Resource Series 5

COAL RESOURCES of the DENVER and CHEYENNE BASINS, COLORADO

by Robert M. Kirkham
and L. R. Ladwig

COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
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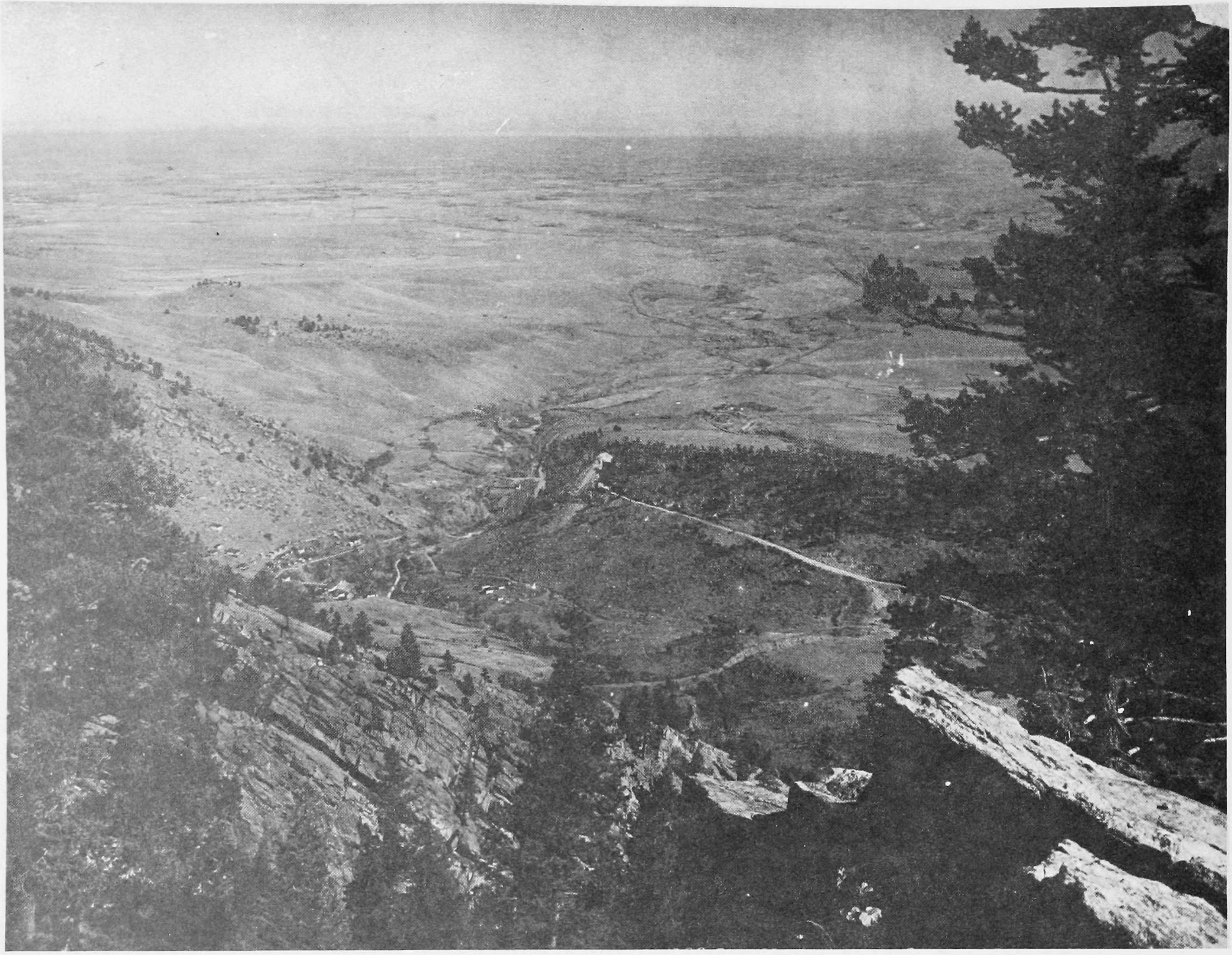

View eastward across the Denver Basin in the early 1900's. South Boulder Creek lies in the middle of the photograph. The town of Marshall is in the upper-right-hand part of the photograph. Coal mining initiated in the study area at Marshall mines in 1863. Coal in this old mining area is presently burning. (Photograph from the Colorado Historical Society).

SUMMARY

The Denver and Cheyenne Basins are one of the major coal- and lignite-bearing regions in Colorado. About 36 percent of the area within Colorado that is underlain by coal at a depth of less than 3,000 ft (900 m) is within these two basins. Subbituminous coal and lignite occur in the Upper Cretaceous Laramie Formation and lignite occurs in the Upper Cretaceous-Paleocene Denver Formation. A total of 130,196,330 tons of coal and lignite have been mined from these two formations in the Denver and Cheyenne Basins. About 20 to 25 billion tons of Laramie Formation coal and 10 to 15 billion tons of Denver Formation lignite remain in place in the study area.

Laramie Formation coal beds occur in a zone 50 to 275-ft (15.0 to 82.5-m) thick within the lower part of the Laramie Formation. The Laramie coal beds were deposited on a delta plain in the poorly drained swamps of overbank areas (Weimer, 1973) and abandoned distributary channels. In general, Laramie coal beds are thicker and somewhat more continuous in the Denver Basin than in the Cheyenne Basin. Individual coal bed thickness is typically 5 to 10 ft (1.5 to 3.0 m) in the Denver Basin, but is only 3 to 5 ft (0.9 to 1.5 m) in the Cheyenne Basin.

About 7,500 mi^2 (19,430 km^2) of the Denver and Cheyenne Basins are underlain by the coal-bearing part of the Laramie. Approximately 1,850 mi^2 (4,800 km^2) of the area are underlain by potentially strippable Laramie coals within 200 ft (60 m) of the surface. Coal beds favorable for in situ gasification may occur at depths of 500 to 1,500 ft (150 to 450 m). Laramie coal beds are found at this depth under approximately 2,040 mi^2 (5,280 km^2) of the area.

Laramie coal quality varies significantly in the study area, ranging from subbituminous B coal to lignite A. Highest quality coals, averaging 8,500 to 10,000 Btu/lb as-received, are in the Boulder-Weld coal field and along the west side of the Denver Basin near the mountain front. Lowest-quality coals, ranging from 6,000 to 7,000 Btu/lb as-received, are on the eastern side of the Denver Basin.

In the Denver Basin thick Early Paleocene lignite beds occur in the upper 300 to 500 ft (90 to 150 m) of the Denver Formation directly below the Dawson Arkose. These lignite beds are not found in the Cheyenne Basin because of the absence of the Denver Formation from this basin. The lignite beds appear to have been deposited in two separate Early Paleocene swamp areas on an alluvial plain just

east of the piedmont complex that extended eastward from the Front Range.

Each of these swamp areas, herein called the northern and southern lignite areas, contain unique sequences of lignite beds, shales, claystones, and sandstones. Lignite beds of the northern lignite area are generally thicker and more continuous than those in the southern lignite area. In the northern lignite area, individual lignite bed thickness is typically 10 to 30 ft (3 to 9 m) and reaches a maximum of 54.5 ft (16.4 m), whereas lignite beds average 5 to 10-ft (1.5 to 3.0-m) thick in the southern lignite area and reach a maximum of about 30-ft (9-m) thick.

Most of the known lignite beds in the eastern part of the Denver Basin are within 200 ft (60 m) of the surface and are strippable. Little is known about the lignite beds in the deeper parts of the basin to the west. Existing data suggest the lignite beds thin, become carbonaceous, and may completely pinch out near the basin axis. This is significant in that it implies lignite beds are thinner and less abundant in areas where the beds are deep enough to be mined underground, either by conventional mining methods or by in situ gasification.

As-received analyses of Denver lignite range from 4,000 to 7,000 Btu/lb, 8 to 30 percent ash, 22 to 40 percent moisture, and 0.2 to 0.6 percent sulfur. Variation in quality is largely dependent on the number and thickness of partings within the bed. Partings may comprise 5 to 30 percent of the total lignite bed thickness. Analyses indicate kaolinite is a primary constituent of the partings. Testing by the U.S. Bureau of Mines has demonstrated that alumina may be extracted from kaolinite. Future mining in areas where thick kaolinite-rich partings are present could involve dual-resource (lignite and alumina) recovery.

INTRODUCTION

PURPOSE AND METHOD OF INVESTIGATION

This report presents a part of the first-year findings from a 2.5-year study of the environmental impacts of energy-resource development in the Denver and Cheyenne Basins, Colorado. The investigation is a cooperative study conducted by the Colorado Geological Survey and funded by the U.S. Geological Survey Grant No. 14-08-0001-G-487.

The primary goal of this investigation is to develop a thorough understanding of the various environmental impacts that may result from energy-resource development in the study area. Another goal is to identify areas underlain by valuable energy-resource deposits, both fossil fuel and uranium, that need to be protected from alternate land uses that may prohibit or inhibit future resource development, as defined in Colorado House Bill 1529 (1973).

A key element in such an impact analysis is a thorough understanding of the distribution, quantity, quality, geologic setting, and development potential of the energy resources. The first year of this study has concentrated only on coal and lignite resources. This report, along with two open-file reports by the Colorado Geological Survey, 78-8 and 78-9, present the results of this phase of the investigation.

The study began by reviewing existing published and open-file reports. These previous investigations are summarized in a later section and are listed in the bibliography. Many reports were very valuable in coal resource evaluation, but most were restricted to specific mining or outcrop areas.

Since outcrops are scarce and of limited extent throughout much of the study area, subsurface information, primarily drill-hole logs, were used to develop a regional understanding of the coal and lignite deposits. Over 1,000 coal exploration drill-hole logs were obtained from industry and used in this investigation. Additional subsurface data were acquired by interpreting geophysical and lithology logs of oil and gas drill holes, water wells, and geotechnical drill holes. The Colorado Oil and Gas Commission and Petroleum Information, Inc. provided geophysical logs of oil and gas drill holes. Geophysical and driller's logs of water wells were obtained from the Colorado

Division of Water Resources. Geophysical and lithology logs of geotechnical drill holes were found in the files of the Colorado Geological Survey and provided by consulting engineering firms.

Summarized versions of part of the logs used in this investigation are available from the Colorado Geological Survey through open-file report 78-8 (see Kirkham, 1978a). This report consists of a map indicating all drill holes for which summarized logs are available. Copies of the summarized logs may be requested by using identification numbers as indicated on this map.

Other valuable sources of data were maps and summary reports obtained from companies actively engaged in exploration for coal and lignite deposits in the study area. Some of the information contained in these studies were used in the preparation of this report.

Records of past coal mining activity were obtained from the Colorado Division of Mines and several published reports. Mine locations, coal-producing formations, coal-bed name, bed thickness, quality, depth, and dip were in part obtained from these sources. All coal mine data and coal analyses compiled during this phase of study are contained in Colorado Geological Survey open-file report 78-9 (see Kirkham, 1978b).

BASIN NOMENCLATURE, LOCATION, AND SIZE

The outline of the Denver and Cheyenne Basins, Colorado, as used in this report, is defined by the outcrop or subcrop of the base of the coal-bearing part of the Upper Cretaceous Laramie Formation (Fig. 1). The outline of the two basins is similar to the Denver coal region described by Landis (1959). The base of the coal-bearing part of the Laramie Formation generally coincides with the base of the Laramie Formation or the top of the Laramie-Fox Hills aquifer of Romero (1976). A basin outline drawn on the base of the Laramie or the Laramie-Fox Hills aquifer would generally agree with the Denver and Cheyenne Basins as defined in this report.

The Denver and Cheyenne Basins, as described in this report, are within the plains of eastern Colorado, adjacent to the Front Range and Laramie Range. All or part of Adams, Arapahoe, Boulder, Denver, Douglas, Elbert, El Paso, Jefferson, Larimer, Morgan, and Weld Counties are within the two basins (Fig. 1). Many of

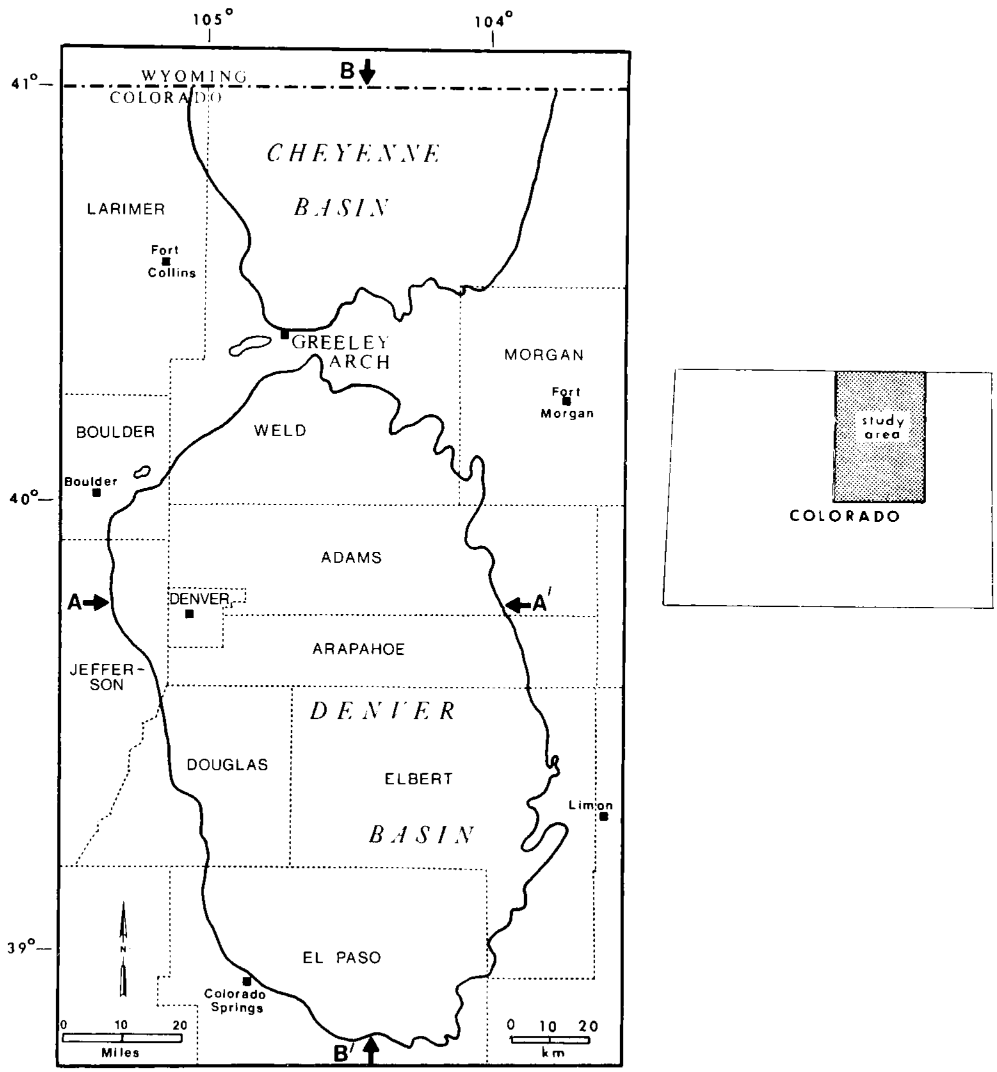

Figure 1. Location map of the Denver and Cheyenne Basins, Colorado.

Colorado's larger cities, including Denver and the Denver metropolitan area, Colorado Springs, Boulder, Greeley, and Fort Collins are in, or adjacent to the study area. Several major highways and railroads service the area.

The general outline of the Denver Basin is roughly oval with its long axis trending north-south. It extends eastward from the Front Range to near Limon and northward from Colorado Springs to just south of Greeley. The Denver Basin covers approximately 5,700 mi^2 (14,760 km^2) of the plains. Only the southern part of the Cheyenne Basin is within Colorado. The Colorado part of the Cheyenne Basin extends southward from the Colorado-Wyoming state line to Greeley and eastward from near Wellington to Buckingham. It encompasses approximately 1,800 mi^2 (4,662 km^2) of the northeastern Colorado plains.

PREVIOUS INVESTIGATIONS

Numerous previous investigations, valuable for coal resource evaluation in the study area, are published or available in open-file form. Due to the number of previous reports, only part of them will be discussed in this section.

Coal was first described in the study area by Hayden (1868) in his paper on the lignite deposits of the west. Hayden visited the Marshall mines which worked Laramie Formation coal beds in the Boulder-Weld field and was impressed with potential uses of the coal. Hayden stated "The next point visited was South Boulder Creek, the Marshall mines, which are probably the most valuable in the west." He goes on to describe potential use of western coal by the railroads and in Nebraska, where fuel was very scarce. Hayden also mentioned that coal from the Marshall mines sold for $12-16 per ton in Denver, not unlike modern prices.

Marvine (1874) described Laramie Formation coal beds and coal mines in the Foothills district and Boulder-Weld field. Apparently several mines were in operation by 1874. Marvine also mentioned that coal was first discovered along what is now called Coal Creek in sec. 20, T.4S., R.65W., but he mistakenly correlated this outcrop of Denver Formation lignite with Laramie coals mined to the west.

G. H. Eldridge (Emmons, Cross, and Eldridge, 1896) discussed in detail the coal geology and mining history of Laramie coals in the Denver Basin. Eldridge also described the Scranton mines which operated northwest of Watkins. He incorrectly correlated the Denver lignite beds worked at the Scranton mines with the "upper shaly division of the Laramie Formation."

Martin (1910) presented coal analyses from the Boulder-Weld field, Foothills district, and Wellington area. Goldman (1910) discussed coal in the Colorado Springs field and included descriptions of Laramie coal stratigraphy, distribution, mining, and coal quality.

Richardson (1917) traced lignite beds in the Denver Formation at Fondis and Calhan to near the Scranton mines. This field evidence, combined with fossil data and one poorly logged drill hole, convinced Richardson that the lignite beds mined at Scranton were in the Denver Formation, not the Laramie Formation.

Dane and Pierce (1936) mapped all post-Fox Hills Sandstone formations in the eastern part of the Denver Basin as either the Dawson Arkose and Laramie Formation. A small-scale reconnaissance map by Dane and Pierce shows coal and lignite bed outcrops and mines. They included the Denver Formation lignite zone in what they termed the "lower-division of the Dawson."

Reichert (1956) studied the post-Laramie rocks in the Denver Basin. His work indicated the Arapahoe and Denver Formations were mappable throughout the basin and that these units should replace the "lower Dawson" of Dane and Pierce (1936). Reichert included the lignite beds exposed near Calhan in the Paleocene part of the Denver Formation.

Landis (1959) studied the coal resources of all of Colorado, including the Denver and Cheyenne Basins. Landis termed the coal-bearing parts of the Denver and Cheyenne Basins the "Denver coal region." This terminology is still commonly used. He summarized the mining history, coal quality, and estimated original coal reserves in the various coal mining areas within the study area.

Lowrie (1966) analyzed the coal industry in the Boulder-Weld field. He named and described seven mineable coal beds in this area. Isopach maps of individual beds and descriptions of areas favorable for future development are included in his report.

Soister (1968a, 1968b, 1972, 1974, 1978a, 1978b) thoroughly studied Denver Formation lignite beds and Uppermost Cretaceous and Tertiary stratigraphy in these six reports. He described in detail the stratigraphy, structure, nomenclature, distribution, and quality of both Denver lignite and Laramie coal based on fieldwork and interpretation of hundreds of drill-hole logs. The work by Soister contributed significantly to this investigation.

Weimer (1973, 1976, 1977) studied Laramie coal beds in outcrops and drill holes along the northwestern margin of the Denver Basin. His concepts on Upper Cretaceous stratigraphy and depositional environments aided evaluation of Laramie coal beds throughout the study area.

Many other investigations were used in the preparation of this report. They include, but are not limited to, Amuedo and Ivey (1975), Braddock and Cole (1978), Bryant and others (1978), George and others (1937), Hodge (1872), Kirkham (1978a, 1978b, 1978c), Kirkham and Ladwig (1977), Kirkham and Rogers (1978), Myers and others (1978), Romero (1976), Romero and Hampton (1972), Sanchez (1976), Scott (1962, 1963, 1972, 1978), Scott and Wobus (1973), Scott and others (1976), Soister (1965), Soister and Tscudy (1978), Spencer (1961), Trimble (1975), Tweto (1976), U.S. Bureau of Mines (1973), and Van Horn (1972, 1976).

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GENERAL GEOLOGY

REGIONAL GEOLOGY AND GEOGRAPHY

The entire study area covers about 11,900 mi^2 (30,840 km^2) of northeastern Colorado. It lies just east of the Southern Rocky Mountain province and is within the Great Plains province of the Interior Plains (Fenneman, 1931). Hammond (1964) places most of the study area within the Rocky Mountain Piedmont province of his Interior Division. Areas underlain by the Ogallala Formation in the Cheyenne Basin near the Colorado - Wyoming line are in the High Plains province of Hammond.

Two classes of land forms are found in the study area (U.S. Geol. Survey, 1970). The northern part is classified as irregular plains with 50 to 80 percent of the areas gently sloping. About 50 to 70 percent of the gentle slopes are in lowlands and the average local relief is about 100 to 300 ft (30 to 90 m). The southern area is described as tablelands with moderate relief. 50 to 80 percent of the land in this area is gently sloping with 50 to 70 percent of the gentle slopes in upland areas. Local relief averages 300 to 500 ft (90 to 150 m).

The mountainous Southern Rocky Mountain province abruptly rises west of the study area. Figure 2 shows the major topographic features and tectonic units of this province and adjacent basins. It is an area of extremely complex geology and topography. The Southern Rocky Mountain province has experienced three major periods of mountain building since the Precambrian. The "Ancestral Rockies" were formed during the Pennsylvanian and later lowered by erosion. New mountains developed during the Late Cretaceous to early Tertiary Laramide orogeny. These mountains were eroded and beveled to the general elevation of adjoining basins during the late Eocene. The present Rocky Mountains began to form during the Miocene and have continued to develop tectonically to the present (Kirkham and Rogers, 1978).

During this same time interval (Cambrian to Holocene) sediments were eroded from the mountains to the west and in part deposited in the study area. Evidence of the extensive mountain-building episodes is expressed in the sedimentary rocks found in the study area. This evidence will be discussed in a later section on stratigraphy.

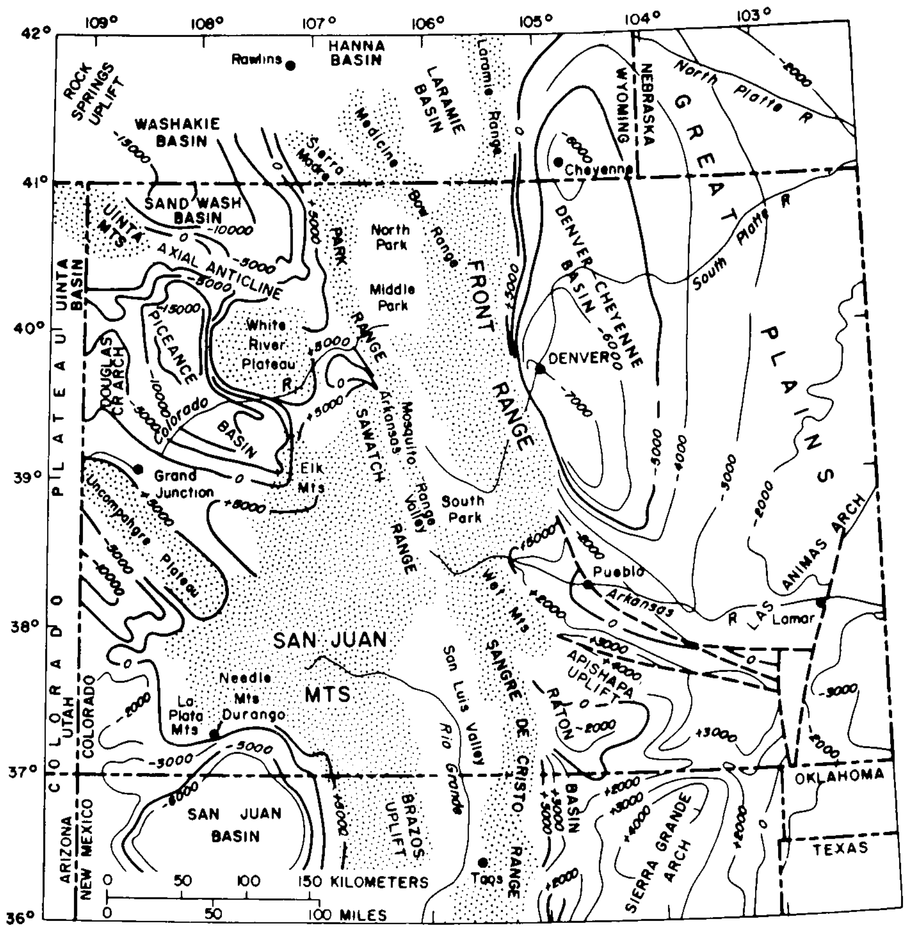


Figure 2. Principal topographic features and tectonic units in the Southern Rocky Mountain province and adjacent basins. Selected contours (in feet) showing elevation of the top of the Precambrian surface. (after Tweto, 1975)

STRUCTURE

Northeastern Colorado and adjacent parts of Wyoming and Nebraska are underlain by a large, regional basin called the Denver-Cheyenne Basin in this report. This basin is also known as the Denver, D-J, and Denver-Julesburg Basin, but the name Denver-Cheyenne is preferred for reasons indicated later in this report. The study area is entirely within this large Denver-Cheyenne Basin.

A structure contour map of the Denver-Cheyenne Basin is shown in Fig. 3. The basin is a doubly plunging syncline with its long axis nearly north-south. It is bounded on the west by the Front Range, Laramie Range, and Wet Mountains, on the east by a gentle, unnamed arch near the Colorado-Kansas border, and on the south by the Apishapa Uplift. The Las Animas Arch forms the southeastern border, the Chadron Arch bounds the northeastern flank, and the Hartville Uplift establishes the northwestern extent of the basin. Elevation differences on the top of the Precambrian surface in the deepest parts of the basin and in the mountains to the west indicate as much as 21,000 ft (6,300 m) of structural relief.

