Coalfields of New Mexico: Geology and Resources

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Coalfields of New Mexico: Geology and Resources

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U.S. Geological Survey, and

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U.S. DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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PREFACE

Calculation of the coal resources of New Mexico is an important part of the evaluation of State, Federal, and privately owned energy potential. As such, it bears directly on the economic growth and development potential of many areas within the State. To be of most use, coal resource data must accurately reflect the quantity of coal present and its accessibility to development. In this report, the State Geologist of New Mexico and the U.S. Geological Survey describe the primary geologic factors that influence the quantity and accessibility of the coal resources of New Mexico. The report gives greatest emphasis to the San Juan basin, an area that has provided much of the publicly available data and that retains a large portion of present coal development interest.

The chapters that follow include brief geological descriptions of New Mexico's coalfields, current estimates of the amount of coal resources present in each of them, analyses of the probable accuracy of such estimates, determinations of thickness of known and projected coal beds or coal zones, and discussions of the geologic factors that affect the coal resources.

The authors have assessed the current state of knowledge of the coal resources of New Mexico, pointing out inadequacies in the data base and understanding of the resources. Though our primary data source has been the National Coal Resources Data System of the U.S. Geological Survey, we have also used data from other sources to make this report as complete as possible.

This report is a product of many people's efforts. Besides the authors and editors, other major contributors from the U.S. Geological Survey include Dorsey Blake, for guidance in computer operations; Courteney Williamson, for data entry, validation, and graphics generation; Noreen H. Rega, for data base development, validation, and resource calculation; Mary E. Lemaster and Patricia T. Kerr, for resource calculation and data validation; and Andre D. Bush and Paula M. Washington, for digitizing and boundary data processing. Margaret F. Johnson and Brian R. Schachte helped with new record processing and provided graphics display support; Frank E. Andreani helped with data formatting, processing, and updating.

Assistance was also given by Laura N.R. Roberts, in computer software use; Jean K. Dillinger, Annabel B. Olson, and James E. Fassett, in San Juan basin geology; and Margaret S. Ellis, in data validation. Many of the personnel above helped with drafting, as did Arthur C. Clark. J. Daniel Cathcart photographed the illustrations. The assistance of the secretarial staff in the preparation of the text is also appreciated.

The authors of chapter E were aided by contributions from other members of the New Mexico Bureau of Mines and Mineral Resources, particularly the drafting of Michael Wooldridge and the useful suggestions of Orin J. Anderson and JoAnn C. Osburn.

CONTENTS

[Letters designate the chapters]

METRIC CONVERSION FACTORS

Data in this volume are reported in customary inch-pound units because the metric system is not currently in use by the coal industry of the United States. Readers wishing to convert measurements to the International System of units (SI) may use the following factors:

U.S. customary unit	SI conversion
Acre	=4,046.87 square meters
Acre-foot	=1,233.49 cubic meters
British thermal unit (Btu)	=1,055.056 joules
Btu/lb	=2,326 joules per kilogram
Foot (ft)	=0.3048 meters
Inch (in.)	=0.0254 meters
Mile (mi)	=1.609 kilometers
Pound (lb)	=0.4536 kilograms
Short ton (ton)	=0.9072 metric tons
Square miles (mi^2)	=2.59 square kilometers
Ton/acre-foot	=0.7355 kilograms per cubic meter

Chapter A

Geologic Framework and Major Coal-Bearing Formations of the San Juan Basin

By MORRIS W. GREEN, JAMES W. MYTTON, DOROTHY T. SANDBERG, and NANCY K. GARDNER

Upper Cretaceous strata preserved in a
Laramide-age structural basin host
New Mexico's largest coal deposits

U.S. GEOLOGICAL SURVEY BULLETIN 1972

COALFIELDS OF NEW MEXICO: GEOLOGY AND RESOURCES

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FIGURES

Geologic Framework and Major Coal-Bearing Formations of the San Juan Basin

By Morris W. Green, James W. Mytton, Dorothy T. Sandberg, and Nancy K. Gardner

Abstract

The San Juan basin, New Mexico's leading coal producing area, is a structural basin formed during the Laramide orogeny (80 to 40 million years ago). The basin lies primarily in northwest New Mexico but extends into southwest Colorado and northeast Arizona and covers an area of about 26,000 square miles on the southeast margin of the Colorado Plateau physiographic province. Approximately 12,000 feet of Paleozoic and Mesozoic rocks are preserved in the basin. Cretaceous rocks, covered by Tertiary rocks in the central part of the basin, account for approximately one-half of the total thickness. The sedimentary interval in the basin locally hosts some of the Nation's most important deposits of coal, uranium, oil, and gas. Coal deposits occur in deltaic and coastal plain lithofacies throughout the Upper Cretaceous interval over relatively wide areas of the basin. The geographic location and stratigraphic position of coal beds of Cretaceous age in the San Juan basin were determined by the location of ancient shorelines along the western border of an epicontinental sea during Late Cretaceous time. Coal deposits originated from thick accumulations of organic matter (peat) in paludal environments on deltaic and lower coastal plains landward of shorelines. These environments formed as a result of periodic transgression and regression of the sea. The coal beds tend generally to be elongate to the northwest, parallel to the shoreline of the sea, which retreated progressively farther northeast with each successive major transgressive-regressive cycle of Late Cretaceous time. By the end of the Cretaceous Period, the sea had withdrawn from the region completely.

The major Cretaceous coal-bearing units, in ascending order, are the Crevasse Canyon and Menefee Formations of the Mesaverde Group and the Fruitland Formation, which contains by far the largest coal resources in the San Juan basin. The thickness and distribution of coal in the Fruitland are inversely related to increase in thickness and stratigraphic rise of the underlying Pictured Cliffs Sandstone, especially where the Fruitland Formation intertongues with the upper part of the Pictured Cliffs. Typically, the coal beds are highly lenticular and difficult to correlate between drill holes; they can be correlated with certainty only where the holes are closely spaced. For these reasons, coal resource calculations can only be made for coal zones, rather than individual beds. Fields or areas in the San Juan basin where the Fruitland Formation is the current or potential coal producer are the Navajo field and Bisti and Star Lake areas. The remaining fields and areas are current or potential producers of coal from the Mesaverde Group and its equivalents, the most notable being the Gallup field.

INTRODUCTION

The San Juan basin of northwest New Mexico is the State's leading producer of coal. The basin's coal and its other energy mineral deposits—uranium, oil, and gas—make it one of the Nation's most important energy-rich sedimentary basins. The coal deposits, restricted in occurrence to the upper part of the basin sedimentary sequence in formations of Cretaceous age, supply fuel for the electric power industry throughout the southwestern United States.

This report contributes to the joint effort by the U.S. Geological Survey and the New Mexico Bureau of Mines and Mineral Resources to provide a current overview of the geology and coal resources for the State of New Mexico.

LOCATION AND GEOGRAPHY

The San Juan basin is located primarily in northwest New Mexico. The northern and western areas of the basin extend, respectively, into neighboring southwest Colorado and northeast Arizona. The basin has dimensions of approximately 200 miles north to south and 130 miles east to west. The basin is irregularly circular and covers an area

of about 26,000 square miles on the southeast margin of the Colorado Plateau physiographic province.

The basin is bounded on all sides by mountain ranges: the Zuni Mountains on the south, the Nacimiento Mountains on the east, the La Plata and San Juan Mountains on the north in Colorado, and the Defiance uplift and the Chuska and Carizzo Mountains on the west near the Arizona–New Mexico border. The boundary of the basin is generally placed where the contact between Cretaceous rocks and underlying older rocks crops out near the flanks of the surrounding mountain ranges (fig. A1).

GEOLOGIC SETTING

The San Juan basin, like other major present-day sedimentary basins in the Western Interior of the U.S., formed during the Laramide orogeny, which spanned the time interval between the Late Cretaceous and the middle Tertiary (80 to 40 million years ago). Approximately 12,000 feet of rocks ranging in age from Cambrian to Cretaceous are preserved in the basin (fig. A2). Only Ordovician and Silurian age rocks are absent in the sequence. Cretaceous rocks, covered by Tertiary rocks in the central part of the basin, account for approximately one-half of the total thickness of the Paleozoic and Mesozoic sequence.

The sedimentary interval in the basin locally hosts some of the Nation's most important deposits of coal, uranium, oil, and gas. Large uranium deposits occur in fluviolacustrine sandstone lithofacies of the Upper Jurassic Morrison Formation in the southern part of the basin. Oil, gas, and coal deposits occur in marine and coastal plain lithofacies throughout the Upper Cretaceous interval over much of the basin.

TERTIARY TECTONIC HISTORY AND STRUCTURE

The San Juan basin is a structural basin bounded by uplifts which formed as a result of Laramide crustal movements. The basin is asymmetrical north to south, having its deeper axial part in the north-northeastern portion (fig. A3). Because the basal Upper Cretaceous Dakota Sandstone is uniformly distributed and widespread in the basin, it is frequently used in depicting Laramide deformation (fig. A4).

The San Juan basin apparently formed on an internally stable, subsiding crustal block surrounded by crustal blocks which were uplifted to form the cores of adjacent mountain ranges. Differential subsidence and uplift of crustal blocks in the San Juan basin (as well as elsewhere in the Western Interior) apparently resulted from regional tectonic compression (crustal shortening) attendant to active

western plate margin tectonism associated with westward motion of the North American plate during the time of the Laramide orogeny.

Locally, pre-Tertiary sedimentary rocks are sharply upturned against the flanks of surrounding uplifts. Structurally deformed sedimentary units strike parallel to the flanks of marginal uplifts and dip steeply basinward—locally exceeding 80°—across the hinge lines separating the uplifted blocks and the subsided block. Basinward, the dip angle of the units abruptly decreases to 3°–5°. Local structural features, generally confined to the hinge areas of the basin, include normal faults and fault zones, small anticlines and synclines, structural platforms, and monoclines. With the exception of faults and fault zones, which trend normal to the flanks of uplifts, local structural features trend parallel to the basin margin. Relative to basin margin areas, the basin interior is essentially structureless, indicating relative stability of the crustal block flooring the basin.

PALEOZOIC AND MESOZOIC TECTONICS AND SEDIMENTOLOGY

Paleozoic and Mesozoic rocks are exposed in laterally continuous belts of outcrop around the margin of the San Juan basin. Underlying metasedimentary and plutonic rocks of the Precambrian basement are exposed in the cores of adjacent uplifts just outside the basin. The Paleozoic and Mesozoic formations in the basin were depositionally continuous with rocks of equivalent age contained in other Laramide basins of the Colorado Plateau and the Western Interior. These formations are products of sedimentary depositional systems that covered much larger areas than the Tertiary San Juan basin.

The Paleozoic rocks in the basin were deposited on a relatively stable, tectonically inactive continental platform which constituted the western margin of the continent throughout the era. Westward, across the Paleozoic continental margin, terrestrial red beds of conglomerate, sandstone, and shale intertongue with marginal marine and marine limestone, siltstone, claystone, and evaporite deposits of the Paleozoic continental slope. Sediment source areas, including the ancestral Rocky Mountains, lay within the area of the present Western Interior of the continent.

Mesozoic sediments of the Western Interior apparently were deposited differentially and sporadically through time from the Middle Triassic to the Late Cretaceous in a north-south elongate geosynclinal trough which spanned the entire Western Interior of the continent. Maximum development of the trough occurred during the Cretaceous. Sediment source areas lay west of the trough in the Cordilleran orogenic belt, which formed along the tectonically active western edge of the North American plate. Epeirogenic subsidence of the Western Interior

Figure A1. Generalized geologic map of the San Juan basin and adjacent region showing distribution of Cretaceous and younger rocks. (Modified from Beaumont, 1982.)
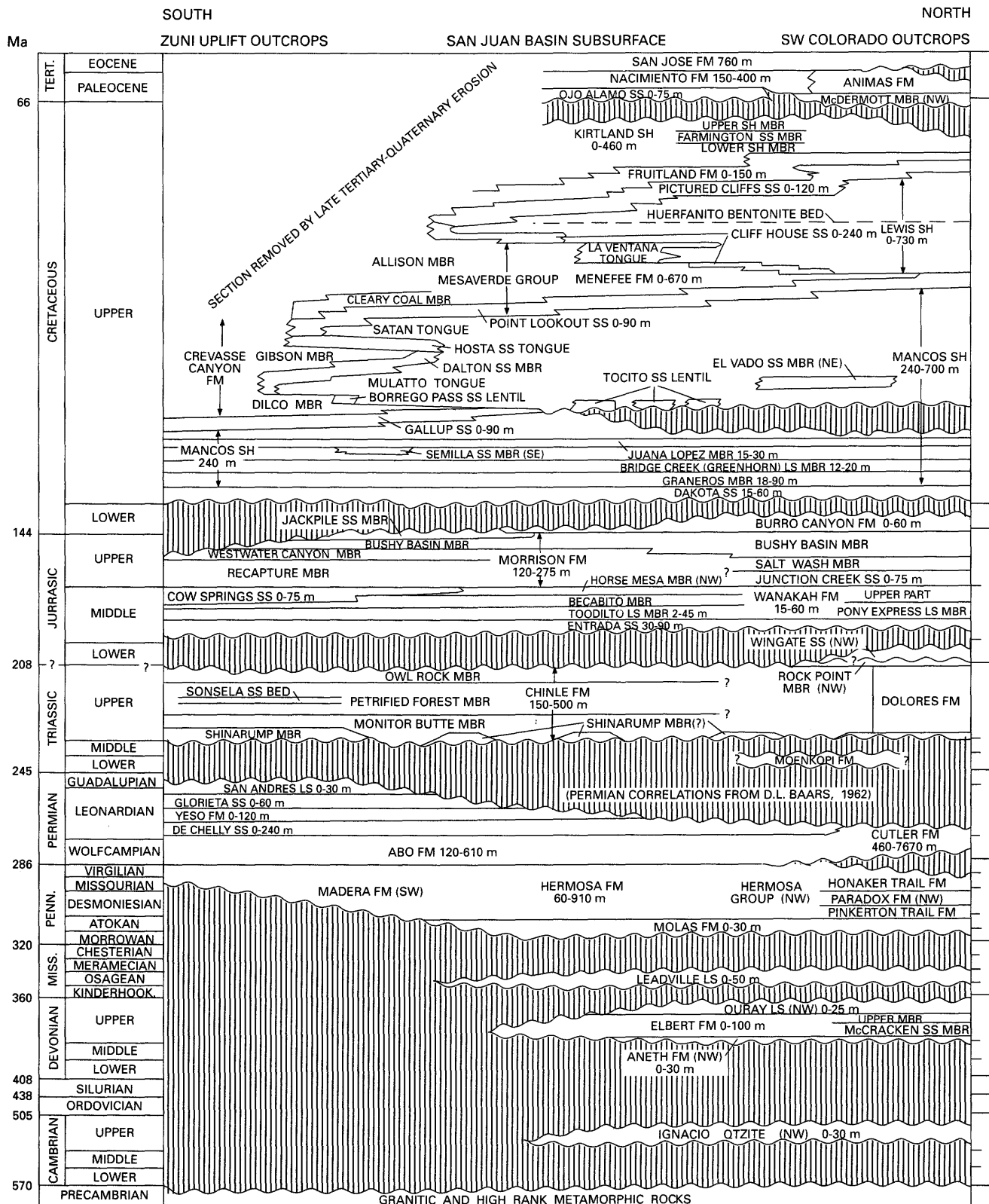
Figure A2. Stratigraphic correlation chart of the San Juan basin. (Modified from Molenaar, 1977; absolute time scale from Geological Society of America.)

SW

NE

Crownpoint
Crevasse Canyon Formation
Chaco River
Pictured Cliffs Sandstone

NEW MEXICO
COLORADO

10,000

8000

6000

4000

2000

SEA LEVEL

−2000

−4000

−6000

−8000

−10,000

ELEVATION, IN FEET

San Andres Limestone and Glorieta Sandstone

Cow Springs Sandstone

Gallup Sandstone

Crevasse Canyon Formation

Menefee Formation

Kirtland Shale

Tertiary rocks, undivided

Fruitland Formation

Lewis Shale

Mesaverde Group, undivided

Mancos Shale

Morrison Formation

Dakota Sandstone

Wanakah Formation

Chinle Formation

Entrada Sandstone

Paleozoic rocks, undivided

Precambrian basement

UTAH
ARIZONA
NEW MEXICO

Durango
COLORADO
NE

San Juan River

Chaco River

Crownpoint

Gallup

SW

Albuquerque

COLORADO

NEW MEXICO

0   10   20   30   40   50 MILES

0 10 20 30 40 50 KILOMETERS

VERTICAL EXAGGERATION X 21

Figure A3. Diagrammatic cross section of the San Juan basin. (Modified from Stone and others, 1983, fig. 10.)
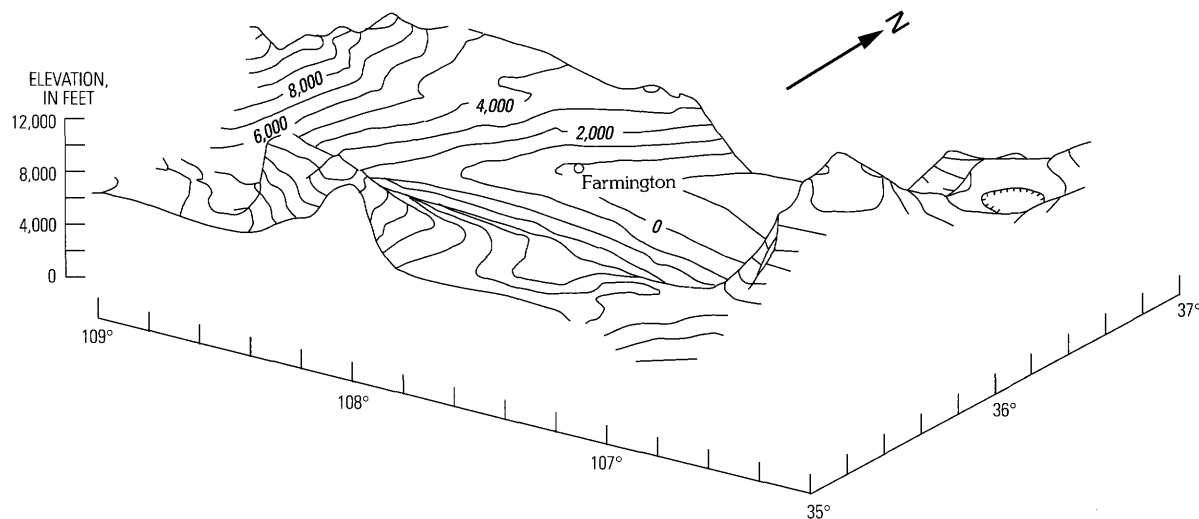
Figure A4. Structure contour perspective on the base of the Dakota Sandstone, San Juan basin. (Modified from Thaden and Zech, 1984.)

apparently resulted from tectonic compression of the crust between the Cordilleran region and the interior craton east of the trough as the western edge of the plate collided with the developing Cordilleran magmatic arc of the orogenic belt.

Western Interior trough sediments of Triassic age derived from Cordilleran source areas consist dominantly of conglomerate, sand, silt, and clay deposited in fluvial, lacustrine, and eolian depositional environments. These sediments were deposited in a number of large subbasins, which formed in the Western Interior as a result of differential subsidence of individual crustal blocks within the geosynclinal trough. On the northern and southern ends of the trough near the continental margins, Triassic and Jurassic continental sediments locally intertongue with marine sequences deposited during periodic marine invasions into the trough.

During the Cretaceous Period, maximum subsidence of the trough and high sea levels, resulting from an increase in the rate of sea-floor spreading east of the continent, caused marine waters to cyclically invade the entire Western Interior from its northern and southern ends to form the Rocky Mountain seaway. During this period the rate of sedimentary infill of the trough was at its maximum. Sediments consisting of cobbles, sand, carbonaceous silt, clay, and peat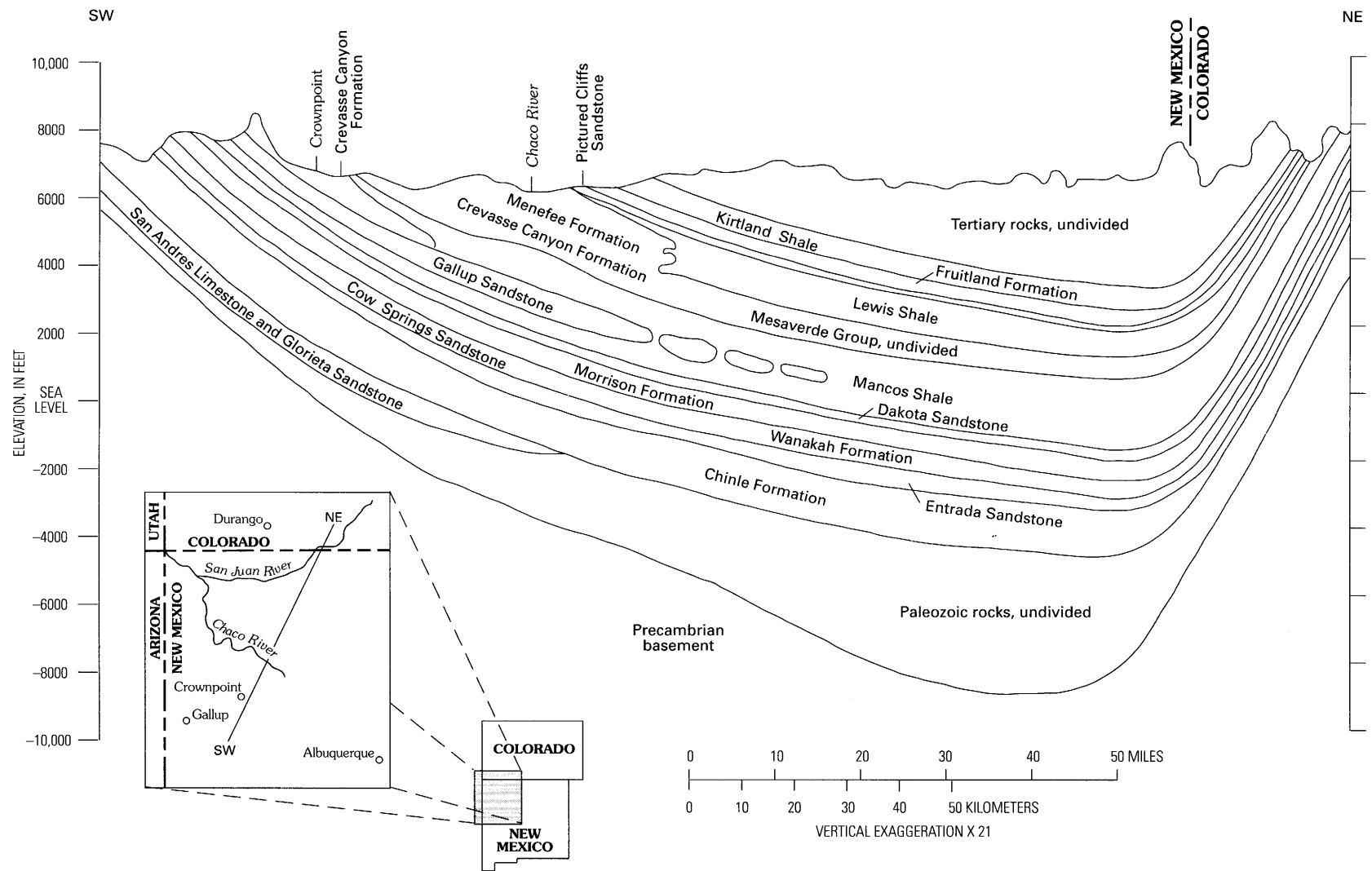 were deposited on deltas, coastal plains, and offshore areas along the western margin of the seaway. Generally, coarse-grained terrestrial lithofacies in the west change into or intertongue with fine-grained, time-equivalent, marine lithofacies to the east across the trough. During this cycle of sedimentation, the Cretaceous shoreline underwent at least five major transgressions and regressions (Molenaar, 1983).

Climatic conditions during the period of Cretaceous deposition were conducive to the luxuriant growth of vegetation along margins of the seaway, resulting in local thick accumulations of peat and organic debris. These organic accumulations later compacted and altered to form the coal deposits preserved today in the San Juan basin and other Laramide basins of the Western Interior.

COAL GEOLOGY

The geographic locations and stratigraphic positions of coal beds of Late Cretaceous age in the San Juan basin were determined by the changing location of the shoreline along the western border of an epicontinental sea of that time. The coal deposits originated from thick accumulations of detrital organic matter (peat) in paludal environments on deltas and lower coastal plains. These environments were present in the San Juan basin as a result of periodic transgression and regression of the Cretaceous sea. The coal beds tend generally to be elongate toward the northwest, parallel to the shoreline.

With each successive major transgressive-regressive cycle, the northwest-trending shoreline retreated progressively farther northeast until, by the end of the Cretaceous Period, the sea had withdrawn from the region completely (fig. A5). At times the shoreline remained in one position long enough for thick coastal sandstone to be deposited and for adjacent swamps to maintain the delicate balance necessary for thick deposits of organic matter to accumulate and alter to coal. The sedimentary record of each major transgressive-regressive cycle includes at least one coal-bearing unit. Although nearly all Cretaceous rocks in the San Juan basin contain some coal, the major coal-bearing units of Cretaceous age in the basin are, in ascending order, the Crevasse Canyon, Menefee, and Fruitland Formations.
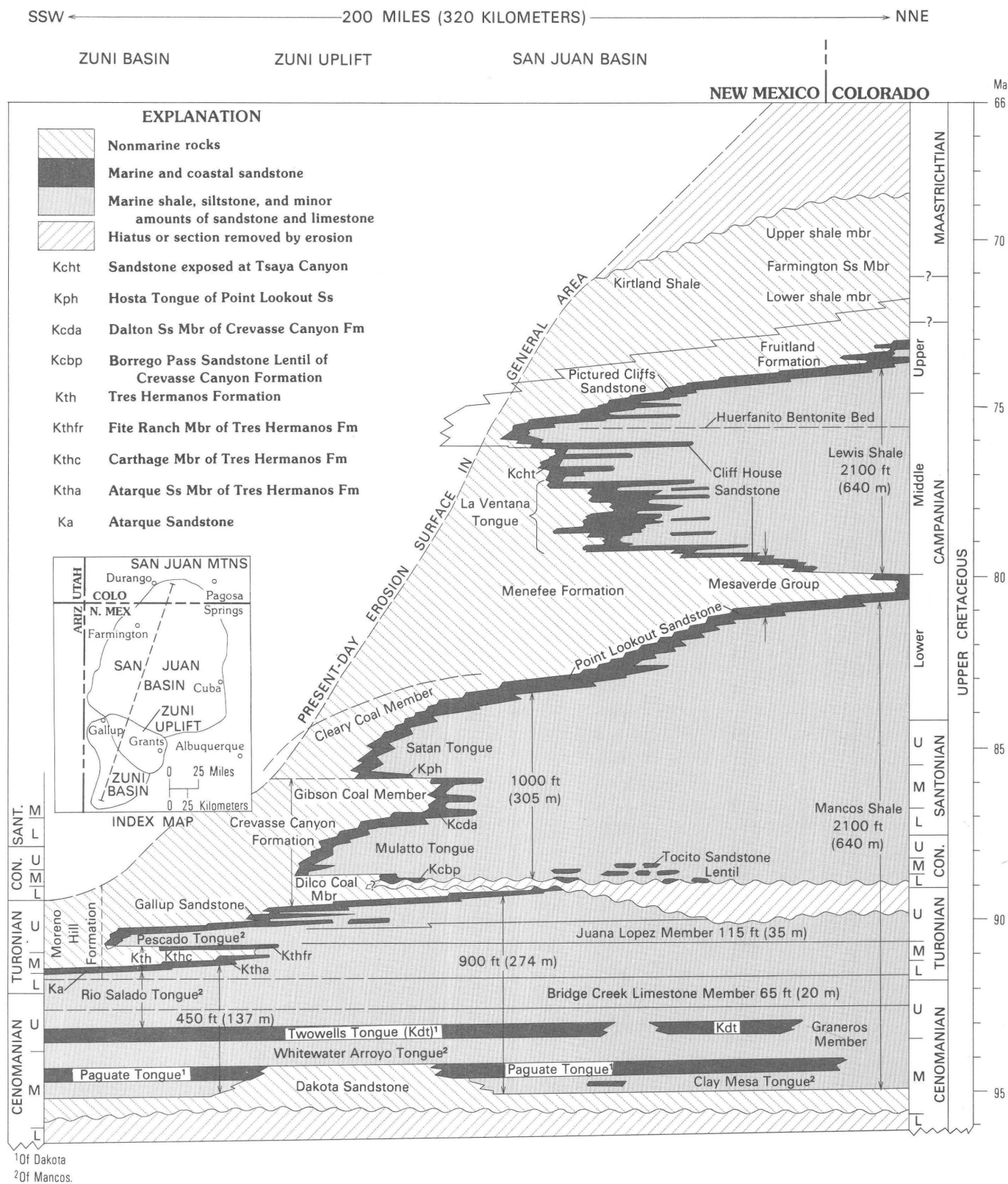
Figure A5. Time-stratigraphic geologic section of Upper Cretaceous rocks, San Juan basin (Molenaar and Baird, 1991).
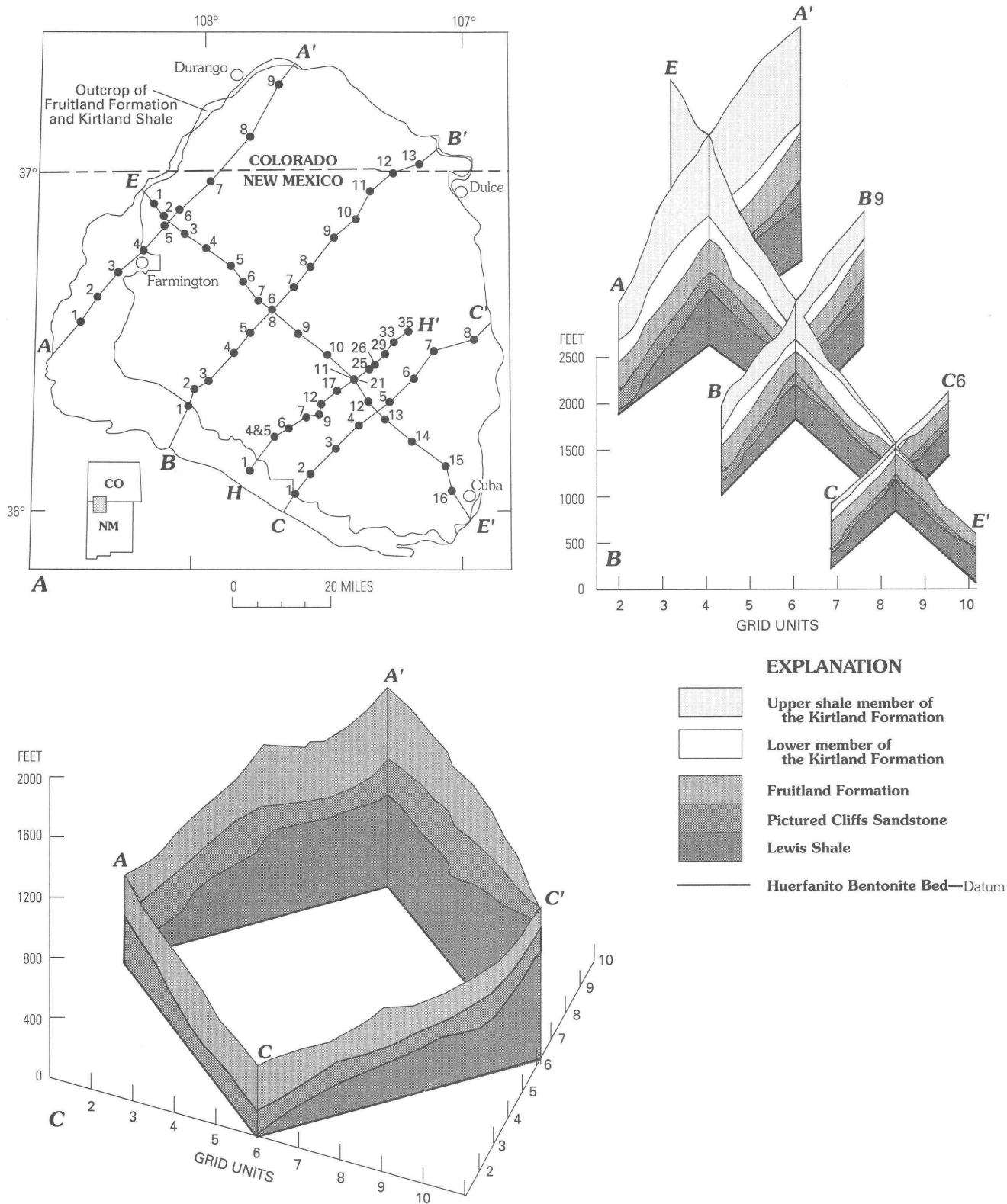
Figure A6. Cross sections *A–A'* through *E–E'*, showing stratigraphic rise of the Pictured Cliffs Sandstone across the San Juan basin (from Fassett and Hinds, 1971, pl. 2); also shown are locations of section *H–H'* and of drill holes H–1 through H–35, presented in figure A7. *A*, Index map showing lines of sections. Numbered points indicate locations of oil and gas wells; electric logs of these wells were used in constructing stratigraphic cross sections. *B* and *C*, Fence diagrams based on sections *A–A'* through *E–E'*. Vertical scales show feet above datum (the Huerfanito Bentonite Bed); horizontal scale shows grid unit across basin (approximately 10 mi each).

