Energy resources and changing land use, Front Range of Colorado: AAPG-EMD field trip guide, in association with the 2001 AAPG-EMD Annual Meeting

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U.S. DEPARTMENT OF THE INTERIOR
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Energy Resources and Changing Land Use, Front Range of Colorado: AAPG-EMD Field Trip Guide, in Association with the 2001 AAPG-EMD Annual Meeting

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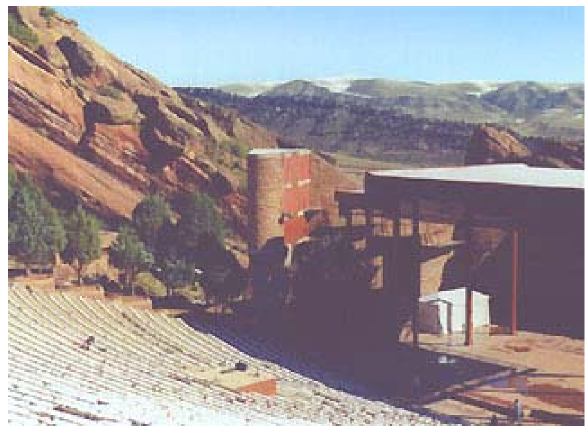
INTRODUCTION

Over the past 30 years, communities in the Northern Front Range of Colorado have experienced tremendous urban and commercial growth rivaling or surpassing that in most other parts of the United States. Much of this growth coincides with areas underlain by critically needed natural resources (such as oil, natural gas, construction aggregate (stone, sand, and gravel), and water), thus presenting serious challenges for city, county, and state planners as well as producers of these natural resources. With projections for as much as a 51 percent increase in population in Colorado over the next 25 years (Colorado Department of Local Affairs, 2001), it is likely that these challenges will increase.

This field trip will blend petroleum and coal geology with discussions of urban development to highlight the interplay between growth in the Front Range and energy resource production. On the trip we will also explore the effects of past production on land use. A total of 6 stops will be made in various locations around the Front Range area (fig. 1).

Stop 1: Red Rocks Park—Overview of Denver Basin

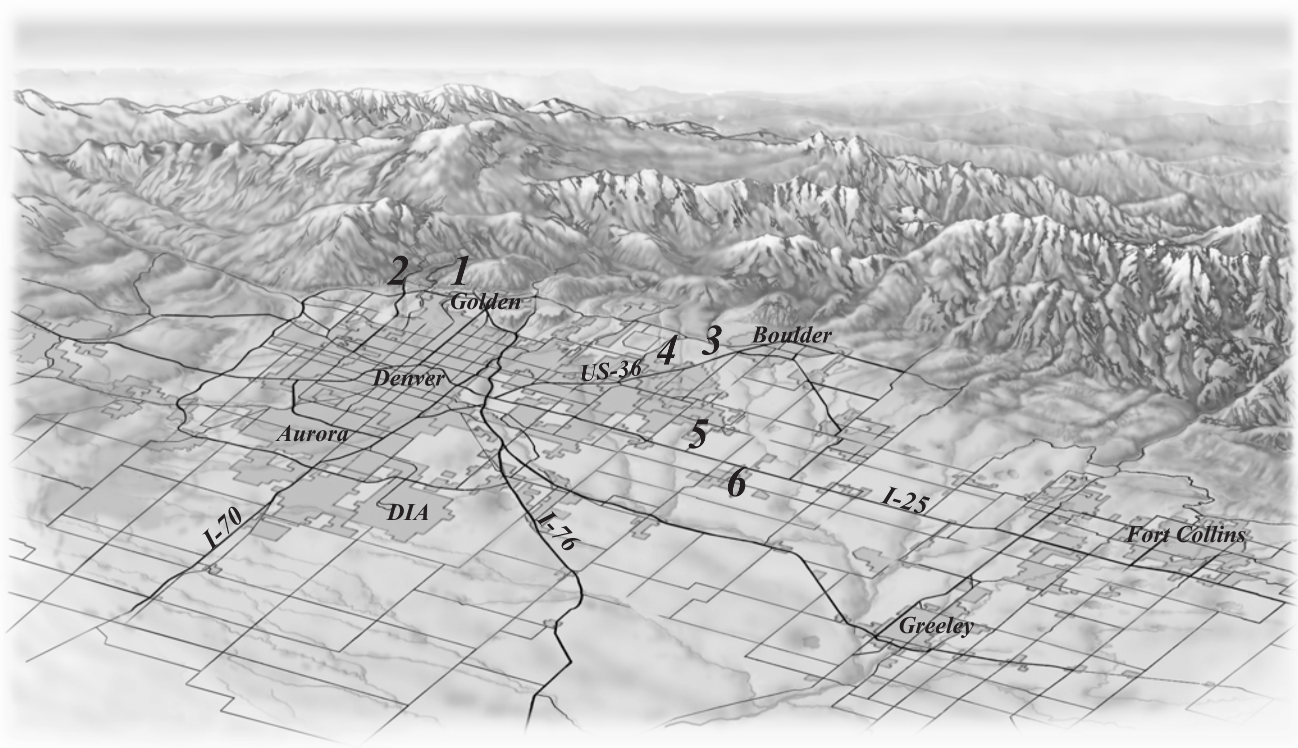


Red Rocks Park, courtesy of City & County of Denver

At this first stop we have a commanding view of the western part of the Denver Basin, as well as much of the city of Denver. The rocks that surround us in the amphitheatre are outcrops of the Pennsylvanian Fountain Formation, with Precambrian igneous and metamorphic rocks in the mountains to our west. The discussion here will focus on sedimentary rocks in the basin, basin formation, and an overview of oil, gas, and coal production.

Stratigraphy

Precambrian- through Cenozoic-aged rocks occur in the Denver Basin (fig. 2). Rocks of interest, those that contain oil, gas, or coal, or are sources of liquid hydrocarbons, are shown in various colors on figure 2. Rocks equivalent to the Pennsylvanian Fountain Formation—those



Stop 1. ***Red Rocks Park***
Overview of Denver Basin
Stop 2. ***Turkey Creek Canyon***
Petroleum Geology
Stop 3. ***Marshall area***
Coal Geology and Past Mining
Stop 4. ***Interlocken Office Park***
Changing Land Use
Stop 5. ***Colorado 7 and I-25***
Coal-bed Methane
Stop 6. ***Southern Weld County***
Land Use Impacts on Energy Development

Figure 1. Map showing the Front Range of Colorado and stops for this field trip.

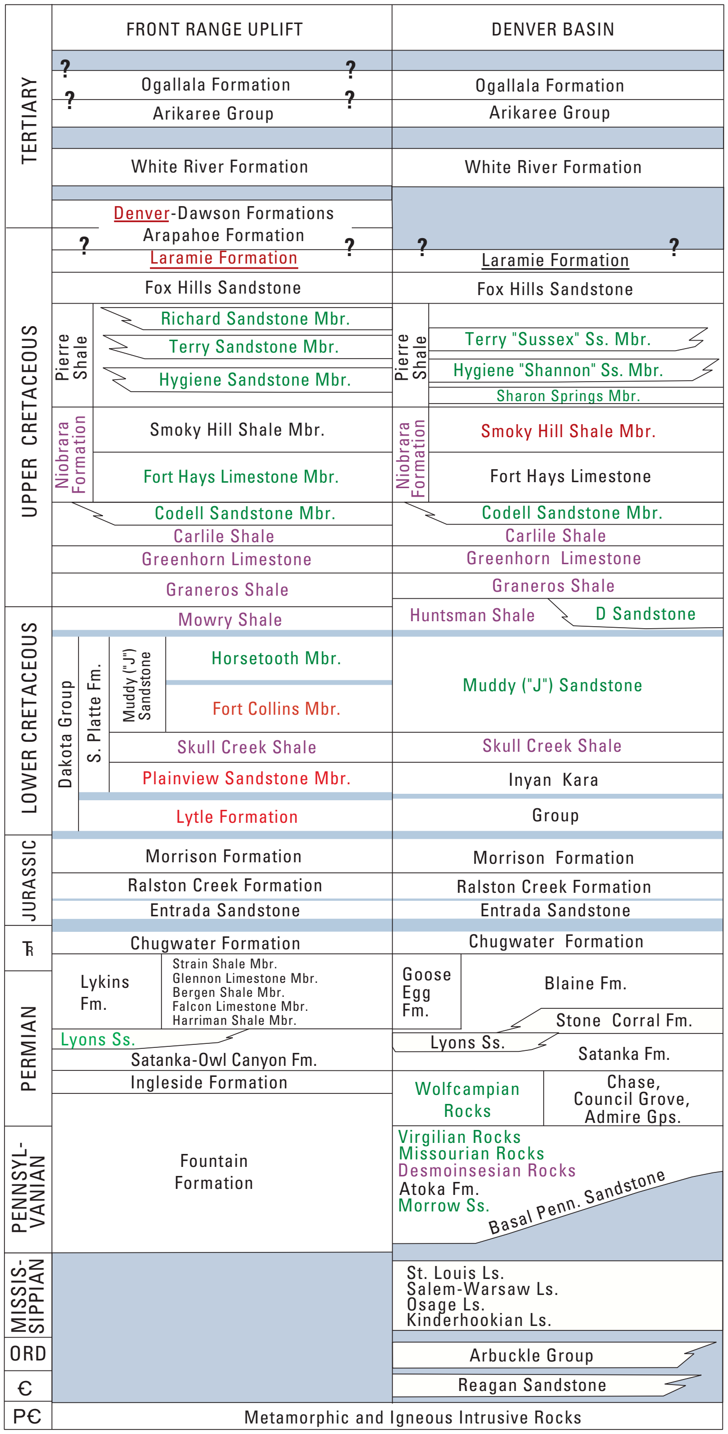


Figure 2. Stratigraphic column showing units that are exposed in outcrops along the Front Range and units in the subsurface in the Denver Basin. Blue intervals represent periods of erosion or non-deposition. Formations labeled in green are those that produce mostly oil whereas those labeled in red mostly produce gas. Rocks from which oil and gas were generated are labeled in purple. Formations that are underlined produce coal or lignite. Uncertainties in stratigraphic boundaries are shown with question marks. Ss, sandstone; Fm, formation; Mbr., member; Gps., group; Penn., Pennsylvanian; Ls., limestone. Modified from D.K. Higley and D.O. Cox, U.S. Geological Survey, written commun., (2001).

surrounding us here in Red Rocks Park—in the Denver Basin produce some oil especially in the eastern part whereas the overlying Permian Lyons Sandstone has produced oil from fields in the western part for more than 40 years. Although there is some production from these Paleozoic units, most oil and gas production in the basin is from Cretaceous rocks, which is why we will focus on rocks from that period.

Cretaceous rocks of most interest for production of oil and gas include 1) the Muddy ("J") Sandstone of the Dakota Group, 2) other sandstones in the Dakota Group such as those of the Plainview Sandstone Member and the Lytle Formation, 3) the "D" sandstone of the Hunstman Shale, 4) the Codell Sandstone Member of the Carlile Shale, 5) the Niobrara Formation, and 6) sandstones in the Pierre Shale such as the Terry and Hygiene Sandstone Members (fig. 2). Of these rocks, the Muddy ("J") Sandstone is the single most prolific producer. Source rocks for the oil and gas in Cretaceous reservoirs include the 1) Skull Creek Shale, 2) Huntsman Shale, 3) Graneros Shale, 4) Greenhorn Limestone, 5) Carlile Shale, and 6) Niobrara Formation (fig. 2).

