older sandstone occurs between the "A" and "B" coals. It averages 19 ft thick and occurs over about 50 percent of the area. This sandstone may represent intertonguing of the "Lower Sandstone" with the "Middle Shale."

The younger sandstone occurs between the "C" and "B" coals. It averages 17 ft thick and occurs over about 20 percent of the area. In some cases this sandstone rests, with a scoured contact, directly on the "B" coal.

Both of the sandstones are composed of white to light-gray, medium to fine quartz sand. The base of each sandstone is usually massive or planar bedded,

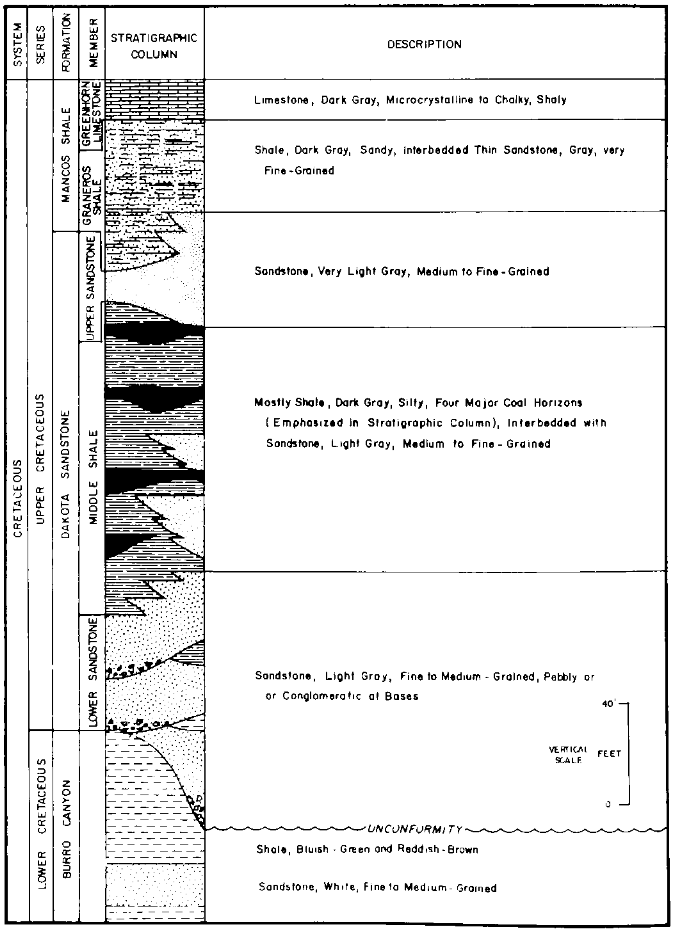

Figure 2.—Dakota Sandstone stratigraphic column, Sage Plain area, Colorado and Utah.

whereas the tops have abundant, thin, dark-gray, rippled shale laminae. Both sandstones are typical of river point bars, deposited by meandering streams. By association, the enclosing shales are mostly overbank flood deposits. It is interesting to note that the number and continuity of sandstone beds decrease upward in the Middle Shale, whereas the number and continuity of coal seams increase.

"Upper Sandstone"

The "Middle Shale" unit is overlain by a unit informally known as the "Upper Sandstone," that has an abrupt, disconformable basal contact. The upper contact is transitional with the marine Mancos Shale. The upper sandstone, and beds immediately overlying it, fine upward from sand through interbedded thin siltstone and very fine grained sandstone to interbedded siltstone and claystone. The authors place the upper contact in Sage Plain at the top of the sandstone that represents shoreface deposition, in a manner consistent with that of Owen (1969) in New Mexico's Chama Basin, and Lamb (1968) in the northern part of the San Juan Basin.

The "Upper Sandstone" ranges from 8 to 35 ft in thickness, averaging 15 feet thick. It is a medium- to fine-grained, well-sorted, quartzose sandstone, varying from white to very light gray on fresh surfaces, yellow when weathered. Locally it is an important aquifer.

The "Upper Sandstone" is composed of a series of sands that collectively demonstrate upper and lower shoreface deposition. The lowest sand is a massive high-angle cross-stratified unit, paleontologically barren, with organic trash occurring near the base. Basal contact is scoured, with this lowest sand resting unconformably on "Middle Shale" carbonaceous clays. This lowest sand of the "Upper Sandstone" is typically 4 ft thick and was probably deposited in an upper shoreface regime dominated by surf zone.

The overlying sands, typically 8 ft thick as a unit, are a sequence of alternating massive, bioturbated sands and thin, planar-bedded, sometimes rippled sands. Such a sequence is interpreted as alternating storm-generated/fairweather deposits just above and below wave base (lower shoreface). Almost identical deposits can be seen in the Upper Cretaceous Blackhawk and Rock Springs Formations of the Colorado Plateau, and in Recent deposits off the Eastern United States coast (J. Balsley, oral commun., 1979).

COAL RESOURCES

Reserves

The 31 holes drilled by AMAX, taken as a group, represent slightly less than 1,000 mi^2, or approximately 31.4 mi^2 each. Four coal horizons greater than or equal to 2.0 ft thick were penetrated 16 times by 10 drill holes. Assuming: (1) that each hole represents 31.4 mi^2 and therefore had the same statistical chance of penetrating coal; (2) an average coal density of slightly more than 2,100 tons/acre foot; and (3) an average total coal thickness penetrated per hole of approximately 7.6 ft, we can infer a reserve of 3.3 billion tons underlying 314 mi^2. Subsequent cluster drilling indicates that the coal occurs in discontinuous lenses covering 15 mi^2 or less. However, this more realistic estimate of the coal body geometry does not alter the authors' original estimate that coal underlies approximately 1/3 of the Sage Plain.

Quality

Twelve coal samples from four core holes were recovered and analyzed by AMAX. Other quality data are published by Doelling (1972, p. 274) and in U.S. Bureau of Mines Technical Paper 574 (1937). In spite of the small number of core samples, if the data are grouped, some useful and interesting relationships can be observed.

The coal ranks mostly as high-volatile B bituminous with some high-volatile C bituminous. However, the average ash content is 36 percent and is almost always more than 20 percent. Btu values are high but vary depending on ash content. The average moisture-free Btu value is 8,985, and values range from 5,723 to 11,216. On a moisture, ash-free basis, the average Btu value is 13,884. The average moisture is quite low, averaging 4.30 percent and ranging from 3.45 to 5.23 percent. Sulfur averages 1.09 percent and ranges widely from 0.50 to 2.92 percent. The "D" seam, which is often overlain by a marine sandstone, has the highest sulfur content, averaging 1.89 percent, whereas the lower seams average less than 1.0 percent sulfur. The high ash content is indigenous rather than localized in partings. Consequently, the coals have very poor wash recoverability. At a 1.65 specific gravity wash, about 55 percent of the coal floats, and about half of the ash will wash out.

CONCLUSIONS

Drill data from the Sage Plain area show Dakota Sandstone stratigraphy similar to that studied by Owen (1969) in Chama Basin, N. Mex., and by Lamb (1968) in northern San Juan Basin, N. Mex. and Colo. Specifically, the Dakota consists of a lower unit of probable braided stream deposits; grading upward into a probable flood-plain/meandering stream complex with coal; overlain by shoreface sand deposits. The Dakota records a classic sequence of transgressive deposition that continued in front of and at the margins of an advancing epeiric sea. The depositional setting is thought to be one of a coastal plain where sediment supply, although variable, was less than the rate of subsidence. This resulted in rapidly shifting shorelines, little or no delta construction, and dirty, lenticular coals.

A surface minable reserve of 3.3 billion tons is inferred for the area of Sage Plain. Development potential is limited because of high ash content and lack of rail transportation.

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COKING-COAL DEPOSITS IN COLORADO

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ABSTRACT

A recent study of the coal resources in Colorado by personnel at the Colorado Geological Survey delineated potential coking-coal deposits in the Uinta, San Juan River, and Raton Mesa coal regions of the State. The coal deposits were classified by rank and by sulfur and ash contents as being either premium (0-1.0 percent S, 0-8.0 percent ash), marginal (1.1-1.8 percent S, 8.1-12.0 percent ash), or latent (1.9-3.0 percent S, 12.1-15.0 percent ash) grade coking coal. Identified original in-place coking-coal reserve estimates were developed for each of the basins using this classification system, general geological and technological considerations, coking-coal evaluation mapping, and previously published coal reserve/resource estimates.

The Raton Mesa coal region has the largest coking-coal reserve of any region in Colorado, amounting to approximately 2 billion short tons of marginal grade high-volatile A and B bituminous coking coal. Approximately 1.7 billion short tons of coking-coal reserves are located in the San Juan River coal region of Colorado, varying in rank and grade from premium grade high-volatile A bituminous to latent grade high-volatile B bituminous coking coal. Although the Uinta coal region contains the most desirable coking coal in the West, only 500 million short tons of premium grade medium-volatile bituminous to marginal grade high-volatile B bituminous coking coal has been identified in the region. The original identified in-place coking-coal reserve estimate for Colorado totals about 4.3 billion short tons. Additional coal resource studies and a modification of the method used to determine reserves (by the addition of presently mined coals below 1,000 ft of overburden to the reserves base) could increase this coking-coal reserve estimate substantially.

INTRODUCTION

In 1977, the Colorado Geological Survey received a grant from the U.S. Bureau of Mines entitled, "Evaluation of Coking-Coal Deposits in Colorado." The grant was renewed in 1978, with funding provided by the U.S. Department of Energy. The primary goal was to establish a comprehensive State-wide data base on coking-coal resources in Colorado, so that intelligent decisions concerning those resources could be made by officials in all levels of government and by workers in private industry.

The grant study was conducted in four main phases. The first phase involved a review of published literature to pinpoint those areas in the State in which coking coal had historically been mined. Next, coal classification systems were reviewed and an applicable system was chosen to evaluate Colorado's coking-coal resources. This classification system and previously published coal reserve/resource estimates were used to deduce the coking-coal reserves in Colorado. For details of these grant study phases, see Goolsby and others (1979).

HISTORICAL BACKGROUND

The numerous ruins of beehive coke ovens in several of Colorado's important coal regions reflect the early importance of coke in the State's metal smelting and locomotive industries. By the end of the 19th century, beehive coke ovens were operating in the Raton Mesa, San Juan River, and Uinta coal regions of the State. Jones and Murray (1978) have noted the occurrence of a dozen beehive coke oven ruins in these regions. However, environmental concern and the greater efficiency of byproduct coke ovens eventually forced the closure of all beehive coke ovens in the State. The byproduct ovens owned by CF&I Steel Corporation at Pueblo have been the only active ovens in Colorado for over 20 years.

Although coke has several important industrial uses, in the West its predominant use today is in fueling blast furnaces for the manufacture of steel. Coke manufactured from Colorado coal is presently utilized by three important steel manufacturing plants in the West: CF&I Steel Corporation at Pueblo, Colo., Kaiser Steel Corporation at Fontana, Calif., and the U.S. Steel Corporation at Provo, Utah. The Raton Mesa and Uinta coal regions serve as the important sources of the Colorado coking coal, with the balance of the blending coal supplied from coal regions in Oklahoma, New Mexico, and Utah.

PROJECT PROCEDURES

To evaluate Colorado's coking-coal deposits, a classification system was needed that could meet two major requirements. First, it had to be specific enough to evaluate the "desirability" of any coal for use as a coke oven feedstock by any of the coke manufacturers; second,it had to be broad enough to use a large amount of previously published coal data from the coal regions in Colorado. Therefore, the limitations imposed on the selection of a classification system were the published coal data available and the general requirements of coke oven feedstocks.

The desirability of any one coal for use as a coke oven feedstock varies significantly from one coke manufacturer to another. This variation in desirability is caused by the practice of using a blend of several coals for feedstocks; each manufacturer tailors a coal blend to meet the specific requirements of their own ovens. The following list summarizes the general factors influencing coke oven feedstocks (Strassburger, 1969): Uniformity; Ash and sulfur contents; Coking properties; Coking strength; Expansion-contraction and pressure characteristics; Availability, mine price, and transportation costs; Coke, gas, and coal chemical yields; Ash composition and decomposition; Moisture content; Storage and handling characteristics; Pulverization and breakage properties.

No classification system reviewed by the Colorado Geological Survey used all of these requirements for determining the desirability of a coking coal. However, the first three requirements are probably the most important general parameters needed in a coking-coal classification system. Several classification systems have been devised that evaluate coking coals based on these three general requirements; among these are systems based on various coal petrographic, plasticity, grindability, and chemical tests.

Although several of the classification systems reviewed could be used to determine if a specific coal met general coke oven feedstock requirements, very little of the coal data required by most of them had been published for Colorado coals. For example, only seven coal samples from Colorado had been petrographically classified and the results published during the grant project. This deficiency in published coal data resulted in the selection of a very general classification system.

The classification system selected for the State-wide coking-coal evaluation was modified from a U.S. Bureau of Mines classification (table 1). This system uses coal rank and coking-coal grade to determine the general desirability of a coal for use in the manufacture of coke. Coking-coal grade is a function of chemically determined coal-ash and sulfur contents. Premium grade coking coals contain 0-1 percent sulfur and 0-8.0 percent ash; marginal grade contains 1.1-1.8 percent sulfur and 8.1-12.0 percent ash; and latent grade contains 1.9-3.0 percent sulfur and 12.1-15.0 percent ash.

Table 1.--Coking-coal classification system used by Colorado Geological Survey

COKING-COAL GRADE	ASTM COAL RANK (BITUMINOUS)					
	LOW-VOLATILE	MEDIUM-VOLATILE	HIGH-VOLATILE A	HIGH-VOLATILE B	SULFUR = ASH =	COKING-COAL "DESIRABILITY"
PREMIUM	PREMIUM GRADE LOW-VOLATILE BITUMINOUS COKING COAL	PREMIUM GRADE MEDIUM-VOLATILE BITUMINOUS COKING COAL	PREMIUM GRADE HIGH-VOLATILE A BITUMINOUS COKING COAL	PREMIUM GRADE HIGH-VOLATILE B BITUMINOUS COKING COAL	0-1.0% 0-8.0%	GREATEST ↑
MARGINAL	MARGINAL GRADE LOW-VOLATILE BITUMINOUS COKING COAL	MARGINAL GRADE MEDIUM-VOLATILE BITUMINOUS COKING COAL	MARGINAL GRADE HIGH-VOLATILE A BITUMINOUS COKING COAL	MARGINAL GRADE HIGH-VOLATILE B BITUMINOUS COKING COAL	1.1-1.8% 8.0-12.0%	
LATENT	LATENT GRADE LOW-VOLATILE BITUMINOUS COKING COAL	LATENT GRADE MEDIUM-VOLATILE BITUMINOUS COKING COAL	LATENT GRADE HIGH-VOLATILE A BITUMINOUS COKING COAL	LATENT GRADE HIGH-VOLATILE B BITUMINOUS COKING COAL	1.9-3.0% 12.1-15.0%	↓ LEAST
COKING-COAL "DESIRABILITY"	GREATEST ←			→ LEAST		

Three coal regions in Colorado were selected for detailed coking-coal evaluations based on the requirements of the coking-coal classification system and general geologic and coke oven feedstock parameters. These three regions are the Raton Mesa, San Juan River, and Uinta coal regions.

Chemical analyses from 313 locations in these coal regions were used to generate maps for detailed coking-coal grade variations in each of the regions. These maps were then used in conjunction with published coal reserve/resource estimates to determine coking-coal reserves. All of the published reserve/resources estimates were modified to reflect the standards of the modern U.S. Geological Survey - U.S. Bureau of Mines coal resource classification system (U.S. Geological Survey, 1976).

COKING-COAL REGIONS IN COLORADO

Raton Mesa Coal Region

The Raton Mesa coal region encompasses a 100-mi^2 area of south-central Colorado (fig. 1). Its boundary is defined by the lower contact of the coal-bearing Vermejo Formation. The region consists of an asymmetrical syncline containing Cretaceous and younger rocks that have been intruded by numerous Tertiary igneous bodies.

Coal in the Raton Mesa coal region occurs in two formations: the Vermejo Formation (Upper Cretaceous) and the Raton Formation (Upper Cretaceous to Paleocene). Coal rank maps compiled by the Colorado Geological Survey (Goolsby and others, 1979) illustrate a gradational change in coal rank from high-volatile A bituminous in the south to high-volatile C bituminous in the northern extremes of the region.

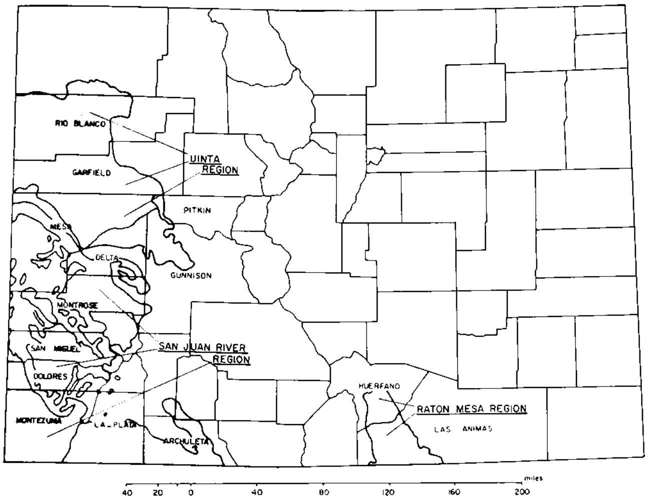

Figure 1.—Colorado coal regions containing potential coking-quality coals.

Using the coking-coal classification system, the Raton Mesa coal region was found to contain an estimated reserve of 1,834,677 x 10^3 st (short ton) of marginal grade high-volatile A bituminous coking coal, and 216,876 x 10^3 st of marginal grade high-volatile B bituminous coking coal. The total estimated original in-place coking-coal reserve base for the region is 2,051,053 x 10^3 st.

San Juan River Coal Region

The boundary of the San Juan River coal region has been defined as that area in southwestern Colorado that is encompassed by the lower contact of the coal-bearing Dakota Formation (Fig. 1). The southern part of the region is dominated by the San Juan Basin, a large synclinal trough that extends into New Mexico. The remainder of the region has relatively simple structure and near-horizontal bedding in the Dakota Formation.Three formations in the region are coal-bearing; the Dakota Formation, the Menefee Formation, and the Fruitland Formation (all Upper Cretaceous). Coal deposits in the Menefee and Fruitland Formations are generally better suited for coking, although poor quality coals in the Dakota Formation have been coked in the past. Coal development in this region is currently hampered by the lack of adequate rail transportation to suitable coal markets.

The San Juan River coal region was found to contain an estimated 1,387,790 x 10^3 st of variable-grade high-volatile A to high-volatile B bituminous coking coal. An additional 392 x 10^6 st of high-volatile bituminous coal in the region could not be classified according to coking-coal grade due to lack of coal chemical analysis.

Uinta Coal Region

The boundary of the Uinta coal region is marked by the lower contact of the Mesaverde Group in western Colorado (fig. 1). The region's structure is dominated by the Piceance Creek Basin, although folding, faulting, and Tertiary igneous intrusions have created locally complex structural areas along the periphery of the region.Coal in the region occurs in two formations in the Mesaverde Group, or in their lithostratigraphic equivalents; the Iles Formation and the Williams Fork Formation. Coal in four of the eight coal fields in the region is of potential coking quality. The Grand Mesa and Somerset coal fields contain high-volatile A and B bituminous coals. Tertiary intrusions in the Crested Butte coal field have resulted in coals with rapid rank changes in this field. The Carbondale coal field contains high-volatile A and B bituminous coals, and medium-volatile bituminous coals that are the most "desirable" coking coals in the West.

The Uinta coal region contains an estimated 446,720 x 10^3 st of premium to marginal high-volatile B to medium-volatile bituminous coking coal. However, this estimate does not include currently mined coal resources that are below 1,000 ft in depth. These coal deposits are not classified as reserves if the standards of the U.S. Geological Survey coal resource classification system are followed.

CONCLUSIONS

Colorado contains an estimated total identified original in-place coking-coal reserve of 2.05 billion short tons. As long as coke is manufactured by conventional coking processes, Colorado will remain an important source of coking coal for the West.

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COAL STRATIGRAPHY OF THE TONGUE RIVER MEMBER, NORTHERN CHEYENNE RESERVATION, MONTANA

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INTRODUCTION

The 500,000-acre home of the Northern Cheyenne Indian Tribe sits in the heart of the northern Powder River Basin, between the coal-mining areas of Decker and Colstrip in southeastern Montana. It is a "big sky" region of pine-covered plateaus and grassy plains dissected by steep coulees that drain into the alluvial lowlands of the Tongue River and Rosebud Creek.

The Tongue River Member of the Paleocene Fort Union Formation is exposed over 90 percent of the reservation, whereas the underlying Lebo Shale and Tullock Members are present in the shallow subsurface. Many minable coal beds occur in the Tongue River Member, which consists of a 1,600-1,800-ft-thick sequence of discontinuous fine sandstones, siltstones, mudstones, and shales separated by extensive coals and clinkers (fig. 1).

PREVIOUS WORK

Little has been previously published on the coal reserves of the reservation. Although coal exploration has occurred on half of the reservation area, the drill data have not been released by the Tribe and the coal companies. Four Federal reports mention reservation geology. Thom and others (1935) included a paragraph on coal and ground water for each township on the reservation in Big Horn County. Warren conducted fieldwork in the east half of the reservation in 1939 but deleted this information from his 1959 publication. Magill and others (1967) compiled a short mineral resource report for the U.S. Bureau of Mines. Mapel and others (1975) compiled limited coal data found in 10 oil and gas-well logs for an administrative report to the U.S. Bureau of Indian Affairs.

This report summarizes information in the geology chapter of Woessner and others, final report of EPA grantR803566 (in press). Research conducted by the author and associates included a reconnaissance field survey of the reservation as well as drilling and coring in three locations underlain by strippable coal—the Logging Creek, Indian Coulee, and Buffalo Jump Study Areas.

STRUCTURE

The reservation lies on the northwestern limb of the Powder River Basin. Strata generally dip less than 1° to the southeast and in places are offset by northeast- to east-trending normal faults with vertical displacements of up to 160 ft. A shallow syncline plunges through the center of the reservation toward the southeast.

STRATIGRAPHY

The Tongue River Member on the reservation consists of coal beds separated by channel sands, levee deposits, crevasse splays, and clays laid down in flood basins. The low sulfur content of the coal, abundance of massive channel sandstones, and general easterly dip of crossbedding suggest deposition by east-trending rivers in fluvial to delta-plain environments. Very little sediment is coarser than medium sand. Individual coal beds, which can be traced across the reservation in some cases, have much more lateral continuity than individual sandstone, siltstone, or shale beds, which generally grade into or are truncated by another type of sediment within a mile or two.

The coal beds accumulated in backswamps or transgressed over abandoned deltas (accounting for the lateral continuity of the coal). Lesser compaction of crevasse splay and channel and levee deposits compared to peat swamps resulted in a stratigraphic record where an upper bench of a coal bed may split rapidly away from a lower bench within a short distance, or a coal bed may "bow" around a sand unit. Scouring by channel sands can also account for rapid thinning in an otherwise thick coal layer. Some channel sandstones crop out as extensive cliffs up to 100 ft high within certain stratigraphic intervals. Small lenses of impure limestone or calcareous sediment are scattered throughout the member. Thin-bedded quartzitic sandstones are fairly common throughout the member. Thin-bedded quartzitic sandstones are fairly common near the top of the member above the Anderson coal. Gray or carbonaceous shale most commonly underlies and overlies coal beds.

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[1] Formerly Northern Cheyenne Research Project, Lame Deer, Mont.

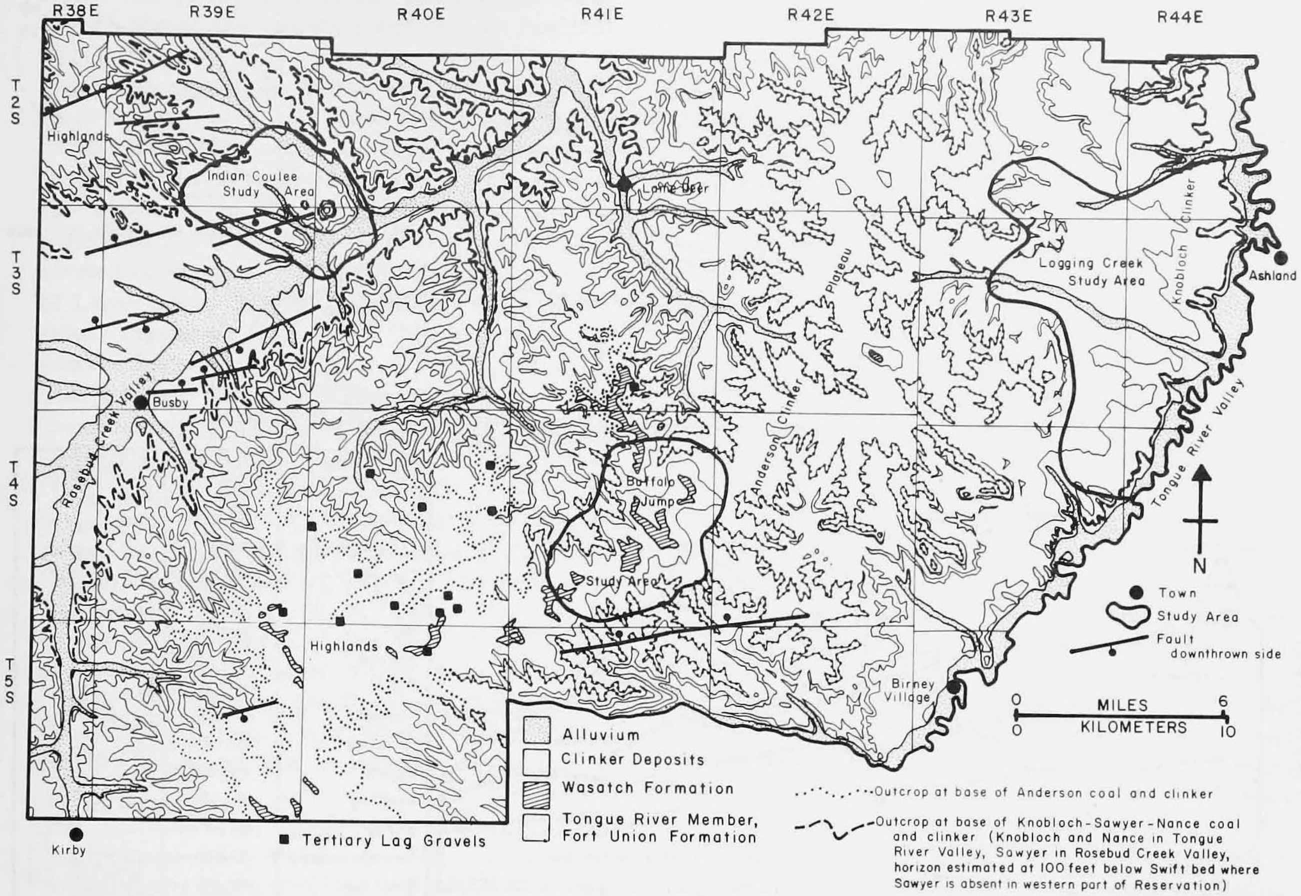


Figure 1.—Geologic map of the Northern Cheyenne Reservation, Montana.

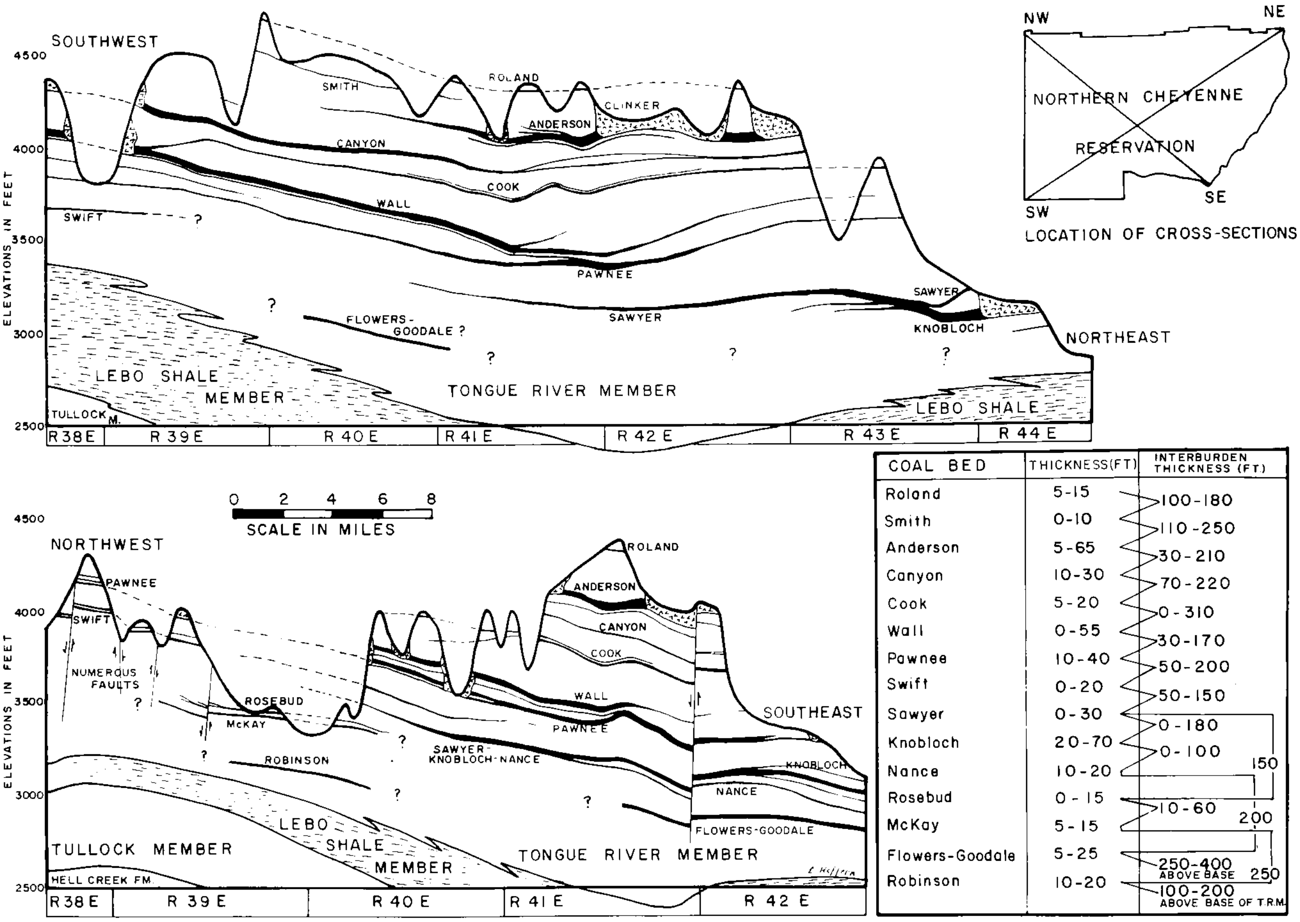
Plant fossils are preserved in limy shales and siltstones as well as in clinkered shales. Especially abundant are metasequoia, katsura tree, sycamore, asia walnut, and viburnum. Freshwater clams and snails also occur.