Coal beds in the Dilco and Gibson Coal Members of the Crevasse Canyon Formation (fig. A5) have long been mined in the southwest part of the San Juan basin. Where the Gibson Member of the Crevasse Canyon Formation and the Cleary Coal Member of the Menefee Formation merge, several coal beds are currently being strip-mined at the McKinley Mine (fig. A8, No. 6), northwest of Gallup (Wilson, 1977, p. 255).

The Menefee Formation, in general, contains coal beds at its base and its top but is essentially barren in the middle part. In the northwestern part of the basin, the coal-bearing units are called the lower and upper coal-bearing members (Hayes and Zapp, 1955). In the southern part of the basin, the Menefee is divided into two members, a lower coal-bearing member, called the Cleary Coal Member, and the overlying Allison Member, which generally includes some coal at the top. Miller (1984) has named the coal-bearing interval at the top of the formation the La Vida Beds of the Allison Member. The upper coal-bearing unit generally underlies, or intertongues with, the lower part of the overlying Cliff House Sandstone. Along the east side of the San Juan basin the lower coal member crops out and can be traced from the southeast northward, nearly to the State line. Along outcrops on the west side of the basin the Menefee Formation in most places includes only a few coal beds except locally where it intertongues with overlying or underlying sandstones (Beaumont, 1971, p. 23). North of the San Juan River the number and thickness of coal beds increase in both coal-bearing members.

A distinctive marker bed, called the Huerfanito Bentonite Bed (fig. A5) of the Lewis Shale, fell as volcanic ash into the Late Cretaceous marine seaway between the time of deposition of Cliff House transgressive sands and the final regression marked by the Pictured Cliffs sands. The Huerfanito Bentonite Bed is a time-stratigraphic marker named and traced in the subsurface throughout the San Juan basin by Fassett and Hinds (1971). They used this stratigraphic marker to demonstrate the stratigraphic rise of the Pictured Cliffs Sandstone as the sea retreated northeastward, and the influence of this rise on coal beds in the overlying Fruitland Formation. Figure A6 shows the lines of section constructed by Fassett and Hinds (1971, plate 2) using the Huerfanito Bentonite Bed as a datum to show the stratigraphic rise northeastward of the Pictured Cliffs and the change in thickness of the overlying Kirtland Shale. Figures A6B and C are computer-generated fence diagrams, based on cross sections A–A' through E–E', to illustrate the concept of the stratigraphic rise. Panel E–E' in figure A6B and A–C in figure A6C parallel the Cretaceous shoreline and suggest essentially no stratigraphic change. Figure A6B also shows the general changes in thickness of members of the Kirtland

Shale. The Kirtland is thickest in the northern part of the basin. (See fig. A6B, line A–A'). The complicated changes in thickness of its members are discussed in detail by Fassett and Hinds (1971, p. 23–28).

The Fruitland Formation, which overlies the Pictured Cliffs Sandstone, contains by far the largest coal resources in the San Juan basin. Most of the coal occurs in lenticular beds in the lower part of the formation. Coal has been surface mined from the Fruitland near the San Juan River in the western part of the basin for many years. The thickness and distribution of coal in the Fruitland is closely related to the increase in thickness and stratigraphic rise of the Pictured Cliffs Sandstone, especially where the lower part of the Fruitland Formation intertongues with the upper part of the Pictured Cliffs. Figure A7 is a computer-generated plot of drill holes showing examples of Fruitland coal and the underlying Pictured Cliffs in a line extending northeastward across the basin for about 40 miles. In the plot, the datum is the base of the Pictured Cliffs Sandstone, and the data are interpreted from geophysical logs of oil- and gas-test holes. Typically, the coal beds are highly lenticular and difficult to correlate between drill holes. The thickest coal beds are generally near the base of the Fruitland, but they can be correlated with certainty only where drill holes are closely spaced. For these reasons, coal resource calculations can only be made for coal zones rather than for individual beds. The coal beds as shown in figure A7 are, in places, at least 20 feet thick, and there is a suggestion of two coal zones between drill holes H–9 to H–35. The thickest Fruitland coal in the basin is south of Durango, Colo., near Carbon Junction, where one bed consists of 80 feet of interbedded coal and partings (Zapp, 1949).

The San Juan basin is subdivided into 21 individual coalfields or coal areas underlain by strippable low-sulfur coal (fig. A8). Those fields or areas in which the Fruitland Formation is the current producer are the Navajo field and the Fruitland, Bisti, and Star Lake areas. The remaining fields or areas have coal resources—either developed or undeveloped—in the Mesaverde Group and its equivalents, the most notable being the Gallup field.

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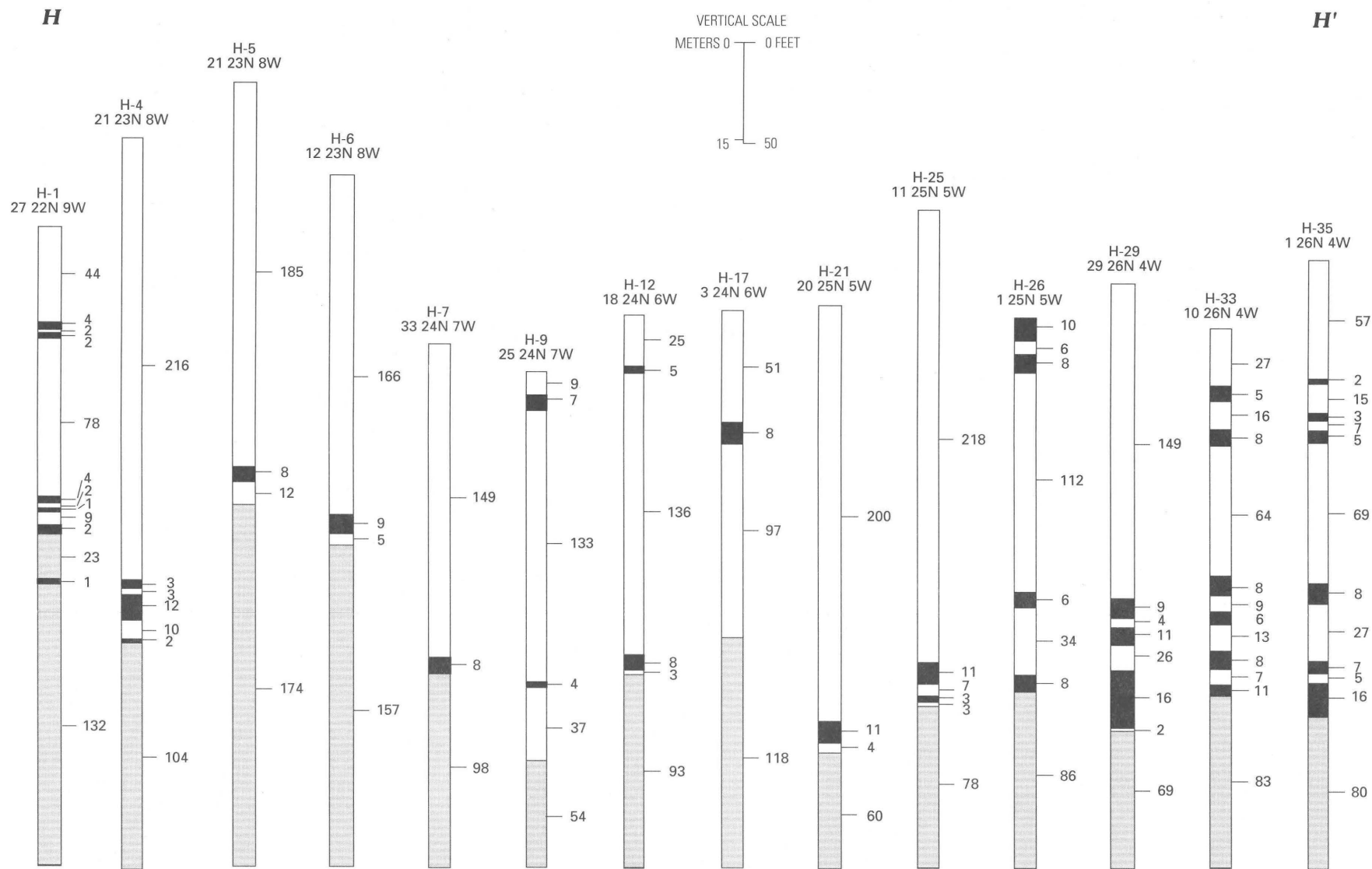
Figure A7. Correlation of well logs along section *H–H'* (fig A6A) showing lenticular nature of the coal beds (black) within the Fruitland Formation (no pattern). Stippled pattern represents Pictured Cliffs Sandstone; datum is the base of the Pictured Cliffs. Numbers next to columns give bed thicknesses in feet.

Figure A8. Fields, areas, and mines containing strippable low-sulfur coal in Upper Cretaceous formations of the San Juan basin. (Modified from Kottlowski and others, 1983.)
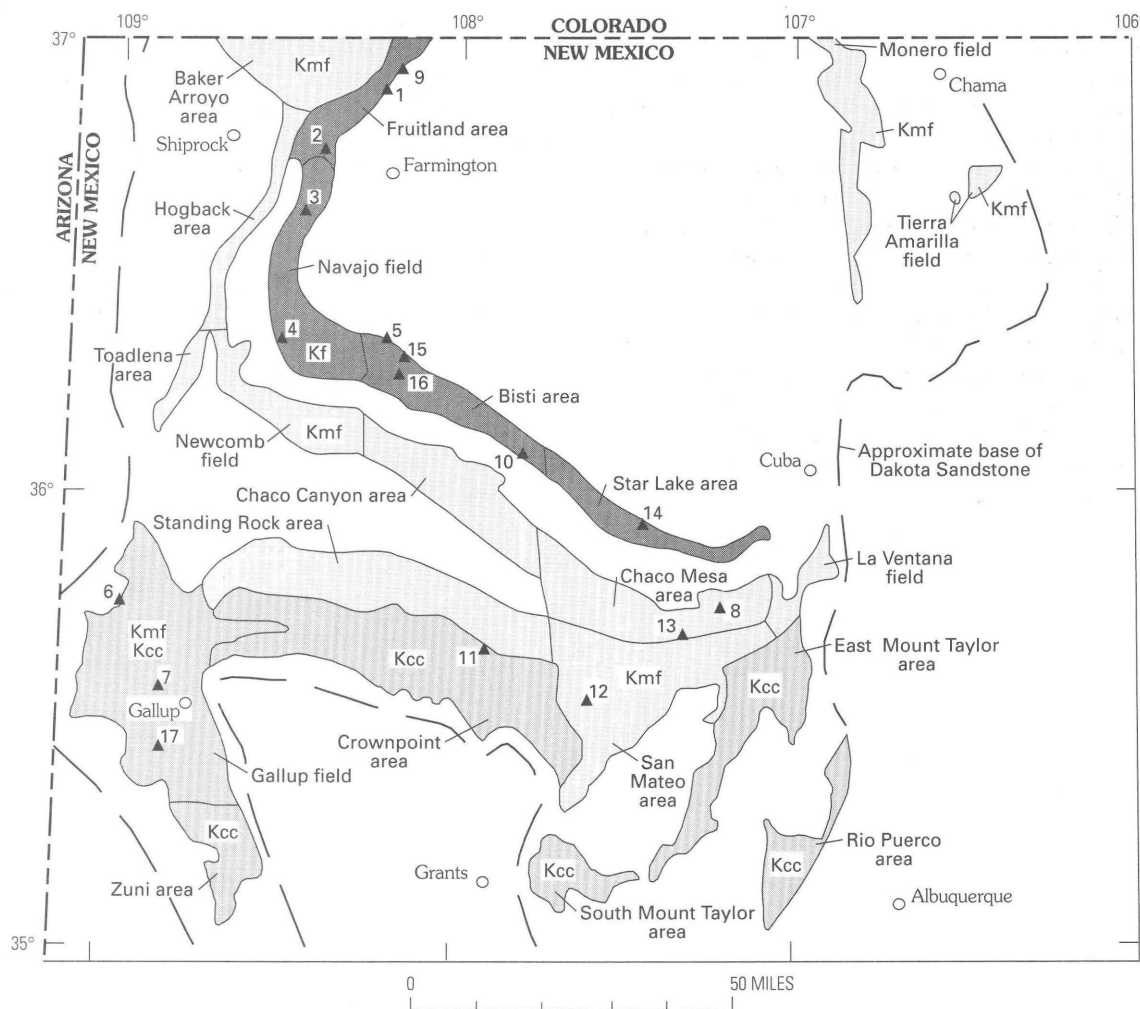
EXPLANATION

Kf	Fruitland Formation
Kmf	Menefee Formation
Kcc	Crevasse Canyon Formation

Active Mines, Permitted Mines, and Mine Permits in Progress

1. Black Diamond	7. Mentmore	13. La Ventana
2. San juan	8. Arroyo No. 1	14. Star Lake
3. Navajo	9. La Plata	15. Gateway
4. Burnham	10. Gallo Wash	16. Bisti
5. De-Na-Zin	11. South Hospah	17. Carbon No. 2
6. McKinley	12. Lee Ranch	

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Chapter B

Coal Resources of the San Juan Basin

By LAURA R. H. BIEWICK, ANTOINETTE L. MEDLIN, JUDY F. HUNTER, and KATHLEEN K. KROHN,

A demonstration of the capabilities of the
National Coal Resources Data System

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Coal Resources of the San Juan Basin

By Laura R.H. Biewick, Antoinette L. Medlin, Judy F. Hunter, *and* Kathleen K. Krohn

Abstract

A working data base of stratigraphic information for the Upper Cretaceous Menefee and Fruitland Formations, the two major coal-bearing units within the San Juan basin, was retrieved from the NCRDS (National Coal Resources Data System) master data base for New Mexico using the PACER data storage and retrieval system on a 32-bit minicomputer. These data were reviewed, and data from other sources were coded and added. Then subsets of data were retrieved, representing drill holes that had penetrated the entire thickness of either of the formations within the digitized boundary areas.

The coal resources of both formations were calculated from this data set using GARNET, one of the graphic analysis and volume calculation programs of NCRDS. Because of the lenticular nature of the coal beds and the large area under study, the resource assessments were made for total coal within each of the formations, rather than for individual coal beds.

The GARNET program uses a point location file, a grid file of coal thickness, and a boundary file to calculate coal volume; then it multiplies the volume by a density factor, which depends on the coal's rank, to produce a coal tonnage estimate. These estimates, for the New Mexico part of the San Juan basin, are 168 billion short tons of coal in the Fruitland Formation and 21 billion short tons of coal in the Menefee Formation. Each estimate is presented in three ways: (1) as a single resource tonnage; (2) as tonnages in the measured, indicated, inferred, and hypothetical categories; (3) as tonnages in various generalized land ownership categories; and (4) as tonnages in various overburden categories by township, range, and county. The GARNET program was also used to produce coal isopach, overburden, and generalized land ownership maps.

INTRODUCTION

The two predominant coal-bearing sequences in the San Juan basin, the Upper Cretaceous Menefee and Fruitland Formations (fig. B1), have been studied using traditional and computerized methods. This study had four objectives:

1. To estimate the total coal resources in the Menefee and Fruitland Formations in the San Juan basin, within the limitations of the available data.
2. To estimate the approximate amounts of the total coal resources that occur in areas within various generalized categories of coal mineral rights ownership.
3. To estimate the amounts of the total coal resources within various categories of overburden thickness.
4. To demonstrate the capabilities of the U.S. Geological Survey's National Coal Resources Data System (NCRDS) for coal resource calculations.

The coal resource estimates presented in this chapter were calculated using the data and programs of the NCRDS. PACER is the data base formatting, storage, and retrieval program and GARNET is the graphic analysis and volume calculation program of NCRDS. A 32-bit minicomputer was used for this study. All of the techniques and procedures illustrated here can be applied at various scales, to areas ranging from federal lease tracts to whole States or regions. Pertinent factors are the amount, reliability, and distribution of available data; the accuracy of boundary definitions; and the categories of resource calculations required.

PROCEDURES

Data Preparation

A working file of stratigraphic information for the San Juan basin was retrieved from the NCRDS master data base for New Mexico (NMSTRAT) using PACER. These data had been compiled from well logs by geologists of the U.S. Geological Survey (USGS) and the New Mexico Bureau of Mines and Mineral Resources. Additional data from recent studies and other sources were coded and added to the working file by the USGS project geologists and NCRDS staff. The geologists checked the designations of stratigraphic units and, where necessary, corrected the working file using the PACER updating capability. Data from this working file were used to produce several products for the geologists' analyses and approval.
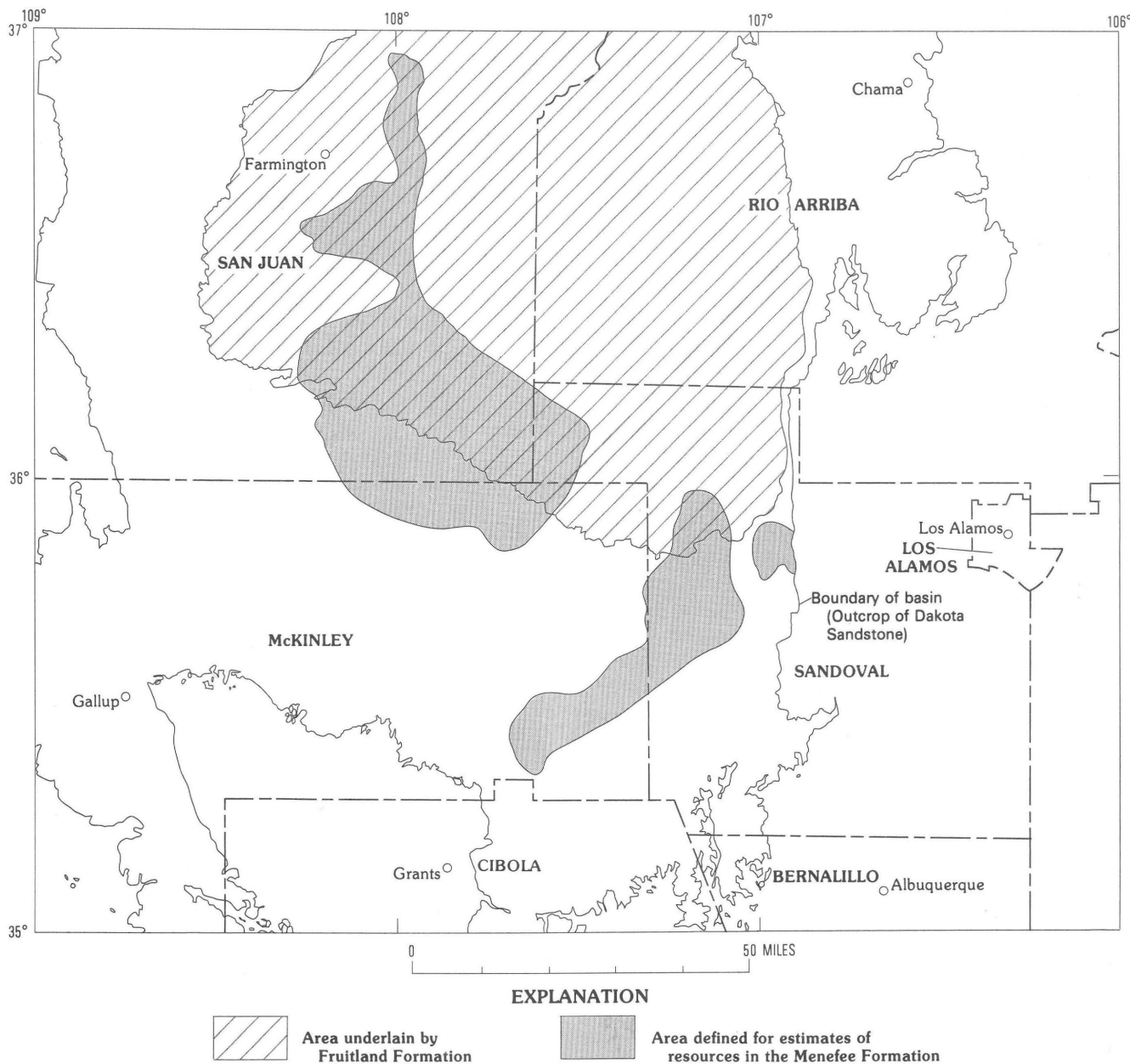
Figure B1. Location of areas defined for estimates of coal resources in the Fruitland and Menefee Formations in the San Juan basin, New Mexico. Area of the Fruitland is bounded by the formation's outcrop; area shown for the Menefee is bounded by a limit-of-estimates line based on available drill hole data.

Because the Fruitland Formation is the only formation in the San Juan basin represented by sufficient NCRDS data to allow detailed analysis, it is discussed first in this report. In order to retrieve data representative of the coal in the complete Fruitland Formation, a single PACER request was made for all drill hole records having Fruitland Formation coal lithostratigraphic units; partial sections were excluded. The request yielded 2,513 records, which were processed using standard NCRDS software to sum the thicknesses of all coal horizons from the same drill hole. This procedure resulted in total Fruitland Formation coal values for 630 randomly spaced point locations. These point

locations and values were then used for input to the GARNET program for graphic display and calculation of coal tonnage estimates.

The first GARNET operation was to use the randomly spaced data point locations to create an evenly spaced grid of estimated coal thickness values. These values were then displayed as contours or isolines at intervals designated by the data analyst. An optimal grid spacing of 3 miles was selected based on the spacing of random data points over the area. The GARNET software provides two gridding algorithm options for interpolation of randomly spaced data: the quadratic algorithm for dense, evenly spaced points and

the planar algorithm for sparse, unevenly distributed points. Fruitland Formation coal thickness data were best represented by the planar gridding option because of the distribution of the data points. The planar algorithm averages the values over a larger area than the quadratic algorithm and produced a coal isopach map satisfactory to the geologists' interpretation of the data (fig. B2).

A second PACER request to the working file retrieved values for the depth to the top (overburden) of the Fruitland Formation coal zone. These overburden values were then gridded using the GARNET program. Sufficient data points were not available to control the overburden contours at the outcrop line in three locations, so the GARNET point-editing capability was used to add control points at these three locations to generate the map shown in figure B3. This map was approved by the geologists

and compares generally to figure 27 in the Fassett and Hinds (1971) study of this area.

Similar procedures were used to generate maps of the Menefee Formation coal and overburden thicknesses (figs. B4 and B5).

Boundary Definition

NCRDS includes the capability to calculate coal resource tonnage estimates from isopach maps within a boundary defining an area of interest. Very generalized land ownership categories were defined in this study to show the concept of estimating coal resources by the following areas of interest:

National parks and monuments
National forest lands
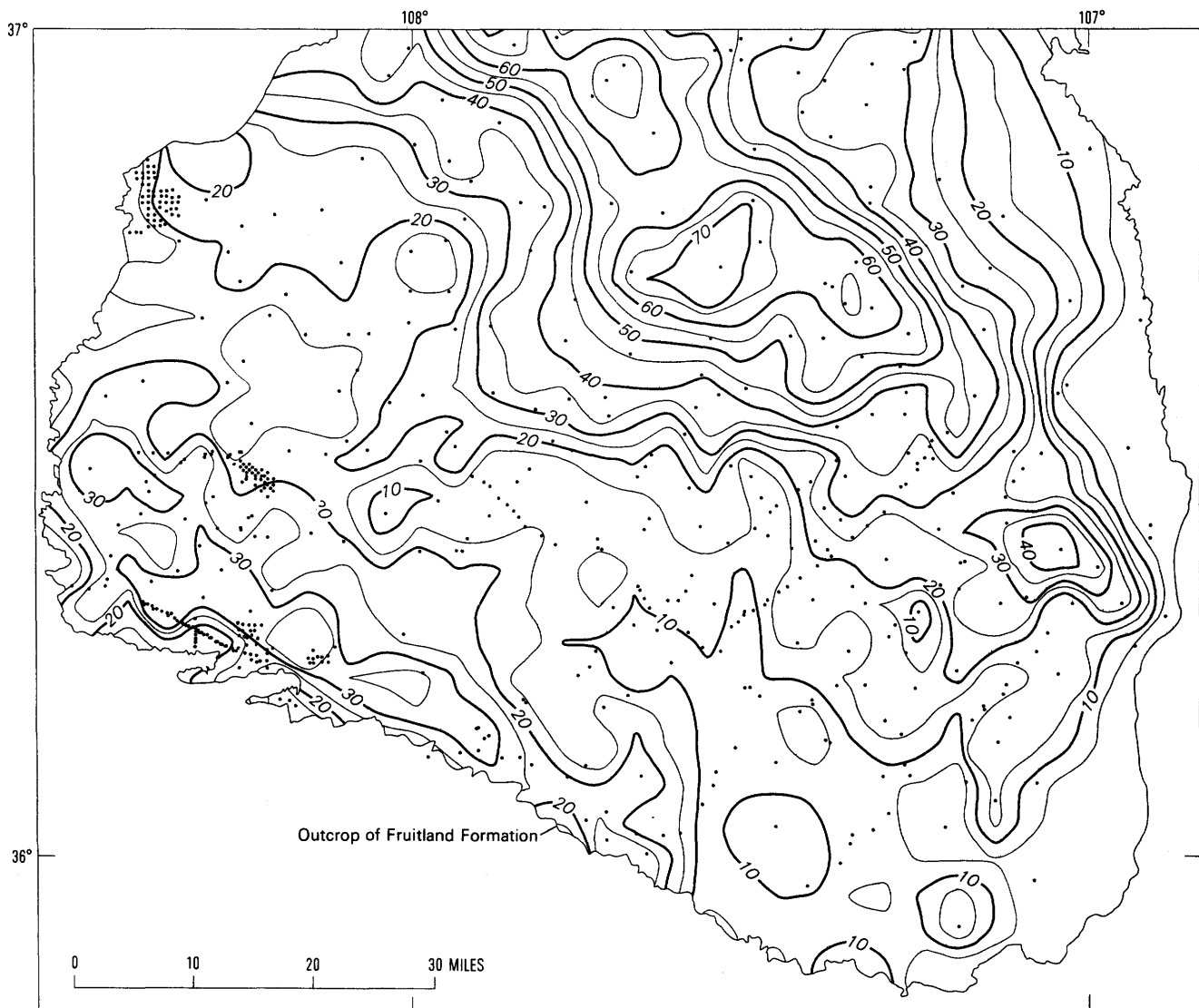
Figure B2. Isopach map of total coal in the Fruitland Formation. Dots represent data points. Contour interval 5 feet. See figure B1 for location of the area shown here.
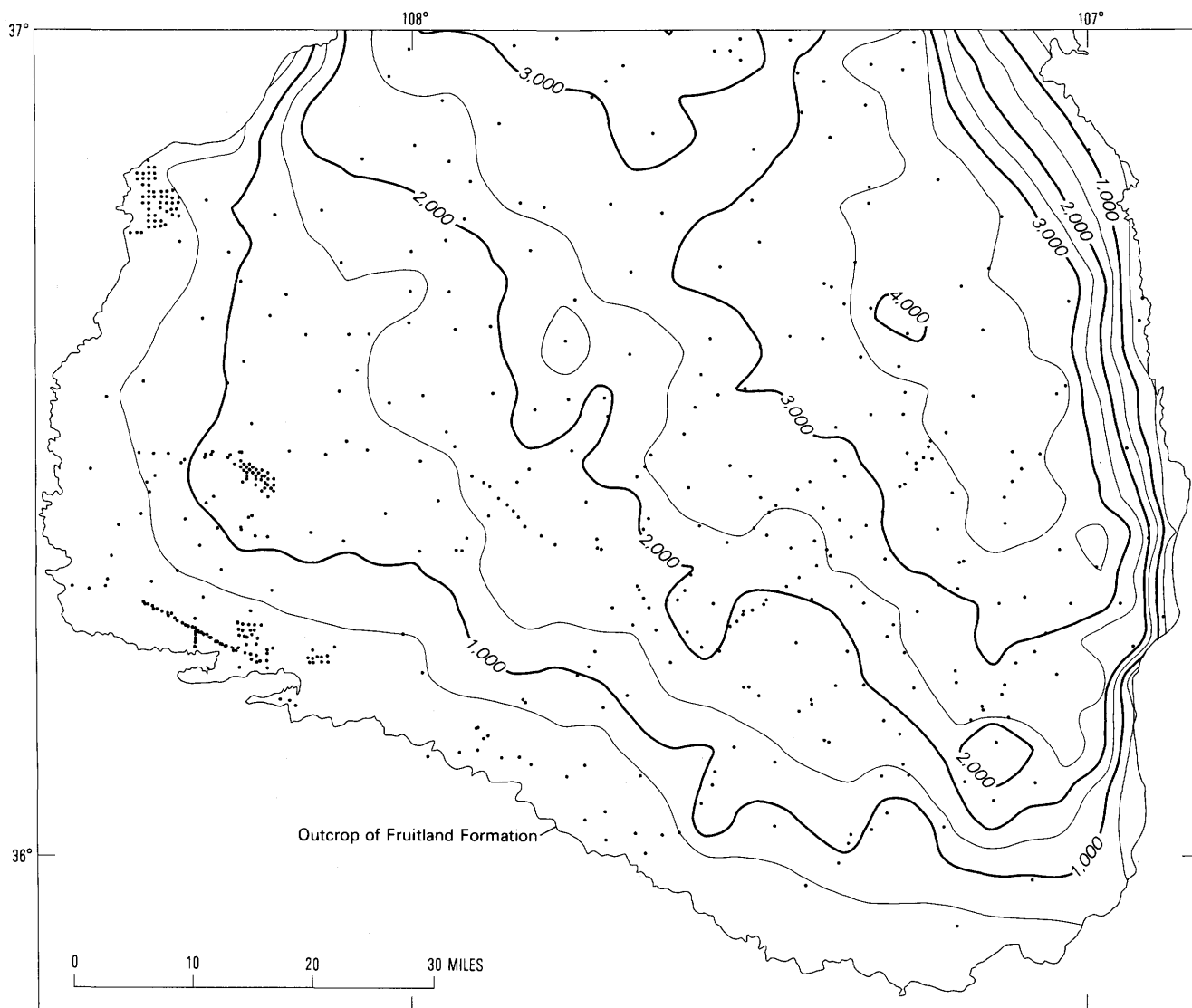
Figure B3. Thickness of overburden on top of coal in the Fruitland Formation. Dots represent data points. Contour interval 500 feet. See figure B1 for location of the area shown here. (Note: configuration of the land surface is very generally represented by the available data.)

Other federal surface and/or subsurface coal ownership
Indian lands and reservations
State and privately owned lands
Counties

Digital files were created to store the boundary data that define each of these areas. Township and range boundaries determined areas used to estimate coal resource tonnages for federal lands. In all areal categories, the data were used to generate tonnage estimates in the following overburden categories:

> 0–500 feet
> 500–1,000 feet
> 1,000–2,000 feet
> 2,000–3,000 feet
> More than 3,000 feet

The GARNET program can process data and calculate results within any digital boundary that can be defined by 20,000 points or less. The boundary categories defined above provide an evaluation of approximate coal resources in the basin to illustrate the capabilities and techniques of NCRDS on a regional scale. The accuracy of the GARNET software tonnage estimates depends on the available data, the selected map scale, the digital boundary accuracy, and the chosen grid interval.