The Dakota Group contains continental, marginal marine, and marine rocks throughout its stratigraphic interval, and was deposited during Early Cretaceous time. The sedimentary rocks within the Dakota Group record both transgressive and regressive depositional sequences that occurred in or adjacent to the shallow Western Interior Cretaceous seaway, an epeiric seaway that at times extended from the Arctic to the Gulf Coast.

Past coal production in the Denver Basin primarily targeted coal beds in the lower part of the Laramie Formation (Upper Cretaceous) (fig. 2), although some coal (lignite) was also produced from the Denver Formation (Tertiary) in limited areas of the basin. However, realized and potential impacts stemming from historic coal mining in the Front Range, such as coal mine fires and surface subsidence above abandoned underground coal mines, relate convincingly to coal production from the Laramie Formation. For this reason, subsequent discussions and field stops emphasizing coal-related issues will focus solely on the Laramie Formation.

The Laramie Formation is a nonmarine succession of sandstone, siltstone, claystone (shale), carbonaceous shale, and coal that was deposited about 65—70 million years ago (Ma) during the Maastrichtian stage of the Late Cretaceous. Minable coal beds in the lower part of the Laramie Formation developed from peat that accumulated in mires on a broad coastal plain adjacent to the western shoreline of the Western Interior Cretaceous seaway (Roberts and Kirschbaum, 1995) (fig. 3). During the Maastrichtian stage, coastal plain, shoreline, and marine environments prograded eastward (fig. 3), as the Cretaceous seaway retreated from the Western Interior. As a result of this progradation, coal-bearing rocks in the Laramie Formation were deposited over a large area of the present-day Denver Basin.

The Denver Basin

The Denver Basin covers an area of approximately 70,000 mi^2 (180,000 km^2) in eastern Colorado, western Nebraska, and southern Wyoming (fig. 4). Studies of Late Cretaceous and Tertiary rocks in the region by Weimer (1978) and Kirkham and Ladwig (1979a) indicated that these rocks either thinned or were eroded over the Greeley Arch (fig. 4); deposition or preservation of

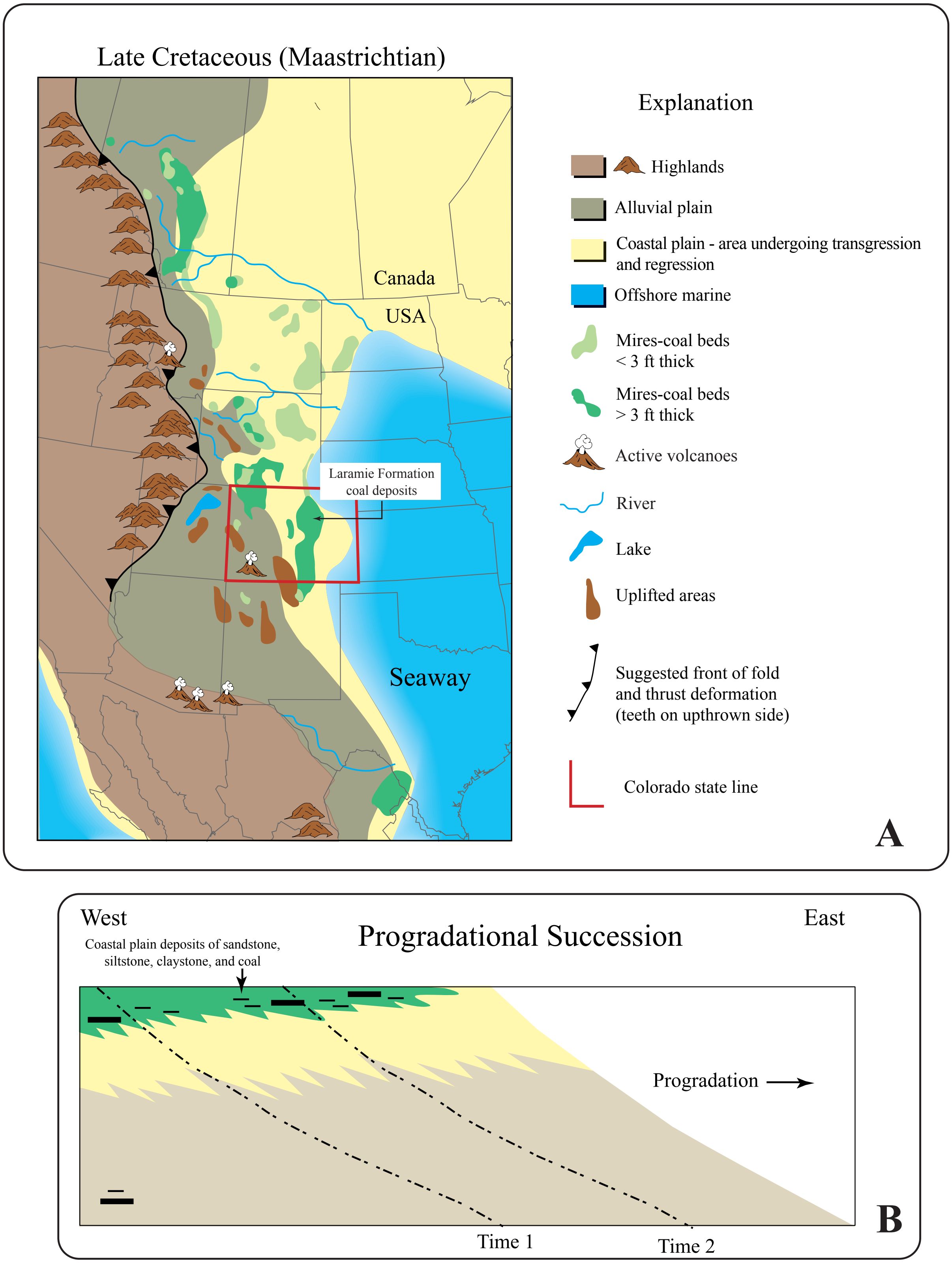


Figure 3. (A) Map showing interpreted paleogeography during Late Cretaceous (Maastrichtian) time. Modified from Roberts and Kirschbaum (1995). (B) Interpretive diagram showing the eastward progradation and generalized depositional setting of Upper Cretaceous strata in the Denver Basin during the Maastrichtian stage of the Late Cretaceous. Modified from Weimer (1977).

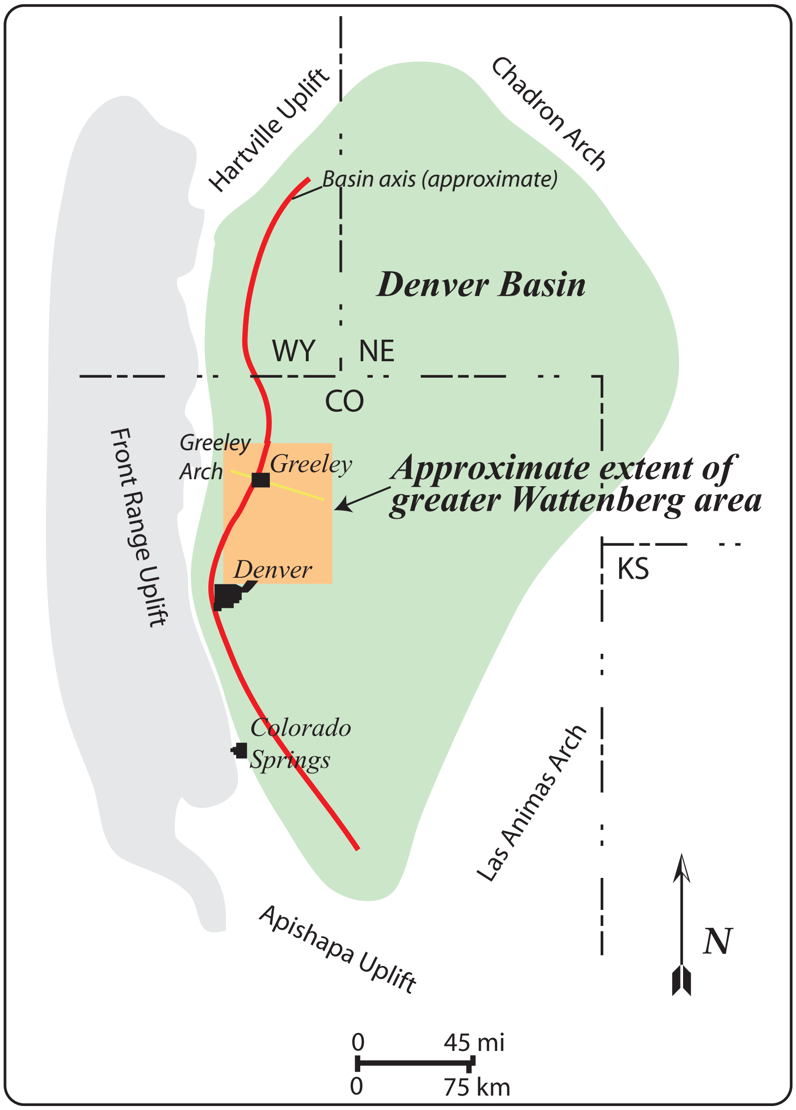


Figure 4. Map showing the approximate extent of the Denver Basin and bounding structural features. Extent of basin based on structure contours on top of the Precambrian basement rocks. Modified from Matusczak (1973). The region labeled greater Wattenberg area is an area of anomalously high heat flow in the basin.

older rocks does not appear to have been significantly affected by the arch. The influence of the Greeley Arch on deposition and/or erosion of some rocks in the region led Kirkham and Ladwig (1979a) to describe the area north of the Greeley Arch as the Cheyenne Basin whereas they referred to the area to the south as the Denver Basin. Because strata older than Late Cretaceous in age do not appear to be significantly affected by the Greeley Arch, including the main oil- and gas-producing units in the region, and because structure contours maps on the Precambrian suggest that it is a single structural basin (Matusczak, 1973), we use the term Denver Basin in our discussion below.

The basin is an asymmetric foreland basin (Matusczak, 1973), with a steeply dipping western flank and a gently dipping eastern flank (fig. 5). The basin axis passes approximately under the western part of Denver (fig. 4). The structural basin formed adjacent to the Front Range uplift during the Laramide orogeny approximately 71 to 50 Ma. Most downwarping of the basin probably occurred between 64 and 50 Ma (Weimer, 1996). Basement rocks flooring the basin are Precambrian igneous and metamorphic rocks that range in age between 1 and 1.7 billion years (Hedge, 1969; Hedge and others, 1967). Total sediment thickness in the basin is more than 13,000 ft, with about 10,000 ft consisting of Cretaceous and lower Tertiary rocks, and the remainder consisting of Paleozoic rocks (Weimer, 1996). Wrench faults of Precambrian age, mapped in the mountains west of the basin, have been projected into or across the basin (see for example Spencer, 1961; Stone, 1969; Warner, 1978; Weimer, 1978). Recurring movement along them may have affected sedimentation patterns and other processes during and after basin formation (Weimer, 1996).

An anomalous thermal gradient occurs within part of the Denver Basin (Meyer and McGee, 1985; Higley and Gautier, 1988; Higley and others, 1992). Several workers have suggested that the high heat flow, particularly in the west-central part of the basin, may be related to the presence of igneous intrusive bodies below the basin floor. This heat flow could well have played a role in the thermal maturation of organic material that ultimately was the source of hydrocarbons within this area of the basin. It is interesting to note that the anomalously hot area is northeast of and along trend with the Colorado mineral belt, a northeast-trending linear zone within which much of the precious and base metal mineralization in Colorado occurs (Warner, 1978; Higley and Gautier, 1988; Higley and others, 1992). The intrusive bodies responsible for mineralization and postulated to have been the source of heat beneath the basin are probably Late Cretaceous to early or mid-Tertiary in age (Mutschler and others, 1987; Weimer, 1996). It is also postulated that heat from these intrusive bodies was transferred into the overlying sedimentary rocks along faults, perhaps some of the wrench faults discussed above (Weimer, 1996), which served to enhance hydrocarbon generation beyond that associated with burial.