Twelve major coal beds present, from lowest to highest, are the Robinson, Flowers-Goodale, Rosebud-McKay, Knobloch-Sawyer-Nance, Swift, Pawnee, Wall, Cook, Canyon, Anderson, Smith, and Roland (fig. 2). These 12 beds contain at least 50 billion tons of coal in place underneath the reservation. Individual beds are as much as 65 ft thick. The coal is generally subbituminous C in rank. As-received analyses range from 7,600 to 9,100 Btu/lb, 4 to 11 percent ash, 21 to 28 percent moisture, and 0.2 to 1.2 percent sulfur.

COAL RESOURCES

Major coal beds in the Tongue River Member, from lowest to highest, are described in following paragraphs. Figure 2 presents cross sections of the stratigraphy.

1. The Robinson coal is about 15 ft thick in the subsurface of the Rosebud Creek valley in T. 2 S., Rs. 39-41 E. and lies 100-200 ft above the base of the Tongue River Member. Total reserves are estimated at 1 billion tons within this area. Lack of data prevents correlation with other beds to the southeast.
2. The Flowers-Goodale bed is about 20 ft thick in the subsurface of the Tongue River valley in T. 5 S., Rs. 41-43 E. and T. 4 S., Rs. 43-44 E. It lies 250-400 ft above the base of the Tongue River Member. Reserves total about 1.5 billion tons. Lack of data prevents correlation to the northwest; possibly this bed merges with the Rosebud-McKay.
3. Coals tentatively correlated with the Rosebud and McKay beds crop out along the sides of the Rosebud Creek valley northeast of the town of Busby. Each bed is about 10 ft thick in the Indian Coulee Study Area. One hundred eighty million tons of coal occur in the study area, and most is strippable. The McKay remains consistently near 10 ft thick east and west of the study area, but the overlying Rosebud bed splits and



COAL BED	THICKNESS(FT)	INTERBURDEN THICKNESS (FT)
Roland	5-15	100-180
Smith	0-10	110-250
Anderson	5-65	30-210
Canyon	10-30	70-220
Cook	5-20	0-310
Wall	0-55	30-170
Pawnee	10-40	50-200
Swift	0-20	50-150
Sawyer	0-30	0-180
Knobloch	20-70	0-100 150
Nance	10-20	
Rosebud	0 - 15	10-60 200
McKay	5-15	
Flowers-Goodale	5-25	250-400 ABOVE BASE 250
Robinson	10-20	100-200 ABOVE BASE OF T.R.M.

Figure 2.—Stratigraphic column and cross sections, Tongue River Member, Northern Cheyenne Reservation, Montana.

thins to the west. The beds are separated by 10-60 ft of interburden. The base of the McKay lies 220-280 ft above the Robinson bed. Total reserves in T. 2 S., Rs. 38-41 E., T. 3 S., Rs.38-40 E., and T. 4 S., Rs. 38-39 E. are estimated at 3 billion tons. Lack of data prevents reserve determination to the south and east.

A massive sandstone, forming cliffs up to 100 ft high, occurs between the Rosebud and the overlying Knobloch bed. This sandstone can be traced from the Rosebud Creek into the Tongue River valley north of the reservation.

4. The Knobloch-Sawyer-Nance coal comprises a number of separate beds that merge into one bed about 60 ft thick near the town of Ashland on the east edge of the reservation. Combined reserves in all the beds total 14 billion tons and constitute the largest coal reserve on the reservation. From 2 to 3 billion tons is strippable in the Tongue River valley. The Logging Creek Study Area was set up to define hydrology and overburden characteristics in part of this area.

Northwest of Ashland, the Sawyer bed splits sharply off from the top of the main Knobloch bed. The Sawyer thickens to the west while the main Knobloch thins, and in the Rosebud Creek valley the Sawyer is about 30 ft thick and forms a prominent clinker, whereas the Knobloch is probably represented by a thin coal known as the Lee. The Sawyer appears to split and thin out west of R. 40 E. Just south of Logging Creek in the Tongue River valley, the Nance bed splits from the base of the main Knobloch. Here, our project cored through 44 ft of Knobloch coal separated by 4 ft of interburden from 17 ft of Nance coal. The Knobloch bed itself splits further south toward Birney Village into upper, middle, and lower benches. The base of the Knobloch-Nance lies about 200 ft above the Flowers-Goodale bed in the Tongue River valley; the base of the Sawyer lies about 150 ft above the Rosebud bed in the Rosebud Creek valley.

5. The Swift bed occurs in the western part of the reservation where it forms the lowest major clinker in the Rosebud Creek valley south of Busby. The Swift also forms a clinkered zone in the highlands in the northwest corner of the reservation. The bed is 15-20 ft thick in these areas but appears to thin out east of the town of Lame Deer. Reserves total at least 3 billion tons. The Swift lies about 100 ft above the Sawyer horizon.
6. The Pawnee bed is widely exposed over the reservation, reaching a maximum thickness of perhaps 40 ft in T. 4 S., R. 41 E. It is about 25 ft thick near Lame Deer, where its clinker caps the ridges above the town. An underground mine in the Pawnee produced coal at Alderson Gulch for a number of years. The bed thins eastward to about 10 ft thick where it is exposed in the lower slopes east of the divide separating the Tongue River from Rosebud Creek. The Pawnee bed lies from 120 to 350 ft above the Knobloch and Sawyer beds. Total Pawnee reserves are estimated at 8.5 billion tons.
7. The Wall bed is up to 55 ft thick in the southwest corner of the reservation, where it consists of a main coal bed separated by a few feet of shale from a 6-10-ft-thick lower bed. The Cook coal splits sharply off from the top of the Wall north of the southernmost part of T. 5 S. The Wall remains thick east to T. 4 S., R. 41 E., but it thins northeast of that township. The bed is very thin or absent in Ts. 2-3 S., R 43 E. The Wall lies from 30 to170 ft above the Pawnee bed. Total reserves are estimated at 9.5 billion tons. The horizon above the Wall contains massive sandstones that appear to thicken toward the northeast, in the same direction in which the Wall coal thins.
8. The Cook coal is continuous over most of the reservation, and it varies from 6 to 20 ft thick. It commonly has a thin rider coal above the main bed. The Cook merges with the Wall bed in the southwest corner of the reservation, but elsewhere up to 310 ft of interburden separates the two beds. Reserves total about 4 billion tons.
9. The Canyon coal forms the highest clinker in the southwest quarter of the reservation, where the coal averages 25 ft thick. A bed thought to be the Dietz splits to the south from the top of the Canyon in T. 5 S., R. 40 E. The Canyon thins and splits in T. 4 S., R. 41 E., and then appears to coalesce and thicken somewhat to the northeast, where it is 10-15 ft thick. Reserves total 4 billion tons. The Canyon lies from 70 to 220 ft above the Cook bed.
10. The Anderson bed forms a thick coal-clinker unit in the east half of the reservation. The thickest area of coal, in Rs. 42-43 E., has almost completely burned to create the most extensive clinker on the reservation and to form a scenic timbered plateau over 1,000 ft above the Tongue River valley. To the southwest, in T. 4 S., R. 41 E., the clinker becomes less extensive, and about 400 million tons of strippable coal reserves are present in the Buffalo Jump Study Area. Hydrologic observation wells here encountered from 42 to 65 ft of coal, generally thinning and splitting to the west. A lower bench of coal about 6 ft thick lies 20 ft below the main bed throughout the study area. Northwest and southwest of the study area, the Anderson thins to under 10 ft thick and appears to grade into carbonaceous shale and bony coal along a northeast line striking through T. 5 S., R. 39 E., and T. 4 S., R. 40 E. Total reserves amount to 1.5 billion tons. The Anderson lies from 30 to 210 ft above the Canyon coal.
12. The Roland is the highest major coal bed exposed southwest highlands of the reservation and thins out to the north. The bed is generally less than 8 ft thick and contains abundant petrified wood. Reserves are minor and total about 20 million tons. The Smith lies from 110 to 250 ft above the Anderson bed.
11. The Smith coal crops out in the south-central and on the reservation. The bed ranges from 5 to 15 ft thick and occurs near the top of a number of hills in the southern highlands. The Roland is from 100 to 180 ft above the Smith bed. Erosion has removed all but 100 ft of strata above the Roland. Reserves are insignificant, totaling about 4 milion tons. The Roland coal is widely regarded as the boundary between the Tongue River Member and the overying Wasatch Formation. No well-defined lithologic break occurs on the reservation between strata over and under the Roland.

COAL CLINKER

Most coal beds over 10 ft thick have burned where exposed, and baked or melted the overburden to form hard red clinker. A typical clinker outcrop consists of an upper zone of slightly baked overburden, an intermediate zone of collapsed overburden and buchite chimneys, and a basal layer of scoria and ash.

About 30 percent of the reservation surface is covered by clinker (fig. 1). The Anderson coal has almost completely burned in the east half of the reservation to produce a massive plateau of clinker up to 230 ft thick covering 73 mi^2 (one-third of the total clinkered area on the reservation). The Knobloch coal has burned to form the next largest clinker zone, which caps the bluffs above the Tongue River. Large strippable coal reserves remain west of the front where the Knobloch stopped burning. The Wall and Canyon coals are bordered by a resistant rim of clinker along the sides of the Rosebud Creek valley in the southwestern part of the reservation. Coal in many other areas has burned to clinker.The thickest clinkers commonly contain a number of enclosed or hourglass-shaped depressions that I have termed "clinker basins," which probably formed by the episodic burning of coal.

Coal beds most likely began burning in late Pliocene or early Pleistocene time, as downcutting rivers first exposed the coal beds of the Tongue River Member, and this process has continued to the present day. Natural coal fires have been documented on at least six separate reservation locations within the past 25 years (Magill and others, 1967). Efforts have been made to bulldoze five of these areas shut. Steam can often be seen rising from clinkered areas on a cold winter's day, indicating that many coal beds may still be burning very slowly at depth.

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THE ANDERSON COAL—A REGIONAL STUDY

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INTRODUCTION

The purpose of this report was to acquire qualitative and quantitative data on the Anderson coal bed in southeastern Montana. Data consisted of drill hole logs and mapped outcrops from Big Horn and Powder River Counties, Montana. These areas were selected for study because they contain the highest rank coal of the Fort Union Formation, that of the subbituminous class, and also one of the highest potential areas for coal mining. Detailed analysis of these areas is needed for both the quantity and quality of coal, because of potential future markets. Because the study area's coal is usually below 0.5 percent sulfur and 5 percent ash, it will be in great demand when compared to the high-sulfur coals in the Appalachian and Illinois basins. The area extends from the easternmost parts of Ts. 7-9 S., R. 38 E., eastward to Ts. 7-9 S., R. 47 E., Big Horn and Powder River Counties, Mont. (fig. 1).

Stratigraphy

The Anderson coal bed and associated coal deposits belong to the Tongue River Member of the Fort Union Formation (Paleocene). The Fort Union Formation includes three members (from youngest to oldest), the Tongue River, the Lebo, and the Tulloch (fig. 2). The Fort Union Formation was named by Meek and Hayden (1861). Subsequent fieldwork resulted in the division of the formation into the three members on the basis of color, topography, and the occurrence of coal. The three members of the Fort Union Formation are recognizable because of the great difference between the Lebo Member and members underlying and overlying it. The Lebo Member consists of dark, drab beds composed of dark-gray to olive-gray shale containing altered and devitrified volcanic ash and abundant brown ferruginous concretions (Rogers and Lee, 1923). The Tulloch and Tongue River members are both light-colored, interbedded fine-grained sandstone, claystone, and siltstone that show similar topographic features. The relatively soft Lebo Member erodes to form long, gentle slopes, whereas the Tulloch and Tongue River Members form steep escarpments capped by prominent resistant sandstone beds. The Tongue River Member is also recognizable because of its thick beds of resistant, reddish clinker formed from the burning of thick coal beds.

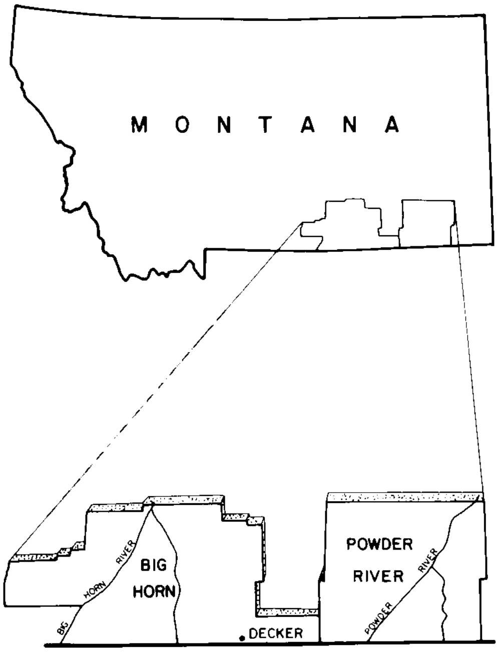


Figure 1.—Index map of study area.

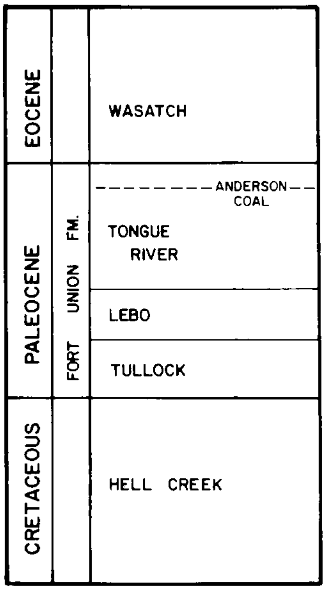


Figure 2.—Generalized stratigraphic section.

THE ANDERSON COAL BED

The Anderson coal bed of the Tongue River Member is a persistent coal bed of southeastern Montana, in Big Horn, Powder River, and Rosebud Counties. The coal ranges from 12 to 36 ft thick over most of its extent and is found about 290-370 ft from the top of the Tongue River Member (fig. 2). The Anderson coal bed is located 110-150 ft below the Smith bed and 0-80 ft above the Dietz No. 1 bed. The dominant structural features of the Anderson coal bed are shallow anticlinal and synclinal structures with a prominent dip towards the south. Two regions of northeast-southwest-trending faults occur in the area and are located in T. 9 S., Rs. 49-50 E., and T. 9 S., Rs. 43-44 E. Matson and Blumer (1973) attributed the faulting to the proximity to the Big Horn uplift and the Powder River Basin axis.

The Anderson coal bed is a low-sulfur and low-ash coal with respective values of less than 0.5 percent and 5.0 percent (as-received basis). The Btu content (as-received basis) of the coal has a range of 5,480 to 9,850, and Btu content tends to increase towards the axis of the Powder River Basin. The highest Btu content occurs in sec. 19, T. 9 S., R. 40 E., and the lowest values occur in sec. 2, T. 9 S., R. 43 E., and sec. 12, T. 9 S., R. 45 E. Incremental analysis of some of the coals with low Btu contents showed higher Btu contents when top or bottom of the bed was excluded. By calculating the moist, mineral-matter-free Btu, the Anderson coal bed is mainly subbituminous B and C with isolated localities of lignite.

ANDERSON RESERVES AND RESOURCES

The Anderson coal bed ranges from 12 to 36 ft thick throughout most of southeastern Montana except in the Decker-Pearl School area. In the W 1/2 T. 9 S., R. 40 E., the Anderson combines with the Dietz No. 1 bed to form a coal 42-57 ft thick, and in the E 1/2 Ts. 8-9 S., R. 39 E., the Anderson-Dietz No. 1 bed combines with the Dietz No. 2 bed to form a coal 68-85 ft thick. In the W 1/2 Ts. 8-9 S., R. 39 E., the Anderson coal bed splits from the combined bed, but the two Dietz beds remain combined to form a coal 30-54 ft thick.

From the isopach data for the Anderson coal bed, the coal reserves and resources were calculated using the method described in U. S. Geological Survey (1976), which classifies coal resources into two major categories, identified resources and undiscovered resources. These categories are further divided, with the identified resources separated into economic measured, indicated, and inferred reserves and subeconomic measured, indicated, and inferred resources. The economic reserves are based on a recovery factor, as follows: if an area of 1,000,000 tons of identified resources is 50 percent recoverable, there would be 500,000 tons of economic reserves and 500,000 tons of subeconomic resources. The undiscovered category is divided into two groups, hypothetical and speculative resources.

The total reserves and resources of the Anderson coal bed total 6,239.8 million tons of economic reserves and 7,817.1 million tons of subeconomic resources.

Large parts of the original near-surface coal reserves of the Tongue River Member have been destroyed by burning at the outcrop and beneath shallow cover. Most good-quality coal beds 5 ft or more thick have burned, and the heat has produced a bright-red clinker. For the Anderson coal bed a total of 98.33 mi^2 have burned, and by using an estimate of 25 ft of coal over this area, a total of 2,737.5 million tons of the Anderson coal have burned at the outcrop and beneath shallow cover.

MINING POTENTIAL

One result of this study was the determination of possible high- and moderate-potential mining areas. One area of extremely high potential occurs in the Decker and Pearl School quadrangles, Montana, the area where the Anderson, Dietz No. 1, and Dietz No. 2 coal beds combine to a thickness of 68-80 ft and where the Anderson splits from the Dietz beds. Figure 3 shows the area of the combined bed and the isopach of the Anderson after it splits from the combined bed. Figure 4 shows the isopach of the Dietz No. 1-Dietz No. 2 coal and of the interburden between the Anderson and the Dietz No. 1-Dietz No. 2 beds. Figure 5 shows the high-potential areas, the moderate-potential areas, and the areas of no potential at present. The areas of potential minability were determined by using overburden-to-coal ratios for the area of the combined Anderson-Dietz No. 1-Dietz No. 2 bed and for the area where the Anderson coal bed splits from the Dietz No. 1 - Dietz No. 2 bed. For the area where the beds were not combined, it was assumed that both the Anderson and the Dietz No. 1 - Dietz No. 2 beds were minable. The high-potential areas are based on an overburden-to-coal ratio of 4.5 to 1. The moderate-potential areas are based on an overburden-to-coal ratio of 6.5 to 1, and the areas of no potential at present are the areas with an overburden-to-coal ratio of greater than 6.5 to 1. Using an 85 percent recovery value for the coal bed in this area and for these overburden-to-coal ratios, 4,644 million of 5,499 million tons should be minable.

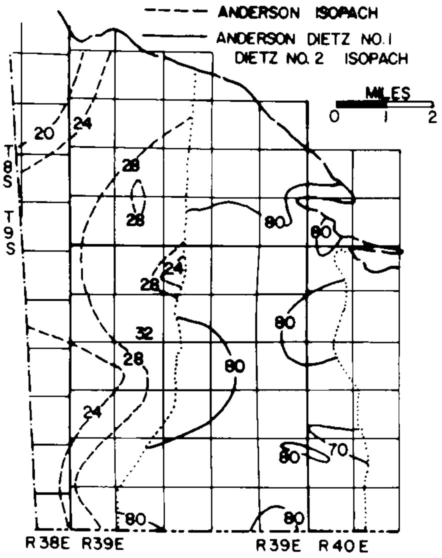


Figure 3.—Isopachs of three named beds and of split of Anderson bed.

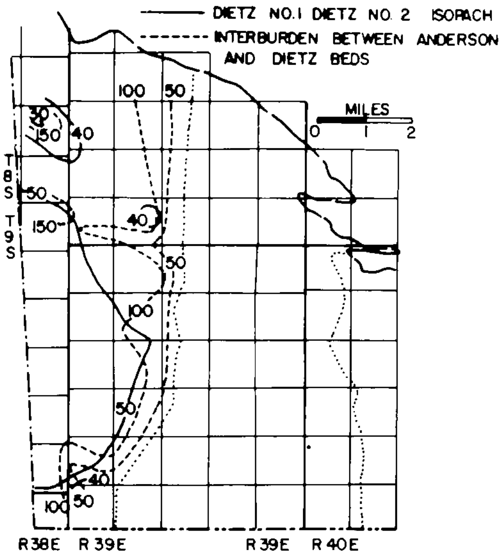


Figure 4.--Amount of parting between Anderson and Dietz and isopach combining Dietz 1-Dietz 2.

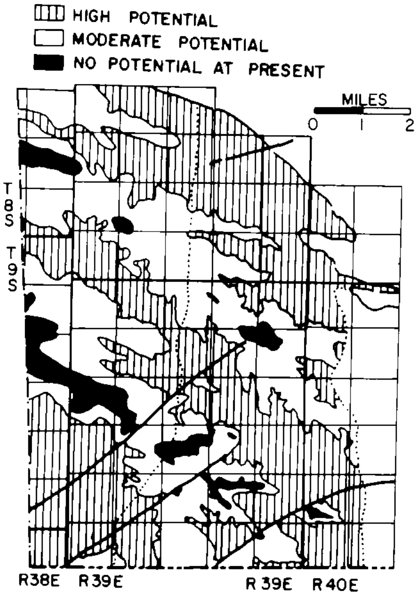


Figure 5.--Minable potential of the coal.

GEOLOGICAL COALIFICATION FACTORS

Early workers in the field of coal were divided in their opinions of what factors caused coal rank: pressure, temperature, or time. Some workers such as Taylor (1926) thought that the original swamp environment determined the coal rank. Hickling (1932) showed that the swamp environment determined the coal type and the coal rank was a combination of heat, pressure, and time. White (1913, 1935) demonstrated that pressure was the major factor in coal rank because the coal in the Appalachian Basin increased in rank towards the more intensely folded rocks. Therefore, coalification was caused by the increased pressure gradient across the basin. Campbell (1930) also noted that folding pressure was the major factor in coalification. However, more recent studies, such as Huck and Patteisky (1964), Teichmuller and Teichmuller (1966), and Stach and others (1975), have shown that static pressure may retard coalification because release of volatiles is inhibited. Stach and others (1975) also stated that the studies concerning the folding pressure in coalification coincided with the areas of deepest subsidence of the coals, so that the increased coal rank was due more to deeper depth of burial than to the pressure exerted on the coals.

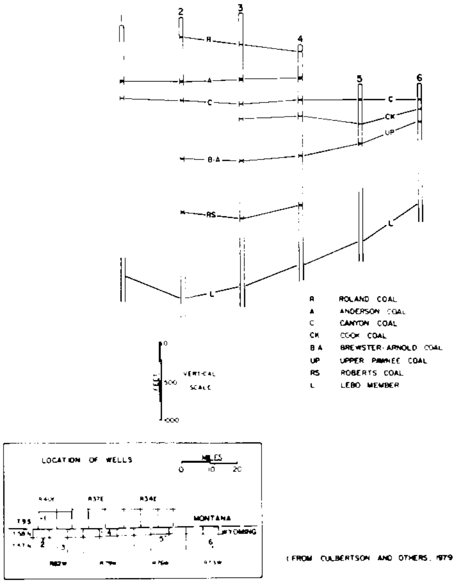
Other early workers believed that the effects of heat and time were most important in coalification. Teichmuller and Teichmuller (1966) showed that time was a major influence by using the high-volatile Miocene phytoclasts from Louisiana as compared to the low-volatile Carboniferous coals in northwestern Germany. The German coals are found at approximately the same depth and rock temperature as the Miocene phytoclasts but have been buried different lengths of time. The Teichmullers (1966) have also shown that large igneous intrusions can raise the geothermal gradient enough for periods of time sufficient to increase the rank of coals, as was demonstrated with the Bramsche Massif in Germany. Other workers have also demonstrated the effects of temperature, time, and depth of burial on coalification; see Damberger (1971, 1974) and Stach and others (1975).

Concerning the depth of burial on coals, Stach and others (1975) have shown with borehole information that the normal increase of rank is caused by rising temperature with depth. This is commonly called Hilt's Law where the deeper the coal, the higher the rank of coal. Stach and others (1975) showed that the lignites in the Moscow Basin, U.S.S.R., never reached higher ranks even though the coals are Carboniferous in age, because coalification was hindered by the shallow depth of burial and the consequent low temperatures (20°-25°C). They also state that coals must be bured at a depth of at least 1,500 m (but more likely 2,500-4,000 m) to achieve temperatures high enough to form bituminous coal.

COALIFICATION PATTERN OF THE ANDERSON COAL

The coalification trend of the Anderson coal bed was determined by using the as-received Btu values of the coal, and this resulted in an increase of Btu value towards the axis of the Powder River Basin. In southeastern Montana this axis trends north-south through the Decker area.

This particular coalification pattern was possibly caused by the increase of depth of burial towards the axis of the basin. Figure 6 is an east-west cross section of the Tongue River Member showing how the strata thickens to the west (well 1 is near the Decker area). If the overlying Wasatch Formation was deposited in the same general thickness patterns, the result would be much greater burial of coals in the vicinity of the axis of the basin. This greater depth of burial would result in higher temperatures of coalification, therefore, a higher rank of coal. In the study area this resulted in a subbituminous B in the Decker area with decreasing rank to the east, west, and north.



(FROM CULBERTSON AND OTHERS, 1979)

Figure 6.--Regional cross section across study area.

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TERTIARY COAL DEPOSITS OF THE HANNA AND CARBON BASINS, WYOMING

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In the Hanna and Carbon Basins of south-central Wyoming, late Paleocene and early Eocene peats repeatedly accumulated in swamps on a poorly drained alluvial plain within a gradually subsiding intermontane basin. At least 70 mappable coal beds have been identified in these basins. These low-sulfur coal beds are characteristically high vitrain, banded coals that vary from less than 1 ft to 60 ft in thickness. Most beds exhibit splitting and (or) coalescing along their outcrops.

Rocks observed in the basins indicate a depositional complex of alluvial-fan and braided stream deposits, particularly along the flanks of the basins, some lacustrine deposits, and flood-plain deposits. Although most coals in the Hanna Basin occur within flood-plain deposits, most coals in the Carbon Basin are apparently associated with braided stream deposits.

Lacustrine and fluvial rocks contain abundant freshwater gastropods, bivalves, and ostracodes, as well as rarer charophytes, fish, and crocodile remains--which attest to the terrestrial origin of the coals. Limited paleobotanical work has shown that at least some of the coals are derived from cypress swamps.

STRATIGRAPHIC SIGNIFICANCE OF RADIOMETRIC AGES FOR EOCENE COALS IN WESTERN WASHINGTON

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The radiometric age dating and stratigraphic significance of marine bentonites, clay beds resulting from the postdepositional alteration of air-fall volcanic ashes, has long been recognized. Less well known, however, is the importance of similar clay partings in coal beds. But coal-forming environments—nearly flat, choked with vegetation, with water tables slightly above or at the surface--are ideal for the entrapment of ash falls free of inorganic contamination. Such occurrences also have minimal chances of being eroded and redeposited, and freedom from contamination is critical for obtaining meaningful radiometric ages from minerals within ash falls. In this regard those minerals in coal have some advantage over marine bentonites, which must settle through appreciable water depths and are subject to reworking by bottom currents and organisms.

Because coal-bearing sequences are wholly or partly nonmarine, they often lack the fossils basic to the various marine chronologies. Nonmarine fauna are sparse, and plant fossils, while abundant, often lack sufficiently precise time significance to be useful. In addition to their value for correlating coal beds and coal-bearing sequences, volcanic ash partings in coal beds are potentially significant as records of volcanic activity through time as well as indicators of environments of coal deposition, rates of sediment accumulation, and patterns of diagenesis.

This study demonstrates the frequency and mode of occurrence of volcanic ash partings in coals from western Washington, as well as the successful dating of their feldspars, zircons, and apatites by K-Ar content and fission-track methods. Six K-Ar ages from the Centralia mine establish an age of about 40 m.y. for the Big Dirty and Smith coal beds. Remarkably little scatter occurs in the data, and this example reflects the precision obtainable by radiometric dating of ash partings in coals. Our data indicate that the 6,200 ft of nonmarine rocks at Green River Gorge were deposited within a probable time span of 2 m.y. Owing to statistical uncertainty in age determinations, the interval could have been as long as 4.5 m.y. or less than 1 m.y. Our data do not indicate any substantial unconformities, although minor diastems may be common, as in any fluvial sequence. A relatively short time span for the Green River Gorge section has implications for Wolfe's (1968) paleobotanical stages since this is their type section. Our data indicate a late Eocene age for the entire section, whereas various authors have suggested a considerably longer time interval for these stages. The rates of deposition for the Green River Gorge section fall between 1.3 and 6.2 ft/1,000 yr with a probable rate of about 3 ft/1,000 yr if a 2-m.y. time span is accepted. While such rates are not in themselves exceptional, sustaining these rates for millions of years may be somewhat surprising.

We predict that ash partings in coals will prove to be common elsewhere and will become valuable stratigraphic markers. This value will accrue both because of the radiometric ages and also because they are physical time markers independent of their absolute ages, exactly like bentonites.