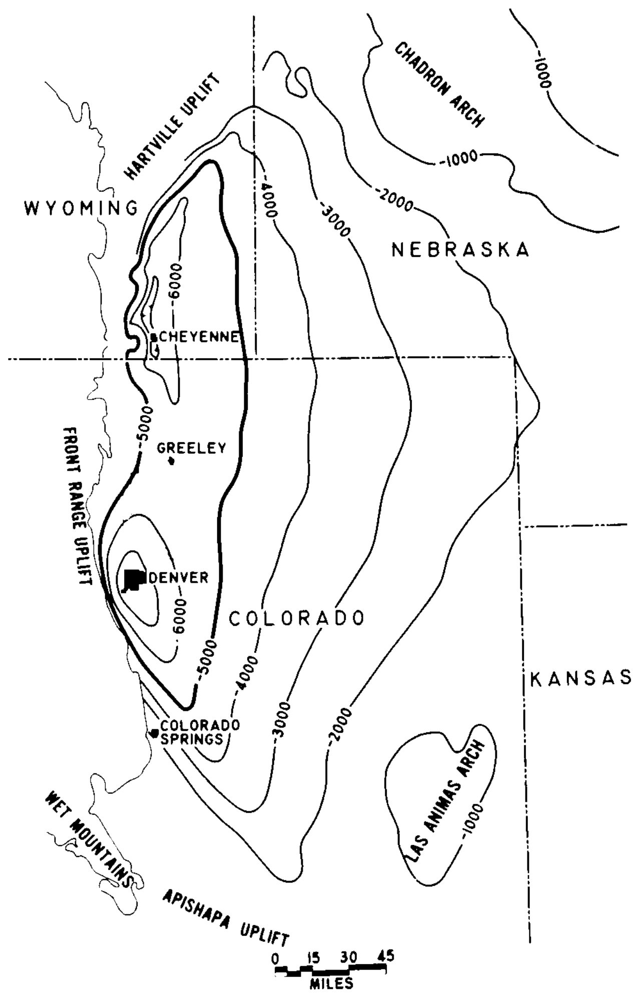


Figure 3. Structure contour map (in feet) on the top of the Precambrian surface in the Denver-Cheyenne Basin. (after Matuszczak, 1973)

The Denver-Cheyenne Basin can be subdivided into two smaller basins based on the outcrop or subcrop of the base of the Laramie Formation coal zone. For this report these two basins, as outlined in Fig. 1, are called the Denver Basin and Cheyenne Basin. The two basins are distinct, doubly plunging synclines within the larger Denver-Cheyenne Basin and are separated by a structural high near Greeley, herein called the Greeley Arch (Fig. 1).

Further justification for subdividing the large basin into the Denver and Cheyenne Basins comes from stratigraphic differences in the two areas. Many of the Paleozoic and Mesozoic formations mappable throughout much of Wyoming extend to near the Greeley Arch, but are not found south of it. Weimer (1978) describes appreciable thinning of the Niobrara Formation and other Cretaceous Formations over the arch. An 1,800 to 4,700-ft (540 to 1,410-m) thick section of strata that includes the Arapahoe Formation, Denver Formation, Dawson Arkose, and Castle Rock Conglomerate occurs in the Denver Basin, but is not found north of the Greeley Arch.

Both the Denver and Cheyenne Basins are oval-shaped with their long axis approximately north-south. The deepest part of the Denver Basin is southeast of Denver near Cherry Creek Reservoir and the deepest part of the Cheyenne Basin is near Cheyenne, Wyoming. Top of the Precambrian in the deepest part of both basins is at 6,000 to 7,000 ft (1,800 to 2,100 m) below sea level.

Figure 4 is a generalized north-south cross section through the Denver Basin and that part of the Cheyenne Basin within Colorado. The Denver Basin is nearly symmetrical in this view. The Greeley Arch is the structural high between the two basins. Only the southern flank of the Cheyenne Basin, where beds dip north, is seen in this cross section.

The overall structure of the two basins is similar, but structural details are quite different. The western margin of the Denver Basin lies at the base of the Front Range. It generally coincides with the structural zone along which the Front Range has been uplifted. This structural zone is a complex zone of basement-controlled, moderate- to high-angle reverse faults and locally overturned monoclines. Most workers believe the monoclines become faults at depth and that the entire structural zone is a single, complex fault zone at depth. The west-flanking structural zone is only 2 to 4-mi (3.2 to 6.4-km) wide. In this zone individual beds dip steeply eastward and locally are vertical or overturned.

Within 1 to 2 mi (1.6 to 3.2 km) east of the steeply dipping outcrop, beds are gently eastward dipping.

A generalized east-west cross section through the Denver Basin at about the latitude of Golden is shown in Fig. 5. Only the uppermost formations, those of greatest interest to this report, are shown in the cross section. The Golden fault dominates the west-flanking structural zone at this location. Approximately 9,000 ft (2,680 m) of vertical movement has occurred on the Golden fault since the Upper Cretaceous (Van Horn, 1976). Sediments on the west side of the fault dip about 30° to 35° east, whereas those directly east of the fault are vertical or overturned. Farther east, the sediments rapidly become less deformed and dip gently toward the basin axis. East of the basin axis, the sediments gently dip westward.

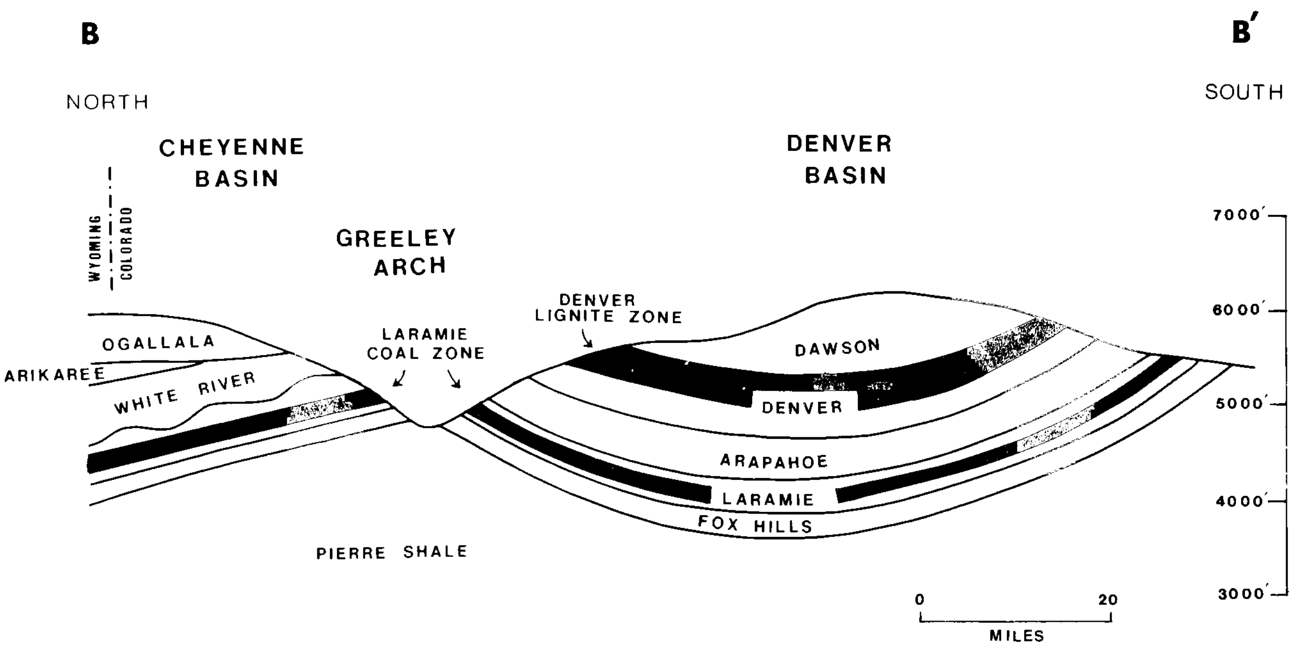


Figure 4. Generalized north-south cross section through the Denver Basin and the south flank of the Cheyenne Basin. See Figure 1 for location of cross section.

On the southern, eastern, and northern margins of the Denver Basin, the beds all dip gently towards the basin center. North of Colorado Springs, along the mountain front and within the west-flank structural zone, the rocks dip 40° to 45° east. The basin margin swings abruptly eastward in this region and near the Colorado Springs area, the beds dip only 1/2° to 3° toward the basin center. The amount of dip seen here is typical of that on the southern, eastern, and northern basin margins.

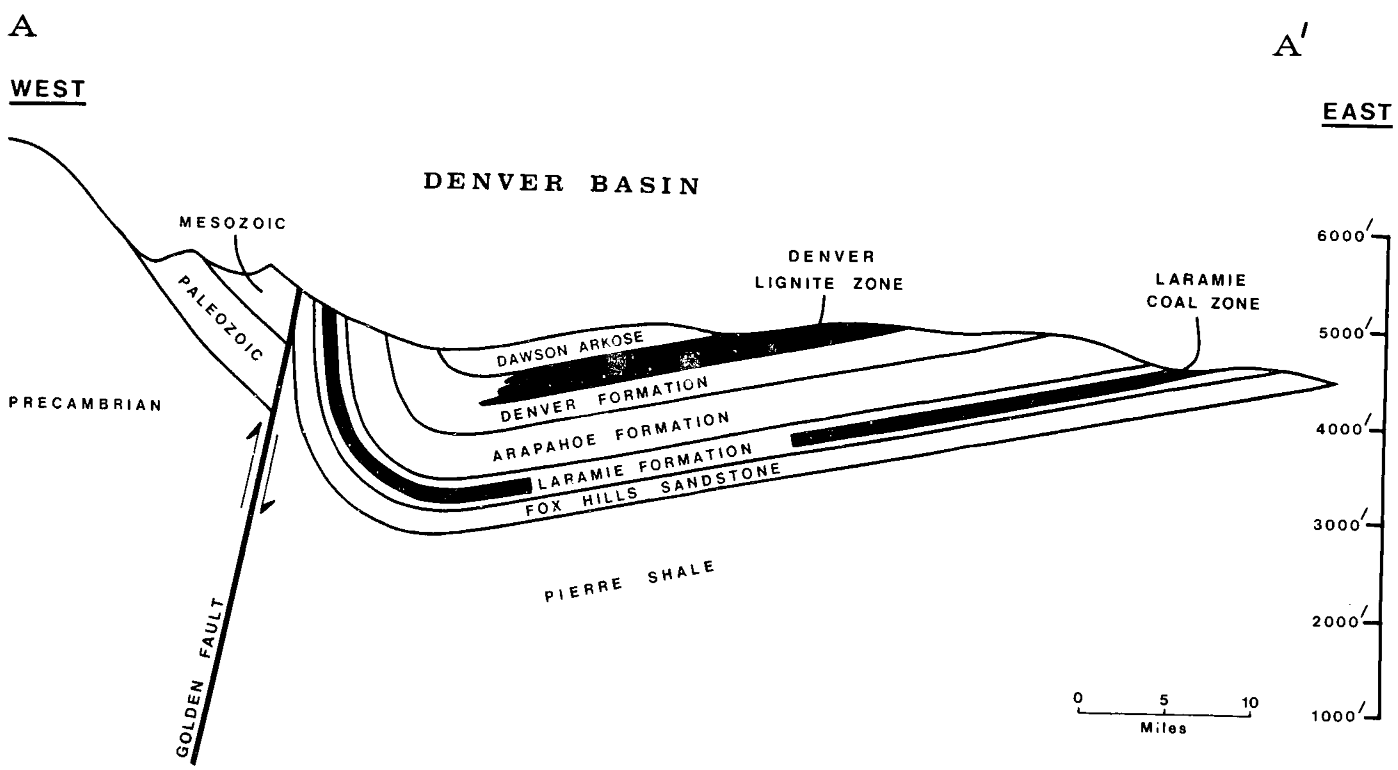


Figure 5. Generalized east-west cross section through the Denver Basin. See Figure 1 for location of cross section.

The northwestern part of the Denver Basin is the only area, besides the western margin, where the basin-margin structure is complex. Structure along the northwestern basin margin is dominated by a series of northeast-trending horst and graben blocks bounded by high-angle normal faults and growth faults (Colton and Lowrie, 1973; Weimer, 1976, 1977; Davis and Weimer, 1976). Up to 300 ft (90 m) of fault displacement is recognized on individual faults. Some of the faults are basement-controlled whereas others are listric faults which appear to die out in the Pierre Shale (Davis and Weimer, 1976). Fig. 6 illustrates these structural relationships.

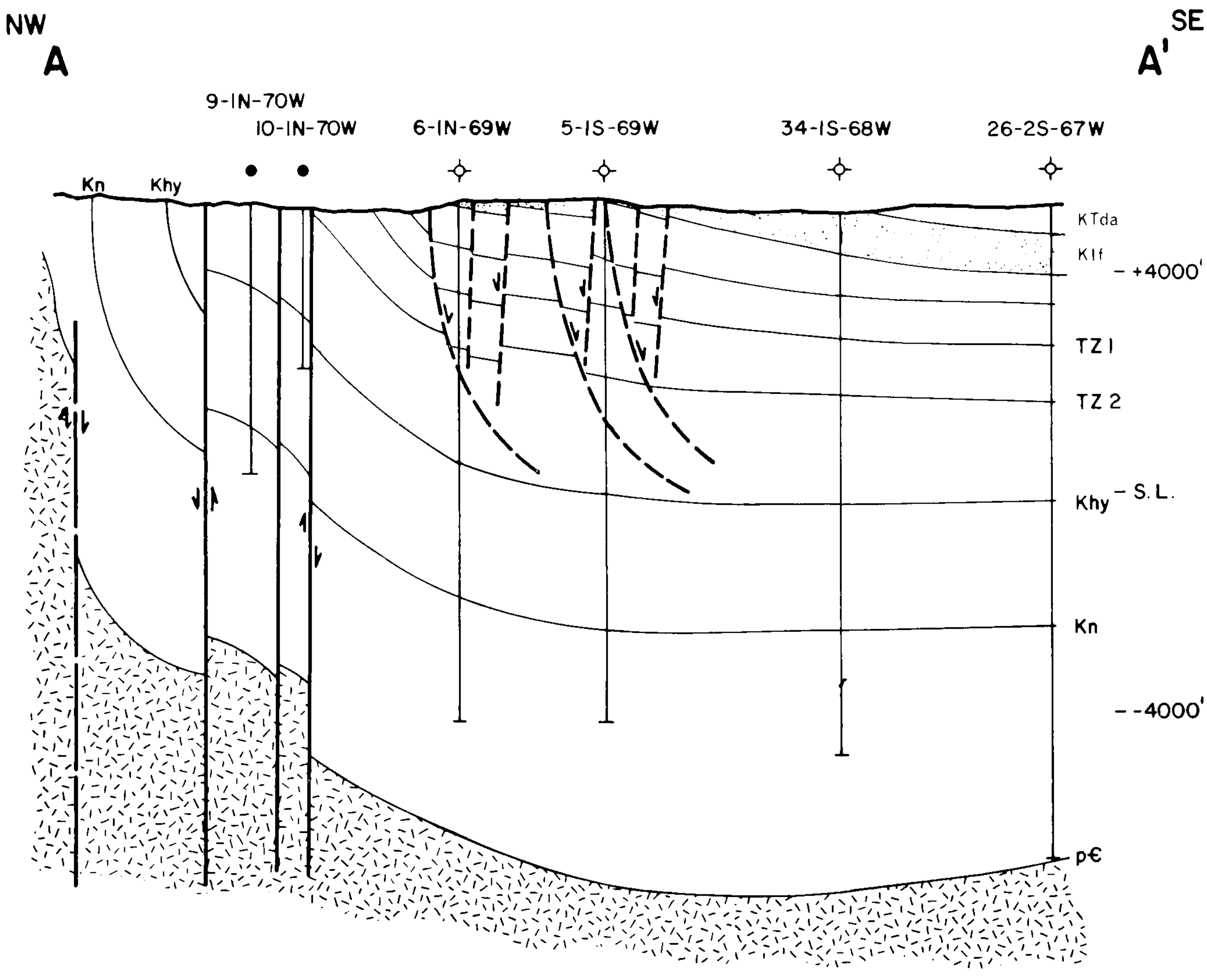


Figure 6. Structure section through the Boulder-Weld field showing high-angle normal and listric faults. (from Davis and Weimer, 1976)

The Greeley Arch separates the Denver Basin from the Cheyenne Basin. The arch roughly trends east-west, but no detailed information on its structural configuration is available. Driller's logs of water wells reveal that Quaternary sand and gravel overlie Pierre Shale over the central part of the arch. This indicates the Laramie Formation, its included coal zone, and locally, the Fox Hills Sandstone have been eroded from the arch. This stratigraphic evidence suggests about 1,000 ft (300 m) of structural relief on the Greeley Arch relative to the adjacent basins since the Late Cretaceous.

The western margin of the Cheyenne Basin, unlike that of the Denver Basin, is not highly faulted and folded. In most areas beds along the western margin dip 5° to 15° east or northeast toward the basin center. Only in a few areas, such as those mapped by Braddock and Cole (1978) in Larimer County, are there faults which affect the western margin of the Cheyenne Basin.

The eastern flank of the Cheyenne Basin can only be approximately located. The Laramie Formation coal zone, upon which the basin outline is drawn, does not outcrop along the eastern basin margin. The subcrop of the coal zone must be approximated from a limited number of drill holes. An angular unconformity truncates the Laramie Formation and Oligocene and Miocene rocks overlie the erosional pinch-out.

Small-amplitude folds and small-displacement faults locally disrupt the regional dip in both basins. These structures usually have no surface expression. The structures are recognizable in drill hole and geophysical survey records, and occasionally in outcrops. A few small, high-angle normal and reverse faults may be observed in outcrops along Station Gulch in Elbert County.

BEDROCK STRATIGRAPHY

In their deepest parts the Denver and Cheyenne Basins are underlain by up to 14,000 ft (420 m) of consolidated and unconsolidated sedimentary rocks. These rocks range in age from Cambrian to Holocene and are underlain by Precambrian igneous and metamorphic rocks. Only the consolidated sedimentary rocks are of interest to this investigation.

Lower Paleozoic Rocks

Lower Paleozoic rocks are restricted to a relatively small area in the Denver Basin near Colorado Springs. Because of their limited distribution, they will not be discussed in detail. The Upper Cambrian Sawatch Sandstone is the oldest sedimentary formation in the study area. It is overlain, in ascending order, by the Upper Cambrian Peerless Dolomite, Lower Ordovician Manitou Limestone, Middle Ordovician Harding Sandstone, Mississippian Williams Canyon Limestone, and Mississippian Leadville Limestone. Thickness of the entire lower Paleozoic section ranges from about 200 to 450 ft (60 to 124 m). No coal of economic significance is known to occur in these rocks.

Pennsylvanian, Permian, Triassic, and Jurassic Rocks

The Permian and Pennsylvanian Fountain Formation overlies the lower Paleozoic rocks in the Colorado Springs area. To the north, near Denver and in the Cheyenne Basin, it unconformably rests on Precambrian rocks. The Fountain Formation consists primarily of reddish-brown arkosic conglomerate, yellowish-gray arkosic sandstone, and thin layers of light green and reddish-brown shale. The Fountain Formation was deposited in a bajada complex adjacent to the "Ancestral Rockies" (Mallory, 1972), an actively rising complex of mountains west of the study area. The formation is 800 to 4,400-ft (240 to 1,320-m) thick with the thickest accumulations occurring in the Colorado Springs area. The lower 100 ft (30 m) of the basal part of the Fountain Formation includes the Glen Eyrie shale member.

Good outcrops of the Fountain Formation are exposed at the Garden of the Gods, Perry Park, Roxborough Park, Red Rocks Park, and the Flatirons near Boulder. In these areas, the Fountain Formation dips from about 40° east to near vertical or overturned, creating spectacular scenery.

Braddock and Cole (1978) indicate the Lower Permian Ingleside Formation overlies the Fountain Formation in the western part of the Cheyenne Basin. The Ingleside Formation consists of gray-white sandstone and crinoidal limestone beds 100 to 130-ft (30 to 42-m) thick.

The Permian Lyons Sandstone overlies the Fountain Formation in the Denver Basin. The formation is a reddish, fine- to medium-grained, quartzose sandstone with local conglomerate, siltstone, and mudstone (Romero, 1976; Braddock and Cole, 1978; Bryant and others, 1978). Depositional environment of the Lyons Sandstone apparently varies. Walker and Harms (1972) demonstrate an eolian origin for the flagstone beds in Boulder County. Weimer and Land (1972) believe the Lyons was deposited in a fluvial environment in Jefferson County. Thickness of the Lyons Sandstone ranges from 30 ft (9 m) near Golden to 800 ft (240 m) near Colorado Springs (Romero, 1976; Scott and Wobus, 1973).

The Permo-Triassic Lykins Formation conformably overlies the Lyons Sandstone. The formation predominantly is reddish-maroon, thin-bedded shale and siltstone with minor light-colored sandstone, gypsum, and crinkled limestone beds (Romero, 1976; LeRoy, 1946). LeRoy divides the Lykins into five members in the Golden-Morrison area. They are, in descending order, the Strain Shale, Glennon Limestone, Bergen Shale, Falcon Limestone, and Harriman Shale. Generally, the formation is poorly exposed except in water gaps and road cuts or where the Glennon Limestone forms a small hogback. The Lykins Formation ranges from 180 to 560-ft (54 to 168-m) thick (Bryant and others, 1978; Romero, 1976; Scott and Wobus, 1973).

The Lower Permian Satanka Formation, Upper Permian Forelle Limestone, and Upper Triassic Jelm Formation are mappped in the Cheyenne Basin (Braddock and Cole, 1978), but not in the Denver Basin. The Santaka Formation consists of red-brown marine mudstone, siltstone, and minor sandstone, limestone, and gypsum. It ranges from 100 to 300-ft (30 to 90-m) thick. The Forelle Limestone is a reddish, dolomitic, marine limestone interbedded with thin red mudstone and gypsum (Braddock and Cole, 1978). It is 20-ft (6-m) thick and is found only north of Lyons. The Jelm Formation is a buff-red, cross-bedded, arkosic, continental sandstone which averages 200-ft (60-m) thick.

The Triassic Chugwater Formation overlies the Jelm Formation in the Cheyenne Basin. The formation primarily consists of red sandstone, siltstone, and shale, and locally contains gypsum (Braddock and Cole, 1978). Thickness of the Chugwater ranges from 300 to 800 ft (90 to 240 m).

The Upper and Middle Jurassic Sundance Formation unconformably overlies the Chugwater Formation in the Cheyenne Basin. The Sundance Formation is a buff, eolian sandstone 100 to 200-ft (30 to 60-m) thick (Braddock and Cole, 1978). In the Denver Basin, the Upper Jurassic Ralston Creek Formation overlies the Lykins Formation. The Ralston Creek Formation rests on a regional unconformity and consists of varicolored limestone, claystone, and gypsum interbedded with thin beds of sandstone ranging from 2 to 110-ft (0.6 to 33-m) thick (Romero, 1976; Bryant and others, 1978).

The Upper Jurassic Morrison Formation overlies the Ralston Creek Formation in the Denver Basin and the Sundance Formation in the Cheyenne Basin. It consists of varicolored, continental shale, siltstone, and claystone, interbedded with sandstone, limestone, and conglomerate. Thickness of the Morrison Formation ranges from about 200 ft (60 m) in the Colorado Springs area to about 400 ft (120 m) near Kassler (Romero, 1976). The formation crops out just west of the Dakota hogback, but most outcrops are covered by colluvial, debris flow, sheetwash, and landslide deposits.

Lower Cretaceous Rocks

Evidence of the transgressing Cretaceous seaway is found within Lower Cretaceous rocks in the study area. The Dakota Group, oldest Cretaceous unit in both basins, unconformably overlies the Morrison Formation. This group of formations is a widespread sequence of rocks deposited in beach, delta, and near-shore environments over the continental Morrison Formation.

The lower part of the group is called the Lytle Formation. It consists of 30 to 100 ft (9 to 30 m) of yellowish-gray, fine- to medium-grained, locally conglomeratic sandstone (Bryant and others, 1978; Romero, 1976; Braddock and Cole, 1978). The upper part of the group is known as the South Platte Formation. Interbedded fine- to medium-grained, gray sandstone and dark gray silty shale constitute most of the South Platte Formation (Romero, 1976; Braddock and Cole, 1978; Bryant and others, 1978). Thickness of the formation ranges from 200 to 350 ft (60 to 105 m). In the Colorado Springs area, Scott and Wobus (1973) and Scott and others (1976) divide the Dakota Group into the Dakota Sandstone (upper part) and the Purgatoire Formation (lower part). This practice was not adopted for this report.

Thin, lenticular coal beds occur in the Dakota Group in the study area. In some parts of Colorado, such as the San Juan River Region (Landis, 1959), the Dakota Group contains economic coal deposits, but in the Denver and Cheyenne Basins Dakota coal beds are not of economic importance.

The Dakota Group forms a prominent topographic feature, the Dakota hogback, along the entire mountain front except in areas where it has been cut out by faulting. Generally the South Platte Formation forms the crest and dip slope of the hogback. The Lytle Formation is exposed west of the hogback crest and in road cuts and water gaps.