Oil and Gas Production

Oil and natural gas were first produced from rocks along the Front Range of Colorado more than 130 years ago, and production has continued to the present, with additional resources estimated to be available for production well into the future (Carpenter, 1961; Higley and others, 1996; D.K. Higley and D.O. Cox, U.S. Geological Survey, written commun., 2001; T. Cook, U.S. Geological Survey, written commun.,

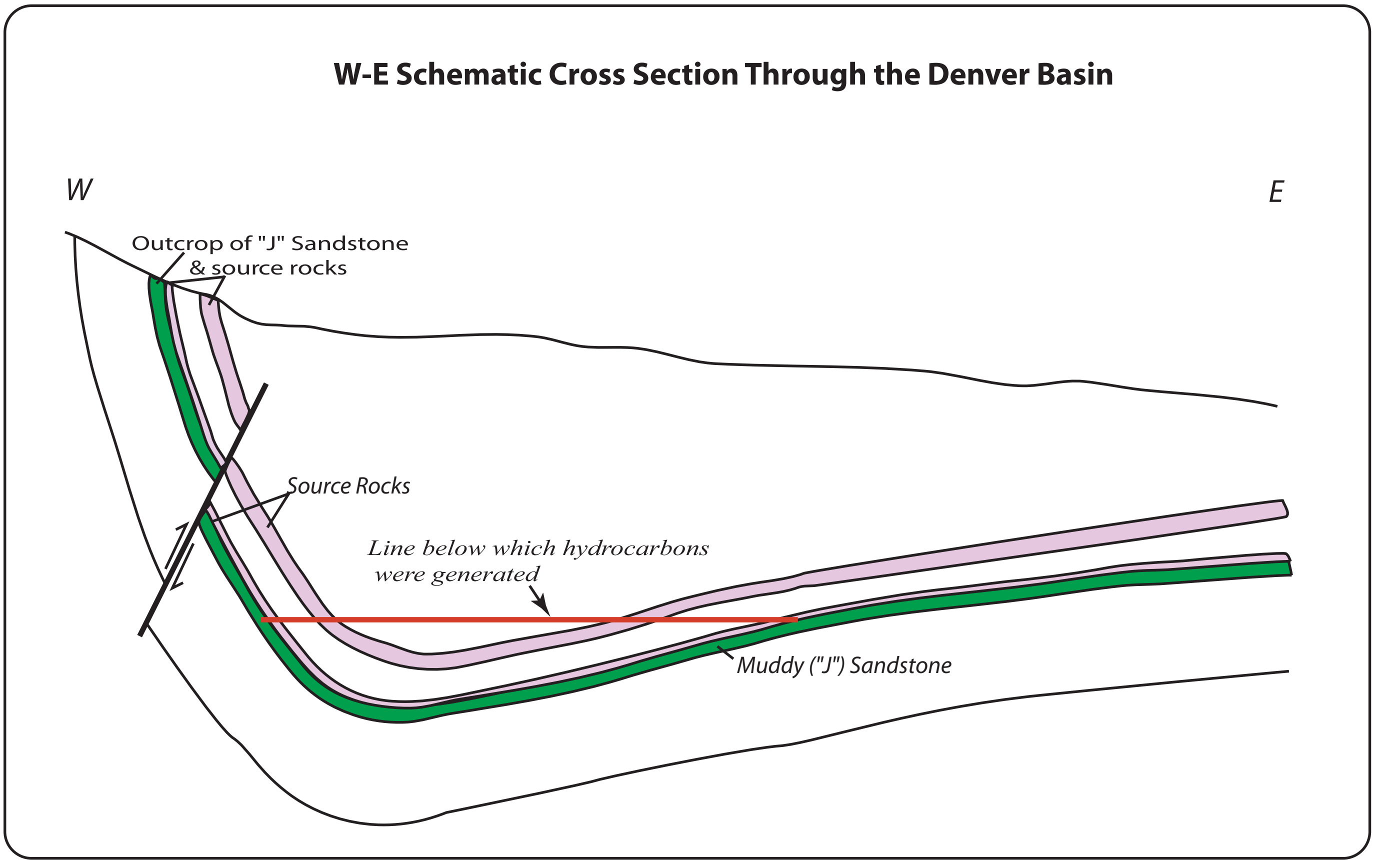


Figure 5. Schematic cross section of the Denver Basin showing the steeply dipping western flank and shallow dip on the eastern flank. Also note where oil and gas generation is thought to have occurred from source rocks in the basin. Modified from Weimer (1996).

2001). Although drilling for petroleum resources began in 1881, most of the oil and gas that has been produced in the region was discovered after about 1970. The large accumulations of oil and natural gas discovered to date have been produced from the Cretaceous rocks discussed above. Most current production occurs within parts of Weld, Adams, Boulder, Larimer, and Denver Counties. Much of the production from the Cretaceous rocks occurs within the greater Wattenberg area (GWA) (fig. 6), a geographic area defined by the Colorado Oil and Gas Conservation Commission for regulatory purposes to ensure the responsible development of contained petroleum resources. More than 12,000 oil, gas, or commingled oil and gas wells currently produce within the GWA. Production from just the GWA, which includes numerous individual oil and natural gas fields, has exceeded 2 trillion cubic feet (tcf) of gas and more than 245 million barrels of oil (MMBO; D.K. Higley and D.O. Cox, U.S. Geological Survey, written commun., 2001). Accessibility to growing local markets has made the GWA an important energy-producing province. Although the dominant producing formation in the basin is the Muddy ("J") Sandstone, other formations, particularly the Codell/Niobrara and Terry Sandstone (see fig. 2) are significant producing horizons as well.

Coal Production

Laramie Formation coal has been mined in the Denver Basin area since the 1850s (fig. 7). Coal mining in the Denver Basin was initiated in the Boulder-Weld coal field in 1859, and mining throughout the basin ended in this same coal field with the closure of the Lincoln Mine in 1979 (Kirkham and Ladwig, 1979). Additional areas of coal mining evolved during the latter 1800s and early 1900s, and ultimately more than 295 mines produced coal from the Laramie Formation within this time period. Coal-bed thickness in the Laramie Formation ranges from a few feet or less to as much as 20 ft locally. The apparent rank of much of the coal ranges from subbituminous B to subbituminous C, and the sulfur content is generally less than 1 percent (Kirkham and Ladwig, 1979). More than 130 million tons of Laramie Formation coal has been produced from the Denver Basin (fig. 8). Of this total, about 82 percent of the production (more than 107 million tons) came from the Boulder-Weld coal field, and about 99 percent of the total production came from the combined Boulder-Weld and Colorado Springs coal fields, and from the Foothills coal district.

Stop 2: Turkey Creek Canyon—Petroleum Geology

At this stop we will discuss in more detail, the important Cretaceous reservoir and source rocks in the Denver Basin. These were deposited about 70 Ma to over 100 Ma (Kauffman, 1977; Obradovich and Cobban, 1975; Weimer, 1984; Weimer and others, 1986). The most significant reservoir in the GWA, the Muddy "J" Sandstone, is featured at this outcrop. It occurs at depths of 4,000 to 9,000 ft in the basin just a few tens of

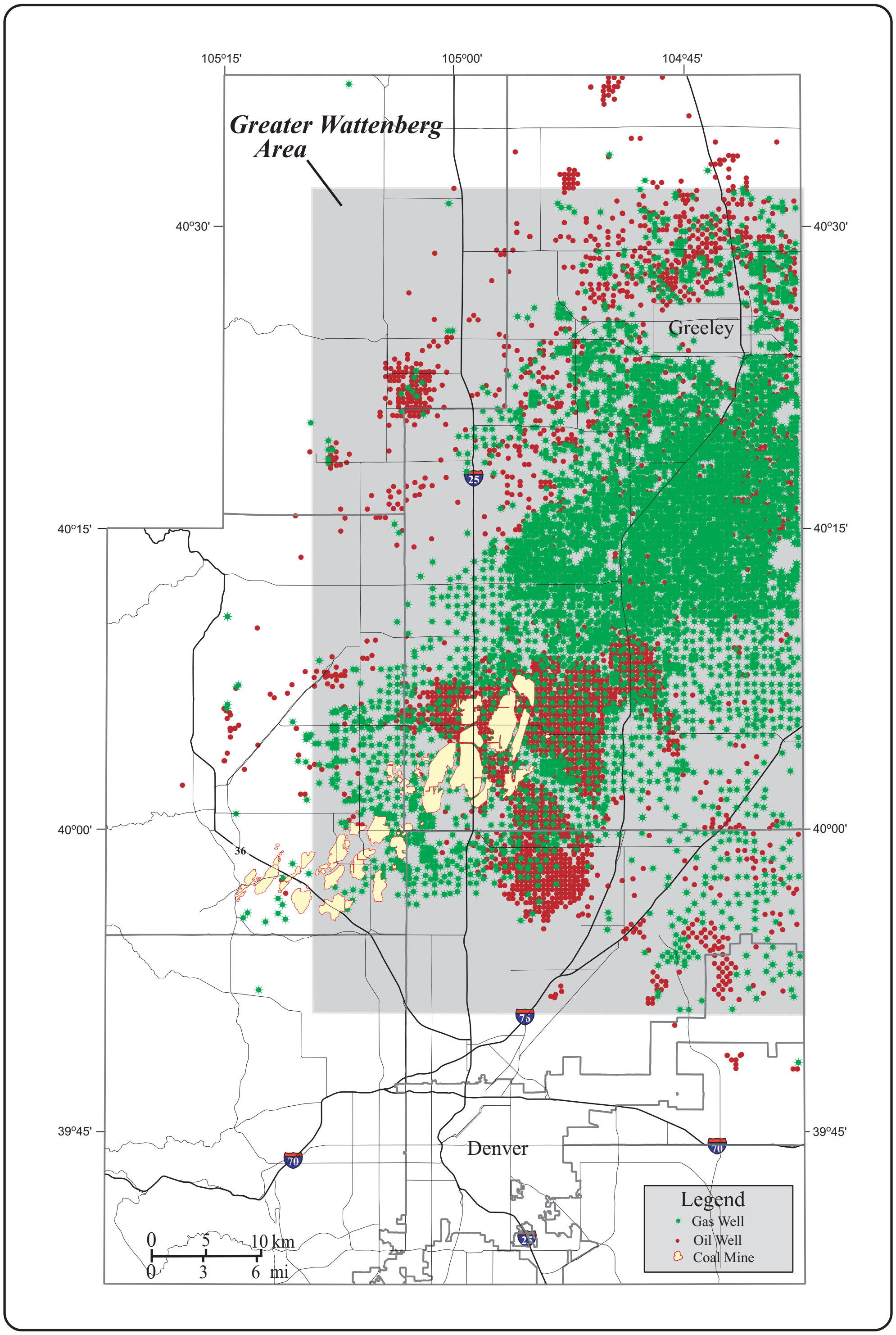


Figure 6. Map showing the location of the greater Wattenberg area (shaded) and the extent of mining (yellow) in coal mines of the Boulder-Weld coal field, northern Front Range of Colorado. Note the numerous oil (red dots) and gas (green dots) wells between Denver and Greeley and how Greeley is entirely surrounded by oil and gas wells. Although extent of coal mining is shown, many mines are interconnected so some mine boundaries are unclear.