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IGNEOUS INTRUSION OF STEEPLY DIPPING EOCENE COALS NEAR ASHFORD, PIERCE COUNTY, WASHINGTON

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INTRODUCTION

Coals of the Rocky Mountain region and west to the Pacific Coast are for the most part early Tertiary in age. Despite their youth, many of these coals have been upgraded in rank beyond their years due to tectonism and thermal metamorphism. One such instance occurs in Pierce County, Wash. Although both tectonism and thermal alteration are present, emphasis is placed here on the effects of igneous intrusion. The Ashford coal field is actually just the southern extension of what historically has been called the Wilkeson-Carbonado coal field. Small-scale prospecting began in the late 1800's, and in 1904, the Mashell Coal and Coke Company began driving a haulageway tunnel into the Ashford field from the town of Ashford. It was a general belief that quality coals similar to those being mined near the towns of Wilkeson and Carbonado could also be obtained at Ashford. After about 5,000 ft of haulageway and removal of only 1,000 tons of coal, the Mashell Mine shut down, supposedly because of problems with faulted structure and methane gas. Igneous intrusion and "burning" of the coal was recognized during this time but was considered a positive attribute for increasing coal rank.

Location and Geologic Setting

Geologic data are reported from an area of 12 mi^2 in the lower half of the Ashford coal field, which comprises approximately 45 mi^2 (fig. 1) and is located in the western foothills of the Cascade Mountains, just east of the Puget Sound lowland. It is bounded on the south by the Nisqually River and on the north by the Puyallup River. The study area is directly north of Ashford and approximately 40 air miles southeast of Tacoma, Wash. The summit of Mt. Rainier is approximately 14 air miles to the northeast.

The Ashford coals are contained within the Puget Group of sedimentary rocks. The Puget Group trends generally north-south and is bounded on the west by the Puget trough, a structural and topographic basin, and on the east by extrusives and plutons of the Cascade orogen. Ashford coals were deposited during the Eocene on what Mackin and Cary (1965) called the Weaver Plain, which extended across the present-day Cascade Mountains. Sediments for the subsiding Weaver Plain were obtained from a provenance east of the present-day Cascades. According to Snavely and Wagner (1963), development of volcanic centers in the late Eocene and early Oligocene created local volcanic provenances and increased the ash content of coals still forming on the Weaver Plain. Orogenic activity during the Miocene and Pliocene lifted the Cascade Mountain Range along with sediments deposited in the ancient Weaver Plain and which are now referred to as the Puget Group on the west side of the Cascades.

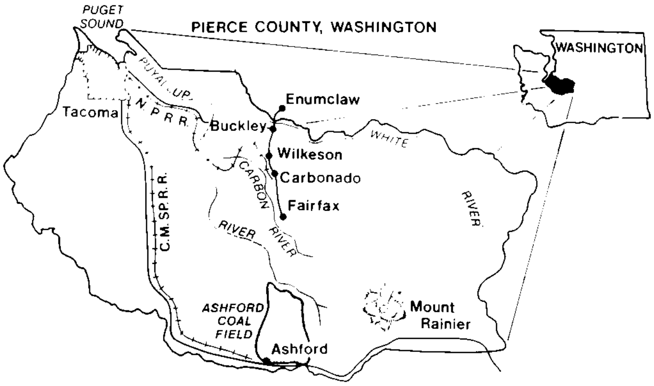


Figure 1.--Location of Ashford study area, Ashford/DOE project, Washington.

TERTIARY STRATIGRAPHY

Puget Group

The Puget Group consists of a thick sequence of mid-to-late Eocene sedimentary rocks of continental fluviatile to volcanic epiclastic and pyroclastic origin. Weaver (1937) estimated the total thickness of this sedimentary sequence to vary from about 10,000 to 14,000 ft. Work by Gard (1968) has led to a redefinition of formational boundaries within the Puget Group which are adhered to in this paper. The total section of Puget Group formations from bottom to top would include Carbonado, Northcraft, and Spiketon. Only the Carbonado and Northcraft Formations occur in the study area.

Carbonado Formation

Coal of the Ashford field is primarily in the Carbonado Formation (middle Eocene), which generally dips east in the Ashford area (fig. 2). This formation is approximately 5,000 ft of interbedded sandstones, siltstones, mudstones, and carbonaceous units consisting of carbonaceous shale and (or) coal. The Wilkeson sandstone is a massive arkose member considered to be a key marker horizon despite its reported lenticularity. The Wilkeson sandstone separates the upper and lower coal bearing zones of the Carbonado.

Northcraft Formation

Above the Carbonado is the Northcraft Formation, a 1,000-2,000-ft sequence of volcanic-derived sediments. The Northcraft is observed to intertongue with the Carbonado in the Ashford coal field. This late Eocene formation consists of volcanic breccia, lava flows, tuff, volcanic conglomerate and graywacke. Silicified and carbonized wood and woody plant material are fairly common in volcanic mudflow breccias within the formation. Fossil plant imprints are often observed within the volcanic graywacke. While only thin beds of coaly laminae exist within the Northcraft, Gard (1968) hypothesized that some of the Northcraft's intraformational coals were incorporated as a "ripup peat" during formation of mudflow breccias. Unlike the Carbonado Formation's eastern provenance, the source of the Northcraft volcanics was to the west of the present-day Ashford coal field.

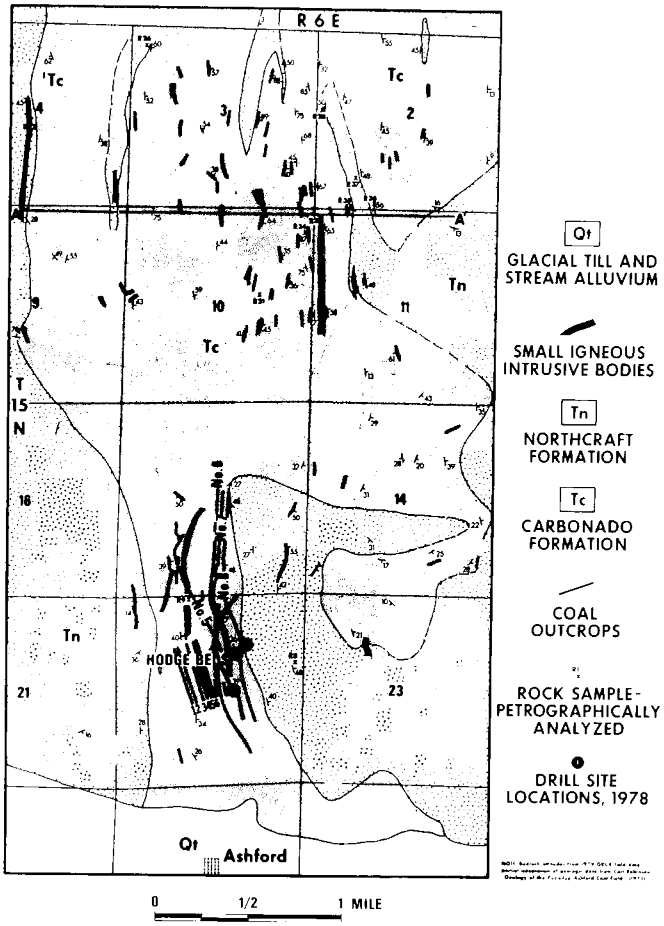


Figure 2.--Preliminary geologic map of the Ashford coal field.

IGNEOUS INTRUSIVES

The igneous rock samples in table 1 were field selected for determination of mineralic composition and lithology because of their direct association with coal and the coal-bearing formation (fig. 2). These limited data indicate an increasing silica trend in lithology of the igneous rocks from east to west. The mineralogy of the Northcraft igneous flow rocks closely matches nearby sill and dike mineralogy. This mineralogic matchup suggests a genetic relationship between the Northcraft volcanics and the coal field's igneous intrusions. Such a genetic relationship places the igneous intrusives of the Ashford study area in the late Eocene age period and younger. The intrusives vary in size but are usually less than 8 ft thick; they can be visualized as forming an interconnected conduit system within the formational rocks (fig. 3). These igneous sills and dikes are usually porphyritic with an aphanitic green matrix. They weather spheroidally with a rust-brown coloration.

Table 1.--Rock Types (fig. 2)

Rock sample	Lithology	Field Note
R-7	Andesite (carbonitized)	Dike.
R-8	Volcanic arenite	Volcanic sediment.
R-9	Andesite (carbonitized)	Dike.
R-21	Lithic arkose (calcite cemented)	Carbonado sediment.
R-22	Quartz diorite	Hypabyssal intrusive.
R-26	Quartz andesite (propylitized)	Igneous flow.
R-28	Basaltic andesite	Igneous flow.
R-33	Quartz andesite (propylitized)	Igneous intrusive.
R-34	Basalt (carbonitized)	Sill.
R-35	Basalt (carbonitized)	Sill.
R-36	Lithic arkose (opaque pore fill)	Intergranular bitumen.
R-37	Diabase	Igneous intrusive.

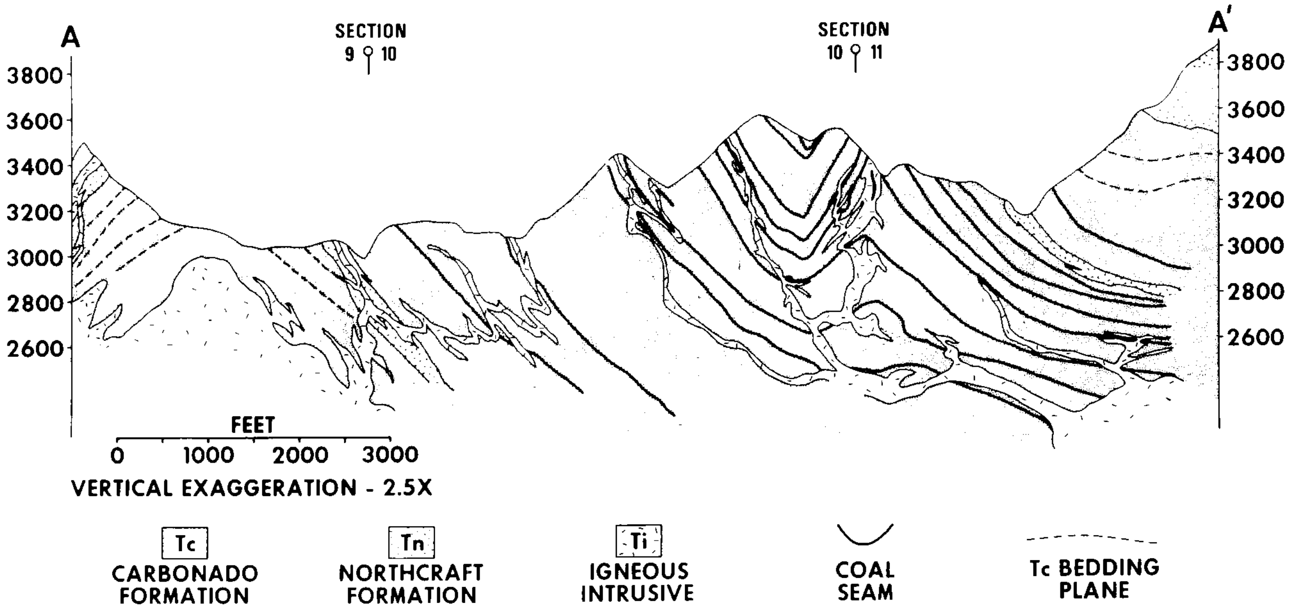


Figure 3.—Hypothetical geologic cross section across $N\frac{1}{2}N\frac{1}{2}N\frac{1}{2}$ secs. 9-11, T. 5 N., R. 6 E.

QUATERNARY STRATIGRAPHY

All glacial till noted appears confined to the southern portion of the study area within the drainage basin of the Nisqually River and adjacent to the town of Ashford. The older Hayden Creek glaciation deposited till up to about the 3,400-ft level in this area while the highest extent of the younger Evans Creek Glaciation is about the 2,200-ft level. Most of these till deposits are only mantles of 20 ft or less. Both glaciations are late Pleistocene in age.

Conformably overlying the topographic surface in the Ashford coal field is from 2 to 18 in of yellow-brown pumice ash. This volcanic ash is referred to as the "Y" layer by Crandell and others (1962) and was erupted from Mount St. Helens 40 air miles to the south about 3,200 yr ago.

IGNEOUS INTRUSION

The Ashford intrusions occur predominantly as sills within lithologic zones of weakness. It is mostly the coal horizons that provided these zones of weakness. The sills show definite zones of cooling where in contact with the bedrock.

Igneous rock intruded into shales often bakes the contact areas into slaty material. Evidence of intrusive effect is most visible where coal seams have been intruded. The coal and ash layers are usually intermixed with blocks and fingers of igneous rock. The original physical character of the intruded coal seam has been rearranged and altered by heat and tectonism of the intrusion. Generally, most of this metamorphism and tectonism occurs within a foot of the intrusive/coal contact. Rock sample No. 37 in table 1 presents an example of volatiles mobilized from intruded coal into a permeable sandstone where they resolidified as an intergranular pore filling. Igneous intrusion of coal seams complicates stratigraphic correlation, since some seams are almost wholly replaced by the intrusive. Carbonized coal material is usually intermixed or intimately associated with these intraseam intrusions, which commonly look like white "trap rock" because of chemical alteration.

COAL ALTERATION

It was assumed in the beginning of the study that a metallurgical grade coal within a continuous seam over 6 ft thick could be located. This assumption was based upon limited documentation of Ashford coals and tentative correlation with well-documented coking coals 20 mi to the north in the Wilkeson-Carbonado district. Work resulting in this report proved Ashford coals to vary radically in grade, rank, and continuity. Coal seams observed and tested in the Ashford coal field ranged in thickness from minor seamlets to 41 ft, including intrusions and partings. Previous to intrusion, the Ashford coals did have coking properties as indicated by microscopic identification of natural coke. Examination of selected representative coal samples using vitrinite reflectance indicated unaltered coal to be of a high-volatile A bituminous rank. Vitrinite macerals in close proximity to intrusions increased in rank, some to anthracite, while vitrinite closest to the intrusion was often volatilized and transformed into a natural coke. It is believed that coal seam alteration was affected by extensive igneous intrusions causing localized thermal alteration and minor tectonism, later followed by regional tectonism and associated formational folding and faulting. Coal alteration then was the result of (1) thermal effects of igneous intrusion, and (2) tectonic effects of igneous intrusion and regional folding and faulting.

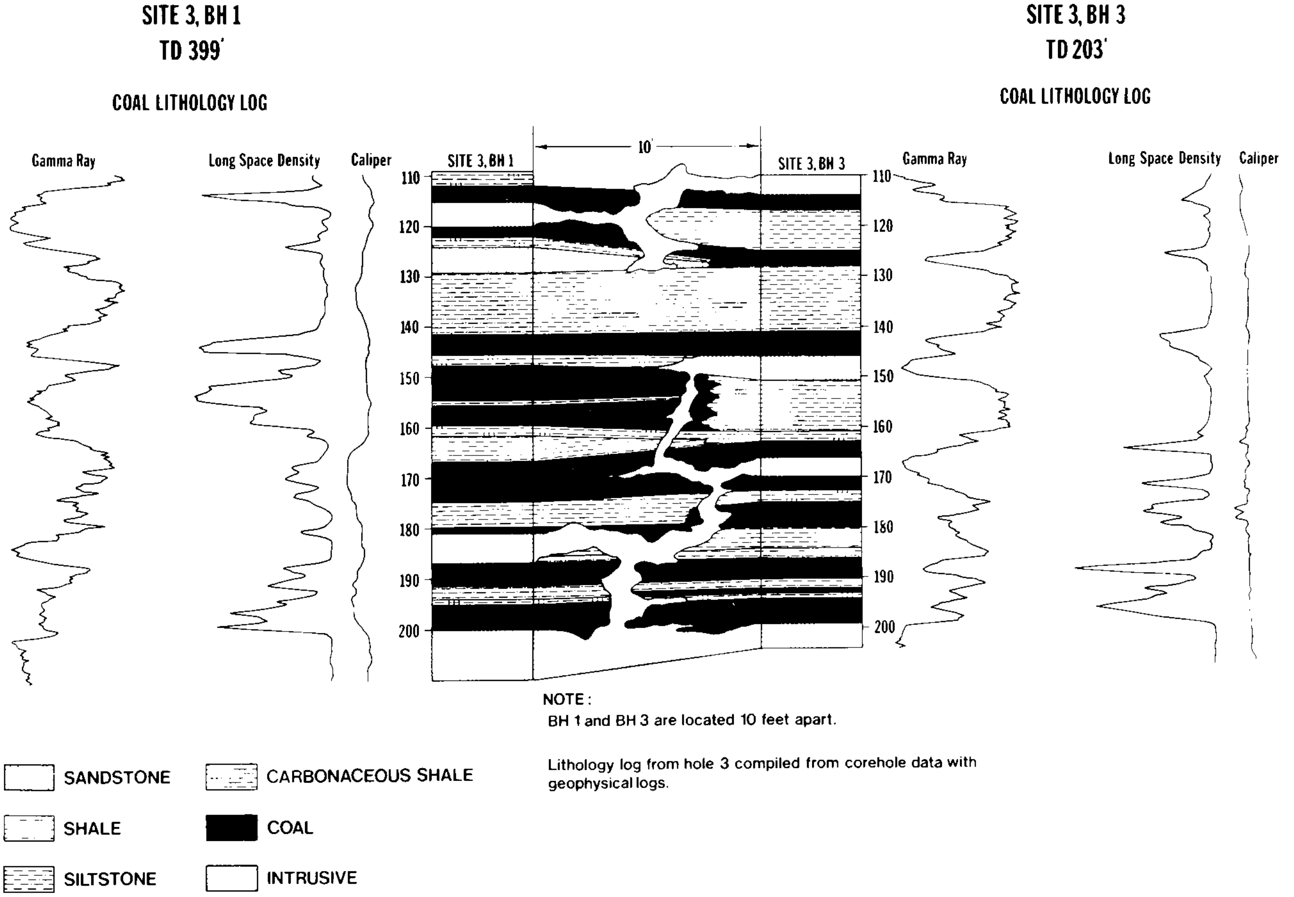
Thermal Alteration

The effects of thermal alteration on coal are related to the proximity of intrusion to various constituents of the coal seam. A thermally altered coal in hand specimen is commonly dull of luster, compact, and hard. The ash yield of the coal increases from unaltered parts of the seam towards the intrusion. This is due primarily to the introduction of materials in solution and from the gaseous phase, which have been derived from volatiles released by the intrusion and the reaction of carbonaceous matter with water. The intrusive itself is usually converted to a gray-white matrix of quartz, carbonates, and clays, as was also noted by Kirsch and Taylor (1966) in an intruded Australian coal seam. Using criteria established by others in laboratory testing and referred to by Stach (1975) and Kirsch and Taylor (1966), we placed the temperature of alteration for the Ashford coals in the range of 500^{o}C to 760^{o}C.

The random and extensive nature of igneous intrusions into the Ashford coals has produced very non-uniform seams of coal where grade and rank are primarily a function of proximity to the intrusive body.

Tectonic Alteration

Tectonism resulting from intrusion is expressed primarily as destruction of primary cleat and bedded structure, intermixing of coal and intrusive, and coal seam replacement with intrusive. Regional tectonism is most evident from the very friable nature of the coal throughout the Ashford coal field. This characteristic is also present in the Wilkeson-Carbonado district, where igneous intrusions are much



NOTE:
BH 1 and BH 3 are located 10 feet apart.

Lithology log from hole 3 compiled from corehole data with geophysical logs.

Figure 4.—Correlation of drill holes, site 3.

less prevalent, but regional tectonism is almost of the same degree as at Ashford. The igneous intrusions no doubt also have a marked effect upon the friable nature of the Ashford coals.

EXPLORATION METHODS FOR IGNEOUS INTRUDED COAL

Methods of exploration and determination used for intruded coals of the Ashford field included: outcrop observation, a magnetometer survey, photogeologic interpretation, downhole geophysical logging, and petrographic analysis of coal. The field observation of coal outcrops served as a visual basis for characteristics of igneous intrusion within coal seams as did observation of coal core and associated intrusions. These first-hand examples served as the basis for diagrammatic models (figs. 3, 4). Vegetation cover precluded very much outcrop observation. The rationale that intrusions preferentially intruded coal seams led to the use of a magnetometer. A ground magnetometer survey was used to delineate subsurface sills and dikes with higher magnetic susceptibilities than formational rocks (fig. 5). This method worked most of the time, but the degree of intrusive weathering or alteration and the proximity to intertonguing Northcraft volcanics created variables hard to account for on the surface. The reliability of these magnetic readings was sometimes suspect unless backed up by field observation.

The geologic interpretation of air photos, used in denoting surface features and linear structures, commonly picked out the larger sill-like intrusions. These intrusions formed resistant ridges that stood out on air photos. Downhole geophysical logging showed a decrease in resistivity in carbonized (thermally altered) coals compared to the usual increased resistivity in unaltered coal (fig. 6). A low gamma radiation reading was also consistently obtained in igneous intrusives. Petrographic coal analysis using polished samples was very helpful in identifying characteristics related to coal seam intrusion. The importance of vitrinite reflectance in microscopic coal work was demonstrated with the Ashford coals. The variable nature of the coal rank within a single coal seam could not have been identified by the usual proximate analysis.

ACKNOWLEDGMENTS

Material support from GRC Exploration Company and encouragement from Charles R. Tatman

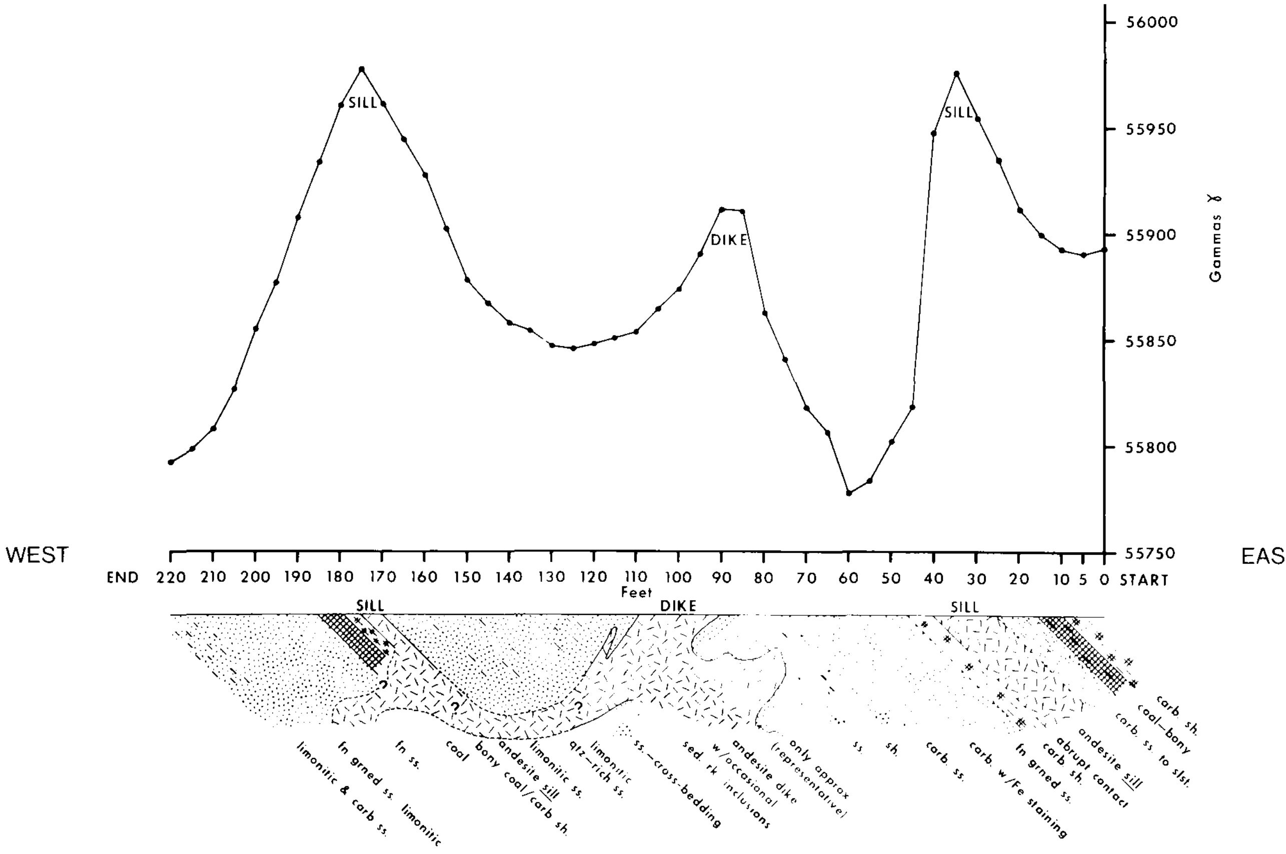


Figure 5.—Magnetometer test #1 (using rod mounted coil). Survey run from east to west cross strike.

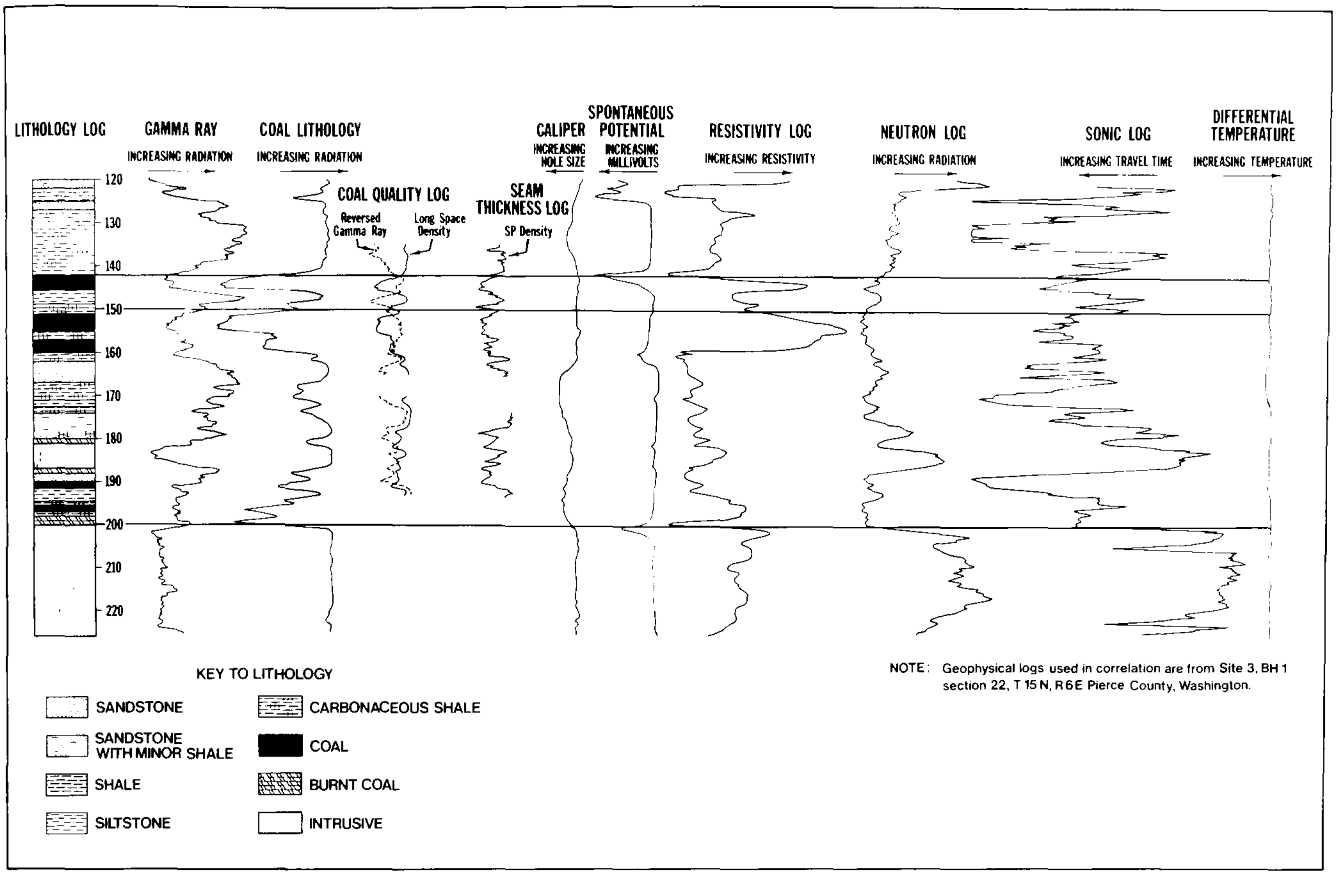


Figure 6.—Correlation of geophysical logs.

made this paper possible. Technical discussions with Ann Verity Oldham of Commercial Testing and Engineering Company and with Robert J. Kuryvial helped immensely in creating an understanding of the petrographic aspects of coal/intrusion association. Illustrations were modeled with the help of Patty DeMetz and the text typed and proofed by Kathryn Cornwall.

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MAGNETIC LOCATION OF CONCEALED IGNEOUS DIKES CUTTING COAL MEASURES NEAR WALSENBURG, COLORADO

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INTRODUCTION

Coal measures near Walsenburg, Colo., are known to have been intruded by sets of near-vertical dikes ranging in thickness from a few meters to many tens of meters. These dikes not only are impediments to mining but also probably stoped into the coal beds to form sills. Because the distance of sill invasion is highly variable, judicious planning of coal-resource investigations requires that exploration drill holes be sited reasonably far from known or suspected dikes in order to avoid drilling into sills instead of coals. The larger and more erosionally resistant dikes are readily mapped with the aid of aerial photographs: but their apophyses may not be as easily seen. Sometimes only a small topographic rise is the only clue to their existence.

Another problem in mapping dikes is the determination of an exposed dike's true lateral extent. Is the terminal edge of a vertical dike necessarily vertical? Perhaps not—at depth the dike may continue farther laterally; perhaps the complete vertical sheet did not cut its way to the level of the present topographic surface, or perhaps the dike had some of its upper part eroded.

Because only a limited number of drill holes can be allocated for a coal-resources evaluation, it is necessary that each drill site be carefully chosen. What we need, therefore, is some quick, easy, and economical method of increasing the probability that a drill site is not near a concealed igneous dike—from the results of our initial field studies (index map, fig. 1), the magnetic method of exploration geophysics appears capable of answering this need.