Upper Cretaceous Rocks

The Upper Cretaceous Colorado Group conformably overlies the Dakota Group throughout the study area. The Colorado Group consists of the Benton Shale (lower part) and Niobrara Formation (upper part). The Benton Shale is 300 to 500-ft (90 to 150-m) thick and composed of dark gray marine shales interbedded with limestone, bentonite, and calcarenite (Romero, 1976; Van Horn, 1976)

Locally, the Benton Shale can be subdivided into three members. The lower part is a dark gray shale called the Graneros Shale member. The Greenhorn Limestone member lies in the middle of the Benton Shale and the Carlile Shale member comprises the upper part of the formation. Recognition of these three members is dependent on the presence of the Greenhorn Limestone member.

The Niobrara Formation constitutes the upper part of the Colorado Group. It consists of 333 to 570 ft (100 to 171 m) of calcareous marine shale and limestone (Romero, 1976; Scott and Wobus, 1973). Usually the Niobrara Formation can be divided into the Fort Hays Limestone member and overlying Smoky Hills Shale member. The Fort Hays Limestone member is 25 to 40-ft (7.5 to 12.0-m) thick and is a gray, hard limestone with thin shale partings. The upper 300 to 530 ft (90 to 159 m) of the Niobrara Formation is the Smoky Hills Shale member, a thin-bedded, fissile, calcareous shale interbedded with thin limestone and marl beds.

The marine Pierre Shale conformably overlies the Colorado Group. It is 3,750 to 7,833-ft (1,125 to 2,350-m) thick (Scott and Wobus, 1973; Braddock and Cole, 1978; Romero, 1976) and is usually subdivided into three or four units. The stratigraphic units within the Pierre are well known locally, but regional correlations cannot be extended throughout the study area. A few thin coal beds occur in the upper transition zone of the Pierre Shale, but they apparently are not of economic significance in the study area.

Figure 7 shows a part of three geophysical logs from petroleum exploration drill holes. The logged interval extends to the upper Pierre Shale transition zone and continues upward through the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, Denver Formation, and Dawson Arkose to the bottom of the surface casing. These logs and indicated stratigraphic boundaries are representative of the hundreds of geophysical drill hole logs used in this investigation.

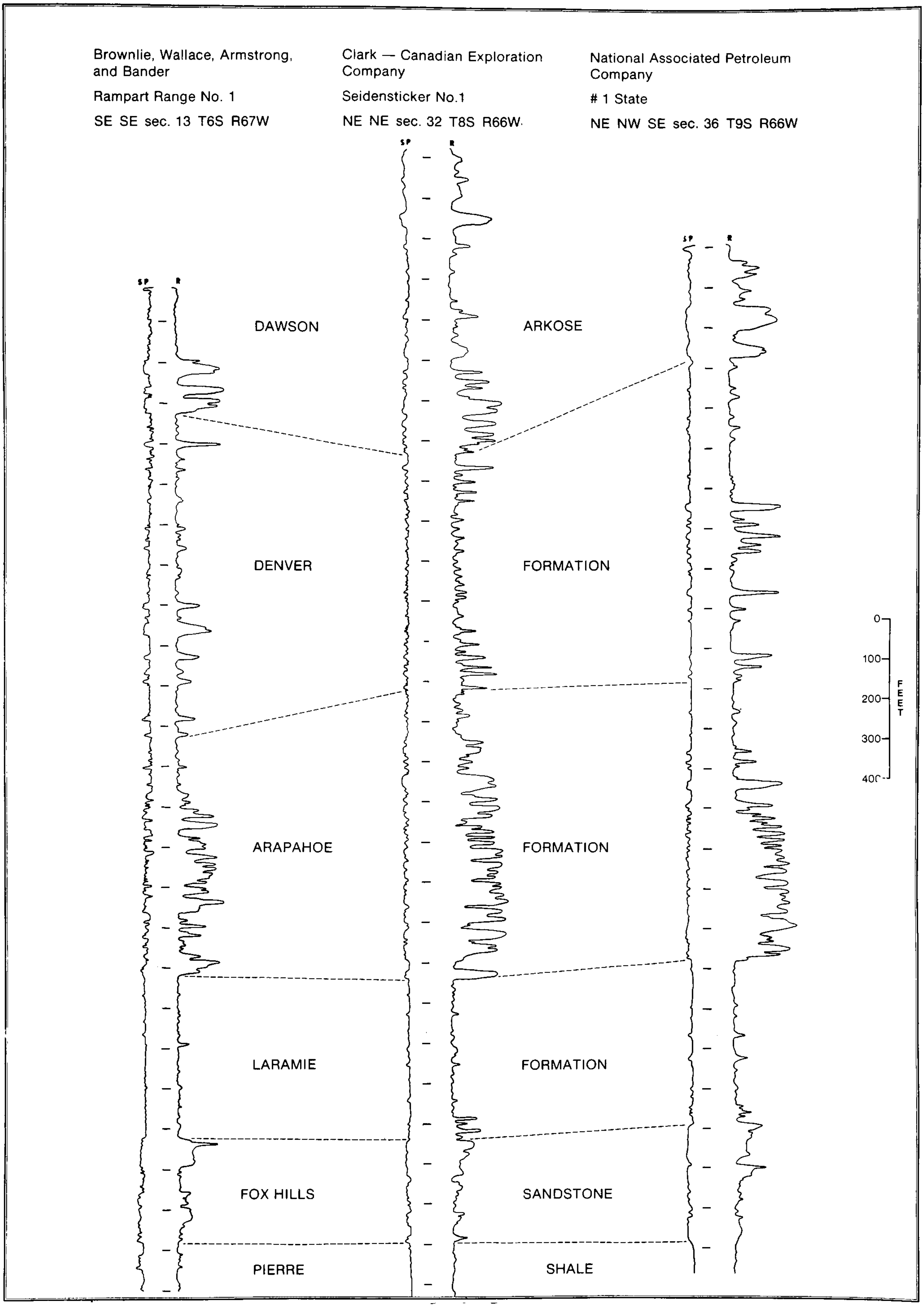


Figure 7. Geophysical logs of oil and gas drill holes that illustrate the geophysical response and stratigraphic boundaries of Uppermost Cretaceous and Lower Tertiary formations in the Denver Basin.

The marine Upper Cretaceous Fox Hills Sandstone conformably overlies the upper transition zone of the Pierre Shale. The contact between the two formations is not always sharply defined and in many areas the contact is transitional. The Fox Hills Sandstone is a sequence of sandy shales interbedded with thin sandstone beds. Near the base of the Fox Hills, shales are common in the unit, whereas thick sandstone beds are prevalent near the top of the unit. Local names, such as the Milliken, Keota, and Buckingham sandstones are often used for the thicker and more continuous sandstone beds. Lenticular, iron-rich concretions are commmon in the upper sandstone beds. Thin coal beds also have been reported within the upper part of the Fox Hills Sandstone (Trimble, 1975; Zawistowski, 1978), but they are not economically significant. Total thickness of the formation ranges from 25 to 400 ft (7.5-120 m).

The non-marine, Upper Cretaceous Laramie Formation gradationally overlies the marine Fox Hills Sandstone. The contact between the two formations near Golden is described as an erosional unconformity by Moody (1947), but most geologists cannot even agree where to precisely place the contact. The Laramie consists of brackish-water and continental sandstones, shales, claystones, and coals. It is one of two formations in the study area that contain economic coal deposits. Most coal in the Laramie Formation is subbituminous in rank, although in certain areas on the eastern flank of the Denver Basin, such as the Buick-Matheson area, it ranks as lignite.

The lower part of the Laramie Formation is 100 to 300-ft (30 to 90-m) thick and is predominantly light, medium-grained sandstone with interbedded thin shale and coal (Soister, 1976; Weimer, 1973). The top of the lower Laramie is defined as the top of the uppermost coal bed in the lower 300 ft (90 m) of the formation. The lower Laramie coal zone is 50 to 275-ft (15.0 to 82.5-m) thick and is entirely within the lower Laramie Formation. In subsurface work the thick sandstones of the lower Laramie Formation are frequently grouped with the Fox Hills Sandstone and together they comprise the Laramie-Fox Hills aquifer (Romero and Hampton, 1972; Romero, 1976), one of the major aquifers in the study area. Figure 7 illustrates the distinctive response of the Laramie-Fox Hills aquifer on geophysical logs.

Some workers map two or three sandstone beds, the A, B, and C sandstones, in the lower Laramie. Our work suggests that this practice is not acceptable for regional applications. Lower Laramie sandstones are very lenticular. For instance, the C sandstone is found only in the Marshall area. Correlation of sandstone beds from outcrop to outcrop or drill hole to drill hole is very difficult and often impossible. Local names may be applied to certain sandstone lenses, but these names should be used only locally and not throughout the entire Denver and Cheyenne Basins.

The upper part of the Laramie Formation is 250 to 600-ft (75 to 180-m) thick and consists primarily of shale, siltstone, claystone, and minor amounts of sandstone. A zone of thin coal beds occurs in upper Laramie over a limited area in the Cheyenne Basin, but none of the beds are economically significant. In general the upper Laramie is thicker and contains more sandstone in the Cheyenne Basin than in the Denver Basin. A complete discussion of Laramie Formation coal stratigraphy is in a subsequent section of this report.

Initiation of the Laramide orogeny and regression of the Cretaceous seas are recorded in the upper Pierre Shale transition zone, Fox Hills Sandstone, and Laramie Formation (Fig. 8). The upper Pierre was deposited in an off-shore, deep-marine environment. As the Laramide mountains began to uplift and the sea regressed, an extensive deltaic system developed. Sediments were eroded from the highlands, transported downstream, and redeposited in delta-front and delta-plain environments. Delta-front sands of the Fox Hills Sandstone were distributed by near-shore currents along the delta front and beach and deposited over the Pierre Shale. Sands, silts, clays, and coals of the Laramie Formation were deposited on the delta-plain in channels, splays, and overbank areas (Fig. 9). These conditions prevailed until continental sedimentation became dominant and the overlying Arapahoe and Denver Formations were deposited.

The post-Laramie Formation history of the Denver and Cheyenne Basins is markedly different and this difference is very significant in evaluation of lignite deposits in the Denver Formation. Figure 10 shows the general stratigraphy of the Denver and Cheyenne Basins. It was prepared to point out differences in post-Laramie stratigraphy in the two basins.

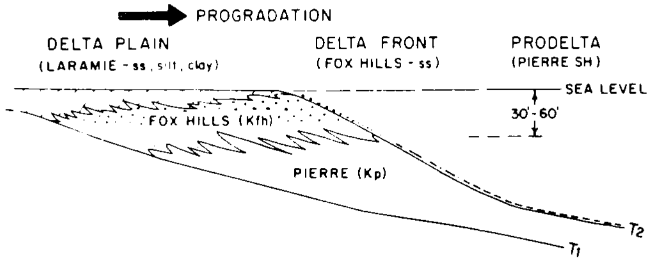


Figure 8. Delta-sedimentation model that relates formations to facies and depositional environments. (from Weimer, 1973)

In the Denver Basin the Arapahoe Formation, Denver Formation, and Dawson Arkose unconformably overlie the Laramie Formation. In the Cheyenne Basin the White River Group, Arikaree Formation, and Ogallala Formation overlie a major angular unconformity which truncates the Laramie Formation. All these formations were deposited in a continental environment. The Arapahoe, Denver, and Dawson are orogenic sediments derived from the Laramide uplifts and deposited in the Denver Basin. These three formations do not exist in the Cheyenne Basin. It is possible that they were never deposited there or that they have been eroded from the basin during the late Eocene, prior to deposition of the White River Group during the Oligocene.

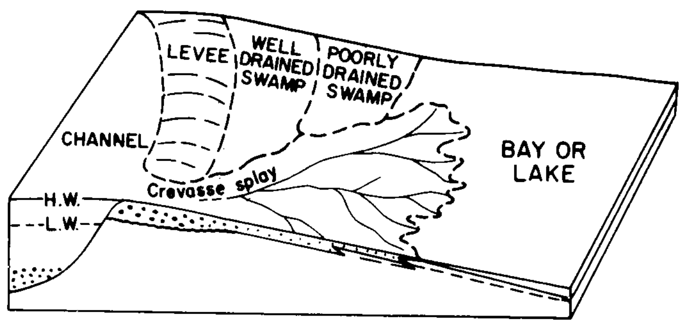


Figure 9. Environments of deposition of the Laramie Formation. (from Weimer, 1973)

PERIOD	DENVER BASIN	CHEYENNE BASIN
QUATERNARY	UNDIFFERENTIATED	UNDIFFERENTIATED
PLIOCENE		
MIOCENE		? ? ? OGALLALA FORMATION
		ARIKAREE FORMATION
OLIGOCENE	CASTLE ROCK CONGLOMERATE	WHITE RIVER GROUP
EOCENE	DAWSON ARKOSE	
PALEOCENE	DENVER FORMATION	
UPPER CRETACEOUS	ARAPAHOE FORMATION	
	LARAMIE FORMATION	LARAMIE FORMATION
	FOX HILLS SANDSTONE	FOX HILLS SANDSTONE
	PIERRE SHALE	PIERRE SHALE
PRECAMBRIAN, PALEOZOIC AND MESOZOIC FORMATIONS, UNDIFFERENTIATED		

Figure 10. Generalized stratigraphy of the Denver and Cheyenne Basins, Colorado.

Renewed uplift and intermediate volcanism in the Southern Rocky Mountains were initiated during the Miocene, and the Arikaree and Ogallala Formations were derived from these uplifted mountains and volcanoes and deposited at this time (Stanley, 1976). These formations are mapped only in the Cheyenne Basin and east of the Denver Basin. It is likely, however, that these formations once extended across the Denver Basin, but have since been removed by erosion. Thick sequences of gravel, similar to Ogallala sediments, have been noted in drill holes and in the field on top of low hills in the easternmost part of the Denver Basin during this investigation. This suggests the Ogallala may have extended across this area at an earlier time.

The Laramie Formation is unconformably overlain by the 200 to 1,000-ft (60 to 300-m) thick Upper Cretaceous Arapahoe Formation. The contact is a scoured erosional surface. A basal conglomerate containing clasts of Precambrian igneous and metamorphic rocks derived from the Front Range overlies the contact. In the eastern part of the area the basal conglomerate is a section of strata 100 to 300-ft (30 to 90-m) thick consisting of quartose and conglomeratic sandstone and claystone. This section of strata is an excellent high-permeability aquifer and generally contains high-quality water. Prominent high resistivity and self-potential responses readily distinguish the lower Arapahoe from the fine-grained upper Laramie (Fig. 7).

Thick beds of dark-gray claystone, shale, and siltstone interbedded with thin sandstones comprise the upper 100 to 700 ft (30 to 210 m) of the Arapahoe Formation. A few drill holes into the upper Arapahoe have encountered thin coal beds (Kirkham, 1978a), but none are of economic interest.

Cenozoic Rocks

The Upper Cretaceous-Paleocene Denver Formation overlies the Arapahoe Formation. The Cretacous-Tertiary boundary lies within the lower part of the Denver Formation (Brown, 1943), but it is not mappable throughout the study area. The boundary can only be established by detailed paleontological work and a color change of questioned value (Van Horn, 1976).

Some workers (Richardson, 1915; Dane and Pierce, 1936; Scott, 1962, 1963; Scott and Wobus, 1973) map the Arapahoe, Denver, and Dawson as one formation, the Dawson Arkose. Other workers (Reichert, 1956; Soister, 1972; Romero, 1976; 1978b;

Soister and Tscudy, 1978) believe the formations can and should be differentiated. Data collected from outcrops and over 1,000 drill holes during this investigation suggest the three formations can be mapped throughout most of the Denver Basin. Only in the southern and southeastern part of the basin is it difficult to establish the Denver-Arapahoe contact.

In general, the Denver Formation consists of about 600 to 1,580 ft (180 to 474 m) of medium-yellow to light-gray claystone, siltstone, and very fine to fine-grained sandstone, and andesitic conglomerate. Several intermediate lava flows are interbedded with upper Denver sediments near Golden. The distinguishing characteristic of the Denver Formation is the presence of andesitic clasts in the conglomerate beds. Emmons and others (1896) define the base of the Denver by the first appearance of eruptive material among the particles derived from the crystalline or older sedimentary rocks. In the eastern part of the basin andesitic material is scarce and the formation boundaries often can only be determined by regional correlation. Thick lignite beds and carbonaceous shales are common in the upper 500 ft (150 m) of the Denver Formation east of the axis of the Denver Basin. The lignite beds are mineable over much of the eastern part of the basin. They will be discussed thoroughly in a later section of this report.

The Denver Formation was deposited in a continental environment. Conglomerate and sandstone beds east of the uplifted mountain front were deposited in a bajada or braided stream complex. East of this depositional complex silts, clays, and lignites were deposited on an alluvial plain in low-gradient streams, overbank areas, and marshes.

The Paleocene-Eocene Dawson Arkose unconformably overlies the Denver Formation. The Dawson Arkose can be subdivided into two mappable members, a lower and upper member (Soister, 1978b). The lower member is a mixed unit, 200 to 400-ft (60 to 120-m) thick, containing both andesitic and arkosic material ranging from claystone to conglomerate. Generally, the base of the member is a 10 to 20-ft (3 to 6-m) thick arkosic conglomerate which is very pronounced in outcrop and on geophysical logs (Fig. 7). Soister (1978b) and Soister and Tscudy (1978) describe thin lignite and carbonaceous shale lenses in the lower member of the Dawson, but they are not economically significant. Pollen samples from the lower member of the Dawson are Late Paleocene in age (Soister and Tscudy, 1978).

An interval of variegated claystone and deeply weathered sandstone and conglomerate caps the lower member. Soister (1978b) believes this horizon is a paleosol which developed during Late Paleocene and Early Eocene time. The paleosol appears to rise in the section westward. In the east part of the basin the paleosol is near the base of the Dawson Arkose. Westward there is over 330 ft (100 m) of lower Dawson below the paleosol. Soister (1978b) suggests the Green Mountain Conglomerate may be equivalent to the lower member of the Dawson west of Denver. Trimble (1978) believes this paleosol may correlate with the Eocene paleosol described by Pettyjohn (1966) in South Dakota, Wyoming, and Nebraska.

Above the paleosol is the 800 to 1,400-ft (240 to 420-m) thick upper member or main body of the Dawson Arkose. It is 70 to 90 percent arkosic sandstone and conglomerate interbedded with 10 to 30 percent sandy claystone (Soister, 1978b). Soister and Tscudy (1978) indicate the upper member is of Eocene age, based primarily on pollen samples and regional correlation. A rhyolitic ash flow tuff, locally called the Douglas Rhyolite, lies near the top of the Dawson Arkose. Some workers indicate the tuff caps the Dawson, while others suggest the tuff is interbedded with uppermost Dawson sediments. Epis and Chapin (1975) correlate this tuff with the Wall Mountain Tuff, which is believed to have erupted in the Mount Princeton area. If this correlation is correct, then the late Eocene erosion surface, on which the tuff flowed, must have been developed by latest Dawson time. This is significant in that the Laramide mountains must have been leveled by erosion by this time.

In the Denver Basin the Oligocene Castle Rock Conglomerate overlies the Wall Mountain Tuff or Douglas Rhyolite. It also overlies the Dawson Arkose when the tuff is absent. Clasts of andesitic material from the Thirtynine Mile volcanic field are contained in the conglomerate. This indicates that paleochannels cut into the late Eocene erosion surface, crossed the Front Range from South Park, and deposited material in the Denver Basin (Epis and Chapin, 1975). The Castle Rock Conglomerate consists of up to 300 ft (90 m) of andesite conglomerate with clasts up to 4 ft (1.2 m) in diameter and arkosic and andesitic coarse sandstones.

In the Cheyenne Basin the section of strata from the Arapahoe Formation through the Castle Rock Conglomerate is absent. The thick lignite beds in the upper part of the Denver Formation are within this missing section of strata and are therefore absent from the Cheyenne Basin.

The fluvial Oligocene White River Group overlies an angular unconformity cut on Laramie Formation, Fox Hills Sandstone, and Pierre Shale in the Cheyenne Basin. The group contains the Upper and Middle Oligocene Brule Formation and Lower

Oligocene Chadron Formation. The Brule is 200 to 500-ft (60 to 150-m) thick and composed predominantly of light-colored, sandy or clayey, ashy siltstone (Scott, 1978). Lenticular channel sandstones or siltstones containing siltstone clasts and granitic gravel occur in the lower part of the formation. Scott (1978) believes this unit is equivalent to the Orella member of the Brule Formation defined by Schultz and Stout (1938).

The Chadron Formation consists of 100 to 250 ft (30 to 75 m) of clayey, blocky, ashy siltstone and montmorillonite clay (Scott, 1978). Channels of silica-cemented sandstone and conglomerate occur scattered throughout the formation and form resistant ledges in outcrops. Fresh-water limestone beds occur in the upper part of the formation. Both the Chadron and Brule Formations contain thick, altered volcanic ash beds derived from intermediate volcanic centers to the west.

The fluvial Lower Miocene Arikaree Formation uncomformably overlies part of the White River Group. In the study area the Arikaree occurs as channel sandstones and conglomerates up to 80-ft (240-m) thick cut into the White River Group. To the east and north the Arikaree becomes more of a blanket-type deposit. The formation was deposited in response to uplift of the Southern Rocky Mountains and to basic volcanism.

The Miocene Ogallala Formation was deposited as a result of continued mountain uplift and volcanic activity. It overlies the Arikaree Formation and White River Group, and where these rocks are not present it overlies the Laramie Formation or older formations. The Ogallala Formation is 50 to 600-ft (45 to 180-m) thick and consists of an upper and lower member. The upper member contains thick deposits of conglomerate and coarse sand, but the identifying characteristics are "mortar beds", calcium carbonate- or opal-cemented sand and silt which form resistant ledges, and a pale-red or pale-orange pisolitic caliche layer or limestone (Scott, 1978). The lower part contains less conglomerate and more volcanic ash.

COAL MINING HISTORY

PAST AND PRESENT MINING ACTIVITY

The earliest records of coal mining in the Denver and Cheyenne Basins come from early published reports by Hayden (1868), Hodge (1872), and Marvine (1874). Hayden discusses the Marshall mines on South Boulder Creek in the Boulder-Weld field and notes that they had been in operation for four or five years at the time he visited them. This indicates the Marshall mines began operating in 1863 or 1864.

Hodge (1872) reported on the coals of the west, all of which he thought were deposited during the Tertiary. Hodge (1872) described quality, stratigraphy, and markets of the coal mined near Golden and along Ralston Creek, and at the Marshall, Wilson, Baker, and Briggs mines.

Marvine (1874) describes numerous active and abandoned mines in the Boulder-Weld field, Foothills district, and an area east of Denver. Marvine (1874) states that the Marshall mines were the first mines to open in the area, starting operations in 1863. Thus, it appears that coal definitely was being mined in the study area at least by 1863. Small unrecorded mines may have operated a few years before 1863, but production probably was very limited.

In 1883 the Colorado State coal mine inspector began keeping the only extensive, state-wide record of coal-mining activity. These unpublished records are held by the Colorado Division of Mines, Department of Natural Resources, at 1313 Sherman Street, Denver, and are referred to as Colo. Div. Mines (1978a) in this report.

Over a dozen mines in the study area were operating in 1883 when the State coal mine inspector began keeping records. A dramatic increase in the number of mines and total yearly production occurred from 1883 into the 1920's. Production and mining activity slowed in the late 1920's and early 1930's and has continued to decrease ever since. There is currently one active mine in the study area, the Lincoln mine, located in the Boulder-Weld field. The Eagle mine, also in the Boulder-Weld field, had been working intermittently through 1976. It was inactive from 1976 until October, 1978 when the mine caught fire and had to be abandoned (Rocky Mtn. News, 1978).

There are indications that this downward trend may be reversed in the near future. Two applications for small surface mines in Laramie coal beds were received in 1978 by the Colorado Mined Land Reclamation Board. Large surface mines near Watkins and Station Creek have been proposed to supply Denver Formation lignite to surface gasification plants. Until specially designed power plants and gasification facilities are constructed, most Denver lignite and Laramie coal will be used for commercial and domestic needs.

The majority of mines in the study area (over 96 percent) are underground mines that utilized adit, slope, or shaft entries (Kirkham, 1978b). A few surface mines have operated in the study area. They include the Erie and York strip mines in the Boulder-Weld field, the Barker, Cox, Jordan, Stimson, and Wright strip mines in the Buick-Matheson area, and three very small strip mines in central Arapahoe County (Holt, in prep.; Colo. Div. Mines, 1978a; Kirkham, 1978b).

PAST PRODUCTION

A total of 130,196,330 tons of coal and lignite have been produced from the Denver and Laramie Formations, Denver and Cheyenne Basins, Colorado since 1883 (Colo. Div. Mines, 1978b; Deborski, 1978). Production from 1863 to 1883 is not accurately known and therefore not included in the total production figures. Probably no more than 30,000 to 40,000 tons of coal were mined during this period.

Of the total recorded production 130,129,356 tons (99.95 percent) were mined in the Denver Basin and only 66,974 tons (0.05 percent) were mined in the Cheyenne Basin. Only 39,376 tons (0.03 percent) of the total recorded production were from the Denver Formation, whereas 130,156,954 tons (99.97 percent) were from the Laramie Formation. 129,941,807 tons (99.80 percent) of the production were from underground mines and 254,523 tons (0.20 percent) were produced from surface mines. Table 1 lists the cumulative coal production for the entire study area by county as of September 30, 1978.

Table 1. Cumulative coal production by county through September 1978, in the Denver and Cheyenne Basins, Colorado. (from Colo. Div. Mines, 1978a, 1978b; Deborski, 1978; Kirkham, 1978b; and Boreck, 1979)

COUNTY	PRODUCTION (short tons)
Adams	37,112
Arapahoe	470
Boulder	41,327,996
Denver	-0-
Douglas	25,667
Elbert	108,948
El Paso	16,164,310
Jefferson	6,622,522
Larimer	54,611
Morgan	-0-
Weld	65,854,664
TOTAL	130,196,330

MINING AREAS

This section briefly summarizes mining activity in the various coal mining areas designated by Landis (1959). Information is also included on isolated mines and mining areas not described by Landis. Figure 11 shows the general outline of mining areas described by Landis. If the reader desires detailed information on individual mine locations, production years, total production, coal-bed name, thickness and depth, and references for each mine, refer to Kirkham (1978b).