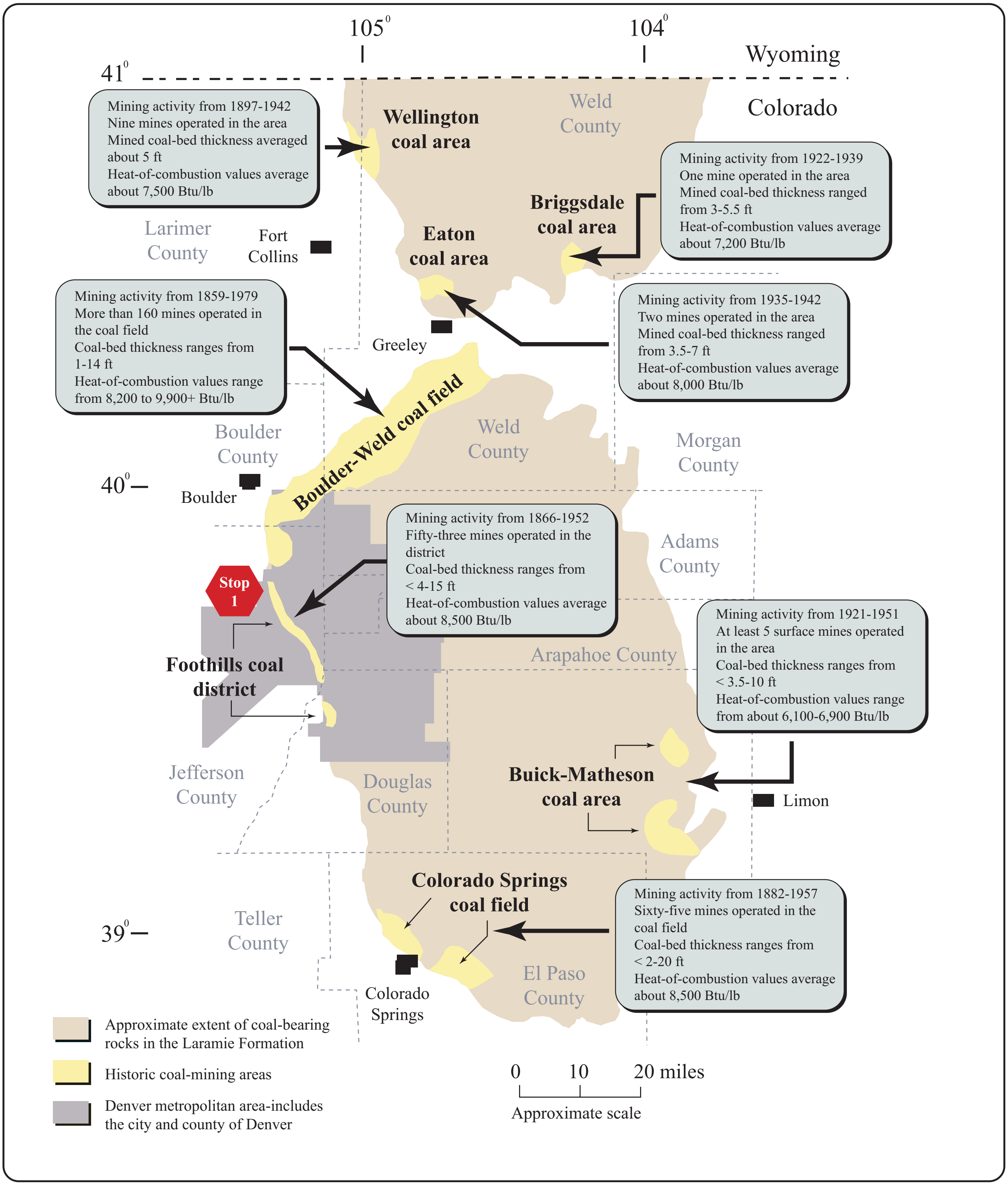


Figure 7. Map of the Denver Basin, Colorado, showing areas of historic coal production from the Laramie Formation, and the dates of mining activity, number of coal mines, coal-bed thickness ranges, and heat-of-combustion values in each area. Map and coal data from Kirkham and Ladwig (1979; 1980).

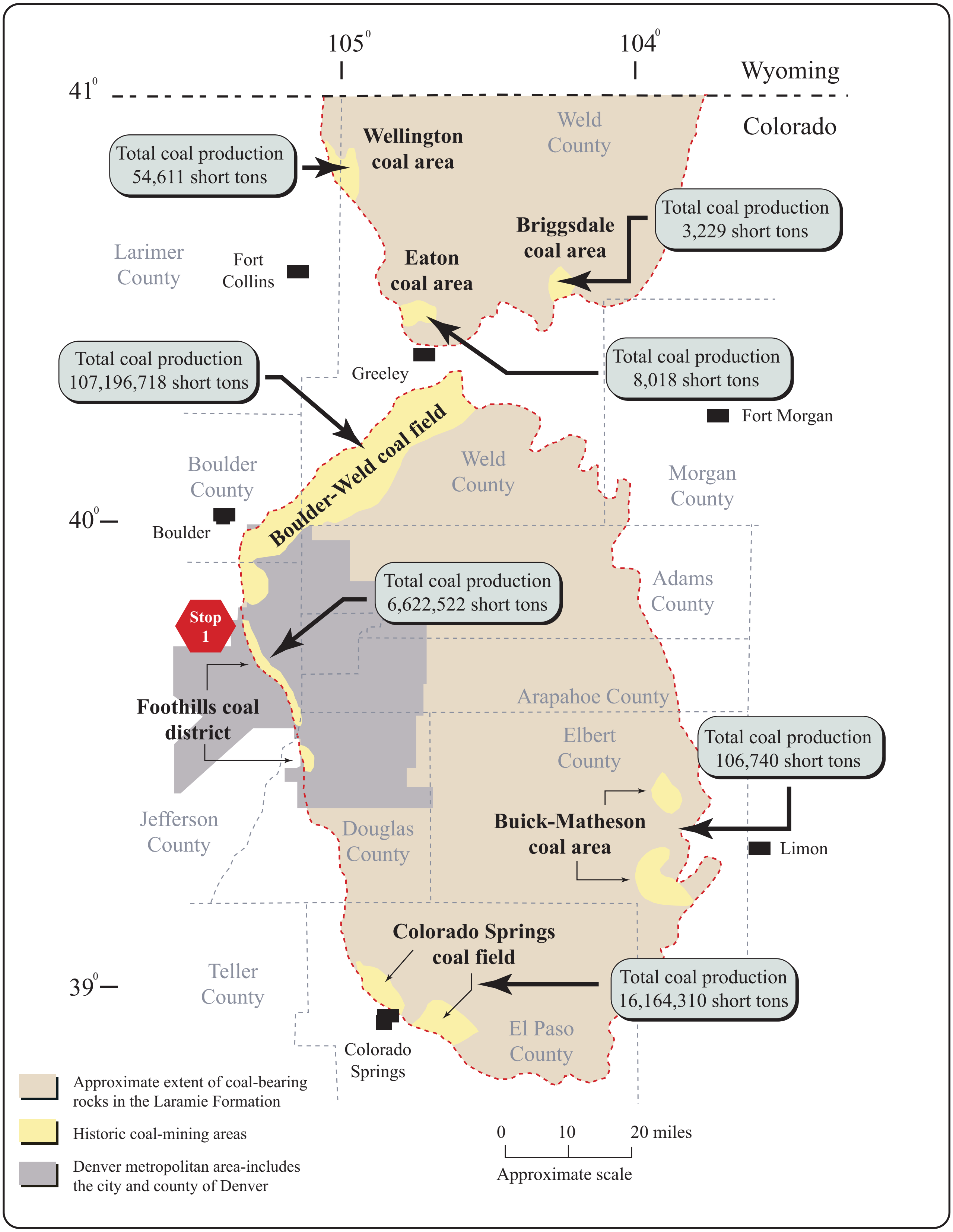


Figure 8. Map showing total coal production from the Laramie Formation in areas of historic coal mining. Map and coal production data from Kirkham and Ladwig (1979; 1980).

miles to the east. At this stop we will also see outcrops of both the Skull Creek and Mowry Shales, which are important hydrocarbon source rocks.

Thickness of the entire Dakota Group at this stop is about 260 ft (Weimer, 1996). The strata were deposited through a series of transgressions and regressions. The basal unit at this locality is the Lytle Formation, consisting of red sandstone, that unconformably overlies the Jurassic Morrison Formation. When placed in a sequence stratigraphic framework, the Lytle, which is a nonmarine fluvial deposit, represents the first sequence in the Dakota Group (sequence 1, fig. 9). It is more than 100 ft thick in this outcrop, but pinches out to the north. The Lytle Formation characteristically lacks fossils and carbonaceous material (Weimer, 1996).

The low stand surface of erosion (LSE) at the top of the Lytle marks the boundary between sequences 1 and 2 in the Dakota Group (fig. 9). The Plainview Sandstone, which is the lower unit in sequence 2, is distinctive from the underlying Lytle because it contains carbonaceous material. The Plainview, only about 12 ft thick at this locality, was deposited in a coastal plain swamp/marsh environment, and contains burrows as well as roots zones.

Overlying the Plainview Sandstone is the Skull Creek Shale (fig. 9). In this exposure, the Skull Creek Shale is about 90 ft thick and consists of gray siltstone and shale, all of which contain varying amounts of carbonaceous material. The deepest water deposits, which represent maximum flooding during a transgression, are found near the middle of the Skull Creek Shale. Above this point, lithologies in the Skull Creek Shale were deposited during regression, in which water depths shallowed.

A sharp scour surface separates the Skull Creek Shale from the overlying Muddy ("J") Sandstone. The contact between these two units marks the boundary between sequences 2 and 3 (fig. 9). At this locality, the Muddy ("J") Sandstone is about 60 ft thick, and consists only of the Horsetooth Member, which was deposited as interbedded sandstone and shale in an incised valley. The uppermost part of the Horsetooth Member here contains sedimentary features, including concentrations of carbonaceous debris or clays on cross-strata foresets that are indicative of deposition in brackish water (Weimer, 1996). Most of the oil produced from the Muddy ("J") Sandstone is from the Horsetooth Member (note oil seep at this outcrop locality), whereas most of the gas is produced from the delta front and shallow marine sandstones of the Fort Collins Member, which unconformably underlies the Horsetooth Member elsewhere in the region. The Fort Collins Member, however, is missing at this locality due to erosion. Where the Fort Collins Member is present, the boundary between sequences 2 and 3 is at the contact between the Fort Collins and the Horsetooth Members of the Muddy ("J") Sandstone.

Overlying the Muddy ("J") Sandstone here is the Mowry Shale, which is about 10 ft thick and composed of gray siltstone and organic-rich black shale. Deposition of the Mowry Shale was in deep waters during a rapid transgression, with probably maximum depths as much as 100 to150 ft (Weimer, 1996).

Generation of the oil in the Lower Cretaceous rocks probably began about 70 Ma (D.K. Higley and D.O. Cox,

Figure 9. Photo showing the sequence stratigraphic framework for the Dakota Group at the Turkey Creek locality, (Stop #2). Note the three distinct sequences that occur in the Dakota Group. Stratigraphic nomenclature of the Dakota Group: Kdl, Lytle Formation; Kdp, Plainview Sandstone ; Kdsc, Skull Creek Shale; Kdjh, Horsetooth Member of the Muddy ("J") Sandstone. Sequence stratigraphic information from Weimer (1996).