MAGNETIC RESPONSES OVER TWO KNOWN DIKES

Magnetic traverses across two dikes in Lathrop State Park (fig. 2) were run at a 3-m station spacing with the sensor atop a 2.4-m staff. Total-field magnetic observations were taken with a geoMetrics model 816 proton magnetometer[1], with a sensitivity of 1 nT (nanotesla). Readings at each station were not accepted until at least two values agreed to within 22 nT. Using a distance-measuring and station-establishment system devised by Maurice W. Major (Colorado School of Mines, oral commun., 1979), a 300-m traverse could be completed in about 1 hr.

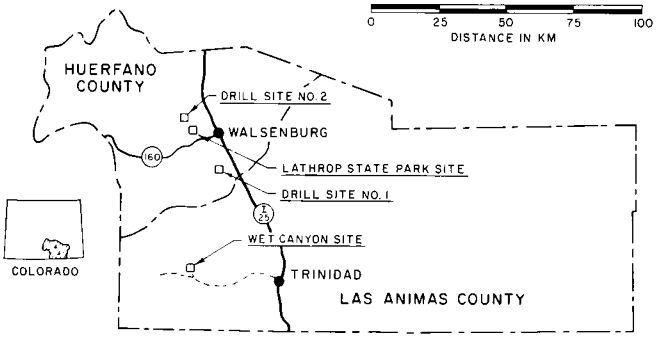

Figure 1.—Index map showing locations (boxes) where magnetic observations were made. Distance from Walsenburg to Trinidad approximately 60 km.

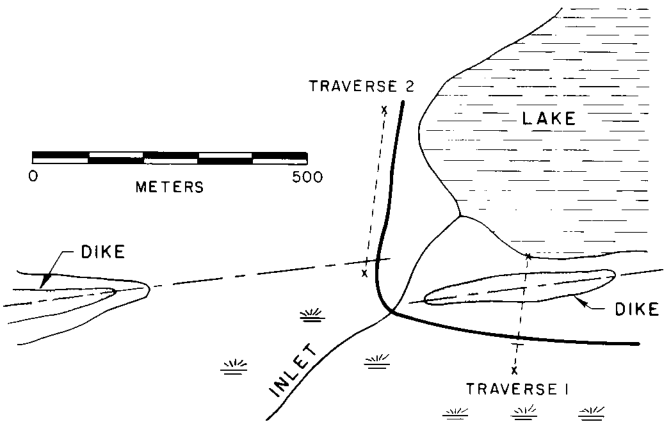

Figure 2.—Sketch map of southwest portion of Lathrop State Park showing magnetic traverses and exposed dikes. Note axes of dikes are parallel but not coincident.

In the total-field magnetic profile obtained from the first traverse over an approximately 15 m thick dike, the maximum peak-to-trough magnetic anomaly

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[1] Use of brand names in this paper is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

is about 400 nT. Massive slump blocks occur along the south side of the dike where the traverse crosses it, and ground north of the dike is strewn with dike material ranging in size from pebbles to boulders. The dashed line of figure 3 is a sketch of the estimated magnetic anomaly as it might appear if terrain effects were corrected and magnetic noise removed. When so smoothed, the maximum anomaly becomes approximately 280 nT.

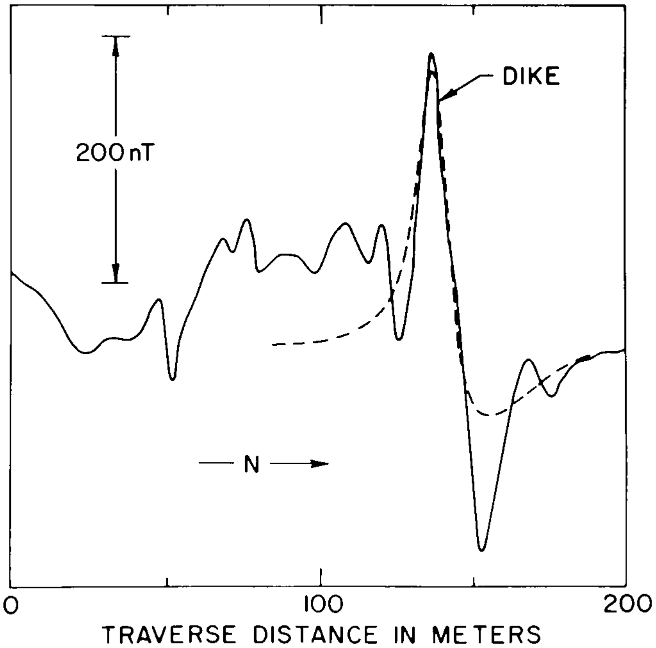

Figure 3.— Total-field magnetic profile across an exposed dike at Lathrop State Park, Colo. Dashed line near the dike represents a noise-free estimate of the dike's magnetic anomaly.

This dike anomaly does not have a textbook appearance: the magnetic low on its north side is too pronounced, and the variations on its south side are too erratic. For qualitative assessment of the presence of a dike, the results are acceptable; for quantitative interpretation of the dike's attitude and depth, the results are unacceptable because they are too noisy.

Magnetic results obtained along the second traverse at Lathrop State Park are shown in figure 4. The south end of this profile begins on a small (about 1 m high) topographic rise capped by a few scattered pieces of igneous rock. As shown on figure 2, the south end of the traverse is directly in line with the axis of an exposed dike approximately 500 m to the west. Although a dike is not exposed along the second traverse, magnetic data indicate the likely presence of a dike near the south end of the traverse.

In addition to the dike anomaly, the magnetic profile along the second traverse (fig. 4) shows magnetic anomalies produced by a barbed-wire fence and a culvert. Because fences and culverts produce magnetic anomalies, their occurrence should be noted in the field notebook and indicated on the magnetic profile. Thus identified, fences and culverts present no serious problem in interpretation. This particular culvert is approximately 0.3 m in diameter and is buried about 0.5 m deep. No culverts exist at the dike position on either the first or second traverse. The area is magnetically noisy, which implies that detailed study of magnetic features, the search for still-termination position, for example, would be difficult. Note, however, that even though the noise is great, it is not so great that the effect of a shallow igneous dike (our immediate target) is lost within the noise.

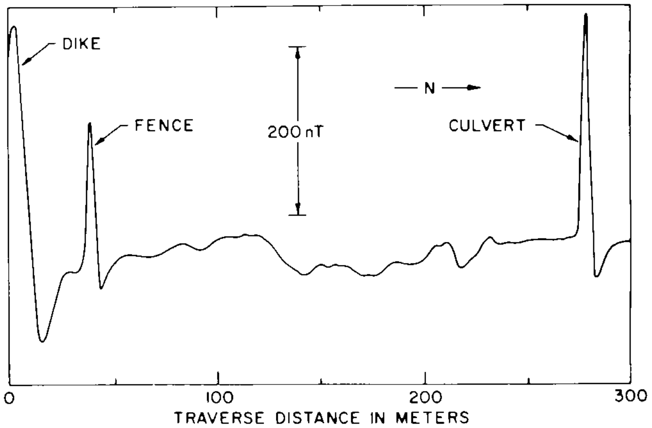

Figure 4.— Total-field magnetic profile at Lathrop State Park, Colo., showing north half of magnetic anomaly produced by a partially concealed dike. Also shown are magnetic field variations due to a fence, a culvert, and a magnetically noisy regolith.

Although a reliable magnetic map cannot be constructed with only two profiles, it is nevertheless tempting to speculate upon the geological signifiance of the magnetic observations:

1. It appears that the dike anomaly on the south edge of traverse 2 is indicative of an eastward extension of the dike to the west, figure 2.
2. The magnitude and characteristic of the dike anomalies (when allowance is made for magnetic terrain effect and for noise produced by blocks of slumped material) are reasonably similar. Thus it is likely that both anomalies were produced by the same dike.

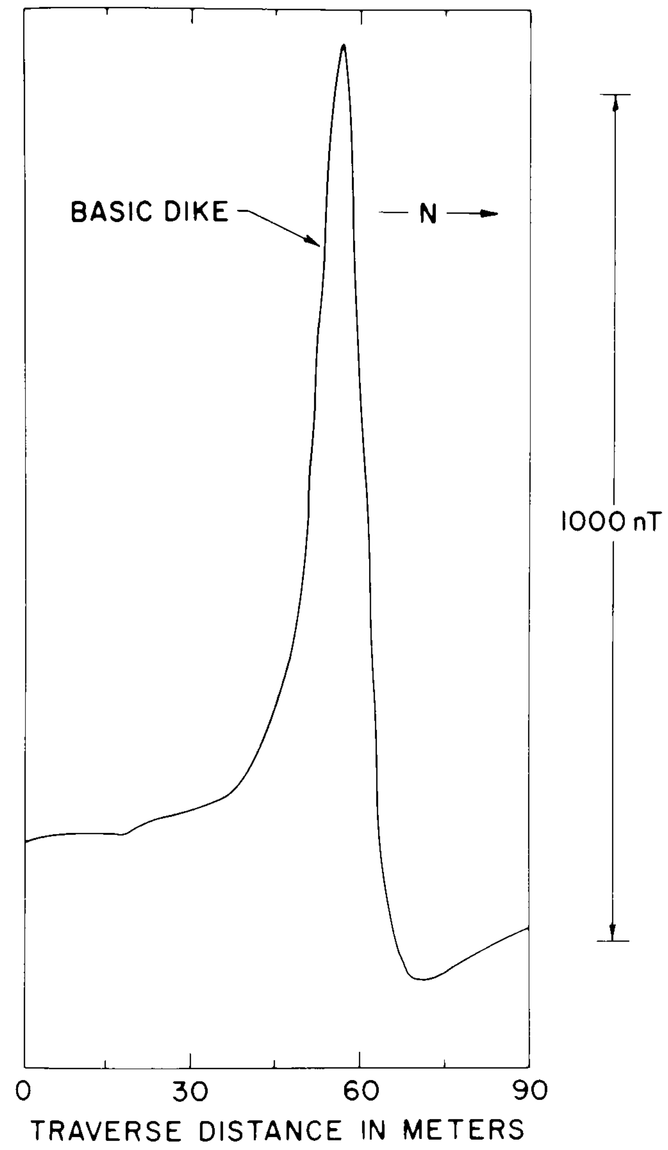

Figure 5.--Total-field magnetic profile across a basic dike exposed at a roadcut along the side of Wet Canyon, Colo.

3. In this area, the dike material is more resistant to erosion than the intruded sediments. It is unlikely, therefore, that the dike has extended either eastward into the lake or westward into the swamp, both topographic lows.
4. It is common for streams in this area to follow faults that have displaced dikes. Note the position of the lake's inlet, fig. 2.
5. The sketch map of figure 2 indicates that the axes of the dikes are roughly parallel, but not alined.

Putting these observations together, we speculate that the two dikes shown on figure 2 are really one that has been faulted, the fault line following the general direction of the inlet. At Walsen Arroyo, some 10 km south-southeast of Lathrop State Park (see Walsenburg South, Colo., 7.5-minute topographic map), a faulted dike of similar pattern can be seen.

Figure 5 shows the results obtained over a 5 m thick basic dike in the Wet Canyon area. Note that the magnitude of this dike anomaly is some three times greater than those observed at Lathrop State Park (maximum anomaly 1,250 nT) and that the surface noise is considerably less. Being located on the side of a canyon, it is reasonable to suppose that magnetic material broken from the dike has been washed down the hillside, and thus the slope is free of noise-producing magnetic float.

MAGNETIC RESPONSES AT TENTATIVE DRILL SITES

Regional geologic mapping at both tentative drill sites indicated that the dikes in the area are vertical and trend east-west. Thus, a south-north traverse would have the best chance of detecting them. Figure 6 shows the total-field magnetic profiles obtained to 150 m south and north of the tentative drill sites. Although the high noise levels along these profiles could mask the anomaly produced by a small dike at depth, it is almost certain that no east-west dike exists near the surface within the distance reached by the traverses.

Taking the magnetic profile at site number 1, figure 6 as representative of the worst-case noise profile, and using computer modeling as a means to determine the anticipated magnetic signal produced by a vertical, finite-thickness, infinite-depth dike, it appears that with the use of a single profile, a dike with a magnetization equal to that of the Lathrop State Park dike could reliably be detected if the depth to its upper surface were less than two dike thicknesses. Thus, a 12-m-thick dike (in the worst case) could be seen at a dike depth of 24 m. Significant improvement in detectability can be obtained if instead of a single profile, a set of profiles are run. When these areal magnetic-field variations are mapped, the dike anomaly will exhibit a definite linear trend, whereas the magnetic noise associated with magnetic float will not.

Both drill sites are located within topographic lows bounded by east-west-trending ridges. And although geologic mapping did not indicate any dikes in the area that point directly to the sites, there was some apprehension that the ridges might be immediately underlain by dikes. The magnetic surveys indicate that this worry was unfounded.

CONCLUSIONS

For the results of our initial magnetic study, the following conclusions can be drawn:

1. The data clearly indicate that no east-west-trending, near-surface igneous dikes exist within a distance of 150 m north and south of the two tentative drill sites.
2. A magnetometer sensitivity of 1 nT is sufficient in this area to reliably reveal existence of an igneous dike whose depth to the top surface is less than two dike thicknesses.
3. Magnetic surface noise on profiles at Lathrop State Park profiles and at the two tentative drill sites is considerably higher (by a factor of 20 or more) than what we have observed in other coal fields. Because of this high background noise, magnetic mapping of thin-sill termination and precise interpretation of magnetic profiles in this area would be difficult.
4. We recommend, because of the high cost of drilling and because of the speed, ease, and apparent effectiveness of magnetic surveying for verifying the absence of near-surface igneous dikes, that all tentative drill sites in the Raton Mesa coal field or similar areas be examined magnetically before final drill-site selection.
5. We also recommend that in those areas in which magnetic noise is very high, a magnetic map (rather than a single magnetic profile) be made in order to better the likelihood of detecting a concealed dike.

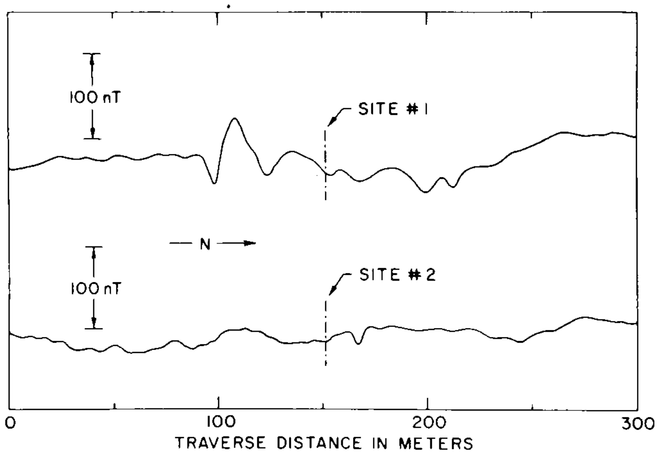

Figure 6. Total-field magnetic profiles across two tentative drill sites west of Walsenburg, Colo.

SEISMIC SEAM WAVES IN THE COAL BASIN OF COLORADO

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Under favorable geologic conditions, a coal seam can be an efficient seismic wave guide. For the first time, seam waves have been observed in a Western United States coal. These observations were made in the Dutch Creek #2 Mine in Pitkin County, Colo. This mine produces high-grade metallurgical coal from depths as great as 2,000 ft. The seam studied is 8 ft thick and has smooth and abrupt contacts with the siltstone roof and floor.

The transmission of both Love-like and Rayleigh-like waves through the seam was observed at an offset of 600 ft across a developed longwall panel. At this distance, a single hammer blow excites Love or Rayleigh waves large enough to be detected easily, but frequencies above 150 Hz are not evident on the records. By contrast, an explosive charge of 0.5 lb produces a Rayleigh wave record clearly showing frequencies up to 170 Hz. The charge also excites a clear refracted P-wave and a following train, of frequency near 360 Hz, which is tentatively interpreted as being associated with a Leaky Mode. The seam is an excellent wave guide.

The dependence of these waves upon the continuity of the coal seam is illustrated both by the observed shadowlike effect of a roadway and by the observed reflection of the Rayleigh wave from a rib. This reflected Rayleigh wave, characterized by frequencies near 130 Hz and group velocities near 4,200 ft/s, is attenuated only by about 20 db after traveling 1,200 ft and being reflected twice.

The fact that an underground roadway will act as a barrier to the transmission of both Love and Rayleigh waves and that evidence exists for a Rayleigh wave reflection from a rib strongly suggests that in-seam seismology can be used to detect geologic features, such as large faults and thick dikes that truncate coal seams. Consequently, in-seam seismic techniques may prove economically useful to the coal mining industry in the Western United States.

HOLE-TO-HOLE SEISMIC SEAM WAVE OBSERVATIONS

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It has been almost 20 yr since the idea of channel waves in coal seams was first introduced. In fact, most coals present a lower velocity and density than the surrounding rocks, thus creating a wave guide in which elastic energy is trapped and propagates with very little attenuation. This idea has been used in Germany (Millanh and Arnetzl, 1979), England (Buchanan and others, 1979), and lately it has been tested with good results in the Western United States (Reeves, 1979). Most of these seam wave surveys have been conducted underground, that is, within a mine, and even though some work has been done in the area of hole-to-hole seismic seam waves, the authors do not know of any prior instances in which applicable results have been obtained. We wish here to show the results from a hole-to-hole seam wave study conducted in the Zulia Coal Basin of Northwestern Venezuela, in June 1979, and to prove the applicability of hole-to-hole surveys in mapping the continuity of coal beds.

The Zulia Coal Basin is the most important coal-bearing basin in Venezuela (fig. 1). The lithology reflects marine, deltaic, and paludal environments of deposition; the rocks are primarily limestones, sandstones, siltstones, shales, and conglomerates. Most coals are located in the Marcelina Formation (lower to middle Eocene), which has been described as a fresh to brackish-water formation; at the type location it is composed largely of interbedded sandstones, shales, sandy shales, and coal beds.

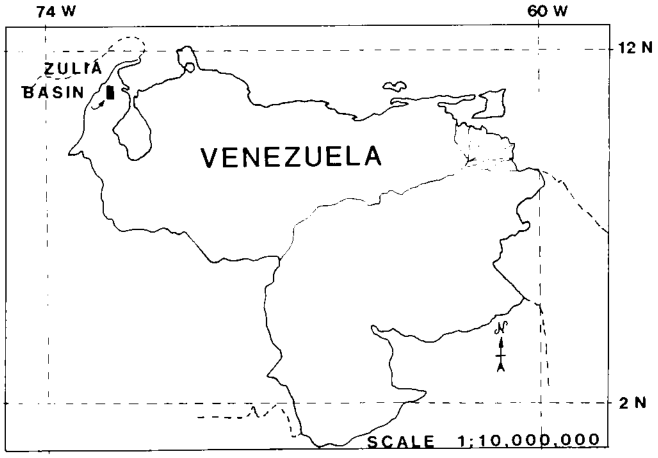

Figure 1.--Location of Zulia Basin, Venezuela.

Figure 2 is a cross section showing certain geologic parameters important to the experiment and the location of shots and detector. A three-component geophone was hydraulically clamped in the middle of the seam in hole PC48. Half-pound charges were detonated in an uphole sequence at hole PC44, 240 m away. The signal from the geophone was fed directly into a six-channel Bison Enhancement Seismograph. The sample rate was 0.76 ms (milliseconds) for all the records. Figure 3 shows three of the field records obtained, which show horizontal displacement as a function of time for three different shots at depths of 80, 88, and 96 m respectively. The horizontal scale is time in milliseconds, between 50 and 240 ms post shot. The first event, best seen on the vertical component records (not shown here), occurred at 68 ms post shot and is interpreted as being the direct compressional wave from the shot. This event is identified by p on figure 3. The calculated compressional velocity using this time is 11,700 ft/s, which agrees with the 11,800 ft/s value estimated from sonic logs. If one assumes a Poisson ratio of 0.25, then the shear velocity in the wall rock should be 6,800 ft/s.

An event having certain characteristics of a seam wave, that is, a large amplitude train arriving after the time of the S-wave, occurs after 100 ms on records 2 and 3 but not on record 1. The frequencies and speeds that characterize this train should be predictable, theoretically, from the model parameters of figure 4, which is a mathematical model of the true geological conditions shown in figure 2. It can be shown that the coal seam in the model is a wave guide and that, in this guide, the speed of seismic waves depends upon frequency. This dependence is termed "dispersion." Theoretical calculations show that the shape of the dispersion curve, that is, the curve showing velocity as a function of period, is characteristic of the particular wave guide. If the parameters of figure 4 are changed, the shape of the dispersion curve will change.

Figure 5 compares theory and observations, showing contours that describe the observation, heavy black lines which are theoretical dispersion curves, and three hatched regions of particular interest. We discuss each of these different components in order. It is possible, via a multifilter analysis, to calculate the instantaneous amplitude of the ground motion, shown by a record like #3 of figure 3, as a function of period and wave speed. These amplitudes might be plotted on a map whose coordinates are speed and period and then contoured. A "topographic" map would result. Figure

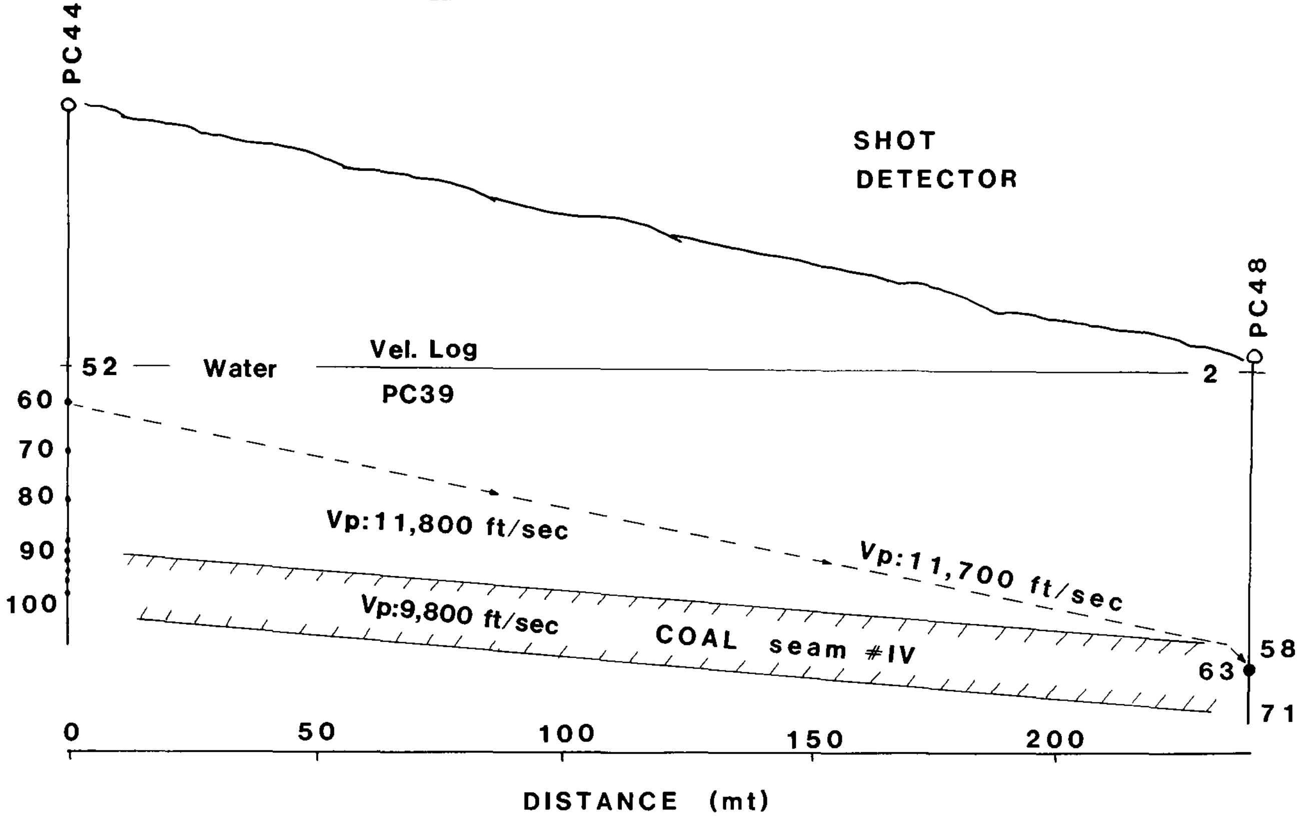

Figure 1.—Cross section of seam wave experiment area.

5 is such a map of the motion of a horizontal seismometer locked inside the coal seam 240 m from the shot. Ridges on this topographic map represent regions of high amplitude in the data. The contour interval is 6 db or a factor of *2 in the amplitude of the ground motion.

The three highest ridges, hatched zones A, B, and C, dominate the map and can be explained theoretically in terms of the calculated dispersion curves, heavy black lines, plotted to scale on the map. Ridge A, located between periods of 3 and 5 ms, and speeds below 2,180 m/s, presents an inversely disperse trend, that is, shorter periods travel faster than longer periods. The heavy line represents the theoretical curve for the fourth higher mode of propagation for the model of figure 4, and it too shows inverse dispersion through this region. The difference in speeds between the theoretical dispersion curve and the observed ridge is only 7 percent, which is a very good agreement. Areas B and C, which lie above the shear speed of the wall rock, are interpreted as possible leaky modes. In theory, leaky modes should be characterized by periods and speeds right above the cutoff points for the normal modes, points for which the phase velocity is equal to the shear velocity in the wall rock. In our case, these areas lie above the theoretical value of the cutoff for both the second and fourth higher modes of propagation. This correspondence between theory and data in the speed-period domain supports the identification of the late arrival as a seam wave in the coal (fig. 6). The way in which the amplitude of this event varies with depth of shot (the amplitude is a maximum inside the seam and decreases rapidly as the shot is moved outside the seam) supports its identification as a seam wave as well.

Our conclusions are as follows:

1. An event having three characteristics of a seam wave is present in the records. Frequencies and group velocities of the late arrival fit a dispersion curve estimated from the parameters obtained from sonic logs and refraction shots. Two early arrivals lie in the range of periods and speeds predicted by theory for leaky modes. The amplitude of the late arrival behaves like that of a seam wave as well; that is, it is a maximum inside the seam and decreases exponentially outside the coal seam.
2. In this particular experiment, covering the period ranging from 3 to 30 ms: Horizontal displacement is better trapped than vertical displacement. Even modes seem to be preferentially excited.
3. These observations prove the applicability of hole-to-hole seismic seam wave methods for mapping the continuity of coal beds having a

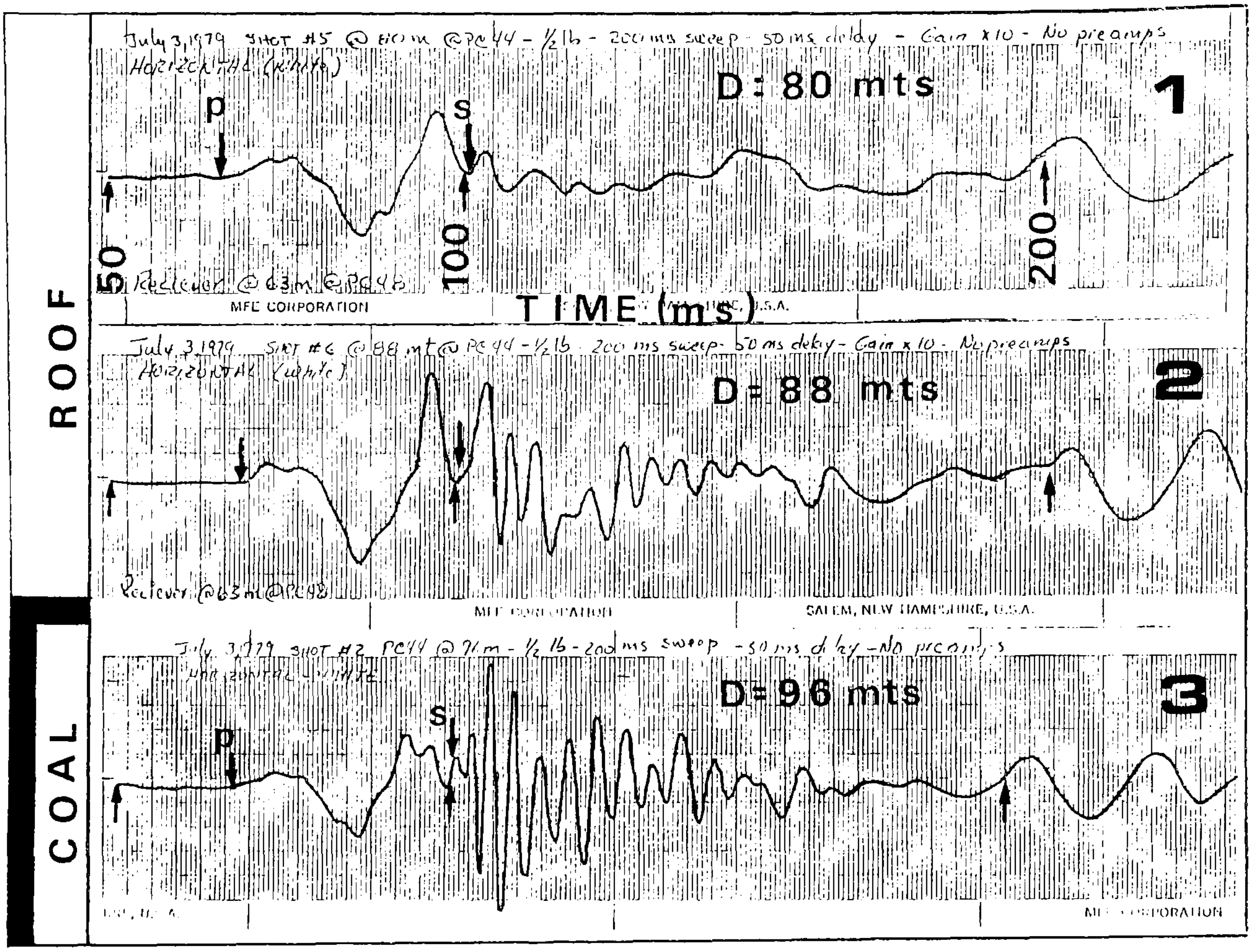

Figure 3.—Field records of shot experiments.

