Chapter 3

# Coal in the Front Range Urban Corridor—An Overview of Coal Geology, Coal Production, and Coal-Bed Methane Potential in Selected Areas of the Denver Basin, Colorado, and the Potential Effects of Historical Coal Mining on Development and Land-Use Planning

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By Stephen B. Roberts

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Compiled by Debra K. Higley

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# Coal in the Front Range Urban Corridor—An Overview of Coal Geology, Coal Production, and Coal-Bed Methane Potential in Selected Areas of the Denver Basin, Colorado, and the Potential Effects of Historical Coal Mining on Development and Land-Use Planning

By Stephen B. Roberts

## Abstract

The Denver Basin contains an estimated 30–40 billion short tons of coal in Upper Cretaceous and Tertiary strata at depths of less than 3,000 feet, and from the late 1850s through the 1970s coal mining was an integral part of many communities in the Front Range Urban Corridor. There has been no commercial coal mining in the Denver Basin for more than 20 years, however, and the likelihood of any significant revival of coal mining seems remote at this time (2004). This is due, in part, to the increased competition for land arising from population growth and the consideration that rapid expansion of urban, commercial, and residential development would probably inhibit coal-mining ventures in many areas along the Front Range. However, even though renewed coal mining will not likely compete with other land-use interests in the foreseeable future, other coal-related issues, such as the potential for development of coal-bed gas (methane) resources and continued effects stemming from historical underground coal mining, might be factors to consider in future land-use plans for certain areas.

Coal deposits within the Laramie Formation (Upper Cretaceous: Maastrichtian) and the Denver Formation (lower Tertiary: Paleocene) are distributed throughout much of the Denver Basin. More than one-third of the total land area in Colorado underlain by coal-bearing rocks at depths of less than 3,000 feet lies within the Denver Basin. During 120 years of coal mining activity, more than 130 million tons of coal was produced. Of this total, more than 99 percent came from the Laramie Formation. The formation ranges from about 350 to 1,800 feet in thickness, and coal of subbituminous rank is concentrated in the lower 300 feet. Laramie coal beds range from less than 1 foot thick to more than 20 feet thick locally. Estimates of the remaining (unmined) coal in beds greater than 2.5 feet thick and at depths of less than 3,000 feet are about 20–25 billion tons. The Denver Formation ranges in thickness from 600 to 1,580 feet, and beds of lignitic coal are concentrated in the upper 500 feet of the formation. Lignite beds are as thick as 55 feet in some areas of the Denver Basin, and estimates of the remaining (unmined) coal resources in coal beds greater than 4 feet thick and at depths of less than 1,000 feet are on the order of 10–15 billion tons.

To date, there has been no coal-bed methane production in the Denver Basin. However, the successful production of coal-bed methane in other basins, particularly in the Powder River Basin (Wyoming and Montana), has helped to stimulate interest in studying the potential for coal-bed methane development in the Denver Basin. This interest might be based largely on the success of coal-bed methane development from subbituminous coal beds that are comparable in rank to coal in the Laramie Formation and on estimates indicating that there could be as much as 2 trillion cubic feet of coal-bed methane (in place) within the combined Laramie and Denver Formations. The Laramie Formation might be more prospective for coal-bed gas than the Denver Formation, given the slightly higher apparent rank of the Laramie coal beds, the widespread distribution of the formation throughout the Denver Basin, and limited desorption data that indicate total coal gas contents of about 24 cubic feet per ton in some Laramie coal beds. In addition, the potential for recovery of “behind-pipe” coal-bed methane resources in existing gas wells penetrating the Laramie Formation might be facilitated in areas such as the Wattenberg gas field, where a gas recovery and transport infrastructure is already established.

Effects from historical underground coal mining operations continue to exist in certain areas of the basin. Even though much of the surface expression of mine development has been removed or masked by increasing urban and residential development, subsurface features of underground mining, such as shafts and open mine rooms, are still present. Because of this, the potential remains for underground fires and for coal-mine subsidence in abandoned mine areas. Coal-mine subsidence is a dynamic process that can occur many years after a mine has been abandoned. Progressive upward collapse of roof rock and overburden above an abandoned mine can cause the development of subsidence features at the

ground surface, thereby creating a potential for damage to new or existing structures (roads, houses, businesses, and so forth) in susceptible areas. Although numerous investigations of coal-mine subsidence in the Denver Basin have identified subsidence-prone areas and have established some criteria for land-use planning above abandoned mines, subsidence prediction is commonly hampered by the availability and quality of historical mine maps and records, limitations in the applicability of established predictive models, and the variability in subsurface mine conditions. Available data can be supplemented by drilling programs, which can improve upon existing mine data and greatly enhance an understanding of present-day mine conditions in specific sites. All of these data are critical for ensuring safe development in undermined areas.

# Introduction

The Denver Basin, as defined by Matuszczak (1973), occupies an area of about 70,000 mi$^2$ in eastern Colorado, western Nebraska, and southern Wyoming (fig. 1). Because the Front Range Infrastructure Resources Project (FRIRP) of the U.S. Geological Survey (USGS) was designed to address issues related to energy, land, water, aggregate, and biological resources in the Front Range Urban Corridor in and near the Denver metropolitan area (for example, see Fishman, this volume), only areas within the Colorado part of the Denver Basin were studied. Therefore, it should be noted that any reference to the Denver Basin in this chapter refers only to the Colorado part of the basin as designated by Matuszczak (1973).

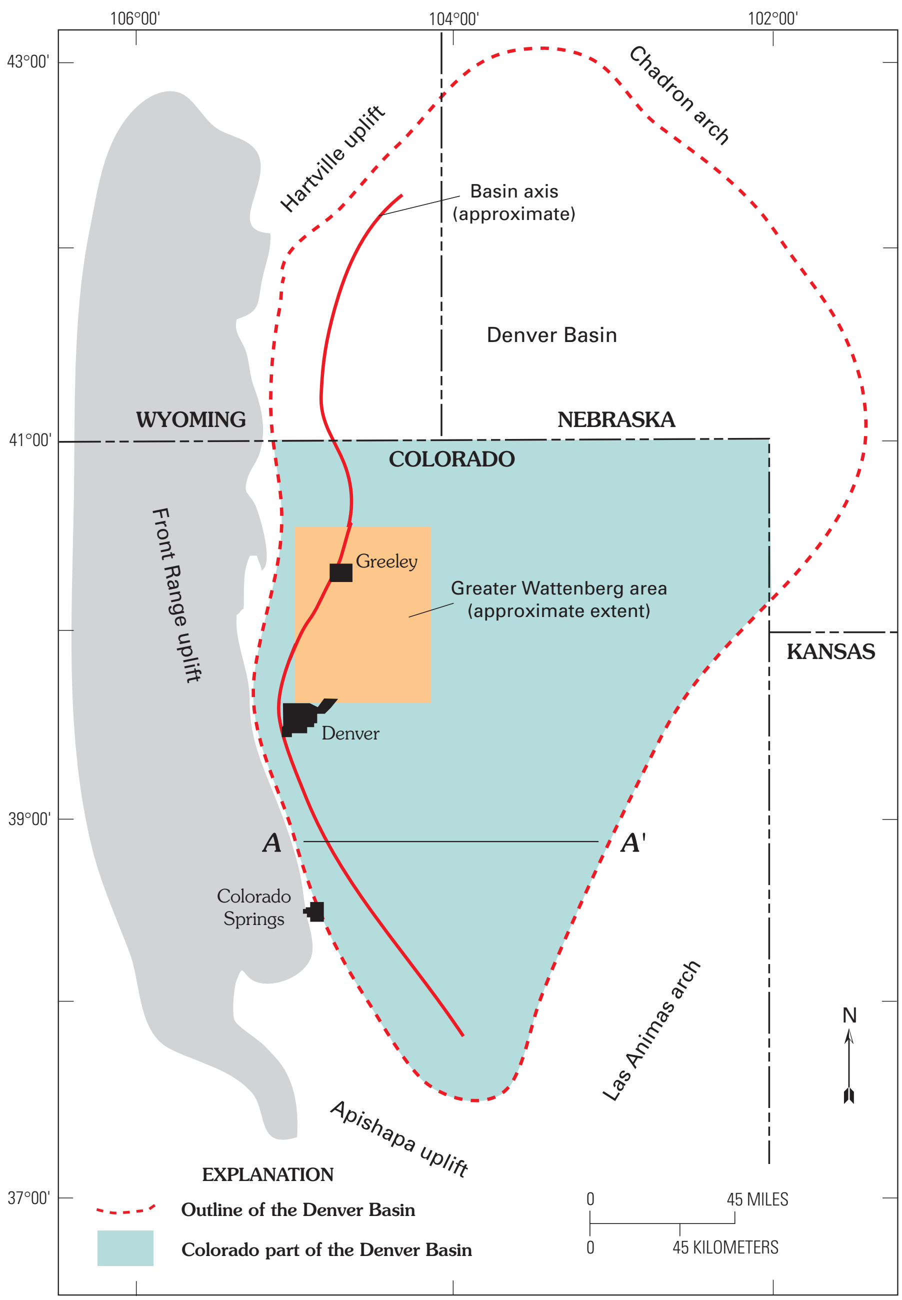


**Figure 1.** Approximate extent of the Denver Basin and bounding structural features, and the location and extent of the greater Wattenberg area (GWA), Colorado. The GWA is an area in which a coal-bed methane pilot study was conducted as part of the Front Range Infrastructure Resources Project. Cross section *A–A′* is shown in figure 11. Denver Basin extent modified from Matuszczak (1973).

The Denver Basin contains an estimated 30–40 billion tons of coal in Upper Cretaceous and Tertiary strata at depths of less than 3,000 ft (for example, see Kirkham and Ladwig, 1979), and from the late 1850s through the 1970s, underground coal mining was an integral part of many communities in the Front Range Urban Corridor. There has been no commercial coal mining in the Denver Basin for more than 20 years, however, and the likelihood of any significant revival of coal mining in the basin seems remote at this time. This is primarily because the coal-production infrastructure has already been dismantled and removed, and the reestablishment of a competitive coal industry in the Denver Basin might be difficult given the established commercial coal production in other Colorado coal fields and in adjacent States such as Utah and Wyoming. Additionally, the competition for land arising from population growth and the associated expansion of urban, commercial, and residential developments would probably inhibit coal-mining ventures in many areas along the Front Range. However, even though coal mining will likely not be renewed in the foreseeable future, other coal-related issues, such as the potential for development of coal-bed gas (methane) resources and continued effects stemming from historical underground coal mining, might be a factor in land-use planning in certain areas of the Denver Basin. Studies of the coal-bed methane potential are still in a relatively fledgling state, and there is currently no production of this resource in the basin. Successful coal-bed methane production in other Colorado basins, and in Wyoming and New Mexico, has helped to spark an interest in the Denver Basin methane potential. If this resource eventually proves to be economic, companies interested in developing coal-bed methane might also enter the competitive quest for land within the basin.

Perhaps the current, most important “coal-related” issues in the Denver Basin stem from historical coal mining. Effects from historical coal mining can range from visible remnants of coal production (for example, railroad beds, abandoned buildings, mine dumps, and so forth) to potentially more serious problems, such as coal-mine fires and coal-mine subsidence resulting from the collapse of open shafts, rooms, and entryways in abandoned underground coal mines. Coal-mine subsidence is a particularly important consideration, as this process can induce sinking or collapse of the ground surface above an abandoned mine, which, in turn, can cause serious structural damage to buildings and infrastructure (for example, roads, gas lines, and so forth) that might exist on or in the subsiding ground. As communities continue to expand into undermined areas where a potential for coal-mine subsidence still exists, careful planning is needed to help ensure that the type of development (for example, residential or commercial) and corresponding construction design are appropriate for these areas. Because this issue has been of considerable interest and concern for some time, numerous studies pertaining to the coal-mine subsidence potential in certain Front Range areas were conducted during the 1970s and 1980s (for example, see Mernitz, 1971; Myers and others, 1975; Hynes, 1987; Dames and Moore, 1985; Turney, 1985, 1986; Matheson and Bliss, 1986; Herring and others, 1986). Some of these studies were initiated because of land-use statutes (laws) enacted by the Colorado Legislature during the 1970s. Provisions within these statutes define natural or manmade subsidence (for example, coal-mine subsidence) as a geologic hazard and stipulate that geologic reports be completed for specific categories of subdivision in unincorporated areas (for example, see Turney, 1986). Because of the continued potential for coal-mine subsidence, land developers might be required to provide relevant geologic and coal-mine subsidence information to city and county planners during the platting process, should the area slated for development overlie abandoned coal mines. In addition, although many land-use decisions ultimately reside with city and county governments, provisions in the State legislation also stipulate that the Colorado Geological Survey (CGS) should serve in an advisory capacity by reviewing geologic and subsidence reports prior to development. Based on these reviews, the CGS can then provide recommendations on the suitability of the proposed development to city and county planners (Turney, 1986). Thus, by recognizing that potential coal-mine subsidence hazards exist in certain areas of the Front Range Urban Corridor, a legislated process has been put in place whereby the CGS, local governments, and developers can work in tandem to determine the most suitable land use or development scheme in undermined areas.

This report summarizes the coal geology and coal-mining history in the Denver Basin, addresses some elements of the coal-bed methane potential based on data in and near the greater Wattenberg area (fig. 1), and provides a broad overview of the basic concepts and potential effects related to coal-mine fires and coal-mine subsidence in abandoned coal-field areas. In regard to coal-mine subsidence, the primary intent of this report is to provide (1) basic information regarding potential issues that might arise from existing or planned residential and urban development in undermined areas, and (2) general descriptions of some of the theories and methodologies (models) applied in past analyses of subsidence potential in the Front Range Urban Corridor. It is hoped that this summary information, as well as the published references listed throughout the text, will help guide the reader to additional and more detailed information regarding the potential effects of historical coal mining. It should also be noted that an extensive repository of detailed information pertaining to abandoned coal mines in the Denver Basin and other Colorado coal areas is housed in the office of the Colorado Geological Survey in Denver, Colorado, and interested readers should consult with the CGS on general matters related to coal-mining effects, as well as for site-specific concerns.

## Denver Basin Coal Geology

Environments conducive for the development of coal were present in the Denver Basin during deposition of the Laramie Formation in the Late Cretaceous and again during deposition of the Denver Formation in the early Tertiary (fig. 2). As a result, coal deposits within these two formations are distributed throughout much of the basin; in fact, more than one-third of the total land area in Colorado that is underlain by coal-bearing rocks at depths of less than 3,000 ft lies within the Denver Basin (Kirkham and Ladwig, 1979). During 120 years of coal-mining activity, more than 130 million tons of coal was produced from nine areas in the basin. Of this total, more than 99 percent came from the Laramie Formation.

## Laramie Formation

The Laramie Formation is Late Cretaceous (Maastrichtian) in age and was deposited about 70 million years ago (Ma) in an alluvial plain/coastal plain setting along the western margin of the Western Interior seaway (fig. 3) (Roberts and Kirschbaum, 1995). Coal beds within the formation developed from peat accumulation in coastal plain mires, inland from shoreline (beach) and nearshore/offshore environments represented by the partly equivalent and underlying Fox Hills Sandstone and Pierre Shale, respectively (fig. 2). Retreat of the Cretaceous seaway during the Maastrichtian resulted in the eastward progradation of marine, shoreface, and coastal plain/mire environments (fig. 3) and the corresponding deposition of Laramie coal across the extent of the present-day Denver Basin in Colorado. Subsequent erosion of Upper Cretaceous rocks along the Greeley arch segmented coal-bearing strata in the Laramie Formation into two distinct areas north and south of the arch (fig. 4) (for example, see Kirkham and Ladwig, 1979; Curtis, 1988). Kirkham and Ladwig (1979) designated the area north of the arch as the Cheyenne Basin and the area south of the arch as the Denver Basin, and they reported that

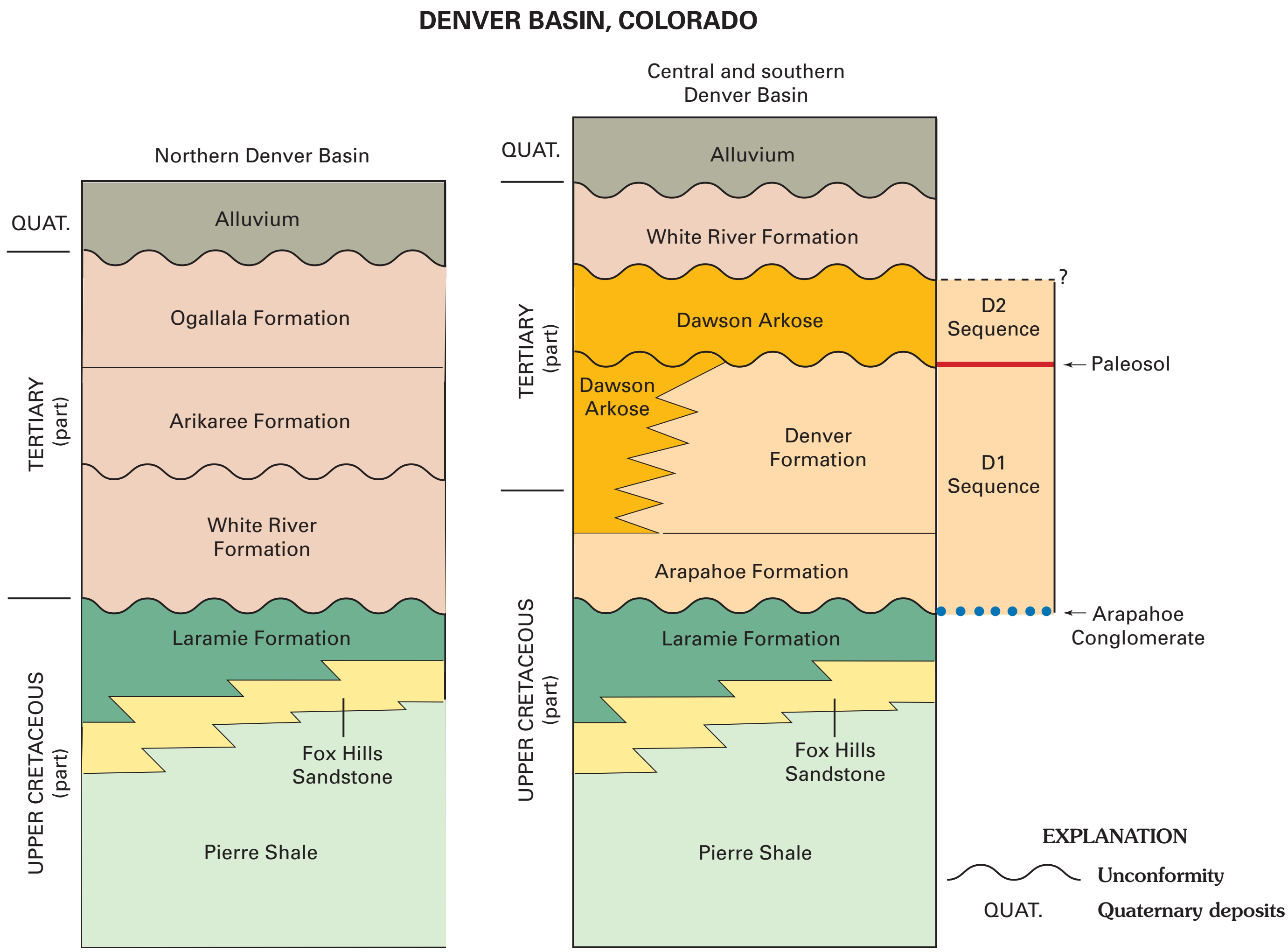


**Figure 2.** Generalized Upper Cretaceous and Tertiary stratigraphy for different areas in the Denver Basin, Colorado. Modified from Kirkham and Ladwig (1979, 1980) and Nichols (1999). D1 and D2 sequences represent Laramide synorogenic deposits as defined by Raynolds (1997). Diagram not to scale.

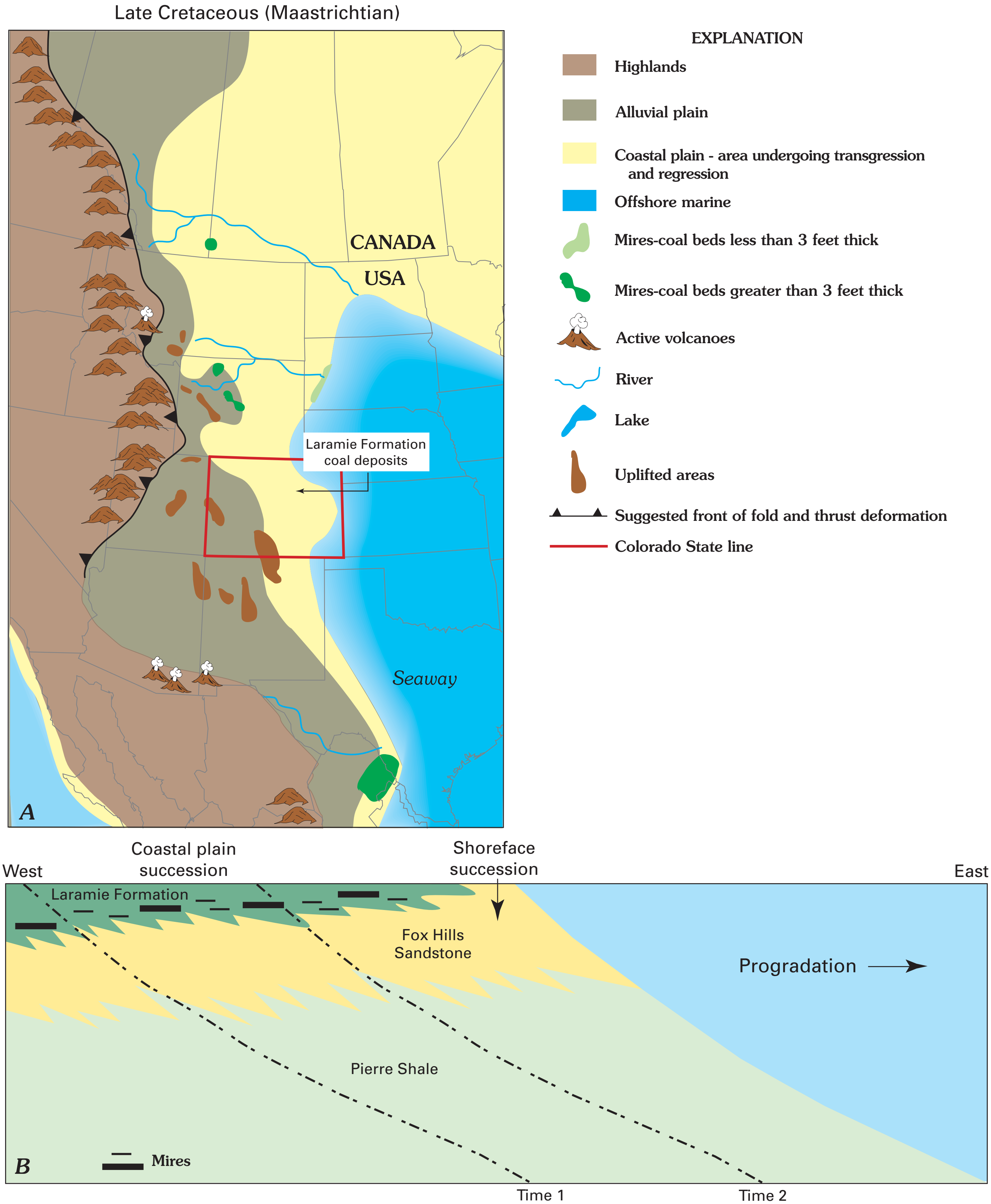


**Figure 3.** Maps and diagrams showing (*A*) paleogeography during Late Cretaceous (Maastrichtian) time, and (*B*) progradational setting of Upper Cretaceous rocks in the Pierre Shale, Fox Hills Sandstone, and Laramie Formation in the Denver Basin, Colorado. Diagram (*A*) modified from Roberts and Kirschbaum (1995); diagram (*B*) modified from Weimer (1977).