A 1:500,000 scale State of New Mexico Land Status Map (DOI, BLM edition of 1982) was used to digitize the boundaries of counties and townships and ranges, and the generalized boundaries of Indian reservations, national parks, national monuments, and national forests. Mineral ownership categories shown on figures B6 and B7 were also
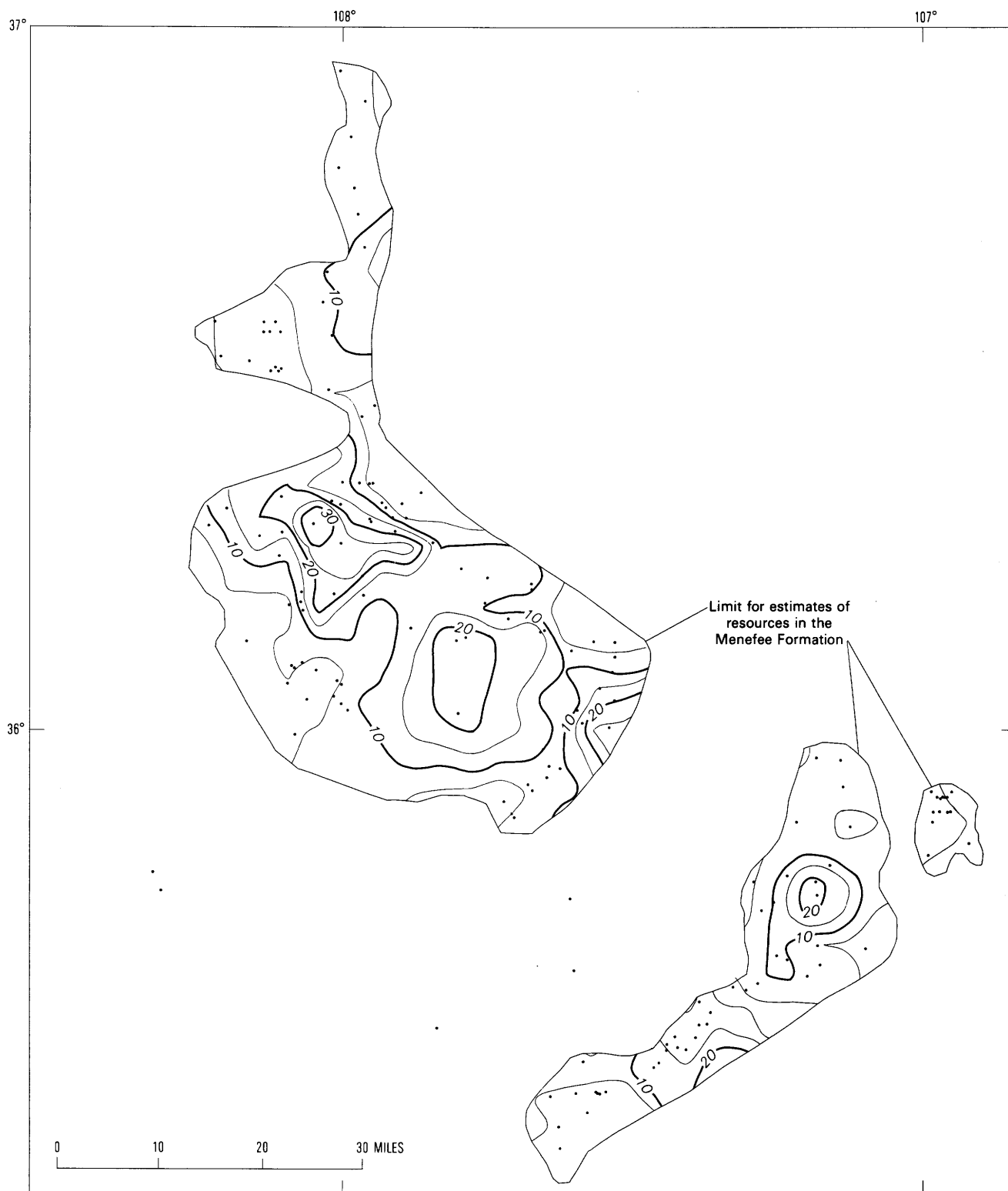
Figure B4. Isopach map of total coal in the Menefee Formation. Dots represent data points. Contour interval 5 feet. See figure B1 for location of the area shown here.

compiled from various Bureau of Land Management 1:100,000-scale land status maps (1978–1983). These boundaries are highly generalized.

Boundaries for each area of interest were digitized using equipment with an accuracy of 0.005 inch. Data from appropriate categories (political, township, range, county)
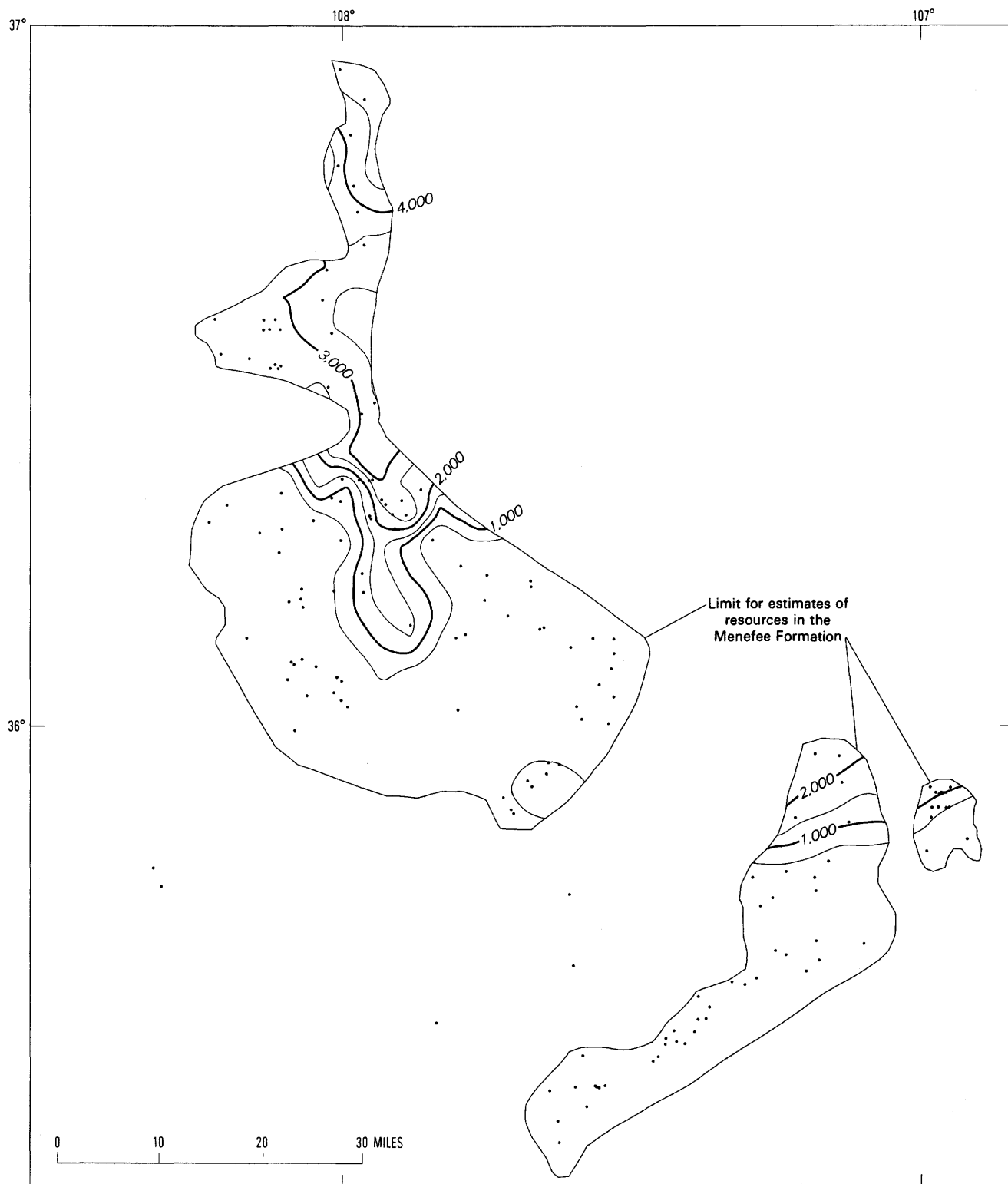
Figure B5. Thickness of overburden on top of coal in the Menefee Formation. Dots represent data points. Contour interval 500 feet. See figure B1 for location of the area shown here. (Note: configuration of the land surface is very generally represented by the available data.)

were combined using the GARNET boundary command. The overburden category boundaries were retrieved directly by subtracting the gridded file of the elevations at the top of the coal beds from the gridded file of the surface elevations; then the overburden categories were combined with the political, land ownership, reliability, and coal thickness categories to define the final subareas for resource estimates. More than 300 subareas were defined with unique boundaries for individual coal resource tonnage calculations.

Localities of Menefee Formation coal data in NMSTRAT are densely distributed in the central and southeastern portions of the basin. In these two areas data are sufficient to allow estimates of coal resources using NCRDS. The Menefee boundary used for the isopach and overburden maps (figs. B4 and B5) represents an irregular
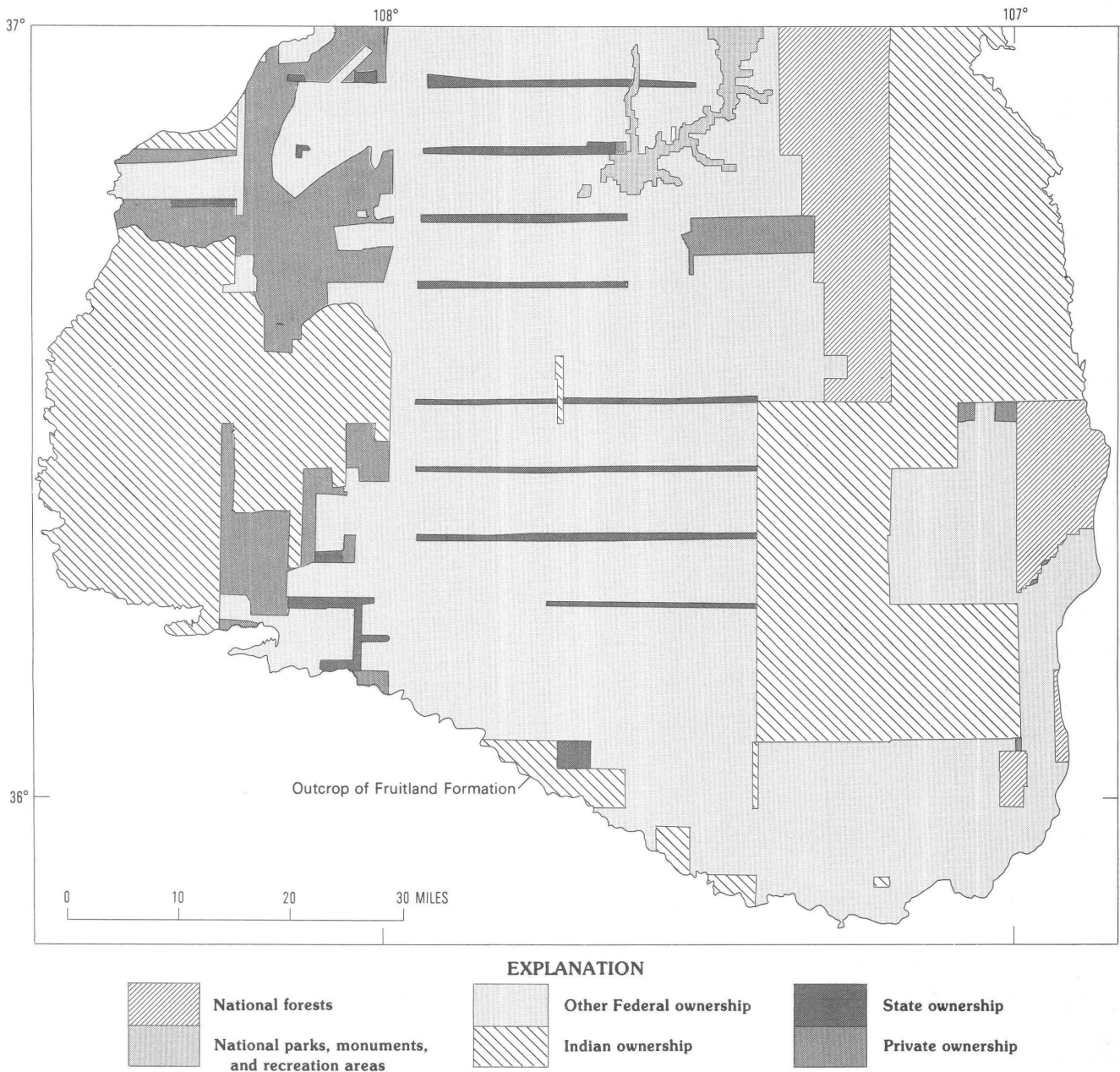
Figure B6. Digitized boundaries of land categories in area underlain by the Fruitland Formation. Boundaries are highly generalized and are intended to represent only the general proportions of each category in a given area. Ownership status of specific parcels of land should not be inferred from this map. See figure B1 for location of area shown here.
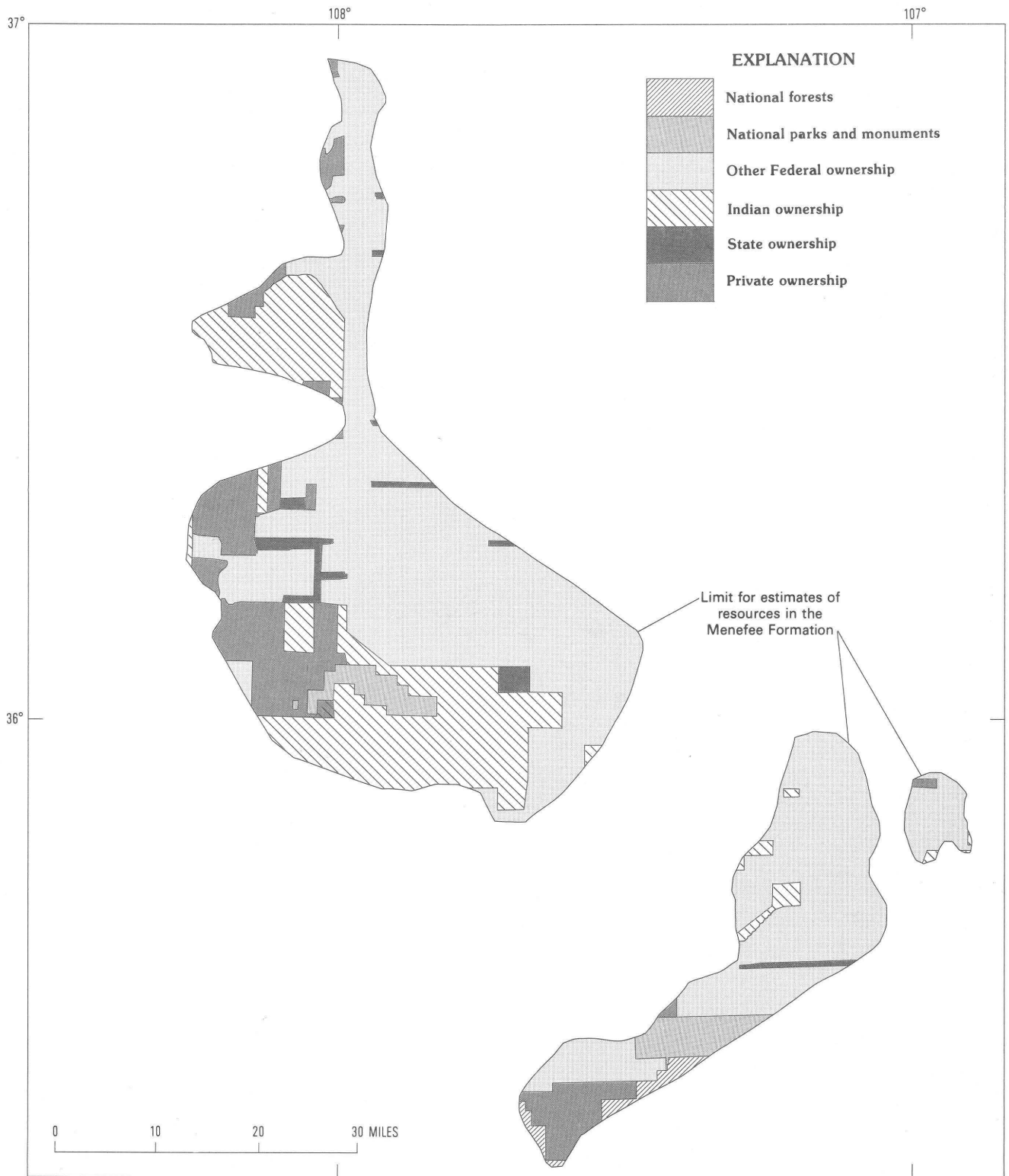
Figure B7. Digitized boundaries of land categories in areas underlain by the Menefee Formation. Boundaries are highly generalized and are intended to represent only the general proportions of each category in a given area; in certain cases, categories may be misapplied. Ownership status of specific parcels of land should not be inferred from this map. See figure B1 for location of area shown here.

limit-of-estimate line generated by the geologists. This artificial boundary is used instead of an outcrop boundary to enclose the area best represented by the available data.

A small, isolated cluster of wells in the northeast portion of the basin also provided Menefee coal data. The coal in this small area is less than 5 feet in total thickness and is quite distant from the other Menefee coal to the south. No reliable resource calculation could be made for the small set of data from this isolated area.

Resource Calculations

The GARNET program uses a point location file, a gridded coal isopach file, and a boundary file to calculate the volume of coal, then the appropriate density factor for the rank of coal being considered is applied to produce a coal tonnage estimate. Coal resource volumes are calculated by determining the area (acreage) and average thickness for all of the grid cells of the coal isopach grid that fall within the area defined by the boundary file and a selected radius from the data point locations. The U.S. Geological Survey has designated specific radii from known coal data points as defining certain reliability classifications of coal resource tonnage estimates (Wood and others, 1983), but any radii can be selected and used in the GARNET program. These volumes are then multiplied by the density factor appropriate for the rank of the coal under consideration. For coal in the Menefee and Fruitland Formations, a density factor of 1,770 tons per acre foot was selected.[1]

The data included in NMSTRAT for the coal-bearing rocks older than the Fruitland and Menefee Formations (in descending order: Crevasse Canyon Formation, Gallup Sandstone, Tres Hermanos Formation, and Dakota Sandstone) are from localities scattered sparsely across the San Juan basin. Coal data in NMSTRAT are insufficient to allow use of computer methods to generate coal tonnage estimates for these rock units. The latest estimates by the New Mexico Bureau of Mines and Mineral Resources for the Crevasse Canyon Formation coal resources, shown below, were derived from coal data for the southern portion of the San Juan basin using a planimeter. Resource calculations done by conventional methods, using measured and indicated resource categories based on radii from known data points (Woods and others, 1983, p. 11), yielded the following estimate of coal in the Crevasse Canyon Formation, in beds more than 1.2 feet thick under less than 250 feet of overburden (Frank W. Campbell, New Mexico Bureau of Mines and Mineral Resources, oral commun., 1985):

[1]Minimum thicknesses specified by Wood and others (1983, table 3) were not used in classifying coal resources for these estimates. Coal quality data are insufficient to discriminate between bituminous and subbituminous coal. Resource estimates in this report represent total coal.

CREVASSE CANYON FORMATION			
Resource classification	Acres	Average thickness (feet)	Estimated tons (millions)
Measured......	38,000	3.5	325
Indicated	151,000	3.5	1,275

RESULTS

The coal resources of the Fruitland and Menefee Formations were estimated by several different techniques for comparative purposes. The resource estimation techniques used were selected on the basis of data distribution, the accuracy and scale of boundary definitions, the size of area to be included, and research goals. All the estimated coal tonnages shown below are reported to the nearest million tons, which is deemed to be the maximum appropriate level of precision for this study.

Calculations using a single large radius from known data points, the Fruitland Formation outcrop, and the limit-of-estimate boundary of the Menefee Formation gave the following estimate of total coal resources:

Formation	Acres	Average thickness (feet)	Estimated tons (millions)
Fruitland	3,720,299	25.4	167,501
Menefee	1,216,901	9.8	21,099

Calculations using the radii specified by Wood and others (1983, fig. 4), the Fruitland Formation outcrop, and the limit-of-estimate boundary of the Menefee Formation gave this estimate of coal resources in the four reliability categories used by the USGS:

Formation and resource classification	Acres	Average thickness (feet)	Estimated tons (millions)
Fruitland:			
Measured	71,225	23.8	3,001
Indicated	400,686	23.7	16,774
Inferred.......	2,533,367	26.1	116,980
Hypothetical	715,022	24.3	30,738
Menefee:			
Measured.....	17,152	9.6	290
Indicated	143,997	8.7	2,229
Inferred.......	835,090	9.8	14,438
Hypothetical	220,661	10.6	4,140

The use of boundaries for some of the very generalized land ownership categories and a single large radius produced the following approximate total coal resource estimates:

Ownership and overburden thickness (feet)	Acres	Average thickness (feet)	Estimated tons (millions)
Fruitland Formation			
National forests:			
0–500	11,894	0.1	1
500–1,000	6,894	0.9	11
1,000–2,000	19,068	2.1	72
2,000–3,000	22,590	10.4	416
>3,000	197,232	36.6	12,778
Total	257,678		13,278
National parks, monuments, and recreation areas:			
2,000–3,000	38,360	46.7	3,170
>3,000	7,728	53.7	735
Total	46,088		3,905
Other federal ownership:			
0–500	343,165	14.0	8,842
500–1,000	227,083	12.8	5,284
1,000–2,000	553,550	14.5	13,352
2,000–3,000	601,801	33.2	36,480
>3,000	323,498	47.4	26,498
Total	2,049,097		90,456
Indian lands:			
0–500	209,267	20.1	7,450
500–1,000	139,483	18.0	4,435
1,000–2,000	328,728	14.2	8,282
2,000–3,000	245,185	16.4	7,115
>3,000	211,296	26.6	9,939
Total	1,133,959		37,221
State lands unclassified:	46,700	37.9	3,129
Menefee Formation			
National forests:			
0–500	13,949	7.4	182
National parks, monuments and recreation areas:			
0–500	19,673	11.2	391
Other federal ownership:			
0–500	313,608	10.8	6,308
500–1,000	76,565	12.7	1,637
1,000–2,000	79,664	10.1	1,552
2,000–3,000	36,452	7.3	458
>3,000	57,294	9.1	869
Total	563,583		10,824

Ownership and overburden thickness (feet)	Acres	Average thickness (feet)	Estimated tons (millions)
Menefee Formation—Continued			
Indian lands:			
0–500	166,273	11.4	3,345
500–1,000	8,745	7.1	109
1,000–2,000	309	9.2	5
2,000–3,000	49,952	4.2	370
>3,000	22,492	7.6	303
Total	247,771		4,132
State lands unclassified:	14,456	16.3	416

Detailed resource estimates for the "Other Federal ownership" category, classified by overburden, county, and township and range, are given in tables B1 and B2 at the end of the chapter.

A comparison of the total coal resources tonnage estimate calculated by the computer and the summation of resource numbers for the various multiple resource calculations shows some differences:

Method of calculation	Estimated total coal resources (millions of tons)	
	Fruitland Formation	Menefee Formation
Based on a single large radius....	167,501	21,099
Total of four reliability categories of Wood and others (1983)	167,493	21,097
Total of estimates for various land ownership categories	147,989	15,944

The significant "shortfall" in the estimates tallied from the land ownership categories results mainly from the exclusion of privately owned resources from these estimates. Other, smaller differences in the total resource estimates are mostly attributable to three factors:

1. The size of the area being estimated (estimates for small areas have a greater margin of error than those for large areas).

2. The grid cell interval.

3. The GARNET resource calculation procedure that includes or excludes all of a particular grid cell depending on its intersection with a boundary.

CONSIDERATIONS AND ISSUES

The variability in number of coal beds across the basin (fig. B8) demonstrates the discontinuous nature of coal beds within the Fruitland Formation coal zone. A comparison of figure B8 with figure B2 will indicate the variability in the number of coal beds in which a given total coal thickness occurs. This information can be used, along with interburden data, to define areas most favorable for development.

Several refinements would improve the utility of the results of these resource calculations. Some of these could be accomplished fairly soon:

1. Improving acreage and tonnage estimates, especially with reference to federal ownership, by using digital boundary data recorded from 1:100,000-scale or larger scale maps.

2. Calculating resources by thickness category of individual coal horizons; that is, summing coal horizons whose thicknesses fall within a given range, such as 10–20 feet or 20–30 feet. These resource numbers categorized according to overburden thickness would reflect information of value for potential development.

Other, longer range improvements would require additional data gathering and study:

1. Expansion and refinement of the stratigraphic data base; location and encoding of additional coal stratigraphic data.

2. Further review and analyses of correlations within the data base.

3. Gathering and encoding sufficient data on coal quality to allow resource estimates to be subdivided into coal quality categories.
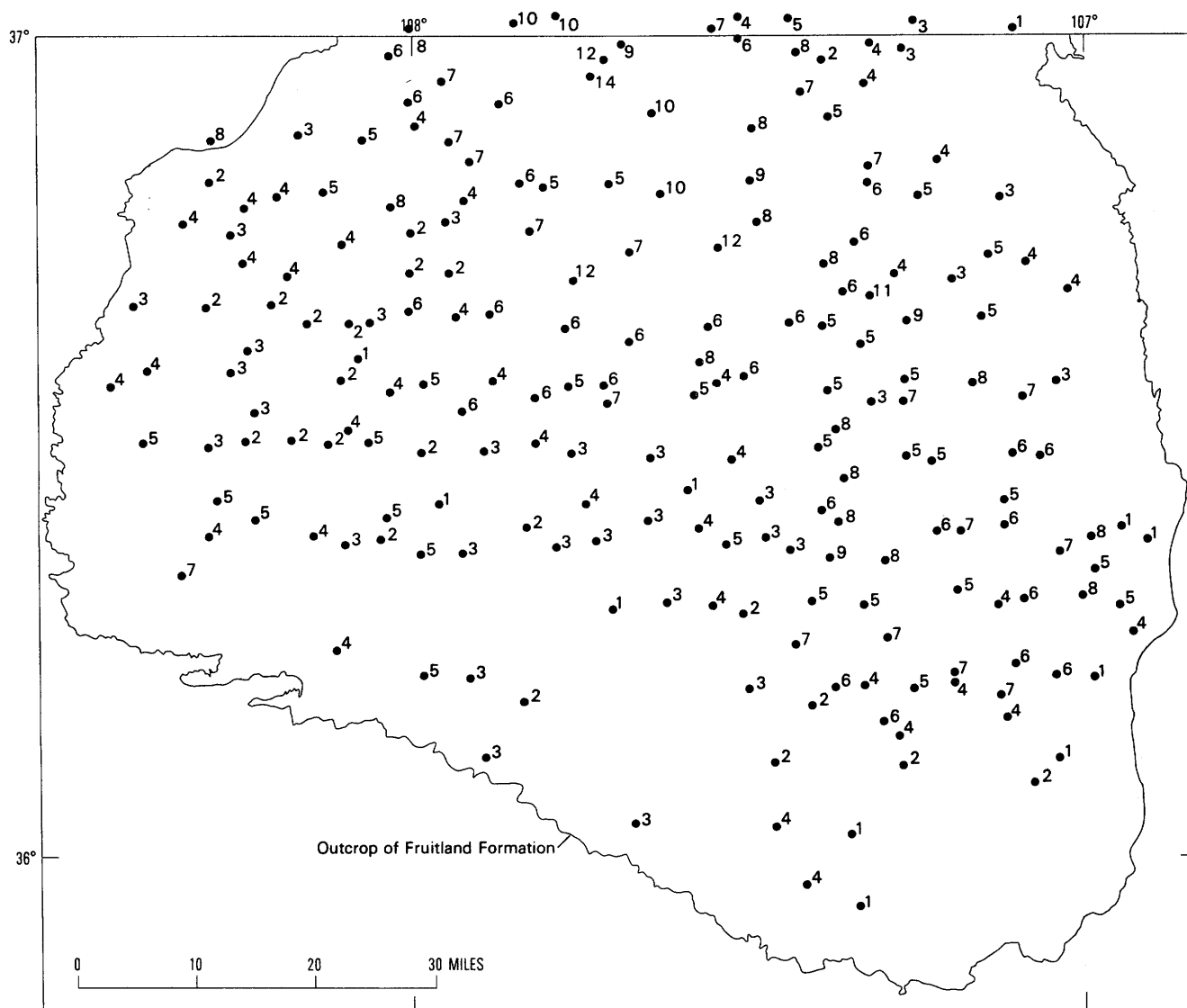
Figure B8. Number of coal horizons in the Fruitland Formation at drill hole localities. See figure B1 for location of area shown here.

Table B1. Estimates of Federally owned subbituminous coal resources in the Fruitland Formation, San Juan basin, New Mexico

[Estimates may include some coal already mined but exclude resources in national parks, monuments, and national forests]

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
McKinley County				
T. 19 N., R. 5 W.				
0- 500	9,042	11.0	176.75	176.75
T. 20 N., R. 5 W.				
0- 500	14,419	7.3	186.87	
500-1,000	8,248	6.8	99.00	285.87
T. 20 N., R. 6 W.				
0- 500	22,015	8.7	337.37	
500-1,000	567	12.4	12.43	349.80
T. 20 N., R. 7 W.				
0- 500	14,287	8.6	216.87	216.87
T. 20 N., R. 8 W.				
0- 500	1,712	26.4	79.86	79.86
Total for McKinley County ---------------				1,109.15
Rio Arriba County				
T. 23 N., R. 1 W.				
0- 500	485	.3	.23	
500-1,000	1,163	2.6	5.39	
1,000-2,000	2,291	4.2	16.82	
2,000-3,000	4,199	9.5	70.93	93.37
T. 23 N., R. 6 W.				
1,000-2,000	13,355	10.1	239.37	239.37
T. 23 N., R. 7 W.				
1,000-2,000	9,807	9.2	159.62	
2,000-3,000	710	10.0	12.52	172.14
T. 24 N., R. 1 E.				
0- 500	2,797	.5	2.69	
500-1,000	195	.2	.07	2.76
T. 24 N., R. 1 W.				
1,000-2,000	5,348	10.9	103.35	
2,000-3,000	13,762	17.2	418.02	
>3,000	1,535	36.7	99.77	621.14
T. 24 N., R. 2 W.				
2,000-3,000	5,721	17.6	178.07	
>3,000	17,056	24.5	740.21	918.28
T. 24 N., R. 3 W.				
2,000-3,000	6,858	22.0	266.86	
>3,000	13,977	25.8	637.02	903.88
T. 24 N., R. 6 W.				
1,000-2,000	17,018	13.2	398.42	
2,000-3,000	4,753	14.2	119.21	517.63
T. 24 N., R. 7 W.				
1,000-2,000	2,740	8.4	40.49	
2,000-3,000	16,300	13.0	374.45	414.94

Table B1. Estimates of Federally owned subbituminous coal resources in the Fruitland Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
Rio Arriba County--Continued				
T. 25 N., R. 1 E.				
500-1,000	1,604	1.8	5.06	
1,000-2,000	1,091	2.2	4.24	9.30
T. 25 N., R. 2 W.				
>3,000	23,975	16.7	708.20	708.20
T. 25 N., R. 3 W.				
>3,000	22,751	30.3	1,218.81	1,218.81
T. 25 N., R. 6 W.				
2,000-3,000	21,276	14.6	549.68	549.68
T. 25 N., R. 7 W.				
1,000-2,000	571	12.6	12.73	
2,000-3,000	18,085	16.6	529.85	542.58
T. 26 N., R. 2 W.				
>3,000	19,435	18.9	650.74	650.74
T. 26 N., R. 6 W.				
2,000-3,000	21,677	20.9	802.87	802.87
T. 26 N., R. 7 W.				
2,000-3,000	18,763	24.5	811.91	811.91
T. 27 N., R. 5 W.				
>3,000	22,629	47.2	1,892.03	1,892.03
T. 27 N., R. 6 W.				
2,000-3,000	9,229	40.2	656.10	
>3,000	10,985	50.7	986.45	1,642.55
T. 27 N., R. 7 W.				
2,000-3,000	18,811	40.6	1,351.17	1,351.17
T. 28 N., R. 5 W.				
>3,000	17.337	59.6	1,827.52	1,827.52
T. 28 N., R. 6 W.				
2,000-3,000	1,720	60.6	184.32	
>3,000	13,636	56.5	1,362.54	1,546.86
T. 28 N., R. 7 W.				
2,000-3,000	17,106	54.8	1,657.97	1,657.97
T. 29 N., R. 5 W.				
>3,000	8,016	63.6	902.29	902.29
T. 29 N., R. 6 W.				
>3,000	10,450	60.2	1,113.41	1,113.41
T. 29 N., R. 7 W.				
2,000-3,000	3,288	77.3	449.53	
>3,000	17,607	75.3	2,348.00	2,797.53
T. 30 N., R. 5 W.				
>3,000	13,518	48.6	1,163.93	1,163.93
T. 30 N., R. 6 W.				
2,000-3,000	557	77.7	76.59	
>3,000	20,789	55.1	2,027.38	2,103.97

Table B1. Estimates of Federally owned subbituminous coal resources in the Fruitland Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total