Boulder-Weld Field

The Boulder-Weld field is defined by Landis (1959) as the "area underlain by coal-bearing rocks of the Laramie Formation in southeastern Boulder County and in southwestern Weld County"..."It also includes a small area in northwestern Adams County" (see Fig. 11).

Coal mining initiated as early as 1863 in the Boulder-Weld field at the Marshall mines (Hayden, 1868; Hodge, 1872; Marvine, 1874). Hence, the Boulder-Weld field is the oldest mining area in the study area and one of the oldest in the entire western United States. Most early mines worked adits into coal outcrops in the southwestern part of the field, but with time, mining progressed northeastward where slopes and shafts were required.

The Boulder-Weld field is the most productive field in the study area. During the 95 years of recorded activity 107,170,297 tons of coal has been produced from this area (Colo. Div. Mines, 1978a; Kirkham, 1978b). Production in the field gradually increased until 1929, the peak production year and first year of the Great Depression, when about 2,700,000 tons were mined. Production and mining activity has gradually decreased since 1929. Only one mine in the field, the Lincoln mine, remains currently active and produces about 100,000 tons per year.

Most production has been from the No. 3 coal bed of Lowrie (1966). Six other coal beds of mineable thickness occur in the field, have been mined to some extent, and are described by Lowrie (1966). Other thin coal beds occur in the area (Trimble, 1975; Zawistowski, 1978), but these probably are not of economic signficance.

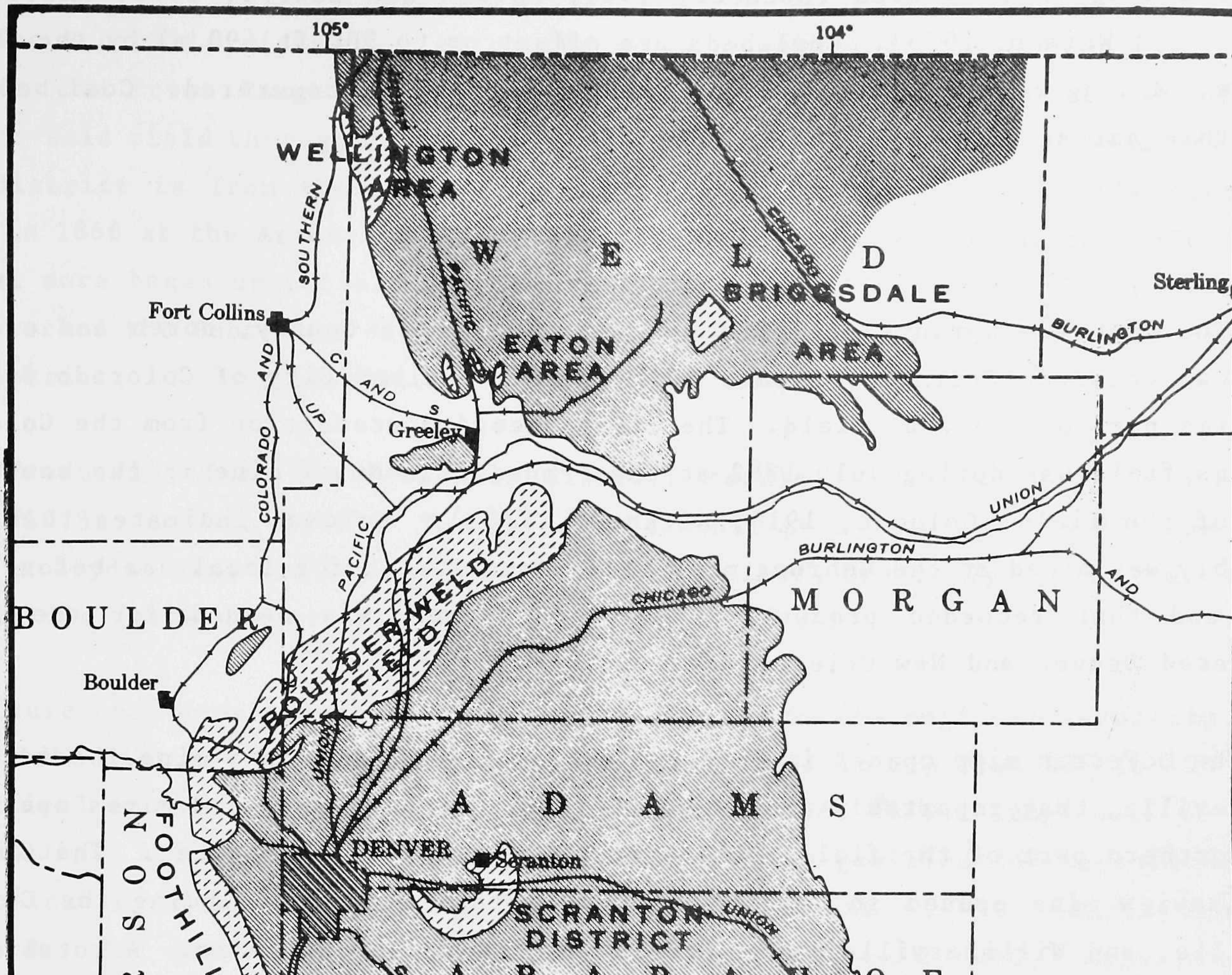


Figure 11. Coal-mining areas in the Denver and Cheyenne Basins, Colorado. (after Landis, 1959)

High-angle normal faults and growth faults control the extent of past and future mining in this area (Spencer, 1961; Colton and Lowrie, 1973; Amuedo and Ivey, 1975; Weimer, 1976). Coal beds are offset up to 300 ft (90 m) by the normal faults. Mining was often stopped when such faults were encountered. Coal beds may also thin across growth faults (Weimer, 1976).

Colorado Springs Field

The Colorado Springs field is in central El Paso County, north and east of downtown Colorado Springs. A part of the now-urbanized City of Colorado Springs overlies part of the coal field. The first recorded production from the Colorado Springs field was during July 1882 at the Franceville No. 1 mine in the southeast part of the field (Goldman, 1910, Kirkham, 1978b). Goldman indicates that coal probably was mined at the Gehrung mine on Monument Creek for local use before this time and that recorded production began when coal was needed for the newly completed Denver and New Orleans Railroad.

The McFerran mine opened in 1885 and until 1896 was the only mine, besides the Franceville, that reportedly was operating. At about 1896 several mines opened in the northern part of the field, but these closed shortly thereafter. The Carlton or Pikeview mine opened in 1897 and several other mines, including the Curtis, Danville, and Williamsville mines, opened in the following years. A total of 65 different mines worked the Colorado Springs field (Kirkham, 1978b; Colo. Springs Planning Dept., 1967). One of these, the Franceville strip mine, was a surface mine. The Pikeview mine was the last mine to work the area, closing in 1957.

Approximately 16,164,310 tons of coal have been produced from the Laramie coal beds in the Colorado Springs field between 1882 and 1957 (Colo. Div. Mines, 1978a; Kirkham, 1978b). The Pikeview mine produced 8,738,174 tons, over half of the entire field production. Goldman (1910) described three Laramie Formation coal beds in the field which, in ascending order, are coal beds A, B, and C. The lowermost bed, coal bed A, is the primary coal bed in the area. Coal bed B was mined in some areas and appears to extend through much of the area. Coal bed C is very thin, discontinuous, and apparently was not worked.

Foothills District

The Foothills district lies on the western margin of the Denver Basin just east of the Front Range. It extends southward from the southwest end of the Boulder-Weld field through Jefferson County and into Douglas County. Production in this district is from the Laramie Formation. Mining in the Foothills district began in 1866 at the Archer mine. A few other mines opened during the 1870's and several more began operations in the 1880's and 1890's. A total of 53 underground mines worked the Foothills district. The Capital mine was the last working mine in the district, closing in 1952.

Production from the Foothills district totals 6,622,522 tons (Colo. Div. Mines, 1978a; Boreck, 1979). The majority of this production, 5,779,893 tons, is from the Leyden mine and Leyden Nos. 1, 2, and 3 mines. Generally, up to 6 mineable Laramie coal beds are present in the Foothills district.

Future coal development in this area is limited by the regional structure. In much of the district Laramie Formation coal beds range in dip from 30° to 40° east to vertical or overturned. Conventional mining methods do not adapt well to such extreme dips, although future mining utilizing in situ gasification techniques may be applicable to the steeply dipping beds. The amount of dip changes rapidly eastward. For instance, coal beds in the Leyden Nos. 1, 2, and 3 mines, a few miles east of the mountain front, dip only a few degrees east.

Buick-Matheson Area

The Buick-Matheson area is in eastern Elbert County on the eastern margin of the Denver Basin (Fig. 11). Mining initiated in this area in 1921 at the Wright strip mine. Several other mines worked the area, including four other strip mines, the Cox, Jordan, Barker, and Stimson. Mining activity ceased in 1951 with the closing of the White Ash mine. Production in this area is from Laramie coal beds. It totals 106,740 tons from 1921 to 1951 (Colo. Div. Mines, 1978a; Kirkham, 1978b). Mine records and drill-hole information indicate there are two primary coal beds in the Buick area, averaging 3.5-ft (1.1-m) and 8-ft (2.4-m) thick and one bed in the Matheson area that averages 10-ft (3-m) thick.

Wellington Area

The Wellington area is on the western margin of the Cheyenne Basin in Larimer County, north of the town of Wellington. The Indian Springs mine opened in 1897 and was the first mine to operate in the area. The Indian Springs mine closed in 1903 and for 28 years there was no further mining in the area. In 1931 four mines, the Benson, Knox, Pioneer, and Veasey mines began production. Within the next four years four other mines were started, accounting for the nine mines which worked the area. The Ideal mine closed in 1942 and since then no coal has been mined in this area. Total production from Laramie coal beds in the Wellington area is 54,611 tons (Colo. Div. Mines, 1978a; Kirkham, 1978b). Mine records indicate two coal beds are present in the area and average about 5-ft thick. Scattered drill-hole information suggests only one bed, which averages 4 to 5-ft (1.2 to 1.5-m) thick, extends laterally from the mined areas.

Eaton Area

Two mines worked Laramie coal beds for a few years near Eaton in Weld County. Both the Comet and Galeton mines opened in 1935. The Galeton mine closed in 1938 and the Comet mine closed in 1942. Thickness of the mined coal bed or beds is 3.5 to 7.0 ft (1.1 to 2.1 m) and total production was only 8,018 tons (Colo. Div. Mines, 1978a; Kirkham, 1978b).

Three small mines worked coal beds to the west and east of the Eaton area. These mines also worked Laramie coal and operated intermittently from 1936 to 1941 producing only 1,116 tons (Colo. Div. Mines, 1978a; Kirkham, 1978b).

Briggsdale Area

One mine, operating under two different names, has worked Laramie coal beds near Briggsdale in Weld County. It opened in 1922 as the Hill mine, changed to the Keota mine in 1935, and ceased operations in 1939. A total of 3,229 tons of coal were mined from a bed ranging from 3 to 5.5-ft (0.9 to 1.7-m) thick (Colo. Div. Mines, 1978a; Kirkham, 1978b).

Scranton District

The Scranton district is in Adams County east of Denver and north of Watkins.

The area was originally named by Eldridge (1896) for the mines that worked Denver Formation lignite beds. The Colorado Division of Mines (1978a) indicates production from 1886 to 1900 in sec. 28, T.3S., R.65W. Other sources (Marvine, 1874; Eldridge, 1896; Soister, 1974) indicate this mine was operating at an earlier date and that there may have been at least two other mines in secs. 16 and 29, T.3S., R.65W.

Total recorded production from the mine in sec. 28 is 35,789 tons (Colo. Div. Mines, 1978a). Since this mine may have been operating before 1886 and there probably are other mines in the area, the total production from the Scranton district may have been more than that recorded by Colo. Div. Mines (1978a). Coal produced in this district was from the northern lignite area. The mines may have worked the E lignite bed.

Ramah-Fondis Area

Four mines near Fondis in Elbert County and five mines near Ramah in El Paso County worked Denver Formation lignite beds (Soister, 1974; Colo. Div. Mines, 1978a). Very little is known about these small mines, but available information suggests that mining began in or before 1909 and ceased by 1940. Apparently the mines worked at least two different beds in the southern lignite area and it is likely that several different beds were mined. Recorded production from this area totals 3,047 tons.

Other Areas

Coal and lignite were mined from a few areas other than those described by Landis (1959). 13,987 tons of Laramie coal were mined at the Drennon mine, southeast of Colorado Springs. The Rush and Golden Dawn mines worked Laramie coal beds in the southeastern part of the Denver Basin and produced a total of 23,679 tons of coal. Laramie coal was also extracted at the Thomas mine in the northeastern part of the Denver Basin, but no production is recorded.

Several small mines worked Denver Formation lignite beds in Arapahoe and El Paso Counties. Most of these mines were operated by ranch families for local use and little is known about the mine characteristics (Kirkham, 1978b).

COAL RESOURCES

LARAMIE FORMATION COAL

Geologic Setting

The structural and stratigraphic settings of the Denver and Cheyenne Basins have been generally described in a previous section. Specific information on stratigraphy and structure, as it applies to the Laramie Formation coal zone, is discussed in this section.

Characteristics of the Laramie coal zone or any other coal zone are primarily dependent upon two factors: 1) environment of deposition and 2) post-depositional structural history. The first factor influences the stratigraphy and distribution of the coal zone and the second factor controls the depth and dip of the coal zone. Both factors play key roles in the making of an economic coal deposit.

Both the Denver and Cheyenne Basins are doubly plunging synclines. The Laramie coal zone has been deformed along with other rocks in the area into this same structural configuration. The coal zone crops out along the basin margin and the deepest coal occurs in the deepest part of the basins. Amount of overburden above the coal zone is, of course, dependent upon the structural configuration, but it also depends on the local topography.

For instance, the structural center of the Denver Basin is southeast of Cherry Creek Reservoir. In this area the top of the coal zone is at an elevation of about 3800 ft (1140 m) above sea level and about 1700 ft (510 m) below land surface. In T.9S., R.66W. the top of the coal zone is at an elevation of only 4100 ft (1230 m), but there is about 2900 ft (870 m) of overburden. Topography significantly influences the amount of overburden and mineability in such areas. Similar overburden relationships hold true in areas where strippable coal exists.

Plate 1 summarizes information on the Laramie Formation coal zone. The outline of the area underlain by the coal-bearing part of the Laramie and the depth to or overburden above the top of the coal zone are illustrated in Fig. 1, Plate 1. The structural configuration and topography of the area are reflected in this map. Approximately 7,500 mi^2 (19,400 km^2) are encompassed by the coal-bearing basins. Detailed studies indicate the Laramie Formation may locally contain thin coal beds or no coal at all. We estimate that 75 to 85 percent of the outlined coal-bearing region, or about 5,600 to 6,400 mi^2 (14,500 to 16,500 km^2) of the area is actually underlain by Laramie coal.

Areas known to be underlain by coal beds at least 5-ft (1.5-m) thick are shown on Fig. 2 of Plate 1. On Plate 1 it appears that less than 10 percent of the total area is underlain by Laramie coal beds 5-ft (1.5-m) thick or greater. However, no coal information is available for a significant part of the area, and many of the drill holes shown on Fig. 2, Plate 1 do not penetrate the entire coal zone. A considerably larger area than that shown on Plate 1 is almost certainly underlain by coal beds 5-ft (1.5-m) thick or greater. Existing drill-hole information suggests about one-third of the Denver Basin and one-sixth of the Cheyenne Basin is underlain by Laramie coal beds at least 5-ft (1.5-m) thick.

In approximately 1,850 mi^2 (4,800 km^2) the top of the coal zone is within 200 ft (60 m) of the surface. The coal zone is found at this depth only near the basin margins. Throughout the rest of the area the coal zone occurs at depths greater than 200 ft (60 m).

The well known Laramie coal zone is a 50 to 275-ft (15.0 to 82.5-m) thick zone of interbedded coal, shale, siltstone, claystone, and sandstone that is within the lower Laramie. The exact stratigraphic position of the coal zone within the Laramie Formation is not agreed upon by all workers. Our investigation indicates the general stratigraphic position of the coal zone is similar throughout the study area, but the details of the coal zone are highly variable.

In this report the top of the lower Laramie is defined by the top of the uppermost coal bed in about the lower 300 ft (90 m) of the Laramie Formation. A few other workers define the top of the lower Laramie by the top of the uppermost massive sandstone in the Laramie Formation. If the Laramie is divided in this manner, the coal zone may be entirely in lower or upper Laramie or it may extend across the boundary and be in both parts of the formation. Our definition of lower and upper Laramie is preferred because 1) the lower, well known coal beds are restricted to the lower Laramie, 2) a minor coal zone near the top of the Laramie in the Cheyenne Basin can be defined as the upper Laramie coal zone, and 3) the massive sandstones are extremely lenticular and in much of the eastern part of the Denver Basin are non-existent; they are not reliable stratigraphic marker beds.

The upper Laramie coal zone is 300 to 500 ft (90 to 150 m) above the lower, well known coal zone. This upper coal zone is found only in a limited area north of Purcell and east of Nunn in the Cheyenne Basin. It consists of up to six coal beds that are a maximum of 1.5-ft (0.45-m) thick. All coal beds in the upper Laramie coal zone are apparently very thin and for this reason were not studied in detail during our investigation. It is possible that these beds are thicker in adjacent areas and may become economically significant, but this can be proven only by additional drilling or geophysical logging of existing water wells.

Stratigraphic details of the lower Laramie coal zone vary considerably. In some areas it contains up to 16 individual coal beds. In other areas only one coal bed is within the coal zone. The thickest lower Laramie coal bed is often directly on or very near the top of the Laramie-Fox Hills aquifer. Several mineable coal beds may also occur above this bed. Lowrie (1966) described four coal beds of mineable thickness above the Laramie-Fox Hills aquifer in the Boulder-Weld field. Zawistowski (1978) has observed 12 coal beds of varying thickness above the Laramie-Fox Hills aquifer in a core hole in the central part of the Boulder-Weld field.

Several workers have noted coal beds interbedded with the Laramie-Fox Hills aquifer. Lowrie (1966) described two coal beds, locally of mineable thickness, in the Laramie-Fox Hills aquifer in the Boulder-Weld field. Zawistowski (1978) recorded four thin coal beds within the Laramie-Fox Hills aquifer in a core hole in the central part of the Boulder-Weld field. Trimble (1975) reported an 8-in (20-cm) thick coal bed within the Fox Hills Sandstone in the Niwot quadrangle. Goldman (1910) described several coal beds in the Colorado Springs area that are within the Laramie-Fox Hills aquifer. Our investigation indicates there are numerous, usually thin coal beds interbedded with the Laramie-Fox Hills aquifer in much of the study area. Only in a few areas, however, such as the Colorado Springs field, Foothills district, and locally, the Boulder-Weld field, are the beds economically significant.

It is apparent from the preceding paragraphs that the stratigraphy of the lower Laramie coal zone is complex. This is a direct result of the environment in which these coals were deposited. The lower Laramie Formation was deposited within a delta-plain facies in channels, levees, splays, swamps, and lakes (Fig. 9). Laramie coals developed primarily in poorly drained swamps in overbank areas adjacent to the channel-margin facies (Weimer, 1973). A few coal beds apparently formed in abandoned channels.

Coal distribution and stratigraphy in the Laramie Formation can be interpreted through use of deltaic sedimentation models. Areas free of Laramie coal were probably channel and channel-margin environments. Fine- to coarse-grained sandstones were deposited in channel environments, light gray, massive claystones were deposited in the well-drained swamps, and light-colored silts and clays were deposited on the levees. Peat and dark gray, organic-rich claystone were deposited in the poorly drained swamps in overbank areas and occasionally in abandoned channels. Fine- to medium-grained sandstones were deposited in overbank areas when crevasse splays broke through the levees.

Because Laramie coal stratigraphy is complex, no attempt to summarize it for the entire study area will be made. Instead, short descriptions of the stratigraphy for a few individual areas will be presented.

Stratigraphy in the Boulder-Weld field is fairly well known. Several workers, including Spencer (1961), Lowrie (1966), Amuedo and Ivey (1975), and Zawistowski (1978), have studied the area and described the stratigraphy of the Laramie coal zone. Figure 12 summarizes the stratigraphic findings of these workers.

The coal zone is up to 265-ft (79.5-m) thick and consists of seven coal beds that reach mineable thickness. As many as nine other thin coal beds also occur in the area, but these are not thick enough to be economically mined. Lowrie (1966) has named the seven mineable beds, in ascending order, the nos. 1 through 7 coal beds. The coal zone is overlain by 300 to 500 ft (90 to 150 m) of claystone, shale, and thin sandstone beds of the upper Laramie Formation. Thick sandstones and interbedded shales of the Fox Hills Sandstone and locally the lowermost Laramie Formation lie beneath the coal zone.

Coal bed no. 1, the lowermost mineable bed, is 1 to 3-ft (0.3 to 0.9-m) thick and is very limited in lateral extent. Lowrie (1966) indicates the no. 1 bed reaches maximum thickness in secs. 13, 14, 22, and 23, T.1N., R.68W. Approximately 20 to 65 ft (6.0 to 19.5 m) above the no. 1 bed is coal bed no. 2. The intervening rock is often a sandstone locally called the "A" sandstone. Coal bed no. 2 is known as the "sump seam" (Lowrie, 1966), because it is 10 to 45 ft (9.0 to 13.5 m) below coal bed no. 3. Coal bed no. 2 is often greater than 2.5-ft (0.75-m) thick and in sec. 20, T.1N., R.68W., it is over 8-ft (2.4-m) thick (Lowrie, 1966).

The "B" sandstone, where it is present, separates coal bed nos. 2 and 3. Coal bed no. 3 is the thickest and laterally most continuous bed in the field. It is the primary bed which has been mined in the field and locally is called the "main bed". Thickness of the coal bed varies from about 2 to 14 ft (0.6 to 4.2 m). The no. 3 bed may coalesce with the no. 4 bed, as it does in secs. 34 and 35, T.1N., R.69W.

GEOLOGIC UNIT				GRAPHIC LITHOLOGY	THICKNESS* (FT.)	DESCRIPTION
LARAMIE FORMATION	UPPER PART, LARAMIE FORMATION				300 - 500	claystone, shale, thin sandstone and lignite lenses
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION		Coal Bed No. 7		2 - 5	coal, nonpersistent lense
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION				30 - 100	shale and sandy shale
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION		Coal Bed No. 6		1 - 8	coal, locally called the "upper seam", nonpersistent lense
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION				20 - 75	shale, sandy shale, and thin sandstone and coal lenses
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION		Coal Bed No. 5		1 - 10	coal, locally called the "middle seam"
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER			10 - 50	shale and sandstone, may be the "C" sandstone
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER	Coal Bed No. 4		1 - 11	coal, nonpersistent lense
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER			0 - 35	shale and occasional thin coal; may pinch out and allow No. 3 and No. 4 coal beds to coalesce
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER	Coal Bed No. 3		2 - 14	coal, locally called the "main or Gorham seam"
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER			10 - 45	sandstone, shale, may be "B" sandstone
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER	Coal Bed No. 2		1 - 8	coal, locally called "sump seam"
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER			20 - 65	sandstone, may be "A" sandstone, thin lignite lenses, shale
LARAMIE FORMATION	LOWER PART, LARAMIE FORMATION	LARAMIE-FOX HILLS AQUIFER	Coal Bed No. 1		1 - 3	coal, nonpersistent lense, within Laramie-Fox Hills aquifer
FOX HILLS SANDSTONE		LARAMIE-FOX HILLS AQUIFER			60 - 300	sandstone, locally contains thin lignite and shale lenses

*thickness not to scale

modified from Lowrie (1966), Amuedo and Ivey (1975), and Zawistowski, pers. comm. (1978)

Figure 12. Generalized stratigraphy of the Laramie Formation coal zone, Boulder-Weld field.

The "B" sandstone, where it is present, separates coal bed nos. 2 and 3. Coal bed no. 3 is the thickest and laterally most continuous bed in the field. It is the primary bed which has been mined in the field and locally is called the "main bed". Thickness of the coal bed varies from about 2 to 14 ft (0.6 to 4.2 m). The no. 3 bed may coalesce with the no. 4 bed, as it does in secs. 34 and 35, T.1N., R.69W.

Coal bed no. 4 is up to 35 ft (10.5 m) above coal bed no. 3. It ranges from 1 to 11-ft (0.3 to 3.3-m) thick and is thickest in the central and southwestern parts of the field. About 10 to 50 ft (3 to 15 m) of shale and sandstone overlie coal bed no. 4. The sandstone, developed only in the Marshall area, is the "C" sandstone. Coal bed no. 5 is also known as the "middle seam" and is 1 to 10-ft (0.3 to 3.0-m) thick. It has been extensively mined in several areas. Coal bed no. 5 reaches its maximum thickness in secs. 25, 34, and 35, T.2N., R.68W.

Coal bed no. 6, known as the "upper seam", is 1 to 8-ft (0.3 to 2.4-m) thick. It is 20 to 75 ft (6.0 to 22.5 m) above coal bed no. 5 and has been mined using both underground and surface mining methods. Coal bed no. 7 is about 30 to 100 ft (9 to 30 m) above coal bed no. 6. It is very lenticular and occurs only in the eastern and southeastern parts of the field. Thickness of coal bed no. 7 ranges from 2 to 5 ft (0.6 to 1.5 m) with maximum thickness in sec. 8, T.1N., R.67W. It is the uppermost mineable coal bed in the Boulder-Weld field.