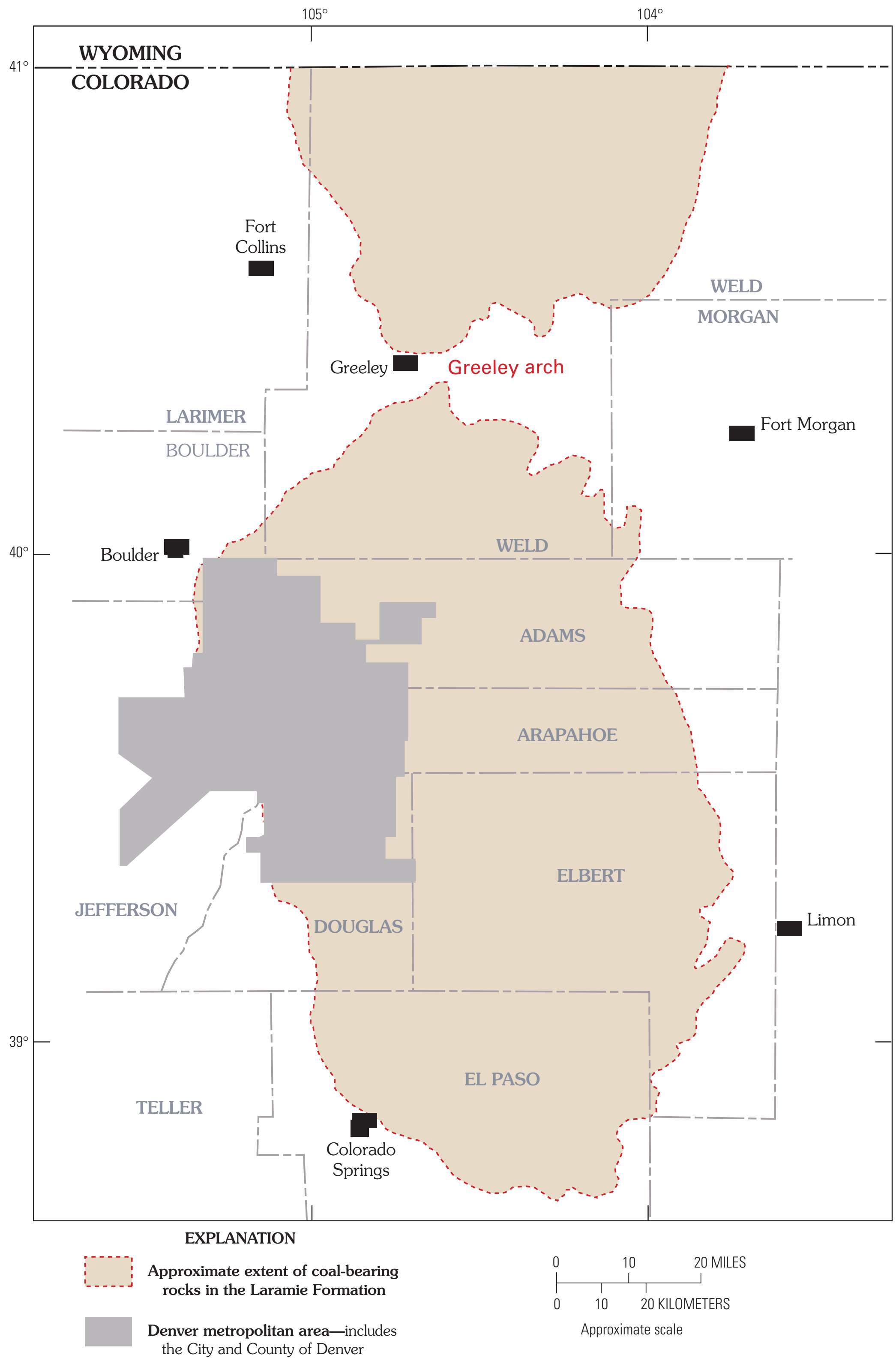


**Figure 4.** Approximate extent of coal-bearing rocks in the Laramie Formation in areas north and south of the Greeley arch, Denver Basin, Colorado. Kirkham and Ladwig (1979, 1980) designated the area north of the arch as the Cheyenne Basin and the area south of the arch as the Denver Basin. In this study, "Cheyenne Basin" terminology is not applied, and both areas are included in the Denver Basin.

there was about 1,000 ft of structural relief on the arch relative to the adjacent basins. In addition, these authors observed that north of the arch, an 1,800- to 4,700-ft-thick interval of uppermost Cretaceous through Eocene (?) strata, including (but not limited to) all or parts of the Arapahoe and Denver Formations and the Dawson Arkose, is absent. As a result, the Laramie Formation to the north of the arch is unconformably overlain by Oligocene deposits of the White River Formation, whereas south of the arch, the formation is unconformably overlain by Upper Cretaceous rocks in the Arapahoe Formation (Kirkham and Ladwig, 1979) or by equivalent strata (in part) included in the D1 synorogenic sequence of Raynolds (1997) (fig. 2). Although these data, as well as additional data in Kirkham and Ladwig (1979) and Curtis (1988), provide support for differing depositional histories north and south of the Greeley arch, the term “Cheyenne Basin” is not applied in subsequent discussions in this report in order to maintain consistency with terminology used in other FRIRP studies (for example, see Fishman, this volume; Higley and Cox, this volume). However, differences in Laramie Formation stratigraphy and coal geology will be addressed specifically for areas north and south of the arch.

In general, the Laramie Formation consists primarily of sandstone, siltstone, claystone, shale, carbonaceous shale, and coal. North of the Greeley arch, the total preserved thickness ranges from about 1,600 to 1,800 ft; south of the arch, the thickness ranges from about 350 to more than 1,000 ft (Weimer, 1977; Kirkham and Ladwig, 1980). The formation is generally divided into lower and upper parts, based primarily on lithologic differences and, to some degree, on the stratigraphic distribution of coal beds. Kirkham and Ladwig (1979) define the top of the lower part of the Laramie as the top of the uppermost coal bed that is present within the lower 300 ft of the formation, and this definition is generally adhered to in this report. The overall lithologic composition of the Laramie is fairly consistent throughout the Denver Basin, although the relative abundance, thickness, and stratigraphic distribution of different lithologies can vary markedly from place to place. For example, in areas north of the Greeley arch, the upper part of the formation includes abundant sandstone beds that range from 10 to 125 ft thick, whereas south of the arch, the upper part of the formation is composed primarily of claystone, shale, and only thin interbeds of sandstone (for example, see Kirkham and Ladwig, 1979, 1980; Dames and Moore, 1985). In addition, the quantity and thickness of coal beds is variable, and, although primary coal deposits are generally concentrated in an interval within 300 ft of the base of the formation, some areas may contain as many as 16 coal beds whereas other areas contain only 2 to 3 beds or are devoid of coal. Individual coal-bed thickness can range from less than 1 ft to more than 20 ft in isolated areas. Kirkham and Ladwig (1980) estimate that approximately one-third of the area south of the Greeley arch and about one-sixth of the area north of the arch are underlain by Laramie coal beds greater than 5 ft thick. Estimates of the remaining (unmined) coal in beds thicker than 2.5 ft and at depths less than 3,000 ft are about 20–25 billion tons (Kirkham and Ladwig, 1979).

## Laramie Formation Coal Geology—North of the Greeley Arch

Coal deposits in the Laramie Formation north of the Greeley arch are relatively thin and discontinuous, and these factors probably account for the limited coal exploration and production relative to other areas of the Denver Basin (for example, see Kirkham and Ladwig, 1980). Because of limited exploration, the distribution of coal and associated lithologies in the Laramie north of the arch is less well known than areas to the south. It has been documented, however, that in addition to the main coal zone in the lower 200–300 ft of the formation, another coal zone is present about 300–500 ft above the lower coal zone in some areas. This upper coal zone includes as many as six beds that are generally 1.5 ft thick or less, although it is unknown as to whether some or all of these beds thicken in adjacent areas (Kirkham and Ladwig, 1979). The limited mining activity (figs. 5 and 6) that did take place north of the Greeley arch, however, only targeted beds in the lower coal zone. Mined coal-bed thickness ranged from about 3.5 to 7.0 ft, and average as-received heat-of-combustion values in the mining areas ranged from 7,200 to 8,000 BTU/lb (fig. 5) (Kirkham and Ladwig, 1979; Kirkham, 1978a).

## Laramie Formation Coal Geology—South of the Greeley Arch

Because of the extensive coal exploration and production in areas south of the Greeley arch, more data are available pertaining to the stratigraphy and coal geology of the Laramie Formation in this area of the Denver Basin. The lower part of the formation ranges from about 100 to 300 ft thick (Kirkham and Ladwig, 1979) and consists of alternating beds of sandstone, siltstone, claystone, carbonaceous shale, and coal. The upper part, which ranges from 200 to more than 1,000 ft thick, is composed predominantly of claystone with only minor sandstone, siltstone, and sporadic, thin coal beds (for example, see Weimer, 1977). Historically, coal was mined primarily from beds in the lower part of the Laramie.

In the Boulder-Weld coal field, as many as 16 coal beds are present locally (Kirkham and Ladwig, 1980). As-received heat-of-combustion values ranged from 8,200 to more than 9,900 BTU/lb, and the apparent rank of the coal ranged from subbituminous C to subbituminous B (Kirkham, 1978a; Kirkham and Ladwig, 1980). Seven potentially minable coal beds in the lower part of the Laramie Formation were identified by Lowrie (1966) and were designated as coal beds No. 1 through No. 7 in ascending order (fig. 7). The following summary descriptions of these coal beds are modified from Myers and others (1975), Kirkham and Ladwig (1980), and Spencer (1986).

Coal beds Nos. 3–6 were the primary targets for past coal production, as coal beds No. 1, No. 2, and No. 7 are generally too thin and lenticular for economic extraction. Coal bed No. 1 ranges from 1 to 3 ft thick and generally lies directly on or

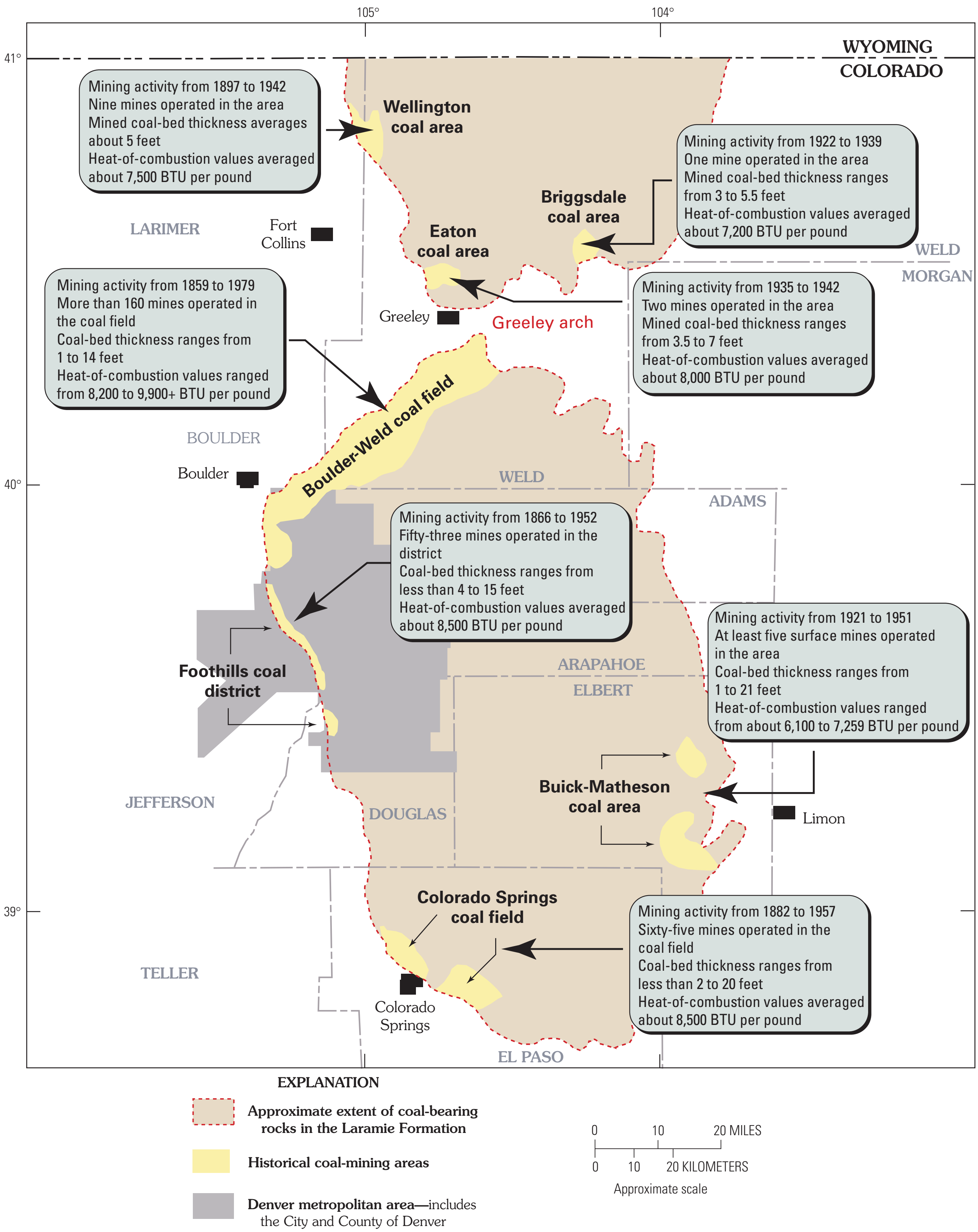


**Figure 5.** Areas of historical coal production from the Laramie Formation and the dates of mining activity, number of coal mines, coal-bed thickness ranges, and heat-of-combustion values in each mining area, Denver Basin, Colorado. Map and coal data from Kirkham and Ladwig (1979, 1980).

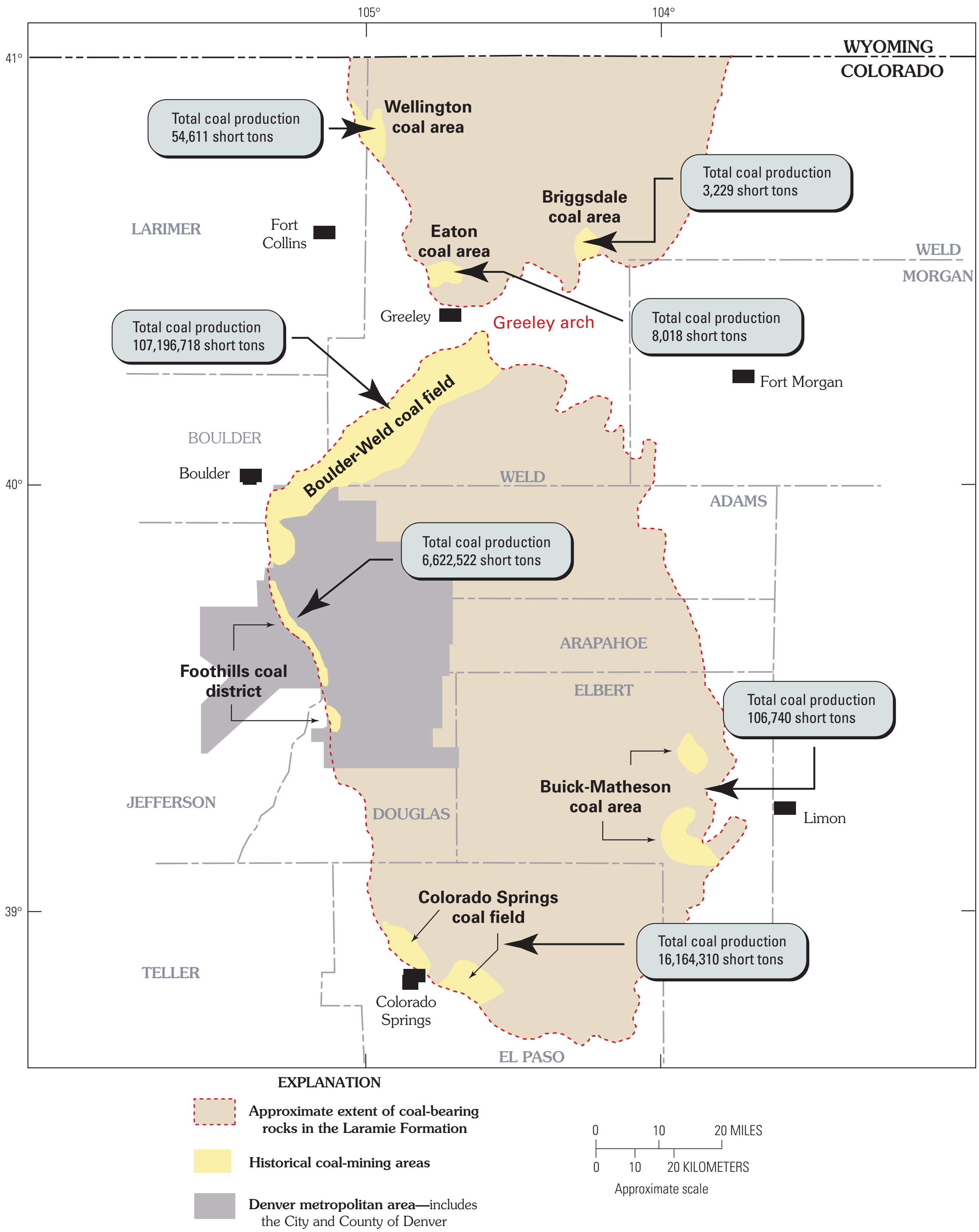


**Figure 6.** Total coal production from the Laramie Formation in areas of historical coal mining, Denver Basin, Colorado. Map and coal production data from Kirkham and Ladwig (1979, 1980).

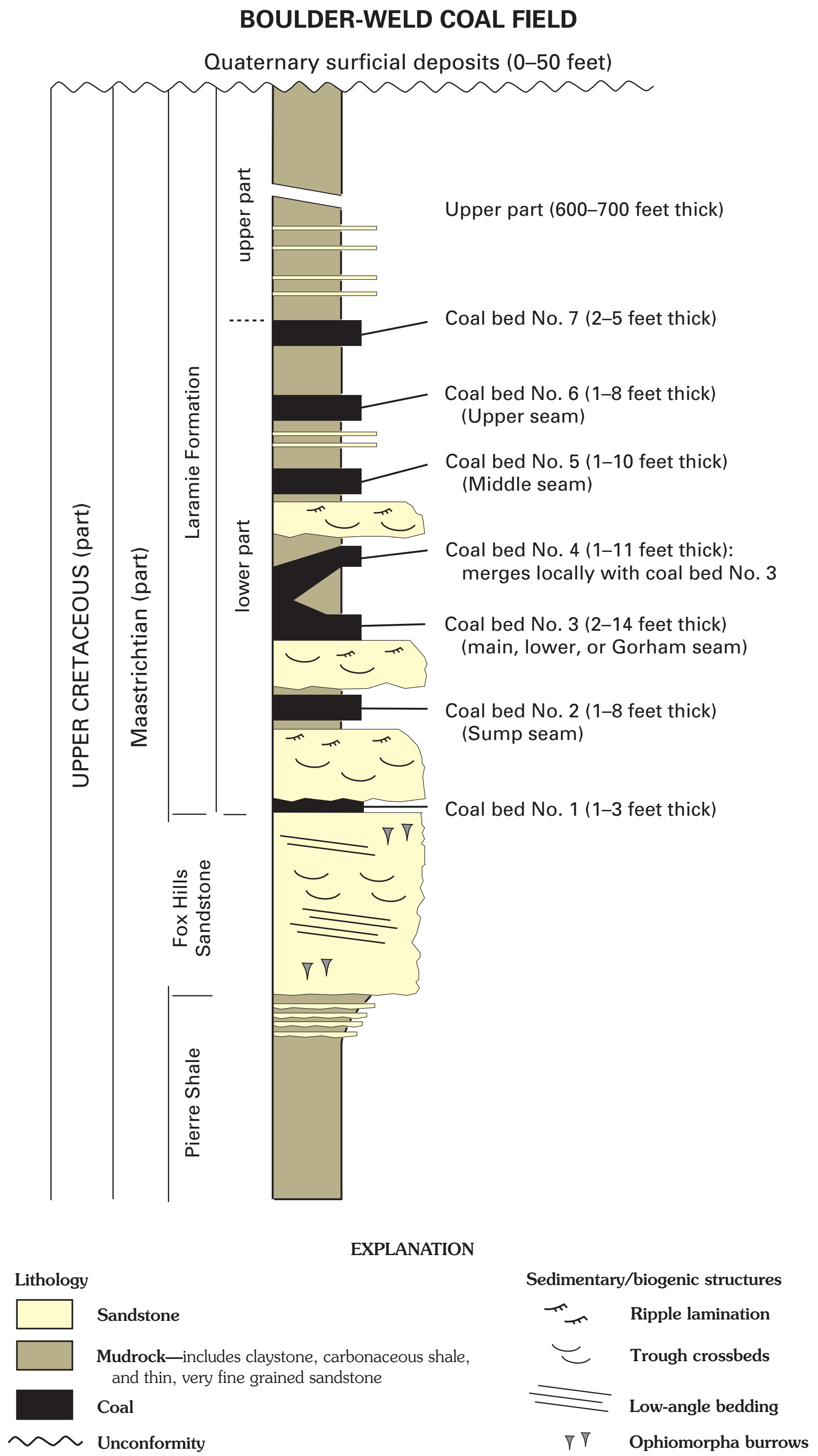


**Figure 7.** Generalized stratigraphic column showing lithology, inferred sedimentary structures, and coal-bed distribution and nomenclature in the Laramie Formation (Upper Cretaceous), Boulder-Weld coal field, Denver Basin, Colorado. Coal-bed nomenclature is based on Lowrie (1966). Column modified from Myers and others (1975) and Kirkham and Ladwig (1979). Column not to scale.

within a few feet above the top of the Fox Hills Sandstone; the base of the coal bed marks the base of the Laramie Formation in the coal field. Overlying coal bed No. 2 ranges from 1 to 8 ft thick and is present some 11–65 ft stratigraphically above the No. 1 bed. Locally, coal bed No. 2 was also designated as the "Sump seam" based on its close stratigraphic proximity to the overlying No. 3 coal bed. Coal bed No. 3, also known as the "main seam," the "lower seam," or the "Gorham seam," is the bed that was mined most extensively in the Boulder-Weld coal field, primarily because of its lateral continuity and thickness, which ranges from 2 to 14 ft. It lies from 10 to 45 ft above the No. 2 bed and locally coalesces with the overlying No. 4 coal bed (fig. 7). Where they are not merged with one another, as much as 30–35 ft of rock may separate the No. 3 and No. 4 coal beds. Coal bed No. 4 ranges in thickness from 1 to 11 ft and is typically from 10 to 50 ft stratigraphically below the overlying bed. The No. 5 coal bed, also known as the "Middle seam," ranges in thickness from 1 to 10 ft and lies some 20–75 ft below the No. 6 coal bed. The No. 6 coal bed, also designated as the "Upper seam," ranges from 1 to 8 ft thick; although this coal bed is laterally continuous over a fairly large area of the coal field, its variable thickness limited production in many areas. The No. 6 coal bed lies from 30 to 100 ft stratigraphically below the overlying No. 7 coal bed, which ranges from 2 to 5 ft thick.