Rio Arriba County--Continued				
T. 30 N., R. 7 W.				
2,000-3,000	9,597	56.9	966.77	
>3,000	5,397	59.5	568.14	1,534.91
T. 31 N., R. 5 W.				
>3,000	4,688	33.1	275.03	275.03
T. 31 N., R. 6 W.				
2,000-3,000	5,759	39.0	397.39	
>3,000	7,255	32.4	415.34	812.73
T. 31 N., R. 7 W.				
2,000-3,000	484	26.9	23.05	23.05
T. 32 N., R. 5 W.				
2,000-3,000	4,572	36.3	293.42	293.42
T. 32 N., R. 6 W.				
>3,000	3,434	29.0	176.48	176.48
Total for Rio Arriba County ------------ 30,292.45				
San Juan County				
T. 21 N., R. 8 W.				
0- 500	5,015	18.9	167.37	167.37
T. 22 N., R. 8 W.				
0- 500	11,686	18.0	373.04	
500-1,000	9,455	19.3	322.46	
1,000-2,000	1,663	17.3	50.97	746.47
T. 22 N., R. 9 W.				
0- 500	21,013	18.5	686.93	
500-1,000	277	10.2	4.99	691.92
T. 22 N., R. 10 W.				
0- 500	19,313	26.4	903.31	903.31
T. 22 N., R. 11 W.				
0- 500	7,154	28.0	354.85	354.85
T. 23 N., R. 8 W.				
500-1,000	4,698	14.7	122.19	
1,000-2,000	18,898	10.2	340.39	462.58
T. 23 N., R. 9 W.				
0- 500	378	21.1	14.11	
500-1,000	13,795	12.0	293.56	
1,000-2,000	6,782	12.2	146.65	454.32
T. 23 N., R. 10 W.				
0- 500	7,608	25.8	347.17	
500-1,000	14,440	20.2	516.39	
1,000-2,000	4,000	16.5	116.67	980.23
T. 23 N., R. 11 W.				
0- 500	15,496	33.8	928.07	
500-1,000	3,761	31.2	207.99	1,136.06
T. 23 N., R. 12 W.				
0- 500	16,641	31.0	914.10	914.10

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total

San Juan County--Continued				
T. 23 N., R. 13 W.				
0- 500	9,633	21.1	358.95	358.95
T. 24 N., R. 8 W.				
1,000-2,000	22,492	10.5	419.73	419.73
T. 24 N., R. 9 W.				
1,000-2,000	21,648	13.2	506.25	506.25
T. 24 N., R. 10 W.				
500-1,000	2,308	21.3	87.16	
1,000-2,000	18,269	19.7	635.40	722.56
T. 24 N., R. 11 W.				
0- 500	2,285	22.2	89.79	
500-1,000	19,198	22.0	746.58	
1,000-2,000	1,212	14.4	30.92	867.29
T. 24 N., R. 12 W.				
0- 500	4,249	33.3	250.20	
500-1,000	7,024	26.9	334.79	584.99
T. 24 N., R. 13 W.				
0- 500	838	33.2	49.27	49.27
T. 25 N., R. 8 W.				
1,000-2,000	16,435	11.3	327.30	
2,000-3,000	7,146	12.4	156.35	483.65
T. 25 N., R. 9 W.				
1,000-2,000	19,291	12.1	412.48	412.48
T. 25 N., R. 10 W.				
1,000-2,000	20,530	15.2	551.86	551.86
T. 25 N., R. 11 W.				
500-1,000	2,330	21.5	88.83	
1,000-2,000	22,085	14.6	569.32	658.15
T. 25 N., R. 12 W.				
500-1,000	5,521	24.4	238.29	
1,000-2,000	16,192	17.3	494.82	733.11
T. 26 N., R. 8 W.				
1,000-2,000	2,761	13.3	65.09	
2,000-3,000	21,262	18.8	708.43	773.52
T. 26 N., R. 9 W.				
1,000-2,000	16,149	16.0	458.26	
2,000-3,000	2,565	23.9	108.46	566.72
T. 26 N., R. 10 W.				
1,000-2,000	20,393	15.2	546.72	
2,000-3,000	815	12.8	18.52	565.24
T. 26 N., R. 11 W.				
1,000-2,000	11,269	15.9	317.00	317.00
T. 27 N., R. 8 W.				
1,000-2,000	3,091	36.1	197.63	
2,000-3,000	20,130	35.1	1,250.66	1,448.29

Table B1. Estimates of Federally owned subbituminous coal resources in the Fruitland Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
San Juan County--Continued				
T. 27 N., R. 9 W.				
1,000-2,000	1,686	41.5	123.75	
2,000-3,000	16,554	36.3	1,062.33	1,186.08
T. 27 N., R. 10 W.				
1,000-2,000	15,983	29.0	820.87	
2,000-3,000	5,014	25.3	224.68	1,045.55
T. 27 N., R. 11 W.				
1,000-2,000	11,984	20.1	427.14	427.14
T. 28 N., R. 8 W.				
2,000-3,000	17,661	48.7	1,522.29	1,522.29
T. 28 N., R. 9 W.				
2,000-3,000	17,699	40.1	1,256.76	1,256.76
T. 28 N., R. 10 W.				
1,000-2,000	9,702	30.2	517.84	
2,000-3,000	8,065	32.0	456.50	974.34
T. 28 N., R. 11 W.				
1,000-2,000	16,244	18.4	528.81	528.81
T. 28 N., R. 12 W.				
1,000-2,000	3,580	17.5	111.16	111.16
T. 28 N., R. 13 W.				
1,000-2,000	1,275	14.1	31.83	31.83
T. 29 N., R. 8 W.				
2,000-3,000	20,538	60.8	2,210.17	2,210.17
T. 29 N., R. 9 W.				
2,000-3,000	20,436	41.4	1,498.00	1,498.00
T. 29 N., R. 10 W.				
1,000-2,000	7,926	25.2	353.65	
2,000-3,000	9,602	26.6	452.43	806.08
T. 29 N., R. 11 W.				
1,000-2,000	17,664	15.3	477.78	477.78
T. 29 N., R. 12 W.				
1,000-2,000	4,453	18.4	144.99	144.99
T. 29 N., R. 13 W.				
1,000-2,000	2,849	16.7	84.15	84.15
T. 30 N., R. 8 W.				
2,000-3,000	15,717	57.9	1,611.04	
>3,000	765	61.9	83.78	1,694.82
T. 30 N., R. 9 W.				
2,000-3,000	18,945	39.7	1,329.51	1,329.51
T. 30 N., R. 10 W.				
2,000-3,000	19,547	31.2	1,079.20	1,079.20
T. 30 N., R. 11 W.				
1,000-2,000	5,402	20.2	192.63	
2,000-3,000	12,024	30.7	653.99	846.62
San Juan County--Continued				
T. 30 N., R. 12 W.				
1,000-2,000	3,747	20.6	136.76	
2,000-3,000	2,367	21.9	91.54	228.30
T. 30 N., R. 13 W.				
500-1,000	291	13.8	7.13	
1,000-2,000	7,714	21.6	294.49	301.62
T. 30 N., R. 14 W.				
0- 500	401	16.2	11.48	
500-1,000	11,751	20.6	428.24	
1,000-2,000	1,428	24.6	62.13	501.85
T. 30 N., R. 15 W.				
0- 500	9,030	17.4	277.57	
500-1,000	692	28.6	34.94	312.51
T. 31 N., R. 6 W.				
2,000-3,000	3,659	43.4	281.31	281.31
T. 31 N., R. 7 W.				
2,000-3,000	13,394	47.8	1,132.53	
>3,000	1,641	43.9	127.64	1,260.17
T. 31 N., R. 8 W.				
2,000-3,000	2,273	71.0	285.57	
>3,000	17,299	59.2	1,811.78	2,097.35
T. 31 N., R. 9 W.				
2,000-3,000	17,512	49.3	1,527.82	
>3,000	526	61.8	57.58	1,585.40
T. 31 N., R. 10 W.				
2,000-3,000	20,306	39.3	1,413.61	1,413.61
T. 31 N., R. 11 W.				
2,000-3,000	22,382	35.9	1,421.46	1,421.46
T. 31 N., R. 12 W.				
2,000-3,000	22,510	31.1	1,237.96	1,237.96
T. 31 N., R. 13 W.				
500-1,000	2,293	16.5	66.87	
1,000-2,000	1,618	31.8	90.93	
2,000-3,000	3,395	31.6	190.01	347.81
T. 32 N., R. 6 W.				
2,000-3,000	9,654	40.5	691.72	691.72
T. 32 N., R. 7 W.				
2,000-3,000	204	45.0	16.27	16.27
T. 32 N., R. 8 W.				
>3,000	15,045	58.8	1,565.95	1,565.95
T. 32 N., R. 9 W.				
>3,000	13,297	54.9	1,292.39	1,292.39
T. 32 N., R. 10 W.				
2,000-3,000	7,811	56.7	783.60	
>3,000	20,455	67.5	2,445.28	3,228.88

Table B1. Estimates of Federally owned subbituminous coal resources in the Fruitland Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
San Juan County--Continued				
T. 32 N., R. 11 W.				
2,000-3,000	13,086	48.8	1,130.57	1,130.57
T. 32 N., R. 12 W.				
2,000-3,000	2,298	40.9	166.44	166.44
T. 32 N., R. 13 W.				
500-1,000	3,029	34.3	183.74	
1,000-2,000	2,197	42.3	163.96	347.70
Total for San Juan County --------------				53,514.82
Sandoval County				
T. 17 N., R. 2 W.				
0- 500	8,140	3.3	47.79	47.79
T. 17 N., R. 3 W.				
0- 500	21,631	7.6	291.22	291.22
T. 17 N., R. 4 W.				
0- 500	21,389	9.6	363.78	363.78
T. 18 N., R. 1 W.				
0- 500	3,028	3.3	17.71	17.71
T. 18 N., R. 2 W.				
0- 500	7,651	5.6	75.38	75.38
T. 18 N., R. 3 W.				
0- 500	22,567	14.6	584.03	
500-1,000	125	4.2	.92	584.95
T. 18 N., R. 4 W.				
500-1,000	1,898	8.5	28.46	28.46
T. 19 N., R. 2 W.				
0- 500	4,271	1.4	10.44	10.44
T. 19 N., R. 3 W.				
0- 500	7,498	4.1	54.57	54.57
T. 19 N., R. 4 W.				
0- 500	15,010	4.9	130.25	130.25
T. 20 N., R. 1 W.				
500-1,000	336	.7	.39	
1,000-2,000	764	2.9	3.96	4.35
T. 20 N., R. 2 W.				
0- 500	4,405	1.3	10.24	
500-1,000	15,503	.7	19.30	
1,000-2,000	1,312	5.3	12.24	
2,000-3,000	12,408	6.6	144.57	186.35
T. 20 N., R. 3 W.				
0- 500	8,150	10.3	148.40	
500-1,000	12,880	8.6	196.72	
1,000-2,000	6,724	7.5	89.15	434.27
T. 20 N., R. 4 W.				
0- 500	11,594	10.3	211.56	
500-1,000	11,089	9.1	178.50	390.06

Table B1. Estimates of Federally owned subbituminous coal resources in the Fruitland Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
Sandoval County--Continued				
T. 21 N., R. 1 W.				
0- 500	4,751	1.0	8.67	
500-1,000	6,917	1.6	19.24	
1,000-2,000	1,726	.6	1.84	29.75
T. 21 N., R. 2 W.				
1,000-2,000	20,721	2.5	92.38	
2,000-3,000	1,777	5.0	15.69	108.07
T. 21 N., R. 3 W.				
1,000-2,000	15,955	6.2	176.27	
2,000-3,000	6,885	12.4	150.80	327.07
T. 21 N., R. 4 W.				
500-1,000	16,913	4.7	140.72	
1,000-2,000	5,466	3.2	30.43	171.15
T. 21 N., R. 5 W.				
500-1,000	9,860	8.1	141.88	
1,000-2,000	12,904	6.9	157.33	299.21
T. 21 N., R. 6 W.				
500-1,000	17,406	12.6	389.24	
1,000-2,000	2,810	11.4	56.78	446.02
T. 21 N., R. 7 W.				
0- 500	7,224	12.6	160.80	
500-1,000	8,672	11.2	171.21	
1,000-2,000	6,828	9.4	114.08	446.09
T. 22 N., R. 1 W.				
500-1,000	2,918	1.0	4.96	
1,000-2,000	5,541	2.1	20.32	
2,000-3,000	1,582	1.3	3.68	28.96
T. 22 N., R. 6 W.				
1,000-2,000	22,888	7.2	292.82	292.82
T. 22 N., R. 7 W.				
500-1,000	8,589	11.9	181.40	
1,000-2,000	14,285	9.4	238.53	419.93
T. 23 N., R. 1 W.				
0- 500	359	.4	.22	
500-1,000	1,337	2.1	4.95	
1,000-2,000	2,688	4.2	19.89	
2,000-3,000	1,351	2.1	4.98	30.04
T. 23 N., R. 6 W.				
1,000-2,000	12,103	6.9	147.89	147.89
T. 23 N., R. 7 W.				
1,000-2,000	10,002	9.8	173.00	173.00
Total for Sandoval County --------------				5,539.58

Table B2. Estimates of Federally owned subbituminous coal resources in the Menefee Formation, San Juan basin, New Mexico

[Estimates may include some coal already mined but exclude resources in national parks, monuments, and national forests]

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons Each interval	Total
McKinley County				
T. 15 N., R. 6 W.				
0- 500	9,175	8.5	137.69	137.69
T. 15 N., R. 7 W.				
0- 500	15,445	6.7	184.21	184.21
T. 15 N., R. 8 W.				
0- 500	3,770	5.6	37.01	37.01
T. 16 N., R. 5 W.				
0- 500	14,820	7.2	189.39	189.39
T. 19 N., R. 7 W.				
500-1,000	607	7.9	8.47	8.47
T. 19 N., R. 8 W.				
0- 500	3,115	5.8	31.91	
500-1,000	3,794	7.8	52.12	84.03
T. 19 N., R. 9 W.				
0- 500	1,470	4.0	10.39	10.39
T. 20 N., R. 7 W.				
0- 500	9,963	16.0	281.41	
500-1,000	3,414	8.1	48.61	330.02
T. 20 N., R. 8 W.				
0- 500	4,895	10.3	89.03	
500-1,000	6,477	7.6	86.67	175.70
Total for McKinley County ---------------				1,156.91
San Juan County				
T. 21 N., R. 8 W.				
0- 500	5,014	9.7	85.97	85.97
T. 21 N., R. 13 W.				
0- 500	3,074	2.4	13.25	13.25
T. 22 N., R. 8 W.				
0- 500	22,943	15.3	620.63	620.63
T. 22 N., R. 9 W.				
0- 500	21,004	21.1	783.72	
500-1,000	326	21.5	12.42	796.14
T. 22 N., R. 10 W.				
0- 500	2,905	17.9	91.93	
500-1,000	8,778	13.9	215.63	
1,000-2,000	12,080	10.7	229.15	536.71
T. 22 N., R. 11 W.				
500-1,000	3,525	10.6	66.32	
1,000-2,000	1,849	10.2	33.28	99.60

Table B2. Estimates of Federally owned subbituminous coal resources in the Menefee Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons Each interval	Total
San Juan County--Continued				
T. 23 N., R. 8 W.				
0- 500	20,667	9.4	342.70	342.70
T. 23 N., R. 9 W.				
0- 500	20,492	12.0	435.29	
500-1,000	775	17.8	24.35	459.64
T. 23 N., R. 10 W.				
0- 500	2,706	11.0	52.60	
500-1,000	8,293	14.6	214.15	
1,000-2,000	15,053	13.3	353.91	620.66
T. 23 N., R. 11 W.				
0- 500	5,339	24.8	234.12	
500-1,000	5,519	20.9	204.42	
1,000-2,000	7,797	17.9	247.53	686.07
T. 23 N., R. 12 W.				
0- 500	16,641	10.7	316.30	316.30
T. 23 N., R. 13 W.				
0- 500	12,735	4.8	108.60	108.60
T. 24 N., R. 8 W.				
0- 500	737	9.9	12.84	12.84
T. 24 N., R. 9 W.				
0- 500	4,831	8.7	74.45	
500-1,000	4,842	6.0	50.99	
1,000-2,000	3,240	2.2	12.72	138.16
T. 24 N., R. 10 W.				
0- 500	1,580	14.2	39.68	
500-1,000	1,544	22.3	60.94	
1,000-2,000	7,275	15.1	194.47	
2,000-3,000	9,894	6.6	115.13	410.22
T. 24 N., R. 11 W.				
0- 500	5,818	28.1	289.71	
500-1,000	7,256	23.4	300.96	
1,000-2,000	2,119	5.4	20.19	610.86
T. 24 N., R. 12 W.				
0- 500	10,869	22.2	427.79	
500-1,000	404	13.9	9.92	437.71
T. 24 N., R. 13 W.				
0- 500	838	5.5	8.11	8.11
T. 25 N., R. 11 W.				
1,000-2,000	6,053	11.8	126.59	
2,000-3,000	7,744	11.5	157.24	283.83
T. 25 N., R. 12 W.				
0- 500	789	13.1	18.34	
500-1,000	1,776	18.8	58.96	
1,000-2,000	2,450	17.8	76.98	154.28

Table B2. Estimates of Federally owned subbituminous coal resources in the Menefee Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
San Juan County--Continued				
T. 26 N., R. 11 W.				
2,000-3,000	1,417	7.6	18.93	
>3,000	7,731	4.2	57.96	76.89
T. 27 N., R. 11 W.				
>3,000	9,380	12.0	198.49	198.49
T. 28 N., R. 10 W.				
>3,000	331	23.1	13.54	13.54
T. 28 N., R. 11 W.				
>3,000	15,333	11.6	315.34	315.34
T. 28 N., R. 12 W.				
2,000-3,000	2,519	7.9	35.06	
>3,000	465	3.0	2.45	37.51
T. 29 N., R. 11 W.				
>3,000	2,040	8.1	29.11	29.11
T. 30 N., R. 11 W.				
>3,000	2,659	6.0	28.22	28.22
T. 31 N., R. 11 W.				
>3,000	15,976	6.4	181.27	181.27
T. 32 N., R. 11 W.				
>3,000	3,379	7.1	42.19	42.19
Total for San Juan County				7,664.84
Sandoval County				
T. 16 N., R. 3 W.				
0- 500	4,735	6.5	54.59	54.59
T. 16 N., R. 4 W.				
0- 500	16,870	5.3	159.22	159.22
T. 19 N., R. 1 W.				
500-1,000	4,242	5.5	41.57	
1,000-2,000	440	6.5	5.02	
2,000-3,000	13,694	5.0	120.55	167.14
T. 19 N., R. 2 W.				
0- 500	2,925	6.5	33.67	
500-1,000	5,088	6.2	56.14	
1,000-2,000	3,091	7.0	38.36	128.17
T. 19 N., R. 3 W.				
0- 500	2,108	7.0	25.94	
500-1,000	7,212	6.5	83.37	
1,000-2,000	13,248	6.2	145.22	254.53
T. 19 N., R. 4 W.				
500-1,000	2,693	8.7	41.21	
1,000-2,000	4,969	7.8	68.79	
2,000-3,000	1,184	5.3	11.09	121.09

Table B2. Estimates of Federally owned subbituminous coal resources in the Menefee Formation, San Juan basin, New Mexico—Continued

Location and overburden thickness (feet)	Acres	Average total thickness (feet)	Millions of short tons	
			Each interval	Total
Sandoval County--Continued				
T. 21 N., R. 6 W.				
0- 500	5,433	17.7	169.79	169.79
T. 21 N., R. 7 W.				
0- 500	22,725	15.4	618.59	618.59
T. 22 N., R. 6 W.				
0- 500	8,171	6.1	87.71	87.71
T. 22 N., R. 7 W.				
0- 500	22,844	5.3	213.36	213.36
T. 23 N., R. 7 W.				
0- 500	6,162	2.6	27.77	27.77
Total for Sandoval County				2,001.96

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Chapter C

Coal Resource Estimation in the San Juan Basin Using Geostatistical Methods

By LEWIS W. BOGER, Jr., and ANTOINETTE L. MEDLIN

Resources of the Fruitland coal zone estimated by the kriging technique

CONTENTS

Coal Resource Estimation in the San Juan Basin Using Geostatistical Methods

By Lewis W. Boger, Jr., *and* Antoinette L. Medlin,

Abstract

This chapter describes the application of the geostatistical method known as kriging to estimate coal resources of the Fruitland coal zone in the San Juan basin. The study should be considered experimental because the method was used to estimate resources over a very large area (7,500 square miles), and the data were not homogeneous.

A semi-variogram model for coal thickness was developed for the entire Fruitland Formation (Upper Cretaceous). It was used to estimate the coal resources in the deposit using large 10×10-km (6.2×6.2-mi) panels. A brief test also shows how maps of kriging variance can be used to project how much the resource estimate could be improved by additional data-collection points in particular locations. In addition, we attempted to calculate semi-variograms for ash, sulfur, and Btu, but the data were insufficient to support this effort.

Total in-place coal resources of the Fruitland Formation estimated by this technique were 159,984 million tons, which compares favorably with the GARNET isopach technique result of 167,501 million tons derived by Biewick and others (this volume, chap. B). However, since this study is experimental, further work is necessary before these results should be used for purposes other than observing trends, designing sampling programs, or gross estimates of in-place coal.

INTRODUCTION

The geostatistical method known as kriging is a useful technique for estimating coal tonnages at a point or over an area of ground. Kriging makes use of a semi-variogram model to create weighting functions for values (in this case, coal thicknesses) at observed sample points.

Estimated thickness may be calculated by summing the products of the sample values and their respective weights. Weighting functions are determined so that the estimate is unbiased and has minimum error variance. Variance is a measure of the difference between the value expected and the observed value. A good overview of the technique can be found in the first four chapters of Mousset-Jones (1980); for a detailed explanation see Journel and Huijbregts (1978).

A geostatistical software system on the NCRDS Prime 9750 computer was used to create a semi-variogram model and perform kriging for coal thickness data, to attempt to define semi-variograms for ash, sulfur, and Btu, and to create kriging variance maps. The following sections present further details of data preparation, semi-variogram model selection, results, and conclusions.

GEOSTATISTICAL METHODS

Data Preparation

A geostatistical analysis leading to the estimation of the quantity of a coal resource requires geologic analysis of the region and separation of the data into geologically homogeneous groups. When the data cannot be so grouped, the quality of the estimates will be lower. Standard statistical studies of the data are done to assure a reasonable degree of statistical homogeneity within subsets.

The same PACER data set retrieved from NCRDS for the GARNET estimation (Biewick and others, this volume) was used in the geostatistical estimation. Only drill hole data representing the complete Fruitland coal zone were used. Outcrop data and measured sections were eliminated to improve the homogeneity in the data set. The data were converted from the PACER format to a format suitable for input to the geostatistical programs. In this conversion, latitudes and longitudes were converted to kilometers in the Universal Transverse Mercator Coordinate System. The

data set was then subjected to standard statistical tests mentioned above to ascertain the consistency of the data, and it was checked for any points with identical locations. Duplicate locations will cause the kriging program to fail. Coal thicknesses were summed for all samples with the same identifier (drill-hole name), yielding total Fruitland coal thicknesses identical to those that were used in the GARNET estimate.

Model Selection

Because an underlying premise of geostatistics is that the variable of interest has some degree of continuity within the area of study, a semi-variogram model must be selected which best depicts this continuity. The semi-variogram is a curve representing the degree of continuity of the variable: in this case, coal thickness (fig. C1). For this application, gamma H, the value of the semi-variogram, is defined as one-half the mean squared difference in total coal thickness (in feet) between drill holes located a given distance apart. In general, the semi-variogram is an increasing function of distance because, usually, the farther samples are from one another, the greater the difference between the sample values.

The semi-variogram of thickness shown in figure C1 was constructed from the Fruitland data set. In this case, at a distance of separation of 6.5 mi, determined by the flattening of this curve, the values become independent of one another. This plateau of constant variance is termed the "sill," and the horizontal distance at which the sill is reached is called the "range." The range defines the area of spatial influence within a given data set. The y-intercept is termed the "nugget." The nugget is a component of uncertainty that is not statistically predictable from the available data. The nugget comprises variability on a scale smaller than can be quantified given the spacing of the data samples, errors in the interpretation of the geophysical logs, and other factors characterized as noise.

The data available from the NCRDS detailed geochemical data base (USCHEM) for the Upper Cretaceous Fruitland Formation were not sufficient in number or distribution to develop any sort of statistical model for any of the basic coal quality parameters. Additional data were retrieved from a second coal quality data base (USALYT), which contains only data from standard proximate and
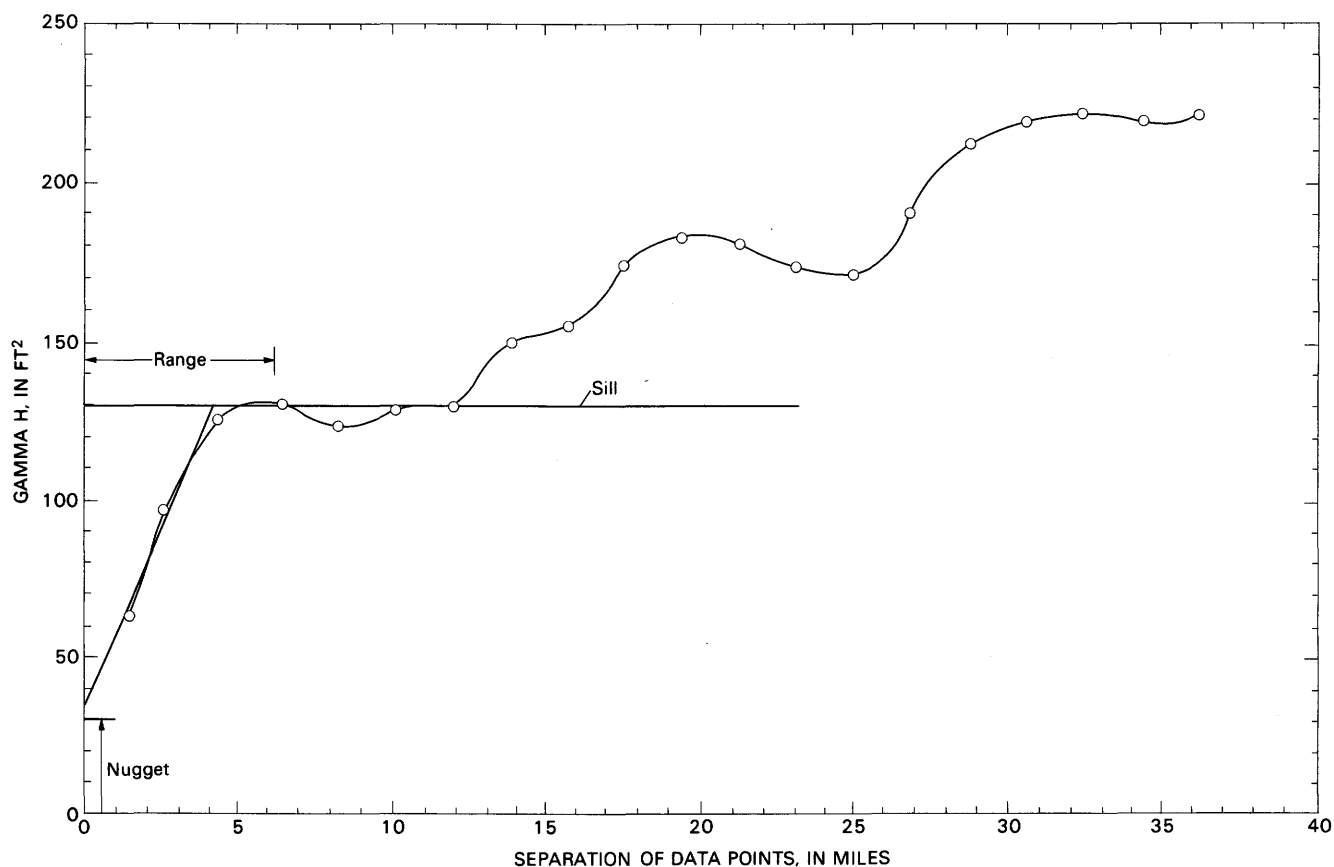

Figure C1. Semi-variogram for coal thickness in the Fruitland Formation, San Juan basin, New Mexico. See text for explanation of "gamma H," "nugget," "range," and "sill."

ultimate coal analyses. This data set included data from 107 Fruitland Formation coal samples, but they were all clustered in the vicinity of the Navajo mine in the northwest corner of the basin. Again the distribution was insufficient to support the kriging analysis for the Fruitland coal. Several models for the distribution of Btu, ash, and sulfur values were tested, but the "best" model had a range of less than 2 mi. This result indicates that the data are essentially only valid for the point locations they represent; no reliable basin models could be developed.

Results

The kriging technique was developed for use in mine planning and development. It produces the most reliable estimates when applied to relatively small, geologically homogeneous areas where the distribution of data is fairly uniform.

Using the kriging technique to determine the coal resources of a large area where the coal beds are thin and irregular is an experimental application of the method.
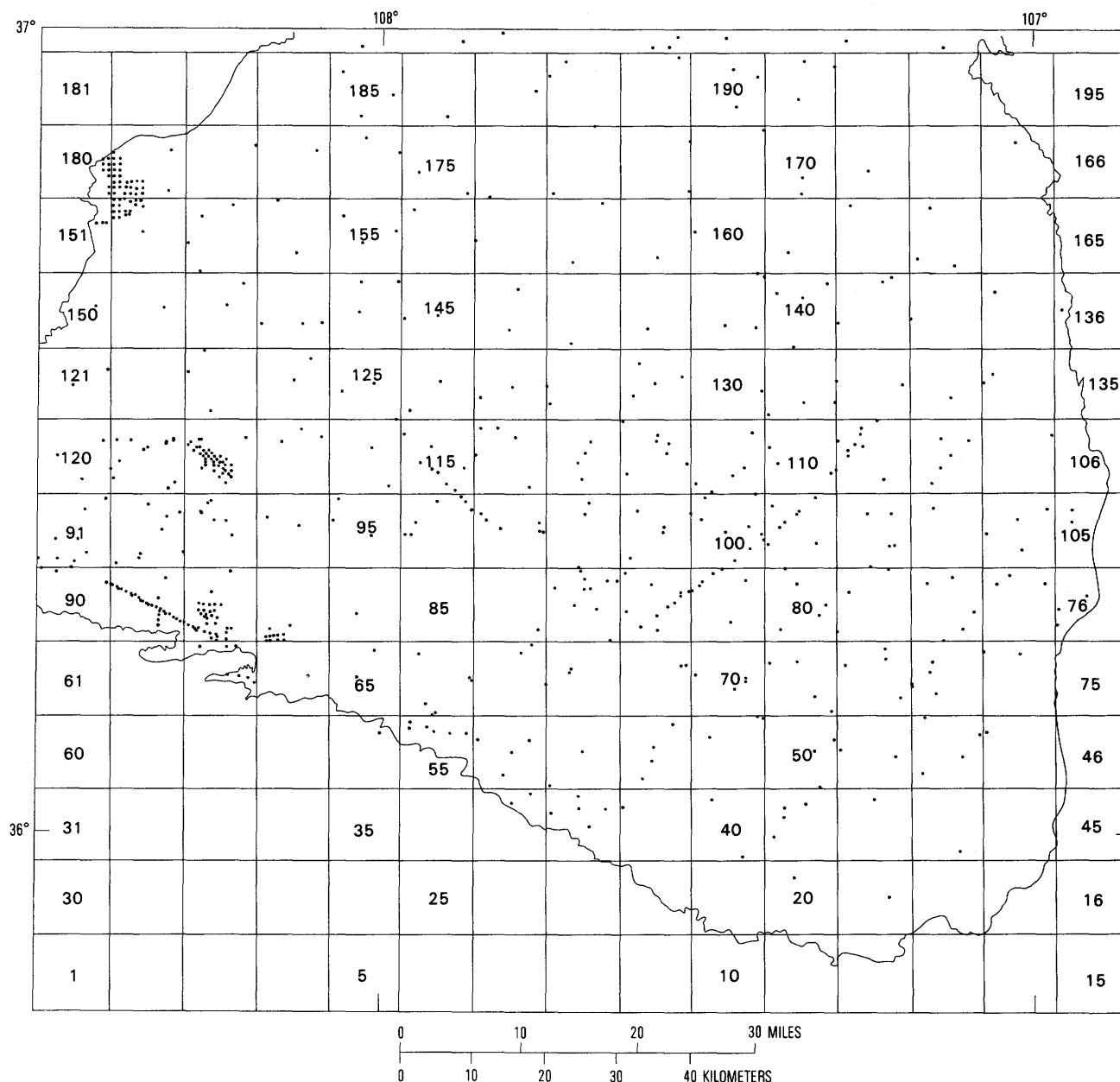
Figure C2. Locations of data collection points and 10×10-km (6.2×6.2-mi) blocks used for kriging to estimate coal resources in the Fruitland Formation, San Juan basin, New Mexico (table C1). See figure B1 of Biewick and others (this volume, chap. B) for location of area shown.
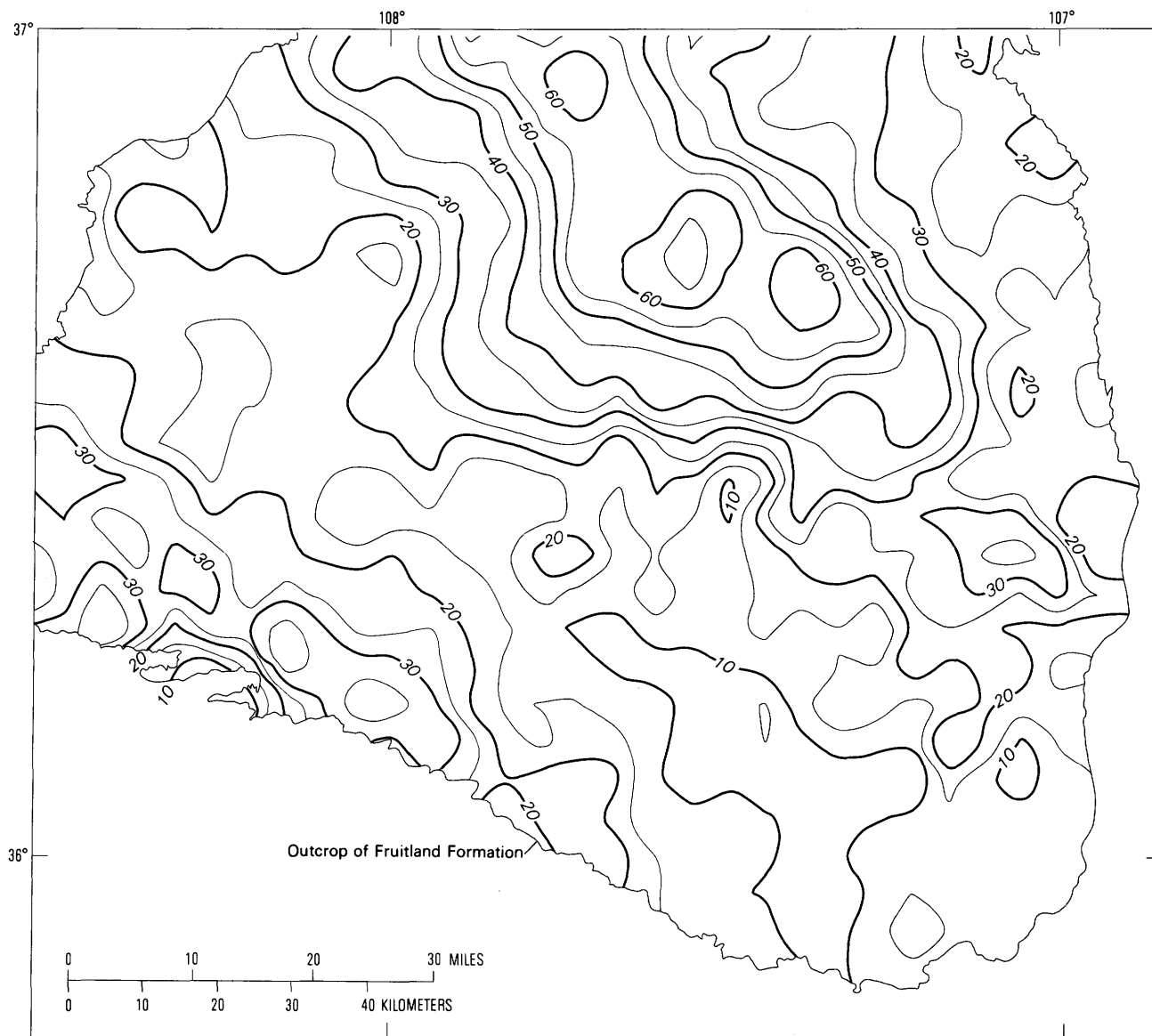
Figure C3. Isopachs of kriged coal thickness values, in feet, for the Fruitland coal zone in the San Juan basin, New Mexico. See figure B1 of Biewick and others (this volume, chap. B) for location of area shown.