The coals in the Boulder-Weld field are believed to have been deposited within a delta-plain facies on the northern margin of a delta whose distributary channels were in the Golden-Leyden Ridge vicinity (Rahmanian, 1975; Weimer, 1977). This hypothesis is supported by the presence of a second delta system north of the Boulder-Weld field in the White Rocks area (Weimer, 1973; 1976) and by occurrrences of the oyster Ostea glabra and highly burrowed beds, which suggest a somewhat brackish-water depositional environment (Rahmanian, 1975).

The Foothills district is south of the Boulder-Weld field along the mountain front. The north end of this district has been studied by Camacho (1969), who indicated there are two coal beds in this part of the district, beds A and B, and attributed the coal to a delta-plain environment. Van Horn (1976) reports there are 1 to 6 coal beds in the Golden quadrangle, central Foothills district. Scott (1962) found four coal beds in the Littleton quadrangle in the south end of the district. Thickness of these coal beds ranges from about 4 to 15 ft (1.2 to 4.5 m) (Kirkham, 1978b). Figure 13 summarizes the Fox Hills and lower Laramie stratigraphy from Leyden Ridge to Golden. Two distributary channels occur in the area. The main channel on the south side of the diagram separates a lacustrine environment on the south from a swamp environment on the north. The A and B coal beds described by Camacho (1969) were deposited in the poorly drained swamps on the north. Coal beds reported by Scott (1962) and Van Horn (1976) were depositea to the south.

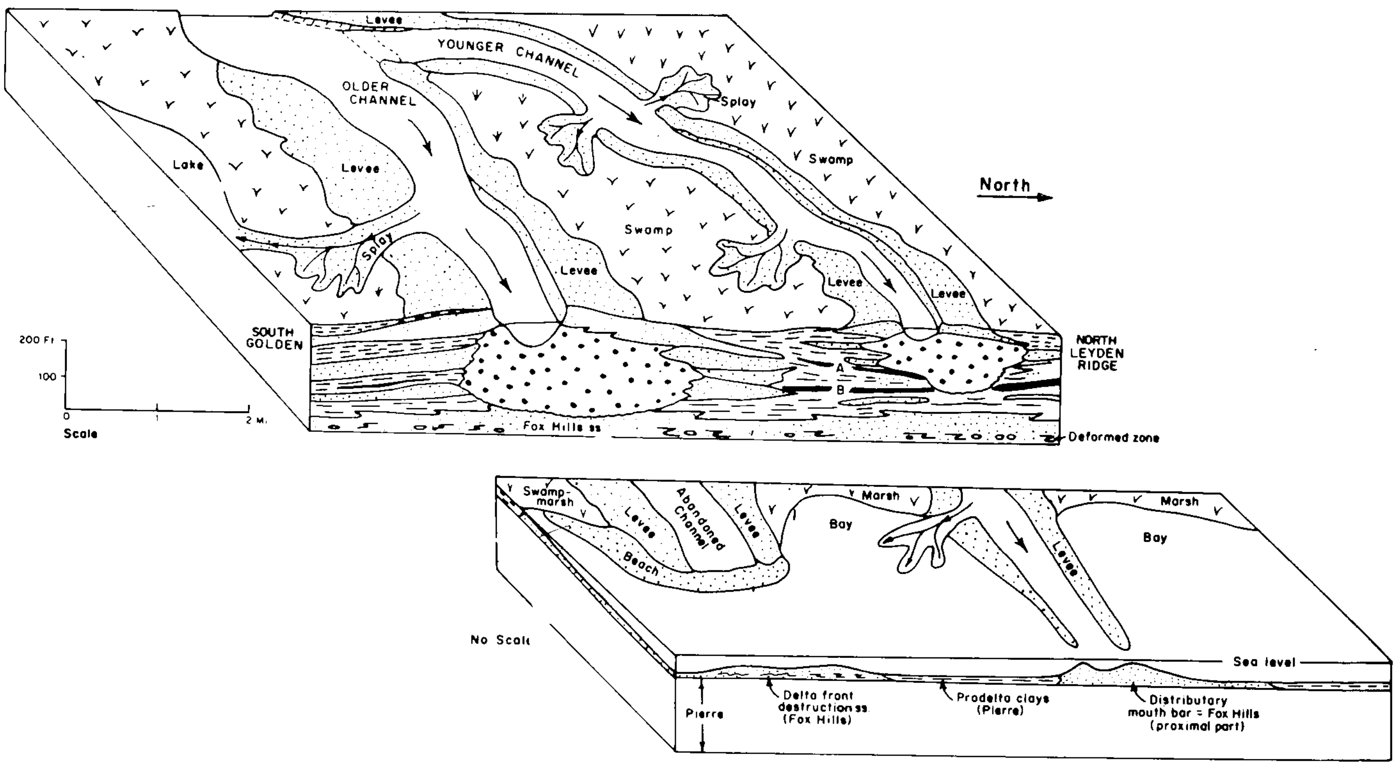


Figure 13. Block diagram of stratigraphic relationships and environments of deposition in the lower Laramie Formation from Leyden Ridge to Golden (upper diagram) and the hypothesized environment to the east (lower diagram). (from Camacho, 1969 and Weimer, 1973)

South of the Foothills district, the coal zone is displaced by the structural zone on the east side of the Front Range. Coal beds do not crop out anywhere between the Foothills district and Colorado Springs field. In this area very little is known about the coal zone. A few drill holes do penetrate the coal zone (Plate 1) and indicate lower Laramie coal beds are present at a depth of about 500 ft (150 m) or more.

The Colorado Springs field has not been studied in detail since Goldman (1910) described the geology and mining history of the field. Most information reported in this investigation on the Colorado Springs field is compiled from Goldman (1910), Kirkham (1978b), and the Colo. Div. Mines (1978a).

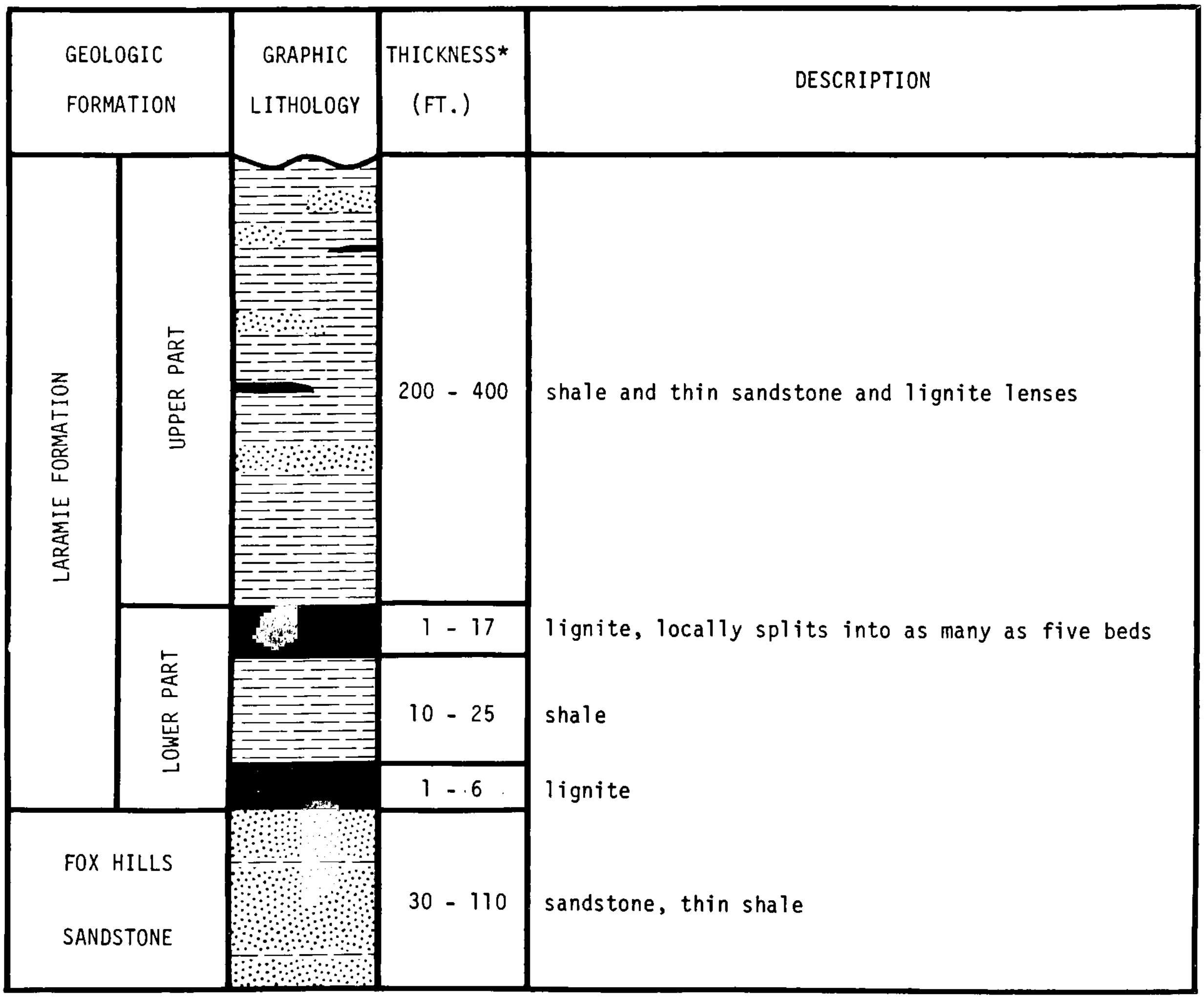
There are three lower Laramie coal beds of interest in the Colorado Springs field. They are, in ascending order, coal beds A, B, and C (Goldman, 1910). A fourth bed, the Fox Hill bed, is described as the bed worked by several mines (Colo. Div. Mines, 1978a), but no specific information on this bed is available. It is likely that the Fox Hill bed correlates with coal bed A of Goldman (1910). Most coal was mined from coal bed A, although a large number of mines worked coal bed B. The Pikeview or Carlton mine produced over half of the entire field production from coal bed A.

Coal bed A is usually about 50 ft (15 m) above the top of the Fox Hills Sandstone. It is not well developed west of Monument Creek, but to the east is up to 20-ft (6-m) thick. Massive sandstones commmonly are above and below coal bed A (Goldman, 1910). Thin shale or claystone beds are locally present, but rapidly give way to massive sandstone.

Coal bed B lies 20 to 30 ft (6 to 9 m) above bed A (Goldman, 1910). Innerburden between the two beds is predominantly massive sandstone. Bed B is up to 13-ft (3.9-m) thick (Kirkham, 1978b). Coal bed C is very lenticular and not found throughout the field. Where it is present, it is 20 to 50 ft (6 to 15 m) above bed B (Goldman, 1910). Generally, innerburden between beds B and C is claystone interbedded with sandstone. Bed C is thin, rarely being over 2-ft (0.6-m) thick. Available data suggest the lower Laramie and included coal beds in the Colorado Springs field are entirely within the Laramie-Fox Hills aquifer of Romero (1976).

Figure 14 summarizes the stratigraphy of the Laramie coal zone near Buick and

Matheson on the east flank of the Denver Basin. The coal zone averages 25 to 50-ft (7.5 to 15.0-m) thick in this area and contains two notable coal beds. The lower coal bed is 1 to 6-ft (0.3 to 2.0-m) thick and usually rests directly on top of the Fox Hills Sandstone. The upper coal bed is 10 to 25 ft (3.0 to 7.5 m) above the lower bed. It is 1 to 17-ft (0.3 to 5.1-m) thick, and locally splits into as many as five thinner beds.



*thickness not to scale

Figure 14. Generalized stratigraphy of the Laramie Formation coal zone, Buick-Matheson area.

Coal beds in the lower Laramie of the Cheyenne Basin generally are thin. Figure 2 of Plate 1 shows areas known to be underlain by coal beds 5-ft (1.5-m) thick or greater. Very few areas in the Cheyenne Basin are underlain by coal beds of this thickness. A few mines in the Wellington field (Fig. 11) report coal beds greater than 5-ft (1.5-m) thick. Examination of drill holes in this area indicates a 4 to 6-ft (1.2 to 1.8-m) thick coal bed is present over parts of the unmined areas. Scattered drill holes throughout the rest of the basin penetrate numerous coal beds, but very few encounter beds 5-ft (1.5-m) thick or greater. Available data suggest that at most one-sixth of the Cheyenne Basin is underlain by Laramie coal beds at least 5-ft (1.5-m) thick.

A few conclusions can be drawn from the preceding stratigraphic discussion which aid exploration efforts for Laramie coals. The upper Laramie, above the coal zone, consists of shale, claystone, siltstone, and minor sandstone. This sequence of rocks is readily distinguishable on geophysical logs in both the Denver and Cheyenne Basins (Fig. 7). It serves as an upper stratigraphic marker which establishes the top of the coal zone when exploring for Laramie coal.

The Fox Hills Sandstone, also easily recognized on geophysical logs, serves as a lower stratigraphic marker of the coal zone. No significant coal beds should be encountered below the top of this formation. Care should be taken, however, to avoid confusing lower Laramie sandstones with the Fox Hills Sandstone, especially in the Colorado Springs area.

Quality

Laramie Formation coal varies in rank from subbituminous B coal to lignite A (Kirkham, 1978b). All Laramie coal, except that in the Wellington area, contains only minor amounts of sulfur (less than 1 percent S). Figure 15 shows the variation in as-received heat value for coal samples from different parts of the two basins. Table 2 lists average as-received Laramie coal analyses for several areas.

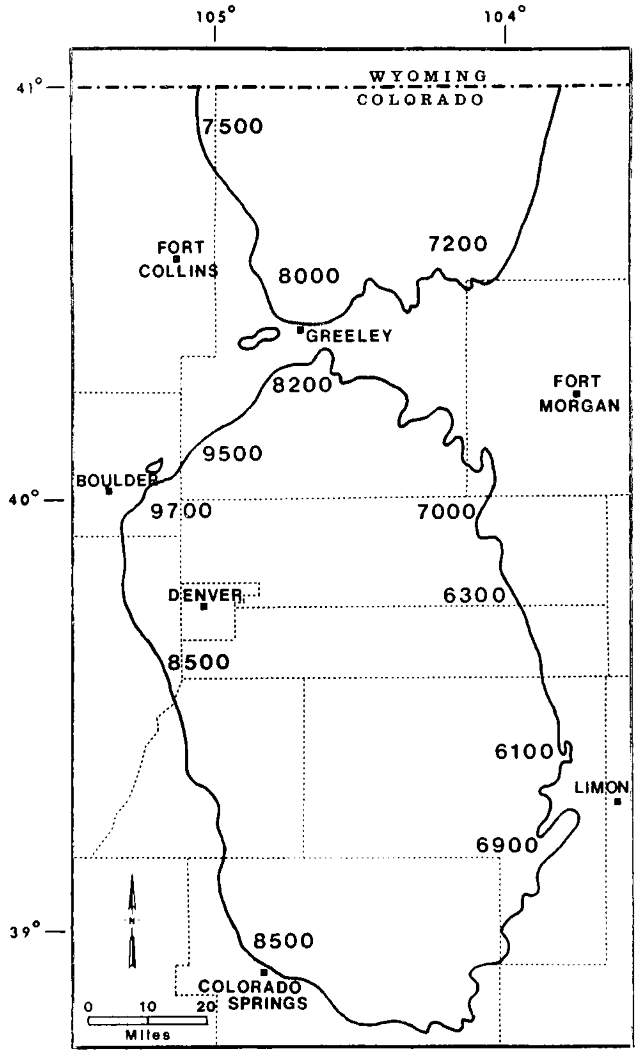


Figure 15. Average as-received heat value for Laramie Formation coal in the Denver and Cheyenne Basins.

Table 2. Average as-received analyses of Laramie Formation coal from various mining areas. (from Kirkham, 1978b)

Location	Moisture (%)	Ash (%)	Heat Value (Btu/lb)	Sulfur (%)
SW Boulder-Weld	21.0	7.0	9,700	0.4
NE Boulder-Weld	30.0	6.0	8,200	0.4
Foothills	26.0	7.0	8,500	0.6
Colorado Springs	23.0	7.0	8,500	0.5
Buick-Matheson	34.0	9.0	6,500	0.4
Wellington	32.0	8.0	7,500	1.7
Briggsdale	33.0	8.0	7,200	0.4

Highest-quality Laramie coal occurs in the Boulder-Weld field, Foothills district, and Colorado Springs field. Coal averages 8,500 to 9,500 Btu/lb as-received and ranks as subbituminous B and C coal in these areas. Within the Boulder-Weld field, coal quality decreases from southwest to northeast. Coal quality in the northeastern part of the field is markedly lower than coal quality in the southwestern part. Lowest-quality Laramie coal occurs on the east flank of the Denver Basin. Near Buick and Matheson, coal averages 6,100 to 6,900 Btu/lb and the apparent coal rank is lignite A. No coal analyses are available for beds in the deepest parts of the Denver Basin.

Coal on the western flank of the Cheyenne Basin is lower in quality than coal on the western margin of the Denver Basin. In the Wellington area, the coal averages 7,500 Btu/lb as-received and has an apparent rank of subbituminous C coal. These coals also have a relatively high sulfur content (greater than 1 percent S). The lateral extent of these relatively high-sulfur coals is not known.

Resource Estimates

Landis (1959) estimated that 5,260 million tons of coal existed in 836 mi^2 (2,274 km^2) of the Denver and Cheyenne Basins. Of this total, 4,295 million tons are Laramie coal in 649 mi^2 (1,687 km^2) and 963 million tons are Denver lignite in 187 mi^2 (486 km^2).

Because Landis (1959) only estimated coal resources in a 649 mi^2 (1,687 km^2) part of the study area and the coal-bearing Denver and Cheyenne Basins cover a much larger area, Hornbaker and others (1976) revised the estimates of Landis (1959). By assuming that two-thirds of the Denver and Cheyenne Basins are underlain by coal beds similar in thickness and distribution to coal in areas studied by Landis (1959), Hornbaker and others (1976) estimated there to be 29,795 million tons of Laramie coal in the Denver and Cheyenne Basins. Myers and others (1978) document a total of 2,278 million tons of Laramie coal in just Jefferson County.

Our investigation indicates most of the Cheyenne Basin generally has considerably less coal in it than the areas for which Landis (1959) made estimates. Also, significant areas in the Denver and Cheyenne Basins are virtually coal-free. A more reasonable estimate of the total remaining in-place resources in coal beds greater than 2.5-ft (0.75-m) thick at depths less than 3,000 ft (900 m) is on the order of 20 to 25 billion tons.

DENVER FORMATION LIGNITE

Geologic Setting

Thick lignite beds occur in a zone in the upper 300 to 500 ft (90 to 150 m) of the Late Cretaceous-Paleocene Denver Formation. The lignite zone has been dated by palynological evidence as Early Paleocene (Soister and Tscudy, 1978) and is 800 to 1,500 ft (240 to 450 m) above the top of the Laramie coal zone (Soister, 1978a).

The lignite zone occurs only in the Denver Basin and extends over a roughly kidney-shaped area (Plate 2). The Denver Formation and included lignite zone are absent from the Cheyenne Basin. The area of occurrence extends from just north of Watkins to several miles south of Calhan encompassing about 1700 mi^2 (4400 km^2). Best exposures of the lignite zone are in West Bijou Creek valley and along Kiowa Creek in stream and road cuts. Several hills in West Bijou Creek valley are capped by baked and fused rock, commonly known as clinker, which resulted from the burning of one or more of the lignite beds. The burning probably occured during the Pleistocene as West Bijou Creek valley began to develop. Exposures of the lignite zone are rare throughout the rest of the area and drill holes must be utilized as the main source of information.

Existence of the lignite beds was first mentioned by Marvine (1874). Many of the early workers believed the lignite beds correlated with the better known Laramie coal beds mined to the west. Richardson (1917) was the first to recognize the lignite beds were in the Denver Formation. The only detailed study of the lignite zone has been by Soister (1972, 1974, 1978a).

In the main area of occurrence the lignite zone consists of three to eight thick lignite beds and several thinner and carbonaceous beds. The zone also contains claystone, siltstone, and sandstone beds. As shown on Plate 2 the total lignite thickness and maximum individual bed thickness are greatest in the eastern part of the area. Lignite beds are thinner and fewer in number to the west.

Most lignite beds contain numerous non-coal partings. Parting thickness ranges from less than 0.1 in (0.25 cm) to over 2 ft (0.6 m). Soister (1974, 1978a) believes lignite bed thickness should be reported as gross bed thickness and net lignite thickness, to demonstrate the amount of partings with the lignite beds. Generally, net lignite thickness is 70 to 95 percent of the gross lignite thickness. Figure 16 shows a lignite outcrop along Kiowa Creek which has several partings.

Many partings are composed of kaolin, a kaolinite-rich rock. Kaolinite is a pale yellowish-brown mineral that occurs in both fine- and coarse-grained crystalline habits and weathers to a light or white color. Some partings pinch out laterally over a short distance. Others appear to be continuous over considerable distance. Soister (1978a) has traced a thick parting for at least 3 mi (4.9 km) in drill holes in the Strasburg NW quadrangle.

In some areas a 2 to 5-ft (0.6 to 1.5-m) thick kaolinite bed overlies individual lignite beds. In parts of West Bijou Creek valley the lignite beds have caught fire and the overlying kaolinite bed has been baked and altered into a dense rock which looks like welded tuff.

Origin of the partings has not been studied in detail. Our investigation suggests that at least a few of the partings are altered volcanic ash layers similar to those described by Bohor and others (1976). These partings may be valuable stratigraphic and depositional-environment guides.

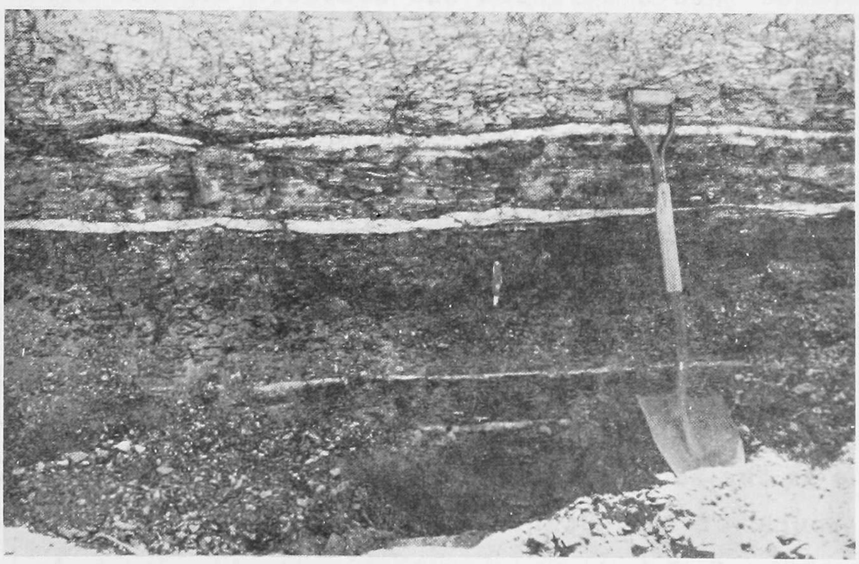


Figure 16. Photograph of a Denver Formation lignite outcrop along Kiowa Creek. Note prominent kaolinitic partings.

The U.S. Bureau of Mines has demonstrated that alumina can be extracted from kaolinite. The process is not yet economic, but may become commercially feasible in the near future, especially if the price of alumina rises significantly. Additional research may result in new processes that may improve the economics of alumina extraction from kaolinite. Table 3 lists average parting analyses. Alumina (Al_2O_3) is a major constituent, of the partings, averaging 24.0 percent.

Table 3. Typical analysis (in %) of kaolinite-rich partings in Denver Formation lignite beds. (from Hand, 1978)

Al_2O_3	24.0	Fe_2O_3	2.1
CaO	0.9	TiO_2	0.6
MgO	0.7	SO_4	0.2
Na_2O	0.4	Free H_2O (100°C)	16.1
K_2O	1.0	loss on ignition	17.0
SiO_2	51.0		

Detailed study of over 500 drill-hole logs in the Denver lignite zone reveals the zone is divided into a northern and southern lignite area, each with its own unique stratigraphy. Figure 1 of Plate 5 is a cross section from the northern lignite area, through an area nearly barren of lignite, and into the southern lignite area. Individual beds are continuous throughout much of the northern lignite area. One lignite bed, the E lignite bed, can be traced for 24 m (38 km) across the entire northern lignite area. Lignite beds of the northern area thin, become carbonaceous, and pinch completely out in an area nearly barren of lignite beds on the southern edge of the northern lignite area (Plate 2). Further south, the lignite beds of the southern lignite area are encountered. These beds are in a stratigraphic sequence completely unlike that of the northern lignite area. Individual beds in the southern area can be traced for several miles in the Station Creek area. South of the Station Creek area, drill holes are scattered and correlation of individual beds becomes difficult. Lignite beds in the southern part of the southern lignite area possibly may not correlate with those in the northern part of the southern lignite area.

Figure 17 illustrates the stratigraphy of the northern and southern lignite areas. Soister (1972) designated five thick lignite beds in the Strasburg NW quadrangle in the northern lignite area. In descending order, they are the A, B, C, D, and E lignite beds. The E lignite bed is also informally known as the Watkins bed, and the B and C lignite beds are, respectively, called the Lowry and Bennett beds.

The E lignite bed is the thickest and most continuous lignite bed in the Denver Formation lignite zone. Gross thickness averages 20 to 30 ft (6 to 9 m) and ranges up to a maximum of 54.5 ft (16.4 m) in sec. 29, T.3S., R.64W. near Watkins (Fig. 1, Plate 3). Lignite beds A through D are often 10 to 15-ft (30 to 45-m) thick and locally are over 30-ft (9-m) thick.