In the Foothills District, south of the Boulder-Weld coal field (fig. 5), one to six coal beds are present in the lower part of the Laramie Formation, and coal-bed thickness ranges from about 4 ft to as much as 15 ft (for example, see Kirkham and Ladwig, 1979). As-received heat-of-combustion values averaged about 8,500 BTU/lb. In the northernmost part of the Foothills District, two coal beds designated as coal bed A (upper) and coal bed B (lower) were mined at depths ranging from 800 to 1,000 ft. The B coal bed lies about 100–150 ft above the base of the Laramie and ranges from about 6 to 11 ft thick. The overlying A coal bed ranges from about 4 to 8 ft thick (Weimer, 1977), and the two coal beds are separated by an interval of claystone and siltstone that varies in thickness from 20 to 80 ft (Camacho, 1969).

In the southwestern part of the Denver Basin, in and near the Colorado Springs coal field (fig. 5), the lower part of the Laramie Formation ranges from 150 to 200 ft thick, and the upper part ranges from 100 to 150 ft thick (fig. 8). Heat-of-combustion values for coal beds in the lower part of the formation averaged about 8,500 BTU/lb (Kirkham, 1978a). The following summary of stratigraphy and coal geology is based primarily on Goldman (1910), Kirkham and Ladwig (1979), and Dames and Moore (1985), and the reader should consult those reports for more detailed information on the Laramie Formation in this area.

The lower part of the Laramie in the Colorado Springs coal field includes alternating beds of very fine to fine-grained sandstone, claystone, and coal, whereas the upper part is composed primarily of claystone with thin interbeds of fine-grained sandstone. Goldman (1910) designated three coal beds in the lower part of the formation as coal beds A–C in ascending order; other unnamed thin and lenticular coal beds are also present in the area (fig. 8). Most of the mines in the Colorado Springs coal field produced coal from the A and B coal beds. Coal bed A is present from 30 to 65 ft above the base of the formation, and as a single bed, is as thick as 20 ft locally. Elsewhere in the coal field, coal bed A splits into two coal beds separated by about 8 ft of rock; in more extreme cases, the bed splits into a series of four to five thin coal beds separated by rock partings. Coal bed B is present from 25 to 50 ft above coal bed A, with massive sandstone typically separating the two coal beds. Coal bed B is as much as 13 ft thick locally, although the bed is more typically 5 ft thick or less throughout much of the Colorado Springs coal field. Coal bed C is lenticular and in places is absent. Where coal bed C is present, it lies from 20 to 50 ft stratigraphically above coal bed B and generally is less than 2 ft thick.

In south-central and southeastern parts of the Denver Basin, in and adjacent to the Buick-Matheson coal area (fig. 5), two primary coal beds, designated coal beds A and B in ascending order, are present in the lower part of the Laramie Formation. Although this terminology is similar to terminology described herein for the Colorado Springs coal field, the stratigraphic relation between identically named coal beds in the two areas is not known. In the Buick-Matheson area, the A coal bed, which splits into upper and lower beds in some areas, is present within 0–15 ft of the base of the Laramie. The B coal bed is 15–50 ft stratigraphically above the A coal bed, or above the upper A coal bed where the A bed is split (Eakins and Ellis, 1987). Thin, sporadic coal beds are locally present above the B coal bed. Where the A coal bed forms a single bed, its thickness ranges from less than 2 ft to as much as 15 ft. Where split, the upper A bed is 1 to 21 ft and the lower A bed is 1 to 10 ft thick. The B coal bed ranges in thickness from 1 to 5 ft (Eakins and Ellis, 1987). As-received, heat-of-combustion values for these coal beds range from 6,100 to 7,259 BTU/lb (Kirkham and Ladwig, 1979; Eakins and Ellis, 1987).

## Laramie Formation Coal Production

Past coal production from the Laramie Formation took place in seven areas of the Denver Basin. Coal mining operations began in the late 1850s and continued until 1979 (fig. 5). Kirkham and Ladwig (1979; 1980) report that a total of 130,156,148 short tons of Laramie coal was produced between 1884 and 1979. Of this total, about 107 million tons was mined from the Boulder-Weld coal field, more than 16 million tons was mined from the Colorado Springs coal field, and about 6.6 million tons was mined from the Foothills coal district (fig. 6). These three areas accounted for more than 99 percent of all the coal mined in the Laramie Formation. Throughout the coal-mining history of the Denver Basin, more than 295 mines were opened. Nearly all of these mines were underground operations, but there were at least seven surface (strip) mines that produced a total of about 254,000 short tons.

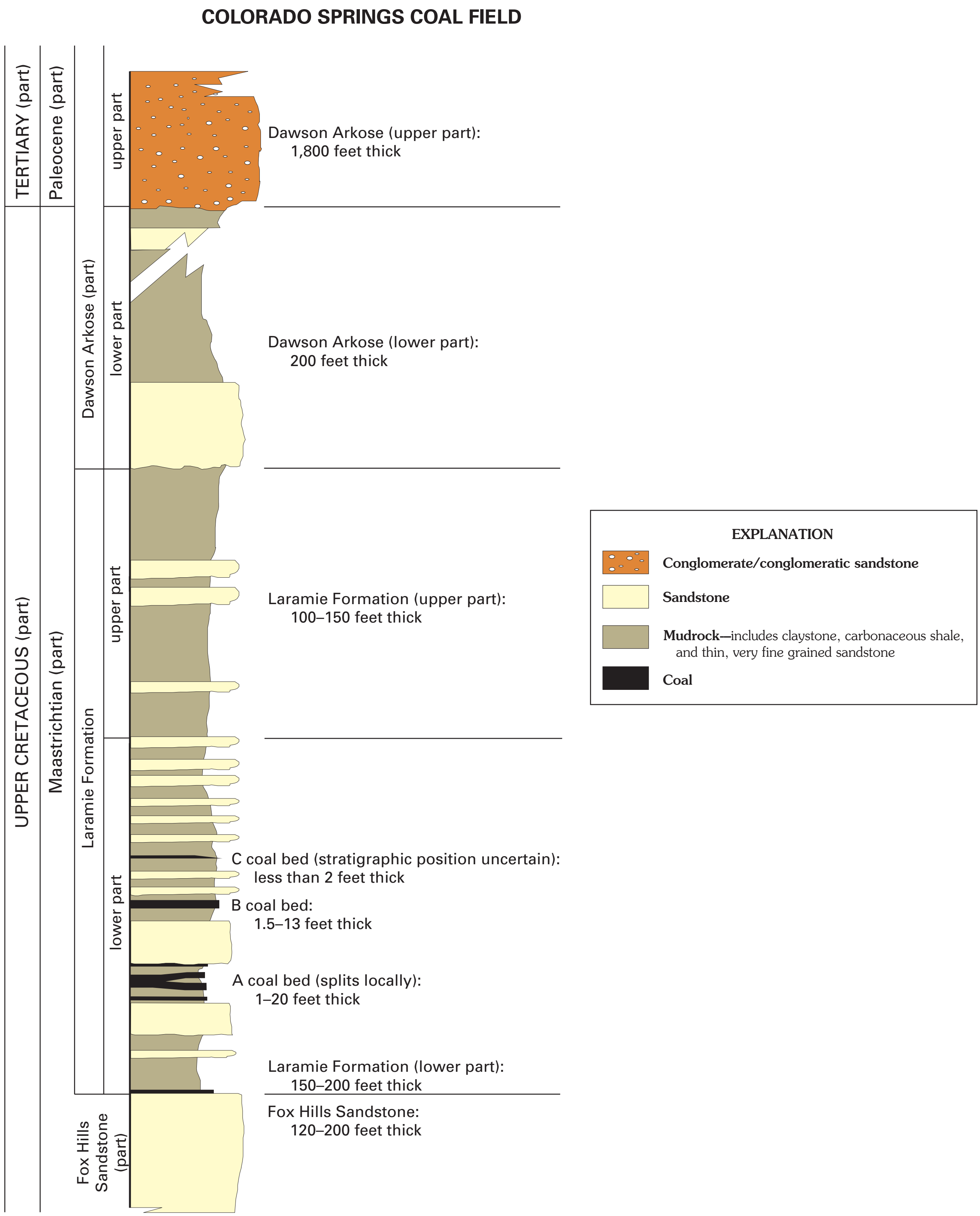


**Figure 8.** Generalized stratigraphic column showing lithology, and coal-bed distribution and nomenclature in the Laramie Formation (Upper Cretaceous), Colorado Springs coal field, Denver Basin, Colorado. Coal-bed nomenclature is based on Goldman (1910). Column modified from Dames and Moore (1985). Column not to scale.

Coal production north of the Greeley arch, in the Briggsdale, Eaton, and Wellington coal areas (fig. 6), totaled only about 67,000 short tons.

Where Laramie coal beds are relatively flat lying or gently dipping, most of the underground mines used room-and-pillar mining methods, with some amount of retreat mining (pillar pulling) upon completion of coal extraction. Coal-extraction percentages in room-and-pillar mines varied from 25 to 75 percent and averaged about 50–60 percent; where retreat mining techniques were used, extraction percentages increased to 70–95 percent and averaged 80–85 percent (Matheson and Bliss, 1986). A schematic diagram depicting the general layout of a typical room-and-pillar mine is shown in figure 9, although it should be noted that many older mines in the Denver Basin did not always adhere to such an orderly scheme of development. Access to the underground coal mines was primarily achieved through vertical shafts or sloped entryways. Vertical shaft dimensions were commonly 6 ft by 6 ft (single compartment), although shafts that were 6 ft by 12 ft (double compartment) were also used to facilitate the raising and lowering of two mine cars simultaneously (Dames and Moore, 1985). The grade of the sloped entryways was typically on the order of 12 percent, although entry grades as steep as 20 percent were used in some mines in the Colorado Springs coal field (Dames and Moore, 1985). Wooden timbers supported both vertical shafts and slope entries. At the level where the vertical or sloped entry intersected the coal bed, the main entry or haulageway was constructed, either perpendicular to or approximately parallel to the strike of the coal bed (fig. 9). The main haulageway generally consisted of two parallel tunnels oriented in such a way that fresh air could be blown in one tunnel, circulated through the mine, and exhausted out of the other tunnel (Hart, 1986). Vertical airshafts, dug from the ground surface to the mine level, provided additional ventilation where needed. Cross entries (fig. 9), cut at right angles to the main haulageway, were used to access mine rooms where coal extraction took place. Mine rooms were generally on the order of 18–20 ft wide and could be as much as 100–300 ft long, although the length of the room was variable, depending on its location in the mine and the historical period during which the mining took place (Dames and Moore, 1985; Hart, 1986). Mined coal was hauled from the rooms to the base of the slope entry or shaft in mine cars, which could hold as much as 2,500 to 3,000 pounds

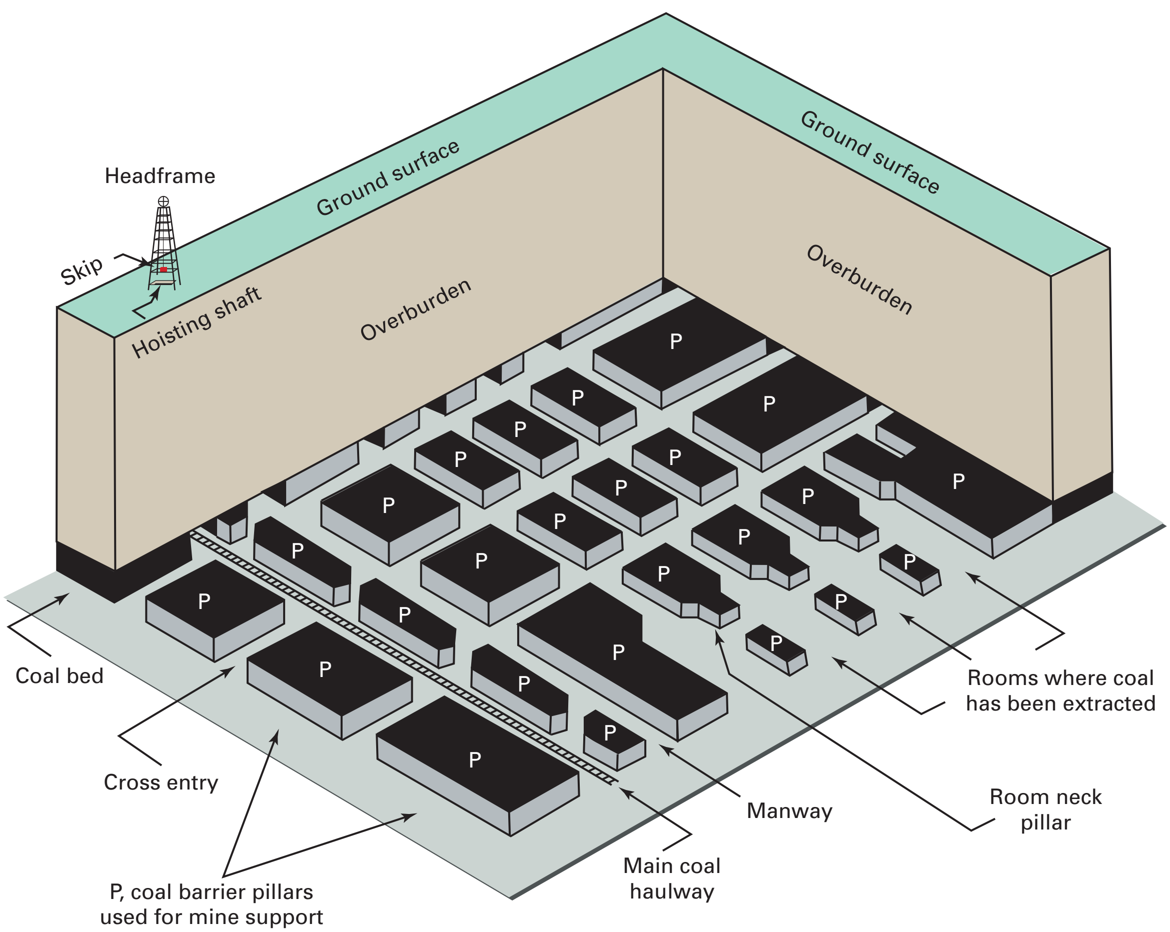


**Figure 9.** Basic components and configuration of a room-and-pillar coal mine. Diagram modified from Dames and Moore (1985).

of coal (Hart, 1986). Mules pulled mine cars until as recently as the 1940s, but through time, electric motors and continuous mining machines with conveyor systems replaced mulepower as the hauling mechanism of choice. During mining, pillars of coal, usually 20–30 ft wide, separated individual mine rooms. When adjacent rooms were mined to their complete length, many of these coal pillars were pulled (mined) as mining retreated from that area (Hart, 1986).

Where coal beds in the Laramie Formation are steeply dipping, such as in the Foothills coal district (fig. 5), a process termed “stope mining” was used. By this method, haulageways were constructed parallel to the strike of the coal bed, and stopes on the order of 30–100 ft high and 50–100 ft wide were driven upward to mine coal above the haulageways (Matheson and Bliss, 1986). Multiple stope levels commonly were developed in these mines, and the vertical dimension between stope levels was on the order of 75–150 ft. For more details on this mining technique, the reader is referred to descriptions by Hart (1986).

## Denver Formation

The Denver Formation ranges in age from Late Cretaceous (Maastrichtian) to early Tertiary (Paleocene) (for example, see Nichols, 1999). Strata within the formation accumulated in a realm of high accommodation (high subsidence) associated with thrust uplift of the Front Range and corresponding subsidence of the Denver Basin (for comparison, see Raynolds, 1997). Coal in the Denver Formation resulted from peat accumulation in mires that developed within interfluve areas east of the Front Range highlands during the Paleocene (fig. 10). The formation overlies the Arapahoe Formation of Late Cretaceous age and is laterally equivalent to (in part) and overlain by the Dawson Arkose (fig. 2), a unit that ranges in age from Late Cretaceous (Maastrichtian) to Tertiary (Eocene) (for example, see Nichols, 1999). Strata within the Dawson Arkose (part) and Denver Formation are included in the unconformity-bounded D1 sequence of Raynolds (1997) (fig. 11) and are considered to represent a west-east continuum of synorogenic deposits consisting of a coarse-grained, proximal facies (Dawson Arkose) along the western margin of the Denver Basin and a dominantly fine-grained distal facies (Denver Formation) near the basin center and on the east basin margin.

The Denver Formation ranges in thickness from 600 to 1,580 ft and consists mainly of claystone and siltstone, with interbeds of very fine to fine-grained sandstone and, more rarely, conglomerate; lava flows are present locally within the formation (for example, see Kirkham and Ladwig, 1979). Coal and associated carbonaceous shale beds are concentrated in the upper 500 ft of the formation, and coal beds are distributed over an area of about 1,700 mi$^2$. As discussed in a previous section, the Denver Formation is not present north of the Greeley arch; thus coal within the formation is present only in areas south of the arch. Estimates of the remaining (unmined) coal resources in the Denver Formation in coal beds thicker than 4 ft and at depths less than 1,000 ft are on the order of 10–15 billion tons (Kirkham and Ladwig, 1979).

### Denver Formation Coal Geology

Thicker accumulations of coal in the Denver Formation are concentrated in and near the Scranton and Ramah-Fondis mining districts (figs. 12 and 13), where historical mining took place from the late 1800s to 1940. The apparent rank of the coal is primarily lignite A, although thin intervals of coal have been analyzed as subbituminous C in apparent rank (Kirkham and Ladwig, 1979). Because of the lignitic nature of the coal, the term “lignite” may be used interchangeably with the term “coal” in subsequent descriptions in order to maintain consistency with terminology applied previously in studies of coal in the Denver Formation (for example, see Soister, 1972; Kirkham and Ladwig, 1979, 1980; Nichols, 1999).

Most all of the lignite beds include numerous non-coal partings that range in thickness from about 0.1 inch to more than 2 ft. Kirkham and Ladwig (1979) estimated that the net lignite bed thickness (excluding partings) is generally 70–90 percent of the gross lignite bed thickness (including partings). In addition, because of observed differences in coal stratigraphy and abundance, the coal-bearing interval has been subdivided geographically into northern and southern lignite areas. Within this framework, the Scranton mining district lies within the northern lignite area and the Ramah-Fondis mining district lies within the southern lignite area (fig. 12). In between the northern and southern lignite areas, coal in the formation is far less abundant and in some cases is absent (for example, see Kirkham and Ladwig, 1979). West of the northern and southern lignite areas, in the deeper subsurface of the Denver Basin, coal is present, but the distribution, thickness, and extent of the coal are less well understood because of limited drill-hole information. In addition, coal beds in the formation tend to thicken and thin abruptly, and although the maximum reported coal thickness for individual beds might be relatively high, the areal extent of thick coal accumulations is generally limited. The following summary focuses on coal data from the northern and southern lignite areas and is based primarily on information in Kirkham and Ladwig (1979, 1980), Brand and Eakins (1980), and Eakins and Ellis (1987); additional references are cited where applicable.

In the northern lignite area, Soister (1972) designated five coal beds as the A–E lignite beds, in descending order (fig. 14). The B and C lignite beds have also been informally referred to as the Lowry and Bennett lignite beds, respectively; the E lignite bed is also known as the Watkins bed. The uppermost A lignite bed occurs at the top of the Denver Formation, just below thick, arkose-rich sandstones in the Dawson Arkose. An additional interval containing numerous unnamed lignite beds is also present below the E lignite bed near the base of the lignite zone. The gross thickness (including partings) of the E lignite bed averages 20–30 ft, and the maximum gross thickness is as much as 55 ft locally. The E lignite bed splits in some areas, and the gross thickness of the upper split

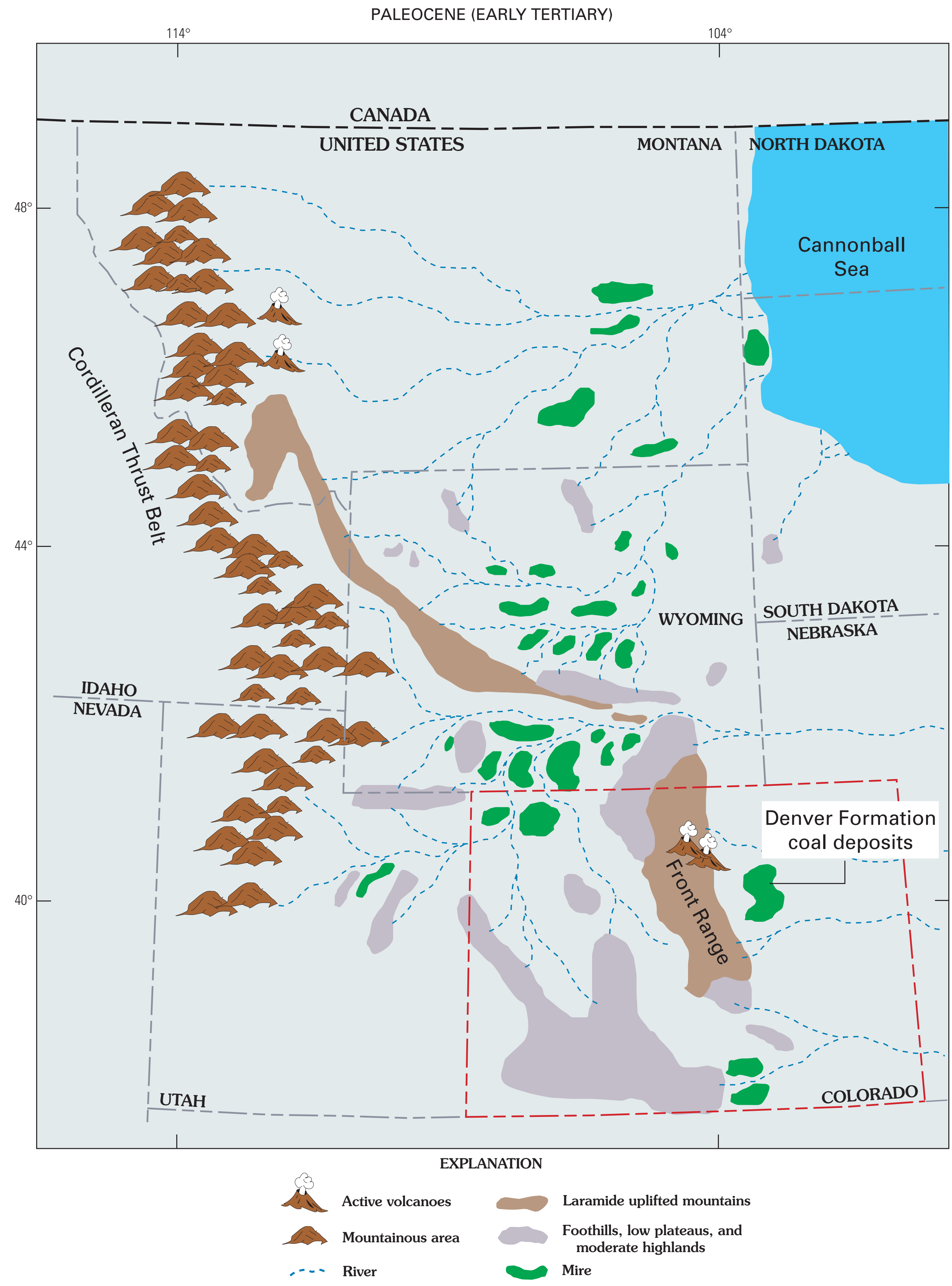


**Figure 10.** Interpreted paleogeography during the early Tertiary (Paleocene) in the Rocky Mountain region. Modified from Flores and others (1997).