U.S. Geological Survey, written commun., 2001), as the source rocks were buried deeply enough (fig. 10), and then gas was generated as burial continued (Higley and Schmoker, 1989; Weimer, 1996). Petroleum source rocks include the Mowry, Graneros, Huntsman, and Skull Creek Shales (see fig. 2), with the Mowry and Graneros Shales being the principal ones (Clayton and Swetland, 1980). The total organic content of these shales is variable, but range from about 1 percent to more than 5 percent (Pietraszek-Mattner, 1995; Higley and others, 1996). Although source rocks were buried deeply enough to generate hydrocarbons, the high heat flow in the greater Wattenberg area of the basin (Meyer and McGee, 1985), from the postulated buried intrusive bodies, may have played a significant role in enhancing hydrocarbon generation, particularly of thermogenic gas (Higley, 1988; Higley and Gautier, 1988; Higley and others, 1992).

Although the main reservoir rock in the GWA is the Fort Collins Member of the Muddy ("J") Sandstone, significant amounts of oil and gas are also produced from the Horsetooth Member of the Muddy ("J") Sandstone, Codell Sandstone Member of the Carlile Shale, "D" sandstone of the Huntsman Shale, Niobrara Formation, and sandstones (Terry and Hygiene) in the Pierre Shale (fig. 2) (Weimer, 1996; D.K. Higley and D.O. Cox, U.S. Geological Survey, written commun., 2001). Additional production also occurs from the Plainview Sandstone and Lytle Formation of the Dakota Group. Porosity and permeability of the Fort Collins Member of the Muddy ("J") Sandstone in the GWA is low, making the unit "tight". Porosity is generally less than 10 percent and median permeability is generally about 0.0035 millidarcies. The "tight" character of the Muddy ("J") Sandstone is due to such factors as deep burial and precipitation of diagenetic cements (Matuszczak, 1973; Higley and Gautier, 1986, 1987; Higley and Schmoker, 1989; Reinert and Davies, 1976).

Types of traps and seals are variable across the Denver Basin. Traps can be either structural (folds and segments of some wrench faults), or stratigraphic (fine-grained units, some of which are the source rocks) or a combination of the two (Martin, 1965; D.K. Higley and others, U.S. Geological Survey, written commun., 2001; Weimer, 1996). However, in places near wrench faults increased permeability due to fracturing and faulting has improved production characteristics for some wells (Weimer, 1996). Seals include 1) overlying shale, 2) rock extensively cemented with diagenetic minerals such as quartz, 3) faults, and 4) unconformity surfaces (D.K. Higley and others, U.S. Geological Survey, written commun., 2001; Weimer, 1996).

Most of the natural gas production from the Fort Collins Member in the GWA occurs within an area bounded by northeast-trending wrench faults that cut across the axis of the Denver Basin. Because much of the production occurs in the synclinal trough of the basin axis, the hydrocarbon accumulations can be characterized as basin-centered (D.K. Higley and others, U.S. Geological Survey, written commun., 2001).

The GWA has seen a growth in estimated reserves over time, in part resulting from the exploration and successful development of new horizons in which to drill and produce petroleum. Although the Muddy ("J") Sandstone has been a prolific producer, significant production from other Cretaceous formations, including sandstones in the Pierre Shale, the Codell Sandstone, and the Niobrara Formation, occurs throughout the Front Range area.

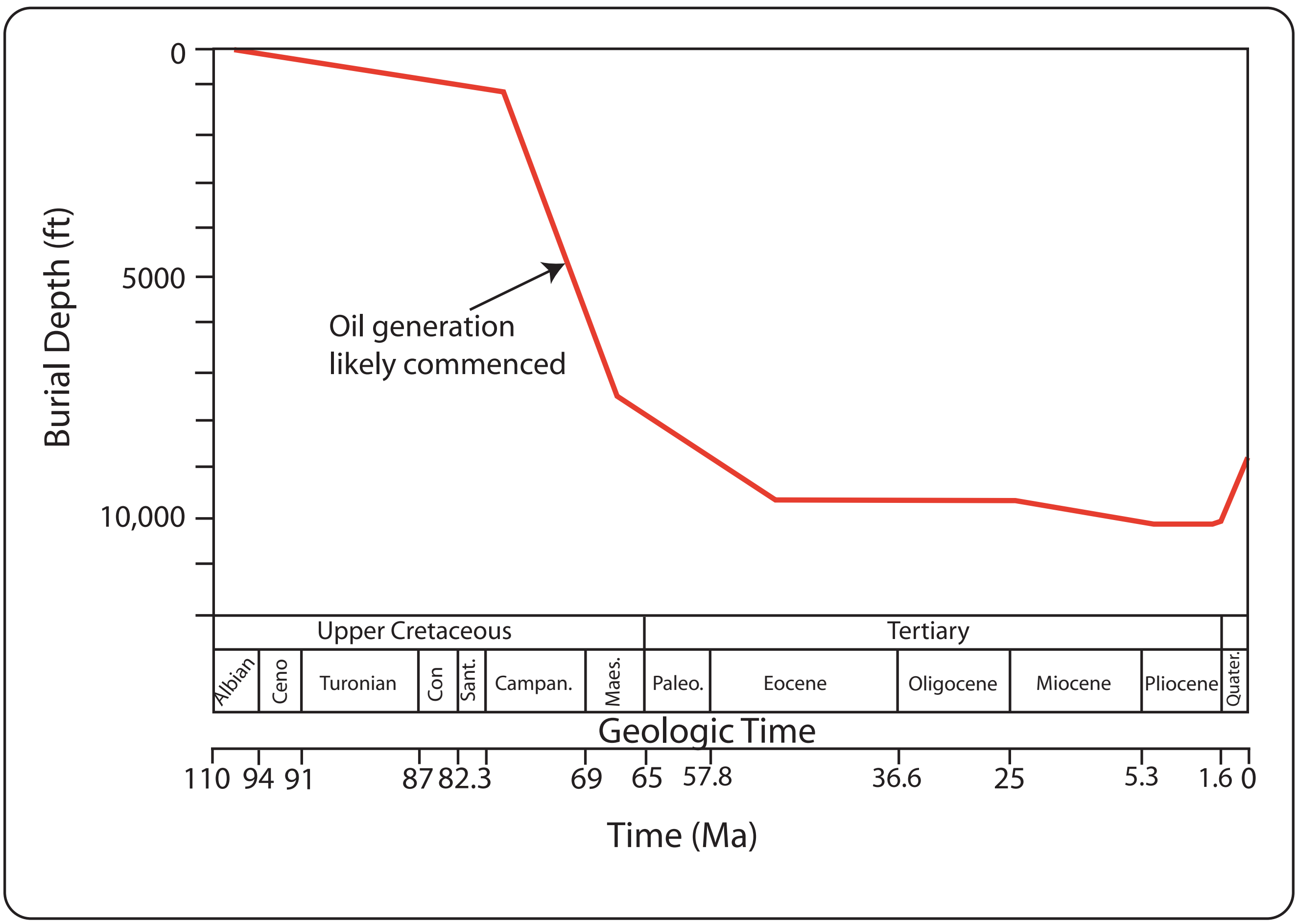


Figure 10. Burial curve for the Dakota Group in the central part of the Denver Basin. Modified from Weimer (1996).

Production has also been realized, at least locally, from the Plainview Sandstone and Lytle Formation of the Dakota Group (fig. 2) beneath the Muddy ("J") Sandstone. Thus, wells currently producing from just the Muddy ("J") Sandstone can be deepened 100 feet or so to tap into production from these underlying units (see fig. 2), which is an inexpensive way to increase reserves and lengthen the life of any given well. In addition, commingled production from all Cretaceous units in the GWA allows operators to recomplete wells to other stratigraphic targets; for example, wells currently producing from the Codell Sandstone Member or Niobrara Formation can be deepened into the underlying Muddy ("J") Sandstone or other Dakota Group units. Indeed, many of the applications submitted in recent years for drilling in the GWA have been requests to deepen existing wells. Thus, the estimated ultimate recovery of petroleum from any given well can be increased fairly inexpensively, and this increased production will likely extend the life of many wells.

Stop 3. Marshall Area—Coal Geology and Past Mining

Geologic setting

Bedrock units present within and immediately adjacent to the Boulder-Weld coal field include, in ascending order, the Upper Cretaceous Pierre Shale, Fox Hills Sandstone, and Laramie Formation (figs. 2, 11, and 12). These strata are well exposed in areas near Marshall, but elsewhere in the coal field, outcrops are generally obscured by widespread Quaternary alluvial and wind-blown deposits that cover most of the area (Myers and others, 1975). The contact between the Pierre Shale and overlying Fox Hills Sandstone is gradational, and is represented by a coarsening-upward transition from marine shale to marginal marine and shoreface sandstone units. The Fox Hills Sandstone is a massive, light tan to white sandstone that is prominent in outcrops surrounding the town of Marshall. The formation varies in thickness from about 115 to 125 ft in this area (fig. 13). The contact between the Fox Hills Sandstone and the overlying Laramie Formation is sharp, and is commonly marked by a thin (1 to 3 ft thick) coal bed that lies directly on top of the sandstone. The Laramie Formation is informally divided into lower and upper parts, based primarily on lithologic variation. The lower part of the formation is from 250 to 300 ft thick, and is composed primarily of sandstone, shale, claystone, carbonaceous shale, and coal beds of minable thickness. The upper part of the formation ranges from 600 to 700 ft in thickness, and is composed predominantly of claystone and sandy shale with subordinate sandstone lenses and thin, lenticular coal beds (Kirkham and Ladwig, 1979; Myers and others, 1975). Only the lower, coal-bearing part of the Laramie Formation is present near Marshall.

Seven potentially minable coal beds were identified by Lowrie (1966) in the Boulder-Weld coal field. These beds are designated as coal beds No. 1 through No. 7, in ascending order (fig. 11). With the exception of the lowermost No. 1 and No. 2 coal beds and the uppermost No. 7 coal bed,