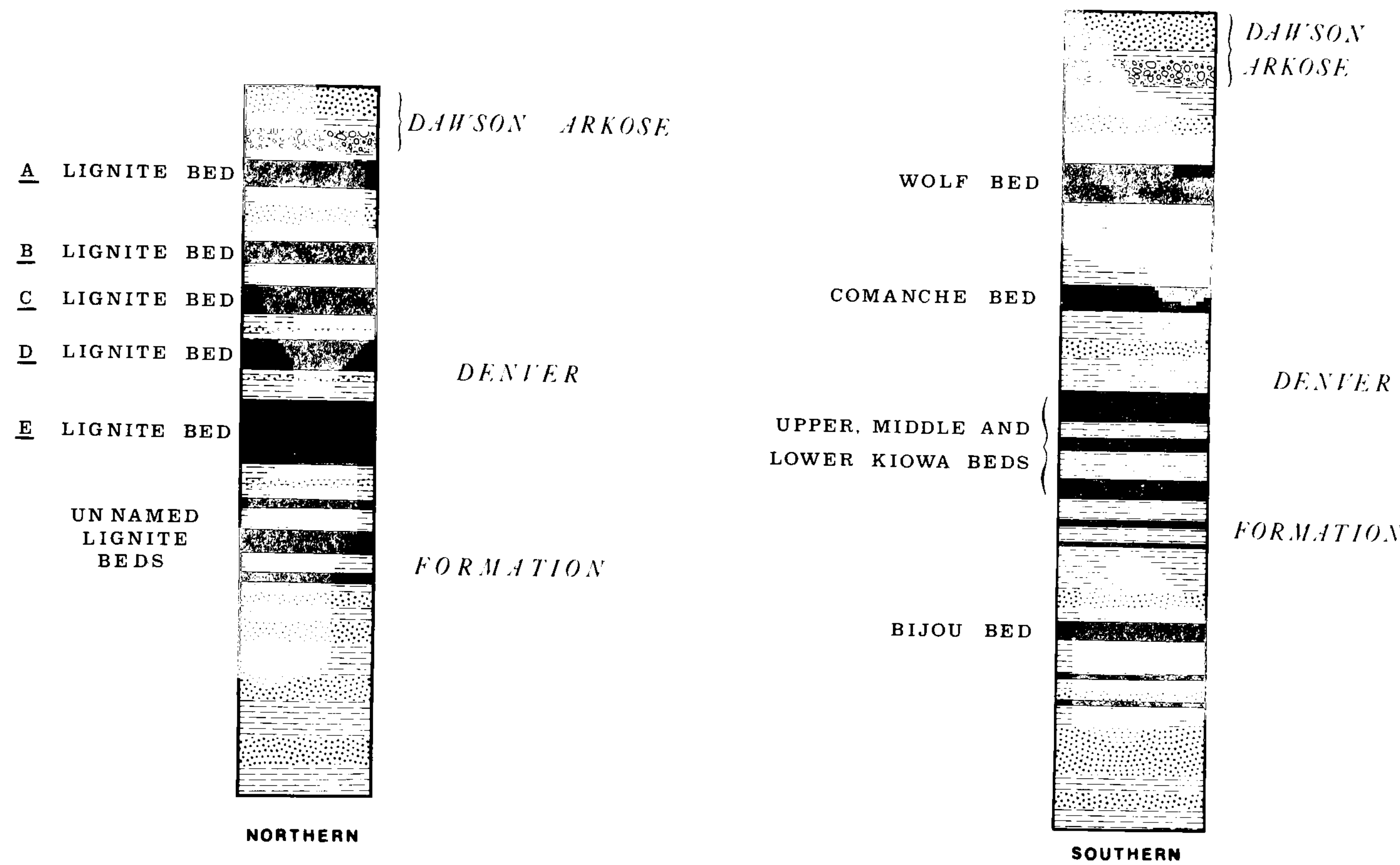


Figure 17. Generalized stratigraphy of the northern and southern lignite areas in the Denver Formation. (bed thickness not to scale)

The A lignite bed occurs at the top of the Denver Formation, just below the thick arkosic sandstones and conglomerates of the lower Dawson Arkose. The base of the Dawson is a readily distinquishable stratigraphic horizon (Fig. 7) which marks the top of the Denver lignite zone. A series of thin, lenticular lignite beds lies below the E lignite bed and completes the lignite zone in the northern lignite area. Locally, these lignite beds reach a thickness in excess of 20 ft (6 m), but generally they are very thin and not of economic interest. A sequence of interbedded sandstone and claystone underlies the lignite zone and serves as a lower stratigraphic marker for the lignite zone.

Lignite beds of the southern lignite area have not been named in published literature. The bed names proposed in this report are adapted from those used by companies exploring for lignite in the Denver Basin. The uppermost lignite bed in the southern lignite area is the Wolf bed. It is the thickest bed in the southern lignite area, ranging from 18 to 28-ft (5.4 to 8.4-m) thick. No analyses or core holes are available for the Wolf bed, but geophysical logs suggest the bed is very dirty and may contain 20 to 40 percent partings. The base of the Dawson Arkose is 25 to 75 ft (7.5 to 22.5 m) above the top of the Wolf bed and marks the top of the lignite zone in the southern lignite area.

Lignite beds below the Wolf bed, in descending order include the Comanche, Upper Kiowa, Middle Kiowa, Lower Kiowa, and Bijou beds. These beds are typically 5 to 10-ft (1.5 to 3.0-m) thick and locally may be up to 24-ft (7.2-m) thick. The Comanche bed is one of the more continuous lignite beds in the southern lignite area. It lies 15 to 100 ft (4.5 to 30.0 m) below the Wolf bed.

The Upper, Middle, and Lower Kiowa beds are in a zone 15 to 80-ft (4.5 to 24.0-m) thick. Locally, the beds coalesce and form one thick bed, the Kiowa bed. The zone which includes all three Kiowa beds is 22 to 110 ft (6.6 to 33.0 m) below the base of the Comanche bed. Little is known about the Bijou bed because it is usually at least 60 to 80 ft (18 to 24 m) below the base of the Kiowa beds and few reliable drill holes penetrate the lignite zone to this depth. Other thin lignite beds occur in the southern lignite area between and below the named lignite beds, but these, apparently, are not of great economic significance.

As in the northern lignite area a sequence of thin, lenticular sandstones, interbedded with claystone and siltstone, underlies the lignite zone in the southern lignite area. These sandstones mark the lower boundary of the lignite zone, are recognizable on geophysical logs, and may be useful for lignite exploration.

The depositional environment of Denver lignite beds is poorly understood. Existing data indicate the Denver Formation consists of continental sediments deposited on an alluvial plain. Data collected during this study suggest Denver lignite beds developed in swamps east of the distal end of the piedmont complex which extended eastward from the Front Range.

Figure 18 schematically illustrates the environment in which Denver lignite beds are believed to have been deposited. During the Early Paleocene, as the Southern Rocky Mountains rose, material was eroded from the uplifted areas and deposited along the east flank of the Front Range, probably in some type of a piedmont or braided stream environment. Some material may have been deposited on alluvial or debris fans along the eastern edge of the uplift. This depositional complex extended eastward from the uplifted area towards the basin axis, one of the lower areas in the region. Uplift and related sedimentation were episodic. The uplifted block probably was never significantly higher than the adjacent sedimentary basins during the Early Paleocene.

East of the distal end of the piedmont or braided stream environment were two large swamp areas that formed in low, poorly drained areas. The two swamps correspond to the northern and southern lignite areas previously described. The area nearly barren of lignite between the two lignite areas is not well understood. No channel sands exist in this area. This indicates a major stream or river did not pass through the barren area. It is possible that the barren area was slightly above the general elevation of surrounding land or that it was a bay connected to a lake to the east.

As the piedmont or braided stream environment prograded eastward, the swamps were forced eastward. Changes in rate of uplift and basin subsidence occassionally allowed the swamps to retreat westward or be covered by sediments, but in general, swamps migrated eastward.

Depositional environments east of the swamp areas are not known because post-depositional erosion has removed the Early Paleocene rocks from the eastern part of the basin. Examination of drill-hole logs indicates individual lignite beds may thin or become carbonaceous in the easternmost part of the basin, suggesting the swamp areas probably did not extend eastward from the outcrop area for any significant distance.

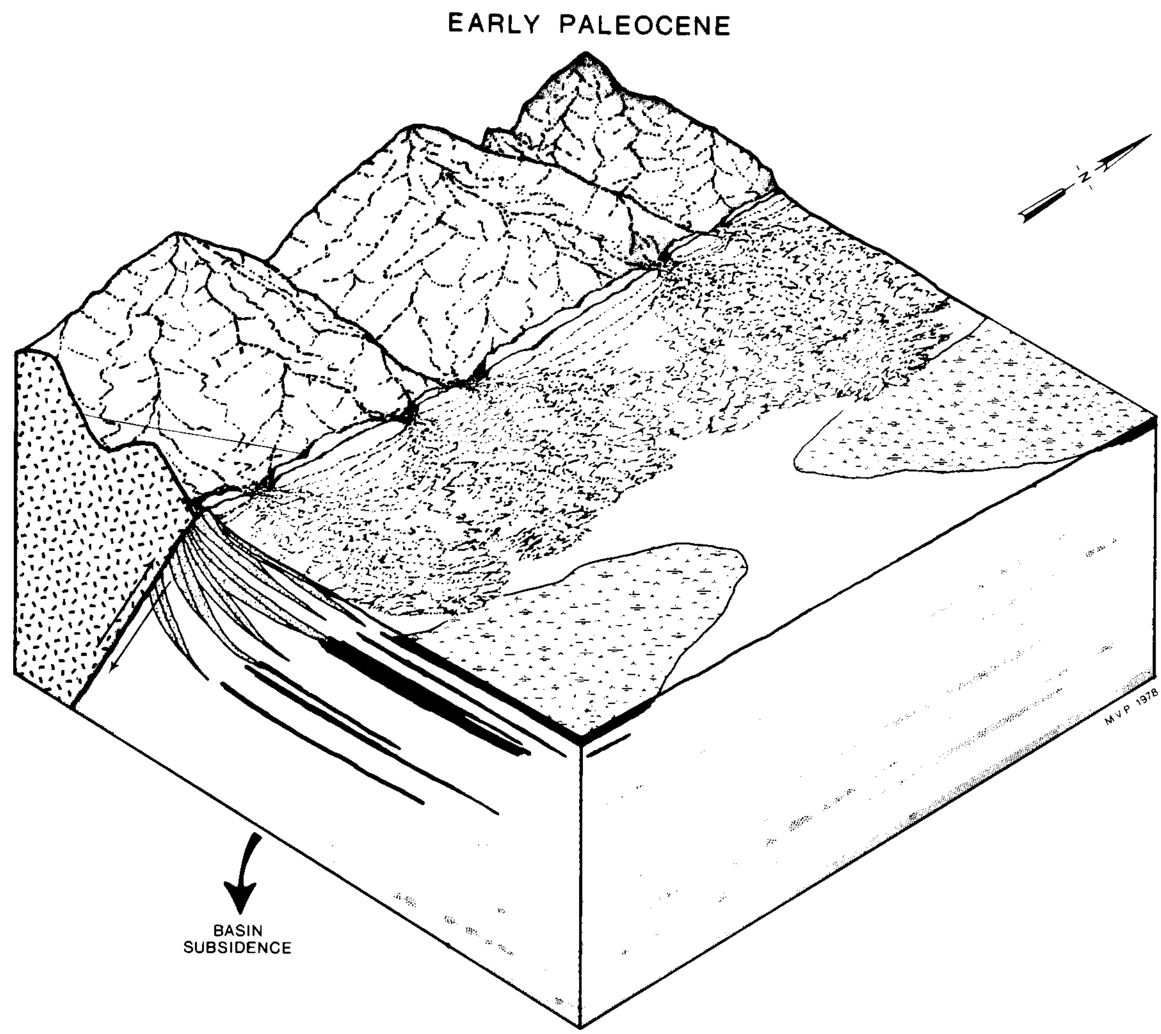


Figure 18. Schematic diagram of the depositional environment of Denver Formation lignite beds. (not to scale)

One of the better known lignite deposits in the Denver Basin occurs near Watkins, east of Denver. Plate 3 illustrates some of the geologic characteristics of the Watkins deposit. Figure 1 of Plate 3 is an isopach map of the E lignite bed or Watkins bed. There are two primary lignite depocenters in the area, one east of Watkins and a second one to the west. The E lignite bed is at least 20-ft (6-m) thick under about 15 mi^2 (39 km^2) east of Watkins. It reaches a maximum thickness of 54.5 ft (16.4 m) in sec. 19, T.3S., R.64W. The E lignite bed is generally thinner west of Watkins, although in about 8 mi^2 (20.8 km^2) the lignite bed is over 15-ft (4.5-m) thick.

Figure 2 of Plate 3 shows the overburden thickness above the E lignite bed and the extent of alluvial valley floors, as defined by Public Law 95-87. The lignite bed is within 200 ft (60 m) of the surface and is strippable throughout the area. The alluvial valley floor associated with Box Elder Creek generally coincides with an area where the E lignite bed is thin or has been removed by erosion. A major part of the deposit can be mined in accordance with the alluvial valley floor clause of Public Law 95-87.

Figure 2 of Plate 5 is a cross section through the Watkins deposit. The E lignite bed is cut out by erosion beneath Box Elder Creek, as seen in drill hole DX-78. The bed thins on the northeast end of the deposit (drill hole DX-73), but thickens southward. Several 5 to 10-ft (1.5 to 3.0-m)-thick lignite beds lie below the E lignite bed in the area, but these beds thin laterally and appear to be very lenticular.

The E lignite bed appears to dip about 25 ft/mi (4.7 m/km) to the north in the Watkins area. This is opposite of the regional dip, which is to the south or southeast. The apparent reversal may be due to a structural fold in the area. However, differential compaction of the lignite beds due to differences in original peat thickness is a more likely explanation of the apparent dip reversal.

Another significant lignite deposit occurs near Station Creek, a small tributary to West Bijou Creek east of Kiowa. The three figures on Plate 4 are maps that isopach the Comanche bed, show overburden thickness above the Comanche bed, and illustrate the total lignite thickness in the Station Creek area. The Comanche bed averages 5 to 10-ft (1.5 to 3.0-m) thick. In a few areas it is less than 5-ft (1.5-m) thick and in part of West Bijou Creek valley it has been removed by erosion. Maximum known thickness of the Comanche bed is 15.7 ft (4.7 m). This occurs in sec. 32, T.8S., R.61W.

Overburden above the Comanche bed is highly variable in the area (Fig. 2, Plate 4). Pleistocene down cutting by West Bijou Creek and its tributaries has resulted in local relief of up to 600 ft (200 m) and has great influence on the amount of overburden above the Comanche. Thoughout much of the area, however, the Comanche bed is within 150 to 200 ft (45 to 60 m) of the surface and can be strip mined. The western edge of West Bijou Creek valley is marked by a large escarpment capped by Dawson Arkose. Beneath this upland area the Comanche bed is more than 300-ft (90-m) deep. A very limited part of the Station Creek area is designated as an alluvial valley floor (Fig. 2, Plate 4) in which strip mining would be prohibited by law.

Figure 3 of Plate 5 is an east-west cross section through the Station Creek area. The Comanche bed is the uppermost lignite bed in the area. The Wolf bed has been either burned, eroded, or was never deposited in most of the area. It is known to occur only in the northeastern corner of the map area. Upper, Middle, and Lower Kiowa beds occur below the Comanche bed. The Middle Kiowa bed appears to pinch out in the eastern part of the area. The Bijou bed lies beneath the Kiowa beds, but drill holes in this particular cross section are too shallow to penetrate the Bijou bed.

Quality

Denver Formation lignite is brownish-black to black, and weathers, slacks, and disintegrates rapidly. Quality of the lignite varies due to the number and thickness of non-coal partings and the physical character and rank of pure lignite. Most analyses indicate the lignite ranks as lignite A, however, thin intervals within thick lignite beds may rank as high as subbituminous C coal. The Comanche bed of the southern lignite area appears to be the highest quality lignite bed in the entire Denver Formation.

Table 4 lists the typical range of as-received analyses of Denver lignite beds. If the reader is interested in specific analyses, refer to Kirkham (1978b). Ash content varies from 8 to 30 percent and is a function of the non-coal partings within a lignite bed. A common characteristic of Denver lignite beds is the presence of numerous partings. All beds have at least one or two thin partings and some have dozens of thin to thick partings. The amount of partings in individual beds also varies laterally.

Table 4. Typical range of as-received analyses of Denver Formation lignite.

Heat Value (Btu/lb)	Moisture (%)	Ash (%)	Sulfur (%)
4,000-7,500	22-40	8-30	0.2-0.6

Partings are primarily clay, but some are clayey or silty sandstone. Most of the clay partings up to 3 to 4-in (7.5 to 10.0-cm) thick are composed primarily of kaolinite. Kaolinite, a potential source of aluminum, may add to the value of the lignite.

Resource Estimates

Landis (1959), in his resource estimates for Colorado coal, reported a total of 963 million tons of Denver Formation lignite in a 187 mi^2 (486 km^2) area encompassing the Scranton district and Ramah-Fondis area. Soister (1974) estimated there to be about 20,000 million tons of lignite in beds 4 ft (1.2 m) thick within 1,000 ft (300 m) of the surface in the Denver Basin. Hornbaker and others (1976) revised the estimates of Landis (1959) and indicated there may be as much as 12,469 million tons of Denver Formation lignite in the Denver Basin. Soister (1978b) restated his resource estimates to suggest there is "more than 10 billion short tons" of lignite in beds 4 ft (1.2 m) thick or greater within 1000 ft (300 m) of the surface.

No formal reserve calculations were attempted during this investigation. Comparison of data gathered during this study with the data and resource estimation methods used in previous reports indicates there is about 10 to 15 billion tons of Denver Formation lignite in the Denver Basin contained in beds at least 4-ft (1.2-m) thick and less than 1,000-ft (300-m) deep. There probably is less than 1 billion tons of lignite at depths greater than 1000 ft (300 m).

METHANE

Methane and numerous other hydrocarbon gases are commonly associated with coal beds. Current research indicates methane may be "drained" from coal beds and used with pipeline natural gas for domestic and commercial uses.

The Colorado Geological Survey is currently conducting a study of methane potential in Colorado coal beds under D.O.E. Grant No. EW-78-G-21-8377. The main source of information comes from residual gas desorption analyses of core samples. To date no samples from the Denver or Cheyenne Basins have been desorbed. However, the Colorado Geological Survey has recently begun U.S.G.S. Grant No. 14-08-0001-G577, a study of the coal resources of the Denver East 1/2° x 1° quadrangle. Both Laramie coal and Denver lignite cores obtained during this drilling project will be desorbed. Specific information on the methane content per ton of coal or lignite will be forthcoming from these investigations.

Existing information, though scant, does indicate there are appreciable amounts of coal gas in Laramie coal beds. No information on methane content is available for Denver Formation lignite beds, but these beds almost certainly contain at least a minor amount of gas.

Fender and Murray (1978) note several Laramie coal mines in the Denver Basin that report gas occurrences. Table 5 lists the mines, locations, and type and year of gas occurrence. The Eagle mine emitted 7,000 ft^3 (196 m^3) of gas per day or 28 ft^3 (0.78 m^3) of gas per ton of coal mined during the first quarter of 1976 (Fender and Murray, 1978).

Additional evidence of gas in Laramie coal beds is contained in the files of the Colorado Division of Water Resources (Romero, 1978b) and the Colorado Oil and Gas Commission (Slyter, 1978). There have been several complaints filed with these offices of gas contamination of water wells. Most owners have thought the gas was related to nearby oil and gas wells or natural gas pipelines. Several water wells have caught fire and have posed threats to lives and property. Study of these problems by the involved State agencies suggests the gas is methane from Laramie coal beds which enters the water wells through misplaced or damaged casing.

Table 5. Gas occurrences in mines of the Denver and Cheyenne Basins. (from Fender and Murray, 1978; see Kirkham, 1978b for detailed mine information)

Mine	Location (county-section-township-range)	Type and Year of Gas Occurrence	Year
Highway	Boulder-28-1S-69W	gas explosion and mine fire(?)	1939
Monarch No. 2	Boulder-28-1S-69W	gas explosion	1936
Nonpariel	Boulder-16-1S-69W	gas explosion	1908
Simpson	Boulder- 2-1S-69W	gas explosion	1912
Standard	Boulder- 1-1S-69W	gas explosion	1908
Sunnyside	Boulder-28-1S-69W	gas explosion	1902
City No. 2	El Paso-33-13S-66W	gas suffocation(?)	-
Pikeview	El Paso-18-13S-66W	gas explosion	1956
Leyden No. 3	Jefferson-27-2S-70W	gassy mine	-
Leyden	Jefferson-26-2S-70W	mine fire	1910
Old Boulder Valley	Weld-18-1N-68W	gassy mine	-
New Boulder Valley	Weld-20-1N-68W	gassy mine	-
Boulder Valley No. 3	Weld- 1-1N-68W	gassy mine	-
Eagle	Weld-15-1N-68W	gassy mine[1]	-
Imperial	Weld-10-1N-68W	gassy mine	-
Lincoln	Weld-24-1N-68W	gassy mine	-
Parkdale	Weld- 6-1S-68W	gas suffocation	1915
Russell	Weld-20-2N-67W	mine fire	1947
Sterling	Weld- 6-1N-67W	gassy mine	-
Washington	Weld-23-1N-68W	gas explosion	1946

[1]The Eagle mine, Weld County caught fire in October, 1978 and was abandoned.

DEVELOPMENT POTENTIAL

Several areas in the Denver Basin and a few areas in the Cheyenne Basin are underlain by coal and lignite geologically favorable for surface and underground mining. In situ and surface gasification may also become viable methods to extract energy from coal and lignite beds in the Denver and Cheyenne Basins. Parts of the study area have undergone intensive urban development and resource recovery may be difficult, if not impossible, in these areas. However, the only operating coal mine in the study area is near an urban area and a nearby proposed small surface mine is also close to the urban area. Large parts of the Denver and Cheyenne Basins, however, are remote and coal development would encounter less opposition there.

Surface mining of Laramie Formation coal may occur in the 1,850 mi^2 designated as potentially strippable areas on Fig. 1 of Plate 1. Within these areas the top of the Laramie coal zone is within 200 ft (60 m) of the surface. Surface mining of Denver Formation lignite is feasible throughout most of eastern part of the Denver Basin. Much of the Denver lignite in the eastern part of the basin that is 5-ft (1.5-m) thick or greater (Fig. 1, Plate 2) may be mined using current strip-mining technology.

Underground mining of Laramie coal is feasible over large parts of the study area where the coals are too deep to strip mine. Underground mines should be deep enough to prevent surface subsidence or be located in areas where surface subsidence would cause no serious damage. In a few areas the roof rock above Laramie coal beds is incompetent and may contribute to roof fall or squeeze problems which could inhibit safe underground mining. This same problem will be encountered in virtually any underground mine working Denver lignite, in that roof rock above Denver lignite beds is generally very incompetent. Roof conditions may preclude mining of Denver lignite by conventional underground methods.

Surface gasification of Denver lignite is also feasible. Cameron Engineers has proposed a surface gasification facility to handle lignite from the Watkins deposit (Hand, 1978b). Urbanization is rapidly nearing the Watkins deposit, but, fortunately, much of the land has been zoned for mineral conservation by Adams County and hopefully will be preserved for future extraction. This proposed project has encountered difficulties because of industry's fears of governmental regulatory interference, citizen lawsuits, problems with federal coal leases, and difficulties obtaining financing (Hand, 1978b), and has not yet begun operations.

In situ gasification of coal and lignite in both the Laramie and Denver Formations may be feasible in the near future. Two of the current prime requisites for in situ gasification are 1) the coal bed must be sufficiently permeable to allow passage of gases and 2) the coal bed must be deep enough (usually about 500 ft (150 m)) to alleviate or minimize subsidence hazards, but not more than about 1500 ft (450 m) to avoid excessive drilling expenses.

Lignite beds are usually permeable and therefore suitable for in situ gasification. Permeability may also be artificially improved by hydro-fracturing or drilling. Denver Formation lignite beds which occur at appropriate depths may readily be gasified in situ. Unfortunately, these lignite beds are generally thin or are carbonaceous in areas where they are deep enough to be gasified. A few thick lignite beds at suitable depths do exist, but these beds are not as common or as thick as the lignite beds found in strippable areas in the eastern part of the Denver Basin.

Approximately 2,040 mi^2 (5,280 km^2) of the study area are underlain by Laramie coal at depths suitable for in situ gasification. In the eastern part of the study area the coal in the Laramie Formation is lignitic and has favorable permeabilities. Thicknesses of 5 to 12 ft (1.5 to 3.6 m) are common in much of the strippable areas in the east. Scattered drill holes suggest similar beds may occur at depths appropriate for in situ gasification to the west. Within the structural zone on the west flank of the Denver and Cheyenne Basins Laramie coal beds range in dip from 45° east to steeply overturned. Techniques used to gasify steeply dipping coal beds may be applicable in this area.

Methane is known to occur in Laramie coal beds in several areas and probably occurs, at least in limited amounts, in Denver lignite beds. Until further testing to determine methane contents is completed, the potential for methane extraction from these coal beds is unknown. At the present, however, water wells which contain methane from coal or lignite beds can be modified to allow for separation of the coal gas from the water and use of the gas for domestic purposes.

One of the major limiting factors to coal development in the study area is water. Virtually all surface water is appropriated and it would therefore be necessary to obtain water rights if tributary water is needed for a particular project. Non-tributary ground water occurs in several formations in the area, but it is limited in quantity. The Colorado Division of Water Resources puts restrictions as to what ground water and how much ground water a particular user can withdraw. This water-supply problem may inhibit large water-consuming projects such as surface gasification plants, but not conventional surface and underground mines, or in situ gasification facilities (Romero, 1978a).

Another type of water problem is water pollution. Laramie coals are often intimately associated with the Laramie-Fox Hills aquifer. Denver lignites are directly below the Dawson Arkose, a prolific water-producing formation, and above sandstones which provide small quantities of water from the lower Denver Formation. Problems of resource recovery versus water quality in these aquifers can be anticipated.