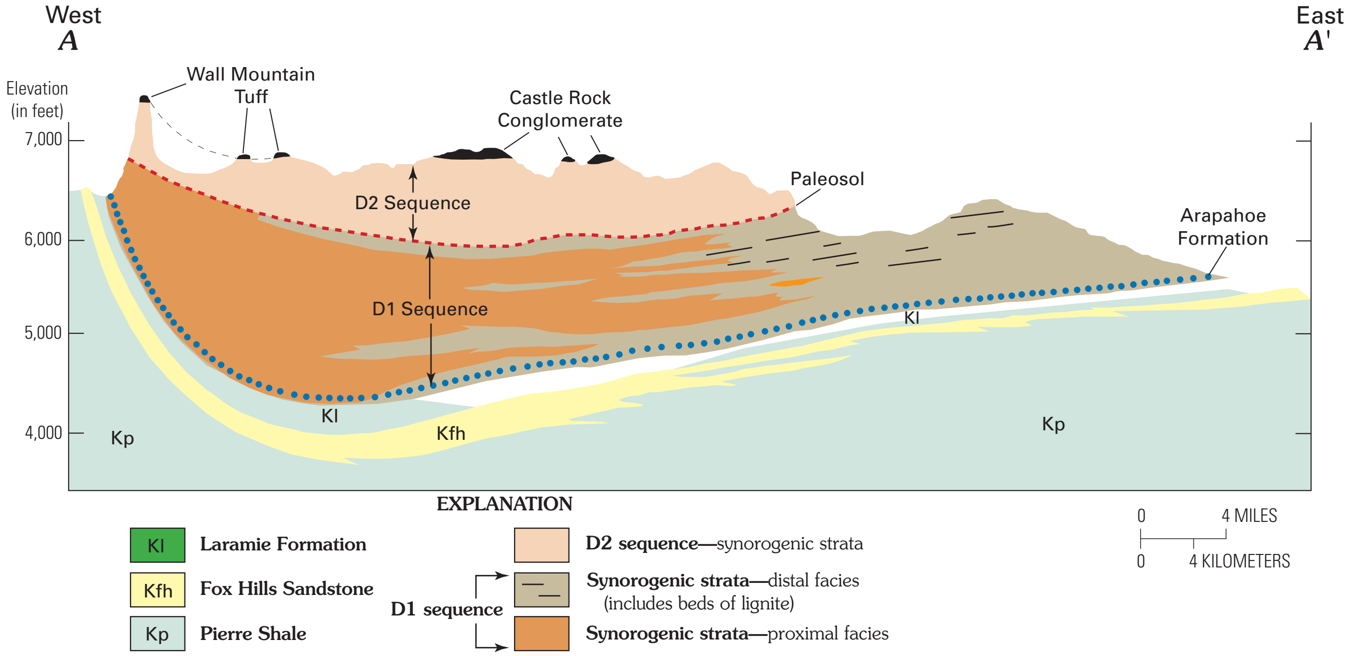


**Figure 11.** West-east cross section *A–A′* showing the distribution of synorogenic deposits in the unconformity-bounded D1 and D2 sequences, Denver Basin, Colorado. Location of cross section is shown in figure 1. Modified from Raynolds (1997).

ranges from less than 5 ft to about 55 ft, whereas the lower split varies from less than 5 ft to 25 ft in thickness. The E lignite bed is the most continuous of the coal beds and has been traced over a distance of about 24 miles. The C lignite bed (Bennett bed) ranges in gross thickness from less than 5 ft to more than 30 ft, and the B lignite bed (Lowry bed) ranges in thickness from less than 5 ft to 30 ft (fig. 14) (for comparison, see Brand and Eakins, 1980). The A and D lignite beds are typically 10–15 ft thick.

In the southern lignite area (fig. 12), informally named lignite beds (descending order) include the Wolf bed, the Comanche bed, the upper, middle, and lower Kiowa beds, and the Bijou bed; additional unnamed lignite beds are also present in the area (fig. 14). The Wolf bed lies about 25–75 ft below the base of the Dawson Arkose, and it is the thickest individual coal bed in the southern lignite area, ranging from 18 to 29 ft in gross thickness. However, as much as 20–40 percent of the gross thickness of the Wolf bed may be attributable to non-coal partings. The Comanche bed lies 15–100 ft stratigraphically below the Wolf bed and is as thick as 26 ft in limited areas near the Ramah-Fondis mining district. The upper, middle, and lower Kiowa beds compose a zone of coal that ranges from 15 to 80 ft thick. The top of the Kiowa coal zone (top of the upper Kiowa bed) is generally within 22–110 ft below the base of the Comanche bed. Total cumulative coal thickness for beds in the zone is as much as 30 ft, although the individual thickness for the upper, middle, and lower Kiowa beds generally ranges from 5 to 10 ft, including partings. Locally the three individual beds coalesce to form one coal bed known as the Kiowa bed. The Bijou bed lies from 60 to 80 ft below the base of the Kiowa coal zone and attains a maximum thickness of 19 ft.

## Denver Formation Coal Production

Production of coal from the Denver Formation amounted to less than 1 percent of the total production in the Denver Basin and was minimal relative to coal production from the Laramie Formation. Most of the production took place in the Scranton mining district, where a recorded 35,789 short tons of coal was produced from one mine from the late 1800s (1886?) until 1900 (figs. 12 and 13) (Kirkham and Ladwig, 1979). In the Ramah-Fondis mining district, just over 3,000 short tons of coal was mined during the period from 1909 to 1940. Few details are available regarding which coal beds were mined and the type of mining method that was used. Because of the limited tonnage of coal produced in these two areas, it is assumed that most of the mines were small surface-mining operations.

# Coal-Bed Methane Potential

The presence of natural gas in coal beds has long been recognized. Historically, gas generated from coal beds was a hazard to the coal-mining industry because of its propensity for ignition and explosion in underground mines. Although coal-bed gas continues to be a potential hazard to the coal-mining industry, this abundant resource has also proven to be a valuable part of the Nation's natural gas endowment. The mean estimate of technically recoverable gas resources from coal beds in the conterminous United States is nearly 50 trillion cubic feet (Tcf) (U.S. Geological Survey National Oil and Gas Assessment Team, 1996).

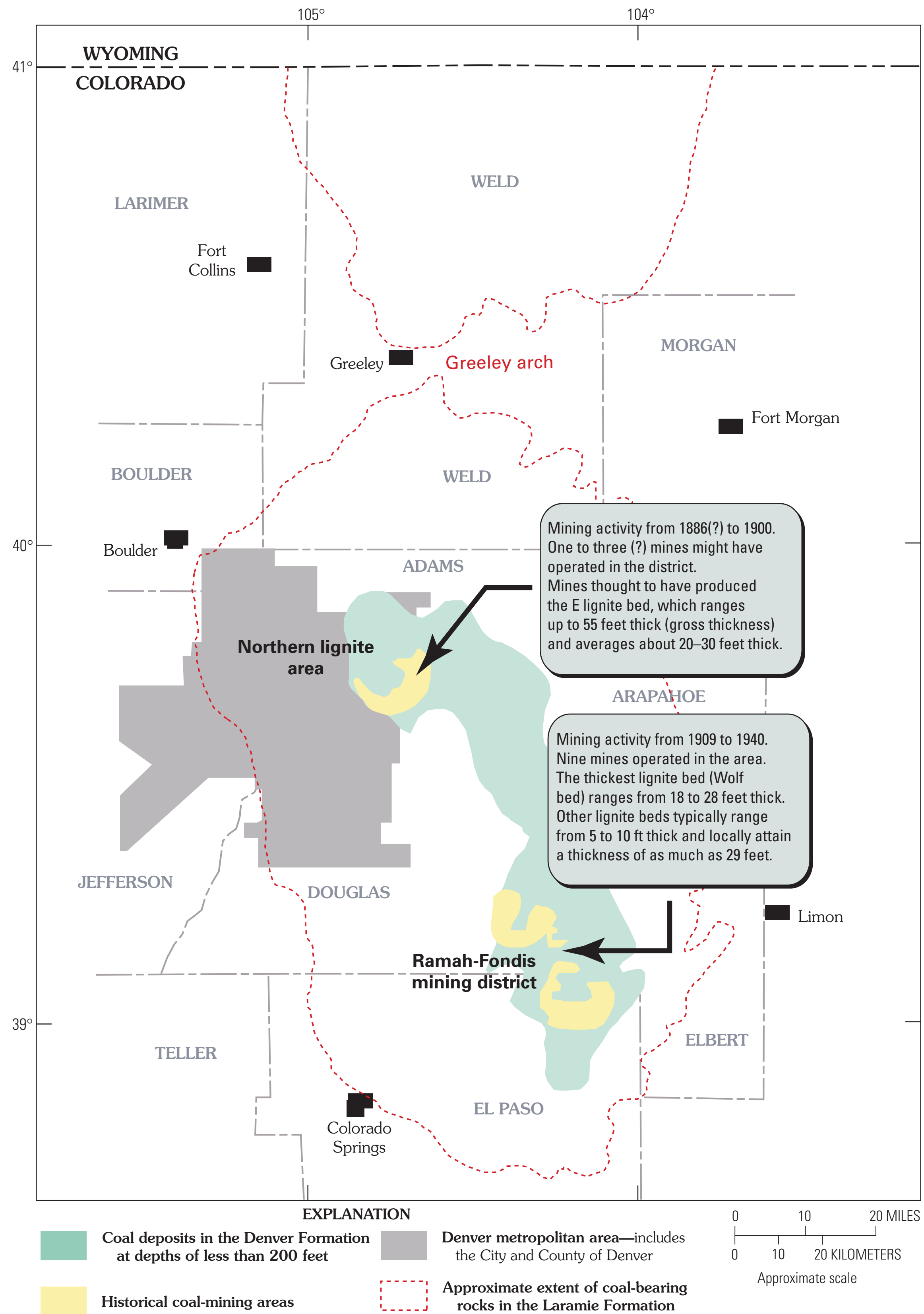


**Figure 12.** Areas of historical coal production from the Denver Formation and the dates of mining activity, number of coal mines, coal-bed thickness ranges, and heat-of-combustion values in each mining area, Denver Basin, Colorado. Map and coal data from Kirkham and Ladwig (1979, 1980).

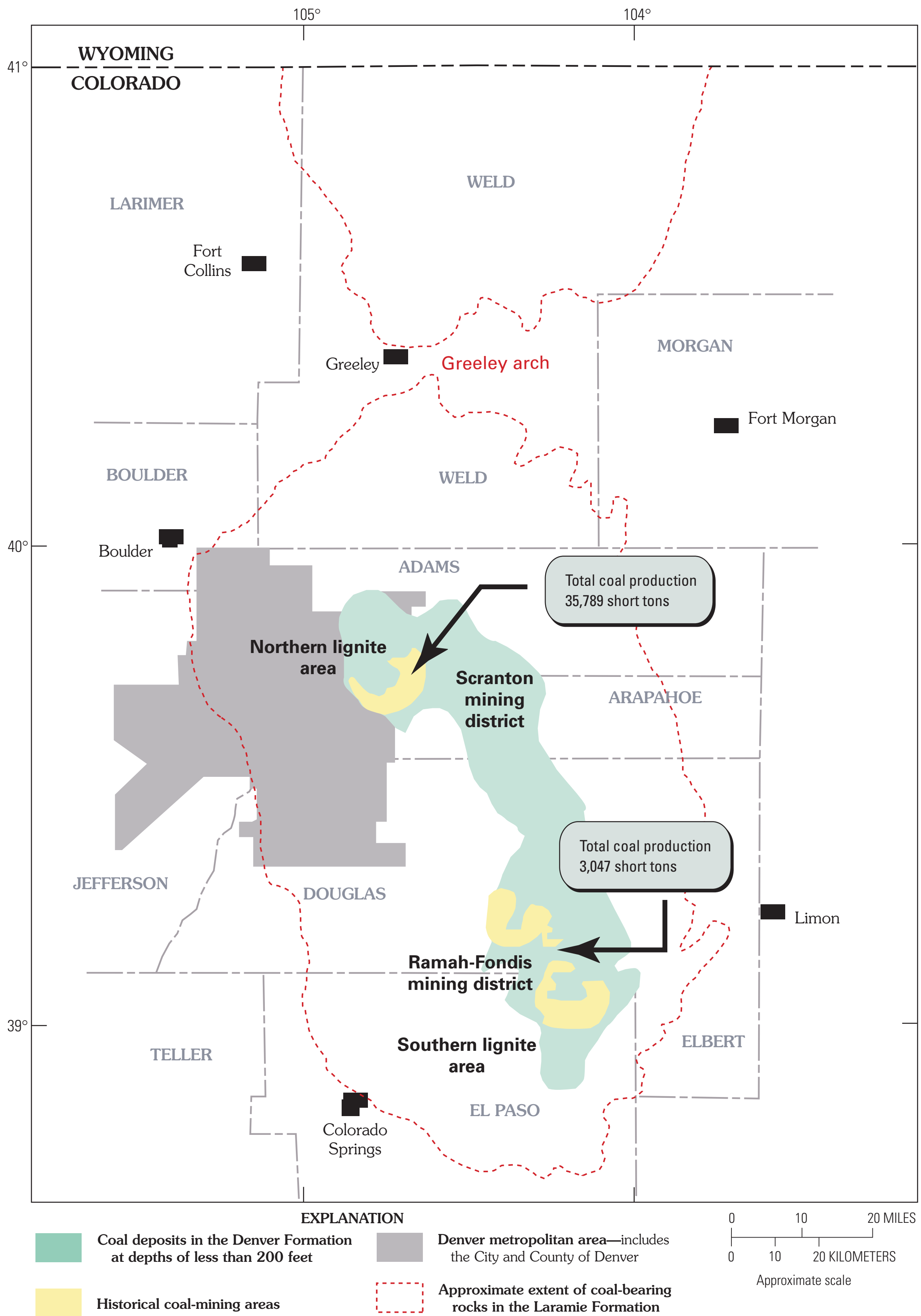


**Figure 13.** Total coal production from the Denver Formation in areas of historical coal mining, Denver Basin, Colorado. Map and coal production data from Kirkham and Ladwig (1979, 1980).

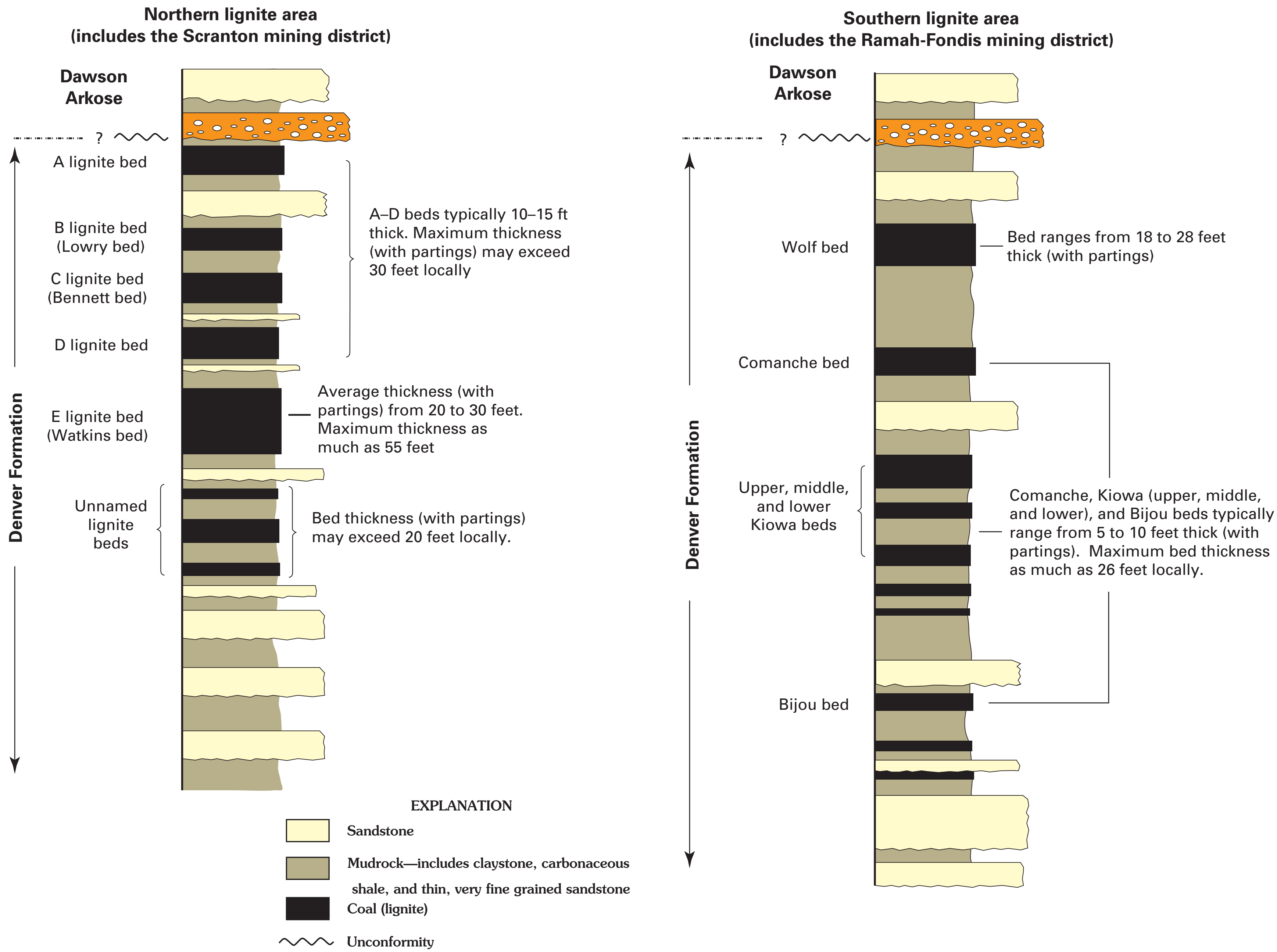


**Figure 14.** Generalized stratigraphic columns showing coal (lignite) beds and associated lithologies in the Denver Formation in the northern and southern lignite areas, Denver Basin, Colorado. Modified from Kirkham and Ladwig (1979). Columns not to scale.

Methane is typically the dominant component of the natural gases within coal beds, although other hydrocarbon gases (for example, ethane and propane) as well as varying amounts of nitrogen and carbon dioxide can also be present (for example, see Rice and others, 1993; Johnson and Flores, 1998). The generation of gas, both biogenic and thermogenic, takes place during coalification, the process by which accumulated plant material (peat) is transformed to coal (for example, see Rice and others, 1993). In general, biogenic gas forms during the early stages of coalification in low-rank coal (such as lignite and subbituminous coal beds) from the decomposition of organic matter by microorganisms. Thermogenic gas is generated during the latter stages of coalification, as increased heat and pressure cause the release of gases rich in methane and carbon dioxide. Initial onset of thermogenic gas (methane) generation generally corresponds to a coal rank of high-volatile bituminous (Rice and others, 1993). A late stage of biogenic gas can also be generated in coal of any rank in areas where ground-water flow again creates an environment favorable for microbial decomposition of organic matter in the coal (for example, see Rice and others, 1993; Johnson and Flores, 1998). Additional information on the generation, characteristics, and resource assessment of coal-bed gas is given by Rightmire (1984), Rice and others (1993), and Mavor and Nelson (1997).

In the United States, the recovery of gas from coal dates back to the 1900s (Rightmire, 1984), when methane recovered from a water well that penetrated coal beds in the Powder River Basin (Wyoming) was used as a source of heating fuel (for example, see Mavor and Nelson, 1997). By the late 1970s, some production of coal-bed methane was established in the Warrior Basin (Alabama and Mississippi) and the San Juan Basin (Colorado and New Mexico). An increase in exploration and production of this resource took place in the 1980s, in large part because of a Federal tax credit given to producers of coal-bed methane (for example, see Rice and others, 1993). Today, continued interest in the development of methane from coal beds has sparked exploration and development projects in many areas of the United States and throughout the world.

Currently, there is no coal-bed methane production in the Denver Basin. However, the successful production of coal-bed methane from areas such as the Warrior and San Juan Basins, coupled with the great increase in coal-bed methane production in the Powder River Basin (Wyoming and Montana), has helped to stimulate interest in the potential for coal-bed methane development in the Denver Basin. Such interest is greatly enhanced by the small, relatively inexpensive drilling rigs and minimal wellhead equipment required for the successful completion of coal-bed gas wells (fig. 15), as well as the fact that in the Powder River Basin production is primarily from subbituminous coal beds that are comparable in rank and depth to coal beds in the Laramie Formation in the Denver Basin.

The Gas Research Institute (GRI) (1999) estimated that there might be as much as 2 Tcf of coal-bed methane (in place) within the Laramie and Denver Formations in the Denver Basin. Of this total, GRI (1999) suggests that some 0.3 Tcf of coal-bed methane could be a recoverable resource. The main difficulty in assessing the coal-bed methane potential for the Laramie and Denver Formations is the limited published data related to the gas composition and gas content of the coal beds. Because the rank of these coal beds is low (lignite–subbituminous), and without thermal maturity and gas composition data to indicate otherwise, it is assumed that coal-bed gas in these formations is primarily biogenic and consists mainly of methane (for example, see Rice and others, 1993).

Tremain and Toomey (1983) compiled desorption data for selected coal regions in Colorado, including total coal-bed gas estimates for coal core samples recovered in five drill holes in the Denver Basin. In two of the drill holes (Biosphere #1 and CGS–10C; fig. 16), coal beds within the Denver Formation were analyzed, and in three drill holes (Marshall #2, CGS–4C, and CGS–5C; fig. 16), coal beds in the Laramie Formation were analyzed. The total gas contents (cubic feet of gas per ton of coal [$ft^3$/ton]) were determined using the U.S. Bureau of Mines direct method, which is described in detail by Diamond and Levine (1981). By this method, the total gas content for each coal sample represents the cumulative (summed) total of lost gas, desorbed gas, and residual gas. Lost gas is that gas lost during the time required to drill, retrieve, and seal the coal sample in an airtight canister. Desorbed gas is that gas emitted by the coal sample while it is sealed in the airtight canister, and residual gas is measurable gas that remains in the coal matrix after all other gas is emitted from the sample in the canister.

A summary of total gas content analyses for coal beds in the Denver and Laramie Formations in the Denver Basin, as reported in Tremain and Toomey (1983), is as follows:

**Drill hole: Biosphere #1 (Sec. 4, T. 4 S., R. 64 W.)**
Formation tested: Denver Formation
One coal bed analyzed: E bed (Watkins bed); core sample
Coal-bed thickness: 29 ft
Desorbed coal sample numbers: 121 and 122
Sample 121: Sample depth from 127 to 135 ft
Apparent rank: subbituminous C
**Total gas content: 4 $ft^3$/ton**
Sample 122: Sample depth from 140.2 to 144.6 ft
Apparent rank: lignite A
**Total gas content: 11 $ft^3$/ton**

**Drill hole: CGS–10C (Sec. 8, T. 5 S., R. 65 W.)**
Formation tested: Denver Formation
One coal bed analyzed: Unnamed; core sample
Coal-bed thickness: 19.4 ft
Desorbed coal sample numbers: 164 and 165
Sample 164: Sample depth from 434.3 to 434.9 ft
Apparent rank: subbituminous C
**Total gas content: 0 $ft^3$/ton**
Sample 165: Sample depth from 435 to 445 ft
Apparent rank: subbituminous C
**Total gas content: 0 $ft^3$/ton**


**Figure 15.** Photographs showing (*A*) truck-mounted drilling rig exploring for coal-bed methane, and (*B*) a completed coal-bed methane wellhead in the Powder River Basin, Wyoming. Photographs provided courtesy of M.S. Ellis, U.S. Geological Survey, Denver, Colorado.