Further work is necessary before the results should be used for purposes other than observing trends, designing sampling programs, or gross estimates of in-place coal.

The range, sill, and nugget parameters obtained from the construction of the semi-variogram were used in the kriging to estimate coal thickness at the grid intersections of a regularly spaced grid (fig. C2). The coal isopach map derived from these points (fig. C3) is generally similar to the one generated by the GARNET program (Biewick and others, this volume, fig. B2); the differences are due to the different gridding algorithms and interpolations used in the two techniques. The kriging algorithm also produces variance estimates at the grid nodes, which were contoured to produce the variance map in figure C4. This map

represents the general reliability of the isopach map by indicating the potential variation of the estimated values. High variance values can be seen on the southern and western edges, in the northeast corner, and in the south-central parts of the contoured area. This high variance probably reflects the lack of data in these areas.

Because kriging variance is not a function of the values encountered at sample locations but a function of the number of sample points, their relative locations, and the spatial variability model, maps of the variance can be very useful in designing future data collection efforts. Hypothetical drill-hole locations can be inserted to assess their impact on the precision of the estimate. Eight such hypothetical drill-hole locations were added to the data set

Table C1. Kriged coal tonnages and kriging variance for 10×10-km (6.2×6.2-mi) blocks of the Fruitland Formation, San Juan basin, New Mexico

Block No. (fig. C2)	Kriged thick- ness[1] (feet)	Coal (millions of short tons)	Kriging vari- ance (ft²)	Block No. (fig. C2)	Kriged thick- ness[1] (feet)	Coal (millions of short tons)	Kriging vari- ance (ft²)	Block No. (fig. C2)	Kriged thick- ness[1] (feet)	Coal (millions of short tons)	Kriging vari- ance (ft²)
20	6.1	268.20	53	93	27.4	1,196.52	7	144	40.0	1,751.51	24
37	19.5	854.45	58	94	20.6	898.89	21	145	26.3	1,749.20	14
38	21.9	957.02	21	95	16.0	699.58	19	146	18.0	786.00	13
39	14.1	616.35	39	96	15.9	693.41	18	147	16.8	733.87	13
40	12.3	538.28	41	97	17.8	776.47	16	148	15.0	655.93	15
41	8.7	381.08	10	98	18.1	789.98	10	149	16.6	727.70	27
42	6.2	269.99	58	99	15.1	658.34	10	150	18.4	805.56	50
43	20.4	892.72	83	100	13.6	593.43	8	151	11.9	519.73	52
47	8.5	373.34	32	101	22.1	966.38	4	152	19.9	868.32	24
48	14.7	644.43	13	102	24.0	1,049.92	14	153	19.5	853.49	12
49	6.6	289.02	15	103	30.1	1,314.83	14	154	21.2	928.94	20
50	7.7	335.73	27	104	34.0	1,486.20	11	155	16.1	702.69	13
51	8.6	374.92	19	105	18.6	811.77	19	156	21.8	952.25	21
52	12.0	525.37	13	106	12.3	538.71	71	157	36.6	1,601.66	27
53	22.0	964.32	10	107	24.3	1,062.51	33	158	59.5	2,600.19	24
54	20.6	902.52	10	108	28.0	1,223.55	11	159	67.4	2,945.76	31
55	28.2	1,232.48	31	109	33.2	1,452.61	6	160	67.1	2,934.17	28
56	29.2	1,274.99	83	110	29.8	1,302.98	7	161	59.5	2,600.84	18
62	11.7	510.11	120	111	14.6	638.35	8	162	42.7	1,866.01	26
63	9.4	410.78	31	112	20.1	877.85	10	163	25.1	1,096.10	15
64	21.5	939.65	19	113	17.0	744.15	11	164	20.6	902.56	44
65	34.8	1,521.62	18	114	12.7	556.12	10	167	11.3	493.40	68
66	30.5	1,332.20	12	115	16.2	706.93	5	168	20.1	878.33	52
67	15.8	689.26	17	116	14.0	612.19	16	169	30.5	1,335.61	22
68	14.1	618.71	13	117	18.1	792.74	20	170	36.6	1,600.35	34
69	9.2	402.69	36	118	15.5	677.19	14	171	47.5	2,078.53	19
70	7.2	317.05	11	119	25.5	1,113.64	5	172	58.0	2,534.71	42
71	12.2	533.33	9	120	32.7	1,428.33	15	173	58.6	2,561.00	31
72	16.5	720.18	13	121	23.3	1,018.91	19	174	33.8	1,477.23	20
73	18.6	814.48	5	122	19.7	861.85	27	175	31.7	1,387.44	12
74	17.8	778.22	25	123	14.5	636.03	15	176	25.4	1,110.84	24
75	11.8	515.75	83	124	15.6	680.60	20	177	22.8	997.43	19
76	19.2	840.94	22	125	19.4	848.42	12	178	19.4	848.02	25
77	20.7	907.33	11	126	24.0	1,051.71	12	179	19.6	858.08	4
78	24.0	1,050.40	18	127	30.9	1,351.92	10	180	13.6	595.00	48
79	14.1	617.70	10	128	34.2	1,494.29	15	181	17.4	758.98	116
80	13.8	602.40	12	129	34.2	1,496.34	10	182	13.9	608.65	69
81	12.7	556.78	10	130	39.5	1,728.98	27	183	23.5	1,029.84	37
82	11.9	521.61	5	131	44.0	1,923.44	10	184	30.8	1,345.54	57
83	10.2	445.38	9	132	41.4	1,811.12	10	185	36.6	1,601.40	15
84	12.2	532.85	52	133	36.9	1,612.86	16	186	35.5	1,550.53	22
85	26.7	1,167.88	58	134	18.4	803.89	27	187	54.8	2,396.98	42
86	29.3	1,282.64	23	137	16.8	732.08	45	188	66.1	2,891.83	25
87	32.1	1,404.28	17	138	35.7	1,559.28	23	189	50.2	2,196.19	48
88	24.4	1,065.71	7	139	51.9	2,270.45	17	190	37.4	1,637.88	24
89	26.8	1,170.63	12	140	60.2	2,632.16	10	191	33.1	1,449.15	12
90	30.7	1,340.73	45	141	53.2	2,325.26	27	192	30.2	1,322.84	46
91	25.2	1,104.02	6	142	52.8	2,308.94	24				
92	25.4	1,112.02	8	143	48.5	2,119.78	25	Total ---		159,983.71	

[1]Kriged thicknesses are rounded here, but were carried out to three decimal places for the calculation of coal tonnages.
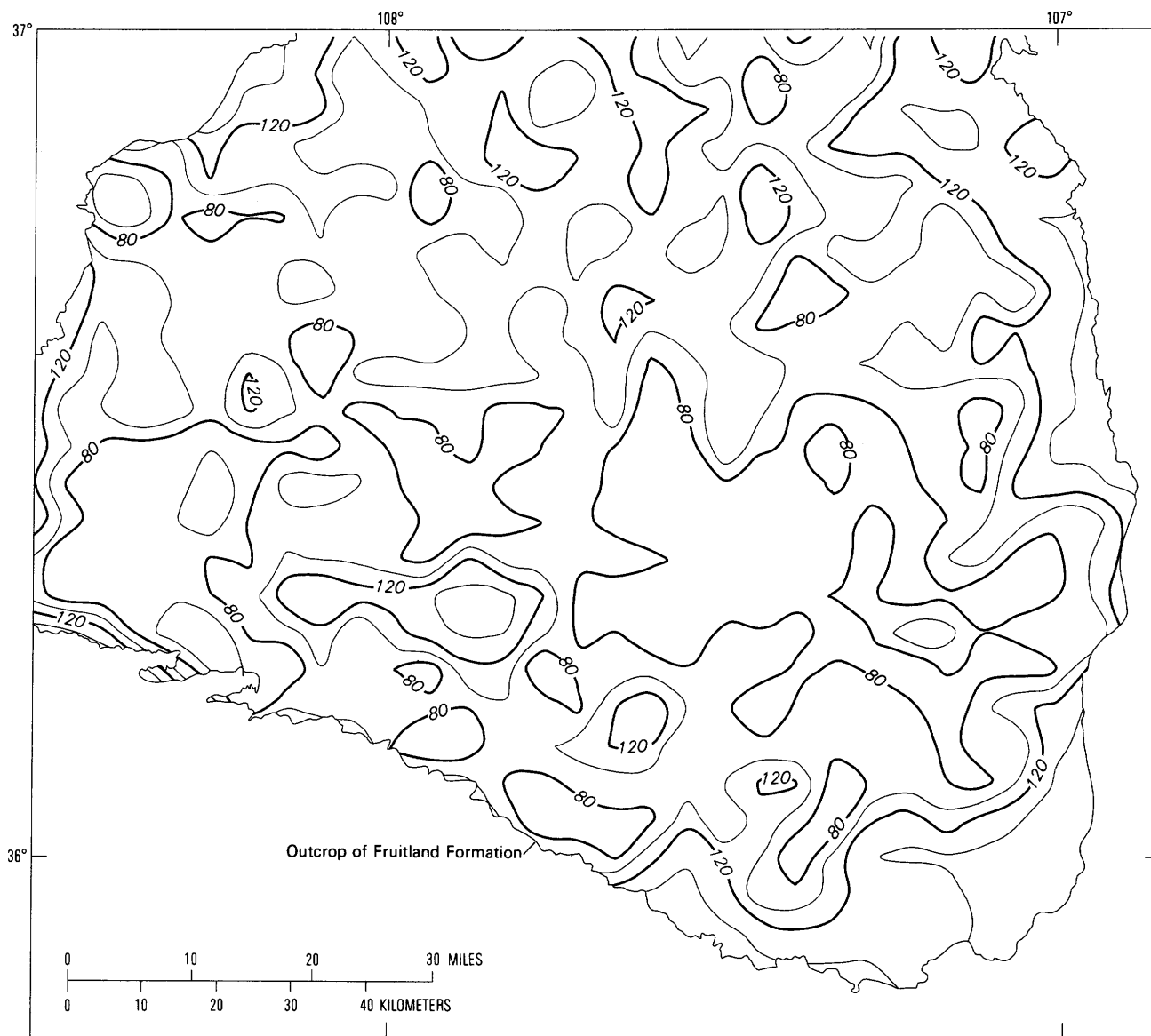
Figure C4. Estimate of thickness variance of coal beds in the Fruitland Formation, based on kriged original data. See figure B1 of Biewick and others (this volume, chap. B) for location of area shown.

in locations of high variance, and a second variance map was generated (fig. C5). A comparison of figures C4 and C5 illustrates how much the estimate can be improved by a limited amount of selected drilling. (Note the southeastern, eastern, and northwest areas of the figures.)

Average coal thicknesses were computed for each 10×10-km (6.2×6.2-mi) grid block within the basin (fig. C2) using block kriging. Coal tonnages were derived from these thicknesses using a value of 43,737,400 tons per foot of thickness (rounded from 43,737,408 tons/ft, which equals 1,770 tons/acre ft × 247.104 acres/km²×100 km² per grid block). Results are shown in table C1. Blocks not listed there were not represented by enough data to allow kriging. Total in-place coal resources estimated by this method are

159,983 million tons; this compares favorably with the GARNET total coal estimate of 167,501 million tons—a difference of less than 5 percent.

CONCLUSIONS

As previously stated, the kriged results of this portion of the San Juan basin study should be considered with an understanding of their limitations:

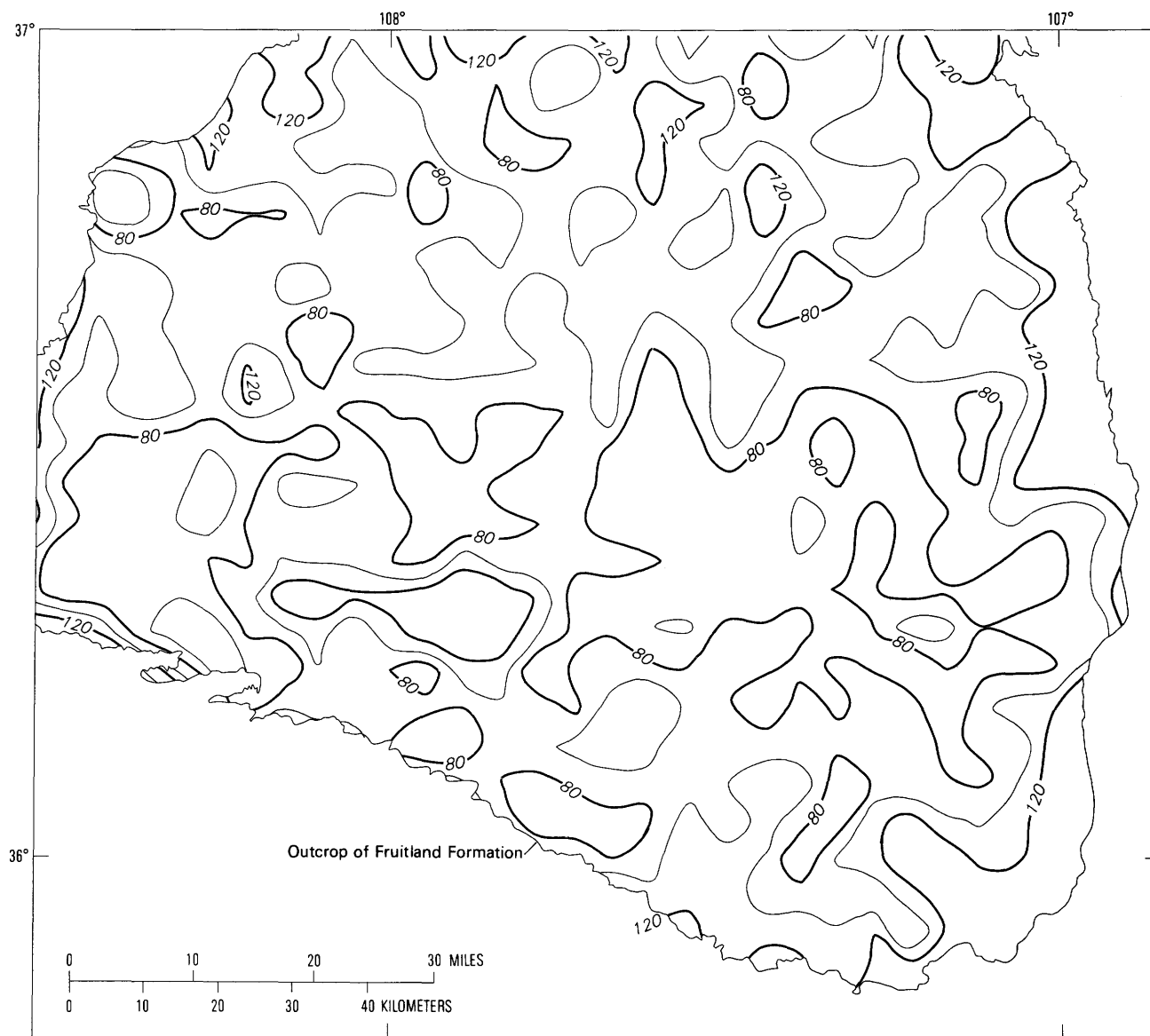1. The area of study is much larger than the typical mine site application.

Figure C5. Modified estimate of thickness variance of coal beds in the Fruitland Formation, generated by adding data for eight theoretical drill holes to the original kriged data. Compare with figure C4.

2. The data set was constructed of summed thickness values and cannot be considered to be homogeneous.

3. The clustering of data in some areas and the scarcity of data in others bias the results.

4. Determining a single semi-variogram model for the entire deposit, rather than determining a separate semi-variogram model for each 10×10-km block, smooths possible localized variations within the area of this study.

5. Variances that are high relative to low tonnages shown for some blocks in table C1 are attributable to one or more of the above four

items; they indicate unreliable estimates over some large areas of the basin.

A further demonstration of the kriging method would be better carried out in an area of similar size where more data are available and closer control can be imposed on data quality.

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Chapter D

Geology and Coal Resources of the Raton Coalfield

By CHARLES L. PILLMORE

Stratigraphic and environmental
framework of an area of coal-bearing
Late Cretaceous and Paleocene rocks

CONTENTS

TABLES

Geology and Coal Resources of the Raton Coalfield

By Charles L. Pillmore

Abstract

The Raton basin is a broad, arcuate depositional trough of structural origin that extends about 85 miles from near Gardner, Colo., to Cimarron, N. Mex. It is the southernmost of the Laramide intracratonic folded basins at the eastern margin of the Rocky Mountains and is a sister basin to the San Juan basin, which lies to the west and contains older but related rocks. The Raton coalfield is the New Mexico portion of the area within the Raton basin that is underlain by coal-bearing rocks. The coalfield covers an area of about 900 square miles and contains large resources of high-quality coking coal in rocks of the Vermejo Formation of Late Cretaceous age and the Raton Formation of Late Cretaceous and Paleocene age. Coal has been mined along the eastern margin of the coalfield since about 1870, but only the York Canyon surface mine and the Cimarron underground operation, in the north-central part of the coalfield, are presently active (1991). Coal beds of the Vermejo Formation were deposited in contemporaneous fluviodeltaic plain and back-barrier coastal environments and are the thickest and most extensive coal beds in the Raton field. The coal beds of the Raton Formation accumulated in poorly drained backswamp environments on flood plains of meandering streams that drained a broad alluvial plain. These coal deposits are lenticular in shape and less extensive than those of the Vermejo Formation.
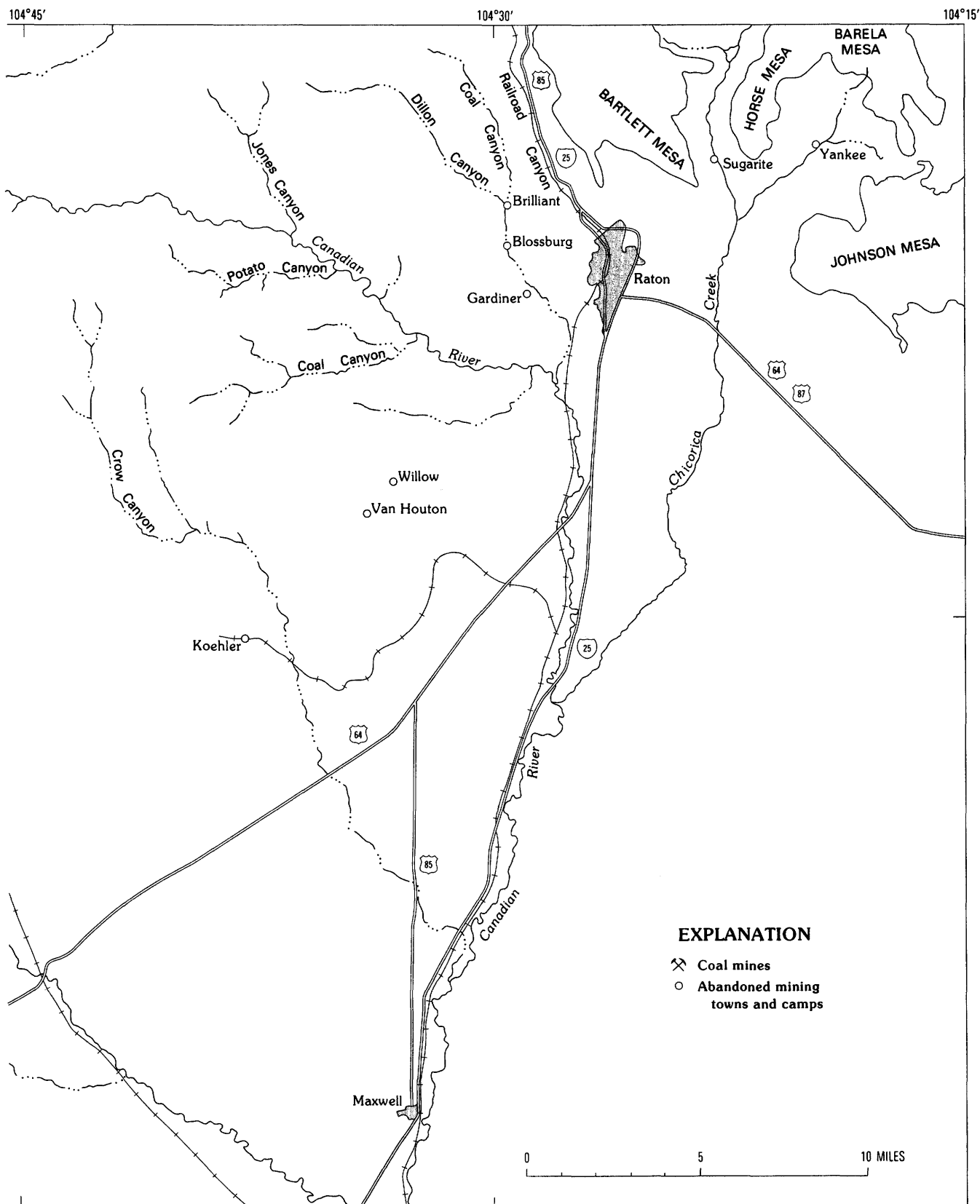
Recent field and subsurface investigations within the coalfield permit delineation of 14 principal coal districts, based on the areal distribution of the thickest coal beds in both formations. Nearly 1.5 billion tons of demonstrated coal resources have been calculated for these districts. Castle Rock, the largest unmined district, is in the west-central part of the coalfield and contains about one-third of the demonstrated resources. The remainder of the resources are distributed among 13 smaller districts, located mostly in the northern part of the field. In addition to the demonstrated resources, about 8 billion tons of inferred resources are estimated for the Raton field—more than twice earlier figures. The inferred resources, which are mainly in thinner beds, are distributed throughout the coalfield in 15 geographic subdivisions.

INTRODUCTION

The Raton coalfield occupies the New Mexico portion of the Raton Mesa coal region, the southernmost part of the Northern Great Plains coal province (Trumbull, 1959). The coalfield covers an area of about 900–1,000 mi^2 in northeastern New Mexico and contains large resources of high-quality coking coal in rocks of the Vermejo (Upper Cretaceous) and Raton (Upper Cretaceous and Paleocene) Formations. An early estimate (Read and others, 1950) tabulated 4.71 billion tons of coal in beds 14 in. thick or greater, beneath less than 3,000 ft of overburden. A more recent appraisal indicates identified coal resources of about 9.5 billion tons, more than twice that earlier figure.

Coal was discovered in the coalfield by the Long Expedition in about 1821 (Lee, 1917) and has been mined commercially since about 1870. Mining activity was concentrated along the eastern margins of the field until 1966, when the York Canyon mine was opened in the west-central part of the coalfield, about 26 mi west of Raton. At present, the York Canyon surface mine and the Cimarron mine, about 6 mi to the northwest, are the only active mines. The locations of these mines and other geographic features are shown on figure D1.

The following brief discussion of the location and general geologic setting of the Raton coalfield is from various reports by Pillmore (1969a; 1969b; 1976), Pillmore and others (1984), Pillmore and Flores (1984; 1987), Wanek (1963), and Lee (1917). Resource estimates shown here have been augmented and changed from those calculated by Pillmore (1969b), using data supplied by Kaiser Coal Corp., for the large part of the coalfield in the coal districts and subdivisions west of Raton, and by Santa Fe Mining Corp. for the Yankee subdivision, east of Raton. I am indebted to both of these corporations for allowing use of their proprietary subsurface data to improve these estimates. Pittsburg & Midway (P&M) Coal Mining Co. purchased Kaiser's mines and coal resources in 1989. Updates on the resources and expected production of the York Canyon and Cimarron mines and the approval to publish this report are much appreciated.

Figure D1. Location of coal mines, abandoned coal mining towns and camps, and other geographic features in and near the

BARELA
MESA

HORSE MESA

BARTLETT MESA

Railroad Canyon

Coal Canyon

Dillon Canyon

Jones Canyon

Canadian

Potato Canyon

Sugarite

Yankee

JOHNSON MESA

Brilliant

Blossburg

Gardiner

Raton

Coal Canyon

River

Crow Canyon

Chicorita

Creek

Willow

Van Houton

Koehler

EXPLANATION

⚒ Coal mines

○ Abandoned mining
   towns and camps

Canadian River

Maxwell

0   5   10 MILES

Raton coalfield, New Mexico.

GEOLOGIC SETTING

The Raton coalfield lies within the southern half of the Raton basin, a large, arcuate, asymmetric structural basin. This basin is the southernmost of the Laramide intracratonic folded basins at the eastern margin of the Rocky Mountains (Baltz, 1965) and is a sister basin to the San Juan basin, which lies to the west (fig. D2) and contains older but related rocks (fig. D3). The Raton basin extends from near Gardner, Colo., on the north, to Cimarron, N. Mex., on the south—a distance of about 85 mi. The structural basin is approximately 70 mi wide at its widest point, along the boundary between Colorado and New Mexico, and narrows both to the north and south. The coalfield is about 50 mi wide at the State boundary. The basin is bounded on the east by the Sierra Grande arch in New Mexico and the Las Animas arch in Colorado. The northern limit is defined by the Apishapa arch (fig. D4). On the west side of the basin, sedimentary rocks of Permian to Tertiary age are steeply tilted to overturned along the east flank of the Sangre de Cristo Mountains. The axis of the basin, which generally separates more steeply dipping strata from the gently dipping beds to the east, is somewhat sinuous and lies near the west side of the basin.

The Raton coalfield lies entirely in Colfax County, N. Mex. The State line separating the Raton coalfield from the Trinidad coalfield, to the north, nearly coincides with the drainage divide between the Purgatoire River in Colorado and the Canadian River in New Mexico. Coal-bearing rocks in the Raton field underlie a highly dissected plateau whose elevation rises gradually from about 7,000 ft in the eastern part to approximately 9,500 ft in the western part. The coalfield's eastern and southern boundaries, in most places, are marked by nearly horizontally bedded, sandstone-capped escarpments standing several hundred feet above the adjoining high plains. Its western margin is marked by more steeply dipping beds that form hogback ridges and parallel valleys along the eastern front of the Sangre de Cristo
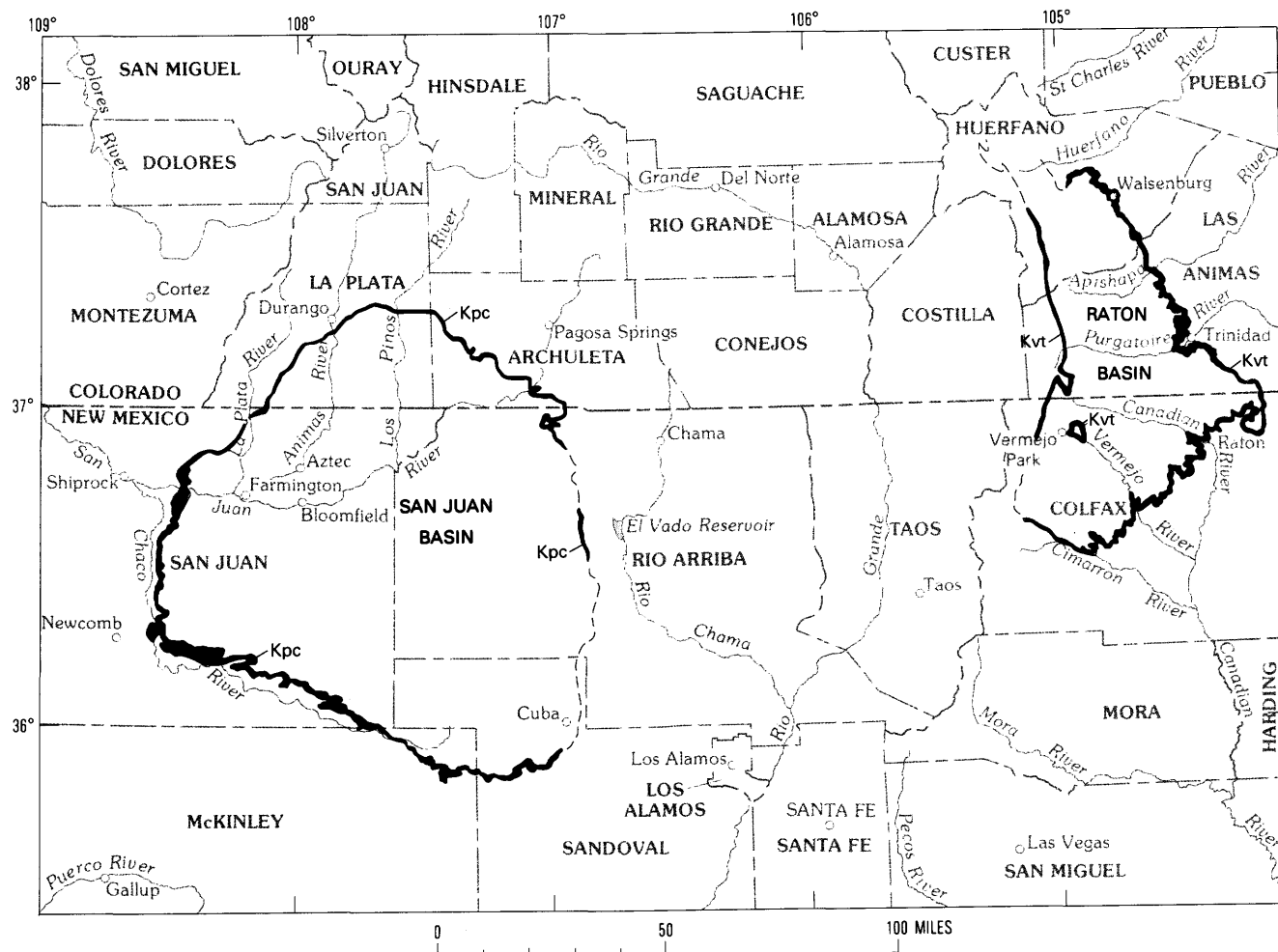

Figure D2. Locations of the Raton and San Juan basins. Kpc, Pictured Cliffs Sandstone; Kvt, Vermejo Formation and Trinidad Sandstone, undivided; all of Late Cretaceous age. (From Fassett, 1976, fig. 1).
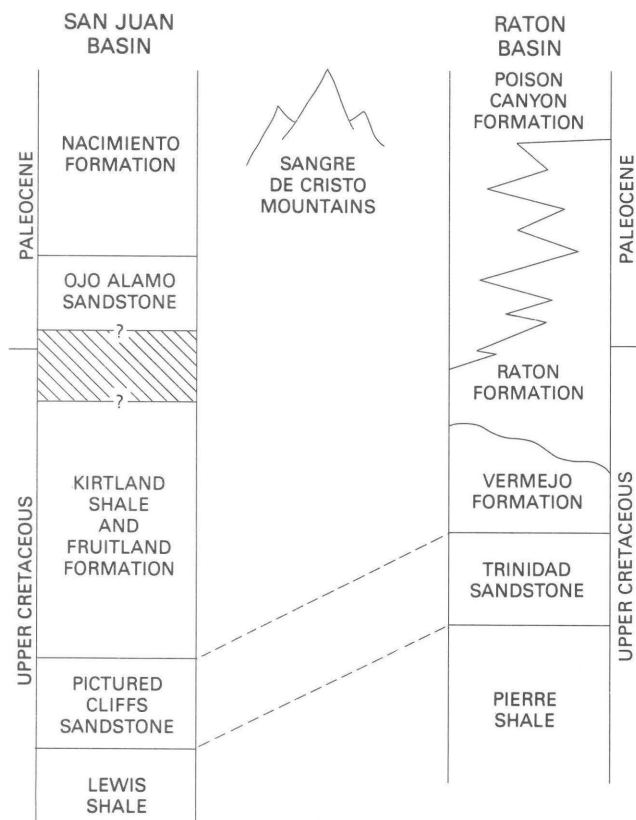
Figure D3. Stratigraphy of Upper Cretaceous and Paleocene rocks of the New Mexico portions of the Raton and San Juan basins.