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MAPS OF THE LARAMIE FORMATION COAL, DENVER AND CHEYENNE BASINS, COLORADO

by Robert M. Kirkham and L. R. Ladwig

1979

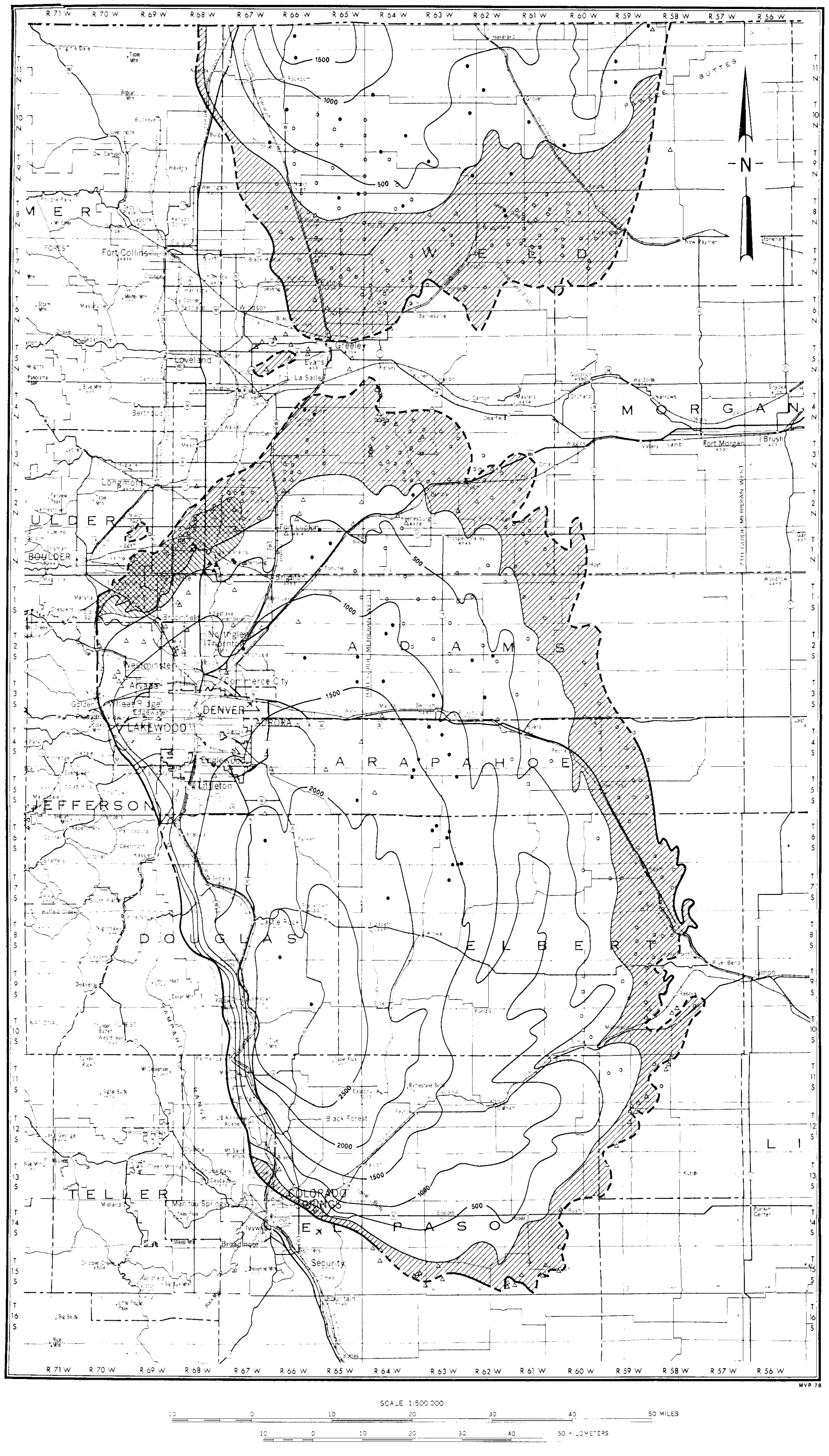

FIGURE 1

DEPTH TO THE TOP OF THE LARAMIE FORMATION COAL ZONE

EXPLANATION

Contour line showing approximate depth to the top of the Laramie Formation coal zone; contour interval 500 feet

Note: A thin coal zone occurs in the upper part of the Laramie Formation in the western part of the Cheyenne Basin, but this zone is not considered on this map.

Area of potentially strippable coal; the top of the Laramie Formation coal zone is within 200 feet of the surface in this area

Area of complex geology and extensive mining; faulting and erosion have locally removed some coal beds; significant parts of this area have been mined out

Outcrop or subcrop line of the coal-bearing part of the Laramie Formation; dashed where approximately located

Data points:
- ○ Coal exploration drill hole
- • Oil or gas drill hole
- △ Water well
- ▲ Miscellaneous drill hole

Note: Mine data was also used to prepare this map, but these data points are not shown; and in areas with few data points, the depth to the top of the Laramie Formation coal zone was approximated from Romero (1976) and unpublished maps by A. K. Wacinski and S. J. Zawistowski of the Colorado Division of Water Resources.

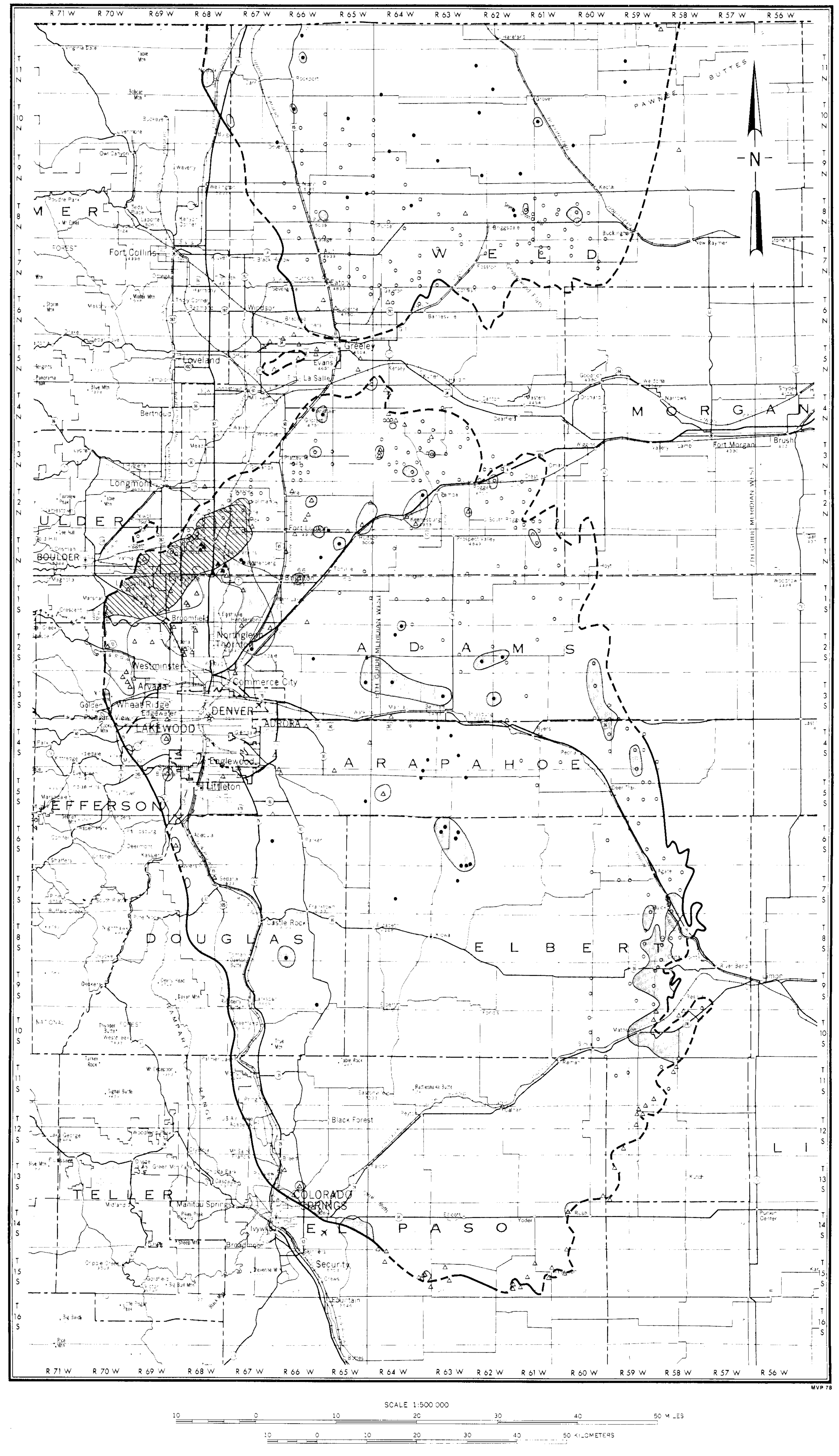

FIGURE 2

AREAS KNOWN TO BE UNDERLAIN BY LARAMIE COAL BEDS, FIVE FEET THICK OR GREATER

EXPLANATION

Approximate outline of areas known to be underlain by Laramie coal beds five feet thick or greater

Area of complex geology and extensive mining; faulting and erosion have locally removed some coal beds; significant parts of this area have been mined out

Outcrop or subcrop line of the coal-bearing part of the Laramie Formation; dashed where approximately located

Data points:
- ○ Coal exploration drill hole
- • Oil or gas drill hole
- △ Water well
- ▲ Miscellaneous drill hole

Note: A part of the area in which drill hole information is sparce is almost certainly underlain by Laramie coal beds at least five feet thick. Thick coal beds may also exist in areas where drill holes do not penetrate the entire coal zone.
Mine data was also used to prepare this map, but these data points are not shown.

COLORADO GEOLOGICAL SURVEY
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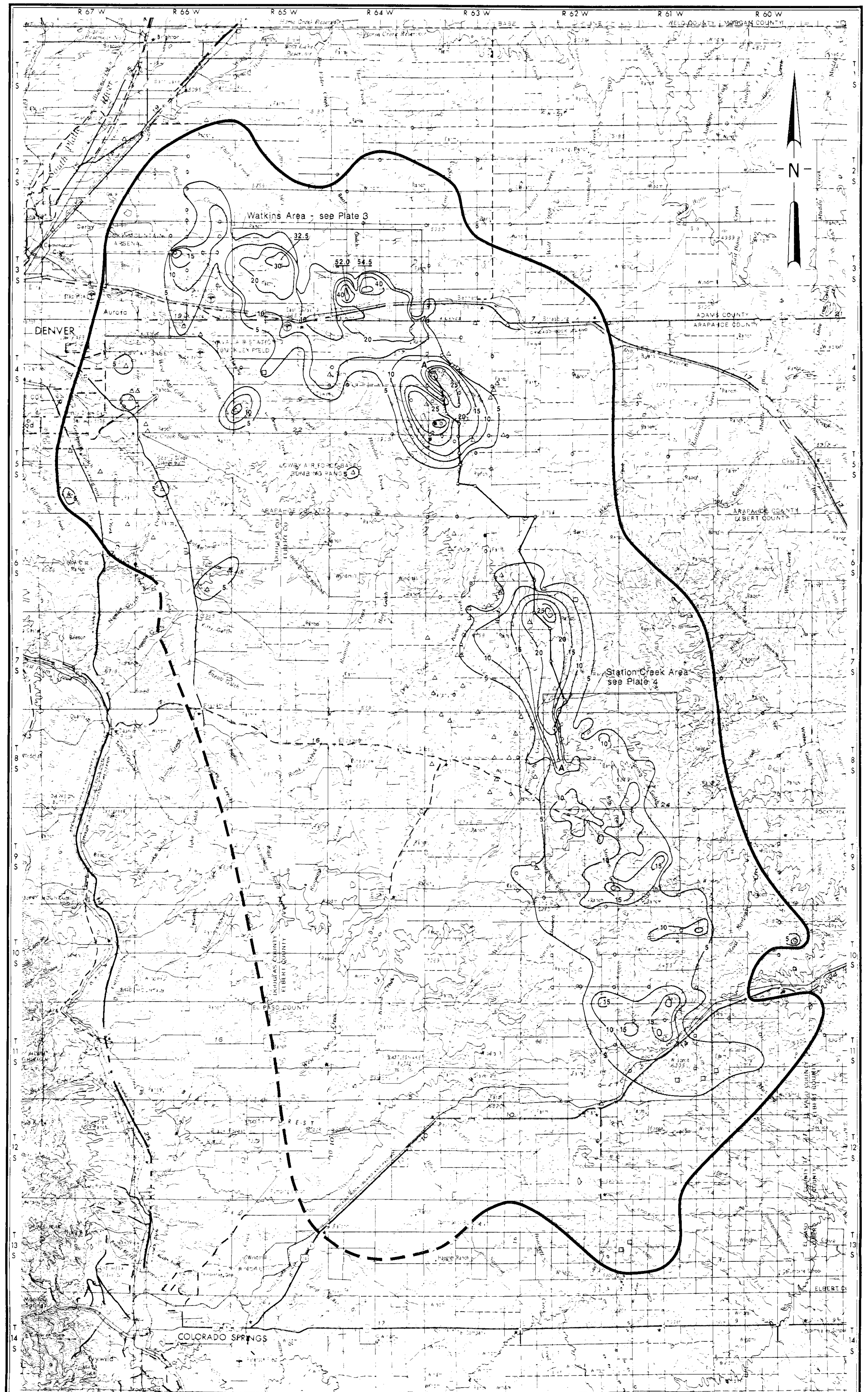
MAPS OF THE DENVER FORMATION LIGNITE, DENVER BASIN, COLORADO

by Robert M. Kirkham and L. R. Ladwig

1979



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5 0 5 10 15 20 25 MILES

5 0 5 10 15 20 25 KILOMETERS

FIGURE 1

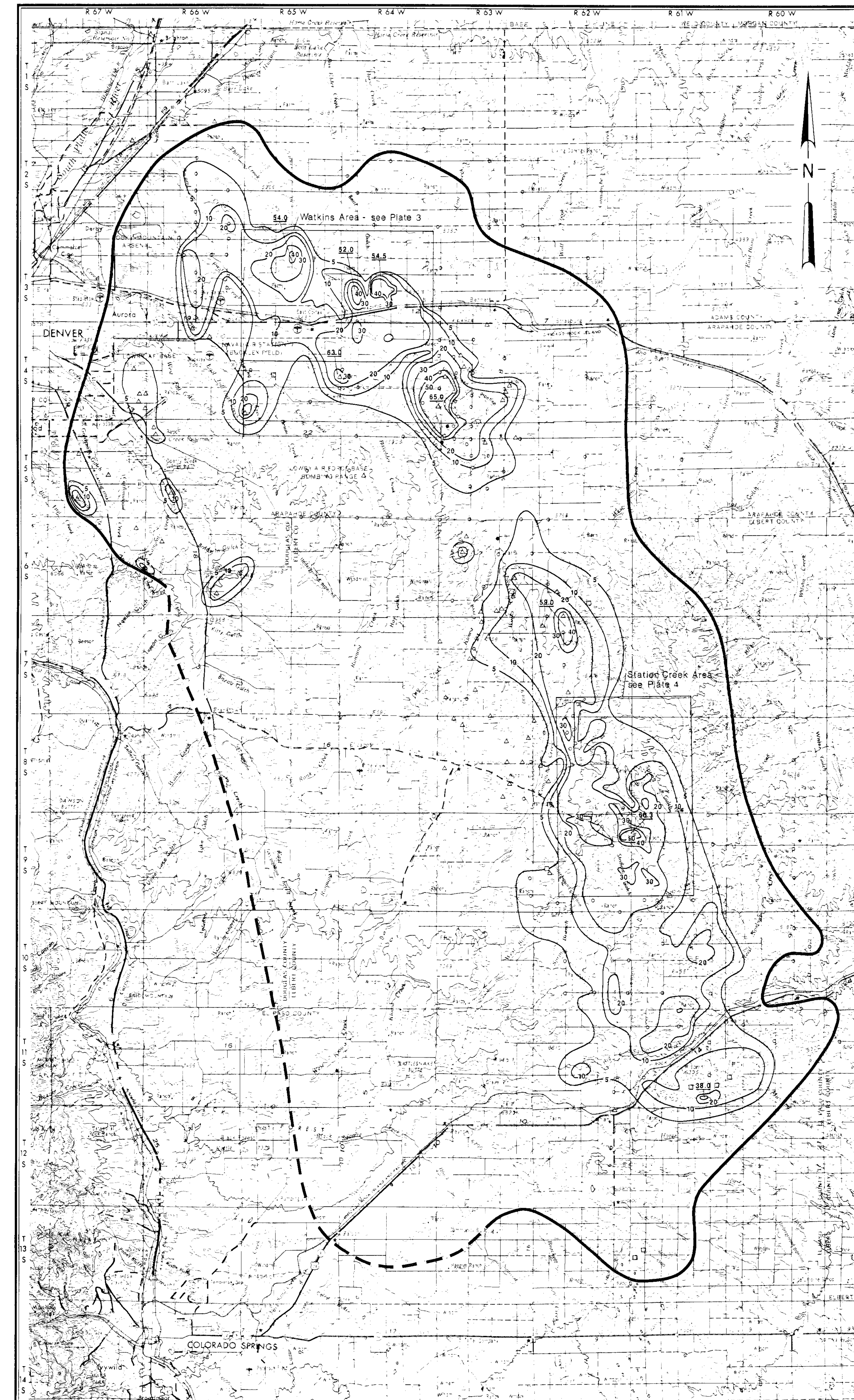
MAXIMUM INDIVIDUAL LIGNITE BED THICKNESS IN THE DENVER FORMATION

EXPLANATION

- Contour Line showing maximum individual lignite bed thickness; contour interval 5 feet, except in the Watkins area, where certain lines are omitted for clarity
- 50.0 — Maximum individual lignite bed thickness in the Watkins area
- Outcrop or Subcrop Line of lignite-bearing rock in the Denver Formation; dashed where approximately located
- A—A' Cross Section Line - see Plate 5

Data points:
- Coal exploration drill hole
- Oil or gas drill hole
- Water well
- Abandoned lignite mine

Note: See Plates 3 and 4 for detailed information about the Watkins and Station Creek areas



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5 0 5 10 15 20 25 KILOMETERS

FIGURE 2

TOTAL LIGNITE BED THICKNESS IN THE DENVER FORMATION

EXPLANATION

- Contour Line showing total thickness of all known lignite beds in the Denver Formation; contour lines at 5, 10, 20, 30, 40, and 50 feet; in some areas certain lines are omitted for clarity
- 50.0 — Maximum total lignite bed thickness in each area
- Outcrop or Subcrop Line of lignite-bearing rock in the Denver Formation; dashed where approximately located

Data points:
- Coal exploration drill hole
- Oil or gas drill hole
- Water well
- Abandoned lignite mine

Note: See Plates 3 and 4 for detailed information about the Watkins and Station Creek areas

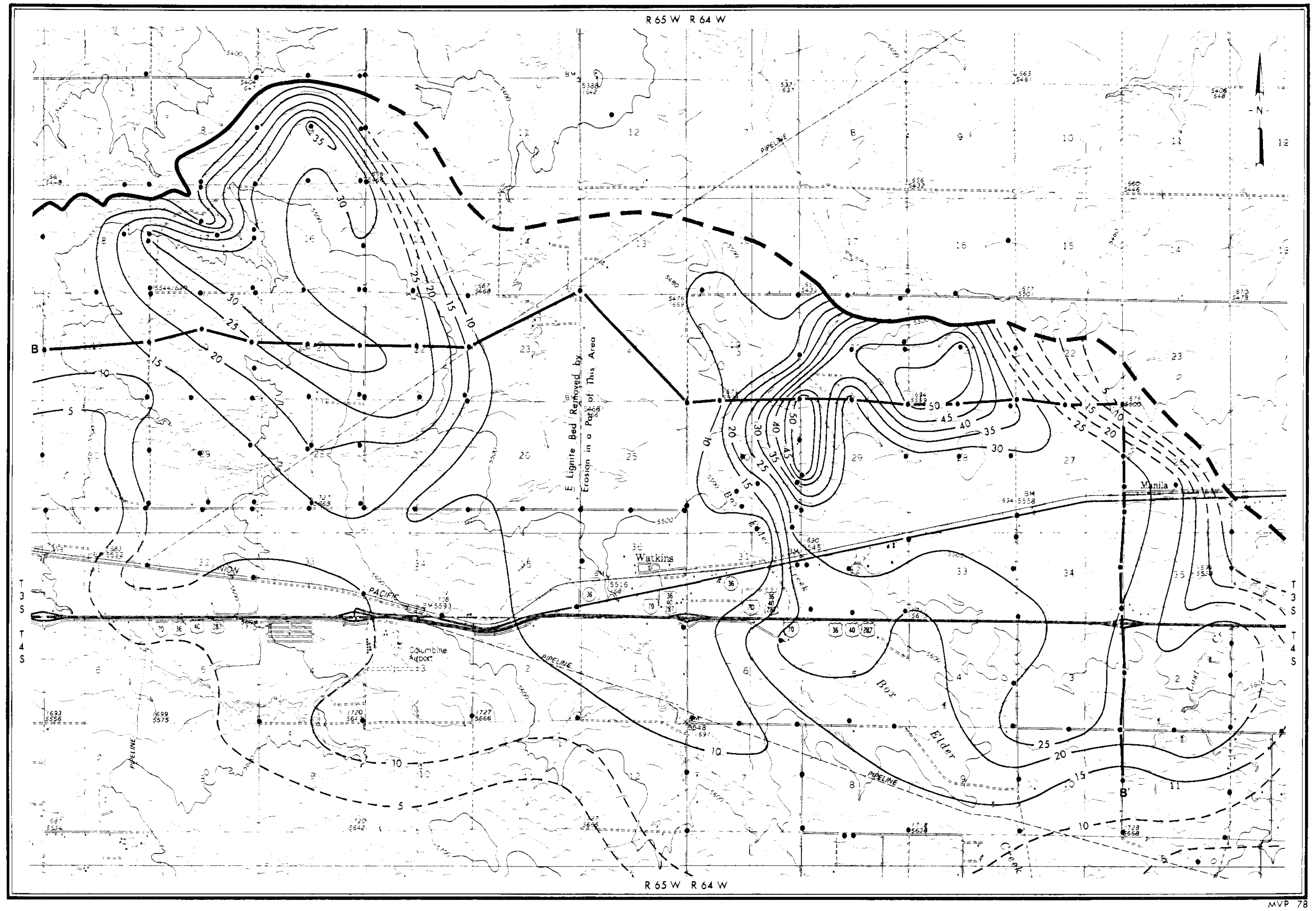
COLORADO GEOLOGICAL SURVEY
DEPT. OF NATURAL RESOURCES
STATE OF COLORADO
JOHN W. ROLD, DIRECTOR

MAPS OF THE WATKINS AREA, ADAMS AND ARAPAHOE COUNTIES, COLORADO

by Robert M. Kirkham and L. R. Ladwig

1979

COLORADO GEOLOGICAL SURVEY
RESOURCE SERIES 5
PLATE 3 OF 5



SCALE 1:50 000

1 ½ 0 1 2 3 MILES

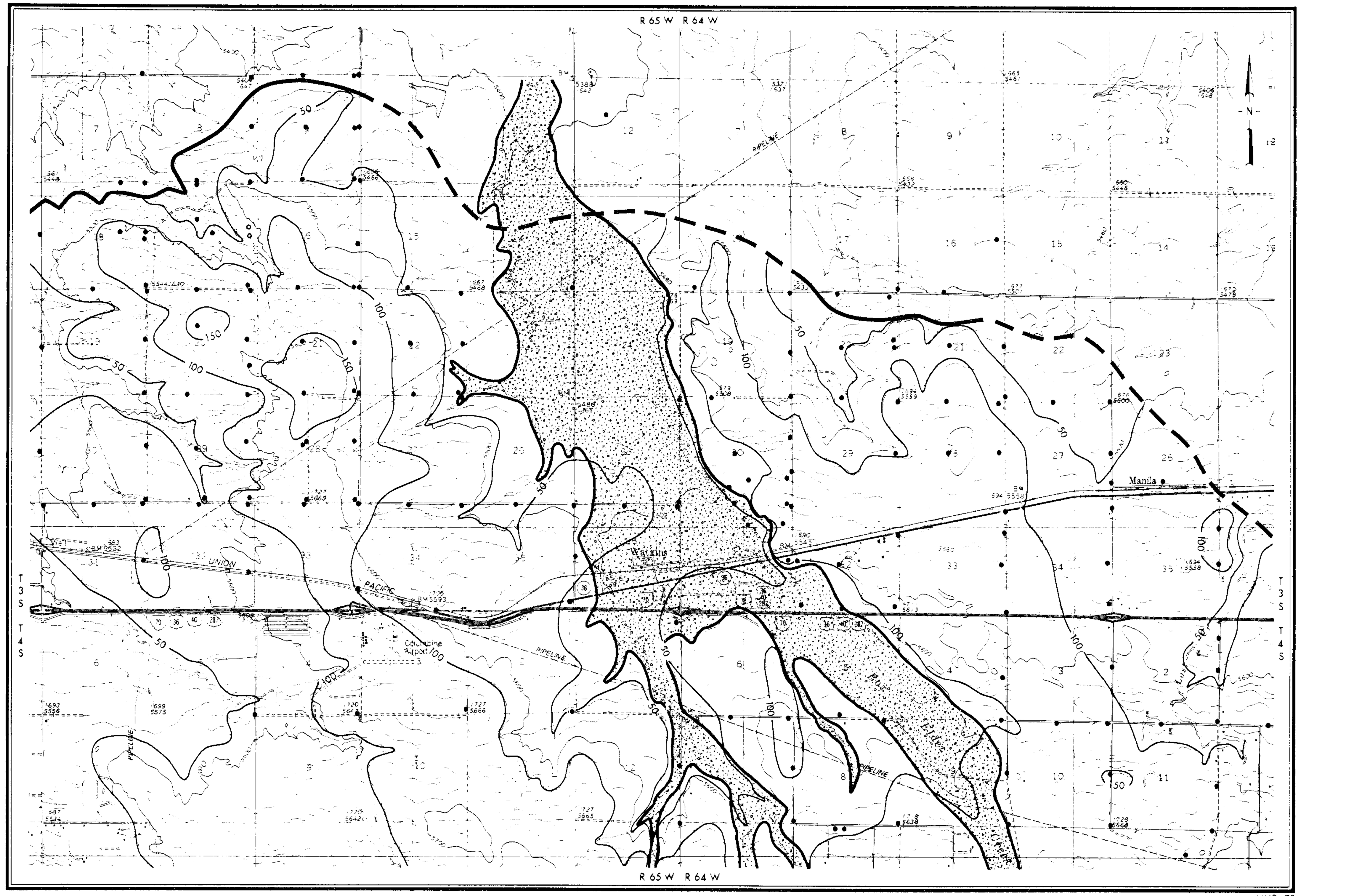
1 .5 0 1 2 3 KILOMETERS

FIGURE 1

ISOPACH MAP OF THE E LIGNITE BED, WATKINS AREA

EXPLANATION

- Isopach Line showing thickness of the E Lignite Bed; dashed where approximately located; contour interval 5 feet
- Subcrop Line of the E Lignite Bed; dashed where approximately located
- B —— B' Cross Section Line - see Plate 5
- • Drill Hole Location