**Drill hole: CGS–4C (Sec. 34, T. 2 S., R. 60 W.)**

Formation tested: Laramie Formation
One coal bed analyzed: Unnamed; core sample
Coal-bed thickness: 5 ft
Desorbed coal sample number: 161
Sample 161: Sample depth from 109 to 114 ft
Apparent rank: subbituminous C
**Total gas content: 4 $ft^3$/ton**

**Drill hole: CGS–5C (Sec. 4, T. 3 S., R. 61 W.)**

Formation tested: Laramie Formation
Two coal beds analyzed: Unnamed; core samples
Coal-bed thickness: 6.7 ft (bed 1) and 8 ft (bed 2)
Desorbed coal sample numbers: 162 (bed 1) and 163 (bed 2)
Sample 162: Sample depth from 306.3 to 308 ft
Apparent rank: subbituminous B
**Total gas content: 24 $ft^3$/ton**
Sample 163: Sample depth from 362.5 to 371 ft
Apparent rank: subbituminous C
**Total gas content: 0 $ft^3$/ton**

**Drill hole: Marshall #2 (Sec. 21, T. 1 S., R. 70 W.)**

Formation tested: Laramie Formation
Two coal beds analyzed: One unnamed bed and the Gorham (No. 3) bed; core samples
Coal-bed thickness: 2.5 ft (unnamed bed) and 9.75 ft (Gorham bed)
Desorbed coal sample numbers: 196 (unnamed bed) and 197–198 (Gorham bed)
Sample 196: Sample depth from 37.5 to 40 ft
Apparent rank: not determined
**Total gas content: 0 $ft^3$/ton**
Sample 197: Sample depth from 81.4 to 84.4 ft
Apparent rank: not determined
**Total gas content: 1 $ft^3$/ton**
Sample 198: Sample depth from 88 to 91 ft
Apparent rank: not determined
**Total gas content: 1 $ft^3$/ton**

Because the gas-content data listed above were derived from the desorption of coal samples at ambient temperature and pressure conditions in the Denver Basin, Tremain and Toomey (1983) suggested that these total gas values might be on the order of 20 percent higher than values at standard conditions (that is, 68°F and 14.7 psia (1 atmosphere). In addition, the direct method might have a 25–30 percent uncertainty, based in large part on unknown factors related to lost gas determinations (as reported in Rightmire, 1984, after Kim, 1977). Results of desorption analyses listed above appear to indicate that gas contents of Laramie and Denver Formation coal beds are somewhat low, especially when compared to gas contents of coal beds in the Warrior and San Juan Basins, which can exceed 500 $ft^3$/ton (for example, see Hewitt, 1984; Choate and others, 1984). However, reported gas contents for subbituminous coal in the Powder River Basin (Fort Union Formation), which can vary from 6 to more than 74 scf/ton, are commonly in the range of 20–40 scf/ton (for example, see Stricker and others, 2000; Boreck and Weaver, 1984). Meaningful comparison between Denver Basin and Powder River Basin coal-bed methane potential cannot be made without additional gas-content data from coal beds in the Denver Basin. The fact that all the sampled coal beds listed above were at shallow depths (88–445 ft) may have affected the analytical results. Previous studies indicate that coal beds at shallow depths (less than 500 ft) could have a significantly diminished potential for coal-bed methane retention (for example, see Rightmire, 1984). However, depth alone does not appear to exert a consistent control on coal-bed methane content, given that significant methane production at depths of 500 ft or less is ongoing in the Powder River Basin (Stricker and others, 2000; Johnson and Flores, 1998). An additional factor resulting in low coal-bed gas contents in one case might relate to the presence of abandoned underground coal mines. The Marshall #2 drill hole (fig. 16), in which gas contents in Laramie Formation coal beds were essentially nil, is located in a heavily undermined area near the Lewis No. 2 and associated underground mines in the southwestern part of the Boulder-Weld coal field. Because of the shallow depth at which these coal beds were sampled (less than 100 ft) and the proximity to shallow, mined-out areas within 100 ft of the surface (for example, see Myers and others, 1975; Roberts and others, 2001), it seems highly probable that any gas generated within the sampled coal beds in this drill hole could have easily leaked (migrated) into surrounding voids or mine cavities. Low gas contents reported for Denver Formation coal samples (drill holes Biosphere #1 and CGS–10C; fig. 16) might be a result of the slightly lower rank of the coal samples (subbituminous C–lignite A), the shallow depth of the samples, or a combination of these factors.

## Greater Wattenberg Area: Coal-Bed Methane Pilot Study

As part of the FRIRP, a small-scale pilot study was undertaken in the greater Wattenberg area (GWA) (fig. 17) to gain some perspective on the coal-bed methane potential in the Laramie Formation in the northern part of the Denver Basin (Roberts and Fishman, 2000). The GWA incorporates about 2,900 $mi^2$ in parts of Jefferson, Denver, Boulder, Weld, Adams, Larimer, and Morgan Counties and extends from T. 2 S. to T. 7 N., and from R. 61 W. to R. 69 W. The area includes most of the Boulder-Weld coal field and additional areas (Eaton and Briggsdale coal areas, fig. 5) where Laramie Formation coal was mined in the past. Significant volumes of natural gas have been produced in this area, primarily from the Wattenberg gas field. In the GWA, commingled gas production from all Cretaceous units is allowed, and recently relaxed drill-spacing requirements (spacing less than 40 acres) might encourage recompletion efforts in existing wells to tap into additional pay zones. Potential coal-bed methane resources in the Laramie Formation overlie targets of current gas

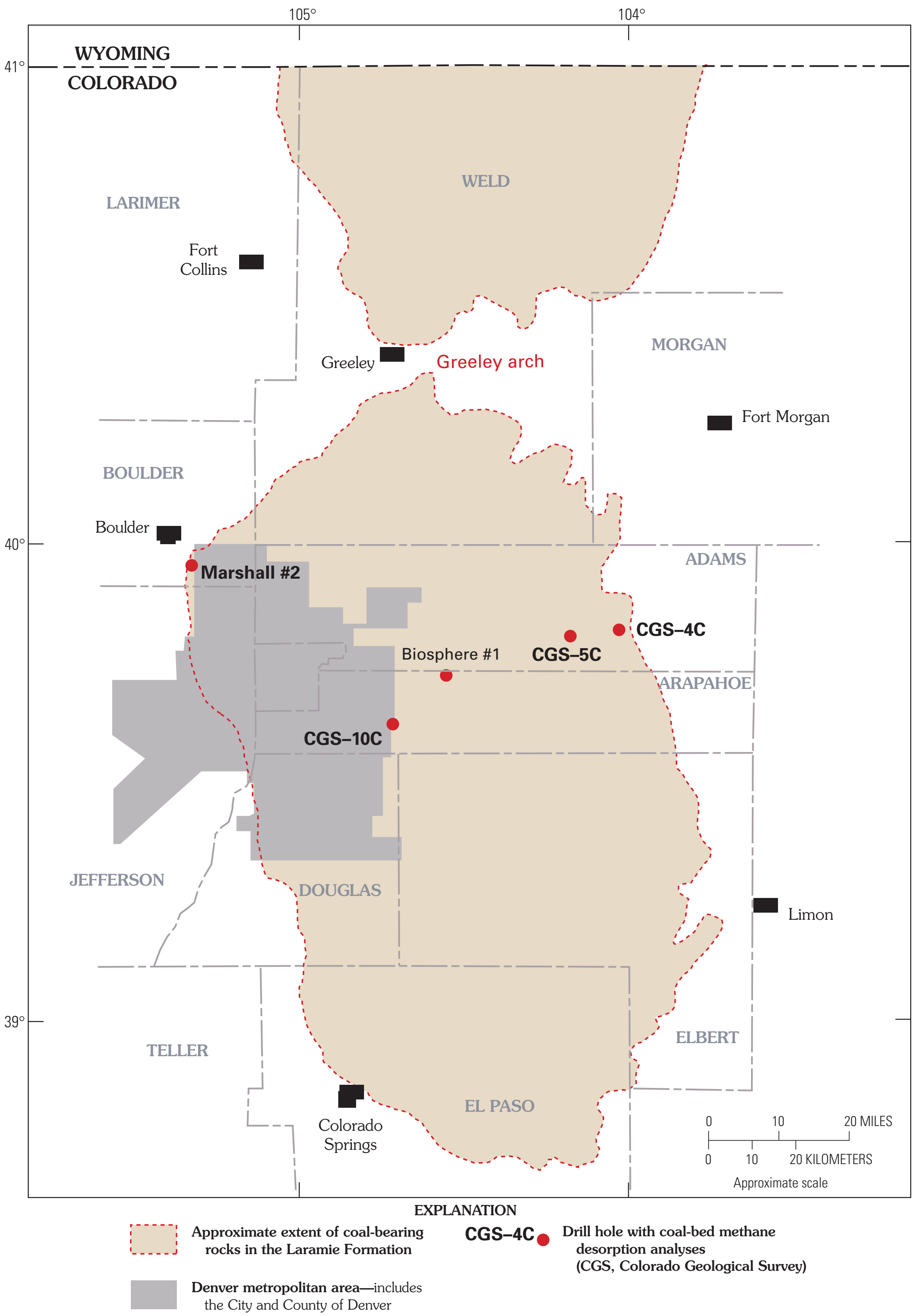


**Figure 16.** Drill holes in which coal beds were sampled and desorbed for coal-bed methane content in the Denver Basin, Colorado. Drill-hole locations based on Tremain and Toomey (1983). Extent of coal-bearing rocks in the Laramie Formation from Kirkham and Ladwig (1979).

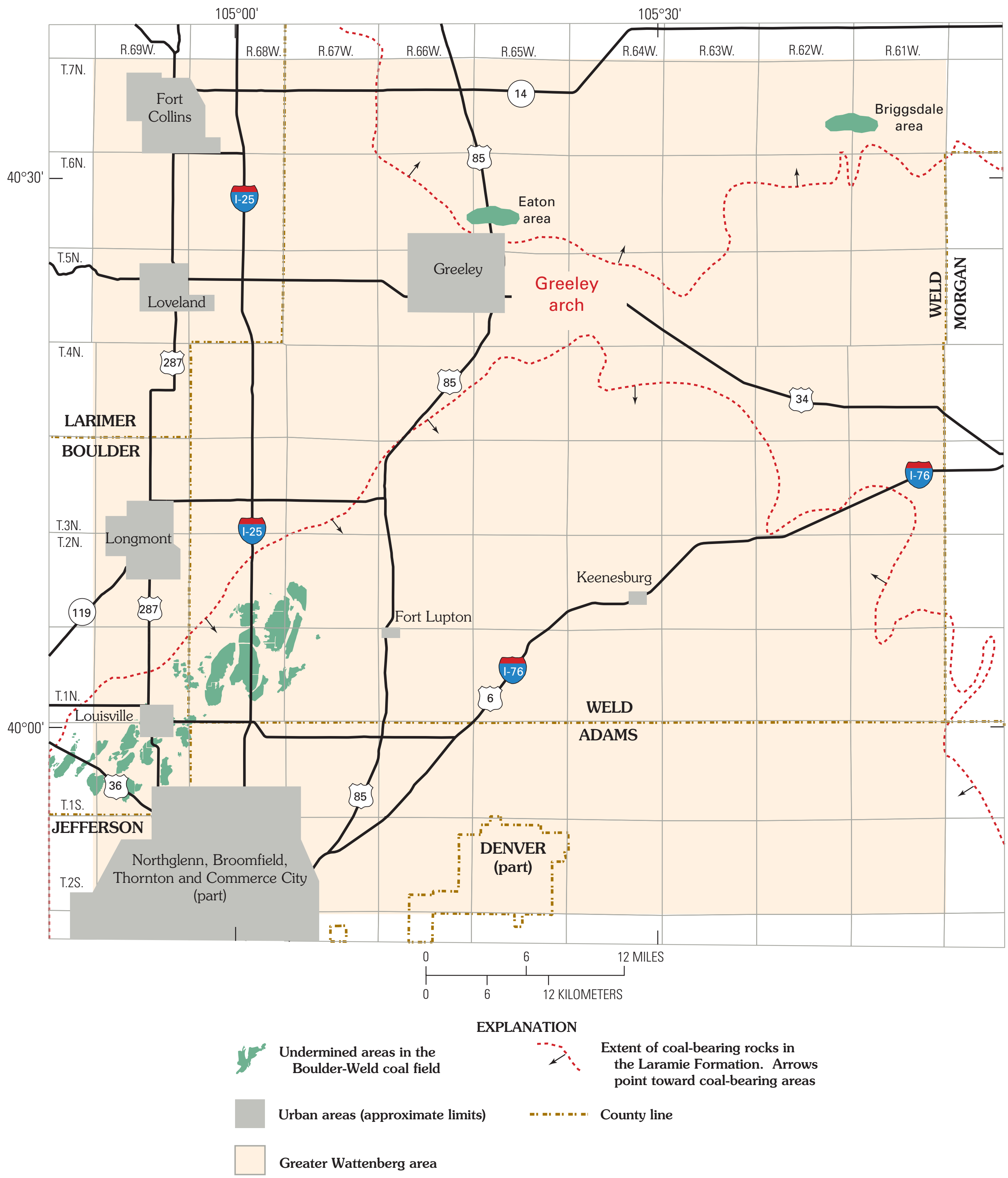


**Figure 17.** Extent of the greater Wattenberg area, Denver Basin, Colorado.

production in deeper, older Cretaceous strata and could be considered as a shallow, "behind-pipe" resource in existing gas wells. For this reason, and because a well-developed infrastructure (for example, roads, pipelines, and so forth) for gas production is already in place, the GWA was chosen for the pilot study.

Evidence for the presence of methane in Laramie Formation coal in the GWA includes (1) coal-bed methane desorption analyses from drill holes CGS–4C, CGS–5C, and Marshall #2 (Tremain and Toomey, 1983) described in the previous section, and (2) reports of mine fires, gas explosions, and gassy mines in the Boulder-Weld coal field (fig. 18) (Fender and Murray, 1978). At least eight mines in the coal field experienced mine fires or explosions during their history, and an additional eight coal mines reported the presence of gas. Perhaps some of the more compelling evidence for the gassy nature of Laramie Formation coal was recorded in the Eagle mine in the northeastern part of the Boulder-Weld coal field (fig. 18), where more than 7,000 $ft^3$ of gas per day (28 $ft^3$ of gas per ton of mined coal) was emitted during the first quarter of 1976 (Fender and Murray, 1978). It is interesting to note that this volume of gas emitted from the Eagle mine is comparable to the desorbed coal-bed methane content (24 $ft^3$/ton) reported for the upper coal bed in CGS–5C (Tremain and Toomey, 1983). However, whether or not these values are indicative of the overall methane content one may anticipate for Laramie Formation coal in the basin is unknown, particularly given the absence of significant gas noted in other desorbed coal samples.

Another key factor for determining the coal-bed methane potential in the Laramie Formation relates to coal thickness and distribution. In the central and southern parts of the GWA, subsurface data from 74 coal exploratory drill holes (Kirkham, 1978b) and interpretations of geophysical logs in 16 oil and gas test wells indicate that the total coal thickness within the lower part of the Laramie ranges from a few feet or less (traces of coal) to as much as 35 ft in T. 1 S., R. 69 W. (fig. 19). In, general, thicker total coal accumulations are present in the western part of the GWA, in and near the Boulder-Weld coal field. Individual coal-bed thickness can vary from less than 1 ft to as much as 9 ft locally, and the number of coal beds varies from 2 to 12.

Plate 1 shows the thickness and distribution of Laramie coal beds within the GWA in east-west (*A–A′*), and north-south (*B–B′*) cross sections. Partial geophysical log records (natural-gamma and resistivity traces) within the coal-bearing part of the Laramie Formation and closely associated strata are shown for each well. The datum in both cross sections is the top of the Fox Hills Sandstone, which is in sharp contact with overlying, coal-bearing strata of the Laramie Formation. In many areas, a thin (less than 2-ft-thick) coal bed overlies the Fox Hills Sandstone. The contact separating the Fox Hills Sandstone and the underlying Pierre Shale is gradational and generally represents the transition from marine shale to marginal marine and shoreface sandstone, siltstone, and sandy shale. On plate 1, the base of the Fox Hills Sandstone, as interpreted from geophysical logs, is placed at the base of the lowest sandstone unit overlying a thick shale succession in the upper part of the Pierre Shale. In drill holes 1–16, interpretations of coal-bed presence and thickness are based primarily on natural-gamma (gamma ray), bulk density, and (or) resistivity logs from oil and gas test wells. Coal-bed interpretations in drill hole CGS–5C are from Brand (1980), and corresponding coal-bed gas content data are from Tremain and Toomey (1983). The primary coal-bearing interval in the Laramie Formation is designated as the lower Laramie coal zone. The upper limit of this coal zone generally corresponds to the top of the uppermost coal bed identified in the Laramie Formation, and the lower limit is the top of the Fox Hills Sandstone. However, in drill holes 5, 6, and 8, queried coal beds that are present stratigraphically above the lower Laramie coal zone were not included as part of the zone because of less definitive geophysical log data and the apparent disparity in coal-zone thickness in these drill holes compared to adjacent drill holes. The maximum thickness of the coal zone in these cross sections is about 290 ft (drill hole 1, *A–A′*; pl. 1); the minimum thickness is about 80 ft in drill hole CGS–5C, near the eastern limit of Laramie Formation coal-bearing rocks. Maximum depth to the top of the coal zone exceeds 1,300 ft near the south-central boundary of the GWA. However, throughout most of the study area, the depth to the top of the coal zone is less than 1,000 ft. Thicker coal accumulations in and near the Boulder-Weld coal field (fig. 19) are at depths of less than 500 ft. Correspondingly, the lower Laramie coal zone is thickest in the coal field area. Individual coal-bed thickness along these lines of cross section ranges from 2 to 8 ft.

In addition to the variability in total coal thickness observed in the GWA, there is also a marked variation in heat-of-combustion (BTU/lb) values for Laramie coal. Average (arithmetic mean), as-received heat-of-combustion (BTU/lb) values for Laramie coal beds, based on analyses of coal-mine samples (for example, see Kirkham, 1978b) and coal core samples (Brand, 1980) range from 7,200 to more than 9,900 BTU/lb (fig. 20). Average, as-received heat-of-combustion values reported for coal beds in the Boulder-Weld coal field are commonly 1,000 BTU/lb, or more, higher than values reported in most other areas of the Denver Basin (for comparison, see Kirkham and Ladwig, 1979, 1980). The Boulder-Weld coal field, in part, overlies a thermal anomaly that has been identified in the Wattenberg gas field (for example, see Myer and McGee, 1985; Higley and Gautier, 1988), just northeast of the coal field. The anomaly is recognized by an unusually high temperature gradient and high vitrinite reflectance ($R_O$) values (fig. 20) determined for the Lower Cretaceous "J" Sandstone and associated hydrocarbon source rocks including the Graneros, Mowry, and Skull Creek Shale units. The apparently anomalous heat flow in this area has been attributed to igneous intrusions emplaced along projected fault trends of the Colorado mineral belt in basement rocks in the northern Denver Basin (for example, see Weimer, 1996; Myer and McGee, 1985). Wrench faults and subsidiary faults at depth might have provided conduits for heat flow into

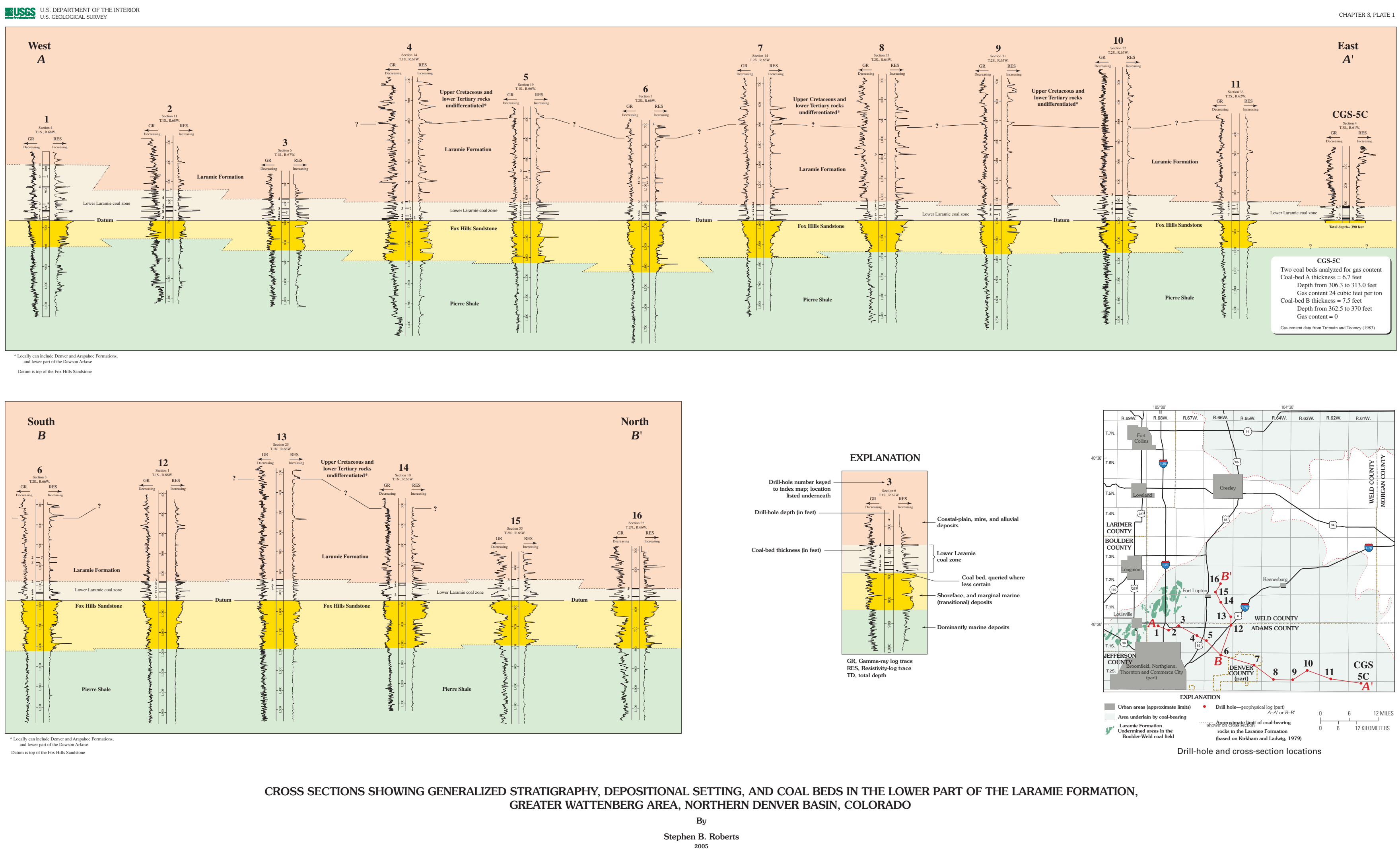


**Plate 1.** Generalized stratigraphy, depositional setting, and coal beds in the lower part of the Laramie Formation, greater Wattenberg area, northern Denver Basin, Colorado. (Click on plate image above to open full-size image for viewing and printing.)