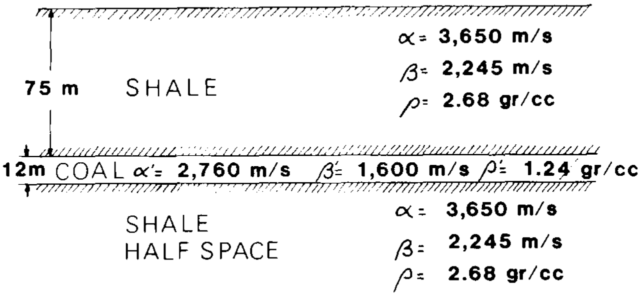

Figure 4.—Mathematical model of experiment of figure 2.

velocity contrast as low as 1.3:1.0 with the surrounding rocks. Such low velocity contrasts seem to characterize coals of the Western United States, and therefore this experiment has broadened the utility of the seam wave methods to include coals of interest here.

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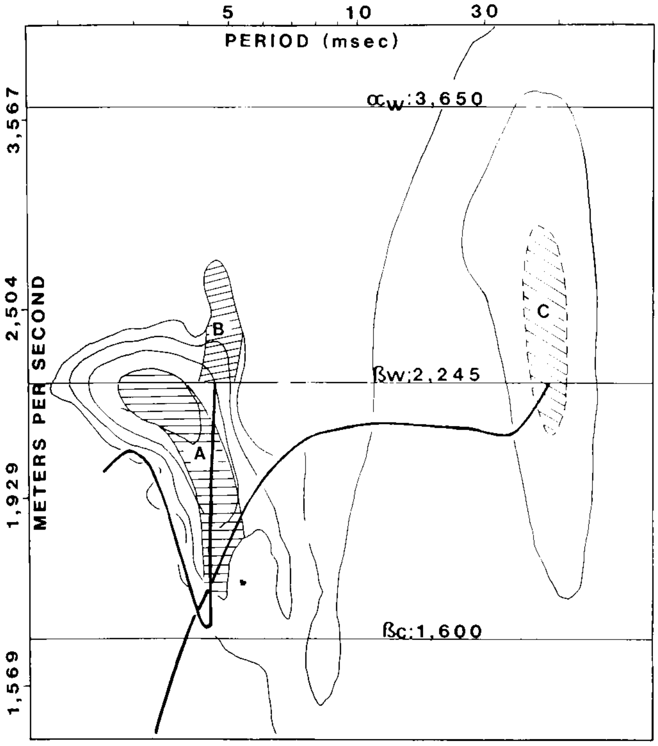

Figure 5.—Contour map of experimental results.

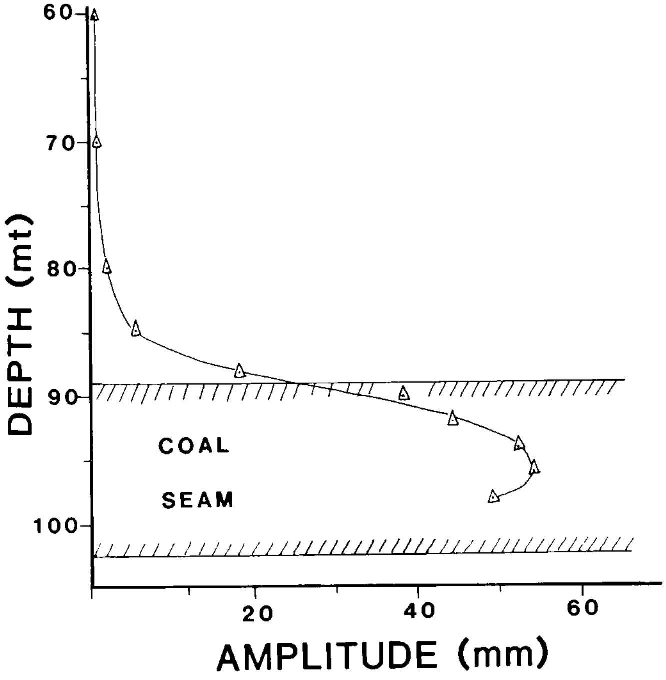

Figure 6.—Behavior of the late arrival as a function of shot depth.

GEOLOGY OF THE DECKER COAL AREA

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Sheridan, WY 82801

The Decker Coal Company controls approximately 18,000 acres of coal leases in Ts. 8-9 S., Rs. 40-41 E., Big Horn County, Mont. The Decker and East Decker Federal coal leases were united in a joint venture between Pacific Power and Light and Peter Kiewit Sons' Co., when Decker Coal Company was formed in August, 1970, with Kiewit as operating partner (fig. 1). Pacific Power and Light retained the West Decker Federal leases, which are now part of NERCO's Spring Creek Coal Co. The East Decker Federal lease became the West Decker mine and shipments to Commonwealth Edison Company of Chicago began in August 1972. Part of the East Decker lease committed to production is now the East Decker mine. The remaining potential reserves on this lease are known as the Holmes-Decker area. The undeveloped coal reserves north of the West Decker mine are called the North Extension area. Permits for this operation are under review. Coal from the Decker mine complex is shipped to Commonwealth Edison, Detroit Edison, and is soon to be shipped to the City of Austin and Lower Colorado River Authority in Texas.

GENERAL GEOLOGY

The Decker area is located at the northwest margin of the Powder River Basin. Strata exposed in the mining area are part of the Tongue River Member of the Fort Union Formation of Paleocene age. The member, about 1,100 ft thick at this location, can be considered a cyclic sequence of sandstone, siltstone, impure shale, and coal. The Wasatch Formation of Eocene age found at higher elevations to the west of the Decker area and on the East Decker coal lease. At least seven coal beds are present within the Decker lease area. They are, using Wyoming (Taff) names,

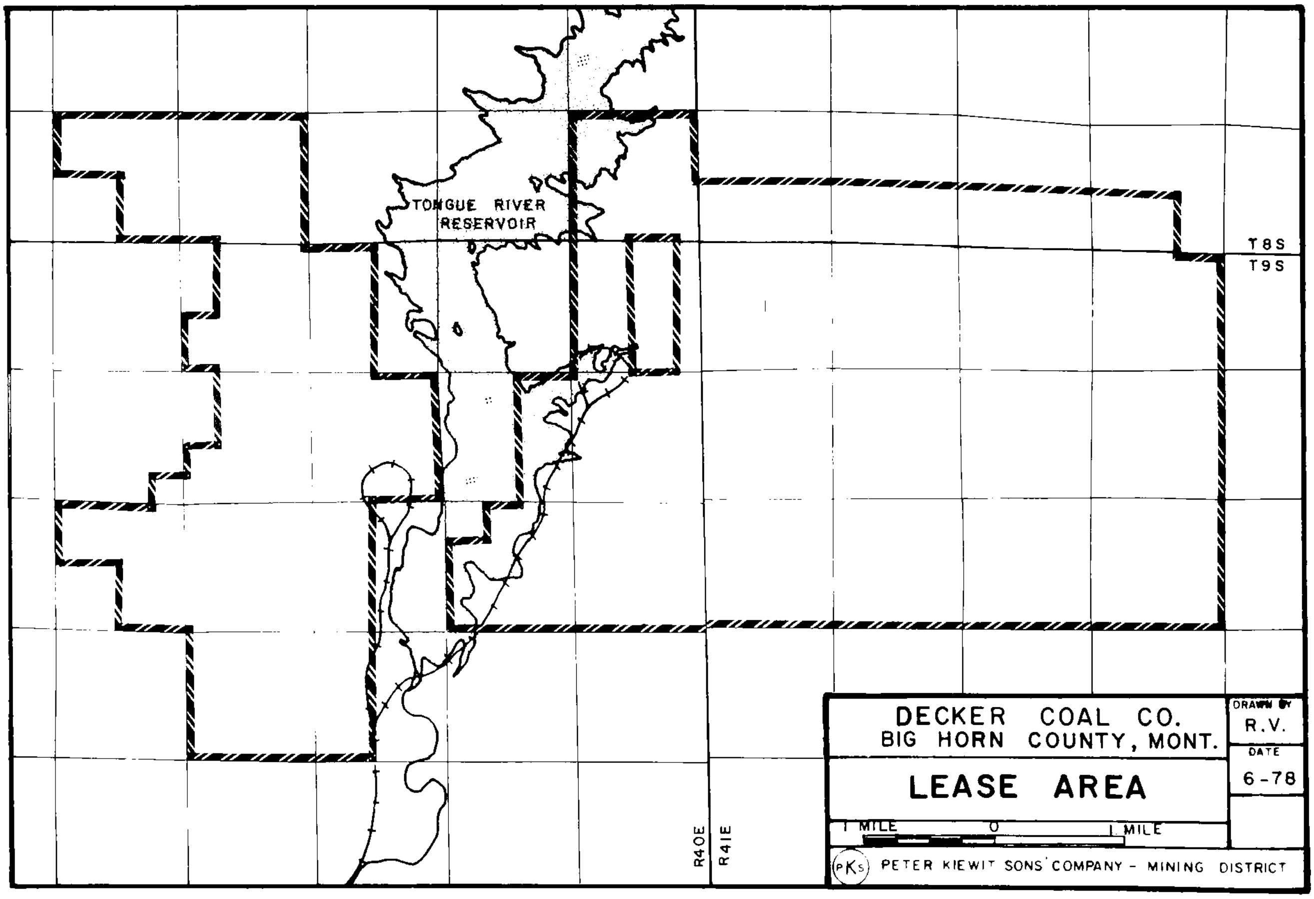

Figure 1.--Decker Coal Co. lease area, Montana.

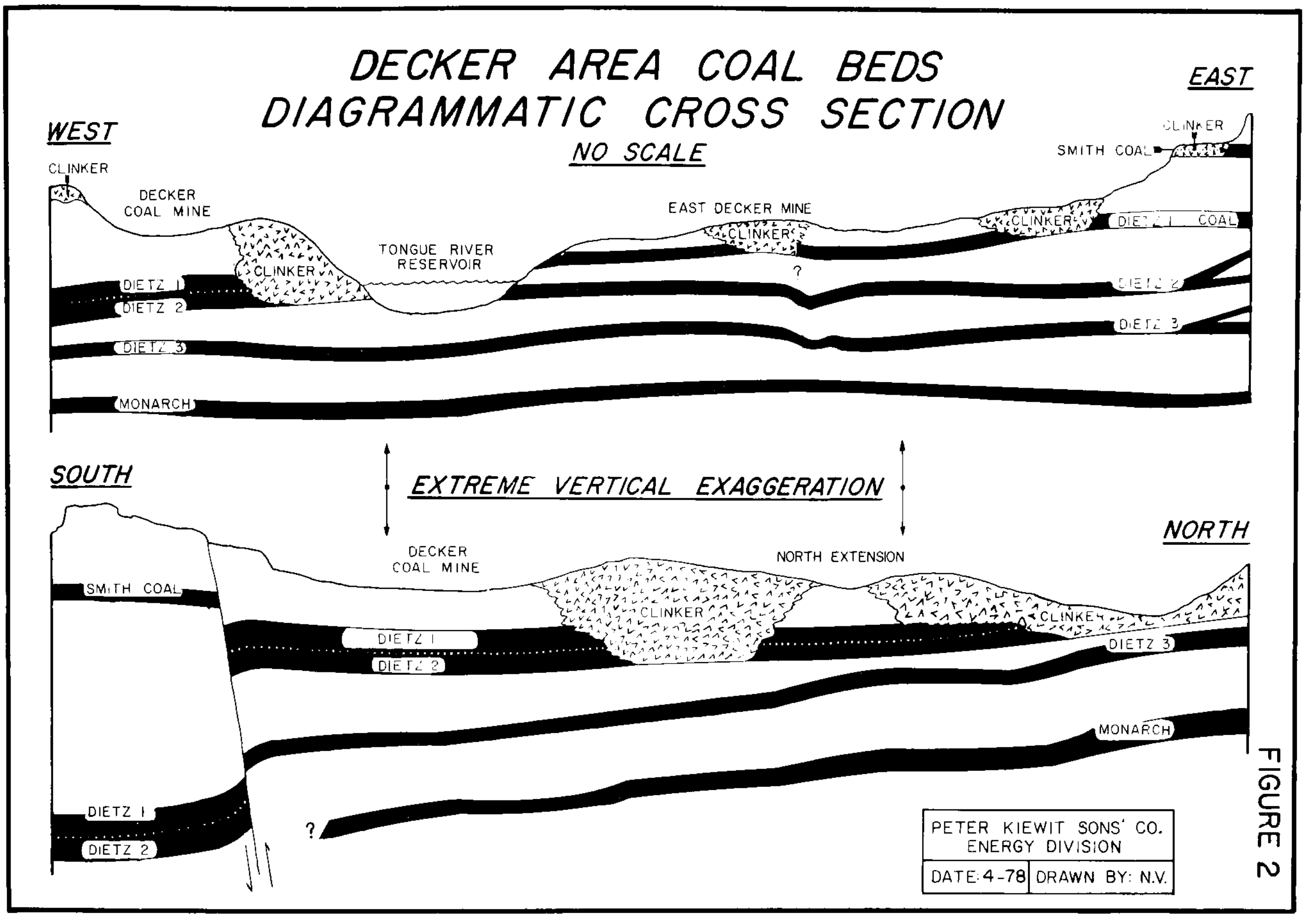

FIGURE 2

Figure 2.—Decker area coal beds, diagrammatic cross section.

listed in descending order: Roland, Smith, Dietz 1 (Anderson), Dietz 2, Dietz 3, Monarch, and Carney. The upper four beds have surface expression within the area and also are responsible for the clinker that covers much of the Decker vicinity (fig. 2).A local bed develops between the Roland and the Smith beds in the Decker area and is probably responsible for some of the confusion regarding bed names.

STRUCTURE

The general dip of the strata is to the southeast at about 1^{o}-2^{o}, but local flexures, faulting, and collapse of overburden above burned-out coal beds have influenced local dips. Undoubtedly the Big Horn uplift and axis of the Powder River Basin have had an effect on the structure. A series of gentle northwest-southeast-trending undulations pass through the Decker area. The coal bed on the crest was exposed by erosion and ignited, while the same coal in the trough was protected by thicker cover and remains today as strippable coal.

Northeast-southwest-trending normal faults are prominent throughout the entire Decker-Acme area. The West Decker coal deposit is cut off by a northeast-southwest-trending fault with almost 200 ft of displacement, with the downthrown block on the southeast side. This fault can be traced southwest into the Squirrel Creek drainage. The northeast end probably fades out under the Tongue River Reservoir. Approximately 1 ½ mi southeast is another fault with a parallel trend and a similar direction of displacement. However, the throw is on the order of 350 ft maximum. This fault enters the southwest edge of the East Decker leases and almost fades out at the northeast corner. At one point along the trace, the clinker over the Roland coal bed on the downthrown block is adjacent to the Smith clinker on the upthrown block. A suspected north-south fault or strained monocline has been mapped near the boundary between secs. 7 and 8, T. 9 S., R. 41 E., and extending into the massive clinker blanket in sec. 6. Displacement, if any, along this structure is probably less than 25 ft.

COAL BEDS

The West Decker mine is developed on a bed that is 50-52 ft thick. It is known as the D1 at the mine but was formed by the merging of the Dietz 1 and Dietz 2 coal beds (Anderson and Dietz 1 in some reports). Last year the mine shipped 10.24 million tons of coal with the following average analysis: Moisture - 23.36 percent; Ash - 4.12 percent; Btu - 9,643; Sulfur - 0.37 percent. This very high grade coal is classified as subbituminous C.

The Dietz 1 and the underlying Dietz 2 coal beds are separated by a band 1-4 in thick that is referred to as a "high ash band." This band is not considered to be a parting because it is indistinguishable from the surrounding coal and has an acceptable Btu content. Core analyses define the Dietz 1 coal as having less sulfur than the underlying Dietz 2. A clay parting 2 in thick develops between Dietz 1 and 2 at the east end of the old West Decker scraper pit. The parting must thicken eastward under the Tongue River Reservoir because the coal reappears as distinct beds on the East Decker lease.

Above Dietz 1 is a rider that is generally 1-4 ft thick. It appears to be thickest in the southeastern part of the mine and is separated from the main bed by a parting approximately one-half to 1 ft thick. The parting is composed of a hard, fine-grained, brown sandstone. The rider bed is salvaged and the parting ripped and cast.

The Dietz 1 and 2 coals increase in elevation to the north of the present pit and have burned out. This burn edge forms the northeastern boundary of the current pit. Remnants of the coal beds appear again about one-half mile north of the burn edge and continue in the subsurface to the north. This area is named the North Extension and is often referred to as North Decker. Two east-west-trending strips of coal are present in the valleys of Pearson and Spring Creeks and are separated laterally by a high ridge of clinker. The Dietz 2 is intact under most of the North Extension valleys but has been completely burned at several isolated locations. The Dietz 1 coal bed was burned over a considerable area, but remnants appear as "islands" in a mass of clinker or surrounded by clinker-derived colluvium.

Stratigraphic cross sections of the East Decker property depict the Dietz 2 coal bed as rising uniformly to the northeast. However, the overlying Dietz 1 coal bed does not follow a uniform pattern. It rapidly diverges and then converges on the Dietz 2 as the interburden varies in thickness between 6 and 120 ft. The Dietz 1 is also burned out over a considerable area in the East Decker mine. The distorted attitude of the Dietz 1 cannot be attributed entirely to differential compaction of the interburden material. Variability in interburden thickness may be partially the result of clastic material that washed into the swamp and interrupted organic deposition. The Dietz 1 bed varies between 22 and 30 ft in thickness.

The Dietz 2 coal bed ranges in thickness between 15 and 20 ft under the Decker area. It is burned in the vicinity of Deer Creek on the edge of the East Decker mine and in the area to the north as it rose in elevation. The bed splits into two thin beds at the east side of the East Decker lease.

The Dietz 3 coal bed, known as D2 at the mines, has been penetrated under most of the Decker lease area. The thickness varies between 14 and 20 ft, being greatest in the northern part of the North Extension. Here the Dietz 3 converges to within 6 ft of the base of the Dietz 2. However, the interburden ranges up to 75 ft under most of the leases.

The Dietz 3 was exposed by erosion and burned along the Tongue River north of the lease area. It will be mined in the proposed North Extension mine and the East Decker pit. The Btu values are slightly less than the D1 beds, but the sulfur content is also very low. The bed subcrops under alluvium in an old buried channel of the Tongue River at the mouth of Deer Creek and splits, like the Dietz 2, into two beds at the eastern boundary of the leases.

The center of deposition for the Dietz beds in the Decker vicinity was just to the west of the lease area. Here, in a zone about 6 mi long and 3 mi wide, the Dietz coals are united in a single bed over 80 ft thick. Peat development was almost uninterrupted, although the bed boundaries are still visible on the gamma ray logs. The Dietz beds are extensions of this zone separated by wedges of clastics.

Approximately 80 to 100 ft below the Dietz 3 is the Monarch coal bed. It can be followed in the subsurface from the Acme area, where the Monarch and the Dietz 3 are separated by a foot of soft shale. The bed is about 20 feet thick under the Decker leases, where it is called D3, and it maintains quality equal to that found in the Big Horn Coal Company mine pits.

The lower bed in the Decker area is the Carney. It is about 17 ft thick and underlies the Monarch with an interburden interval that varies between 80 and 160 ft. Another coal bed, often referred to as the Masters, is separated from the Carney by a parting that varies between 0 and 20 ft thick. This lower bed is about 8 ft thick and where merged with the Carney forms a coal bed 25 ft thick. This bed may be correlative with the Wall bed if it continues to increase in thickness to the northeast into Montana.

The Dietz 1 coal bed, or the rider at West Decker, is overlain by a thick section of coarse sandstone 70-150 ft thick. Highwall exposures of the sandstone reveal vertical inclusions of banded coal. They are 3-5 ft high and 6 in to 1 ft wide. The inclusions may represent a displacement of a thin bed of soft carbonaceous material from the horizontal into a vertical fracture caused by a shrinking of the overlying sandstone as it was compacted and dewatered.

The Smith coal bed overlies the Dietz 1 with an interval that varies in thickness from 120 to 250 ft. The bed has been removed by erosion on the Decker lease west of the river, except south of the major fault that forms the mine boundary. The Smith is intact in the downthrown block and has burned at the outcrop. The Black underground mine was opened in the Smith bed close to the fault plane in sec. 22. The mine was inspected by Baker (1929) and the coal measured to be about 16 ft thick. The hills and ridges west of the West Decker mine are capped with Smith clinker.

The Smith can be found in the high ground on the East Decker lease both north and south of the Deer Creek valley. The bed is 11-16 feet thick and has burned along much of the outcrop. It subcrops against the fault plane in the downthrown block south of the major fault that is the East Decker mine cutoff. Coal analyses can be found in Matson and Blumer (1974).

The uppermost bed in the Decker area is the Roland coal. It occurs at higher elevations under flat benchlands in the southeastern part of the area where the bed averages about 10 ft thick. The Roland can be located by the red clinker outcrop about 200-230 ft above the Smith bed. A local bed about 2 ft thick lies between the Smith and Roland coal beds on the eastern part of the East Decker lease. This local bed is known as the Squirrel Creek or Powers bed. It may be the Roland bed of Taff (1909).

The boundary between the Fort Union and Wasatch formations is under dispute but is considered by some to be at the top of the Roland Coal bed. Clastic sediments between 600 and 1,000 ft thick overlie the Roland and underlie the first coal bed in the Wasatch.

Several levels of gravel-capped benches have been mapped on the leases. The material, never more than 6 ft thick, is composed of igneous and sedimentary rocks that are of typical Big Horn Mountain origin. The location of the terraces is shown on the map in Law and Grazis (1972).

ACKNOWLEDGMENT

The writer wishes to express appreciation to the staff in the Kiewit Mining District for all their help and encouragement in the preparation and editing of this paper, with particular thanks to Thomas A. Gwynn and Robert A. Gjere.

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ROMOCOAL FIELD TRIP 1980

Aerial view of Vermejo Park anticline looking west over the western part of the Raton coal field to the crests of the Sangre de Cristo Mountains.

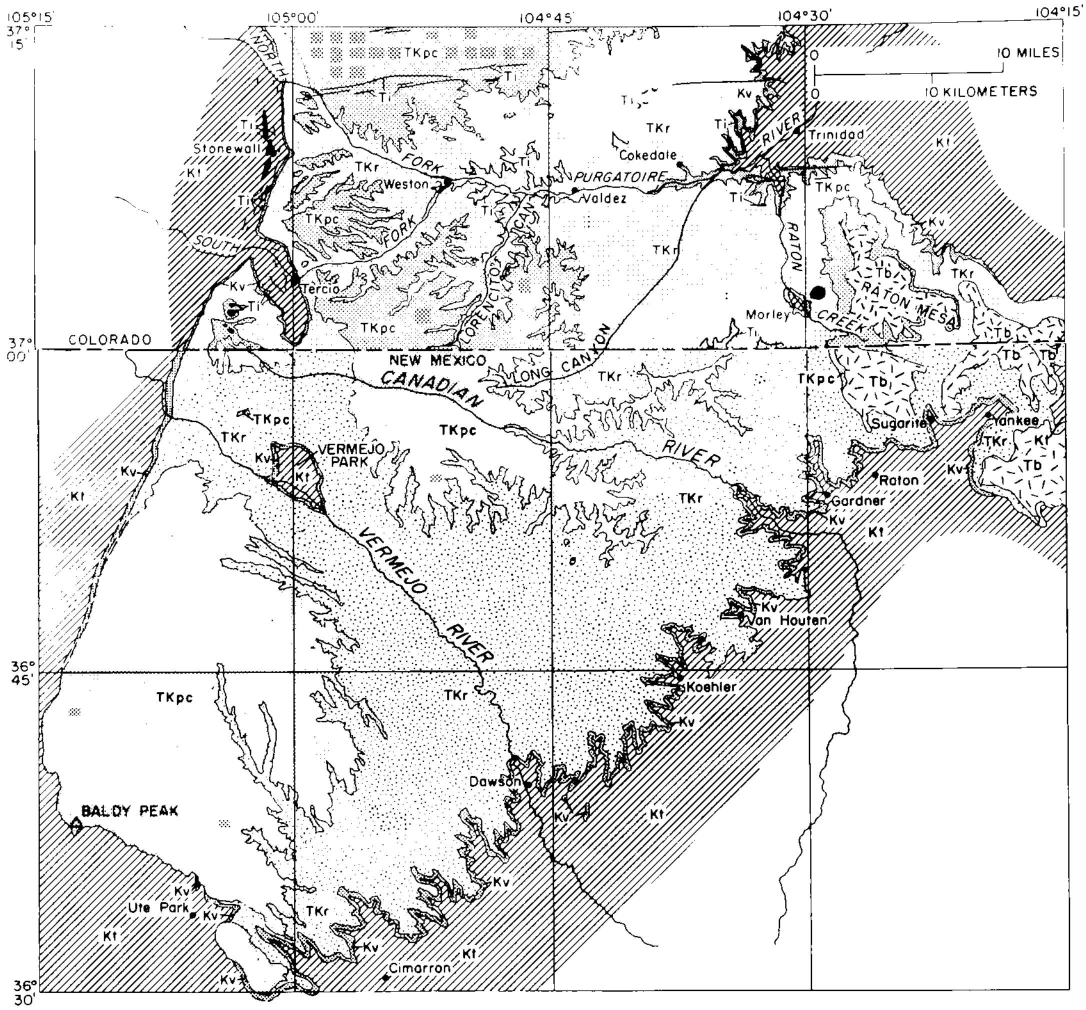


Figure 1.—Generalized geologic map of Raton and Trinidad coal fields. Kt, Trinidad Sandstone and older rocks; Kv, Vermejo Formation; TKpc, Poison Canyon Formation; Tb, basalt lava flows; Ti, Tertiary dikes and sills. Modified from Johnson (1969).

Table 1.--Generalized stratigraphic section of Cretaceous and Tertiary rocks in the Raton coal field

[Position of Cretaceous-Tertiary Boundary from Pillmore, 1969]

AGE		FORMATION	GENERAL DESCRIPTION	APPROXIMATE THICKNESS (ft)	(m)
TERTIARY	PALEOCENE	POISON CANYON FORMATION	Sandstone, coarse to conglomeratic, beds 5 ft (1.5 m) to more than 50 ft (15 m) thick, interbeds of soft yellow-weathering clayey sandstone; thickens to west at expense of underlying rocks.	500+	(150+)
		RATON FORMATION	Sandstone, very fine grained to fine grained, with interbeds of claystone, siltstone, and coal; commercial coal beds in upper part. Lower few feet conglomeratic; intertongues with Poison Canyon to the west. Generally sharp erosional contact with underlying Vermejo Formation.	0-2,000	(0-610)
CRETACEOUS	LATE CRETACEOUS	VERMEJO FORMATION	Sandstone, very fine grained to medium grained, interbedded with mudstone, carbonaceous shale, and coal; extensive thick coals top and bottom.	0- 380	(0-115)
		TRINIDAD SANDSTONE	Sandstone, very fine grained to medium grained; contains casts of Ophiomorpha sp.	0- 130	(0- 40)
		PIERRE SHALE	Black shale, limestone concretions, silty in upper part; grades up to sandstone.	2,500+	(760+)
		NIOBRARA FORMATION	Limestone and calcareous shale; consists of the Smoky Hill and Fort Hays Limestone Members.	500+	(150+)
		CARLILE FORMATION	Black shale, gray calcareous shale, and calcarenite; consists of the upper black shale unit, and Juana Lopez, Blue Hill Shale, and Fairport Members.	250	(76)
		GREENHORN FORMATION	Limestone and calcareous shale. Consists of the Bridge Creek Limestone Member and the Hartland and Lincoln Members.	130	(39)
		GRANEROS SHALE	Black shale and shaly limestone.	110	(33)
	EARLY CRETACEOUS	DAKOTA SANDSTONE	Quartzitic sandstone.	145	(44)

1980 ROMOCOAL FIELD TRIP
GENERALIZED FIRST DAY ROAD LOG
FROM DENVER SOUTH THROUGH CASTLE ROCK, COLORADO SPRINGS, PUEBLO, AND TRINIDAD, COLORADO TO RATON, NEW MEXICO

Charles L. Pillmore
U.S. Geological Survey
Denver, CO 80225

TUESDAY, APRIL 29, 1980
ASSEMBLY POINT: Green Center,
Colorado School of Mines
Golden, Colorado
DEPARTURE TIME: 3:30 P.M.

Buses will load for the field trip in front of the Green Center at about 3:00 p.m. following the last session of the symposium on Tuesday afternoon, April 29. We will proceed to the Holiday Inn for a short stop so that people can leave or pick up bags and make other arrangements as necessary. The buses will leave the Holiday Inn, pass through Denver, and head south on Interstate 25 for Raton, N. Mex.

Denver to Castle Rock: Through Denver and south from the city, the route is underlain by the Denver Fm. of Cretaceous and Paleocene age. About 10 mi south of the city, the route passes into rocks of the Dawson Arkose, of Paleocene and Eocene age, which is overlain by the Castle Rock Conglomerate of Oligocene age. At Castle Rock, the small butte northeast of town is capped by the conglomerate and is the type section.