SCALE 1:50 000

1 ½ 0 1 2 3 MILES

1 .5 0 1 2 3 KILOMETERS

FIGURE 2

EXTENT OF THE ALLUVIAL VALLEY FLOOR AND OVERBURDEN THICKNESS ABOVE THE E LIGNITE BED, WATKINS AREA

EXPLANATION

- Contour Line showing overburden thickness above the E Lignite Bed; cashed where approximately located; contour interval 50 feet
- Approximate limits of the Alluvial Valley Floor, as defined by Public Law 95-87
- Subcrop Line of the E Lignite Bed; dashed where approximately located
- • Drill Hole Location

COLORADO GEOLOGICAL SURVEY
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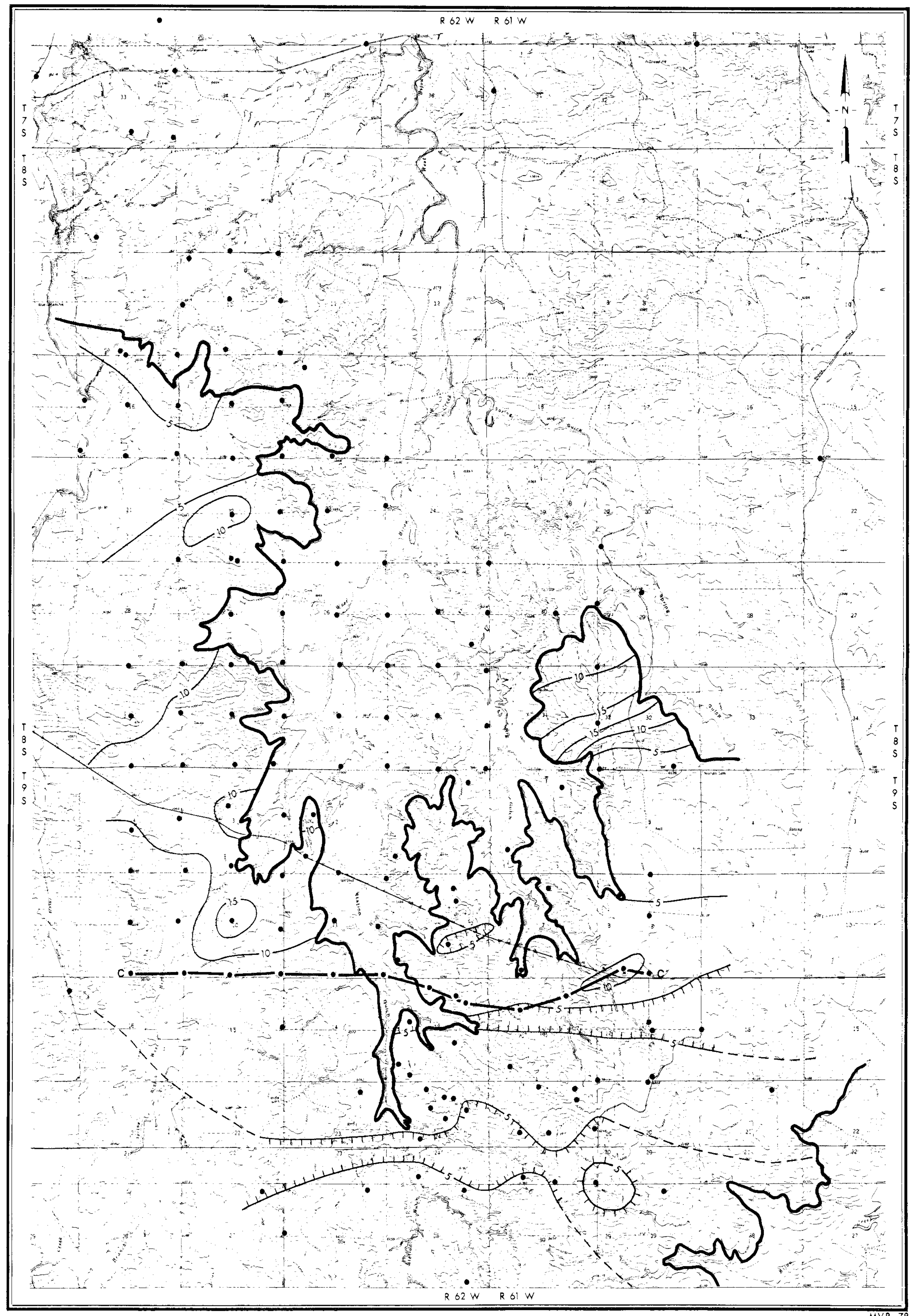
STATE OF COLORADO
JOHN W. ROLD, DIRECTOR

MAPS OF THE STATION CREEK AREA, ELBERT COUNTY, COLORADO

by Robert M. Kirkham and L. R. Ladwig

1979



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3 MILES

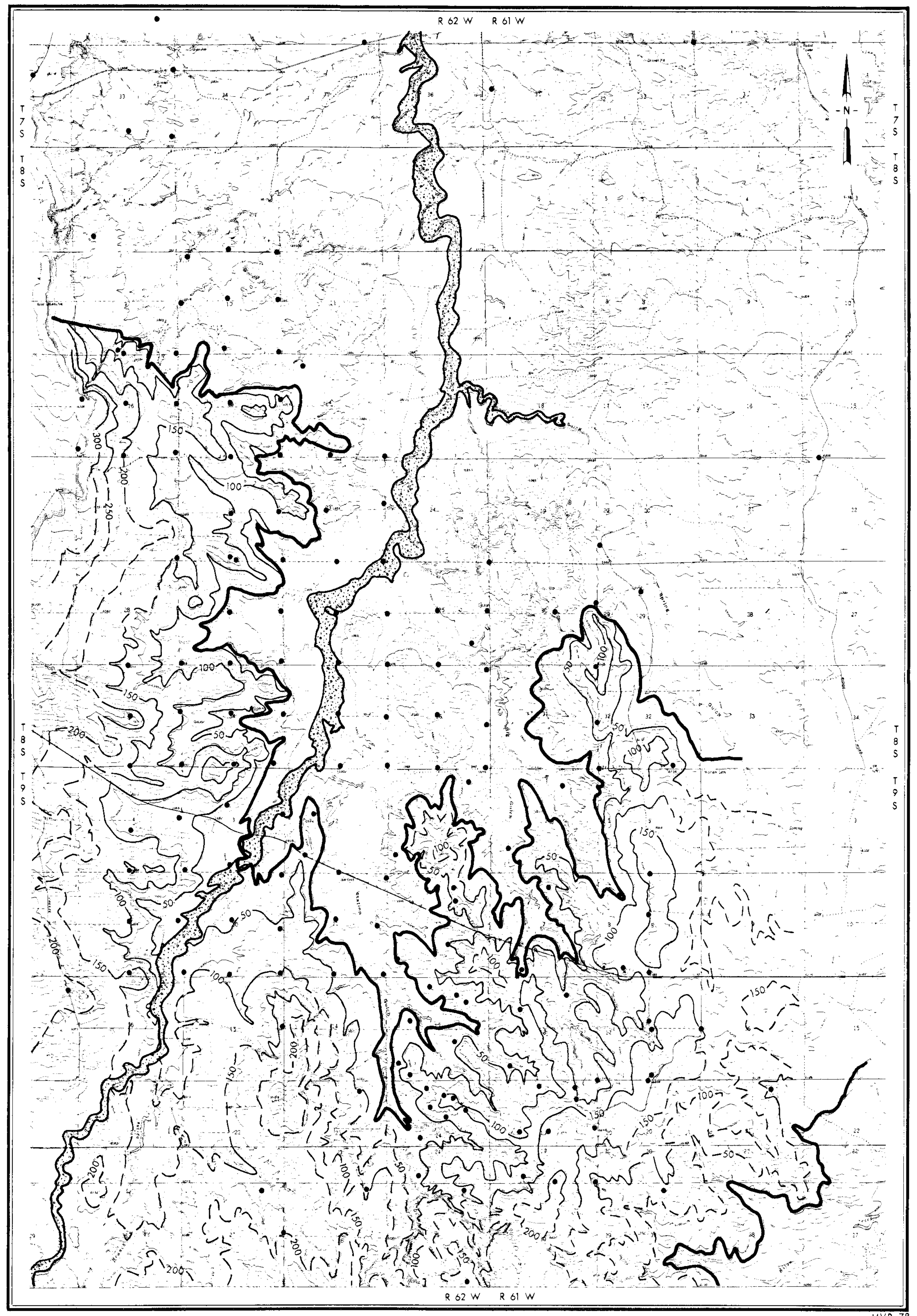
3 KILOMETERS

FIGURE 1

ISOPACH MAP OF THE COMANCHE BED, STATION CREEK AREA

EXPLANATION

- Isopach Line showing thickness of the Comanche Bed; dashed where approximately located; contour interval 5 feet
- Outcrop or Subcrop Line of the Comanche Bed
- C — C' Cross Section Line - see Plate 5
- Drill Hole Location



SCALE 1:50 000

3 MILES

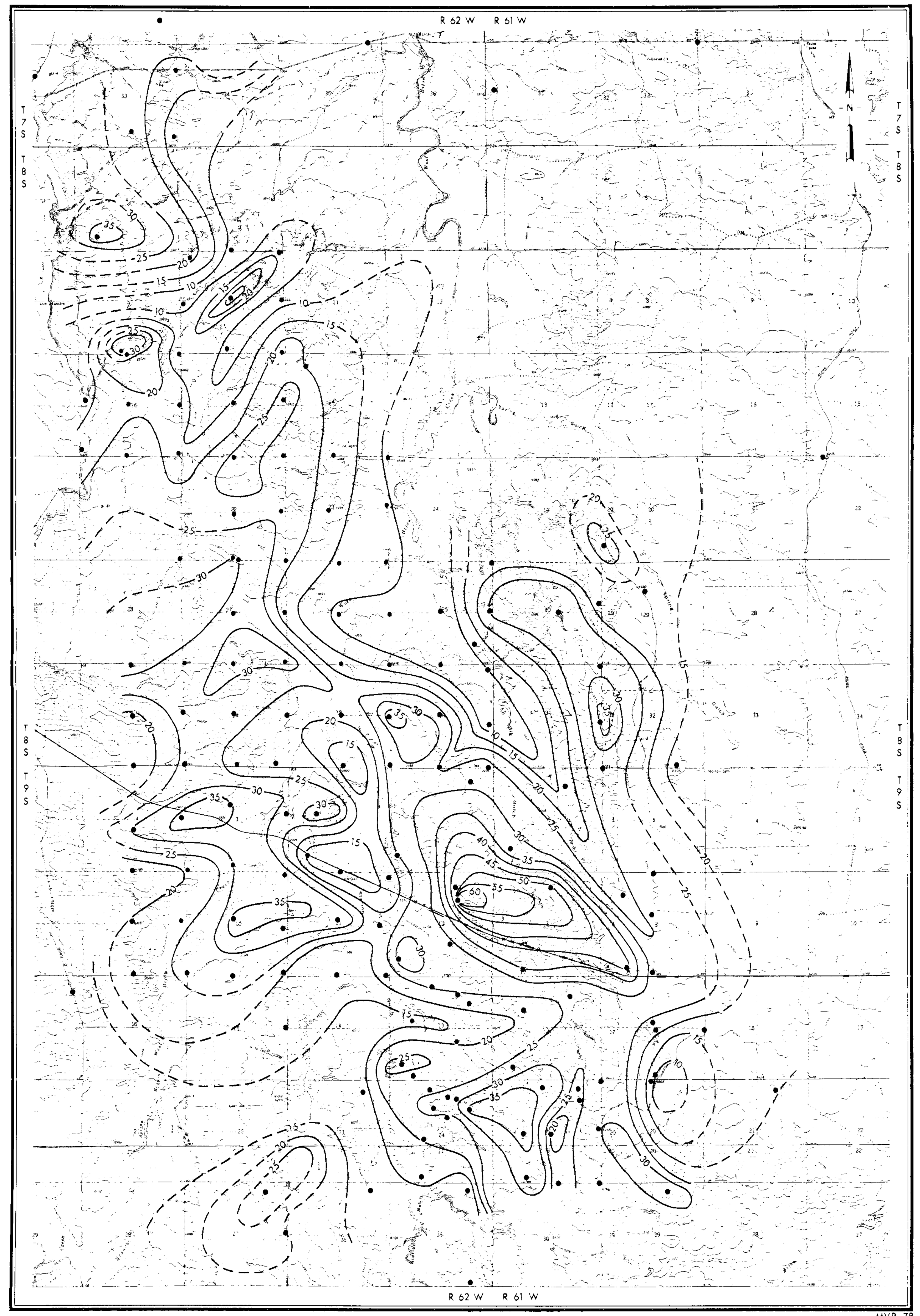
3 KILOMETERS

FIGURE 2

EXTENT OF THE ALLUVIAL VALLEY FLOOR AND OVERBURDEN THICKNESS ABOVE THE COMANCHE BED, STATION CREEK AREA

EXPLANATION

- Contour Line showing overburden thickness above the Comanche Bed; dashed where approximately located; contour interval 50 feet
- Approximate limits of the Alluvial Valley Floor as defined by Public Law 95-87
- Outcrop or Subcrop Line of the Comanche Bed
- Drill Hole Location



SCALE 1:50 000

3 MILES

3 KILOMETERS

FIGURE 3

TOTAL THICKNESS OF LIGNITE BEDS IN THE DENVER FORMATION, STATION CREEK AREA

EXPLANATION

- Isolith Line showing total known thickness of the lignite beds in the Denver Formation; dashed where approximately located; contour interval 5 feet
- Drill Hole Location

COLORADO GEOLOGICAL SURVEY
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STATE OF COLORADO
JOHN W. ROLD, DIRECTOR

CROSS SECTIONS OF THE DENVER FORMATION LIGNITE BEDS, DENVER BASIN, COLORADO

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COLORADO GEOLOGICAL SURVEY
RESOURCE SERIES 5
PLATE 5 OF 5

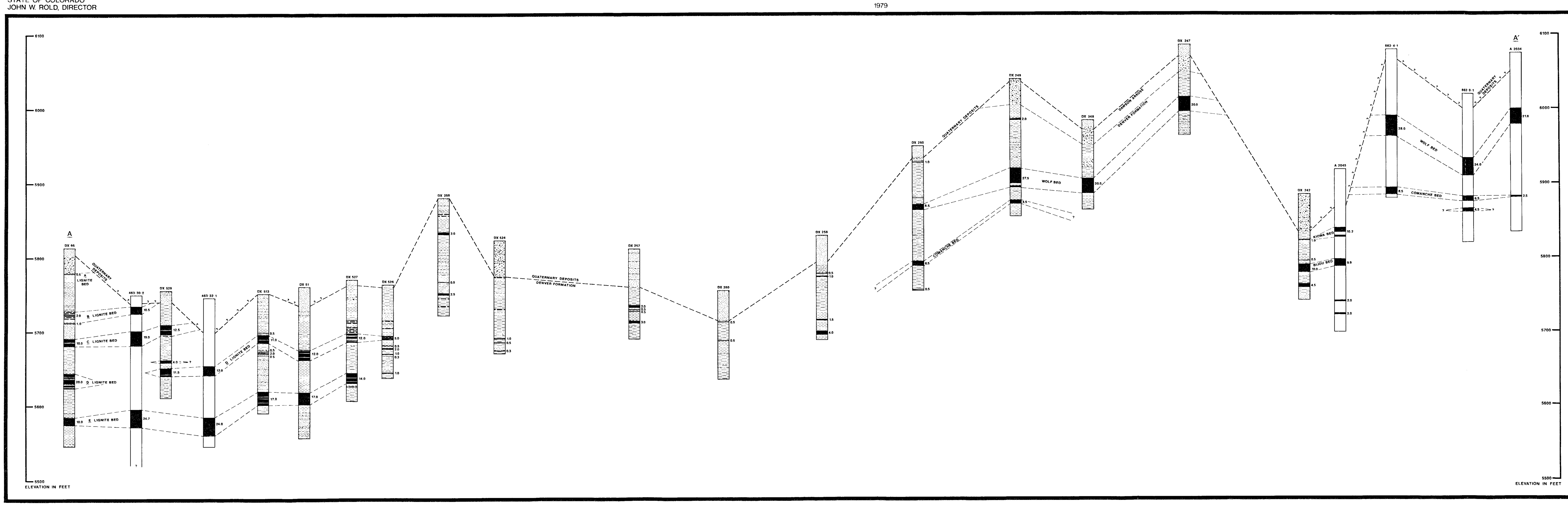

FIGURE 1

CROSS SECTION A – A'
NORTH-SOUTH CROSS SECTION THROUGH THE DENVER FORMATION LIGNITE ZONE

HORIZONTAL SCALE 1 : 48,000
VERTICAL SCALE 1 : 600
VERTICAL EXAGGERATION 1 : 80
DATUM IS MEAN SEA LEVEL

EXPLANATION

- Gravel or Conglomerate
- Sand or Sandstone
- Silt or Siltstone
- Clay or Claystone
- Limestone or Marl
- Carbonaceous Clay or Silt
- Lignite; number indicates total bed thickness in feet

Note: Descriptive detail of each log is variable.

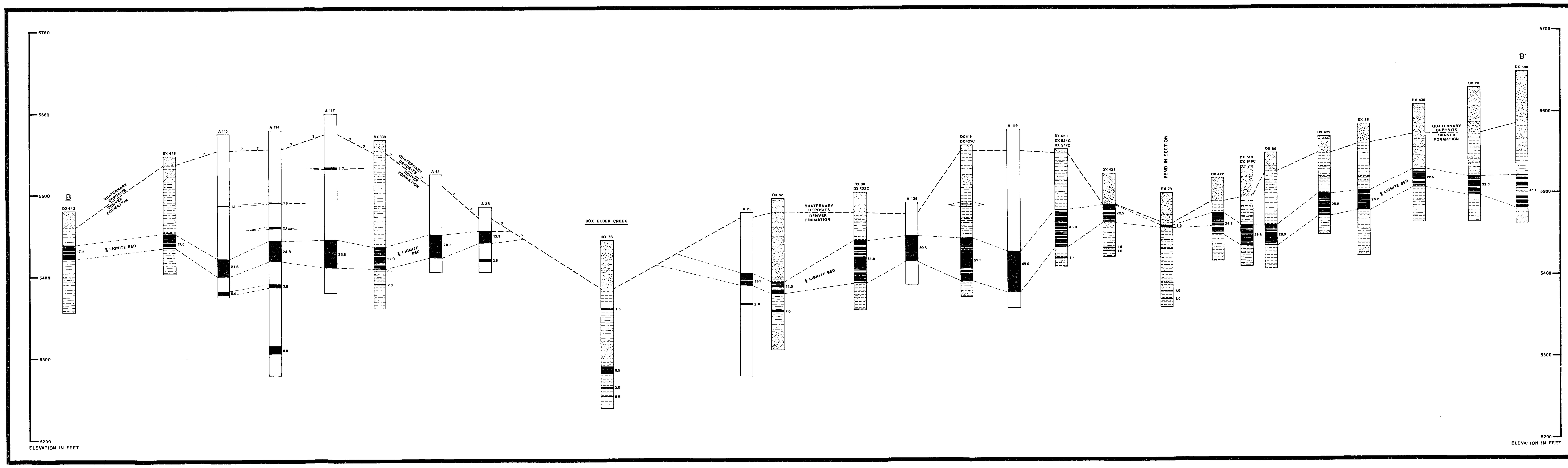

FIGURE 2

CROSS SECTION B – B'
CROSS SECTION THROUGH THE WATKINS LIGNITE DEPOSIT, ADAMS AND ARAPAHOE COUNTIES

HORIZONTAL SCALE 1 : 25,000
VERTICAL SCALE 1 : 600
VERTICAL EXAGGERATION 1 : 41.7
DATUM IS MEAN SEA LEVEL

EXPLANATION

- Gravel or Conglomerate
- Sand or Sandstone
- Silt or Siltstone
- Clay or Claystone
- Limestone or Marl
- Carbonaceous Clay or Silt
- Lignite; number indicates total bed thickness in feet

Note: Descriptive detail of each log is variable.

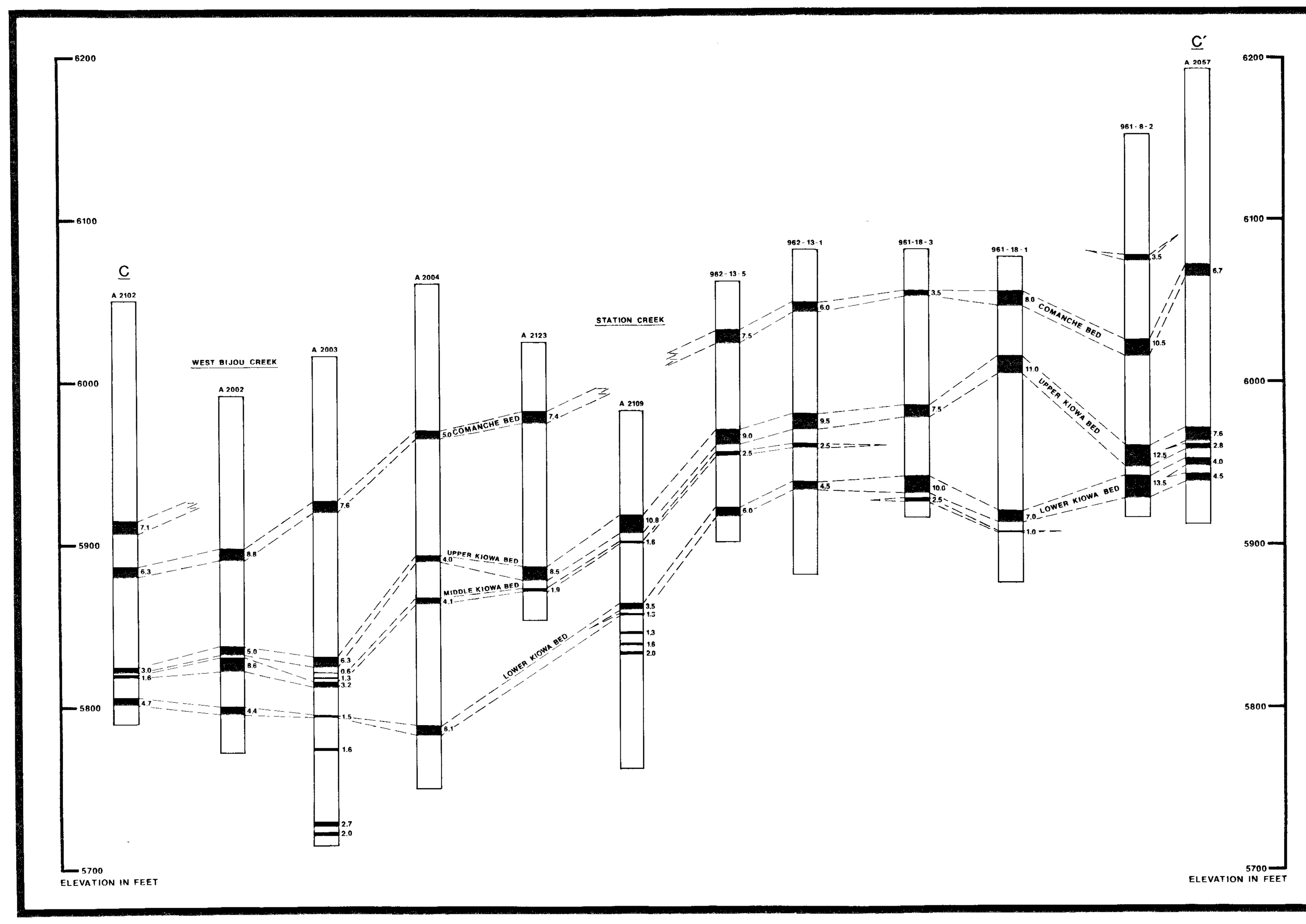

FIGURE 3

CROSS SECTION C – C'
CROSS SECTION THROUGH THE STATION CREEK LIGNITE DEPOSIT, ELBERT COUNTY

HORIZONTAL SCALE 1 : 25,000
VERTICAL SCALE 1 : 600
VERTICAL EXAGGERATION 1 : 41.6
DATUM IS MEAN SEA LEVEL

EXPLANATION

- Lignite; number indicates total bed thickness in feet

Note: Descriptive detail of each log is variable.