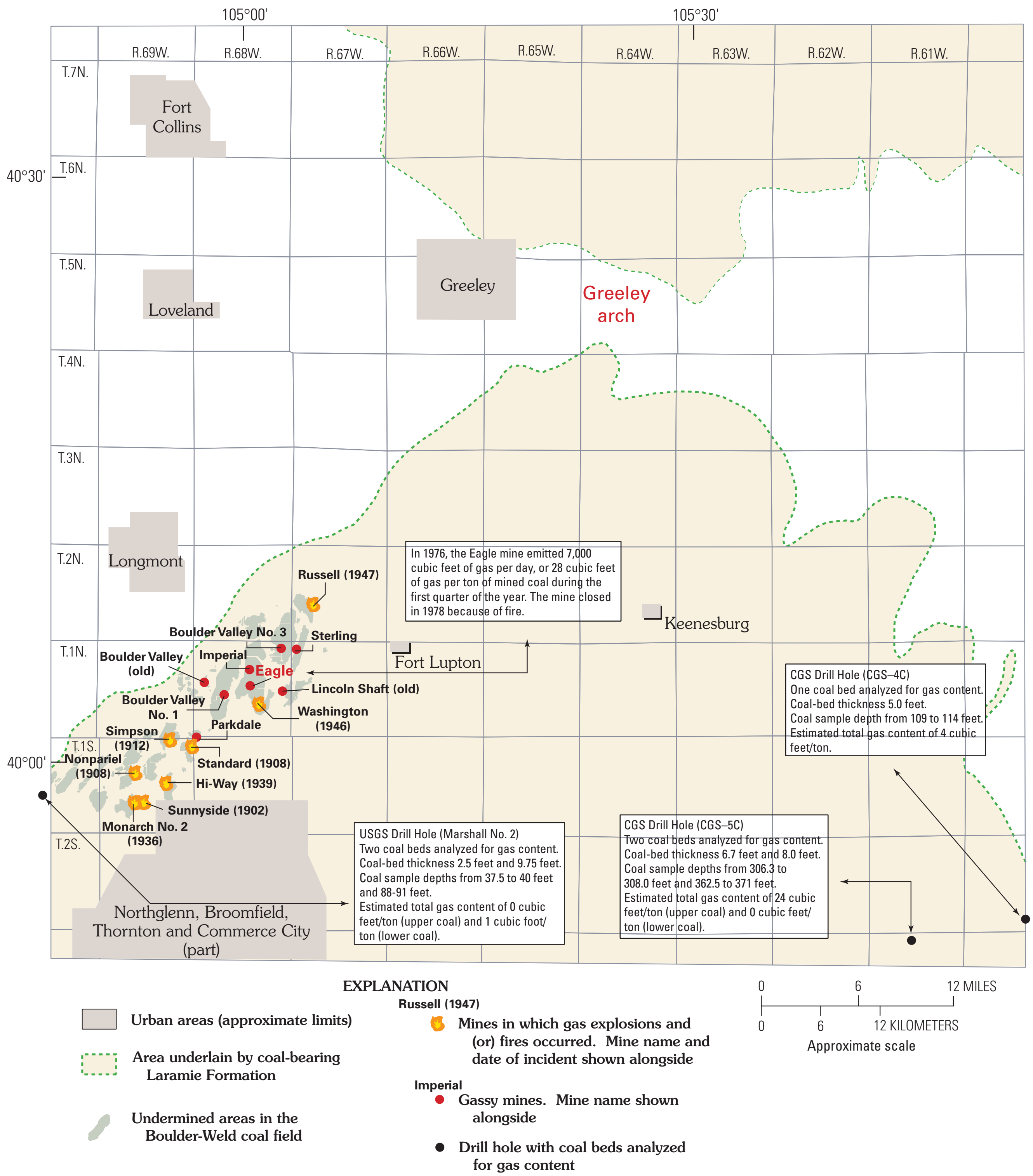


**Figure 18.** Locations of gassy coal mines, or coal mines that experienced fires or gas explosions, and the locations of drill holes in which Laramie Formation coal beds were analyzed for total gas content in the northern part of the Denver Basin, Colorado. Mine data from Fender and Murray (1978). Data on coal-bed gas content from Tremain and Toomey (1983).

overlying sedimentary units. Higher heat-of-combustion (BTU/lb) values in coal-beds in the Boulder-Weld coal field might also relate to heat flow from intrusions at depth, although this concept is speculative. Regardless of the causal mechanism, higher heat-of-combustion values in the Boulder-Weld coal field likely relate to higher coal ranks (albeit slight) and possibly a corresponding higher potential for coal-bed gas generation relative to the rest of the GWA.

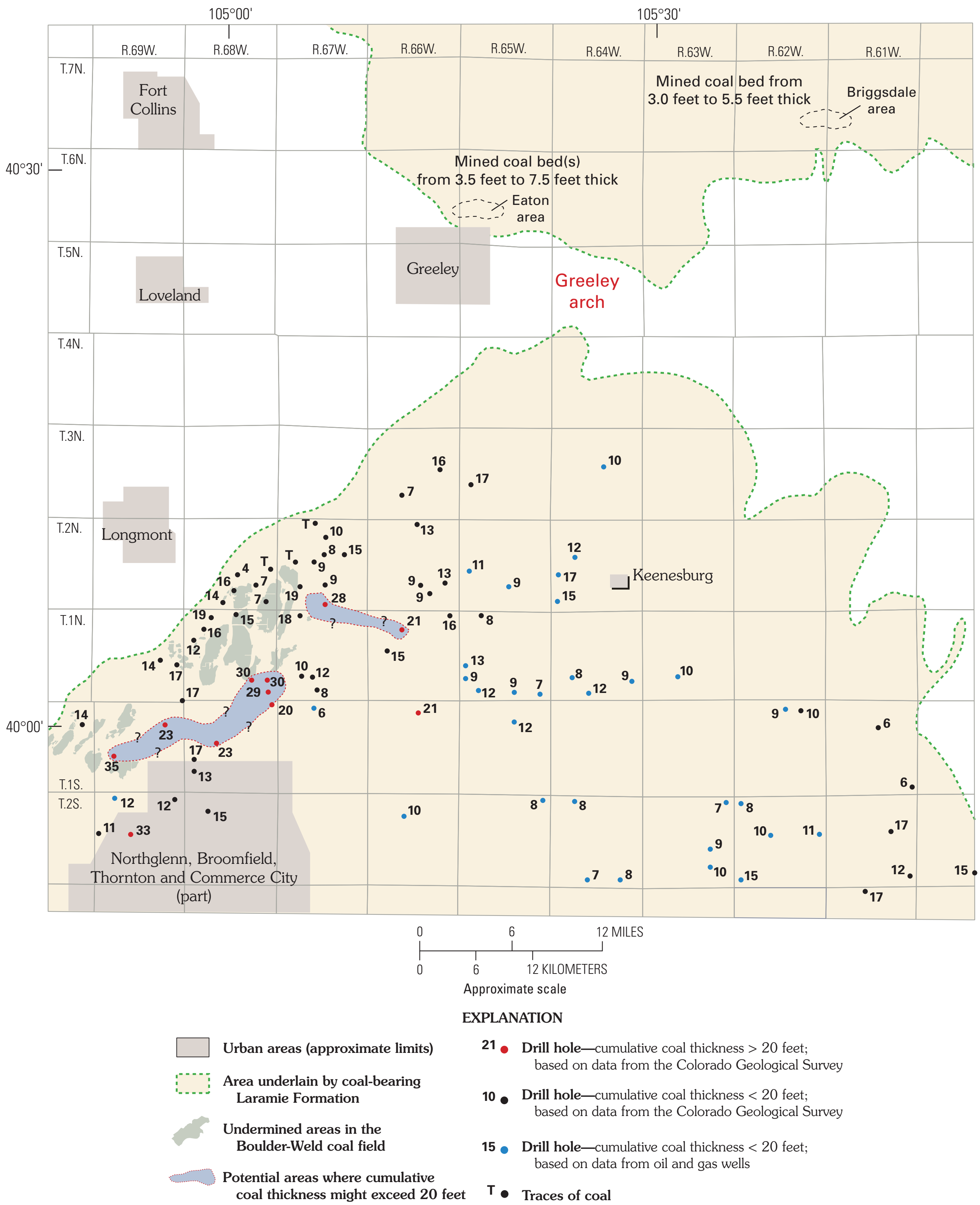


**Figure 19.** Total coal thickness in drill holes penetrating the lower part of the Laramie Formation in the northern part of the Denver Basin, Colorado. Total coal thickness data based on interpretations of geophysical logs from oil and gas test wells and from drill-hole data reported by Kirkham (1978b), Brand (1980), and Brand and Caine (1980).

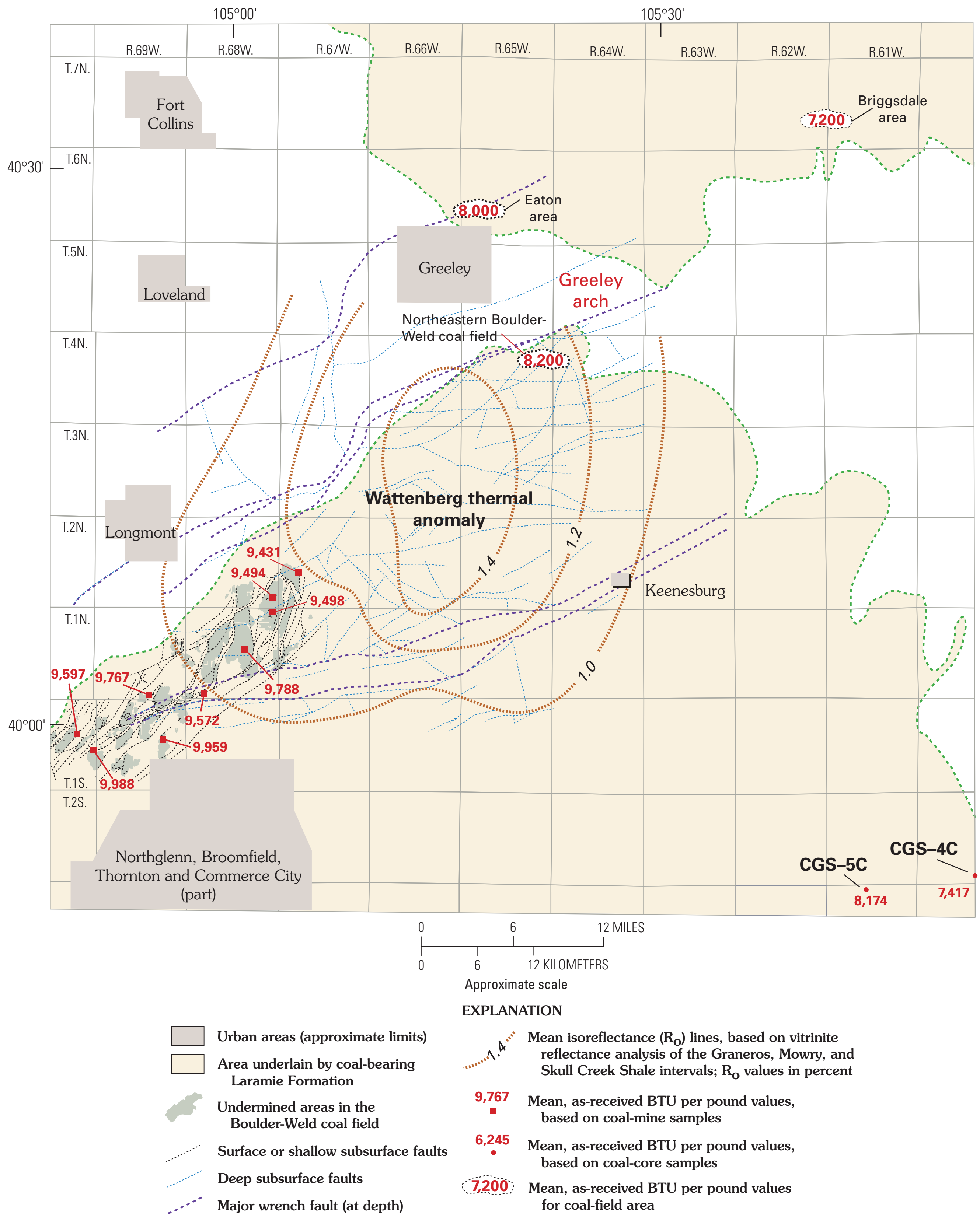


**Figure 20.** Heat-of-combustion values for coal beds in the lower part of the Laramie Formation in the northern part of the Denver Basin, Colorado. The position of the Wattenberg thermal anomaly is based on vitrinite reflectance data from the Graneros Shale, Mowry Shale, and the Skull Creek Shale intervals. Heat-of-combustion values are from Kirkham (1978a) and Tremain and Toomey (1983). Vitrinite reflectance data (isoreflectance lines) are from Higley and Gautier (1988) and Higley and others (1992).

Although the data listed herein are inconclusive with regard to the coal-bed methane potential for the Laramie Formation in the GWA, positive indicators for a potential coal-bed methane resource include (1) the presence of coal-bed gas, as evidenced by historical records of gassy mines and gas explosions (or fires) in coal mines in the Boulder-Weld coal field, (2) estimated total gas contents of as much as 24 $ft^3$/ton at some locations, (3) a relatively continuous distribution of coal beds in the Laramie Formation throughout the area, and (4) cumulative (total) coal-bed thickness exceeding 30 ft and individual coal-bed thickness of as much as 12 ft locally. Conversely, certain geologic factors characteristic of the GWA could limit the developmental potential of this resource. For example, in places where total coal accumulations exceed 20 ft and where individual coal beds can be 8 ft thick or more, the lower Laramie coal zone is generally shallow (depth of less than 500 ft) and coal beds are in close proximity to faulted and undermined areas in the Boulder-Weld coal field. The shallow depth and proximity to faults and abandoned underground mines could limit coal-bed gas retention because of leakage through mined-out cavities (voids) or faults, or the updip migration of gas to nearby outcrops. In addition, in the south-central part of the GWA where greater coal depths (more than 500 ft) might enhance coal-bed methane retention, reported total coal accumulations are typically less than 20 ft and commonly less than 10 ft. The limited volume of coal in these areas could also reduce the coal-bed methane resource potential.

## Coal-Bed Methane Summary

Conceptually, the mere presence of coal in the Denver Basin signals a potential for coal-bed methane resources. However, certain factors could limit or possibly negate successful coal-bed methane development. Comparison to the successful development of shallow, coal-bed methane resources from low-rank coal in the Powder River Basin indicates that similar production in the Denver Basin might be feasible. It is important to consider, however, the extreme differences in coal thickness and coal resource volumes between these two basins. In the Powder River Basin, individual coal-bed thickness can exceed 200 ft (for example, see Mapel, 1959; Roberts, 1986), and current coal-bed methane production commonly targets coal beds as thick as 100 ft or greater (for example, see Stricker and others, 2000). Most of that production is from coal beds in the Wyodak-Anderson coal zone, which is as much as 550 ft thick and can include as many as 11 coal beds that average as much as 25 ft in thickness (Stricker and others, 2000; Flores and Bader, 1999). Total coal resource estimates in the Wyodak-Anderson coal zone in the Wyoming part of the Powder River Basin are about 510 billion short tons (Ellis and others, 1999).

Individual coal beds in the Laramie can be as thick as 20 ft; however, they are more commonly less than 10 ft thick throughout most of the Denver Basin. Coal resource estimates for coal beds greater than 2.5 ft thick and at depths less than 3,000 ft are about 20–25 billion short tons (Kirkham and Ladwig, 1979). Denver Formation lignite beds are as much as 55 ft thick locally but usually contain non-coal partings that range in thickness from several inches to more than several feet. Estimated lignite resources, in beds at least 4 ft thick and at depths of less than 1,000 ft, are about 10–15 billion short tons; resources at depths of more than 1,000 ft are probably less than 1 billion short tons. It is apparent that coal volumes in the Wyodak-Anderson coal zone in the Powder River Basin are more than an order of magnitude greater than coal volumes in the Laramie and Denver Formations combined. The great volume of coal associated with thick coal beds in the Powder River Basin, even though the coal beds are of low rank, has undoubtedly enhanced coal-bed methane production (in part) because of the potential for large volumes of coal-bed gas per unit area of land (for example, see Choate and others, 1984). Thus, even if gas contents of coal in the Denver Basin prove to be comparable to gas contents in coal beds the Powder River Basin, the much smaller volume of coal resources could limit the overall coal-bed methane potential in this area.

Another factor that should be considered is the close association of coal beds in the Laramie Formation with the Laramie-Fox Hills aquifer, which is pervasive throughout the Denver Basin and is one of the primary sources of freshwater for residential, agricultural, and commercial use. The aquifer is present in basal sandstone units of the Laramie Formation, sandstone and siltstone units in the Fox Hills Sandstone, and more rarely, siltstone and sandstone units in the uppermost part of the Pierre Shale (Robson and others, 1981). Thin coal beds in the lower part of the Laramie are commonly interbedded with the aquifer in much of the Denver Basin; in areas such as the Boulder-Weld and Colorado Springs coal fields and the Foothills coal district (fig. 5), the aquifer includes thicker coal beds historically targeted for mining (for example, see Kirkham and Ladwig, 1979). To successfully develop a coal-bed methane resource, a process of dewatering might be required in order to remove in-situ water from the coal bed(s) and allow for the release of methane from the coal matrix (desorption) to a well bore for recovery (for example, see Rice and others, 1993). Water yields related to coal-bed methane production are variable; for example, water production associated with coal-bed methane development in the Powder River Basin has ranged historically from 0 to as much as 1,000 barrels of water per day in some wells (Tyler and others, 1995). Production of substantial quantities of water can result in drawdown of existing subsurface water tables with time and can require special constraints with regard to disposal of the produced waters. Given that coal beds with potential methane resources in the lower part of the Laramie Formation are within or immediately overlying the Laramie-Fox Hills aquifer throughout the Denver Basin, careful consideration to development of any coal-bed methane resource is necessary to ensure that associated water production would not impinge on the quality of the aquifer.

Additional studies detailing the subsurface thickness and distribution of coal beds, combined with more definitive analyses of coal-bed gas content and composition, are needed in order to better understand the coal-bed methane potential in the Laramie and Denver Formations. Although the Denver contains the thickest coal beds in the Denver Basin, the relatively low rank and abundance of non-coal partings, coupled with relatively low gas contents (0–11 $ft^3$/ton) recorded to date (Tremain and Toomey, 1983), might reduce the potential for significant coal-bed methane resources within this formation. Coal beds in the Laramie Formation might be more prospective for coal-bed gas, to some degree, based on their higher rank, relatively higher gas contents, and widespread distribution throughout the Denver Basin. Although individual coal beds in the Laramie Formation are generally thin (less than 15 ft thick), total (cumulative) coal accumulations in the lower 200–250 ft of the formation exceed 20–30 ft in a number of areas throughout the basin (for example, see Brand and Eakins, 1980; Eakins, 1986; Eakins and Ellis, 1987). In areas where these thicker accumulations are present, coal-bed methane recovery from multiple coal beds within a relatively narrow stratigraphic interval could enhance the potential for development, should coal-bed gas contents be of sufficient volume. Higher heat-of-combustion values measured in coal beds in the Boulder-Weld coal field could reflect a slightly elevated rank and a corresponding increase in the potential for coal-bed methane resources in that area. In addition, recovery of “behind-pipe” coal-bed methane in existing gas wells penetrating the Laramie Formation might be considered in areas such as the Wattenberg gas field in the northern part of the Denver Basin. Recompletion in these existing wells, if feasible within economic and engineering constraints, might decrease the need for new drilling. Additional gas production would be facilitated by the gas recovery and transport infrastructure that is already established in these areas.

# Effects from Historical Coal Mining

Although there has been no active coal mining in the Denver Basin for more than 20 years, potential effects from previous mining still exist in certain areas of the basin. Because historical production of coal in the Denver Formation was essentially limited to shallow operations in fairly small areas, little or no detrimental effect to date has resulted from these mining operations. However, underground coal mining in the Laramie Formation was quite extensive, and potential effects related to these abandoned underground mines still linger in fields where Laramie coal was produced. Most of the major surface remnants of these underground mines, such as mine dumps, surface excavations, hoisting frames (headframes), and the buildings necessary for mining operations, have been removed, often to accommodate or facilitate urban growth. Removal of such structures and the subsequent development or expansion of residential and urban facilities into coal-field areas have significantly masked the imprint of previous mining activities. However, even though much of the surface expression of mine development has been mitigated, subsurface features of underground mining, such as shafts, slope entries, and open mine rooms are still present. Because of this, potential effects such as fires in the abandoned mines and ground-surface collapse (subsidence) over undermined areas still exist in heavily mined areas along the Front Range corridor.

## Coal-Mine Fires

Coal-mine fires can occur during the active process of mining and well after mining activity has ceased. These fires can result from the accidental or intentional ignition by man and by the process of spontaneous combustion (for example, see Dunrud and Osterwald, 1980; Herring and others, 1986; Rushworth and others, 1989) that results from rapid, highly exothermic chemical reactions that can raise the temperature of the coal to the point of ignition (Rushworth and others, 1989). In coal mines that have been abandoned for a significant period of time, spontaneous combustion can be a more likely cause of fires. Factors that control spontaneous combustion in coal include the rate of airflow, moisture content of the coal, and coal rank (Kim, 1977). Coal of subbituminous rank, such as coal beds in the Laramie Formation, is prone to self-ignition in abandoned underground mines where air and moisture entering the mine workings can induce these exothermic reactions, causing unmined coal to ignite spontaneously. The resulting coal mine fire then propagates through the unmined coal toward a source of oxygen, such as an open mine room or entry. Fire propagation can also be facilitated by the development of fire-induced fractures or fissures that form in the overburden (roof rock) as the fire burns. These features provide additional conduits for oxygen flow, which continues to fuel the fire (Rushworth and others, 1989). Coal fires in abandoned mines can be quite striking and at times are visible at the ground surface (fig. 21). Fires in shallow mines emit noxious fumes, steam, and heat to the ground surface through active vents, which typically form just in front of the advancing fire (J.L. Herring, U.S. Geological Survey, oral commun., 1984, as reported in Rushworth and others, 1989). Additionally, coal fires can generate sufficient heat to bake and fuse overlying and adjacent rocks, resulting in the formation of clinker deposits within the abandoned mines and on the ground surface.

In the Denver Basin, fires in abandoned coal mines near the town of Marshall (fig. 22) in the Boulder-Weld coal field were documented as recently as 1988 (Rushworth and others, 1989). Such fires have been observed since the early 1900s, and local residents have reported anomalously high ground-surface temperatures and the occurrence of methane explosions with fire plumes soaring high into the air (Herring and others, 1986). Historical coal-mine fires in the area are also evidenced by deposits of clinker, which are present within


**Figure 21.** Photograph of an active fire in an abandoned underground coal mine near Sheridan, Wyoming. Photograph from Dunrud and Osterwald (1980).

the Marshall Nos. 1 and 3 and the Lewis Nos. 1 and 2 mines (Herring and others, 1986). Underground mines near Marshall are commonly at depths of less than 100 ft (for example, see Myers and others, 1975; Roberts and others, 2001), and the shallow depth to old workings might have, in part, facilitated ignition of the fires. In the early 1980s, steam plumes generated from an underground fire associated with the abandoned Marshall No. 3 coal mine (fig. 22, site A) were clearly visible during winter months along the east side of Highway 93. In 1982, the USGS and the Office of Surface Mining (OSM) undertook a shallow drilling project to better define the limits of the active fire in a small study area surrounding the fire site (S.B. Roberts, USGS, unpub. data, 1982). During the course of this study, anomalously high temperatures (that is, higher than ambient temperatures of 50° to 60°F) were recorded in shallow drill holes (less than 100 ft) near the site, indicating a possible underground, extraneous heat source such as burning coal in the abandoned mine. Qualitative assessment of subsurface temperatures within the study area indicated that the active burn was restricted to a small area along the western edge of the Marshall No. 3 mine (fig. 22). The fire was subsequently smothered by the addition of a 2-ft-thick cover of fill dirt on the ground surface above the mine (Herring and others, 1986). In 1988, the Colorado Geological Survey (CGS) reported that there was an active fire in the abandoned Lewis No. 1 and No. 2 coal mines, also near Marshall (fig. 22, site B) (Rushworth and others, 1989). A fire at this location had been previously reported by Myers and others (1975) and was also observed by personnel of the CGS and the Colorado Inactive Mine Reclamation Program (CIMRP) in 1984. A return visit to the site by CGS workers in 1988 revealed little change from 1984, although vents emitting heat and smoke on the hillside overlying part of the mine were still evident. Minor damage resulted from the fire, and some 800 ft of an irrigation ditch breached by the fire had to be rebuilt and reinforced during a reclamation project in 1986 (Rushworth and others, 1989).