Castle Rock to Colorado Springs: South of the town of Castle Rock, many of the mesas are capped by the silicic Wall Mountain Tuff, an ash flow tuff (34.8±1.1 m.y. old, J. D. Obradovich, written communication) of the Thirtynine Mile volcanic field, which lies in the mountains to the west. The route continues in the Dawson Arkose nearly to Colorado Springs. Outstanding examples of pediments of three ages, capped, from highest to lowest, by Rocky Flats, Verdos, and Slocum Alluviums, can be seen north of the highway in the vicinity of the Air Force Academy. The two large scars visible on the mountain front of the Rampart Range are quarries in limestone of Paleozoic age that were developed for concrete aggregate. Just past the south entrance of the Air Force Academy, I-25 crosses Monument Creek and passes through the coal-bearing Laramie Fm. (a light-colored outcrop in the roadcut) and the Fox Hills Sandstone (mostly covered) down into Pierre Shale, all of Late Cretaceous age. Much of the area south of Monument Creek is underlain by abandoned coal mines in the Laramie Fm.. Continuing on south into Colorado Springs, good views are afforded of Pikes Peak, which is underlain by the Precambrian Pikes Peak Granite (1.04+ billion years old), and Cheyenne Mountain, which houses the large underground installation of NORAD. A large reverse fault trends along its eastern base. A huge rockfall that may have been triggered by an earthquake along the fault covers about 3 mi^2 of Pierre Shale at the base of the mountain. The campus of Colorado College can be seen to the east of the highway in the northern part of the city, and in the southwestern part, the famous Broadmoor Hotel can be seen.

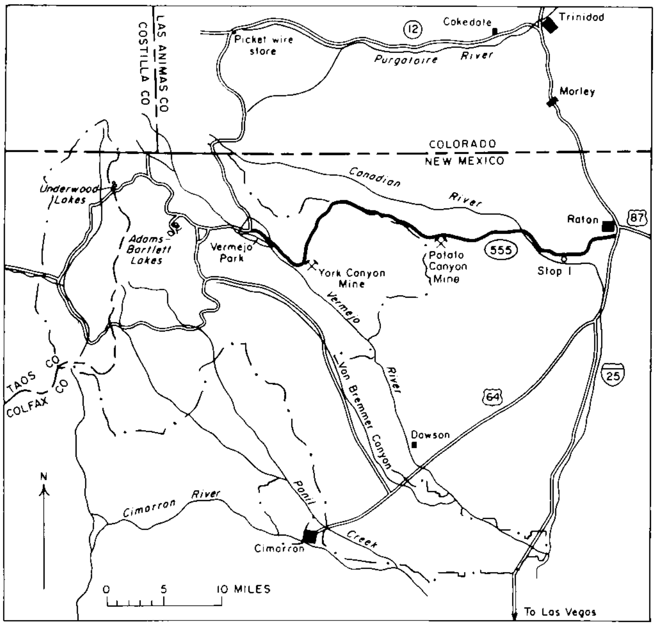
Colorado Springs to Pueblo: Proceeding south from Colorado Springs, the route continues in Pierre Shale all the way to Pueblo. The immense training grounds of Fort Carson army base lie to the west of the Interstate for many miles south of the city.

In Pueblo we pass into the underlying Cretaceous Niobrara Fm. at about the point we cross the Arkansas River. South of the river we pass the Colorado Fuel and Iron steel plant (CF&I) and can observe the new Comanche power generating plant to the southeast of the steel plant. This plant was constructed mainly to provide power for electric furnaces at CF&I. Coal for the steam plant is brought from AMAX's Belle Ayr mine near Gillette, Wyo. by unit train; coking coal for the steel plant is produced at the Allen and Maxwell mines west of Trinidad. CF&I also purchases some supplemental coal from Kaiser Steel Corporation's York Canyon mine west of Raton, N. Mex.

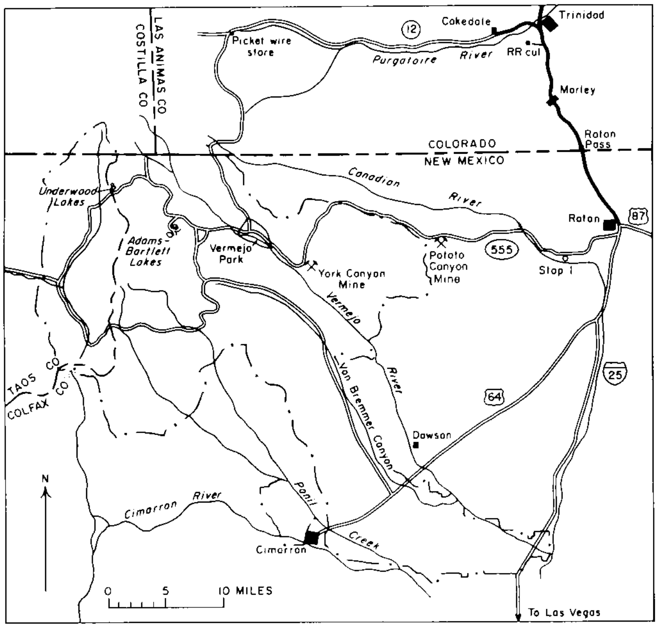
Pueblo to Trinidad: South from Pueblo we will drive through gently rolling, dissected terrain underlain by Upper Cretaceous rocks of the Niobrara, Carlile, and Greenhorn Fms., past ridges and mesas supported mainly by the Fort Hays Limestone Member of the Niobrara and the Bridge Creek Limestone Member of the Greenhorn Fm.

Just south of the Colorado City exit from I-25, we cross Greenhorn Creek and pass through the oldest of the Cretaceous units in this area as we climb up a large ridge supported by Dakota Sandstone, which is exposed on the south side of a large fault that trends about east-west, parallel to the creek. South from the top of the ridge we leave the Denver Basin and proceed for several miles back up section through the progressively younger Graneros, Greenhorn, Carlile, and Niobrara Fms. into the Pierre Shale of the Raton Basin. The Raton Basin is a large arcuate structural basin that extends from here south into New Mexico. (In the Denver Basin, the Dawson Arkose is roughly equivalent to the Poison Canyon Fm. of Raton Basin terminology; the Denver Fm. is approximately equivalent to the Raton Fm.; and the Laramie Fm. and Fox Hills Sandstone essentially correlate with the Vermejo Fm. and the Trinidad Sandstone).

We continue in Pierre Shale for about the next 50 mi past Walsenburg and Aguilar along the margin of the Tertiary rocks of Raton Basin. This margin, which defines the eastern limits of the Walsenburg and Trinidad coal fields, is marked by abrupt cliffs formed by the Cretaceous Trinidad Sandstone and the overlying coal-bearing Vermejo Fm. and the Cretaceous and Paleocene Raton Fm.. The scenery along this part of the route is dominated by the Spanish Peaks, which lie to the west. Spanish Peaks are formed by intrusives considered to be about 22 m.y. old (see "Third Day Road Log") and are well known for the large number of dikes that radiate from them for distances of several miles. At Trinidad we enter the region covered by the "Third Day Road Log" and proceed over Raton Pass to the Holiday Inn at Raton, N. Mex.



Second day road log route (heavy line).
(Dash-dot line shows boundary of Vermejo Ranch).



Third day road log route (heavy line).
(Dash-dot line shows boundary of Vermejo Ranch).

1980 ROMOCOAL FIELD TRIP
SECOND DAY ROAD LOG
FROM RATON TO VERMEJO PARK THROUGH THE RATON COAL FIELD VIA THE YORK CANYON MINE

(as modified from the second day road log of
Vermejo Park Field Trip
1976 Guidebook of the
New Mexico Geological Society)

Charles L. Pillmore
U.S. Geological Survey
Denver, CO 80225

WEDNESDAY, APRIL 30, 1980
MILEAGE POINT: La Mesa Race Track frontage road.
DEPARTURE TIME: 8:00 A.M.
ASSEMBLY POINT: Holiday Inn, Raton, New Mexico

The RoMoCoal Field Trip route proceeds west from Raton on the York Canyon mine road, N.M. 555, through the Tertiary coal-bearing rocks of the Raton coal field to Vermejo Park. Beginning in the nearly flat lying Pierre Shale, the route proceeds up the Canadian River through the Trinidad Sandstone and Vermejo Fms. and along Potato Canyon through sandstone and shale beds of the Raton Fm. past the site of Kaiser Steel Corporation's new exploration mine in the Potato Canyon coal bed at mileage point 14.4. Several coal beds of the Vermejo and Raton Fms. are exposed in roadcuts along the route. The road crests on rocks of the Poison Canyon Fm. (mile 19) that form the Park Plateau surface. For 12 mi the route follows the divide between the Canadian River and Vermejo River, providing spectacular vistas to the west of the Cimarron and Culebra Ranges of the Sangre de Cristo Mountains. Leaving the ridge, we enter Vermejo Park lands and descend back down through the upper part of the Raton Fm. along Road Canyon to the York Canyon mine, which lies in the west central part of the Raton coal field.

From York Canyon mine, we continue on through the Vermejo gate to the Vermejo River. Vermejo Park is closed to the public; the entry gate is manned at all times and advance permission is required to enter. We will stop in Vermejo Park at Casa Grande, the headquarters of Pennzoil's Vermejo Park Ranch. Lunch will be provided and we will have an opportunity to visit the grounds and also study the Trinidad Sandstone, which is well exposed around the rim of the park. Following lunch, we will return to the York Canyon Mine, where Kaiser Steel officials will discuss the mining and reclamation operations and we may examine the coal and enclosing rocks.

0.0 Set mileage at entrance to La Mesa Park. Turn right on access road (adjacent to highway). Note sign "Vermejo Park Hdq. 40 miles." The panorama to the south affords a view of the Raton volcanic field in the southeast quarter. Ahead is Eagletail Mountain, a broad shield volcano, about 10 mi south of Raton. At 9:00 are high mesas with attendant basaltic caps; the high basalt-covered mesa is Johnson Mesa; Hunter Mesa extends out as a tongue from Johnson Mesa; and Maloche Mesa is the small outlier that is detached from the main flow. At the foot of the mesas, erosional surfaces of Levings (1951) are visible: the highest, the San Miguel surface, is restricted to a small remnant on the southwest flank of Johnson Mesa; below the San Miguel is the more extensive Beshoar surface, which extends out from the mesa flanks; and below that, the Barilla surface, the lowest and most extensive. (See Pillmore and Scott (Guidebook,1976) for a more complete discussion.) As seen readily from the road, outcrops of formations below the basalt are quite scarce due to landslides.

0.2 Turn right on N.M. 555 at sign to York Canyon.

0.3 Entrance to new Raton Hospital to left; La Mesa Racetrack on right at 12:00. The canyon walls of the Canadian River are formed by Raton Fm. underlain by a thin sequence of coal-bearing rocks of the Vermejo Fm., which is in turn underlain by the light-gray cliffs of the Trinidad Sandstone. The gray slopes below the Trinidad are the Pierre Shale. Far across the valley at the foot of the slopes, the entrance to Dillon Canyon can be seen at 2:00. At this entrance, but not visible from this road, is the abandoned town of Gardiner, and the nearby dump and coke ovens of the old Gardiner, Blossburg No. 4, and Brilliant No. 1 mines. The Blossburg No. 4 was operated from 1882 to 1898.

0.6 Entrance to Raton Flying Service airport. Across the broad valley at 12:00, the Beshoar pediment, characterized by pine trees, and barren Barilla pediment are well exhibited. Other lower terrace remnants are present along the south side of the Canadian River valley.

1.2 Railroad crossing. Gravel pits on left, just above and behind the crossing. Bridge over Dillon Creek. Remnant of Barilla surface at 3:00.

2.4 Junction with alternate road into Raton. Veer left and continue on York Canyon mine road. To right, landslide deposits overlie Pierre Shale.

2.8 STOP 1; ORIENTATION. Surface exposures are Pierre Shale. Landslide deposits occur at the base of the slope and consist mostly of sandstone from overlying formations; porous soil supports the growth of Pinon Pine and Rocky Mountain Juniper. To the east, the balalt-capped Johnson, Hunter, and Maloche Mesas and their accompanying landslide deposits are visible. To the southeast, the Raton volcanic field and associated cones and flows are clearly visible.

Eagletail Mountain is at about 8:00 on the southern horizon. The Barilla and Bashoar pediments are clearly seen from here, along with the lower terrace surfaces of the Canadian River. The high remnant on the right is probably equivalent to Levings' (1951) San Miguel pediment. To the southeast, basalt flows appear to rest on surface that conforms to the Barilla surface. It is apparent that some major eruptions during the late stages of the volcanic activity flowed onto the Barilla or related surfaces. On the ridge crest, at 3:00, coal beds in the Vermejo Fm. are underlain by light-colored sandstones of the Trinidad. The Vermejo is thin (45 ft, Lee, 1923), and the Raton coal bed is about 20 ft above the top of the Trinidad.

3.8 Exposure of Pierre-Trinidad transition zone and overlying Trinidad is at 3:00.

4.6 To south across canyon are dissected fan and terrace deposits.

5.7 Roadcut exposes Trinidad Sandstone and upper part of Pierre Shale. To left is mouth of Coal Canyon, one of the major tributaries of the Canadian River. Thick sandstone beds of lower part of Raton Fm. form ledges on upper slopes of ridges on left.

7.4 Gravel pits on left; gravel is mostly locally derived sandstone of Trinidad and Raton Fms. Gravelly alluvium in flood-plain deposits of the Canadian River was used extensively by Kaiser Steel Corp. for mine road. To right of road is a toreva-block or rotational landslide of Trinidad Sandstone in the shale.

7.8 Roadcut exposes transition zone of Pierre Shale. At top of exposure, thin very fine grained sandstone beds are interbedded with silty shale of the Pierre. Blocks and pieces of Trinidad Sandstone form landslide deposits that cover the slopes along the road.

7.9 Roadcut into transition zone shows sandstone beds increasing in number and thickness upward. Trinidad Sandstone immediately above roadcut.

8.5 Junction with small road to right. Trinidad Sandstone directly above road on right.

8.7 Road crosses Canadian River. Trinidad Sandstone in streambank and at 12:00.

8.9 Road again crosses river. Recent road construction has cut out loop in the road.

9.1 Cross Canadian River, near top of Trinidad.

9.3 From curve, ranch buildings visible at 12:00. On north side of canyon, good exposure of coal and carbonaceous beds of Vermejo Fm. (See Bohor and Pillmore, 1976, for description.) Position of base of Raton Fm. is uncertain.

9.6 Gravel pits on left; Holocene alluvium on north bank. Mouth of Deer Canyon.

9.6 Thick sandstone beds of Raton Fm. on right.

10.2 Road crosses Potato Creek and proceeds up Potato Canyon. Thick sandstone beds of lower part of Raton Fm. on right. Sills intrude sandstone near base of the Raton, in south creek bank of Canadian River.

12.6 Roadcut in dark mudstone and sandstone interbedded with thin beds of carbonaceous shale and coal of the Raton Fm. For the next 0.5 mi, road proceeds through lower part of the Raton Fm.

13.0 Junction with old, abandoned logging road. Tin Pan coal bed in bulldozer cut. The coal zone is 7.5 ft thick and contains 74 in. of coal. A tonstein occurs as a 2-in.-thick parting about in the middle of the coal. (See Bohor and Pillmore, Guidebook 1976, for measured coal section.)

13.6 Sandstone outcrop on south bank of stream, apparently formed by slumping or sandstone-foundering.

14.1 Bulldozer scrape on right side of road exposes Potato Canyon coal bed.

14.4 STOP 2; POTATO CANYON MINE. Kaiser Steel Corp. is opening an exploration mine to test roof conditions above the Potato Canyon coal bed and study mining costs for future production of steam coal. The Potato Canyon coal bed lies about 950 ft above the top of the Trinidad Sandstone in the middle part of the Raton Fm. and ranges from 0 to more than 8 ft thick. It lies about 100-150 ft above the Tin Pan coal bed and is characterized by numerous shale partings as shown on the accompanying section of the coal, measured at a prospect entry about 0.2 mi west up the road:

10+	Sandstone,
1.0	Shale
1.0	Sandstone
1.25	Shale
2.0	Coal
.1	Shale
1.5	Coal
.15	Coaly shale
2.65	Coal
.5+	Carbonaceous Shale

At this stop, we will also examine a large faulted channel-fill sandstone body that crops out near the mine area on the south side of the canyon.

14.6 Prospect entry into Potato Canyon coal bed. The mine extends only a few tens of feet.

16.1 Junction with old logging road to right. In roadcut at 12:00, an 8-10-in.-thick coal bed crops out in a sequence of mudstone and siltstone beds.

16.3 Landslide deposits. A 22-in.-thick coal bed is exposed near top of cut. The coal contains three thin tonsteins as described by Bohor and Pillmore (Guidebook,1976).

16.9 Grayish-red and orange colors indicative of a reducing environment begin to appear, marking beginning of Raton-Poison Canyon transition zone. Thin carbonaceous streaks are present in roadcut.

17.4 Cattle guard. Transition zone between Raton and Poison Canyon Fms. Grayish-orange to yellowish-gray- weathering clayey sandstone interbedded with irregular lenses and beds of fine-grained sandstone that contain grains of fresh potash feldspar. Coarsens upward to very coarse grained and granule-sized grains.

18.2 Road crests ridge. Thick sandstone beds in Poison Canyon Fm.

18.6 Turnoff to Armstong Fire Lookout Tower on left.

19.5 Road to left goes to Koehler by way of Crow Canyon. At 12:00, Purgatory Peak (elev. 13,676 ft) in Colorado.

20.7 Panoramic view over western part of the Raton coal field centered at about 2:00. West and East Spanish Peaks are visible over the tree-covered horizon to the north. Looking to the right, the Colorado part of the Sangre de Cristo Mountains can be seen, including Purgatory and other peaks over 13,000 ft in elevation; Purgatory Peak is at 12:00. To the left, the headwater area of the Vermejo River is visible, and farther to the left, at 10:00, the next highest point on the ridge is Little Costilla Peak (elev. 12,584 ft). At 9:30, Copper Mountain and Baldy Peak, which are in Philmont Scout Ranch, can be seen. Ahead, the tree-covered rolling hills constitute the western part of the Raton coal field; they are mostly underlain by rocks of the Poison Canyon and upper Raton Fms. Vermejo Park (not visible) lies to the left at 11:00. On the left, lying just beneath the Poison Canyon, is the Chimney Divide coal zone, which contains coal beds 2-4 ft thick under only 50-100 ft of cover on long fingerlike ridges. The rocks exposed here and for some distance along the road are representative of the Poison Canyon Fm., arkosic sandstone that ranges from very fine grained to very coarse grained with streaks and seams of granule sandstone and conglomerate. Many of the beds weather grayish-orange to pink. Interbeds of clayey sandstone or sandy claystone form grayish-orange to yellowish-gray slopes. The sandstone layers are irregularly bedded and are mostly discontinuous lenses. For the next 11 mi, the road continues along the drainage divide between the Canadian and Vermejo Rivers. The entire crest of the divide is underlain by the

Poison Canyon Fm. The fences on the left separate Kaiser Steel Corp. property from the Vermejo Ranch.

30.3 Undrained depression of probable eolian origin on left. During the 1965-66 drought, pits were dug in several natural basins such as this to capture water for cattle.

30.7 Cattle guard; enter Vermejo Ranch. Loading pens and corrals on right; road to Chimney Divide and Caliente Canyon on left. About 2 mi southeast the most recent wildcat oil well in the area was drilled to 6,335 ft T.D. in 1973-74 (American Fuels Corp. No. 10 NMB). The Fort Hays Mbr. of the Niobrara Fm. was the oldest unit penetrated.

30.9 Beginning of transition zone between Raton and Poison Canyon Fms.

31.7 Approximate base of transition zone.

In areas where lithologies are not significantly different and color differences indistinct, the contact is placed above the highest coal or carbonaceous zone and beneath the lowest persistent bed of arkosic granule sandstone.

32.2 Chimney Divide coal bed (4 ft thick) in roadcut.

33.5 Stock pond and dam on left. Ridge crest at 10:30 underlain by 4-ft-thick Chimney Divide—coal in 4.5-ft zone.

34.2 Stock pond. Bulldozer scrape on east side permits view of Raton sequence of channel sandstone resting on irregular surface cut into mudstone below.

34.7 Excavation on left at 9:00. Air intake for northern workings of York Canyon mine.

35.1 Approximate northern limit of outcrop of York Canyon coal bed.

35.3 Outcrop to left, at 9:00, is probably discovery point of York Canyon coal bed, as it is one of the rare outcrops (12 ft thick). To the right, about 25 yd south of the outcrop, is a slumped burned exposure in which the coal does not crop out. The coal bed is commonly covered with talus and slope debris from an overlying resistant sandstone. Where the coal has burned on the outcrop, it is reduced to ash, leaving a void filled with overlying rocks. Adjacent to the road on the right and straight ahead, rounded slopes are typical of areas reclaimed by Kaiser Steel Corp. after strip mining. The York Canyon bed, 9-12 ft thick beneath the point of this ridge, was completely mined; reclamation is nearly completed. Surface mining is continuing to the west. Overlying the York Canyon coal is a nearly continuous tabular sandstone that forms a resistant roofrock in most places underground. In surface mining, this caprock creates problems when it breaks out in large blocks.

35.6 Prospect entries and vent fan for York Canyon coal mine. The York Canyon coal bed is exposed beneath the tabular sandstone at the Prospect entry site and in the midslope of the ridge on the east side of the canyon. The coal (11 ft thick) has a parting 1 ft thick located about 18 in. from the top. At the right limit of the exposure, the coal beneath a fault that dips 30°-40° S. This fault displaces the coal bed about 50 ft and continues to the southeast. The fault was not observed on the west side of the canyon during strip mining; apparently it swings north and ends farther up the canyon. The York Canyon coal bed was originally opened by Kaiser Steel to deliver coal for a test run at the Fontana Steel plant in Fontana, Calif. in 1964. A road was built, and the coal was trucked about 40 mi back up Road Canyon, along the divide, and down through Crow Canyon to the Koehler wash plant; there it was washed and shipped to Fontana by rail. The test was successful and plans were then made to open the main entries of the York Canyon mine, nearly a mile to the south. The preparation plant at York Canyon was completed in 1966 and the mine was opened that same year. The wash plant is especially designed to recycle the water used in washing coal. Powdered magnetite from Kaiser's Eagle Mountain operation is used as a heavy-media agent in the plant. Availability of water is a principal concern; to supplement the meager surface and subsurface flow in York Canyon, water is pumped from the Vermejo River up to the mine.

35.8 Road junction. Turn right to Vermejo Park.

36.0 Junction with main coal-haulage road. CAUTION—Coal trucks cross the road from nearby surface mines. This road also leads to the Upper York Canyon prospect, which was opened July 10, 1976, about 6 mi northwest of here in the Left Fork of York Canyon. The mine was opened on the Upper Left Fork coal bed, which lies about 60 ft stratigraphically above the lower bed and about 300 ft below the

York Canyon coal bed (Pillmore in Guidebook,1976). The beds range from 3.5 to 11 ft thick and, based on extensive drilling data, reserves exceed 100 million tons. The mine is scheduled to begin operation early in 1981.

36.6 Crest of ridge between York and Vermejo Canyons. In gully immediately ahead, the York Canyon coal bed consists of upper and lower coal beds separated by a 12-ft parting that thickens (to 35 ft) rapidly to the west.

38.6 Vermejo Ranch entry gate (locked), permission required to enter.

38.8 Junction with Vermejo River road. Adobe ruin across valley.

38.9 Gravel pit into river terrace. Gravel, used for road to mine, is composed of a wide variety of rock types; the most resistant are rhyolite from Ash Mountain and quartzite pebbles and cobbles from various sedimentary units. Crops are cultivated for stock feed on soils developed in alluvium along the Vermejo River floodplain and at Vermejo Park.

39.6 Folded beds of the Vermejo Park anticline become apparent. Road to Juan de Vaca canyon to the left. Approximately 0.5 mi up No. 1 canyon to the right, a coal bed crops out that appears correlative with the upper Left Fork bed.

39.8 Left Fork coal zone exposed in the roadcut, dipping 10° E. This coal zone is the lowest coal of significant thickness in the Raton Fm. in the western part of the Raton coal field. The coal can be seen on the south (left) side of the canyon near a lone pine tree. About 1 mi up Juan de Vaca canyon, at the last known exposure of this bed, the zone measured 4.75 ft thick and contained nearly 4 ft of coal.

40.9 Mouth of Reed canyon on right. Base of Raton Fm. crosses road. Ledge on both sides of road is formed by conglomerate, the basal unit of the Raton Fm. The covered slope ahead is underlain by the coal-bearing Vermejo Fm. East entrance to Vermejo Park. Vermejo Park is a broad dissected anticline that plunges southeast.

41.0 Vermejo coal bed at 3:00; prospect pit 60 ft beneath top of the Vermejo Fm.

41.3 Two- to three-foot-thick sill of intermediate composition intrudes lower part of Vermejo Fm. in the interval occupied by the Raton coal bed.

41.4 At 9:00, the Trinidad crops out across the river. Trace fossils can be observed at this exposure.

41.6 Top of Trinidad Sandstone at 3:00, about 50 yd north of road. Outcrop of Raton coal bed, coked by the intrusive, lies above the Trinidad.

41.7 Approximate base of transition zone between Pierre Shale and Trinidad Sandstone. Up gully to right a complete section of the Trinidad is exposed, which contains the best examples in the area of the trace fossil *Diplocraterion*, (Pillmore and Maberry, Guidebook, 1976).

41.8 Pond to right. For the next 0.5 mile, Pierre Shale is overlain by a large landslide.

42.4 STOP 3; LUNCH. Bartlett mansion gate. On point at 2:00 is a pavilion on Trinidad Sandstone Here the upper part of the Pierre and most of the Trinidad are well exposed. The tree-covered slope above the Trinidad cliffs is the Vermejo Fm., and the sandstone cliffs at the top of the ridge are the basal Raton conglomerate. High peaks of the Sangre de Cristo Mountains visible at 12:00. To the left of the Park are landslides. Entrance to Vermejo Park guest area, Park Headquarters and Bartlett mansion. (Refer to "History of Vermejo Park," Laurie, Guidebook, 1976, reprinted in this volume.)

Return to Raton via a stop at the York Canyon mine. (Refer to "Underground and surface operations at the York Canyon mine", Guidebook, 1976, reprinted in this volume).

1980 ROMOCOAL FIELD TRIP
THIRD DAY ROAD LOG
FROM RATON TO COKEDALE OVER RATON PASS THROUGH THE EASTERN PART OF THE TRINIDAD COAL FIELD, COLORADO

(as modified from the second day road log of the
Vermejo Park Field Trip
1976 Guidebook of the
New Mexico Geological Society)

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THURSDAY, MAY 1, 1980
ASSEMBLY POINT: Holiday Inn, Raton
DEPARTURE TIME: 7:30 A.M.

Leaving Raton we will proceed north over Raton Pass towards Trinidad on Interstate-25. Driving up the Pass, the route progresses through rocks of the Trinidad Sandstone and Vermejo and Raton Fms., nearly to the contact of the Raton and Poison Canyon Fms. which is near the top of Raton Pass. Several coal beds and sills can be observed in roadcuts along the route. We will make an orientation stop at the Raton Pass rest area at the top of the pass and will also make one or two short stops along the way for a look at sedimentary structures in the Raton Fm. As we proceed north down the pass toward Trinidad, the effects of the Morley dome can be observed at the abandoned coal-mining town of Morley, and coal dumps along the way present evidence of early mining in the area. At Trinidad, we will turn west and proceed to the area of the new Corps of Engineers dam where some excellent exposures of the Trinidad Sandstone have been produced by construction of a new railroad bypass around the lake. In this area, the Trinidad shows evidence of being formed in a deltaic environment; a stop will be made to examine some of the aspects of sedimentation.

Following examination of the railroad cuts, we will proceed across the valley of the Purgatoire River to the old mining town of Cokedale, where residents of the town will serve lunch and discuss the function of the beehive coke ovens and other aspects of the history of mining in Cokedale.

After lunch, we will return to Trinidad and proceed north on I-25, exiting at Ludlow Junction, about 10 mi north of Trinidad. We will drive west past the site of the historic Ludlow massacre, up Delagua Canyon to the Delagua mine. Delagua mine officials will lead us through the mine and discuss the surface-mining operation. Following a brief opportunity to examine the coal, the buses will return to Denver via I-25, arriving at the Green Center about 6:00 p.m.

0.0 Leave Holiday Inn.

0.2 Enter Interstate 25 northbound. Ahead and to the east, the sedimentary rocks of the Pierre Shale, Trinidad Sandstone, and Vermejo and Raton Fms. are mostly covered by landslide debris from basalt-covered Bartlett and Johnson Mesas.

1.2 To right, just before overpass, the middle part of the Pierre Shale (Exiteloceras jenneyi zone) is exposed in ditch along road.

1.3 Road on overpass leads to the abandoned mining town of Sugarite, where the Sugarite coal, a noncoking variety, was mined for many years.

1.5 At curve, along ridge to east is a remnant of the Beshoar pediment (Levings, 1951). Gray to light-gray sandstone of the Trinidad crops out in the middle lower slope to the right. Above the Trinidad are sandstone, shale, and coal beds of the Vermejo and Raton Fms. In the Raton area, the contact between the Vermejo and the Raton commonly is not well defined.

2.6 Outcrop of Pierre Shale in roadcut at overpass.

3.2 Thin sandstone stringers of Pierre transition zone.

3.7 Trinidad Sandstone in roadcut. Thin coal beds and carbonaceous shales of the Raton coal bed, the lowest in the Vermejo Fm., can be seen lying directly on the Trinidad above the roadcut.

4.2 More coal beds visible near top of the Vermejo Fm.

4.3 Raton Fm. sandstone in outcrop. Roadcuts show typical interbedded sequences of mudstone, siltstone, and sandstone.

5.0 Large landslide from the flanks of the mesa above. The road follows the valley alongside the Santa Fe Railroad; the railroad proceeds through a tunnel near the top of the pass.

5.5 Raton Fm. sandstone, carbonaceous shale, coal and mudstone exposed for several miles along here.

5.7 A brown-weathering sill intrudes a sandstone sequence near the base of Raton Fm.

6.9 STOP 1: Brief examination of coal intervals in roadcut, one at base of sequence, another about midway. Upper coal is absent below a channel-fill sandstone that appears faulted.