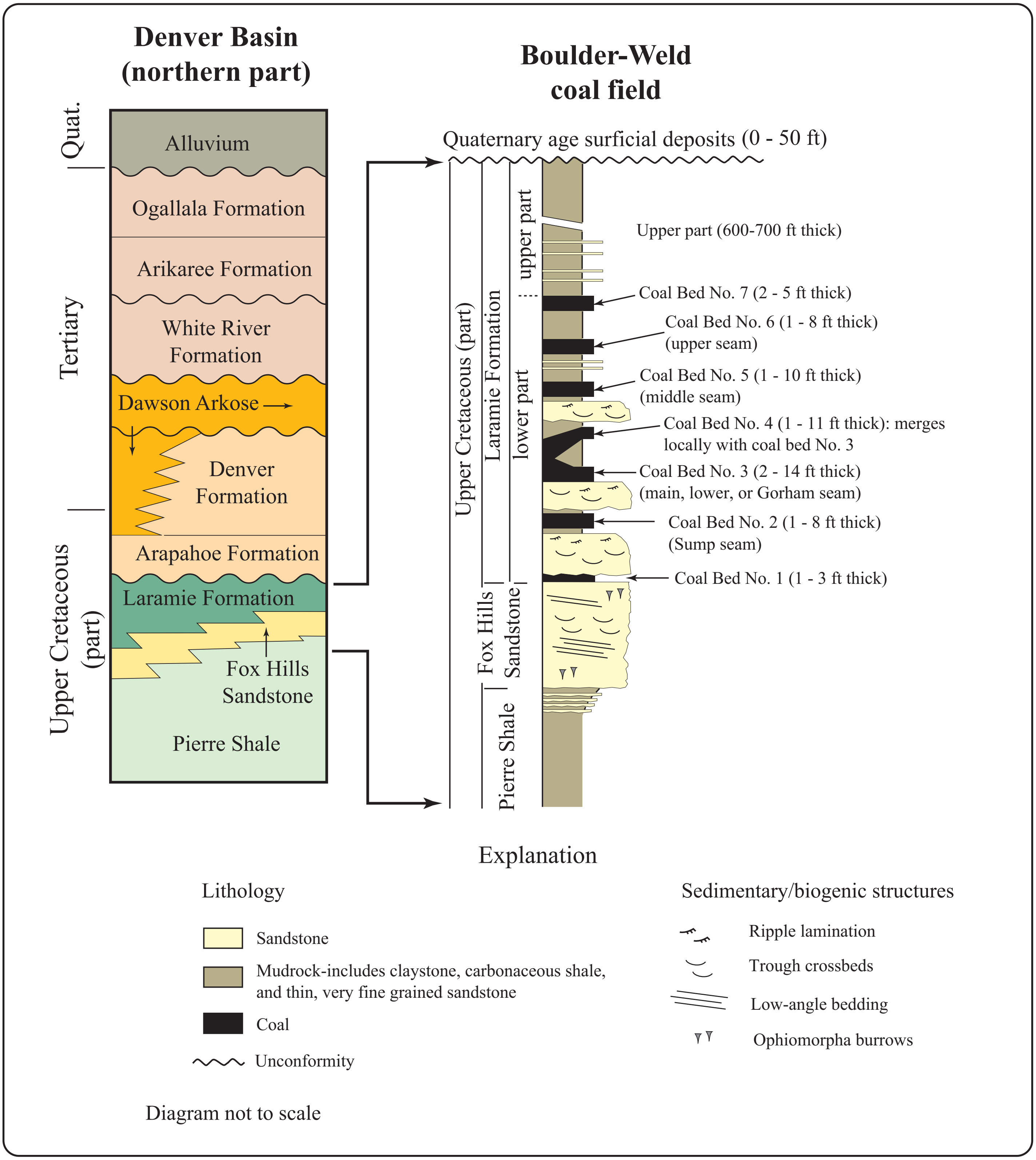


Figure 11. Generalized stratigraphic and lithologic sections showing Upper Cretaceous and Tertiary stratigraphic nomenclature in the northern part of the Denver Basin, and the stratigraphic distribution, thickness, and nomenclature of coal beds in the Laramie Formation in the Boulder-Weld coal field, Colorado. Sections modified from Myers and others (1975), Kirkham and Ladwig (1979; 1980), and Nichols (1999). Diagrams not to scale.

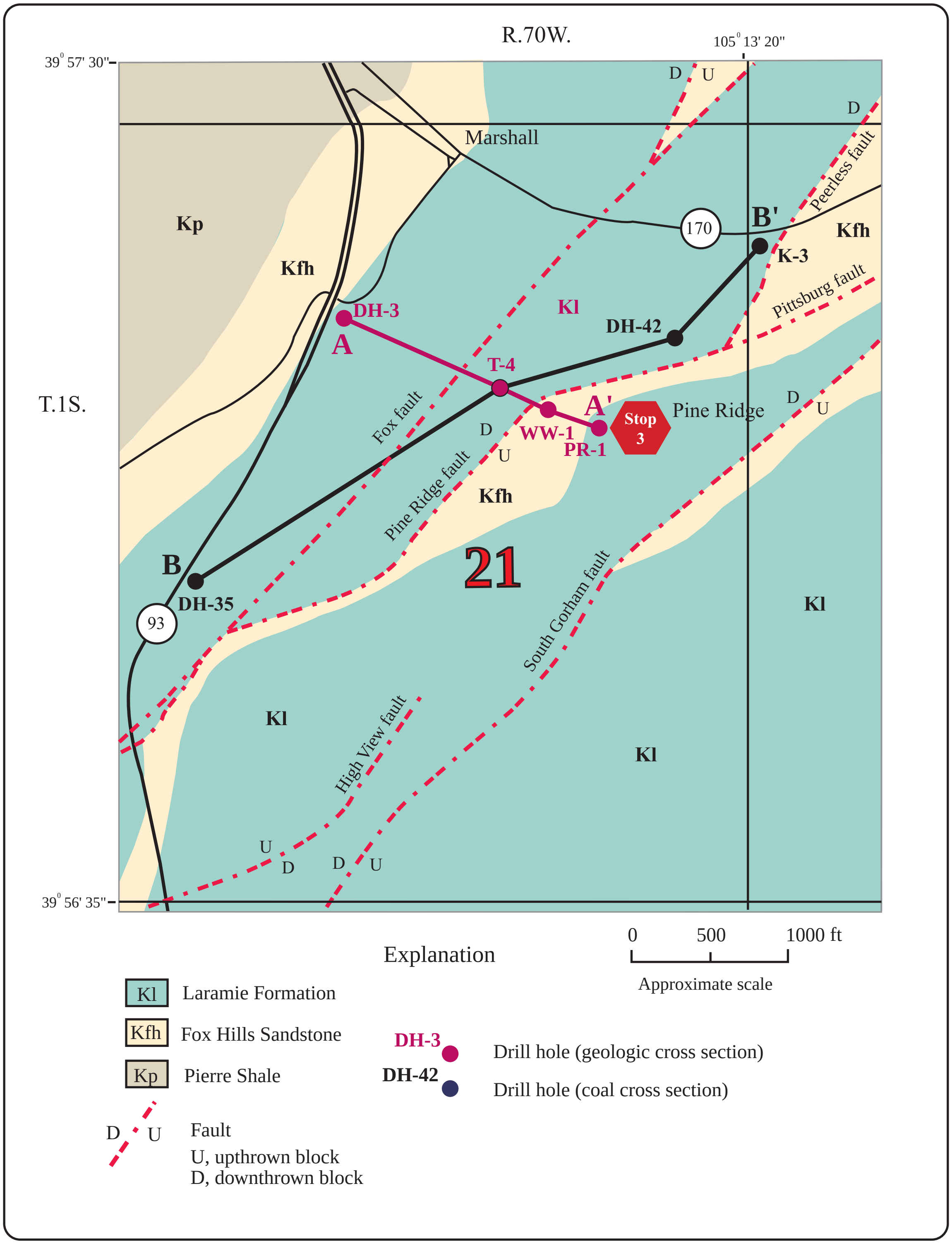


Figure 12. Map showing generalized geology and locations of subsurface cross sections near the town of Marshall, Colorado. Geology modified from Spencer (1961).

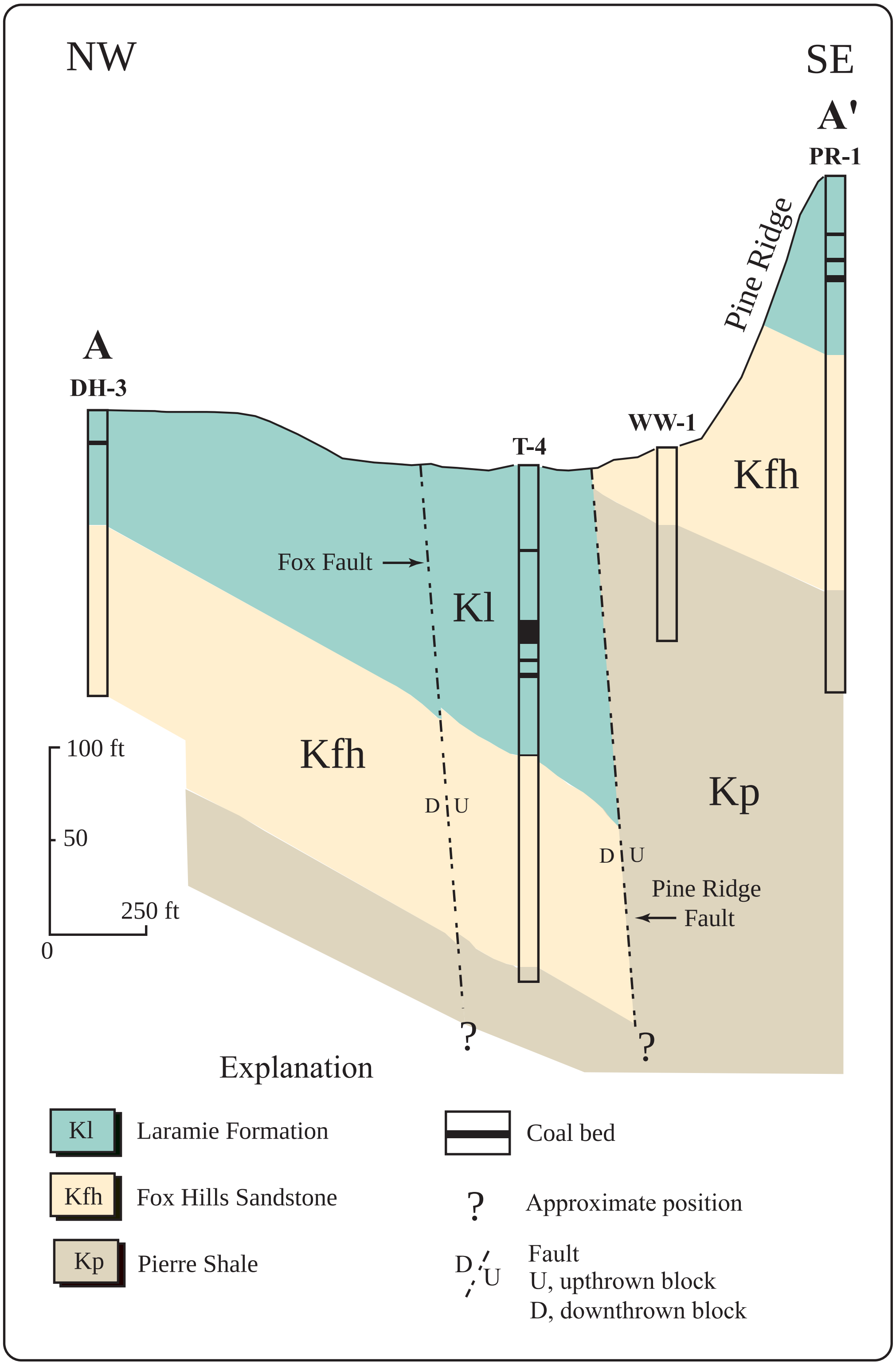


Figure 13. Generalized geologic cross section A-A' showing correlations of Upper Cretaceous strata and relative fault displacement, based on drill hole data from shallow wells drilled near the town of Marshall, Colorado. Location of cross section shown in fig. 12. Fault positions based on Spencer (1961).

all other coal beds (Nos. 3 to 6) have been mined to some extent within the Boulder-Weld coal field (Kirkham and Ladwig, 1979). Coal bed No. 3, which is also known as the "main seam," the "lower seam," or the "Gorham seam," is the coal bed that has been mined most extensively owing to its lateral continuity and thickness, which ranges from 2 to 14 ft. In the Marshall area, the No. 3 coal bed coalesces locally with the overlying No. 4 coal bed (figs. 11 and 14); where not merged, as much as 30 to 35 ft of rock may separate the two beds.

Intense faulting is present throughout the Boulder-Weld coal field. Though not expressed on the surface because of the widespread cover of Quaternary alluvial deposits throughout much of the area, the faults have been identified primarily from published mine records, coal mine maps, and coal exploration drill hole data. Fault displacements range from a few feet to as much as 400 ft (Weimer, 1977). Displacement along numerous reverse faults near Marshall (figs. 12 and 13) resulted in the repeated occurrence of Laramie Formation coal beds at relatively shallow depths, which greatly facilitated the development of underground coal mines in this area.

Impacts of historic coal mining

Coal mining began in the Marshall area in 1859, and continued for some 80 years. Early coal mines were small wagon mines from which local residents obtained coal for domestic use. Through time, the scale of coal mining increased, and rapid expansion of coal production followed the development of rail lines in the area during the 1870s (see, for example, Mernitz, 1969). Coal production prospered until about 1939, when Rocky Mountain Fuel Company declared bankruptcy, and the Marshall coal operation was abandoned.