## Coal-Mine Subsidence

An additional and perhaps more widespread effect of historical coal mining in the Denver Basin relates to ground surface subsidence above abandoned underground coal mines. Coal-mine subsidence is well documented along the Front Range, particularly in the Colorado Springs and Boulder-Weld coal fields (for example, see Myers and others, 1975; Dames and Moore, 1985; Herring and others, 1986; Matheson and Bliss, 1986). Aerial photographs of the Marshall area (figs. 23 and 24) in the southwestern part of the Boulder-Weld coal field attest to the visible scarring that can result from ground surface subsidence in undermined areas. Coal-mine subsidence is a dynamic process that can take place concurrently with mining or can occur many years after a mine has been abandoned. Once a volume of coal (or rock) is extracted within an underground mine, the void (cavity) that remains after extraction can serve as a focal point for collapse of the mine roof and subsequent sagging or collapse of the overburden above the mined-out cavity. Progressive upward collapse/sagging of the overburden with time can cause subsidence features (depressions) to develop on the ground surface. Because of the rapid expansion of urban and residential development over undermined areas in the Denver Basin, an obvious ramification of the subsidence process is the potential for damage to new or existing structures (roads, houses, businesses, and so forth).

Terms such as depressions, local depressions, sags, troughs, localized troughs, holes, sinkholes, potholes, and subsidence pits have been used by previous authors to describe the various ground-surface features resulting from subsidence over abandoned coal mines (for example, see Myers and others, 1975; Dunrud and Osterwald, 1980; Turney, 1985; Dames and Moore, 1985; Matheson and Bliss, 1986). Additional surface features include tension cracks that can form at the margins of subsidence depressions and compression bulges that form within the depressions themselves (Dunrud and Osterwald, 1980). In general, there is a dimensional hierarchy of surface collapse features, ranging from small subsidence pits and sinkholes to substantially larger troughs and depressions.

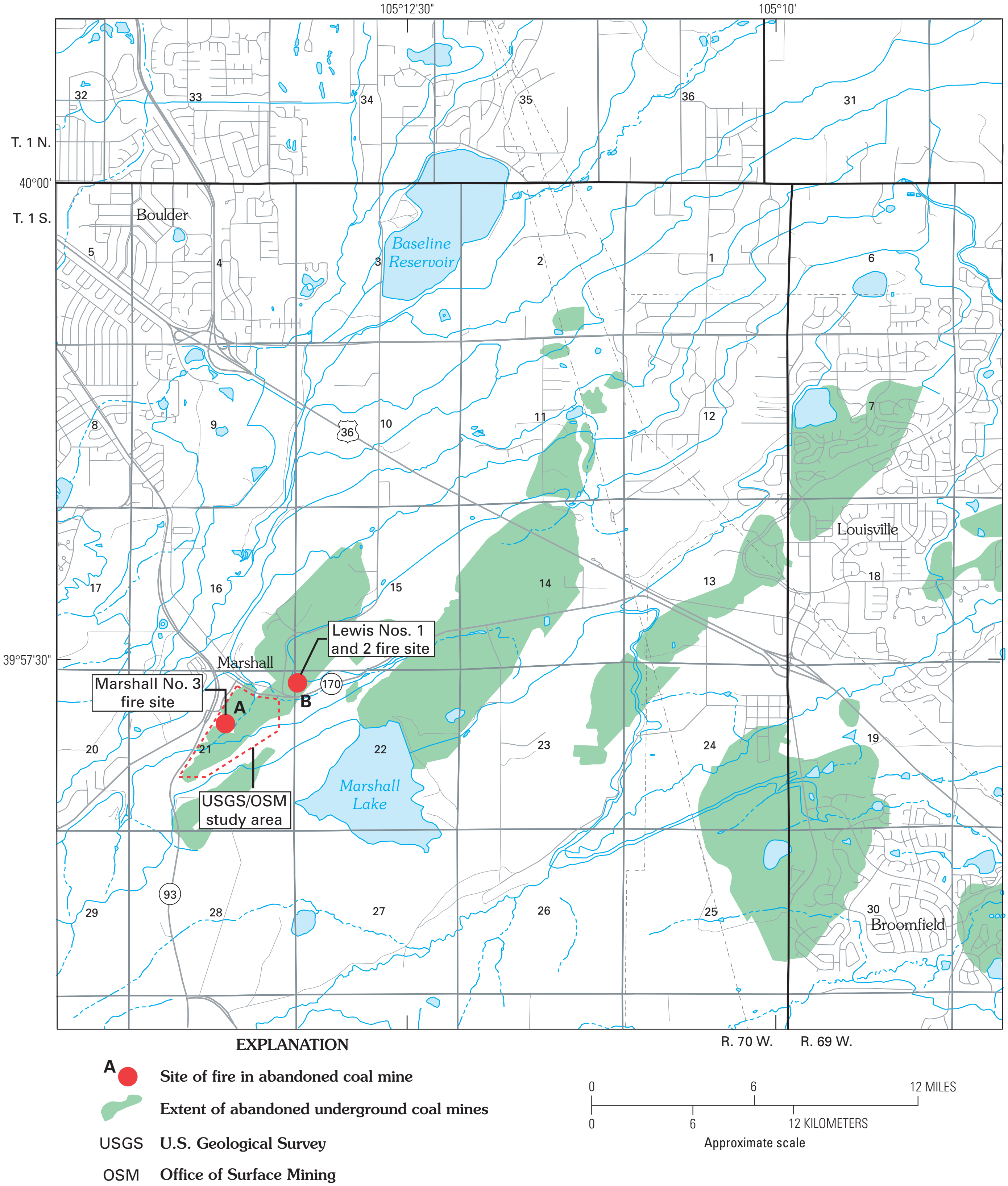


**Figure 22.** Extent of abandoned underground coal mines, the location of a 1982–83 cooperative U.S. Geological Survey (USGS) and Office of Surface Mining (OSM) coal-mine fire study site, and the location of historical underground coal-mine fires near the town of Marshall, Colorado. Location of the Lewis Nos. 1 and 2 fire site from Rushworth and others (1989). Extent of abandoned mines based on Myers and others (1975) and Roberts and others (2001).


**Figure 23.** Oblique aerial photograph (looking northwest) showing surface subsidence features caused by the collapse of underground coal mines near the town of Marshall, Colorado, in 1973. Photograph courtesy of R.B. Colton (scientist emeritus), U.S. Geological Survey, Denver, Colorado.

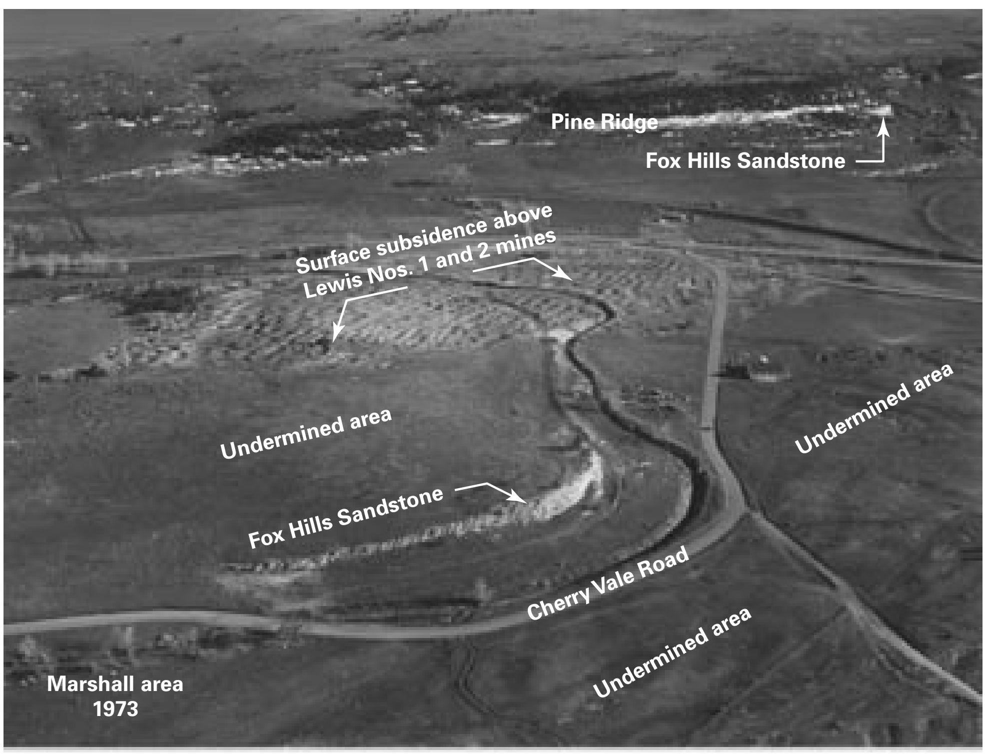


**Figure 24.** Oblique aerial photograph (looking south) showing surface subsidence features caused by the collapse of underground coal mines along the Cherry Vale Road, near the town of Marshall, Colorado, in 1973. Photograph courtesy of R.B. Colton (scientist emeritus), U.S. Geological Survey, Denver, Colorado.

For this report, the term subsidence pit is used in reference to the smaller features (for example, sinkholes and potholes), and the term trough is used to describe larger collapse features. It is important to bear in mind, however, that the basic “cause and effect” processes that form subsidence pits and troughs are similar in many respects, and the differences relate more to the variations in their surface expression, size, and effect.

Subsidence pits can be as much as several tens of feet in breadth, generally have circular to elliptical shapes, and can exceed 10 ft in depth in certain areas of the Denver Basin (for example, see Myers and others, 1975; Matheson and Bliss, 1986). These pits can develop rapidly, usually within a period of hours to a few days (Turney, 1985). Where mined coal beds are essentially flat lying, subsidence pits form in response to a process termed “chimney subsidence” (Matheson and Bliss, 1986). Chimney subsidence results from the collapse of roof rock and overlying overburden into an underground void, such as an abandoned room in a coal mine. Through time, continued collapse (caving) of the overburden into the void results in the migration of the void upward, toward the ground surface (fig. 25). In steeply dipping coal beds, a process termed "stoping" results in a similar, upward void migration in an updip direction, along the coal bed toward the ground surface (Turney, 1985). Subsidence pits develop as intervening strata between the mine cavity and the ground surface collapse into or sag downward toward the void (fig. 26). In general, the breadth of a subsidence pit is more or less coincident with the breadth of the underlying mine cavity (fig. 27). The depth of a subsidence pit, however, can be influenced by several factors, including (but not limited to) the thickness of the mined coal, the nature of the ground-surface material above the mine, and the bulking characteristics of the overburden between the mined horizon and the ground surface (Dames and Moore, 1985; Turney, 1985). Logically, the height of an underground void generally corresponds to the thickness of the mined coal bed; theoretically, the maximum depth of a subsidence pit should correspond closely to this mined-coal thickness. However, in cases where the ground surface consists of loosely consolidated sediment or soil, the pit depth can exceed the mined-coal thickness because loose surface material can be washed into the underlying mine and subsequently be dispersed by ground-water movement through the abandoned mine (fig. 27) (Turney, 1985).

The bulking characteristics of the mine roof and overburden also serve to control the depth of a subsidence pit above a collapsed room. In general, the term "bulking" relates to the volume and density of the loosely packed rubble column that accumulates in a mine void as a result of roof/overburden failure. When consolidated roof/overburden rock collapses and accumulates as rubble in the underlying mine void, the volume of space occupied by the collapsed rubble is always greater than the volume occupied by that same rock prior to collapse (for example, see Herring and others, 1986). During chimney subsidence, multiple phases of upward void migration and caving result in a series of vertically stacked "bulking zones" of rubble, which form as the collapse of roof/overburden rock propagates upward and caved material drops into the remaining void space (for comparison, see Dames and Moore, 1985). In this process, the first (lowest) phase of collapse has the greatest magnitude of vertical movement because caved materials have the full thickness and extent of the mined horizon in which to fall. This magnitude of vertical movement allows for the collapsed material to "bulk" fully within the original mined horizon, potentially filling a significant volume of the void space. Correspondingly, this first bulking zone also achieves a minimum density relative to the density of the consolidated material prior to collapse (Dames and Moore, 1985). Through time, as the void continues to migrate upward because of caving, successive bulking zones should exhibit decreased bulking and density changes as the magnitude of vertical displacement in the void decreases. Ultimately, this process can terminate when the accumulated (bulked) rubble column has essentially filled the void and has the strength to support the overlying rock (for example, see Dames and Moore, 1985). If an underground void has migrated to a level conducive to ground-surface sagging or collapse, the magnitude of the surface subsidence should correspond closely to the height (thickness) of the remaining void. If most of the void has been filled by rubble, the depth of the resulting surface subsidence feature might be significantly less than the thickness of the original, mined-coal horizon. In deep mines, it is feasible that a cycle of chimney subsidence, from the initial roof collapse to the point of stability, could take place with no surface subsidence effects at all (for comparison, see Hynes, 1987). However, although depth to the abandoned mine is certainly a factor influencing the magnitude of surface subsidence, and the majority of subsidence pits related to chimney subsidence are over mines within 100 ft of the ground surface, some pits have formed above underground mines as deep as 350 ft (Turney, 1985).

In contrast to subsidence pits, subsidence troughs are broad, "dish-shaped" areas of lowered (subsided) ground surface that form in response to the process of trough subsidence (for example, see Turney, 1985; Matheson and Bliss, 1986). Troughs are larger in areal dimension than subsidence pits and can be hundreds to thousands of feet in breadth (Matheson and Bliss, 1986). A single trough might actually include numerous subsidence pits, which can form after the subsidence trough has developed (for example, see Dunrud and Osterwald, 1980). Troughs tend to develop over areas where continuous, high-extraction mining of a coal bed has generated a large, open cavity with little or no roof support. As the mine roof sags or collapses into the unsupported void, the overlying overburden can collapse or sag correspondingly. Ultimately, a trough of depression can form on the ground surface, as the sag is propagated upward (fig. 28) (Myers and others, 1975). The surface disturbance resulting from trough subsidence exceeds the areal dimension (breadth) of the underground void (for example, see Myers and others, 1975). In areas where room-and-pillar methods were used for coal extraction, trough subsidence can occur where multiple coal pillars in an abandoned, underground mine have collapsed simultaneously or in rapid succession, resulting in the development of a large open void encompassing all or parts of multiple mine rooms; this chain reaction of pillar failure can initiate when the weight of the overburden exceeds the strength of the existing coal pillars (Turney, 1985). As one pillar collapses, overburden stress on adjacent pillars increases, potentially causing successive pillar failure over a large area. Coal-mine fires in room-and-pillar mines can also facilitate trough subsidence through the process of burning multiple pillars of coal as the fire propagates through the mine, resulting in collapse of the overburden above the burned pillars. Additionally, subsidence troughs can also form as a result of "pillar punching" when the weight of the overburden essentially pushes intact coal pillars downward, into a softened mine floor, causing sag in the overlying rock (fig. 29) (for example, see Roenfeldt and Holmquist, 1986).

In addition to subsidence features caused by chimney and trough subsidence, there is also the potential for pits and holes

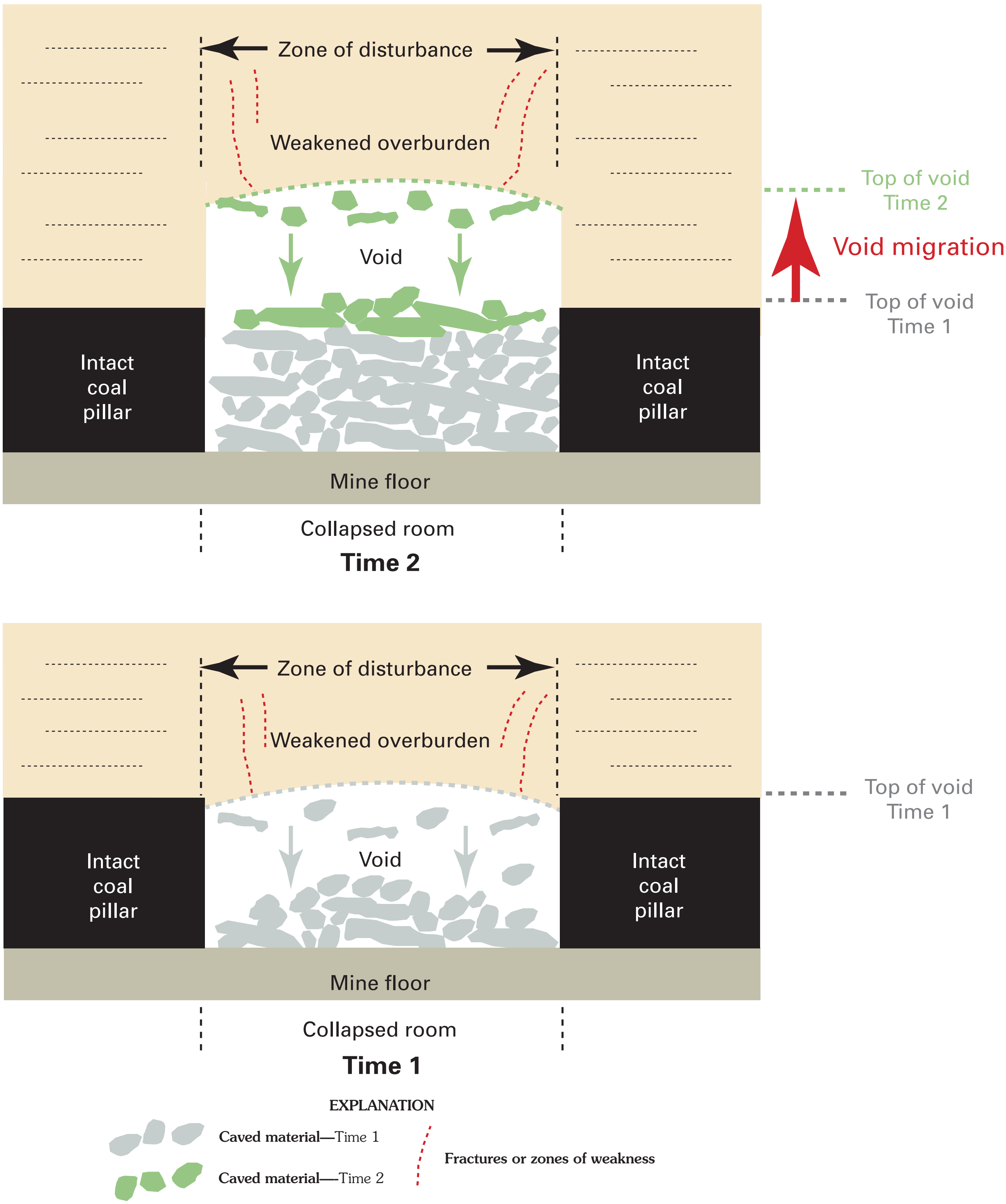


**Figure 25.** Diagram showing the process and results of roof and overburden collapse (chimney subsidence) into an abandoned room of an underground coal mine. From time 1 to time 2, progressive failure (collapse) of weakened roof rock or overburden above the mine room results in the accumulation of caved material (rubble) in the open cavity and the apparent upward migration of the void. In this process, bedded rock units in the zone of disturbance might be subject to downward sagging or separation as the effects of mine collapse are propagated upward. Diagram not to scale.

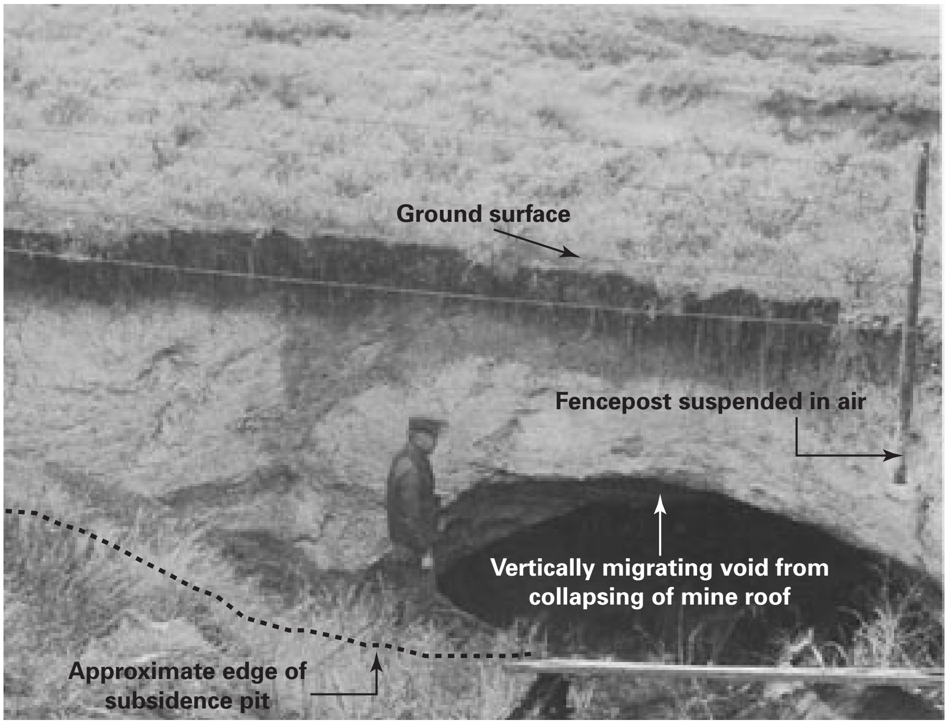


**Figure 26.** Photograph showing surface subsidence pit and associated void that has migrated upward above an abandoned underground coal mine near Sheridan, Wyoming. Depth to the original mine workings is about 30 ft below ground surface. Photograph from Dunrud and Osterwald (1980).

to form by the sudden and rapid collapse of abandoned mine shafts and steeply sloped entryways. Upon abandonment of the mine, these shafts might have been poorly backfilled with unconsolidated mine material and waste in attempts to seal the entries. Through time, this unconsolidated material can fail downward, allowing for the shaft to reopen suddenly. Additionally, where inclined slope entries (adits) used for mine access were at or close to the ground surface and constructed in poorly consolidated surficial material, there is a potential for the collapse or caving of the ground surface overlying these shallow adits (Turney, 1985).

## Subsidence Prediction

Because of the potential damage that can result from coal-mine subsidence, subsidence prediction has become an important tool for land-use considerations in the Denver Basin. However, although the processes of subsidence are reasonably well understood, difficulty arises when trying to accurately predict when and where subsidence will occur. Numerous techniques (models) aimed at determining the subsidence potential in undermined areas have been developed, and reports by Myers and others (1975), Hynes (1987), Dames and Moore (1985), and Matheson and Bliss (1986) contain detailed information on the application of various models in mine-subsidence investigations in Denver Basin coal fields. In addition, Roenfeldt and Holmquist (1986) provide a detailed review of past and present analytical approaches to subsidence prediction related to underground coal mining. The following discussion provides a general overview of some basic concepts and models generally applied to subsidence prediction, and describes other factors that can influence subsidence potential.