7.3 Thick outcrop of basalt composing Bartlett Mesa at 2:00. The hummocky surfaces below are due to landsliding.

7.7 Serious engineering problems with the highway here; failures have necessitated major reconstruction on both sides of Raton Pass at about the same altitude. C. S. Robinson, geologic consultant to the Colorado Highway Department, determined the principal problem on the Colorado side to be highway fill that was laid across the regional dip and dammed a sandstone aquifer. Hydrostatic pressure in the aquifer increased behind the fill until it was overcome, liquified and flowed. In the old days, the Denver and Rio Grande Railway used springs from this aquifer in filling their engine boilers, but the implications of this historical note were lost to the highway builders. Alas for history, within the hour after the Governors of Colorado and New Mexico met on the pass at the state line to cut the ribbon and formally open this stretch of highway, the southbound lane on the Colorado side skiied off downhill on its liquified fill. Robinson suggested that $5,000 worth of porous blanket spread on the aquifer under the fill would have saved the hundreds of thousands of dollars spent on subsequent repairs, which consisted of installation of a caisson wall and pumping wells drilled into the Colorado side and an offset of the roadcut into the bedrock. A similar situation on the New Mexico side removed the southbound lane twice, and the state eventually used Colorado's experience to direct their own repairs on the highway.

8.8 STOP 2: Rest area—roadside park on top of Raton Pass. Sign at rest area reads:

RATON PASS

"Raton Pass, named by the Spanish for the rock rats found there, was crossed by the Mountain Branch (also called the Bent's Fort Branch) of the Santa Fe Trail. Originally part of an old Indian trail, the pass was used by Spanish expeditions at least as early as 1718 and probably much earlier. When the Cimarron Branch of the Santa Fe Trail was abandoned because of its dangerous desert stretches, pioneer traffic increased over Raton Pass. Kearny's Army of the West came this way in 1846 with some of the first vehicular supply wagons to cross the pass "Uncle Dick" Wootton, frontier scout, built a road over the pass in 1865 and collected tolls, often at the point of a gun until the coming of the railroads in 1878. For two years, a controversy raged between the Denver and Rio Grande and the Santa Fe Railroads to determine which company had the right-of-way over Raton Pass. After several section crew fights and much legal maneuvering, the Rio Grande gave up its claim to Raton Pass and the Santa Fe agreed not to contest another disputed right-of-way through the Royal Gorge."

The view from the parking area includes the Trinidad coal field, the Spanish Peaks, and the high peaks of the Sangre de Cristo Mountains. The Spanish Peaks form a landmark that is visible throughout hundreds of square miles. The area lying between Raton Pass and the Spanish Peaks contains several hundred million tons of coal resources, and several companies are evaluating the area's remaining coal-producing potential. The oil and gas potential is also being explored, but, to date, no commercial quantities have been produced from rocks in the Raton Basin. The contact between the Raton and Poison Canyon Fms. lies just above the top of Raton Pass. The top of the Trinidad Sandstone is 1,270 ft below the top of the pass The thickness of the Vermejo Fm. is estimated to be about 70 ft in this vicinity, making the Raton about 1,200 ft thick. To the west, in the central part of the basin, thicknesses are about 2,000 ft for the Raton and about 300-500 ft for the Vermejo.

The Spanish Peaks plutons have been dated at 21.7±1.0 m.y. B.P. (Stormer, 1972, East Peak granite) and 22.9±2.0 m.y. B.P. (Smith, 1973, West Spanish Peak stock). Other dates from 19.8±1.6 m.y. to 39.5 m.y. B.P. have been reported from intrusive rocks in the Spanish Peaks area, but the 39.5 m.y. B.P. date appears questionable and most others fall into the 20-25 m.y. B.P. range (Isochron West, 1974, p. 32-33). The sills and dikes in the Vermejo Park area were intruded at about the same time (J. D. Obradovich, written commun., 1976). The basalts capping the high mesas to the east flowed out between 3.5 and 7.2 m.y. ago (Stormer, 1972).

Leave rest area and continue north on I-25.

11.4 Exit to Wootton, which has a colorful place in early Colorado and New Mexico border history. This was a place where "Uncle Dick" Wootton collected his tolls, charging by the wagon, buggy, horse or passengers. If time allows, a short stop will be made near here to examine some well-exhibited sedimentary structures in the Raton Fm.

11.7 Sandstone beds dipping south in roadcuts exhibit first effects of Morley dome. Ahead are the lower beds of the Raton and the Vermejo Fms.

12.5 In roadcuts on right, two dikes cut through the Trinidad Sandstone into the Vermejo Fm. They intrude the coal zone, and in the northernmost dike, the igneous material tended to spread out into the coal. Coal is commonly coked in this process, and some natural coke can be seen within the dike material here. The baked zones and some intrusives typical of the Raton coal field are very well exposed.

12.6 Coal of the Morley (Raton) bed overlies the Trinidad Sandstone in the roadcut.

12.7 Dump pile of the old Morley mine at 9:00. Morley began as a railroad town on the A.T.&S.F. line in 1879, and trains often divided here before beginning the difficult climb over Raton Pass. Inactive during the late 1800's, Morley became a coal-mining company town in 1906, when the Colorado Fuel and Iron Co. (CF&I) opened the Morley mine. The fine-grade coking coal mined here was utilized by the steel mills in Pueblo and by Santa Fe Railroad locomotives. Peak coal production was 500,000 tons per year, reached in the late 1920's, when the town had a population of over 1,000. The Morley mine was never mechanized; the use of blasting powder and machinery was prohibited because of significant amounts of methane gas underground. Instead, the coal was extracted by hand labor and a herd of mules was maintained to haul the coal out of the mine. Cutbacks in steel production at Pueblo halted coal production in the early 1950's, and the mine was closed for good on May 4, 1956, when all workable deposits had been exhausted. From 1907 until 1956 the Morley mine produced 11 million short tons of coking coal. Most of the several hundred inhabitants of Morley moved to Trinidad, leaving the vacant ruins visible from I-25 today.

12.8 Morley dome has about 450 ft of closure mappable on surface beds. Its axis passes through Morley, where Raton Creek has cut down to the Pierre Shale. The fold is apparently caused by a Tertiary plug or laccolith, which crops out about 1 mi northeast of the town. Although the crest of the fold is mapped between the town and the plug, the closing contours extend around the far north and east sides of this igneous intrusion.

Coal seams in the Raton Fm. have been mined to the contact with the igneous plug, apparently without evidence of natural coking or metamorphism. In one case a slight oil seep was noticed in the mine workings. CF&I drilled two coal-gas relief wells on the low flanks of the structure to reduce gas in the coal mines. In 1948, Stanolind drilled a dry hole on the crest of the structure to a total depth of 6,831 ft into granite. This well penetrated 450 ft of igneous rock between the Dakota and Purgatoire Fms., which approximately equals the amount of surface closure on the structure (Barksdale and others, 1956).

13.1 Pierre Shale exposed in roadcuts.

13.4 Trinidad Sandstone dips to north, forming northern flank of the Morley dome.

14.2 Coal zone within sandstone sequence of Raton Fm. exposed in roadcut.

14.6 Two sandstone beds, apparently channel fillings, come together here, forming a thick body of sandstone. This sandstone thins rapidly, intertonguing with thinner siltstone, carbonaceous shale and mudstone beds, and the lenticular nature of the sandstone is well portrayed.

18.4 Approximate contact of Raton and Vermejo Fms.

18.5 Coal beds of Vermejo Fm. Strip mine at 3:00. The white beds are sandstone interbedded with carbonaceous shale and coal beds of the Vermejo.

19.1 Old coal dump of an early mine on right. Several small prospects are visible on side hills. This is about the position of the Sopris No. 2 coal bed (Raton coal-equivalent) lying above the Trinidad. Town of Starkville west of highway.

20.0 Turnoff to Starkville Road (Exit 4). At this point we will leave the Interstate and proceed west about a mile to the newly relocated C&W railroad around Trinidad Lake. Along the railroad cuts, Romeo Flores of the USGS will lead us through exposures of rocks of the Upper Cretaceous Pierre Shale, Trinidad Sandstone, and Vermejo Fms. he considers to represent an upward-coarsening sequence typical of delta-front and delta-plain depositional environments. Afterwards, we will continue on to Cokedale for lunch. Roadlog continues on I-25 at Starkville exit.

20.2 Coal outcrop below underpass. Ahead across valley is the type section of the Trinidad Sandstone. Pierre Shale is on the underlying slopes and Trinidad caps the ledge at the top of the slope. (An excellent place for night-time geology because a large neon sign clearly labels the sandstone.)

21.1 Trinidad Sandstone in roadcuts.

22.6 Leave I-25 at Exit 7 to Monument Lake. Proceed west on Colorado Highway 12.

22.8 Turn left. Follow Prospect Street about 0.1 mile; then turn right. Road passes tennis courts and new gymnasium at Trinidad Junior College and bends left again. On the route through town, the Trinidad Sandstone forms white cliffs along the ridge north of the road and the Pierre Shale forms the slopes beneath the cliffs.

The site of Trinidad was an Indian ceremonial ground, and experienced the visits of Onate and other Spanish explorers, priests and soldiers; French and American trappers and traders; and Kearny's and subsequent U.S. forces on their way to occupy and pacify New Mexico. The first permanent settlement, a sheepherder's cabin on the south bank of the Pugatoire River, was erected in 1859, and the area soon attracted numerous farmers and traders. The early years of Trinidad were turbulent; conflict between American and Mexican settlers, and between the townfolk and the Ute Indians were common in the 1860's. Coal mining began in 1867, when Frank Bloom opened a small mine primarily to promote the sale of stoves he sold. The coming of the railroad from the north in the 1870's, which provided cheap transportation for coal to smelters and the steel mills in Pueblo, and simultaneously stimulated a flourishing cattle industry, initiated a period of rapid growth for Trinidad. The population reached 9,000 (slightly less than it is now) by 1889. Coal mining is still an important industry, and the town serves as a supply center for a large contiguous rural area.

24.9 New Corps of Engineers' dam on Purgatoire River. Here the road leaves the valley and goes up around the proposed lake. To south at 9:00 is Fishers Peak--a striking sentinel crag of basalt that stands high above the town of Trinidad.

25.1 Road cuts through Trinidad Sandstone.

25.4 Roadcuts at top of hill expose carbonaceous shales, coal beds and irregularly bedded sandstones of the Vermejo Fm. In the Trinidad-Starkville-Cokedale area, several coal beds occur in the Vermejo.

26.6 Road crosses Carpios Canyon, a major tributary to Purgatoire River. At 3:00 is a well-exposed sequence of the upper part of the Vermejo Fm. At top of section, brown sandstones of the Raton Fm. rest on gray shales of the Vermejo.

27.5 Igneous sill intruded into coal sequence. The coal appears impure and is not well coked. Several excellent examples of sills and coking coal beds can be seen in road and railroad cuts up the valley.

30.0 LUNCH STOP: Cokedale junction. The coal waste pile on the north and coke ovens to the south indicate a large operation. According to Danilchik, (oral communication, 1980),the Cokedale coal bed is about 6 ft thick in this area and lies about 220 ft above the Trinidad Sandstone.

After lunch, we will return to Trinidad and proceed north on I-25 exiting at Ludlow Junction, about 15 miles north of Trinidad. Along the route, Pierre Shale is exposed beneath cliffs formed by Trinidad Sandstone to the west of the highway. Leaving the Interstate, we will drive west through Ludlow, the site of the historic Ludlow massacre, crossing the Trinidad Sandstone and Vermejo Fms. and the lower part of the Raton Fm. to the Delagua mine. According to Danilchik, the Delagua coal bed lies about 850 ft above the Trinidad Sandstone and is about 5 ft thick. A second bed, the Three Pines, also about 5 ft thick, underlies the Delagua about 30 ft. Delagua mine officials will lead us through the mine and discuss the surface-mining operation. Following a brief opportunity to examine the coal, the buses will return to Denver via I-25, arriving at the Green Center about 6:00 pm.

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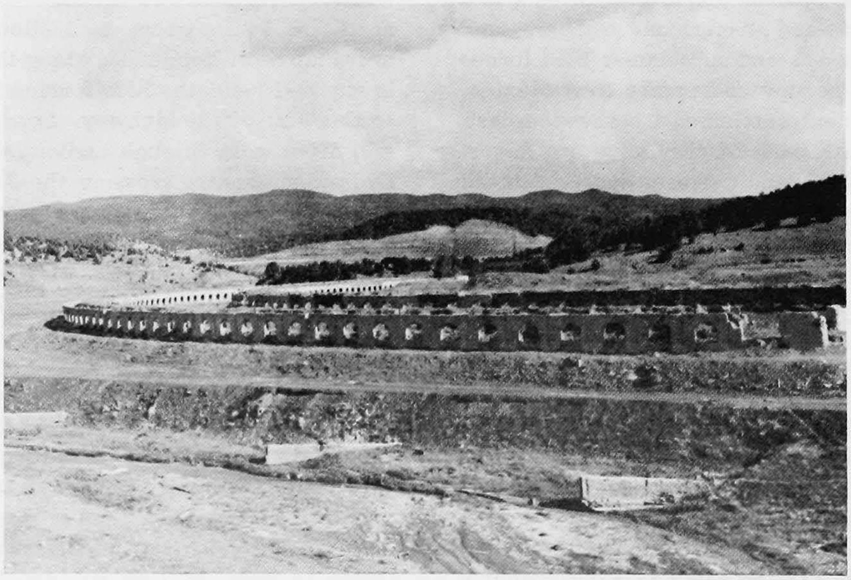

Cokedale mine, Colorado; abandoned coke ovens.

HISTORY OF VERMEJO PARK

KAREN PILLMORE LAURIE
Vermejo Park, New Mexico

From the time Indians ruled the southwestern plains, men and events have shaped the unique history of the Vermejo country. Occupying about 480,000 acres of unspoiled wilderness in northern New Mexico, the Vermejo Park Ranch remains one of the largest blocks of privately owned land in the United States. Part of the Maxwell Land Grant, Vermejo retains qualities and remnants of its rich earlier history.

EARLY DAYS

Before the advent of white settlers or adventurers in New Mexico, Utes and Jicarilla Apaches roamed the valleys and parks of northern New Mexico's Sangre de Cristo Mountains. Though New Mexico was part of the land claimed by Spain in 1524, several hundred years passed during which Indians seldom encountered white men. In 1821 the Mexican government took charge of the land and retained the Spanish policy of awarding land grants in its new colonies; most of these were grants in New Mexico. Under Spanish rule the laws governing the grants had been vague and complicated, resulting in a serious land-grant problem. Mexico inherited this problem and caused its own complications by amending and repealing rules and regulations pertaining to land grants. Consequently, its grant policy was not consistent, and many pitfalls stood between the grants and their final confirmations.

BEAUBIEN-MIRANDA

During this period of inconsistent land-grant policy, Carlos Beaubien, a French-Canadian trapper who had become a Mexican citizen, and his partner Guadalupe Miranda, private secretary to Governor Manuel Armijo of Santa Fe, petitioned the governor for a land grant. In their petition, presented on January 8, 1841, they pointed out the need for the land to be "reduced to possession," so that its natural resources could be put to use. An influential factor in their attaining a grant was proof of their intention to colonize or cultivate the land. Three days after Beaubien and Miranda presented their petition, Governor Armijo answered it, granting them the requested land to be put to good use. They did nothing to reduce the land to possession and ownership for two years. Then, on February 13, 1843, they asked Taos Justice of the Peace Don Cornelio Vigil to sign an order promising them possession of the granted land, which he did. A document, dated February 22, 1843, was drawn up and signed by Vigil, stating that he had marked the boundaries of the Grant in accordance with Beaubien and Miranda's description of the land in their original petition and that he declared the partners to be in full possession of the land.

Father Antonio José Martinez actively resisted the Grant on the grounds that the lands should be opened to the poor people and not granted in large tracts to the wealthy. He filed papers in Santa Fe contesting Beaubien and Miranda's right to land that, he said, rightfully belonged to the people who had for generations grazed their livestock on it. On February 27, 1844, after an investigation into its terms, Governor Don Mariano Chavez suspended the rights of Beaubien and Miranda to the Grant. The partners attempted to prove that the poor people had no objection to the Grant and pointed out some benefits that would come from their cultivation of the land; they thus appealed to the legislature for reinstatement of their claim to the Grant. On April 18, 1844, the assembly sustained their claim.

When the American army invaded New Mexico in 1846, Miranda fled with Governor Armijo to Mexico while Beaubien remained in Taos, becoming loyal to the United States. Along with the new territory, the United States inherited the land-grant problems. Large tracts of land had been granted to many citizens, such as Beaubien and Miranda, under ambiguous, complex laws, and many of the land-tract boundaries were vague. The United States agreed to protect the property rights of the citizens when it took over New Mexico, and thus tried to interpret the old laws and determine definite boundaries. Congress hired a surveyor to study the claims, report on their legitimacy and confirm valid claims. The Beaubien and Miranda Grant was confirmed in this way in 1857, but controversy over this Grant and others continued for several decades.

MAXWELL

Lucien B. Maxwell, pioneer, explorer and adventurer, became involved in the affairs of the Beaubien and Miranda Grant when he married Luz Beaubien, daughter of Carlos Beaubien and one of the heiresses to his interest in the Grant.

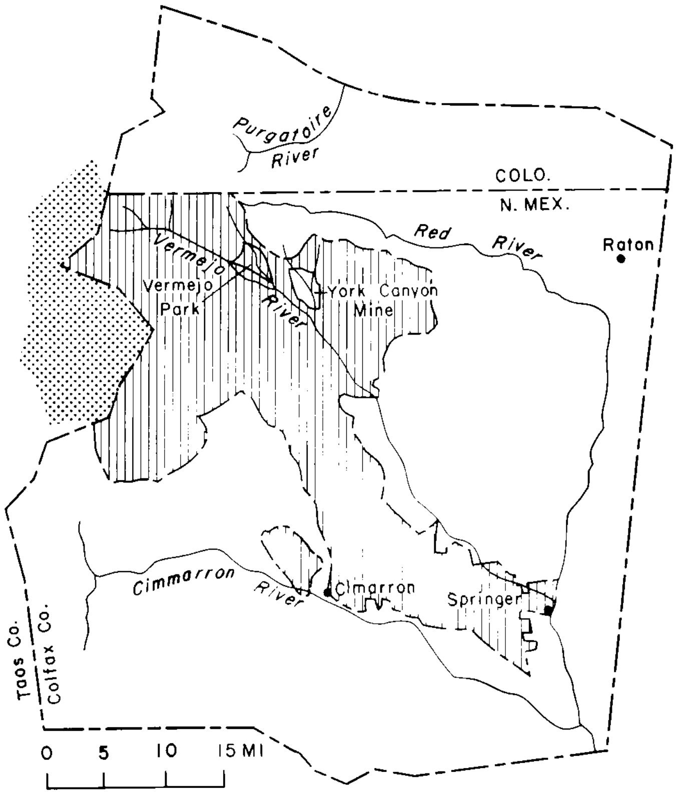

Figure 1. The Maxwell Land Grant. The hachured area shows the part of the Vermejo Park Ranch lying within the Grant boundary; the stippled area shows the part of the ranch acquired outside the Grant.

Beaubien turned over the management of his share of the Grant to Maxwell, who moved onto the Grant, settling at Rayado in 1849. Miranda, no longer interested in land in New Mexico, sold his share of the Grant to Maxwell. After Beaubien's death in 1864, Maxwell bought out all other heirs to the property, thus acquiring the rest of the Grant. By 1865 Maxwell and his wife had become sole owners of what by that time was being referred to as the Maxwell Land Grant, which encompassed 1,714,765 acres. The Grant included the town sites of Springer, French, Maxwell, Otero, Raton, Vermejo Park, Ute Park and Elizabethtown in New Mexico; and in Colorado, Virgil, Stonewall, Torres, Cuerto, Tercio, Primero and Segundo.

Maxwell's residence, renowned throughout the area as large, lavish and extravagant, became a principal stopping point on the Santa Fe Trail and a base for hunters, trappers and prospectors. Maxwell loved gambling, drinking and entertaining; and the rooms in his house reflected his tastes—a gambling room, a billiard room, a dance hall and a huge dining room for the men. Women were not allowed into these rooms; their quarters were in the rear of the house.

Maxwell's relationships with people he knew to be living on his land were peaceful, and in many instances he developed working relationships with them (Miller, 1962, p. 272).

> "He started many a small rancher in the stock business, giving him a herd of cattle, sheep, or horses and a small ranch to be run on shares. The agreement was always a verbal one and sometimes two or three years would pass without a division. Then, when Maxwell needed more stock, hay, or grain to fill his government contracts, he would call in his shareholders, ask for an accounting, always verbal, and direct them to bring in the surplus to him, which was done without question."

Also living on Maxwell's land were people whose ancestors had built homes and ranches and who, for generations, had grazed their livestock on the land and cultivated it without ever having heard of Beaubien, Miranda, or Maxwell. These people undoubtedly believed that they were the owners of the land. Settlers from the East had also moved in and settled on the Grant, hoping to establish homesteads. These people too thought they were entitled to the land upon which they had settled.

Gold was discovered on the Maxwell Land Grant along Willow Creek in 1866. When its presence became known the following year, a rush of prospectors invaded the area and mining camps were established. Elizabethtown sprang up and gold was found along many of the creeks and on Baldy Mountain as well; the surrounding area became a frenzy of mining activity. Placer mining spread into what is now part of the Vermejo Ranch, but most of the gold mining activity on the ranch occurred between 1890 and 1900, when La Belle flourished as a mining town. La Belle, along with most other camps and mines, was abandoned about 1900 because of the low grade of the ore.

The discovery of gold on the Grant came as no surprise to Maxwell, as he had known of its existence for some time. The rush of prospectors and mining camps brought by the gold discovery, however, prompted him to invest in gold mining. Shortly afterward Maxwell sold the Grant, for reasons that are still uncertain. According to some references, including Keleher (1975), Maxwell's investments in gold mining were a failure. Other references are vague about his reasons for selling and suggest that Maxwell was still quite wealthy at the time of the sale. Pearson (1961) contended that Maxwell made a decent profit from his investments in gold mining, but sold the Grant because of outside pressures to sell and because the management and control of the Grant had become a burden. Big businesses had begun looking into the Maxwell Land Grant after hearing that gold had been discovered on the Grant and that great coal, lumber and mineral potential existed, in addition to the grazing and farming possibilities.

ENGLISH CONTROL

Operating for an English syndicate, three financiers obtained an option to purchase the Grant from Maxwell in 1870 for a reported sum of $1,350,000 (Pearson, 1961). Maxwell sold the Grant, and after a brief unsuccessful banking venture in Santa Fe and several other financial reverses, he returned to ranching at Fort Sumner and lived there until his death in 1875.

The English syndicate formed the Maxwell Land Grant and Railway Company, which soon made an effort to remove squatters from the land by politely informing them that they were on Grant land and asking them to leave. Those who had lived on the Grant for many years with only Maxwell's verbal consent became irate at now being asked to leave by foreign absentee landlords. The Spanish and American people living on more remote portions of the Grant, who thought they owned their land, could not understand why they were being asked to leave. Many did leave, but others vigorously resisted. Anti-Grant sentiment grew strong and men throughout the area took up the cause, some with the aid of Winchester rifles and Colt revolvers. This period of violence, directly related to the problem of land title, became known as the Colfax County War. Conflicts continued—on the lands with gunfights and in the courts between Grant men and anti-Grant men. Lives were sacrificed with few repercussions until a minister, F. J. Tolby, known to sympathize with the squatters, was murdered. He became a martyr to the anti-Grant cause; and another minister, O. P. McMains, took up the cause. He displayed renewed vigor and published an anti-Grant newspaper filled with fiery editorials on the Grant situation.

DUTCH CONTROL

Within five years after purchasing the Grant, the Maxwell Land Grant and Railway Company was bankrupt, even unable to pay salaries and 1874 taxes. Debts mounted and the situation worsened for several more years, until foreclosure proceedings were initiated in 1879. In 1880 the Maxwell Land Grant Company was formed under the laws of the United Netherlands, and the Grant came under control of a Dutch group that included several wealthy American industrialists. Financial problems continued to plague the Company and anti-Grant sentiment increased.

In 1885 the pro-Grant faction prevailed upon Governor Lionel A. Sheldon to authorize the organization of a company of National Guards to control the situation. News leaked out that Jim Masterson, brother of gunfighter "Bat" Masterson from Dodge City, was to lead this company of militia and that these men intended to kill. This news aroused the anti-Grant men, who went to the governor and convinced him to have the militia disbanded; this action, in turn, angered Masterson and the Grant men. Grant-related violence raged on, and the Dutch Company's financial situation worsened, necessitating a reorganization that was finally completed in 1888 (Pearson, 1961). The preceding year, the case of the United States vs.

The Maxwell Land Grant Company had gone to the Supreme Court and been decided in favor of the Company. The settlers and squatters were forced to abandon hope of ever obtaining legal rights to the land upon which they lived. At this point most of the squatters left, and the Maxwell Land Grant Company sold land to some of the remaining squatters.

BARTLETT

In 1900 William H. Bartlett, a wealthy grain operator of the Chicago firm of Bartlett, Frazier, and Company, and one of the five men who cornered the Chicago grain market at the turn of the century, began negotiations to purchase a large tract of land from the Maxwell Land Grant Company. Bartlett had first looked into property in the Southwest because his younger son, William H., Jr., had tuberculosis and doctors had suggested that the southwestern climate could help his condition. In 1902 Bartlett purchased 205,000 acres of Grant Land including Vermejo Park. He made an agreement allowing him to withhold the last payment to the Maxwell Land Grant Company until all squatters on the land had been removed: "They are given two years to get the Mexicans off and I hold back $10,000" (letter to H. W. Adams, March 25, 1902).

At that time there was, and had been for generations, a predominantly Mexican settlement along the banks of the Vermejo River south of the present Park area. All of the families in this area were squatters on Grant land. The land supported crops and cattle, and many families tended small orchards. A little community existed in the 1880's that included a store, a church and even a small school. The close-knit nature of the community is illustrated by the *Springer Stockman* newspaper, July 6, 1883 edition, which reported on a Fourth of July party on the Vermejo: "At Vermejo Park the settlers up there had quite a celebration in the old fashioned way. The exercises consisted of singing, reading of the Declaration of Independence, speech-making, a basket dinner, and a big dance in the evening. Several parties from Raton went up there, but as they have not returned, it is impossible to give a full report of the good time had" (Stanley, 1952, p. 221). Apparently many of these squatters would not leave, so when Bartlett took over he let some of them remain and put them to work. Adobe ruins visible today along the Vermejo River from just below the Park area all the way downriver to the site of Dawson are the only evidence of the ranches that belonged to these squatters.

After buying the land, Bartlett built most of the buildings that make up the present Vermejo Park area. Casa Minor, the first residence built for the Bartletts, was completed in 1903. The second mansion, which was the largest and was situated between the two mansions remaining today, was begun shortly afterward. This mansion contained a huge kitchen and dining room and 27 bedrooms. In 1908 Bartlett began what is now called Casa Grande. The largest room was a library, 60 ft long by 30 ft wide, to house his collection of books, numbering more than 10,000 volumes. The house had 18 rooms: a kitchen but no dining room, a sunporch, six baths, and several bedrooms. Casa Grande became known as Bartlett's house; Casa Minor, his son Willy's house; and the center one, his son Norman's, used mainly for guests.

Although Bartlett did not move his residence to the ranch until July of 1910, his sons lived there continuously from 1903. The elder, Norman, first took charge of the lumber, which was only cut as ranch needs dictated. Later he was trained by H. W. Adams, Bartlett's cattle manager and owner of a part of the interest in Vermejo. Norman took over Adam's position when Bartlett bought out Adam's interest in Vermejo in December 1917. Bartlett's younger son, Willy, who lived at Vermejo with his wife, Virginia, was Postmaster of Vermejo.

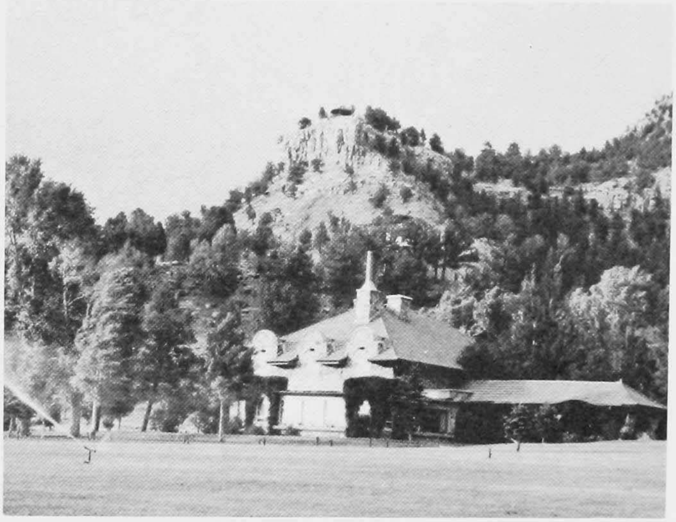

Figure 2. Casa Minor, completed in 1903; the first mansion built by W. H. Bartlett, owner of Vermejo Park. The pavilion sits atop a cliff in the upper left.

Bartlett, an avid fisherman, developed and named Adams, Bartlett, Merrick, Bernal, Munn, and Marys Lakes, stocking most of them with Eastern trout. He tried stocking some lakes with varied types of fish, such as he mentioned in his March 19, 1909, letter to the Bureau of Fisheries: "I have two more lakes that are disconnected from the trout streams, in which I would like to put some black bass, yellow perch, some croppies and some walleyed pike." Only trout remain in the lakes, the other fish could not spawn and died out. Bartlett built cabins by many of the lakes, in which he and his friends stayed occasionally.

Bartlett built Costilla Lodge as a fishing and hunting lodge, and often took his good friends and frequent visitors there to stay. Among them were Noel S. Munn, for whom Munn Lake was named, and George P. Merrick, whose name was given to Merrick Lake and to "Merrick's ranch" which Bartlett built nearby.

Bartlett operated a coal mine in Spring Canyon, which supplied the ranch needs and heated the houses. The mine had coal carts that ran on tracks; the mine entry, air shafts, weigh house, and related buildings still stand in Spring Canyon at the north entrance to Vermejo Park.