Figure D4. Areal distribution of coal-bearing Upper Cretaceous and Paleocene rocks in the Raton basin. The Raton coalfield is the New Mexico portion of the stippled area.

Mountains. Faults are rarely observed in outcrop, but coal offsets and faults with minor displacement are relatively common features in underground and surface mines in the coalfield. The Vermejo Park anticline, with about 2,500 ft of structural relief, is the only major structure in the coalfield. The position of Vermejo Park and the distribution of the coal-bearing rocks of the Vermejo and Raton Formations are illustrated on the geologic map in figure D5. The cross section in figure D6 shows the anticline, and the stratigraphic sections in the same figure show changes in the Vermejo Formation and some of the principal Raton Formation coal beds.

STRATIGRAPHY

The stratigraphy of the Upper Cretaceous and Paleocene rocks of the Raton coalfield is shown in table D1, and their relationship with equivalent units in the San Juan basin is shown in figure D3. The offshore-marine Pierre Shale (Campanian to Maastrichtian) and the overlying marginal-marine Trinidad Sandstone (Maastrichtian) underlie the nonmarine Upper Cretaceous and Paleocene rocks in the basin. The position of the Raton basin with respect to the Late Cretaceous epeiric sea is shown in figure D7. Non-
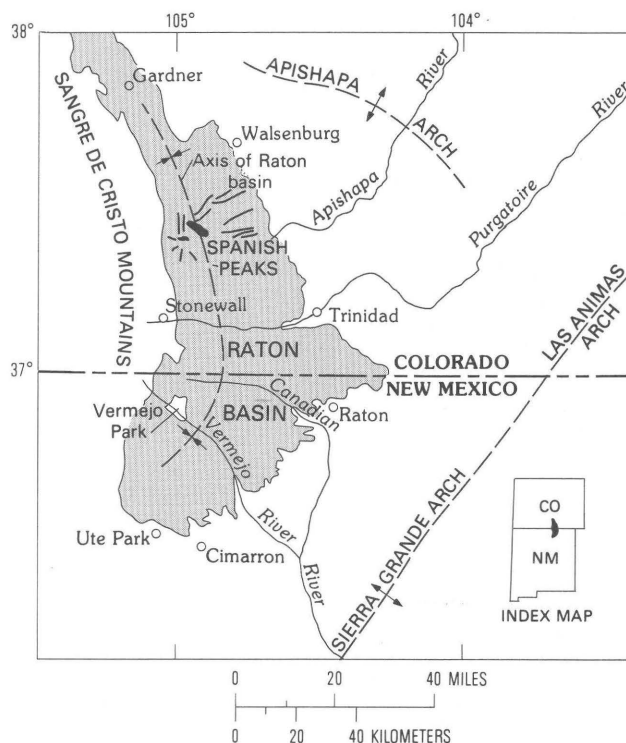
marine sedimentary rocks in the coalfield, from oldest to youngest, include the coal-bearing Vermejo Formation (Maastrichtian) and Raton Formation (Maastrichtian and Paleocene) and the non-coal-bearing Poison Canyon Formation (Maastrichtian and Paleocene), which overlies and intertongues with the Raton Formation. Much of the following discussion of the rocks and their depositional environments is from Pillmore and Flores (1987).

Pierre Shale and Trinidad Sandstone

The oldest map unit shown on figure D5 is the Trinidad Sandstone and older rocks unit of Late Cretaceous age. In most parts of the map area, this unit includes only the Trinidad Sandstone and the Pierre Shale. The Pierre formed in prodeltaic and offshore-marine environments and consists of 2,000–2,700 ft of dark, silty, noncalcareous shale. The Pierre Shale grades up into the cliff-forming Trinidad Sandstone, which was deposited in contemporaneous delta-front and interdeltaic barrier-bar environments (Pillmore and Flores, 1987). The Trinidad Sandstone underlies the coal-bearing formations of the Raton coalfield and consists of very fine grained to medium-grained, calcareous to slightly clayey sandstone that ranges in thickness from 0 to 130 ft. Zones of abundant *Ophiomorpha* trace-fossil bioturbation are characteristic of its upper part.
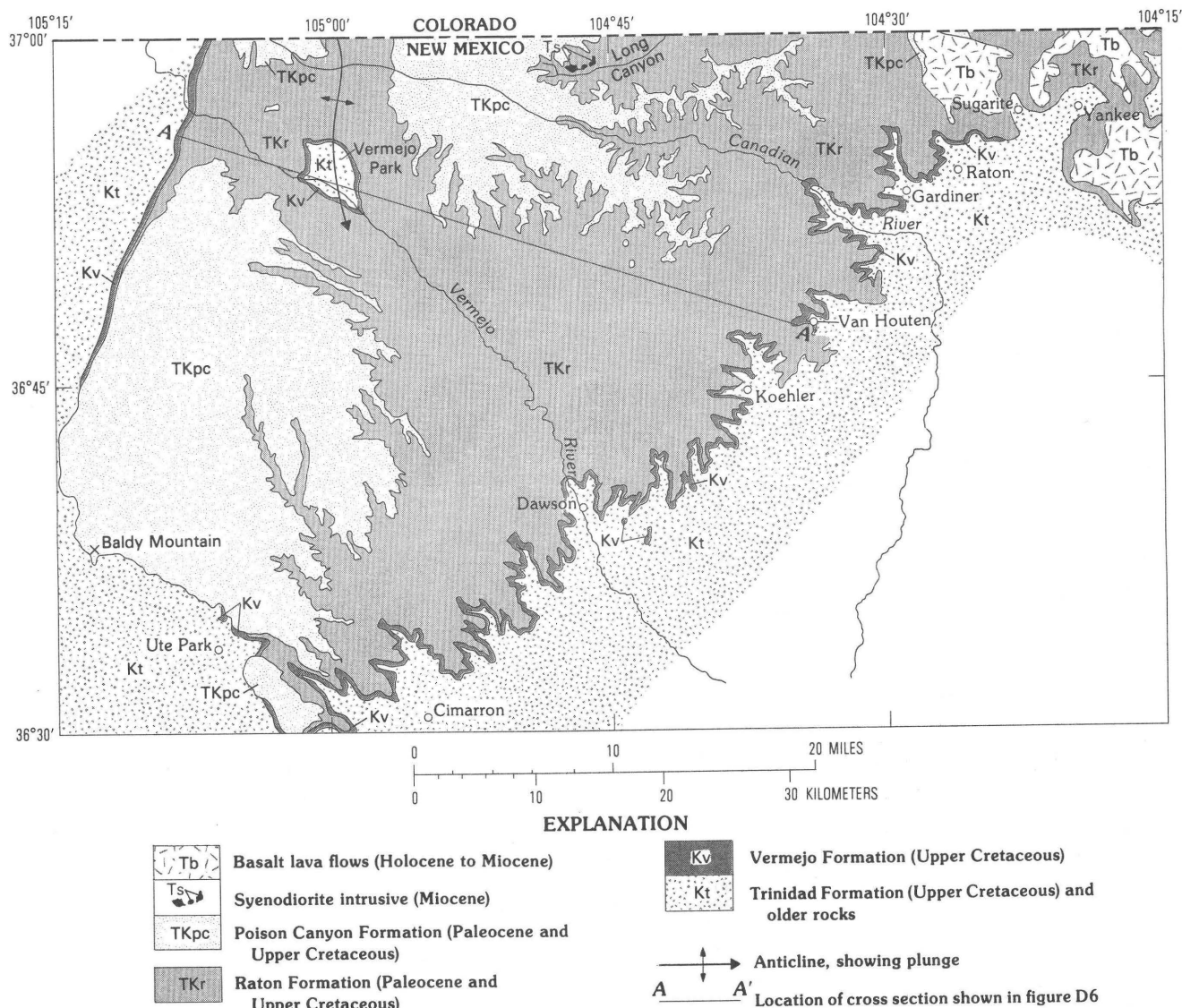
Figure D5. Generalized geology of the Raton coalfield, New Mexico.

Vermejo Formation

The Vermejo Formation consists of interbedded sandstone, siltstone, shale, carbonaceous shale, and coal that together form steep, generally debris-covered slopes above the cliffs of the Trinidad Sandstone. The Vermejo Formation ranges in thickness from about 375 ft at Vermejo Park and along the western border of the coalfield to 0 ft in the eastern part, east and south of Raton, N. Mex. Coal beds, as thick as 12 ft, occur near the top and bottom of the formation. The Vermejo Formation was deposited conformably on the Trinidad Sandstone in con-temporaneous fluviodeltaic plain and back-barrier environments. The upper part of the Vermejo Formation in the west-central part of the coalfield was deposited in an alluviated upper delta plain (Flores and Tur, 1982). The

Vermejo Formation intertongues with the Trinidad Sandstone along the southern margin of the coalfield, from a point north of Cimarron northeastward about 11 mi to Dawson, N. Mex. (Wanek, 1963), but this relationship has not been seen in any other areas of the field.

The organic material that ultimately formed the extensive coal beds in the lower part of the Vermejo Formation accumulated in poorly drained, brackish-water swamps or marshes behind barrier islands throughout most of the coalfield and also along the lower reaches of distributary channels of a prograding delta system in the northernmost part of the field. The thick back-barrier coal deposits are aligned subparallel to a north- to northeast-trending, eastward-prograding, Late Cretaceous shoreline, whereas the coal deposits related to the distributary channels are more randomly oriented. Coal beds that formed

landward, in the upper part of the formation, accumulated in poorly drained backswamps on flood plains of meandering streams in the upper reaches of a fluviodeltaic plain (Pillmore and Flores, 1987).

Raton Formation

The Raton Formation consists of sandstone, siltstone, mudstone, coal, carbonaceous shale, and conglomerate. It ranges in thickness from more than 2,000 ft in the west-central part of the coalfield to about 1,100 ft in the eastern part. A basal conglomeratic sandstone bed marks the lower contact and forms a persistent cliff throughout much of the Raton coalfield. Lee (1917) originally divided the Raton Formation into a basal conglomerate, a lower coal zone, a cliff-forming or barren series, and an upper coal zone. However, because the basal conglomerate is absent in the northeastern part of the coalfield, near Raton, it is here included in the lower coal zone, as described fully in Pillmore and Flores (1987). As redefined, this zone contains all of the Cretaceous part of the Raton Formation. Thus only three zones, as modified from Lee (1917), are considered to be consistent and identifiable throughout the Raton basin: the lower coal zone, the barren series, and the upper coal zone.

The lower coal zone, 100–300 feet thick, generally has a basal sequence of ledge-forming, conglomeratic channel sandstone 10–30 ft thick (locally absent), which grades up into slope-forming, overbank, flood-plain deposits. The flood-plain deposits consist of interbedded sequences of mudstones, siltstones, carbonaceous shales, and thin coal beds (mostly noncommercial) interbedded with lenticular channel and tabular crevasse-splay sandstones. The tabular crevasse-splay sandstones show rippled and small-scale cross lamination. The carbonaceous shale beds and thin coal beds were deposited in well-drained backswamps that formed repeatedly and expanded over the flood plain during nonflood conditions. However, in the eastern part of the coalfield, about 3 mi northeast of Raton, poorly drained swamp conditions existed over a large area (approximately 30 mi^2) for a prolonged time at the end of the Cretaceous. Peat deposits accumulated in this swamp, nearly uninterrupted by detrital deposits, to form a 6-ft-thick coal bed known as the Sugarite coal bed at the top of the lower coal zone of the Raton Formation. The palynological break that defines the Cretaceous-Tertiary (K–T) boundary occurs near the top of the coal bed in a kaolinitic, iridium-enriched claystone bed that apparently formed as a result of asteroid impact (Pillmore and Flores, 1987). This K–T boundary claystone bed has been found at several sites in the Raton coalfield and at other sites as far north as Alberta, Canada. It is useful as a chronostratigraphic marker.

The barren series, 175–600 ft thick, is dominated by cliff-forming, multiple-stacked, en echelon channel sandstones that are mostly fine to medium grained. The channel sandstones are nested to form a series of ledges and cliffs, but they are locally interbedded with and laterally grade into minor flood-plain deposits of mudstone and siltstone. Associated backswamp carbonaceous shale and coal beds are mostly thin and limited in extent.

The upper coal zone, 600–1,100 ft thick, consists of flood-plain deposits of sandstone, mudstone, siltstone, and carbonaceous shale interbedded with thick beds of coal, which represent occasional prolonged backswamp accumulations of peat. Coal beds in the upper coal zone are generally thicker and less restricted than those in the lower coal zone; however, most are lenticular and less than 3 ft thick. The upper zone includes several commercial beds, attaining thicknesses of 10 ft or more, and many are considered economically minable. The flood-plain and backswamp deposits of the upper coal zone are interbedded with crevasse-splay and channel sandstones.

Poison Canyon Formation

The Poison Canyon Formation overlies the Raton Formation over most of the eastern part of the basin but to the west and southwest it intertongues with all zones of the Raton and thickens at the expense of the Raton. In this area the Poison Canyon typically consists of thick to massive, lenticular, ledge-forming beds of coarse-grained to conglomeratic arkosic channel sandstone intercalated with beds of nonresistant, yellowish-gray- to grayish-orange-weathering, sandy, micaceous mudstone. These fine-grained rock types represent overbank flood-plain deposits. They grade laterally into and are interbedded with the channel sandstones. The Poison Canyon Formation is barren of coal and is interpreted as deposits of braided streams in an upper alluvial plain.

Igneous Rocks

Igneous flows, dikes, and sills, although not shown in figure D5, crop out in many places in the Raton coalfield. Basalt flows 3.5–4.0 m.y. old (Scott and Pillmore, 1989; Scott and others, 1990) cap the mesas along the northeastern border of the field, and lamprophyric dikes of mafic to intermediate composition, mostly about 25 m.y. in age (Scott and Pillmore, 1989) are found in almost all parts of the field. The dikes generally caused little alteration of the intruded beds; in contrast, the sills commonly intruded and stoped along coal beds, especially in the Raton coal zone of the Vermejo Formation, and have assimilated, coked, altered, and destroyed much coal (Pillmore, 1976). It is not known if the coking character of the coal beds in the Raton coalfield can be attributed to heat from igneous activity at depth.
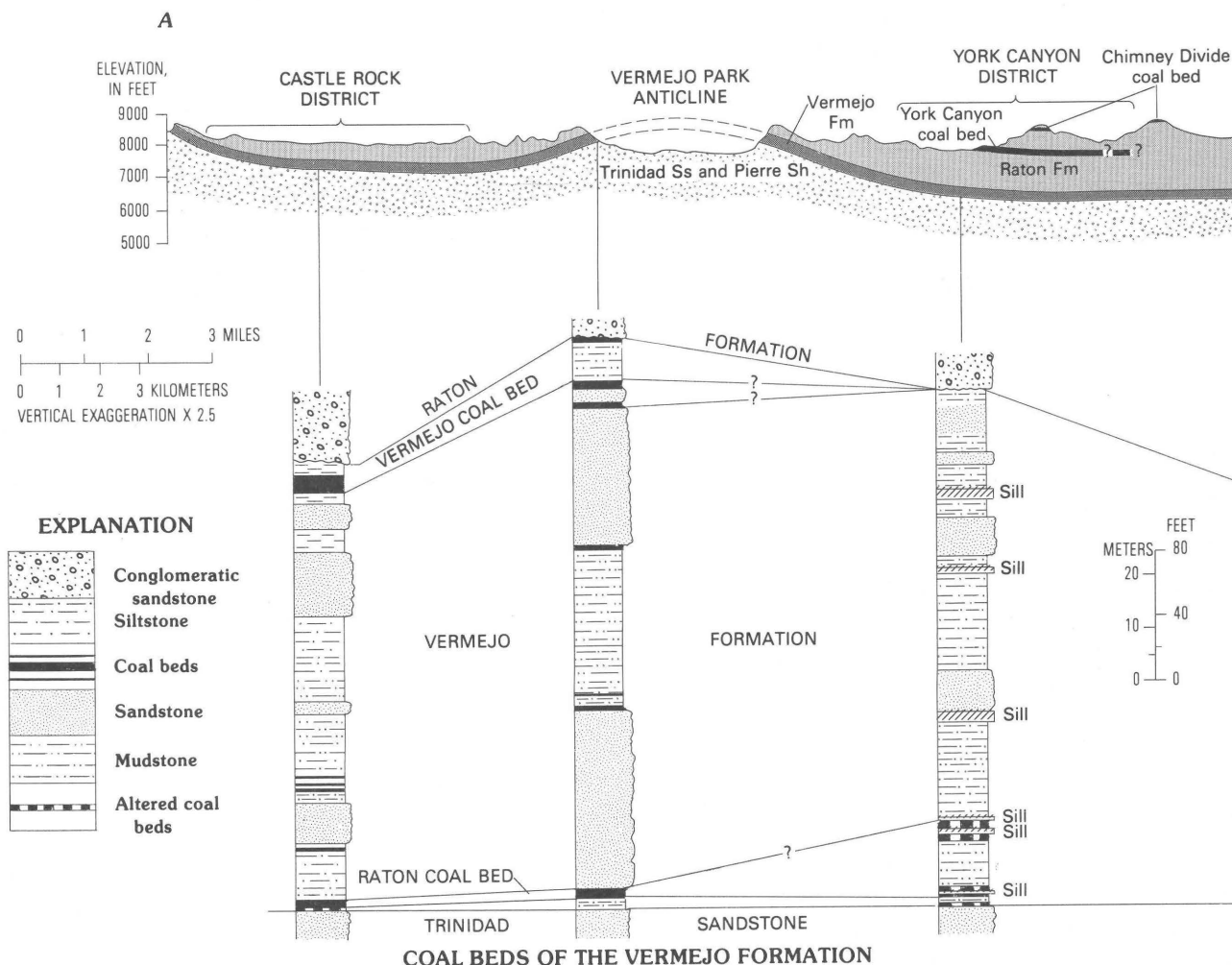
Figure D6. Diagrammatic geologic cross section and columnar sections showing Vermejo Park anticline and lithologic shown on figure D5. The cross section is extended diagrammatically to the east to show the thinning of the Vermejo Formation.

COAL RESOURCES

The Raton basin contains modest coal resources compared to some coalfields now being prospected, developed, and mined elsewhere in the western United States; however, the coal from the Raton field has high heating values, is of high rank, yields a high-quality coke, and may be of greater economic importance than coal from other larger fields. The coal is all high-volatile A to B bituminous rank; some representative coal analyses are given in table D2, and additional data on volatile matter and sulfur are shown in table D3 (Pillmore, 1976).

The Raton coalfield is unusual in western coal lands in that it consists almost entirely of fee land, where domestic energy companies have owned and developed the mineral rights over a long period. Under these circumstances, the buried coal resources of the field have not been thoroughly evaluated by either the State or the Federal Government. However, various field surveys and surface investigations have been carried out, beginning with the earliest territorial surveys and work by Orestes St. John in the late 1800's (St.

John, 1896), followed by W. T. Lee's investigations in the early 1900's (Lee, 1917). The U.S. Geological Survey (USGS) began investigations in the coalfield again in the mid-1900's (Wanek, 1963; Pillmore, 1969a and b, 1976), and since that time the work has been sporadic. The underground resources of large parts of the field have been explored by drilling and evaluated by Kaiser Steel Corporation (1954–84), Kaiser ·Coal Corporation (1984–89), and, most recently, by P&M Coal Mining Company (1989-present). These companies have provided much useful information but have asked not to have specific drilling sites and depth and thickness data published.

Coal resources for the various districts in the Raton coalfield are listed as demonstrated resources in table D4 (Pillmore, 1976). The demonstrated category includes measured and indicated resources calculated by standard techniques from drill hole data and limited outcrop information. P&M Coal Company prefers not to release resource information in any more detailed resource categories. The company's tonnage calculations are based on 85 lbs/ft^3 or 1851 tons/acre ft for bituminous coal in place, as
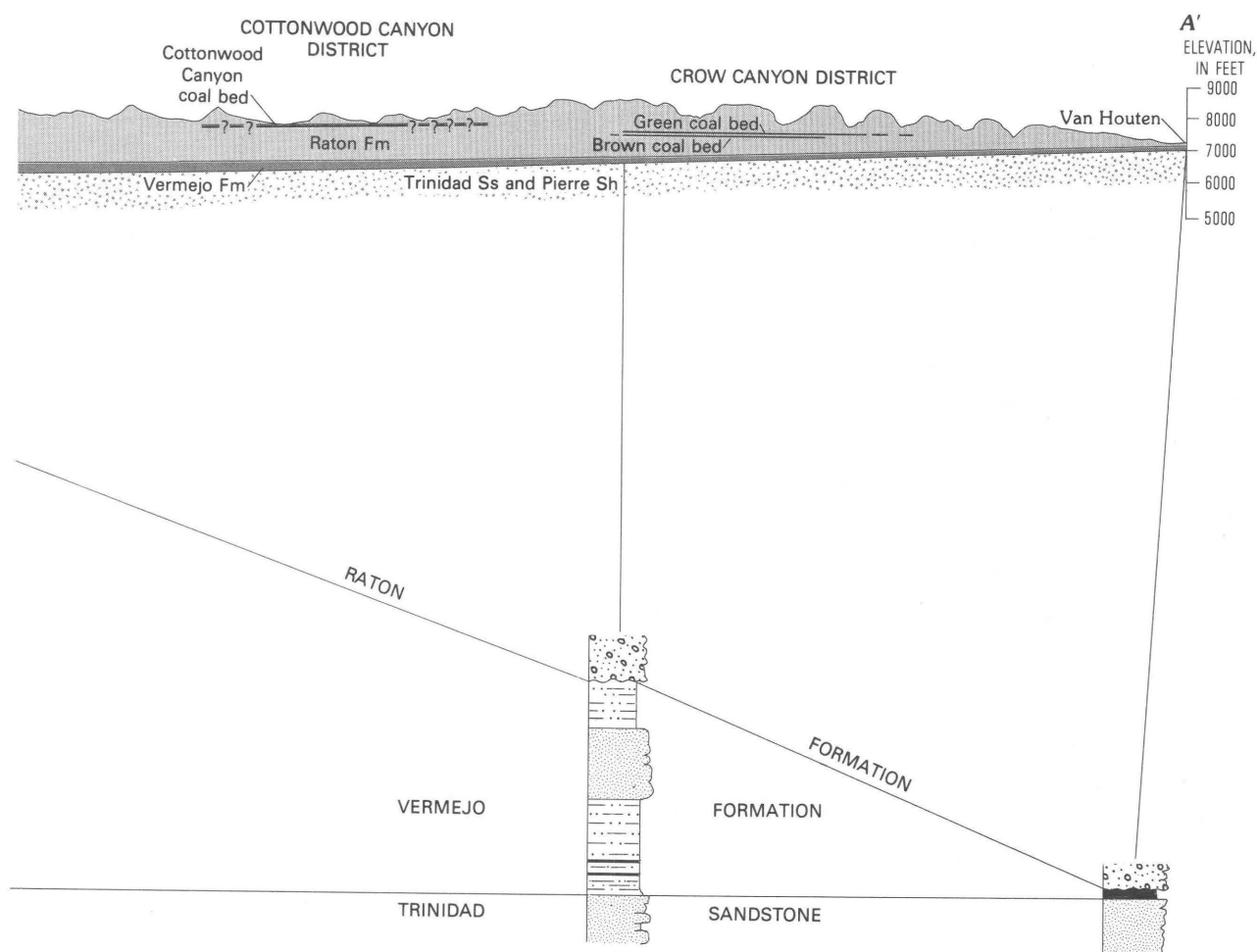
changes and coal beds in the Vermejo Formation across the northwestern part of the Raton coalfield. Trace of cross section

compared to 1800 tons/acre ft, which is the figure commonly used by the U.S. Geological Survey (Wood and others, 1983) to calculate bituminous coal in place.

Coal beds of potential commercial interest—here considered to be those beds at least 30 in. thick—occur throughout much of the area that is underlain by coal-bearing rocks. However, many of the beds are of limited extent, and available data are too sparse to allow the beds to be considered separately in this report. The most extensive and valuable deposits are the Raton and Vermejo coal beds, in the Vermejo Formation, and a group of coal beds that include the York Canyon and Upper Left Fork coal beds, presently being mined, in the upper coal zone of the overlying Raton Formation. The distribution of these formations is shown on the geologic map (fig. D5). The areas underlain by the beds of former, present, or future commercial importance are here informally called coal districts, and the most important of these districts are shown on figure D8.

Both formations also contain beds less than 30 in. thick. Demonstrated resources have not been calculated for

these beds and they are listed here as inferred resources. To show a rough distribution of these inferred resources, the coalfield has been arbitrarily divided into 15 geographic subdivisions (fig. D9), which overlap with but are distinct from the districts defined for the demonstrated resources (fig. D8). Minimum total coal thicknesses in both the Vermejo and Raton Formations have been estimated for each of the various subdivisions that make up the Raton coalfield. In each subdivision, drilling records, electric logs, and outcrop data were examined and interpreted, and a value representing the minimum total coal thickness of beds 14 in. thick or greater was assigned for each formation (table D5). The numbers are based on geologic subsurface and surface data, but the values are subjective in that no statistical approach was used for their generation. The resources are listed as inferred rather than hypothetical because of the large amount of data available throughout much of the coalfield; however, estimates for the southern part of the coalfield (the Ponil and Lower Bremmer subdivisions) are less reliable than those for other parts because drill holes there are more widely spaced. When
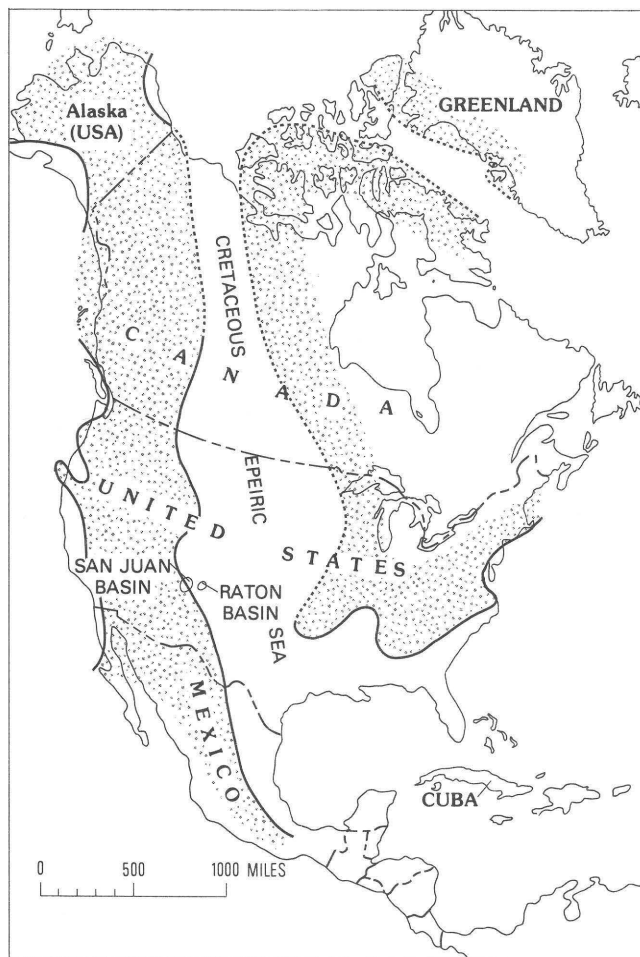
Figure D7. Western Interior seaway during Late Cretaceous time, showing the locations of the Raton and San Juan basins. (Modified from Gill and Cobban, 1966, fig. 15.)

these inferred resources (table D5) are added to the demonstrated resources calculated for the districts (table D4), the total gives a rough indication of the potential coal resources of the entire coalfield.

Coal Deposits in the Vermejo Formation

As shown in figure D6, the principal economic coal beds of the Vermejo Formation are the Raton coal bed (not to be confused with the formation of the same name), which lies at the base, and the Vermejo coal bed, which is near the top in the west-central part of the coalfield and is shown in the sections at Castle Rock and Vermejo Park. Although other coal beds as thick as 3–4 ft occur in the Vermejo, only these two are known to have sufficient extent and thickness to be considered potentially economic. The most economically important districts, defined by coal deposits in the Vermejo Formation that have not yet been mined, are Castle Rock and Rosado (fig. D8).
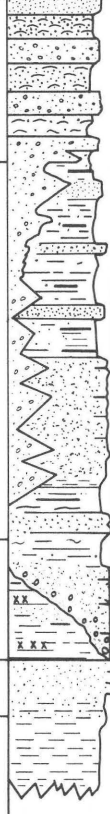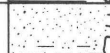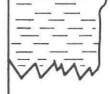
The Raton coal bed underlies most of the Raton coalfield. However, subsurface investigations indicate large areas where much of the coal has been altered or destroyed by sills that have intruded the Raton coal bed. In some areas, the presence of sills is known only from isolated drill holes and the extent of intrusive activity is uncertain. Several large districts in the coalfield are defined by the presence of thick coal in the coal zone on or immediately above the Trinidad Sandstone. Most of these districts have been extensively mined and, because only sketchy records remain, the areal extents of these thick coal beds are uncertain. The mines that saw most of the early activity are those at or near the abandoned mining towns of Gardiner, Brilliant, Willow, Van Houten, Koehler, and Dawson, and they are essentially worked out. (The Brilliant district, as shown in fig. D8, is a north and northwest extension of the old Gardiner and Brilliant districts.) Coal deposits of these old districts are described by Lee (1917; 1924).

Castle Rock District

The Castle Rock district contains the largest known coal deposits in the coalfield. The Raton and Vermejo coal beds underlie about 25,000 acres, or nearly 40 mi^2, in the Castle Rock district (fig. D8). This large district extends from the western margin of the coalfield about 4 mi eastward, nearly to Vermejo Park, and has been traced in a north-south direction for about 9 mi. Along the western margin of the district the rocks dip eastward as steeply as 25°–30°. In the areas considered minable, the stratigraphic distance from the Trinidad Sandstone to the Raton coal bed ranges from 5 to 35 ft (mostly 10–15 ft or less); the Vermejo coal bed lies about 250 ft above the Raton coal bed. The coal beds range in thickness from 3 to 15 ft and constitute a demonstrated coal resource containing more than 500 million tons (table D4). The overburden ranges from 0 along the outcrop to more than 3,000 ft below the high mesas in the southwestern part of the bed area. The Raton coal bed underlies fine-grained rock sequences consisting mostly of mudstone and shale. The Vermejo coal bed also mostly underlies fine-grained rocks, but locally the basal conglomerate of the Raton Formation rests directly on the coal bed.