Mining operations in the Boulder-Weld coal field primarily used room and pillar mining methods. In room and pillar mines, a network of underground haulways, cross-cut passages, and entries connected numerous mine rooms from which coal was extracted and hauled out of the mine (fig. 15). Pillars of unmined coal were left in place to support the mine roof above haulways and rooms. Chain pillars that were about 50 ft wide and 60 ft long divided the main entry into two primary passageways (double entry), and 50- to 100 ft-wide flank pillars supported the mine roof along the sides of the entry. Mine rooms, which were at right angles to the main entry, were generally on the order of 18 to 20 ft wide, and were separated by 20- to 30 ft-wide pillars (Hart, 1986). When coal extraction was completed within adjoining rooms, coal pillars separating the rooms were pulled (harvested) as mining retreated from the area. Where vertical shafts were used for mine entry, mine cars (skips) were hoisted to and lowered from the surface by pulley and cable systems supported by a headframe on the ground surface (fig. 15). Most of the major surface remnants of underground coal mining near Marshall, such as mine dumps, tipples, headframes, and the varied buildings necessary for mining operations, have been removed. 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 impacts such as fires in the abandoned mines, and ground surface collapse (subsidence) over undermined areas, still exist in the Marshall area, as well as at other coal mining areas in the Denver Basin.

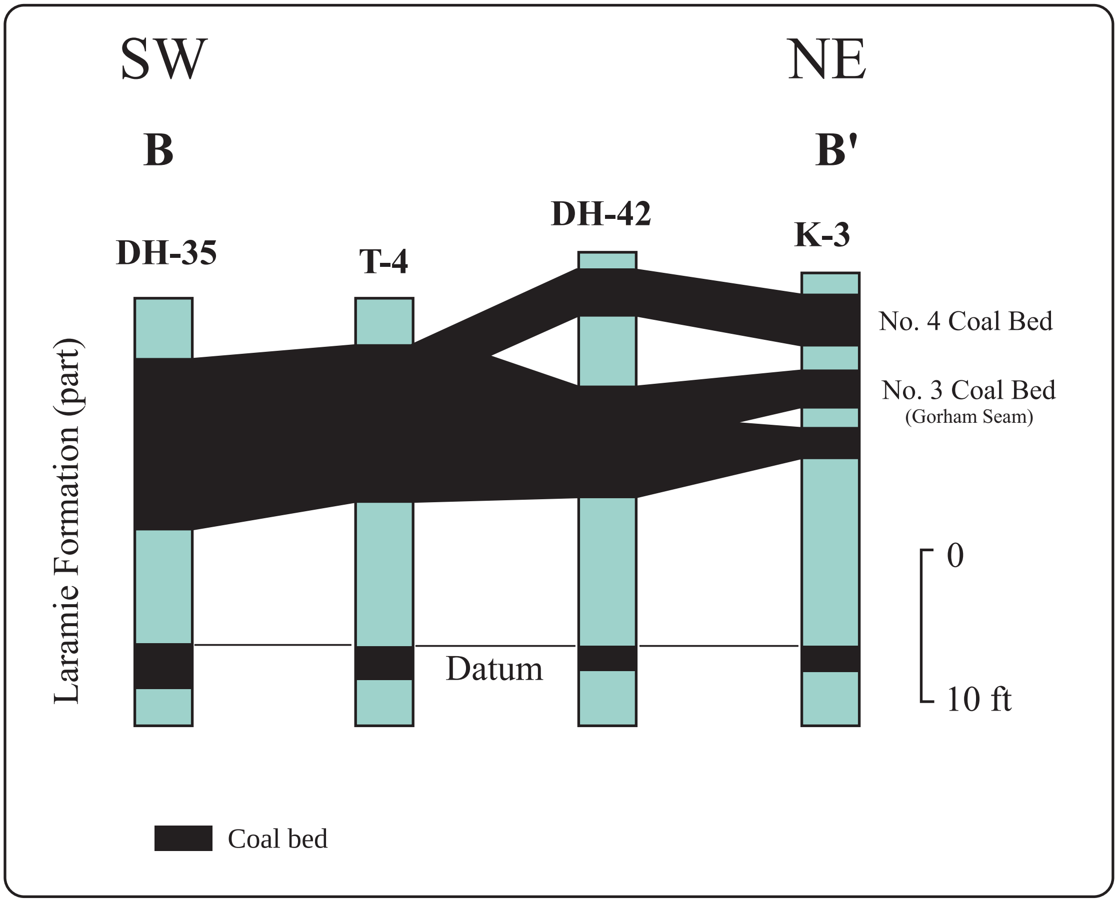


Figure 14. Generalized cross section B-B' showing correlation of the No. 3 and No. 4 coal beds based on drill hole data from shallow wells drilled near the town of Marshall, Colorado. Location of cross section shown in fig. 12. Coal-bed nomenclature based on Lowrie (1966).

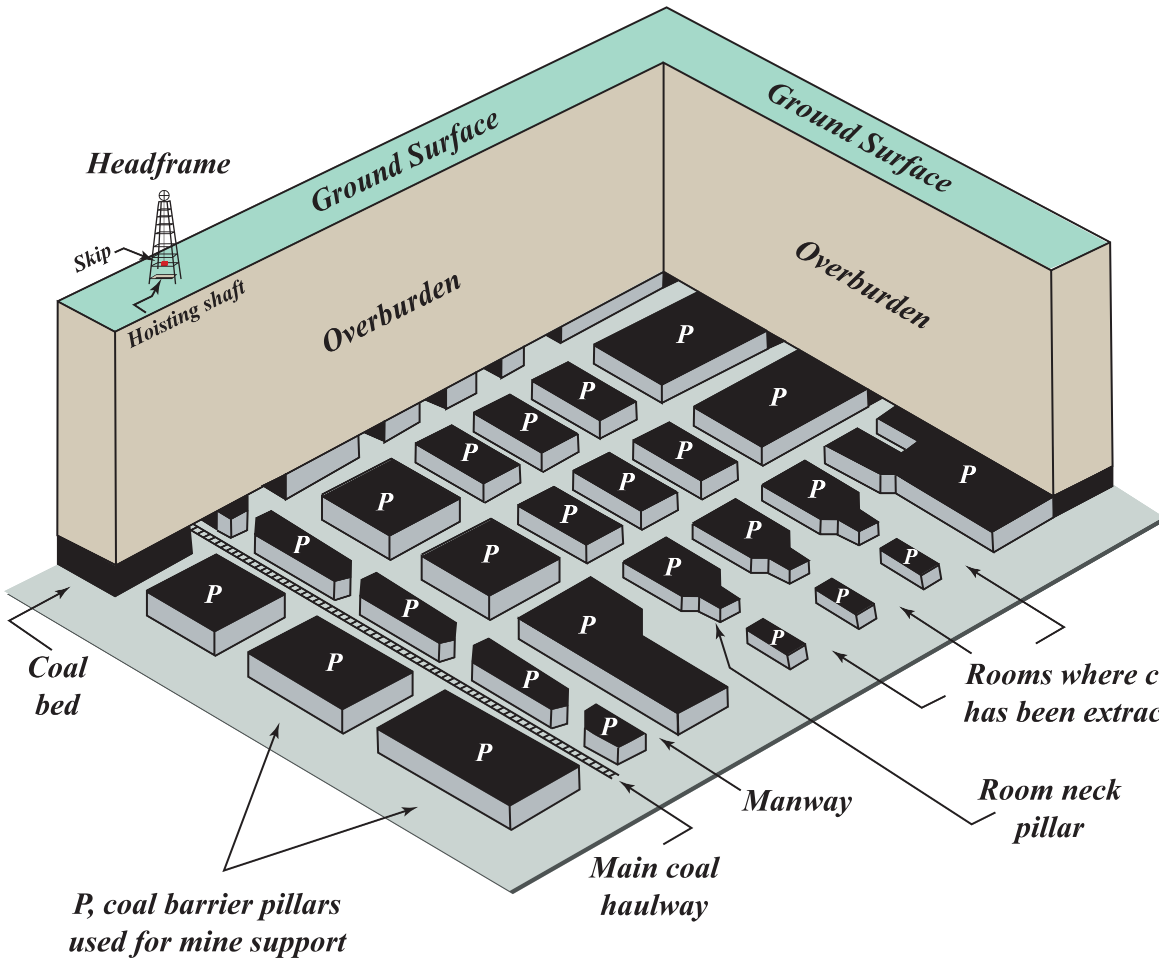


Figure 15. Schematic diagram showing the basic components and configuration of a room and pillar coal mine. Diagram modified from Dames and Moore (1985).

Coal mine fires can occur during the active process of mining, and well after all mining activity has ceased. These fires can result from accidental or intentional ignition by man, and by the process of spontaneous combustion (see, for example, Dunrud and Osterwald, 1980; Herring and others, 1986; Rushworth and others, 1989). In coal mines that have been abandoned for a significant period of time, spontaneous combustion may play a more critical role in the generation of fires. As air and water enter abandoned mine workings, unmined coal in pillars or in the abandoned coal face can ignite spontaneously. The resulting coal mine fire then propagates through the unmined coal toward a source of oxygen, such as open mine rooms or entries. Fire propagation is also facilitated by the development of fire-induced fractures (fissures) that can form in the overburden (roof rock) as the fire burns. These fractures provide additional conduits for oxygen flow, which continues to fuel the fire (Rushworth and others, 1989). Fires in shallow mines may emit noxious fumes, steam, and heat to the ground surface through active vents, which typically form just in front of the advancing fire (J. 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.

Fires in abandoned coal mines near Marshall (fig. 16) have been documented as recently as 1988 (Rushworth and others, 1989); such fires have been observed throughout most of the area's mining history, and could still be occurring today. Historic accounts by local residents have documented high ground surface temperatures and the occurrence of methane explosions with fire plumes soaring high into the air (Herring and others, 1986). Historic coal mine fires in the Marshall area are also evidenced by deposits of clinker, which are present within the Marshall 1and 3, and the Lewis 1 and 2 mines (Herring and others, 1986). In the early 1980s, steam plumes generated from an underground fire associated with the abandoned Marshall No. 3 coal mine (fig. 16; site A) were clearly visible during winter months along the east side of Highway 93, just south of the town-site of Marshall. In 1982, the U.S. Geological Survey 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 (Roberts, 1983). During the course of this study, anomalously high temperatures (that is, higher than ambient temperatures of 50º to 60º F) were recorded in shallow drill holes (depth less than 100 ft) near the site, suggesting an underground, extraneous heat source such as burning coal in the abandoned mine. Qualitative assessment of subsurface temperatures within the study area indicated that the extent of active burning was restricted to a small area along the western edge of the Marshall No. 3 mine. 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. 16, site B) (Rushworth and others, 1989). A fire in this same 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