First hand accounts of life as a worker on Bartlett's ranch describe it as happy and peaceful. Bartlett built a store, a schoolhouse that was attended by 65 students, a coal-fired electric power plant, a fish hatchery, an ice house, a smoke house and greenhouses, in addition to the residences built for the ranch employees. Many parties and dances were given for his friends, and his workers were welcome to join in many of them. The pavilion on the cliff above Casa Minor is said to have been the site of some of Bartlett's parties, and the place where name bands and orchestras played, "filling the park with music." Annual Christmas parties included a huge Christmas tree in the library of Casa Grande, and Bartlett provided gifts for all the children and employees on the ranch.

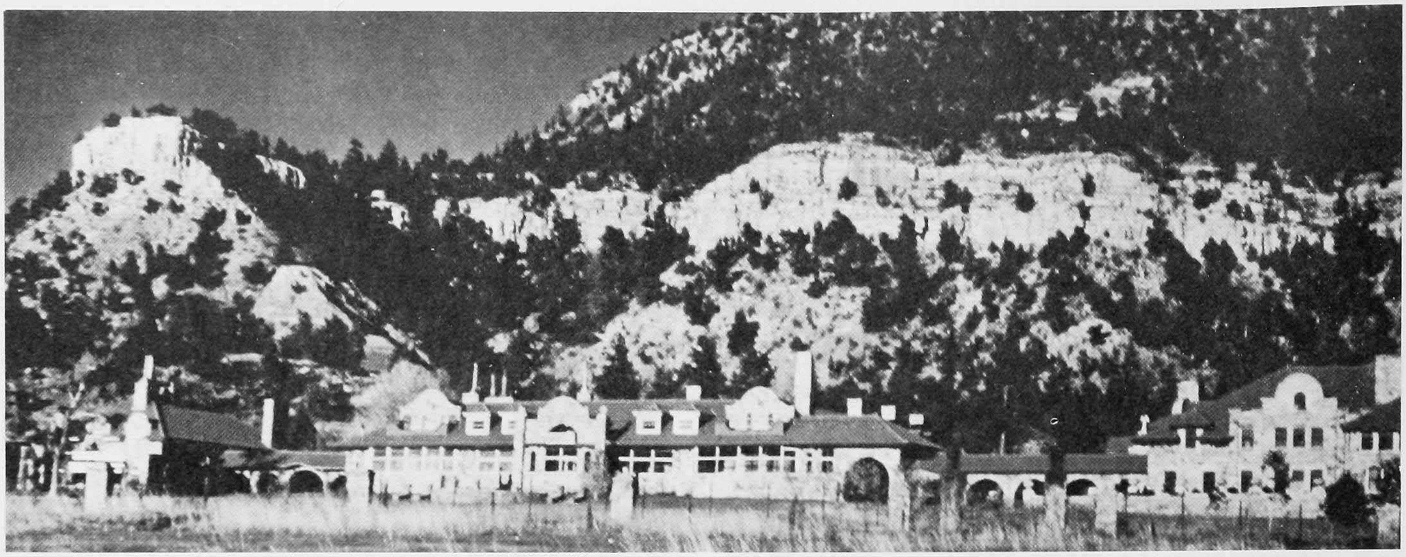

Figure 3. The Guest House (Norman's House), containing 27 bedrooms. It burned to the ground in 1955 after being remodeled by W. J. Gourley. Photograph courtesy of Mrs. Evelyn Drake, Vermejo Park, New Mexico.

At the same time that Bartlett was developing this magnificent ranch, lumber camps and mining towns were growing up in the surrounding parts of the Grant land. In 1907 T. A. Shomberg, an associate of the Maxwell Land Grant Company, formed the Continental Tie and Lumber Company. He offered to sell Bartlett one-fourth interest in the venture, but Bartlett declined. The Cimarron and Northwestern Railway Company was formed as a subsidiary. Originally, the plan was to build a railroad from Cimarron into the new logging towns on Ponil Park and on up to Van Bremmer Park, with branches to surrounding timber areas (now all within Vermejo Ranch boundaries). After completion, the railroad ran from Cimarron up North Ponil Creek to Ponil Park. It looped around at Bonito, but never reached Van Bremmer Park. The logging business around these towns flourished for a long period, supplying lumber for mines in the Raton vicinity, cross ties for the railroads and timber for the buildings. The timber supply in the area began dwindling around 1920, the last railroad tracks were pulled up in 1923, and the logging towns were abandoned.

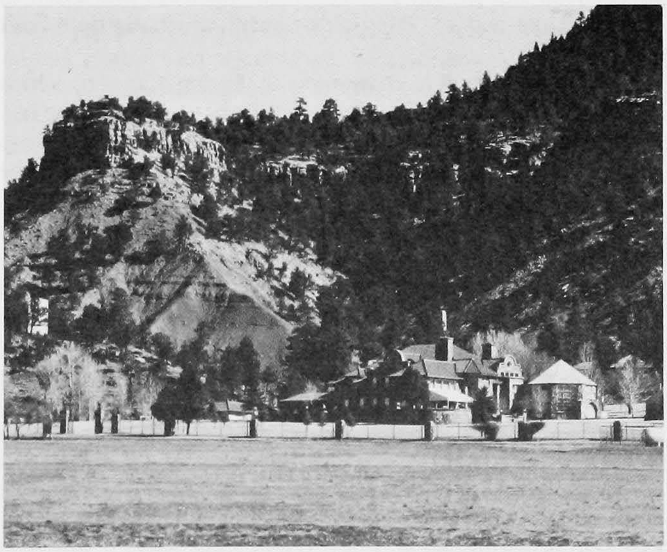

Figure 4. Casa Grande. Began for Bartlett in 1908.

Bartlett was still making improvements on the ranch when he died suddenly of heart trouble on December 10, 1918. Both of Bartlett's sons died soon after—Norman on September 5, 1919, and Willy on January 5, 1920. In the words of John Brewer, a former cow foreman at the Vermejo Ranch, who knew the Bartletts personally, "They had ever'thin' they was to have and they did ever'thin' they was to do; then they all up and died" (oral communication, 1963). The estate was left to Willy's widow, Virginia.

VERMEJO CLUB

In 1926, Virginia Bartlett and her second husband, Robert H. Doulton, sold the ranch to Harry Chandler, of the Los Angeles Times Mirror, and others who formed an elite hunting, fishing, and recreational retreat known as the Vermejo Club. Membership in the club was by invitation only, and the cost for a lifetime was $5,000. The limited membership of the Vermejo Club was "carefully selected from men worth knowing who have been prompted to give it countenance by their sympathy with its ideals and their confidence in its purpose" (Vermejo Club, 1926, p. 33). Members included William Banning, Max C. Fleischmann, Will H. Hays, Herbert Hoover, Thomas W. Warner, Harvey Firestone, Cecil B. deMille, Douglas Fairbanks, Mary Pickford, and Andrew Mellon. In this remote mountain hideaway, hunting was a popular sport and a favorite source of food. According to Elliott Barker, New Mexico State Game Warden, who spent 1930-31 working for the Vermejo Club, "The elk were the most spectacular and important game on the area, but not the most plentiful, for deer greatly outnumbered them. This elk herd has perhaps attracted more attention than any other in the state because it was the first introduced and established after the species had been exterminated over the entire state in the early 1890's" (Barker, 1946, p. 188).

The natural setting and relaxation from everyday stresses and strains were emphasized in the promotional book printed by the Club. Every effort was made to preserve the unpol-

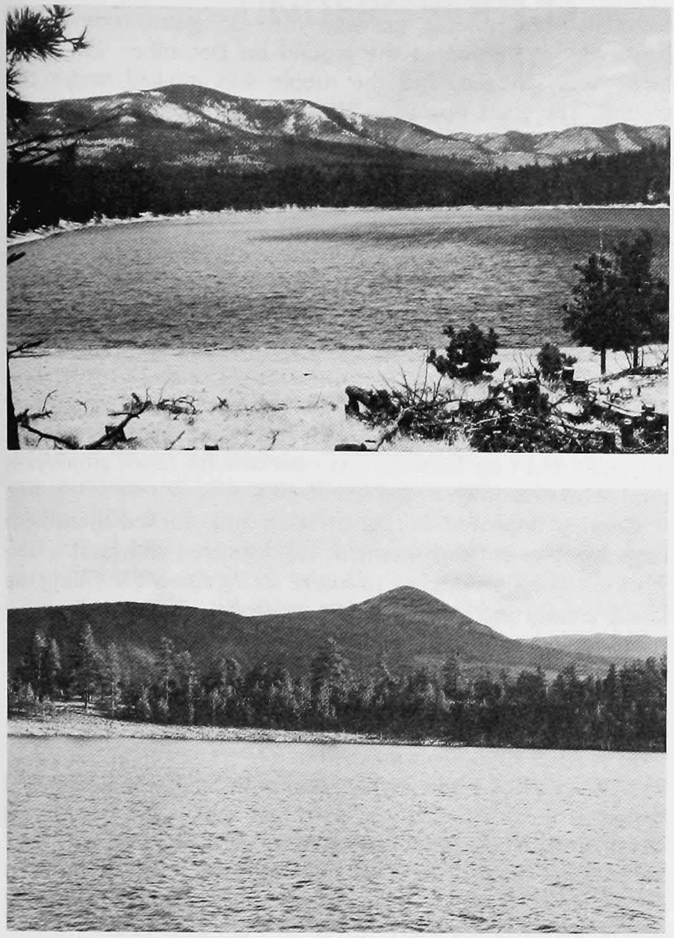

Figure 5. Bartlett (upper) and Adams (lower) Lakes, developed by Bartlett for scenic and fishing enjoyment.

luted, untouched wilderness aspect of the ranch. The mansions that Bartlett built were used as guest houses and club houses. A pool table in Bartlett's library and the tennis courts on the mansion grounds were available to members' use, and a landing field was built on club property. Members could come and camp, stay in one of the isolated lodges, or enjoy the wilderness free from its hardships by staying at the headquarters and engaging in a variety of activities there.

The Vermejo Club promotional book summed up what a membership entailed (Vermejo Club, 1926, p. 13):

> "A life member is entitled to all of the privileges of the club for himself and all dependent members of his family, who are at liberty to visit the club at any time as though it were their own estate. They have at their disposal the Club headquarters with its luxurious buildings, its adjoining comfortable cottages, or the various outlying hunting lodges and camps, and they may in addition, at a nominal rent of $5.00 per year, secure building sites for hunting lodges or camps of their own at any point which will not interfere with the general enjoyment of the property by its other members."

William Banning chose the latter option and built Banning ranch on Leandro Creek near Merrick. Harry Chandler's lawyer and close friend, W. T. Cresmer, was given a building site and surrounding land near Leandro Creek at the foot of Ash Mountain, where he built Cresmer Lodge in 1929. The ruins of Banning's and Merrick's ranches give some idea of the elaborate facilities that existed in this wilderness playground.

Figure 6. The "Stables." Gourley converted Bartlett's personal stables into an elegant dining room for ranch guests. The "Stables" are shown from the rear in the upper photograph and the front in the lower photograph. The pavilion is on the top of the cliff in the background.

Literally thousands of discarded bottles that had contained imported wines, fancy Hungarian mineral water, a variety of beers, and other unidentified liquids were found in the dump at Merrick's ranch, along with such exotic things as oyster shells!

The Vermejo Club, unable to sustain its membership when the depression hit, disbanded. In an effort to preserve the club, Harry Chandler and one of his family corporations, the Southwest Land Company, took over the land and leased it to Ira Aten to raise cattle. The mansions were closed down, and the ranch operations continued under Aten for several years.

GOURLEY

W. J. Gourley, a Fort Worth industrialist who founded the American Manufacturing Company of Texas, manufacturer of oil-field equipment and munitions, began purchasing land in the Maxwell Grant area in 1945. He first purchased 108,000 acres adjacent to the Vermejo Park land from the W. S. Land and Cattle Company, together with 3,300 head of cattle. In July of that year, he applied for a lease on land in the Ponil and Van Houten area, which contained 90,000 acres adjoining his ranch. He was granted the lease for 10 years and later exercised an option to purchase it for $4.00 an acre. Then on

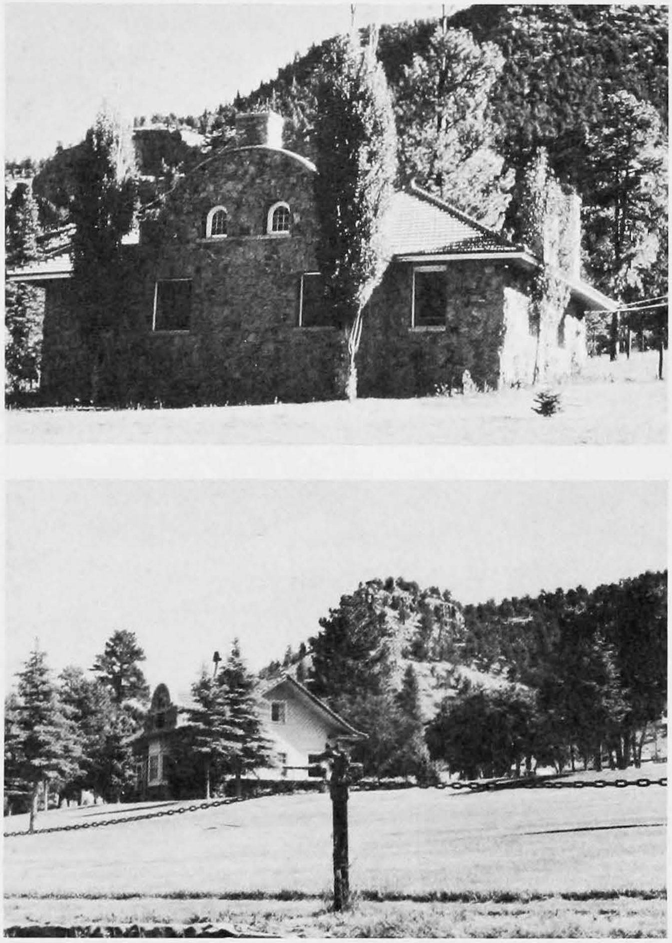

Figure 7. Guest houses. Gourley had the employees' stone cottages remodeled to accommodate fishing and hunting guests.

October 14, 1948, Gourley bought the Southwest Land Company's Vermejo Ranch property. "Within a few years he became owner of thousands of adjoining acres, most of it in Colfax County, some in Taos County, and a little in Costilla County, Colorado" (Pearson, 1961, p. 276). Gourley put together the largest single tract of land carved from the Grant. He maintained a thriving cattle business on the ranch and installed cowboys at headquarters and outlying cow camps to care for the cattle. For several years Castle Rock Park was the location of the main cow camp, as it had been in the past.

Big-game hunting became an important part of the ranch operation, and Gourley tried to enlarge the herds. In 1957, he purchased several hundred elk from Yellowstone National Park at $5.00 each and had them trucked to the ranch. He kept them in the "Elk Trap," a pasture enclosed by a high ten-strand barbed wire fence, and released them after they grew accustomed to their new surroundings. Hereford cattle and a small buffalo herd now graze in that pasture. Gourley also purchased and raised wild turkeys at the park area in the 1960's. He carefully protected the young birds from marauding predators and then released the full-grown turkeys to roam the ranch.

After purchasing the property, the Gourleys re-opened the mansions. Casa Minor was remodeled for their residence during their visits. They began a guest operation in 1952, and remodeled the middle mansion into 35 guest rooms with baths, but it burned to the ground on December 23, 1955. Little was salvaged, and the rubble was plowed under the ground. The guest operation closed down for a year after the fire. Mrs. Gourley had Bartlett's personal stable converted into the "Stables," a large kitchen, bar, and dining area, and had the adjacent stone cottages remodeled to accommodate guests. Vermejo opened for business again for the summer fishing season of 1957. When Casa Grande was remodeled for the Gourleys in the early 1960's, Casa Minor was also converted into guest accommodations. A house originally built for Adams, Bartlett's cattle manager, was used as the ranch headquarters; Ken Orr, ranch manager during Gourley's ownership, had his office there and a cook house was located in the rear of the building, where the ranch hands were fed. The store, originally built by Bartlett, was operated for ranch employees until it burned down in the late 1950's.

Gourley improved the ranch lakes and stocked them with large trout to entice fishermen. He organized and built a network of diversion ditches to utilize spring run-off in filling the lakes, greatly increasing their recreational potential. Gourley restored and re-opened existing hunting lodges at Cresmer and Costilla, and built Shuree Lodge on Middle Ponil Creek.

PENNZOIL

In August 1970, Gourley died of a heart attack at the age of 81. The ranch was put up for sale for 26.5 million dollars and remained in Mrs. Gourley's possession for three years, during which time the National Park Service, the United States Forest Service, the State of New Mexico and several private interests attempted to purchase it. In August 1973, Pennzoil Company purchased the entire Vermejo Ranch from Mrs. Gourley.

Under Pennzoil control, Vermejo has continued as a working ranch, and the guest operation has been expanded. A new office was built in 1975 near the mansion area, and the old headquarters' office now houses departmental offices, such as fish and game, forestry, and cattle management; the cook house still remains in the back section.

Although Vermejo Ranch is only a fragment of the original Maxwell Land Grant, it remains one of the largest privately owned blocks of land in the United States today. From the days of Beaubien and Miranda through Maxwell, the Dutch, Bartlett, the Vermejo Club, and Gourley to the present-day corporate ownership of Pennzoil, Vermejo has catered to an exclusive few and remained private to the general public.

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UNDERGROUND AND SURFACE OPERATIONS AT THE YORK CANYON MINE

KAISER STEEL CORPORATION

INTRODUCTION

Kaiser Steel Corporation purchased the 530,000 acre coal property in northern New Mexico in August, 1955, from the St. Louis, Rocky Mountain & Pacific Company. At that time, the Koehler mine was the only operating mine on the property, and it was being worked on a very limited basis.

Kaiser Steel modernized and expanded the Koehler operation to a capacity of 2,000 tons per day. At the same time, the company began a long-term exploration program to determine the potential of the area. During the next eight years, this exploration program outlined several substantial deposits, with the most attractive prospect for development in the York Canyon region. Studies found the coal quality to be good; the coal was desirable for blending purposes and access to the coal seam was favorable.

A test mine was opened in 1963. The coal was trucked to the Koehler mine for washing and subsequent shipment to Fontana for verification of the quality of the coal for blast-furnace use. Plans for construction of the new mine at York Canyon were finalized in late 1964, and construction work began in 1965. Design called for a mine capable of producing 700,000 tons per year. A spur line was built by the Santa Fe Railway connecting the new mine with the railroad's main line. Equipment and men were transferred from the Koehler mine. The move to York Canyon was essentially completed by September, 1966, and the Koehler mine was closed.

MINING OPERATIONS

The main York Canyon seam ranges in thickness from 4 ft to 10 ft, is relatively flat and crops out along the canyon walls. The seam is thickest at the outcrop and pinches rather rapidly as it extends into the hillside. A large percentage of the seam is in the 4 to 6 ft range. Cover is not excessive, ranging from 30 ft near the outcrop to a maximum of 700 ft under the ridges. The roof rock is quite variable and may be classed as tender; it frequently requires supplementary steel beam support in addition to conventional roof bolting.

Production is divided between the underground mine opened in 1966 and a new strip mine started in 1972. Coal from these two mines is processed in the preparation plant adjacent to the mines.

UNDERGROUND MINE

The underground mine was developed with a four-entry system that extends in from the portal about 9,000 ft; entries are driven right and left to develop mining panels for continuous mining units and the newer longwall mining units. Underground equipment consists of five sets of continuous mining equipment and two longwall mining units.

Each set of continuous mining equipment consists of a continuous miner, loading machine, two shuttle cars, a twin-boom rotary roof bolter (Fig. 1), scoop-tram or supply tractor, feeder-breaker and a belt conveyor. Two types of continuous miners are in use: 16-year-old Joy 6CM ripper miners, and newer Joy 11-CM drum-head miners. New Lee-Norse HH-386 continuous miners are being purchased to phase out the old ripper type. The older longwall mining unit consists of 110 chocks (Fig. 2), a double-drum bidirectional shearer (Fig. 3), armored face conveyor, stage loader, power pak, electrical power center and a belt conveyor. A new shield-type longwall mining unit has recently been put into operation.

Figure 1. Twin-boom roof bolting machine.

Coal mined by the continuous miners is hauled by shuttle cars (Fig. 4) to a feeder-breaker. It breaks large lumps down to 8 in. size or less and discharges the coal onto a 36 in. wide conveyor belt, which carries the coal to the 48 in. main con-

Figure 2. View looking down the chocks of a longwall unit showing the hydraulic roof supports. Each hydraulic leg has a 110-ton capacity, two-stage hydraulic extension.

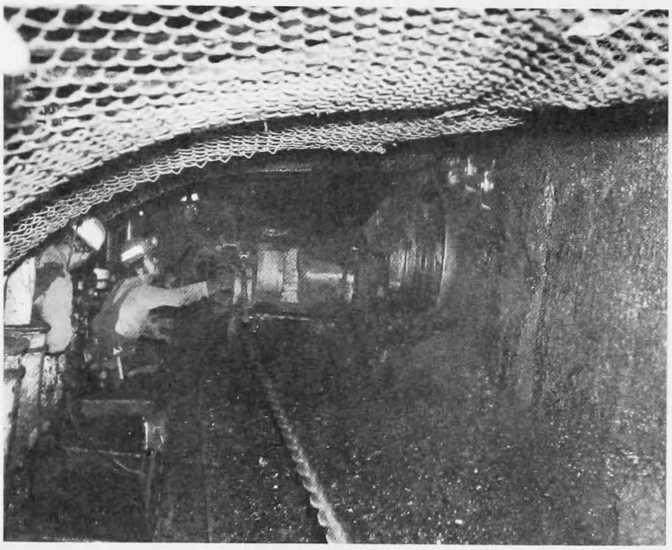

Figure 3. Looking at cutting end of 300 h.p., double-drum shearer on longwall face. Because of the weak friable nature of the roof in this part of the mine, 100 percent of the roof is covered with wire mesh.

veyor belt for transport to a 100 ton surge bin at the portal. Coal from the longwall shearer is conveyed on an armored flight conveyor to the stage loader at the head-gate of the face, then to a 42 in. extensible conveyor belt which discharges onto the 48 in. main conveyor.

STRIP MINING AND RECLAMATION

The strip mine is approximately 1 mile from the cleaning plant and is operating in the same seam as the underground mine. Overburden ranges from 30 ft to 240 ft; but mining is currently restricted to the low cover areas, having a maximum thickness of 70 ft, because of the limitation of overburden removal bulldozers and two front-end loaders (Fig. 5).

A 30 cubic yard walking dragline with a 275 ft boom is now being assembled on the ridge and will be used to strip the heavier overburden and bring capacity up to half a million tons per year of strip coal. The overburden is drilled with a 7¾-inch-diameter, truck-mounted blast-hole drill and blasted with an ammonium nitrate-fuel oil explosive. Bulldozers and front-end loaders remove the loose overburden down to the coal seam, which is then drilled with a twin-boom coal drill and blasted for loading by a front-end loader.

Figure 5. Fifteen-yard front-end loader awaits arrival of truck in the background to begin loading of overburden.

The coal is loaded into 67 cubic yard trucks and hauled to a truck dump station near the preparation plant. Coal from the truck-dump stockpile is carried by conveyor belt to the surge bin at the underground-mine portal and blended with the underground coal before cleaning.

Surface mining equipment serves double duty in reclaiming mined-out areas (Fig. 6). Reseeding is underway and reforestation will follow.

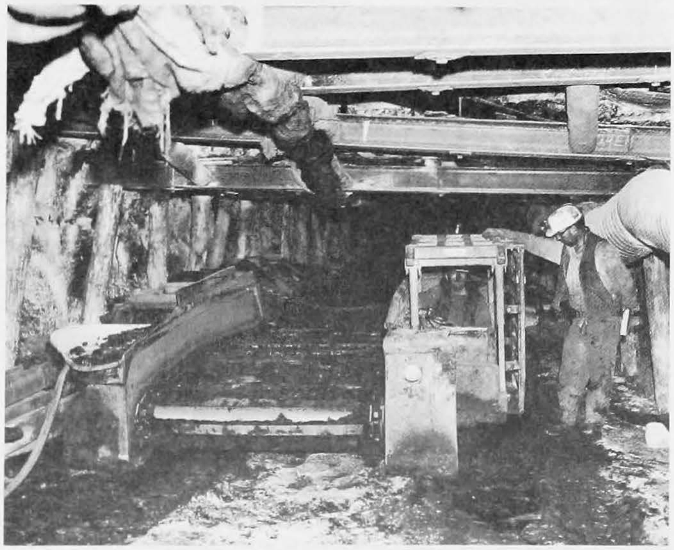

Figure 4. 10 SC shuttle car.

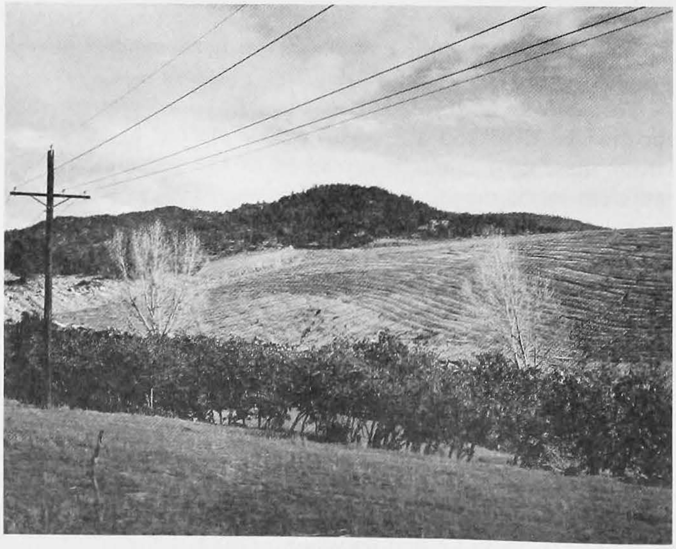

Figure 6. View to northeast across York Canyon showing mined-out areas that have been graded and covered with topsoil.

COAL PREPARATION

The first step in processing is to size the coal. The coal from the mine is broken in a 4 in. breaker station and then stored in a raw-coal stockpile. The 400 tons per hour feed rate preparation plant uses heavy-media and flotation cleaning circuits followed by screen, centrifuge and vacuum-filter dewatering. Clean coal then passes to a 70,000 ton stockpile located directly over the railroad-train-loadout track. The coal is carried to the stockpile by means of an elevated conveyor, which discharges coal 125 ft above the center of the cone-shaped pile.

PRODUCTION

The York Canyon mine presently produces high-quality coking coal from the underground and surface operations at a combined rate of approximately 1,000,000 tons per year. With the recent completion of a 120 ft diameter water clarification thickener (Fig. 7), the preparation plant has a capacity of about 1,300,000 tons. In the future, to meet the high demand for this coal, production can be raised to 1,500,000 tons annually by limited additions to the coal preparation plant and by placing additional strip and underground mining equipment in service.

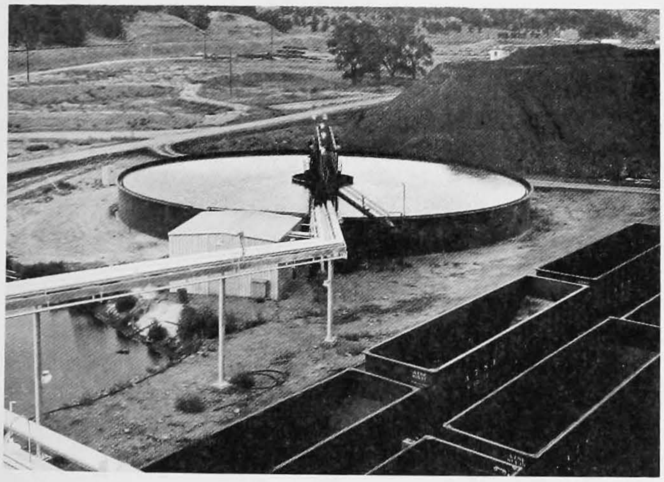

Figure 7. New 120 ft diameter thickener for clarifying the water and settling out of flotation tailings.

TRANSPORTATION OF CLEAN COAL

Opening of the York Canyon mine was accompanied by an efficient railroad unit train system (Fig. 8) for transporting large volumes of coal a distance of 1,802 miles to KSC's steel plant in Fontana, California.

The Santa Fe Railway constructed a 37.5 mile spur line to connect the mine with their main line; they provided 100 100-ton flat-bottom gondola cars with attendant assignment of locomotive units to support the operation of the 84 car unit train between the mine and steel plant on a four day turn around basis.

With the clean coal stockpile positioned directly over the railroad tunnel, high capacity car loading is achieved. As the unit train proceeds through the tunnel at a controlled speed of about ¾ mile per hour, the load-cut operator opens and closes a hydraulically operated gate, filling each car as it passes the loading chute. Typically, the 84 car trains are loaded in approximately 1.5 hours. When loading is completed, the operator raises the chute, and the train continues around the loop to start the journey to the steel plant.

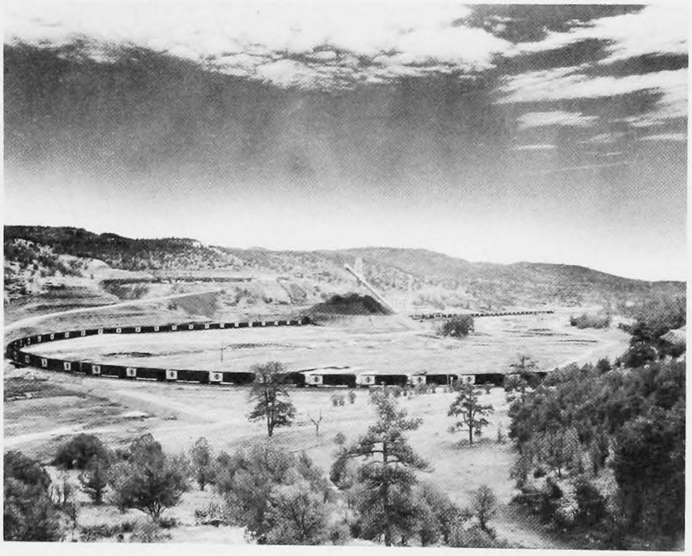

Figure 8. Mine and loading facility at York Canyon showing loaded 100 ton gondolas.

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