According to corporate mining experts, problems related to roof rock and depth of cover in the Castle Rock district can be solved by the use of yieldable arches and modern longwall mining methods; however, the economics of using these methods will be the chief factor controlling the development of this district. Mining problems would be more severe in the areas of steeply dipping coal seams, along the western margin of the coalfield, but the rocks dip more gently in most parts of the district, and mining is not expected to be too difficult.

Table D1. General stratigraphic description of the Raton coalfield, New Mexico

AGE	FORMATION NAME	GENERAL DESCRIPTION	LITHOL-OGY	APPROXIMATE THICKNESS IN FEET
PALEOCENE	POISON CANYON FORMATION	SANDSTONE—Coarse to conglomeratic; beds 15–50 ft thick; interbeds of yellow-weathering, clayey sandstone. Thickens to west at expense of underlying Raton		>500
PALEOCENE	RATON FORMATION	Formation intertongues with Poison Canyon Formation to the west UPPER COAL ZONE—Very fine grained sandstone, silt-stone, and mudstone with carbonaceous shale and thick coal beds BARREN SERIES—Mostly very fine to fine grained sandstone with minor mudstone, siltstone, carbonaceous shale, and thin coal beds LOWER COAL ZONE—Same as upper coal zone; coal beds mostly thin and discontinuous. Conglomeratic sandstone at base; locally absent		0?–2,100 K-T BOUNDARY
UPPER CRETACEOUS	VERMEJO FORMATION	SANDSTONE—Fine- to medium-grained; also mudstone, carbonaceous shale, and extensive thick coal beds. Local sills		0–380
UPPER CRETACEOUS	TRINIDAD SANDSTONE	SANDSTONE—Fine- to medium-grained; contains cast of *Ophiomorpha*		0–130
UPPER CRETACEOUS	PIERRE SHALE	SHALE—Silty in upper 300 ft. Grades up to fine-grained sandstone. Contains limestone concretions		2,000–2,700

EXPLANATION

—	Coal bed		Conglomeratic sandstone		Mudstone
x x x	Sill		Shale		Carbonaceous shale
	Sandstone		Clayey sandstone		Siltstone
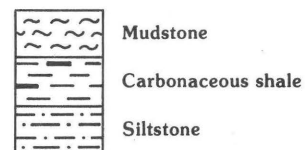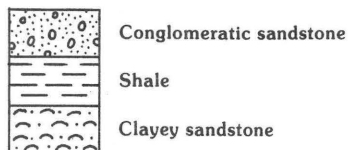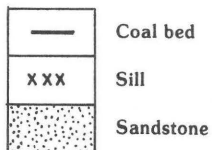
Rosado District

South of Vermejo Park, in the Rosado district, the Raton and Vermejo coal beds underlie an area of about 9,500 acres, mainly in Juan Baca Canyon. These beds constitute a demonstrated coal resource of about 127 million tons (table D4) and appear to form an eastward extension of the Castle Rock district, though the continuation of these beds from one district to the other is uncertain. The Vermejo coal bed is present throughout most of the district and constitutes the greater part of the resource. Locally, the basal conglomerate of the Raton Formation rests directly on the coal, but in most parts of the district it lies 15–30 ft above the coal bed. The beds dip south about 10°–15° along the south rim of Vermejo Park, south of the Vermejo Park anticline, but dips flatten rapidly away from the structure.

Entries developed in the Vermejo coal bed in the Rosado district, on the southeast flank of the Vermejo Park anticline, could provide access to the large underground resources of the Castle Rock district to the west of Vermejo Park. Exploitation of the Castle Rock district from the Rosado district might prove to be less disruptive environmentally than any other approach.

The Raton and Vermejo coal beds also crop out on the flanks of the Vermejo Park anticline and underlie the area north of Vermejo Park. These areas do not appear to contain resources sufficient to define a separate district. At the old Bartlett (Dead Easy) mine, at the north entrance to Vermejo Park, the Vermejo coal bed is about 6 ft thick, and coal was mined for several years for local ranch use. Both coal beds locally reach a thickness greater than 8 ft at outcrops around

Table D2. Representative proximate analyses of selected coal beds in the Raton coalfield, New Mexico

[Data in percent, except for Btu]

Mine or location	Coal bed	Volatile matter	Fixed carbon	Ash	Sulfur	Btu	Source of data
Raton Formation							
York Canyon mine -	York Canyon ---	35.7	54.9	8.8	0.6	14,340	1
Chimney Divide ---	Chimney Divide	38.4	47.6	13.4	.5	13,980	1
Ancho Canyon -----	Ancho Canyon --	36.3	54.0	8.6	.5	13,835	1
Brilliant --------	Tin Pan -------	37.0	46.5	16.5	.6	12,470	2
Yankee -----------	Yankee --------	38.7	48.7	12.6	.6	12,700	2
Vermejo Formation							
Vermejo Park -----	Vermejo -------	28.2	53.7	18.0	0.5	10,030	3
	Raton ---------	25.4	60.5	14.1	.5	11,440	3
Dawson (No. 3) ---	-- do ---------	38.2	49.3	12.5	.8	13,230	2
Koehler (No. 1) --	-- do ---------	37.5	50.0	12.5	.7	13,100	2
Van Houten (No.4)	-- do ---------	37.1	51.6	11.3	.9	13,220	2

SOURCES OF DATA

1. Bulk core sample data courtesy of Kaiser Steel Corporation. Btu results obtained from coal washed in heavy liquid (specific gravity 1.4).
2. Mine analysis, moisture free, selected from Ellis (1936, p. 44-48).
3. Weathered outcrop sample analysis courtesy of U.S. Bureau of Mines (generally higher ash and lower calorific values); low volatile content probably caused by intrusive rocks.

Table D3. Ranges of volatile matter and sulfur in 164 core samples of the major coal beds in the Raton coalfield, New Mexico

[Moisture- and ash-free basis. Data from whole-bed core samples washed in a heavy liquid (specific gravity about 1.5). Samples included partings and coal splits, so aggregate values represent the character of coal that would result from a beneficiation process. Data courtesy of Kaiser Steel Corporation, 1976]

Sample locality and coal bed	Number of samples	Volatile matter (percent)	Sulfur (percent)
York Canyon mine area:			
York Canyon main bed	8	39.1-41.4	0.40-0.59
Cimarron mine area:			
Upper Left Fork bed	17	35.6-40.1	.44- .56
Lower Left Fork bed	10	37.4-41.0	.48- .57
Castle Rock area:			
Raton bed ----------	41	29.2-42.5	.60- .90
Vermejo bed --------	34	32.4-41.9	.63- .93
Central area:			
Ancho bed ----------	21	43.1-46.1	.50- .65
Green bed ----------	18	40.6-45.4	.46- .69
Brown bed ----------	9	37.2-39.8	.45- .55
Potato Canyon bed --	6	39.6-44.0	.51- .74

the perimeter of Vermejo Park, but the beds seem less extensive than in the Castle Rock district, and sills probably have intruded the coal locally. The extent of the coal beds north from Vermejo Park is unknown.

Brilliant District

The Brilliant district is north and northwest of Raton (fig. D8). It consists of about 16,000 acres in the area drained by Dillon Canyon and its tributary, Coal Canyon, and in the part of the Railroad Canyon drainage west of Interstate Highway 25. Coal was mined extensively from the Raton coal bed in the old Blossburg mining district (not shown on fig. D8), which is south of the Brilliant district and included the mines at Blossburg, Gardiner, and Brilliant in Dillon Canyon. Undisturbed coal resources in the Raton coal zone have been defined by subsurface investigations in the Brilliant district, mainly north and northwest of the old mines. Potentially economic coal beds extend also under the area east of Interstate 25, redefined as the Brilliant East subdistrict. Demonstrated coal resources in the Brilliant district total 79 million tons (table D4 in beds of the Raton coal zone. The Raton coal zone locally consists of two or three coal beds separated by partings as much as 10 ft thick; the coal beds in the zone range in thickness from 3 to 8 ft (Lee, 1924). The Brilliant district is potentially economic because of the high quality of its coal and its close proximity to Raton and to rail transportation in Railroad Canyon.

Brilliant East subdistrict.—The Brilliant East subdistrict includes roughly 5,000 acres east of Interstate 25, as shown on figure D8. The eastward extent of the Raton coal zone beneath the basalt cap of Bartlett Mesa is uncertain (fig. D5); however, the Raton coal zone is known to be

Table D4. Demonstrated coal resources of commercial thickness (>30 in.) within mining districts of Raton coalfield, New Mexico

[Courtesy of Kaiser Coal Corporation]

District	Approx- imate area (acres)	Coal bed or zone	Average coal thick- ness (feet)	Demon- strated resour- ces (10⁶ tons)
Resources in the Vermejo Formation				
Castle Rock --	25,600	Vermejo -------	5.5	250
		Raton ---------	6.0	270
Rosado -------	9,500	Vermejo -------	5.5	102
		Raton ---------	4.0	25
Brilliant ----	4,200	-- do ---------	5.0	79
Brilliant East	3,200	-- do ---------	5.0	30
Koehler¹ -----	4,500	-- do ---------	5.0	19
Dawson² ------	11,200	-- do ---------	3.0	196
Vermejo Formation total ------------------				971
Resources in the Raton Formation				
York Canyon ---	5,500	York Canyon ---	5.0	6
Upper York ----	9,375	Upper Left Fork	6.0	94
		Lower Left Fork	4.0	39
Cottonwood Canyon ------	4,000	Cottonwood ----	5.5	40
Ancho Canyon: Ancho -------	2,200	Ancho zone ----	5.0	25
Gachupin- Bracket ---	1,600	Ancho, Bracket	4.0	11
Chimney Divide: Caliente Canyon ----	5,400	Chimney Divide-	3.0	23
		"L" Seam ------	2.5	17
Salyers Ridge	3,900	Chimney Divide	3.0	21
Crow Canyon ---	7,040	Green ---------	6.5	86
	5,700	Brown ---------	5.0	55
Brilliant -----	4,200	---------------	4.0	26
Potato Canyon -	11,500	Potato Canyon -	4.0	70
Raton Formation total ------------------				513
Total for both formations --------------				1,484

¹Partly mined out; remaining tonnage estimated.
²Modified from Wanek (1963).

present, and 30 million tons of demonstrated resources were assigned to this subdistrict following preliminary subsurface evaluation.

Dawson and Koehler Districts

Coal was produced from the coal mines at Dawson from the late 1800's until 1950, and at Koehler from 1906 until 1966, when production was started at York Canyon. The Koehler district (fig. D8) produced 14 million tons of coal and still contains demonstrated resources of 19 million tons (table D4). The Dawson district (fig. D8), owned by Phelps Dodge Corporation, produced 33 million tons of coal between 1899 and 1950 and surely has large reserves remaining. Some drilling has been done in the district in recent years, but the resulting data are not available. Wanek (1963) calculated demonstrated resources of 196 million tons of coal in beds of the Vermejo Formation in the Dawson district, mainly based on surface investigations. The district is of interest because of its relatively easy access to transportation (the Santa Fe Railway crosses the district in the Vermejo River canyon) and possible outcrop mine entries.

Other Areas

The intrusion of sills appears to have destroyed much of the coal in the Vermejo Formation in areas east of Vermejo Park and along the Vermejo River south of the Ancho subdistrict (fig. D8). During the summer of 1989, a large area in Van Bremmer Canyon was the focus of heavy drilling activity in the search for coal-bed methane by Pennzoil Corporation. Preliminary evaluation of the data indicates the presence of significant coal beds in the Vermejo Formation and also suggests that the Castle Rock and Vermejo Park–Rosado thick coal trends possibly extend south into this area.

In most districts of the coalfield, both the Vermejo and Raton Formations contain thin, local coal beds in addition to those thicker, more extensive beds that define the districts. Coal resources in the Vermejo Formation in beds 14 in. thick or greater are inferred to underlie the subdivisions of the coalfield shown on figure D9. The resources listed in table D4 are based on geologic inference and represent a minimum estimate of inferred coal resources contained in both the Vermejo and Raton Formations. The estimate for the Upper Bremmer–Gachupin and Lower Bremmer subdivisions are probably low, based on the new Pennzoil drilling data.

Coal Deposits in the Raton Formation

A large part of the coal resource of the Raton coalfield is in coal beds of the Raton Formation. As described above, these beds were formed in poorly drained swamps on flood plains developed along meandering streams of a broad, latest Cretaceous and early Paleocene alluvial plain. Because of their fluvial setting, these swamps were not as extensive as the back-barrier swamps that formed the Raton coal bed. The proximity of the Raton basin at this time to an actively uplifting source area, the San Luis Highland (Tweto, 1980), usually precluded the prolonged stable conditions that would have been needed to create widespread thick accumulations of peat and, hence, widespread thick coal deposits. However, multiple beds
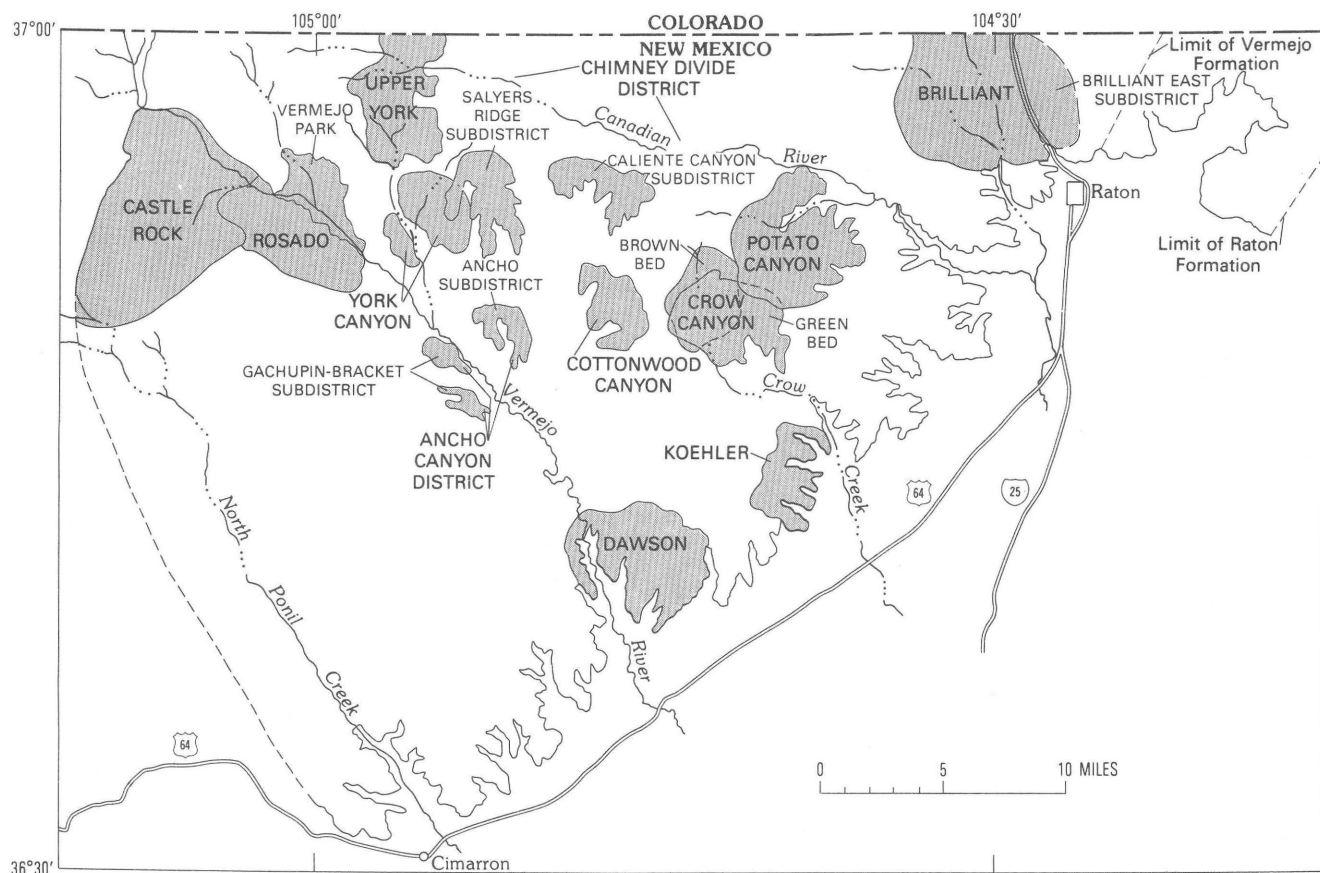
Figure D8. Districts of the Raton coalfield, New Mexico, that have demonstrated coal resources, as outlined by subsurface exploration.

ranging in thickness from 2 to 4 ft together with the thicker beds that define the districts constitute a viable resource in the coalfield. Many areas underlain by the upper coal zone of the Raton contain aggregate coal thicknesses in excess of 15 ft, in beds 14 in. thick or greater, which constitutes a potential resource of several billion tons, in addition to the resources reported for the coal districts discussed below.

Because the Raton Formation coarsens to the west and interfingers with beds of the overlying Poison Canyon Formation, commonly only thin coal streaks occur along the western margin of the coalfield, and thick coal deposits appear to be restricted to areas that lie east of a line that trends north to northwest about 2–3 mi west of Vermejo Park. The principal Raton Formation coal districts are defined by coal beds that lie east of Vermejo Park in the central part of the Raton coalfield. Some of these beds are shown on the Casa Grande 15' geologic quadrangle map (Pillmore, 1969a). Several other districts are to the east in the adjacent Brilliant 15' quadrangle, including the Brilliant district, which is partly in the Raton 15' quadrangle.

York Canyon District

The York Canyon district (fig. D8) constitutes an area of about 6,500 acres east of Vermejo Park, where presently

only surface mining is being carried out (the underground mine was closed in 1986). The York Canyon coal bed lies about 1,200–1,280 ft above the base of the Raton Formation, and it ranges in thickness from a few inches in the southeastern part of the outcrop to more than 12 ft near the main entries of the underground mine. The coal bed is consistently at least 6 ft thick throughout the bed area northeast of the mine entry. Measured underground coal resources in 1969 totaled 30 million tons in beds 4 ft thick or greater (Pillmore, 1976), but the coal bed has been mined out underground where it was 5 ft thick or greater (1988), and remaining underground resources of coal less than 5 ft thick are uncertain. At West Ridge, on the west side of the district (fig. D8), the York Canyon coal bed and some thinner beds that overlie the York Canyon are being strip-mined. In the West Ridge deposit, remaining strippable coal reserves are estimated at about 2 million tons (Roy Pillmore, P&M Coal Co., oral commun., 1991), and the life of the strip mine is estimated at about 3 yr. Production to date (1991) from the York Canyon coal bed totals about 20 million tons. Minable resources of strippable coal in the York Canyon district remaining after mining to date are about 2 million tons.
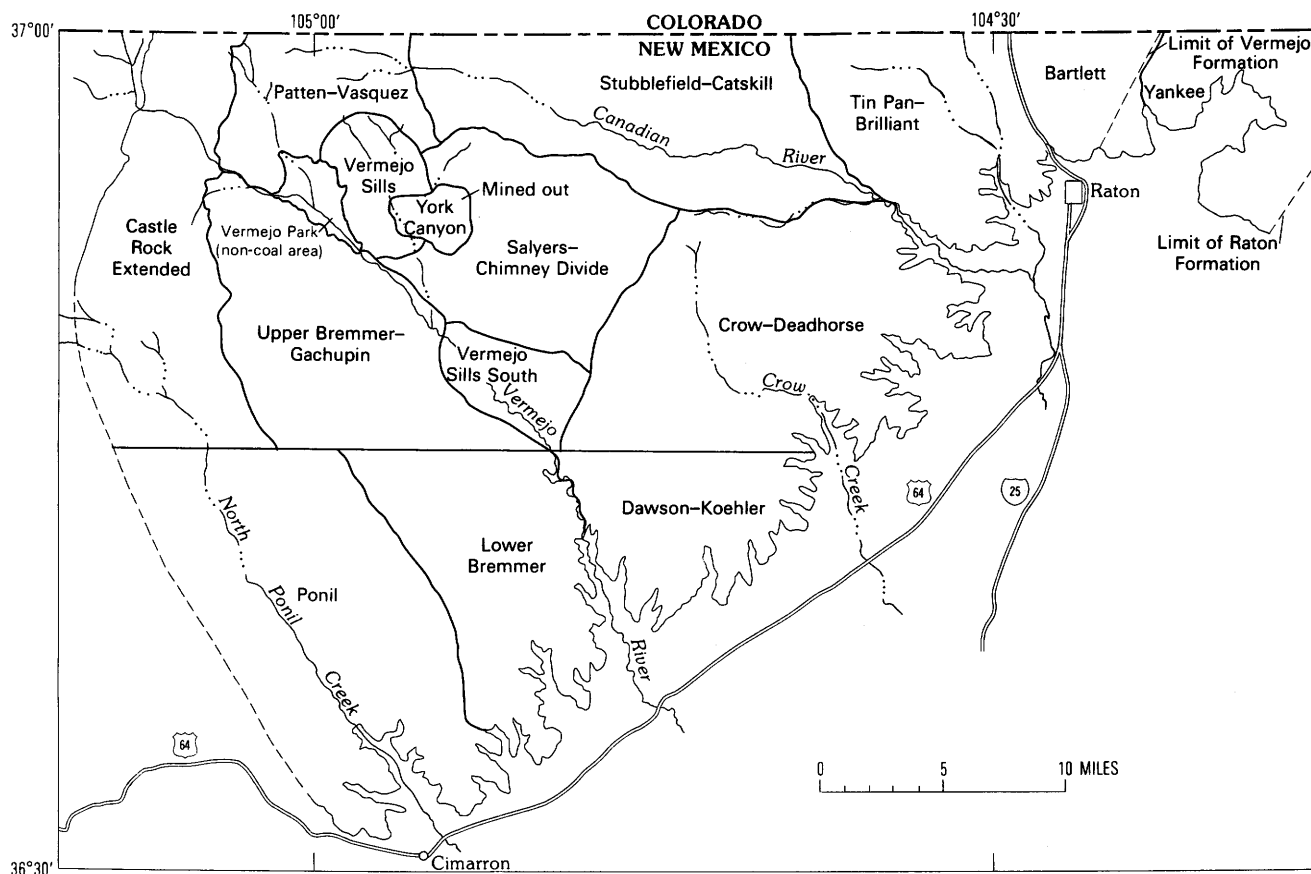
Figure D9. Geographic subdivisions of the Raton coalfield, New Mexico, used to describe inferred coal resources.

Upper York (Left Fork) District

Coal beds of the Upper York district (fig. D8) underlie nearly 9,400 acres 4 mi north of the York Canyon mine. The Left Fork coal deposit consists of two beds that are about 300 ft beneath the York Canyon coal bed. They are about 50–60 ft apart stratigraphically and lie 900–950 ft above the base of the Raton Formation. These beds constitute the lowest commercial coal deposits in the Raton Formation in the central part of the coalfield. The beds range in thickness from about 3½ to 11 ft, based on extensive drilling data, and demonstrated resources exceed 130 million tons (table D4). Areas where the Left Fork coal beds possibly could be strip-mined extend north to the State line and south toward the York Canyon strip mine, but they are considered nominally economic, and the district should be regarded as a deposit to be mined primarily by underground methods. An underground test mine was opened on the upper seam in 1969, and the coal was found to be of excellent quality. Entries for a new mine called the Cimarron mine were begun late in 1983, and coal is presently being produced by longwall mining methods. Minable reserves in the upper seam presently being mined total 16 million tons, and production from the Cimarron mine will be 1.8 million tons per year (Roy Pillmore, oral commun., 1991).

Cottonwood Canyon District

The Cottonwood Canyon district (fig. D8) is about 7 mi east of York Canyon, a short distance south of the York Canyon mine road, New Mexico Highway 555. The Cottonwood Canyon coal zone is in the upper coal zone of the Raton Formation, about 1,100–1,200 ft above the base of the Raton Formation. It underlies about 4,000 acres and ranges in thickness from 3 to 8 ft. Demonstrated resources of this district are estimated at 40 million tons (table D4), 10 million of which are considered strippable, depending on market conditions and equipment used. The multiple thin-seam occurrence of the coal and the dissected hill-and-valley terrain of the eastern part of the coalfield both make conventional strip-mining techniques impractical, and stripping ratios are difficult to assess. The resources considered strippable would change if demand and price of coal increased sufficiently.

Ancho Canyon District

The Ancho Canyon district (fig. D8) is considered here as two subdistricts: the Ancho, which lies north of the Vermejo River, and the Gachupin-Bracket, which lies to the south.

Estimated minimum inferred coal resources within subdivisions of the Raton coalfield, New Mexico

Subdivision or area (see fig. D8)	Area (acres)	Inferred coal resources				
		Raton Formation		Vermejo Formation		Total for both formations (10^6 tons)
		Thickness[1] (feet)	Resources (10^6 tons)	Thickness[1] (feet)	Resources (10^6 tons)	
Bartlett -------------	14,950	6	166	2	55	221
Yankee ---------------	24,310	3	134	0	0	134
Tin Pan-Brilliant ----	41,350	6	459	4	306	765
Stubblefield-Catskill	59,780	6	1,106	10	553	1,659
Patten-Vasquez -------	22,820	5	211	4	168	379
Castle Rock extended -	53,210	0	0	3	295	295
Upper Bremmer-Gachupin	52,410	5	485	4	388	873
Salyers-Chimney Divide	41,350	6	459	4	306	765
Crow-Deadhorse[2] ------	77,820	4	576	4	576	1,152
York Canyon ----------	3,590	4	26	3	20	46
Vermejo Sills --------	10,560	5	97	3	58	155
Vermejo Sills South --	11,760	4	87	3	65	152
Dawson-Koehler[2] ------	29,890	2	110	3	165	275
Ponil[2] ---------------	91,270	3	502	2	303	805
Lower Bremmer[2] -------	46,230	3	236	4	216	452
Total for all subdivisions ----------		4,654		---	3,474	8,128

[1]Estimated average total thickness of coal.
[2]Modified from Wanek (1963). Does not include most demonstrated resources at Dawson and Koehler districts (table D2).

Ancho subdistrict.—The Ancho Canyon coal zone lies roughly in the same stratigraphic position as the Cottonwood Canyon coal bed. It underlies about 2,200 acres north of the Vermejo River and contains about 25 million tons (table D4) of coal considered strippable. No underground mining is planned in this subdistrict. The coal bed lies mostly less than 100 ft beneath the crests of ridges in this dissected portion of the coalfield. The coal occurs in a zone as much as 15 ft thick, which contains several shale partings. These partings are expected to cause problems during mining. The maximum discrete bed thickness is about 4 ft.

Gachupin-Bracket subdistrict.—The Ancho Canyon coal zone also underlies the Gachupin-Bracket subdistrict (fig. D8). The subdistrict consists of about 1,600 acres. The zone is as thick as 9 ft and contains coal beds as thick as 4 ft, most of which include shale partings. Strippable demonstrated resources of the Ancho coal bed total about 9 million tons. A second coal bed, called the Bracket, lies about 40–60 ft above the Ancho and contains estimated strippable demonstrated resources of about 2 million tons, giving a total of 11 million tons (table D4). The southwestern and western limits of the subdistrict have not been completely defined, and underground reserves may eventually be proven and outlined. No underground operations are planned at present.

Chimney Divide District

The Chimney Divide coal bed and its equivalents underlie a large area that is usually divided into two subdistricts (fig. D8):
1. The Salyers Ridge subdistrict, which includes Salyers Ridge (between Salyers and Road Canyons) and Chimney Divide (between the East Fork of Chimney Canyon and Salyers Canyon); and
2. The Caliente Canyon subdistrict, which includes the areas that lie to the east of the East Fork of Chimney Canyon, and the Caliente Canyon area.

Because of the similarities of the subdistricts, they are not discussed individually.

The Chimney Divide coal bed and its equivalents crop out below the crests of the long fingerlike ridges and high drainage divides throughout an area of more than 50 mi^2 along the drainage divide between the Vermejo and Canadian Rivers. The coal bed commonly consists of two beds about 2 ft thick separated by a shale parting as thick as 1 ft. The maximum thickness of coal in the zone is about 4.5 ft. A coal bed termed the "L" bed locally lies 20–30 ft beneath the Chimney Divide coal bed and averages about 30 in. thick. Total demonstrated coal resources for the district exceed 60 million tons (table D4). The coal is of good

quality for power generation but not particularly suited for metallurgical purposes. These coal beds are the highest beds in the sequence and lie near the top of the upper coal zone of the Raton Formation, about 1,800 ft above the base.

Lee (1924) discussed the coal beds in the Raton Formation in the Brilliant and Raton quadrangles and described the thickness, stratigraphic position, and mines of each bed. Several beds as much as 8 ft thick occur in the eastern part of the field and are of commercial value. However, most beds are less than 4 ft thick, are areally restricted, contain partings of shale or bone, and were considered by Lee to be less desirable for the manufacture of coke. Figure D10 shows the general relations of some of the beds in the eastern part of the coalfield to those in the central part.

Potato Canyon District

The Potato Canyon coal zone underlies an area of about 6,500 acres, mainly on the ridge dividing Coal and Potato Canyons and along adjacent ridges and valleys,

though it also extends south into the heads of Crow and Coal Canyons. The zone lies about 950–1,050 ft above the Trinidad Sandstone. In Potato Canyon the zone is as thick as 8.4 ft and has a total coal thickness as great as 7.2 ft, but individual beds within the zone rarely reach 3 ft in thickness (Lee, 1924). The coal zone is characterized by several shale partings. It was excavated along the outcrop for several hundred yards on both sides of Potato Canyon and is also exposed in bulldozer cuts at the head of Coal Canyon. The coal zone is 6 ft thick near the mine in Potato Canyon and is 7.5 ft thick (including 6.3 ft of coal) 2.5 mi farther south, in the head of a tributary to the Canadian River called Coal Canyon. An experimental mine, opened in 1981, was driven 2,000 ft into the south wall of Potato Canyon to test the continuity and quality of the coal. The test was completed in 1982 and the mine was closed. Total demonstrated coal resources in the district are 70.4 million tons (table D4). Small parts of the district are underlain also by the Green coal bed on the south (fig. D8) and by the Tin Pan coal bed in the northeast; both lie stratigraphically beneath the Potato Canyon coal bed.

Crow Canyon District

The Crow Canyon district (fig. D8) is defined by two areally overlapping coal beds: the Green, which is the highest stratigraphically, and the Brown. These may correlate, respectively, with the upper and lower Left Fork coal beds in the Upper York district to the west, but this speculation is based solely on stratigraphic position.

Green coal bed.—The Green coal bed crops out in the bottom of Crow Creek and has been traced in the subsurface throughout an area of several square miles. It overlies a large portion of the Brown coal bed area and extends to the south and east several miles (fig. D8). The bed occurs as a zone, as thick as 16 ft, composed of alternating thin coal layers and carbonaceous shale partings mostly less than 1 ft thick. It lies in the lower part of the upper coal zone of the Raton Formation, approximately 700–750 ft above the Trinidad Sandstone. The coal bed at location 386 of Lee (1924, p. 171) may be this bed; he described it as a zone 12.9 ft thick containing 9.6 ft of coal. Lee reported a second zone 12.5 ft thick that lies 125 ft stratigraphically above the Green coal bed, but it contains only 3.1 ft of coal and is not considered economic under present conditions.

The Green coal bed underlies about the same size area as the Potato Canyon coal bed, but outcrops of the Green are sparse and thickness ranges are uncertain. The coal bed contains demonstrated coal resources of 86 million tons (table D4).