Surface effects of mine subsidence that result in property damage principally arise from vertical subsidence, associated primarily with chimney subsidence processes, and horizontal ground strain, tilt, and curvature of the ground surface resulting primarily from trough-type subsidence (for example, see Hynes, 1987; Turney, 1985). Subsidence, whether vertical or with an oblique component, can cause appreciable damage to structural foundations as well as disruptions of adequate grades necessary for proper drainage in sewer lines, ditches, and streams (Hynes, 1987). Horizontal ground strain, both compressive and tensional, can be imparted on structures affected by the development of a trough of depression (zones of tension and compression, fig. 28). Strain is the measure of the change in length of an object (relative to its original length) when placed under stress; compressive strain results in “shortening” whereas tensional strain results in “lengthening” of the object (for example, see Hynes, 1987). Compressive strain can result, for example, in the buckling of roads and sidewalks, and tensional strain can cause damage to buildings (such as cracks in walls, ceilings, and foundations) by forces literally pulling the structure apart (for example, see Turney, 1985). An additional component termed tilt, which is also commonly associated with trough subsidence, can adversely affect drainage gradients in sewer lines and drainage ditches and can place significant tensional strain on a structure as it tilts into the edge of a trough; taller buildings (more than three stories) and longer structures are more susceptible to damage resulting from surface tilt (Hynes, 1987). Curvature, which is the change in tilt over a given distance, generates tensional and compressive strains and can also induce rotational stresses

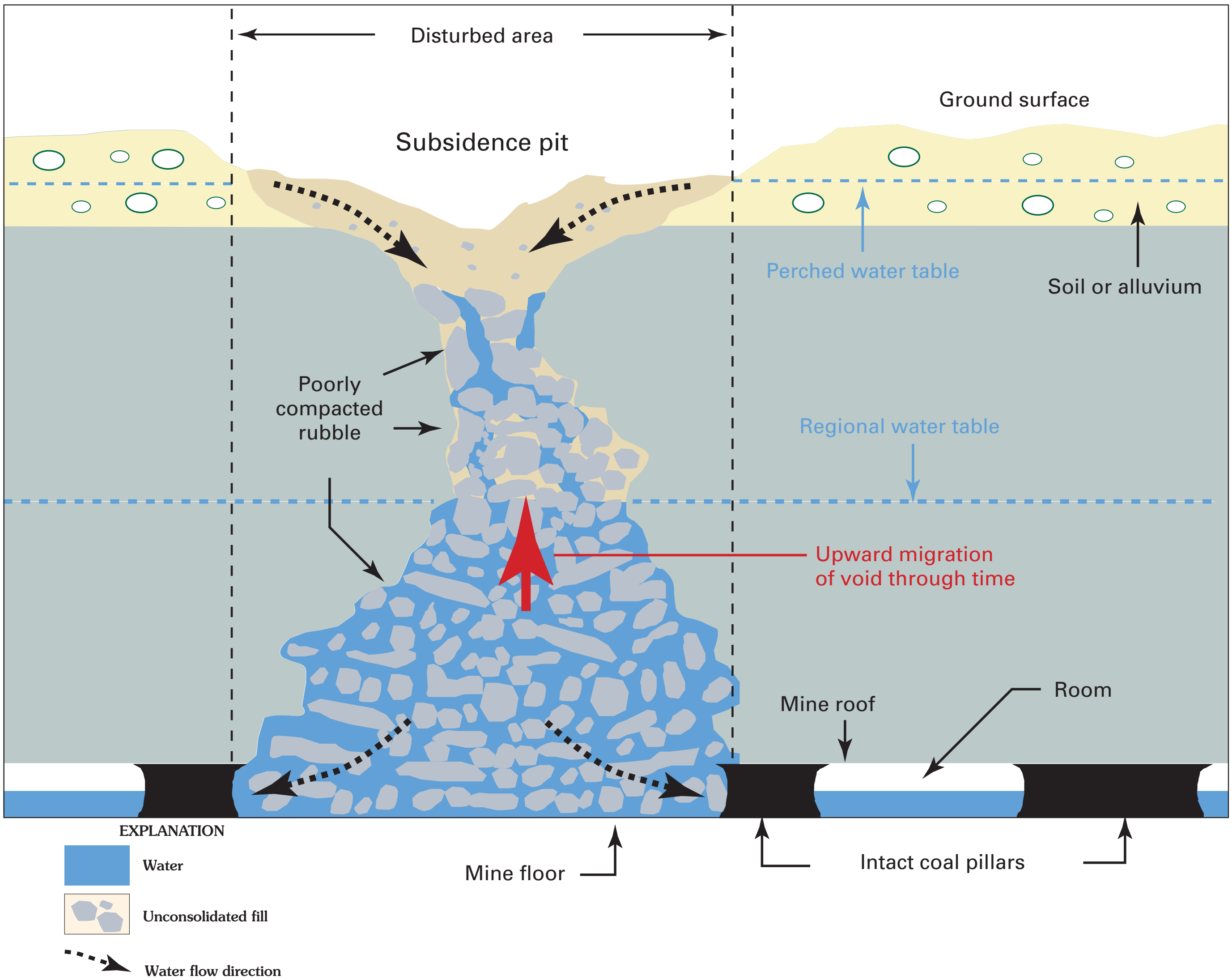


**Figure 27.** Diagram depicting the chimney subsidence process and its potential effects on the ground surface. Overburden collapse and upward void migration above an abandoned room in an underground coal mine has resulted in the development of a subsidence pit (sinkhole) on the ground surface. In chimney subsidence, the areal dimensions of the subsidence pit correspond closely to the dimensions of the collapsed mine room below ground. In this scenario, the depth of the subsidence pit increases as shallow water washes loose surface material downward through the caved rubble into the collapsed mine room. Diagram not to scale. Modified from Turney (1985).

that can damage rigid underground pipes, gas lines, and conduits (Hynes, 1987).

The processes of chimney and trough subsidence described in previous sections are basic concepts that aid in interpretations of surface subsidence potential above abandoned coal mines. However, application of these theories in subsidence prediction is not always straightforward, as varying conditions related to mining techniques, overburden characteristics, and data availability might necessitate modification to the subsidence concepts on a site-specific basis. In all cases, it is critical to have accurate map data depicting such elements as mine elevation, orientation and extent of mining operations, room-and-pillar locations and size, major and minor haulageways, entries, and shaft locations. Most, perhaps all, of the underground mines in the Denver Basin are now inaccessible, so improvements of or additions to the existing map information usually are not feasible without extensive and costly drilling programs. Maps for some of the older mines, which might have been abandoned since the late 1800s or early 1900s, are highly variable in terms of accuracy and completeness. Because such maps are key to analyzing the potential for subsidence, attempts at subsidence prediction in some areas can be hampered significantly if the available maps are inadequate. In addition, information on the mined coal-bed thickness, dates of mining, mining sequence, number of beds mined, coal extraction percentages, and retreat mining

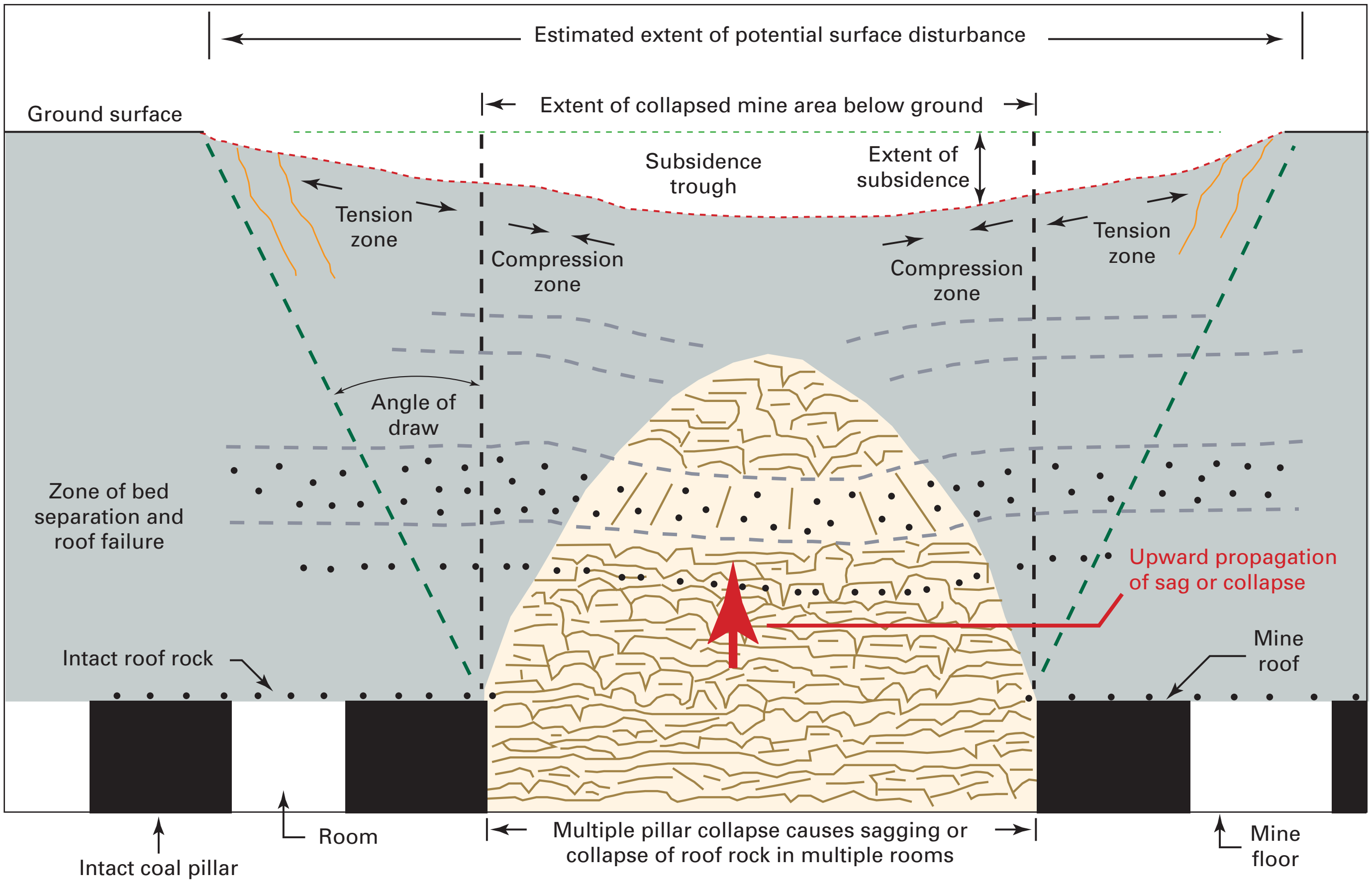


**Figure 28.** Diagram depicting the process and potential ground-surface effects of trough subsidence. In this scenario, the collapse of multiple coal pillars separating adjacent mine rooms results in the development of a large underground void. Overlying strata are weakened and sag or collapse into the underlying void. As this sagging/collapse propagates upward, a subsidence trough can develop on the ground surface. In trough subsidence, the areal dimensions of the subsidence trough on the ground surface exceed the areal dimensions of the underground cavity. Diagram not to scale. Modified from Turney (1985).

practices (pillar pulling) is also critical for accurate determinations of the subsidence potential in any given area (for comparison, see Roenfeldt and Holmquist, 1986).

In many cases, the prediction of surface effects caused by chimney subsidence is based heavily on an understanding of the bulking characteristics of the roof rock and overburden in the area of concern. If a model for prediction of the potential surface subsidence is constrained within a framework of bulking characteristics alone, the theory of harmless depth can be applied (Hynes, 1987). According to Hynes, the harmless depth theory, which dates back to the 19th century (for example, see Roenfeldt and Holmquist, 1986), relies on the concept that as a caving void migrates upward, the volumetric increase because of bulking will fill the void as long as there is a sufficient thickness of overburden to generate the volume of rock required to fill the original void. Harmless depth, then, is that depth beyond which subsidence (caving) in underground workings will have no effect on the ground surface. Because of the variability and lateral discontinuity of rock types in the Laramie Formation, bulking characteristics of roof rock and overburden can vary, both vertically and laterally, within a fairly small area. Bulking characteristics for different rock types can be determined through laboratory experiments, resulting in the calculation of a bulking factor (bulking coefficient) that reflects the percentage increase in the volume of rubble generated by the collapse of a specific rock type (for example, see Hynes, 1987; Herring and others, 1986). Hynes (1987) reported bulking factors ranging from 1.25 to 1.30 (25–30 percent volume increase) for sandstone and siltstone, and from 1.1 to 1.2 (10–20 percent volume increase) for shale and claystone in the northeastern part of the Boulder-Weld coal field. Bulking factors such as these can then be used to estimate the thickness of overburden required to fill a void, using the equation:

$$d = t/[(v_f - v_i)/v_i]$$

where $d$ is the thickness of overburden required to fill the void, $t$ is the thickness of the mined interval (void height), and $[(v_f - v_i) / v_i]$ represents the bulking factor (bulking coefficient), based on laboratory estimates of the initial ($v_i$) and final ($v_f$)

rock volumes before and after collapse, respectively (for comparison, see Herring and others, 1986). An application of this formula is as follows. If a composite bulking factor of 1.1 (10 percent volume increase) is assumed for the overburden above a mined void thickness of 10 ft, a rock column of 100 ft in thickness would be required to fill the void. By changing the bulking factor to 1.05 (5 percent volume increase), a rock column of 200 ft would be required to fill the same void (Hynes, 1987). In the first example, if the depth to the void was greater than 100 ft, then theoretically no surface disturbance should result from underground mine collapse. Thus, 100 ft is considered as the "harmless depth." It is important to remember, however, that this calculation relies primarily on bulking characteristics alone and assumes essentially flat-lying coal beds. For this reason, this approach might not be applicable in all areas of the Denver Basin. An additional model, which incorporates bulking aspects described here combined with a stable arch concept, can also be useful in predicting subsidence over room-and-pillar mines; Hynes (1987) has provided details of this model. Because bulking properties are so critical to interpretations of potential surface subsidence using these concepts, extensive drilling and rock-sample analyses may be required to accurately assess these properties when used for predictive purposes.

Models used to analyze larger scale trough-subsidence potential are commonly based on studies of subsidence above longwall mines. One of the more widely used models was devised through subsidence studies over longwall mines in the United Kingdom, sponsored by the National Coal Board (NCB) of Britain (for example, see Hynes, 1987; Roenfeldt and Holmquist, 1986). In longwall mining, coal is extracted from a large, continuous room (panel), which has no internal roof support except along the coal face that is being actively mined. Coal extraction by this method typically approaches 100-percent recovery in modern longwall panels (Lee Osmonson, U.S. Geological Survey, oral commun., 2001). The NCB model is based on the principle that the continuous and virtually complete extraction of coal, coupled with the corresponding lack of roof support in a longwall panel, causes a predictable fracturing and caving of the immediate mine roof and a corresponding collapse or sagging of the overburden into the void created by mining (for example, see Roenfeldt and Holmquist, 1986). The sag is propagated upward through the overburden and can result in the development of a trough of depression at the ground surface; the maximum depth of the depression will be no more than the thickness of the mined coal bed in this model (Myers and others, 1975). Subsidence over longwall mines is commonly concurrent with the active process of mining. As coal extraction in a longwall panel progresses, shallow troughs of depression can form on the ground surface, with the deepest part of the trough centered over the underground mine opening. Maximum subsidence (maximum depth) of the surface trough is achieved once an underground mine opening has reached a critical width (for example, see Myers and others, 1975), which is constrained (in part) by the thickness and depth of the mined-coal interval, size of the panel, and the physical characteristics of the overburden. If mining continues beyond the point of critical width, the maximum depth of the subsidence trough will remain constant, but a larger area of the ground surface will be subjected to maximum subsidence. After mining has ceased, subsidence can continue steadily or stop for a period of time until subsequent failure of the overburden results in the resumption of subsidence (Myers and others, 1975). As a tool for the prediction of potential subsidence effects, the NCB model can help determine the vertical and horizontal displacement of the ground surface, horizontal ground strain, and ground-surface tilt and curvature above longwall panels; the magnitude of these ground-surface features is closely tied to the width, depth, and height of the coal extraction zone (Hynes, 1987).

The NCB model has served as a basis for interpretations of trough-type subsidence in studies of Denver Basin coal fields (for example, see Myers and others, 1975; Hynes, 1987; Turney, 1985). However, practical application of the NCB model in the Denver Basin is limited because the vast majority of coal mines along the Front Range used room-and-pillar extraction techniques, which in contrast to longwall mining do not typically result in the development of a large, completely unsupported coal extraction zone in the subsurface. Even where retreat-mining (pillar pulling) practices were invoked, it is unlikely that all coal pillars or manmade supports were removed, either for engineering or safety reasons. Because the remaining coal pillars and supports could continue to provide roof stability for an indeterminant amount of time, the development of subsidence troughs on the ground surface above room-and-pillar mines might not follow as orderly and predictable a pattern as would be expected over longwall mines (Myers and others, 1975). In a study of mine subsidence in the Colorado Springs coal field by Dames and Moore (1985), troughlike subsidence over room-and-pillar mines was observed to be irregular, and the authors of that report interpreted that the interior of any given subsidence trough would likely undergo varying periods of tension and compression, depending on the timing required for failure of existing coal pillars and supports. They also suggested that as overburden above the room-and-pillar mine decreases, trough subsidence would primarily be a series of sinkholes resulting from the collapse of mine rooms with scattered larger depressions (troughs) forming from the general failure of pillars or mine floor over the larger areas. The NCB model, therefore, is less applicable in areas where historical mining conditions do not completely mimic longwall mining conditions (for example, see Hynes, 1987).

Other interrelated factors that can influence subsidence prediction include the amount of time that has elapsed since mining ceased and the particular subsurface conditions in the abandoned mines. In a study of chimney subsidence in the Front Range area, Matheson and Bliss (1986) suggested that the dominant portion of subsidence takes place within 30 to 40 years after mining; after that amount of time, subsidence continues but at a much slower rate. In addition, the surface expression of most of the subsidence pits (sinkholes) studied in the Denver Basin did not appear until 10 to 20 years after mining ceased. These authors also reported that in the decade between 1976 and 1986, the majority of chimney subsidence features that developed were the result of surface collapse over slope entries and shallow haulageways in abandoned mines rather than subsidence above abandoned mine rooms. Because so much of the underground mining (particularly the shallow mining) in the Denver Basin ceased 40 to 50 years ago (fig. 5) (Kirkham and Ladwig, 1979), it is possible that a significant portion of the potential coal-mine subsidence effects have already manifested themselves in certain areas of the basin (for example, see Myers and others, 1975; Dames and Moore, 1985; Herring and others, 1986; Matheson and Bliss, 1986). However, Dames and Moore (1985) suggested that chimney subsidence associated with room-and-pillar mines might not be completed for hundreds of years after the closure of a mine, depending on the strength characteristics of the mine roof and overburden, ground-water conditions in the mine, and the condition and abundance of manmade mine supports.

Subsurface conditions in abandoned room-and-pillar mines can also impede or hasten subsidence processes in an unpredictable fashion. For example, in mines that are flooded, softening of the mine floor can induce pillar punching and associated trough subsidence in overlying strata (fig. 29) (for example, see Roenfeldt and Holmquist, 1986). Conversely, water in a completely or partially flooded mine can also inhibit subsidence by providing buoyancy support to the mine roof and overburden above flooded areas and by slowing the weathering degradation of coal pillars, thus preventing or delaying pillar and roof collapse for an unpredictable number of years (Turney, 1985). Through time, regional or local lowering of the water table could subsequently free all or part of the mine from water. The loss of water would decrease support of the mine roof and overburden and allow for the hastened degradation of coal pillars due to slaking and weathering in the air-filled cavities (Turney, 1985).

In summary, subsidence prediction in undermined areas of the Denver Basin is hampered to some degree by (1) availability and quality of historical mine maps and records; (2) limitations in the applicability of established predictive models in some cases; and (3) the variability in subsurface mine conditions resulting from the incomplete removal of pillars and support structures, local mine flooding, and the time elapsed since mine abandonment. Available data can be supplemented

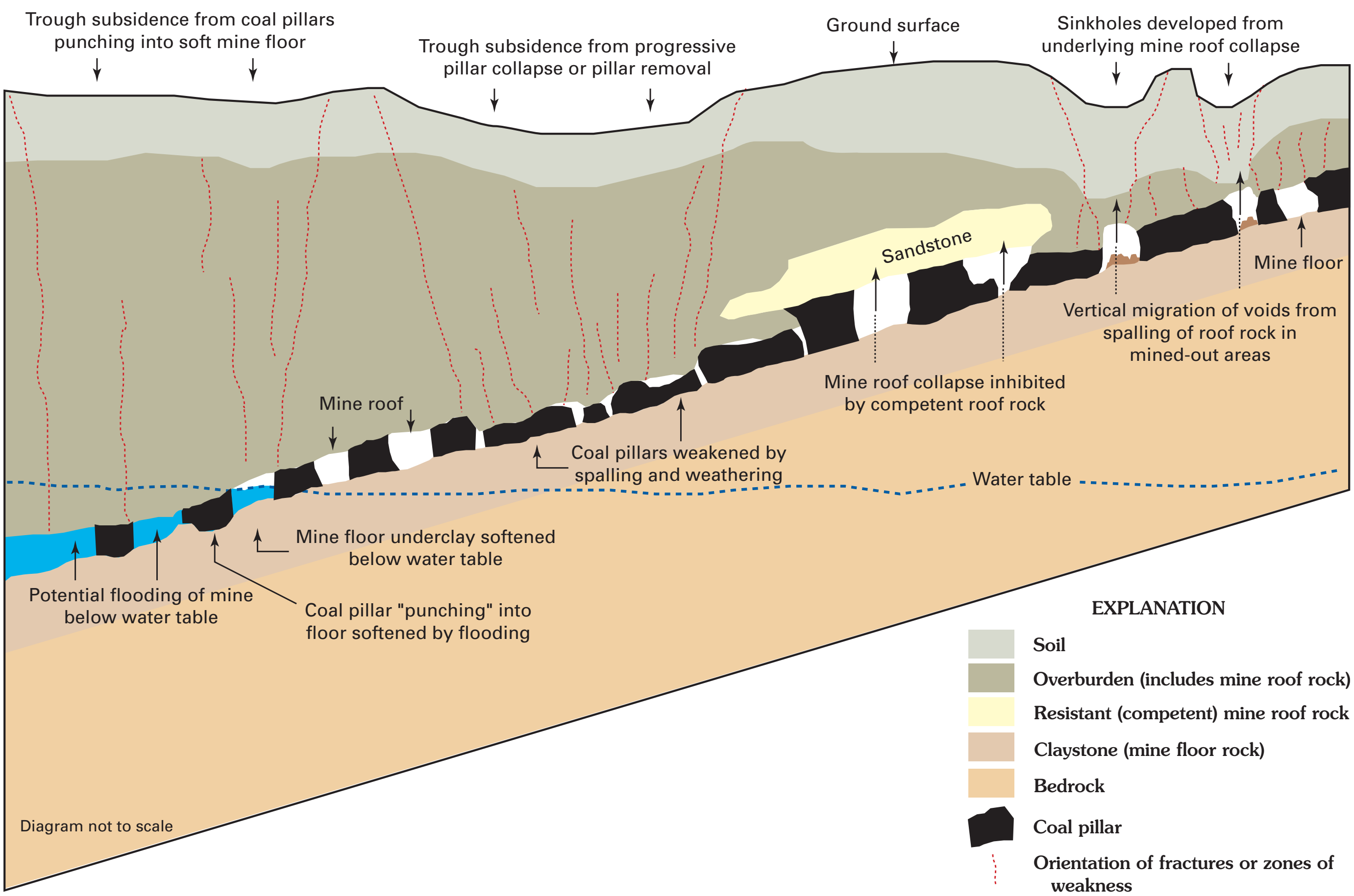


**Figure 29.** Schematic diagram summarizing ground-surface collapse (subsidence) resulting from mine roof and pillar collapse and from pillar punching in abandoned underground coal mines. Diagram is not to scale and is modified from Roenfeldt and Holmquist (1986).

by additional drilling, borehole logging, and core sample analyses, which can improve upon existing mine data and greatly enhance an understanding of present-day mine conditions in specific sites. Additional drilling data are also invaluable for anticipating engineering and structural requirements necessary for safe development and mitigation of potential subsidence effects. However, drilling programs can be costly and difficult (if not impossible) to undertake in undermined areas that have already been overtaken by urban and residential development. Thus, the greater need for new drilling programs might apply to undermined areas slated for new urban, residential, or commercial development.

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