Brown coal bed.—The Brown coal bed averages 5 ft in thickness and lies about 100 ft beneath the Green coal bed, near the base of the upper coal zone. It is one of the lowest beds in the eastern part of the coalfield. It may correlate with the Tin Pan bed, which lies in approximately
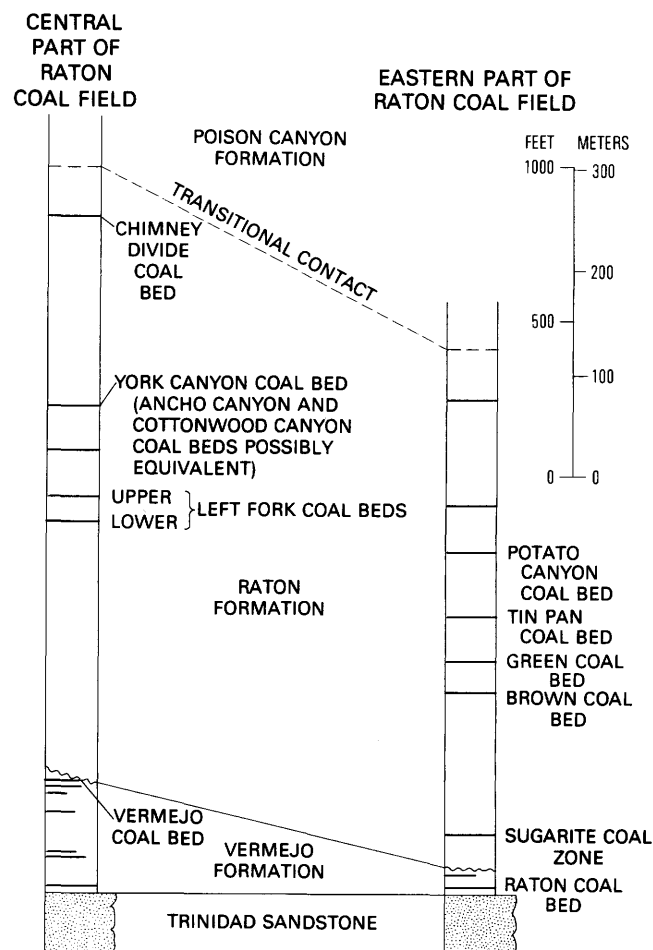

Figure D10. Diagrammatic stratigraphic section showing relations of coal beds in the central and eastern parts of the Raton coalfield, New Mexico (from Pillmore, 1976).

the same stratigraphic position in the Brilliant district. In the vicinity of Crow, Coal, and Potato Canyons, the Brown coal bed underlies a poorly defined area of several square miles, presumed to be similar in size to the area underlain by the Green coal bed, and contains demonstrated resources of 55 million tons (table D4). The Brown coal bed is about 600–650 ft above the Trinidad Sandstone (Kaiser Coal Corporation, written commun., 1976).

Brilliant District

Several Raton Formation coal beds occur in the Brilliant district, including the Tin Pan, Rombo Canyon, and Savage Canyon beds. These and other beds underlie ridges in the Brilliant district and parts of the Tin Pan–Brilliant subdivision (fig. D9). For instance, a 6-ft coal zone that crops out in Jones Canyon, a tributary of the Canadian River, about 0.7 mi west of Raton, may be equivalent to the Tin Pan coal bed or the Potato Canyon seam, but the correlation is indefinite and its lateral extent is not known. The coal resources that can be inferred to be present in these and all other coal beds in the Tin Pan-Brilliant subdivision total 459 million tons (table D5) of which 26 million tons (table D4) are the demonstrated resources in coal beds of the Raton Formation in the Brilliant district.

The Tin Pan coal bed underlies an area of about 25,000 acres, mostly north of the Canadian River, extending westward from a point about 4 mi northwest of Raton (Lee, 1924). The coal bed lies 615–720 ft above the Trinidad Sandstone (Kaiser Coal Corporation, written commun., 1976). Near Brilliant, the zone containing the Tin Pan bed is as much as 13.3 ft thick and has a total coal thickness of 9.4 ft (Lee, 1924), but individual coal beds in the zone rarely reach thicknesses greater than 5 ft and the bed generally contains one or more shale partings. The coal bed crops out in canyons adjacent to and along Dillon Canyon and the Canadian River. Coal was produced from the Tin Pan coal bed for several years at Brilliant; but, according to Lee (1924), the coal is softer than the older coal of the Raton coal bed and produces a weak and "in some ways inferior" coke. However, a satisfactory coking blend is obtained when this coal is mixed with coal from the Raton coal bed. Separate resource estimates for the Tin Pan coal bed were not calculated because the bed was largely mined out from mines in Dillon Canyon. The unmined portions of the bed are included in resource estimates for Tin Pan–Brilliant subdivision (fig. D9; table D5).

The lowest coal bed of commercial thickness in the Raton Formation is in the Sugarite zone, which lies from 80 to more than 100 ft above the base of the Raton Formation and extends throughout an area of about 64,000 acres in the eastern part of the coalfield (Lee, 1924). Recent subsurface investigations reveal that in the old Blossburg district of Lee (1924), west of Raton, a zone equivalent to the Sugarite is 40–50 ft thick and lies 140–190 ft above the base of the Raton Formation (Kaiser Coal Corporation, written commun., 1976). The coal bed is as thick as 5.5 ft in the mine at Sugarite and nearby localities; in other places, it is thinner and contains several shale partings. The Sugarite coal bed underlies an undetermined area beneath the basalt-capped Bartlett Mesa in the Bartlett subdivision (fig. D9), and it is also present in the northern part of the Yankee subdivision, where it underlies Barela Mesa and extends north into Colorado. Although the coal is noncoking in character, it has high heating value and was sought after as domestic fuel because its high resin content causes it to burn freely, without notable clinker (Lee, 1924).

Other Coal Beds in the Raton Formation

Parts of the Raton coalfield contain several coal beds in addition to those that define individual districts. Lee's reports (1917; 1924) and Pillmore's reports and maps (1969a, b; 1974; 1976) indicate that many parts of the field that have been investigated contain as much as 15 to 20 ft of coal in beds 14 in. thick or greater. Table D5 shows minimum coal resource values based on minimum total coal thicknesses inferred in the subdivisions shown on figure D9.

Geophysical and drilling records indicate the presence of other coal beds in various areas, and field investigations have discovered several more. For instance, southwest of Vermejo Park, beds as thick as 5 ft crop out at the heads of Pooler and Juan Baca Canyons, but these beds could not be traced along outcrop for any great distance, and subsurface data are not sufficient to define the limits of the beds. These coal beds lie at about the same stratigraphic position as those in the Upper York (Left Fork) district to the northeast. A higher coal zone, which is as thick as 9 ft, underlies about 600 acres at the head of Juan Baca Canyon, but it does not contain sufficient reserves to warrant development at this time. West of Vermejo Park, a coal bed as thick as 5 ft underlies ridges in the drainage area of Mestas Canyon. This coal bed may also be stratigraphically equivalent to one of the Left Fork beds. Again, the bed area appears to be too small to warrant development. However, a coal zone that may have commercial importance crops out north of Vermejo Park, in Spring Canyon; it includes about 5–6 ft of coal, underlies an area of unknown extent, and warrants further investigation. The inclusion of these and other known coal beds in table D4 would significantly add to resource estimates, but detailed correlation studies would be needed to determine whether such inclusion is warranted.

Subsurface investigations in the Yankee subdivision show inferred coal resources of about 134 million tons (table D5) contained in approximately 24,000 acres, most of which lie beneath the basalt caps of Barela, Horse, and Johnson Mesas, about 3–5 mi northeast of Raton. Drilling information provided by Santa Fe Mining Corporation shows that about 16,000 acres of the subdivision, lying mostly beneath Barela and Horse Mesas, contains 85

million tons of coal that could be classed as demonstrated resources. The Yankee is the easternmost subdivision in the coalfield, and the coal is contained mostly in the Sugarite coal bed (lower coal zone), and the Kellog, Dirty, and Yankee coal beds (upper coal zone). The Raton Formation thins to the east across the coalfield, and the Yankee coal bed, which is near the base of the upper coal zone, is only 300–400 ft above the top of the Trinidad Sandstone. The Yankee coal bed is possibly stratigraphically equivalent to the Tin Pan or one of the other lower beds in the upper coal zone described above, but outcrops are obscured by soil and vegetation cover, so tracing of the beds on the ground is nearly impossible. According to Lee (1924), the coal rarely occurred in beds thicker than 2.5–3 ft, and comparatively little coal has been mined from this bed. Thicker coal occurs in the Kellog and Dirty coal beds of the district, mainly in the northern part beneath Barela Mesa. Coal beds of the upper coal zone are absent in the eastern part of the Yankee subdivision beneath the basalt flows that cap the eastern part of Johnson Mesa; it is unlikely that the Sugarite coal bed is of minable extent and thickness beneath the mesa.

Lee (1924) provides descriptions of many coal beds and zones in the eastern part of the coalfield that are not included or described here. Geophysical records of oil wells drilled in 1972, and more recent drilling by Pennzoil Corporation for coal-bed methane in 1989, suggest that coal deposits of potential commercial value underlie a large area around Van Bremmer and Cerrososo Canyons. The quality, thickness, and areal extent of any beds in this area have yet to be determined. Information from outcrops in the Cimarron area, at the southern limit of the coalfield, does not suggest the presence of thick coal beds in either the Vermejo or Raton Formation in that area.

CONCLUSIONS

The Vermejo and Raton Formations contain more than 9 billion tons of coal resources in the Raton coalfield. These resources are sufficient to sustain large-scale mining operations to meet nearly any predictable market need. However, even though the coal is of high quality and a sought-after product, difficult mining conditions and high production costs may preclude large-scale development in the face of competitively priced coal from large mines in the Powder River basin in Wyoming.

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Chapter E

Geology and Coal Resources of New Mexico's Small Coalfields

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Descriptions of 11 fields outside the
San Juan and Raton basins, which may
hold more than 2 billion tons of coal

CONTENTS

FIGURE

Geology and Coal Resources of New Mexico's Small Coalfields

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Abstract

The small coalfields of New Mexico, outside the San Juan basin and the Raton field, may contain resources of more than 2 billion tons of coal, which is mostly subbituminous but includes some anthracite and coking coals. Fields with reasonable economic reserves are the Salt Lake, Sierra Blanca, Datil Mountains, Cerrillos, and Carthage fields. The coal beds are in the lower part of the Upper Cretaceous Mesaverde Group or its equivalents, and the coals have medium ash content (10–20 percent) and low sulfur content (less than 1 percent).

INTRODUCTION

Most of New Mexico's coal is in two major areas: the San Juan basin in the northwest in the Colorado Plateau physiographic province, and the Raton area in the north-central part of the State in the Great Plains province. The other coalfields in the State are relatively small and are in the southeastern part of the Basin and Range province and the southeastern part of the Colorado Plateau province.

Among these "small" coalfields (Tabet and Frost, 1978), the ones that contain the largest amounts of resources are the Salt Lake field and the Datil Mountains field in west-central New Mexico and the Sierra Blanca field in south-central New Mexico (fig. E1). The Cerrillos and Carthage fields have been mined extensively in the past and still contain usable resources. The Hagan, Tijeras, Jornada del Muerto, and Engle coalfields contain lesser amounts of coal resources. The Rio Puerco and Tierra Amarilla fields are outliers of the San Juan basin coal sequences.

These small coalfields are of considerable historical interest. The Spanish used small amounts of coal from

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several of them as early as the 17th century. Anthracite was mined from the Cerrillos field as early as 1835. Mining began on a significant scale in 1861, when the U.S. Army troops at Fort Craig opened a mine in the Carthage field. Present economic interest in the small coalfields is largely confined to the Sierra Blanca field, because of its location on the Southern Pacific Railway, and the Salt Lake coalfield, which lies about 50 miles east of the power plants in east-central Arizona.

SALT LAKE FIELD

The Salt Lake coalfield (fig. E1), in west-central New Mexico, covers about 750 mi^2 straddling the Cibola-Catron County line in Tps. 1–8 N. and Rs. 15–21 W. This is a transitional area between the Zuni-Gallup basin to the north and the Datil-Mogollon volcanic field to the south. New Mexico Highway 32 provides access to U.S. Highway 60 to the south at Quemado and northward to Interstate 40 at Gallup.

Structurally, the Salt Lake field is simple, with a few low-displacement normal faults, and some small-scale flexures. Dips are generally less than 5°.

Upper Cretaceous coal-bearing units crop out in a westward-opening arcuate belt along Carrizo Creek. Most of the coal beds occur in the Moreno Hill Formation (McLellan and others, 1983a), which correlates northward and eastward with the Carthage and Fite Ranch Members of the Tres Hermanos Formation, the Pescado Tongue of the Mancos Shale, the Gallup Sandstone, and the lower part of the Crevasse Canyon Formation (Hook and others, 1983).

Minable coals are in the lower member of the Moreno Hill Formation, which has a maximum thickness of 798 ft; individual beds reach a maximum thickness of 13.2 ft but average 4.1 ft. Some thin coals (1–3 ft) are found in the Upper Cretaceous Dakota Sandstone in the western part of
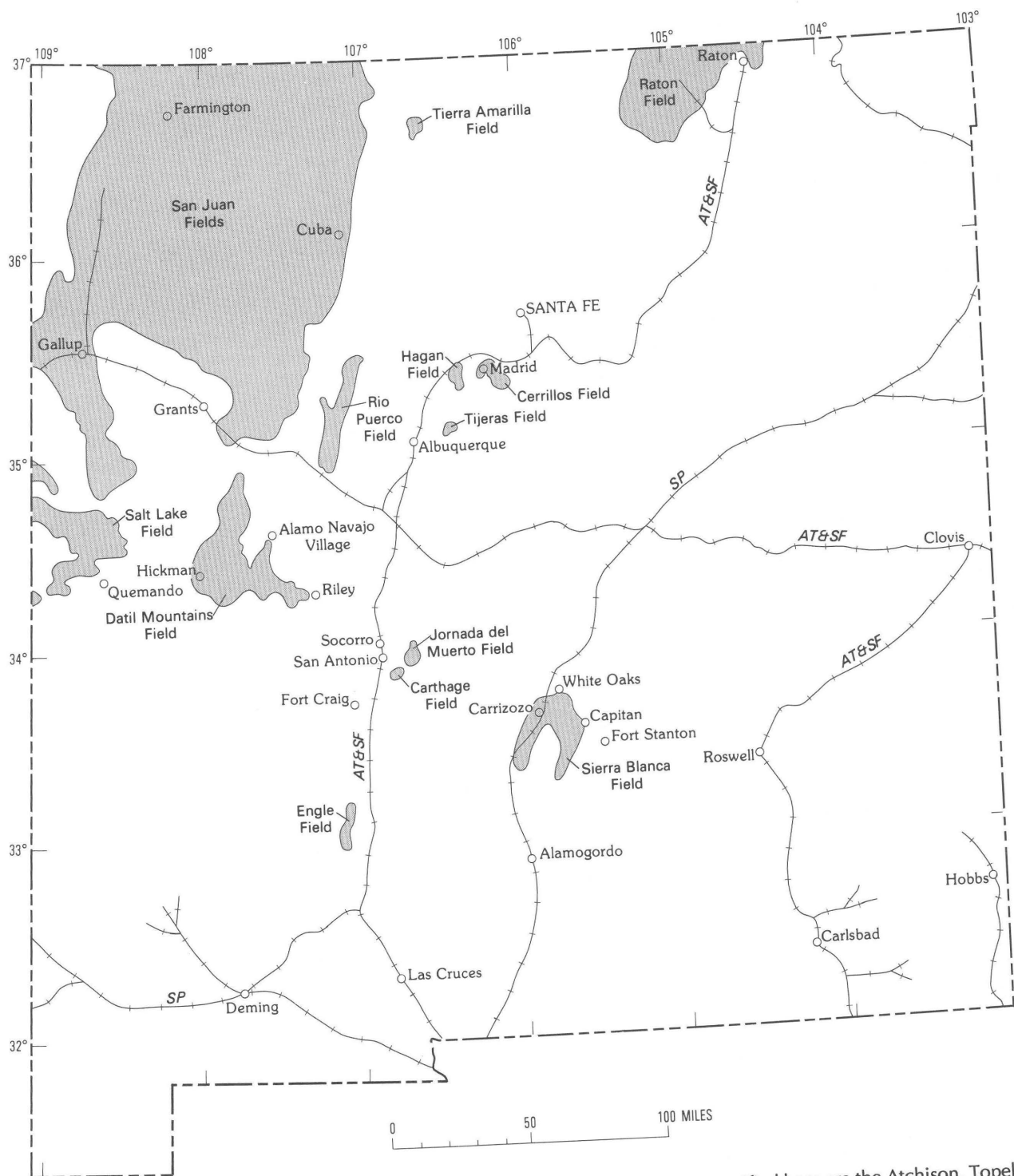
Figure E1. Coalfields, rail lines, and pertinent localities in New Mexico. Railroads identified here are the Atchison, Topeka, and Santa Fe (AT&SF) and the Southern Pacific (SP).

the field. Coals in the Salt Lake field are of a high-volatile C to B bituminous rank, as shown below:

Proximate analyses (123 samples; data in percent, except Btu/lb)	
Moisture.......	11.01±5.60
Ash	18.04±8.51
Volatile matter .	31.65±5.53
Fixed carbon...	37.41±7.25
Btu/lb:	
As received...	9,244±1,507
Mineral matter	
free	11,342±1,659

Major oxides (36 samples; data in percent)	
SiO_2..........	54.28±7.91
Al_2O_3	23.12±5.30
Fe_2O_3	3.84±2.23
TiO_2	1.61±0.65
CaO..........	5.01±3.51
MgO	0.72±0.40
Na_2O..........	0.33±0.29
K_2O..........	0.86±2.42

Ultimate analyses (81 samples; data in percent)	
Carbon	51.49±6.75
Hydrogen	4.23±3.34
Nitrogen.......	0.98±0.12
Oxygen........	9.92±2.15
Sulfur	0.91±1.69

Trace elements (3 samples; data in parts per million)	
As	1
Cu	18
Hg	8
Li.............	4
Mn............	210
Pb............	6
Sb............	15
Se............	1
Th	10
U	5
Zn	70

The Salt Lake coalfield is estimated to have coal resources of 480 million tons (coal beds with minimum thickness of 1.2 ft) and coal reserves of 240 million tons (minimum thickness of 2.5 ft), based on recent geologic mapping, drilling, and coal-resource evaluation of the field by the New Mexico Bureau of Mines and Mineral Resources and the U.S. Geological Survey (Anderson, 1981, 1982; Campbell, 1981, 1984; McLellan, Haschke, and Robinson, 1982; McLellan, Robinson, and others, 1982; McLellan, Haschke, and others, 1983a, b; McLellan, Robinson, and Haschke, 1983; McLellan and others, 1984; Roybal, 1982; and Roybal and Campbell, 1981). Out of these total resources and reserves, 144 million tons has a stripping ratio of 20:1 or less (Campbell and Roybal, 1984).

DATIL MOUNTAINS FIELD

The Datil Mountains coalfield (fig. E1) lies at the junction of Socorro, Catron, and Cibola Counties, in the northern foothills of the Datil, Gallinas, and Bear Mountains, generally in the upper drainage basin of the Rio Salado between Riley and Hickman. The field covers about 760 mi^2. Access to the rugged area is by ranch roads and New Mexico Highway 52 to Alamo.

The geological structure of the field is complicated by broad-scale folding, igneous intrusions, and faulting, mostly of Laramide and Tertiary age. Southward the coal-bearing units are overlain by thick volcanic tuffs and flows. The coal beds are in the Tres Hermanos and Crevasse Canyon Formations. The Crevasse Canyon Formation coal beds are

the time equivalent of the Dilco Coal Member of the Crevasse Canyon Formation in the San Juan and Acoma basins (Molenaar, 1974). Coals range from subbituminous A to high-volatile C bituminous in rank, as shown below:

Proximate analyses (26 samples; data in percent, except Btu/lb)	
Moisture.......	7.42±5.66
Ash	12.50±5.60
Volatile matter .	36.20±4.00
Fixed carbon...	43.77±4.63
Btu/lb:	
As received...	10,871±1,597
Mineral matter	
free	12,453±1,712

Major oxides (7 samples; data in percent)	
SiO_2..........	58.42±8.22
Al_2O_3.........	16.83±1.85
Fe_2O_3	4.64±0.72
TiO_2	1.22±0.17
CaO..........	4.59±0.86
MgO	1.35±0.41
K_2O..........	0.81±0.19
Na_2O.........	0.50±0.18

Ultimate analyses (26 samples; data in percent)	
Carbon	62.41±6.77
Hydrogen	4.98±0.42
Nitrogen.......	1.10±0.19
Oxygen........	0.46±8.37
Sulfur	0.57±0.12

Trace elements (3 samples; data in parts per million)	
As	8±9
Cu	15±11
Hg	0.35±0.31
Li.............	11±7
Mn............	151±330
Ni.............	8±4
Pb............	8±4
Sb............	13±17
Se............	3±2
Th	8±4
U	3±1
Zn	14±9

Read and others (1950) estimated resources of the Datil Mountains area as more than a billion tons, but recent detailed mapping and drilling suggest this estimate is too high. For the eastern part of the field, Osburn (1982, 1983, 1984) estimated measured and indicated resources as 85 million tons in beds averaging 2.7 ft in thickness and attaining a maximum of 4 ft. However, Winchester (1921) reported thicker coal beds in the northwest part of the coalfield.

SIERRA BLANCA FIELD

The Sierra Blanca field, also known as the Capitan field, is in south-central New Mexico, on the northeast margin of the Tularosa basin, in Lincoln and Otero Counties. Coal-bearing units crop out on the edges of the Sierra Blanca syncline and also flank the extrusive-intrusive complex of Sierra Blanca on its east, north, and west sides, covering about 435 mi^2. Structurally, the field is a north-plunging syncline, which has limbs dipping 15°–29°. The geology of the field is further complicated by many faults, dikes, and sills.

U.S. Highway 54 and the Southern Pacific Railway cut across the west edge of the field, and U.S. Highway 380 trends southeastward across the northern part. The coal seams have been mined near Capitan, White Oaks, Fort Stanton, and Carrizozo.

Minable coals appear to be southeastward equivalents of the Crevasse Canyon Formation (Arkell, 1983; Hook and others, 1983). Available analyses indicate that the coals are high-volatile C and B bituminous:

Proximate analyses (14 samples; data in percent, except Btu/lb)		Ultimate analyses (12 samples; data in percent)	
Moisture	5.53±4.51	Carbon	61.33±7.74
Ash	13.51±5.32	Hydrogen	4.58±0.49
Volatile matter	31.46±7.91	Nitrogen	1.17±0.16
Fixed carbon	47.24±5.93	Oxygen	13.37±5.78
Btu/lb:		Sulfur	0.75±0.16
As received	11,175±1,787		
Mineral matter			
free	12,983±2,047		

Major oxides (4 samples; data in percent)		Trace elements (4 samples; data in parts per million)	
SiO_2	60.19±6.42	As	8.13±0.25
Al_2O_3	15.78±1.26	Cu	14.04±6.33
Fe_2O_3	2.60±0.29	Hg	0.10±0.05
TiO_2	1.25±0.10	Li	8.52±1.10
CaO	4.41±0.48	Mn	32.73±30.17
MgO	0.88±0.11	Ni	4.38±2.13
K_2O	0.32±0.03	Pb	7.97±3.26
Na_2O	0.65±0.14	Sb	1.60±0.77
		Se	2.81±0.78
		Th	5.10±2.21
		U	2.85±0.96
		Zn	8.49±7.42

Where they are near igneous intrusions, the coals are of coking quality. Read and others (1950) estimated original resources of about 1.6 billion tons. However, the steep dips of many of the coal beds and the numerous faults, dikes, and sills, make mining difficult. Coal beds north of Carrizozo may be favorable for strip mining, but reserve calculations for them are proprietary. Seam thickness, as determined from sparse data, average 2.3 ft, but several lenses near Capitan (Bodine, 1956) are as much as 7 ft.

RIO PUERCO FIELD

The Rio Puerco coalfield is a small outlier of the San Juan basin (fig. E1), lying about 15 miles southeast of the main basin. Interstate 40 crosses the southern tip of the field, along the lower part of Rio Puerco drainage.

The coal-bearing units are within the Rio Puerco fault zone occur in narrow, steeply dipping fault blocks outlined by a north-northeast-trending swarm of high-angle faults on the border between the Rio Grande rift and the San Juan basin.

Outcropping coal beds are in the Dilco and Gibson Coal Members of the Crevasse Canyon Formation. The Dilco coal beds are thin; those in the Gibson Member appear to average 2.5 ft in thickness, although seams as thick as 9.6 ft have been mined for local use in the northern part of the field (Shomaker and others, 1971). The coal beds

appear to range from subbituminous A to high-volatile C bituminous in rank, based on analyses of three as-received samples:

Proximate analyses (3 samples; data in percent, except Btu/lb)		Ultimate analyses (2 samples; data in percent)	
Moisture	16.27±5.84	Carbon	55.05±0.85
Ash	8.60±1.64	Hydrogen	6.15±0.35
Volatile matter	34.67±2.62	Nitrogen	1.00±0.00
Fixed Carbon	40.47±1.82	Oxygen	29.00±1.60
Btu/lb:		Sulfur	0.93±0.41
As received	9,473±195		
Mineral matter			
free	10,452±208		

All data on bed characteristics and coal quality for the Rio Puerco field are based on outcrop data, as no drilling data are available. The total reserves for the northern part of this field, within 250 ft of the surface, are estimated at 185 million tons. Resources (0–250 ft) for the southern part of the Rio Puerco field are estimated at 175 million tons. Because of the paucity of data for these coal beds, the steep dip of the beds, and the abundance of high-angle faults within them, the coal resource potential in this field is considered to be low. Information that could be gained by drilling would help to clarify the true coal potential and the extent of the coal-bearing formation.

TIERRA AMARILLA FIELD

The Tierra Amarilla coalfield in north-central New Mexico, in the southeast corner of the Tierra Amarilla Land Grant and in the eastern part of the Chama basin, is an outlier of the San Juan basin, about 12 miles east of the eastern margin. U.S. Highway 84 skirts the east edge of the field.

The coal beds, in the Menefee Formation of the Mesaverde Group, are thin and lenticular; the maximum coal seam thickness is 4.1 ft. Two analyses indicate the coals are subbituminous A in rank and give these averages:

Proximate analyses (2 samples; data in percent, except Btu/lb)		Ultimate analyses (1 sample; data in percent)	
Moisture	18.70±0.80	Carbon	57.20±0.00
Ash	8.50±0.80	Hydrogen	6.10±0.00
Volatile matter	32.60±0.50	Nitrogen	1.30±0.00
Fixed Carbon	40.20±1.10	Oxygen	26.70±0.00
Btu/lb:		Sulfur	1.05±0.05
As received	9,875±235		
Mineral matter			
free	10,883±156		

Landis and Dane (1969) estimated the total resources to be 4.5 million tons of inferred coal in the Tierra Amarilla field.

CERRILLOS FIELD

The Cerrillos field is in north-central New Mexico, in the broken foothill country north of the Ortiz Mountains and south of the broad valley of Rio Galisteo; it is traversed by the main line of the Atchison, Topeka, and Santa Fe Railway. New Mexico Highway 14 crosses the field from south to north and serves the main town, Madrid.

The field is a complex syncline in which the coal-bearing rocks have been broken by many faults and have been intruded by swarms of dikes and sills. Near the thick igneous intrusions the coals have been metamorphosed to semianthracite and anthracite.

The coal-bearing strata are in the Mesaverde Formation. The major beds are as much as 6 ft in thickness and have yielded considerable tonnages of anthracite and bituminous coals. Some of the bituminous lenses are of medium coking coal. Anthracite is restricted to the parts of the White Ash seam that are near the intrusive rocks and to a thinner, unnamed seam immediately overlying the intrusive body.

As much as 45,000 tons of anthracite was mined annually from the Cerrillos field during the period 1888 to 1957 and was supplied to users throughout the central and western parts of the nation. Read and others (1950) estimated resources of 47.5 million tons of bituminous coal and 5.7 million tons of anthracite. Analyses of 82 samples as-received gave the following averages:

Proximate analyses (82 samples; data in percent, except Btu/lb)		Ultimate analyses (13 samples; data in percent)	
Moisture.......	3.15±2.13	Carbon	77.69±4.98
Ash	10.26±4.60	Hydrogen......	3.85±1.29
Volatile matter .	21.77±12.88	Nitrogen.......	1.25±0.11
Fixed Carbon ..	65.90±14.37	Oxygen........	7.69±2.55
Btu/lb:		Sulfur	0.97±0.52
As received...	12,913±1,018		
Mineral matter			
free	14,503±864		

CARTHAGE FIELD

The Carthage coalfield lies in central New Mexico on the northwest edge of Jornada del Muerto, an extensive syncline-graben of that semiarid region. U.S. Highway 380 cuts across the northern edge of the field. The area is 8 miles east of San Antonio, which is served by the Atchison, Topeka, and Santa Fe Railway and by Interstate Highway 25.

Two coal seams, ranging from 4 to 7 ft in thickness, occur in the Crevasse Canyon Formation. Only the lower coal, the Carthage seam, has been mined; it is excellent coking coal of high-volatile C bituminous rank.

This small field occupies about 10 mi^2 and is cut into a mosaic of small fault blocks, making mining difficult and expensive. U.S. Army troops stationed at nearby Fort Craig opened mining in this field in 1861, the earliest "large-scale" mining in New Mexico. In the late 1800's and early 1900's, the Carthage field supplied coking coal to many smelters in southwestern New Mexico and northern Mexico, but between 1950 and 1975 only a single small underground mine operated intermittently to provide coal for local heating (Kottlowski and others, 1984).

Most of the easily mined coal has been removed; remaining reserves may be as much as 30 million tons. The averages of 11 analyses on an as-received basis follow:

Proximate analyses (11 samples; data in percent, except Btu/lb)		Ultimate analyses (4 samples; data in percent)	
Moisture.......	3.36±1.30	Carbon	69.38±3.52
Ash	11.55±3.01	Hydrogen......	5.25±0.21
Volatile matter .	36.55±2.64	Nitrogen.......	1.28±0.11
Fixed carbon...	48.68±3.08	Oxygen........	12.50±3.66
Btu/lb:		Sulfur	0.83±0.15
As received...	12,508±560		
Mineral matter			
free	14,405±533		

HAGAN FIELD

The Hagan field lies in north-central New Mexico in a dissected valley drained by Tongue Arroyo northeast of the Sandia Mountains and southwest of Ortiz Mountain.

The coal seams are 3–5 ft thick, occur in the Mesaverde Group, are of high-volatile C bituminous rank, and are cut by numerous faults. Several small underground mines operated near Hagan in the early 1900's and again from 1927 to 1939 (Kelley and Northrop, 1975). The field's remoteness and difficulties of mining caused by the complex geologic structure closed the mining operations. Read and others (1950) estimated resources of 17.3 million tons for this field (then called the Una del Gato field). The averages of 10 analyses on an as-received basis follow:

Proximate analyses (10 samples; data in percent, except Btu/lb)		Ultimate analyses (4 samples; data in percent)	
Moisture.......	10.56±2.14	Carbon	62.30±4.76
Ash	8.26±2.42	Hydrogen......	5.01±1.06
Volatile matter .	38.00±3.90	Nitrogen.......	1.26±0.04
Fixed carbon...	43.20±3.09	Oxygen........	19.00±4.06
Btu/lb:		Sulfur	0.66±0.13
As received...	10,508±1,477		
Mineral matter			
free	11,625±1,653		

TIJERAS FIELD

The Tijeras field is amid the rolling eastern foothills of the Sandia Mountains in north-central New Mexico. The coal-bearing rocks are in the Mesaverde Group and occur in a small down-dropped fault block, the Tijeras graben. The strata are folded into two synclines and an intervening anticline, and they dip steeply (Kelley and Northrop, 1975). Several thin beds of bituminous rank coal crop out, but only a few tons have been mined for minor local use. Read and others (1950) estimated resources of 1.6 million tons. The averages of three as-received analyses follow (proximate analyses; results in percent, except Btu/lb):

Moisture...................	4.20±3.82
Ash.......................	15.83±10.81
Volatile matter............	34.93±2.76
Fixed carbon..............	45.03±7.11
Btu/lb:	
As received..............	11,104±1,997
Mineral matter free........	13,631±2,424

JORNADA DEL MUERTO FIELD

Five to twenty miles east and northeast of the Carthage field, Mesaverde Group coal-bearing rocks underlie the northwest edge of Jornada del Muerto. Windblown sand conceals much of the bedrock, the area is remote, and there has been no appreciable mining. The few known outcrops of coal have maximum thickness of only 3 ft (Tabet, 1979a). However, drilling might delineate additional reserves, as the Cretaceous strata extend for at least 10 miles in a north-south direction. Analyses of three coal samples as received show an average composition similar to that of the Carthage field coals (proximate analyses; results in percent, except Btu/lb):

Moisture...................	2.3±0.64
Ash.......................	16.3±5.80
Volatile matter............	38.2±3.01
Fixed carbon..............	43.1±4.71
Sulfur....................	2.3±0.64
Btu/lb:	
As received..............	11,410±1,353
Mineral matter free........	13,897±700

ENGLE FIELD

The geologic setting of the Engle field is similar to that of the Jornada del Muerto field, although the Engle field is about 50 miles farther south. It lies on the west edge of the Jornada del Muerto syncline on the alluvial fans east of the Caballo Mountains. Prospect pits have opened thin lenses of

coal, and drill holes have penetrated several coal beds in the Mesaverde Group, but the apparent maximum thickness of coal seams is 4 ft. Information from drilling indicates 32 million tons of deep coal (Tabet, 1979b) having an average as-received composition as follows (proximate analyses; results in percent, except Btu/lb):

Moisture...................	6.5±5.50
Ash.......................	20.0±0.15
Volatile matter............	18.9±6.41
Fixed carbon..............	54.7±12.30
Sulfur....................	0.5±0.12
Btu/lb:	
As received..............	9,745±2,080
Mineral matter free........	12,429±2,637

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