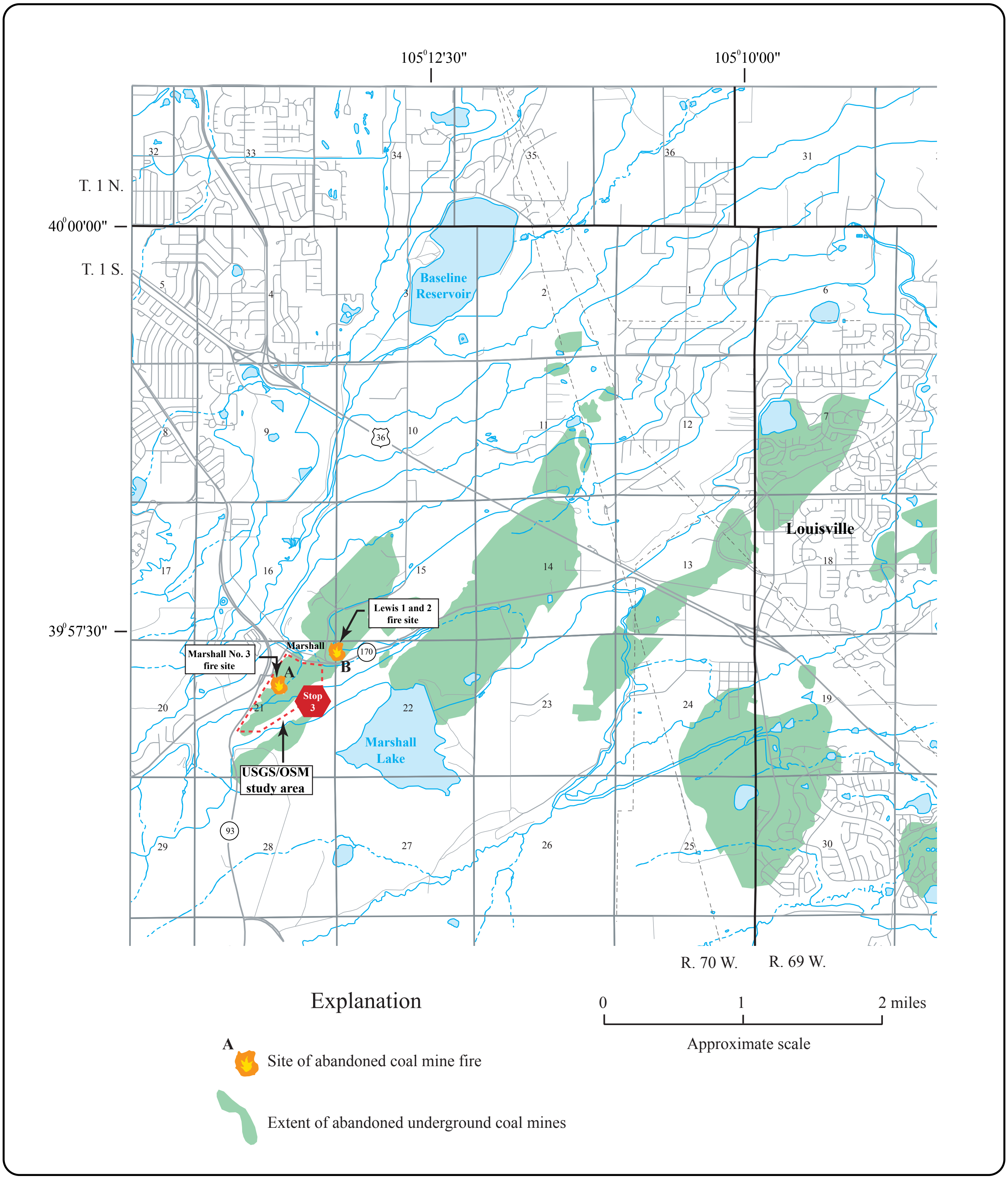


Figure 16. Map showing the extent of abandoned underground coal mines, the location of a 1982 to 1983 cooperative U.S. Geological Survey (USGS) and Office of Surface Mining (OSM) coal mine fire study site, and the location of historic underground coal mine fires near the town of Marshall, Colorado. Location of the Lewis 1 and 2 fire site from Rushworth and others (1989) is also indicated. Extent of abandoned mines based on Myers and others (1975) and Roberts and others (in press).

1988 revealed little change from 1984. Vents emitting heat and a limited amount of smoke on the hillside overlying part of the mine were still evident. Although little damage resulted from the fire, 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).

An additional, and perhaps more widespread impact of historic coal mining in the Denver Basin relates to ground surface subsidence above abandoned underground coal mines. This phenomenon is well documented along the Front Range, particularly in the Colorado Springs and Boulder-Weld coal fields (see, for example, Myers and others, 1975; Dames and Moore, 1985; Herring and others, 1986; Matheson and Bliss, 1986). A photograph of Marshall (fig. 17), taken from an airplane in 1973, attests to the visible scarring that can result from ground surface subsidence in undermined areas. Mining-induced subsidence is a dynamic process that can take place concurrently with mining, as well as occurring many years after the 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 sagging or collapse of the overburden above the mined-out cavity. Progressive upward collapse/sagging of the overburden with time can cause the development subsidence features (depressions) 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) in areas overlying abandoned coal mines.

Terms such as depressions, local depressions, sags, troughs, localized troughs, holes, sinkholes, potholes, and subsidence pits have been used by previous investigators to describe the various ground surface collapse features resulting from subsidence over abandoned coal mines (see, for example, Myers and others, 1975; Dunrud and Osterwald, 1980; Turney, 1985; Dames and Moore, 1985; Matheson and Bliss, 1986). Additional surface features associated with subsidence include tension cracks that can form at the margins of subsidence depressions, and compression bulges that form within the depressions (Dunrud and Osterwald, 1980). In general, there is a dimensional hierarchy of surface collapse features, ranging from small subsidence pits and sinkholes to large troughs and depressions. For simplification, the term “subsidence pit” will be used in reference to smaller features (for example, sinkholes and potholes), and the term “trough” will be used to describe the relatively larger collapse features. It is important to bear in mind that the basic “cause and effect” process that forms subsidence pits and troughs is similar in many respects and the differences in these features relate more to the variations in their surface expression, size, and impact.

Subsidence pits may be as much as several tens of feet in breadth, generally have circular to elliptical shapes, and can exceed depths of 10 ft in certain areas of the Denver Basin (see, for comparison, Matheson and Bliss, 1986). These pits can develop rapidly, usually within a period of 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 primarily results from the collapse of roof rock and overlying overburden into an underground

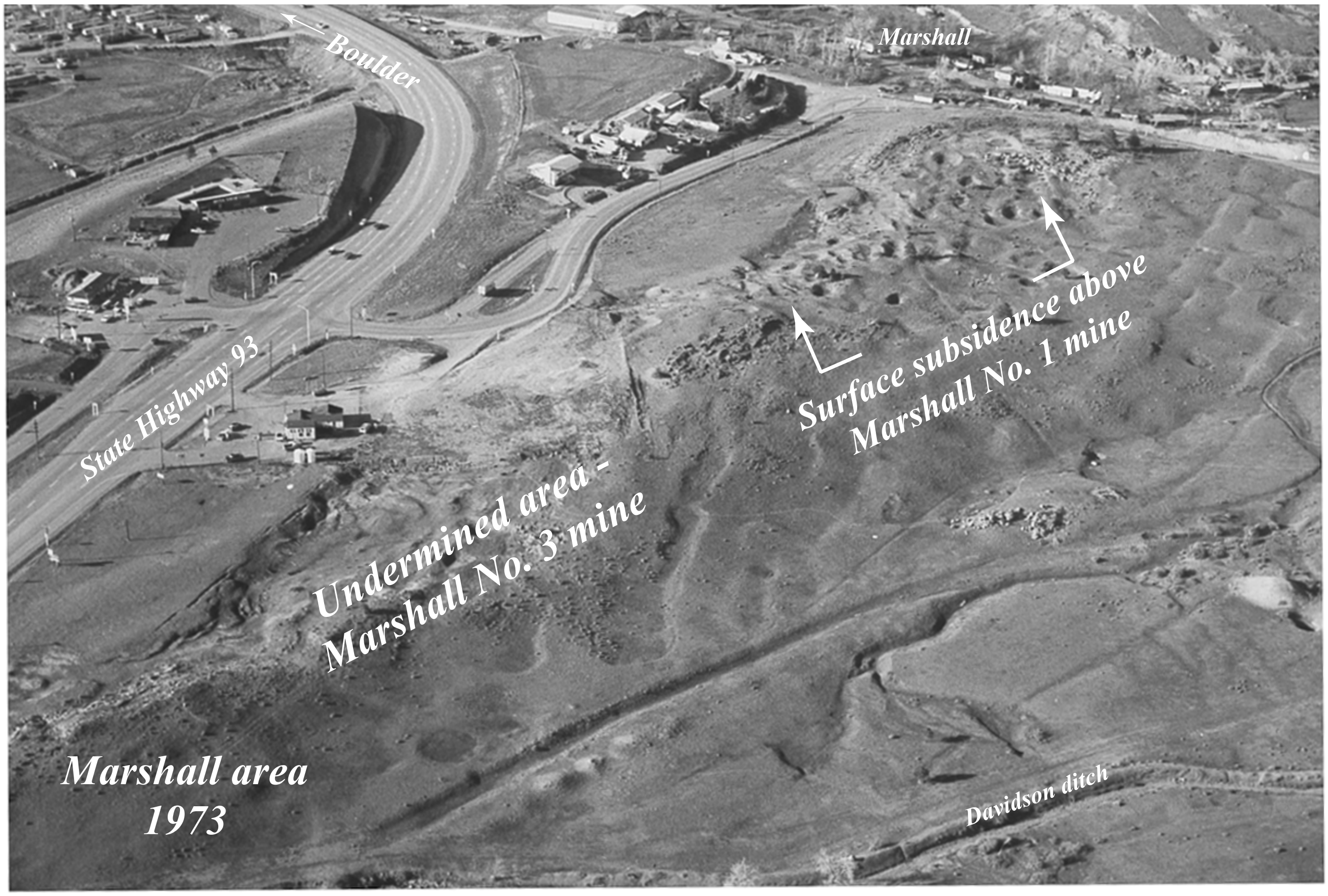


Figure 17. Photograph showing surface subsidence features caused by the collapse of underground coal mines near the town of Marshall, Colorado, in 1973. Photograph courtesy of R.B. Colton (scientist emeritus), U.S. Geological Survey, Denver, Colorado.

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. 18). In steeply dipping coal beds, a process, termed "stoping", results in the similar migration of a void up-dip, along the coal bed toward the ground surface (Turney, 1985).

In general, the breadth of the subsidence pit is more or less coincident with the breadth of the underlying mine cavity. 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 surface material overlying the collapsed room, and the bulking characteristics of the rock (overburden) between the mined horizon and the ground surface (Dames and Moore, 1985; Turney, 1985). 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 (collapse). Logically, the height of an underground void should correspond to the thickness of the mined coal bed, and 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 may exceed the mined-coal thickness because loose surface material may be washed into the underlying mine, and subsequently dispersed by groundwater movement through the abandoned mine (fig. 19) (Turney, 1985). Additionally, the bulking characteristics of the mine roof and overburden rocks also play an important role in controlling the depth of a subsidence pit above a collapsed room. When consolidated roof/overburden rock collapses and accumulates as rubble in the void, the volume of space occupied by the collapsed rubble is always greater than the volume occupied by the in-place rock material prior to collapse (see, for example, 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 (see, for comparison, Dames and Moore, 1985). 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 (see, for example, Dames and Moore, 1985). Thus, 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 (see, for comparison, harmless depth concept; Hynes, 1984). If, however, the migrating void reaches a point at or near the ground surface, a subsidence pit can form as a result. In this case, the depth of the subsidence pit is constrained (in part) by the height (thickness) of the remaining void. If most of the void has been filled by rubble, the depth of the surface subsidence may be less than the thickness of the original mined-coal horizon. 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 occur over mines within 100 ft of the ground surface, some pits have formed where underground mines are as deep as 350 ft (Turney, 1985).

Subsidence troughs are broad, "dish-shaped" areas of lowered (subsided) ground surface that form in response to the process of trough subsidence (fig. 20) (see, for

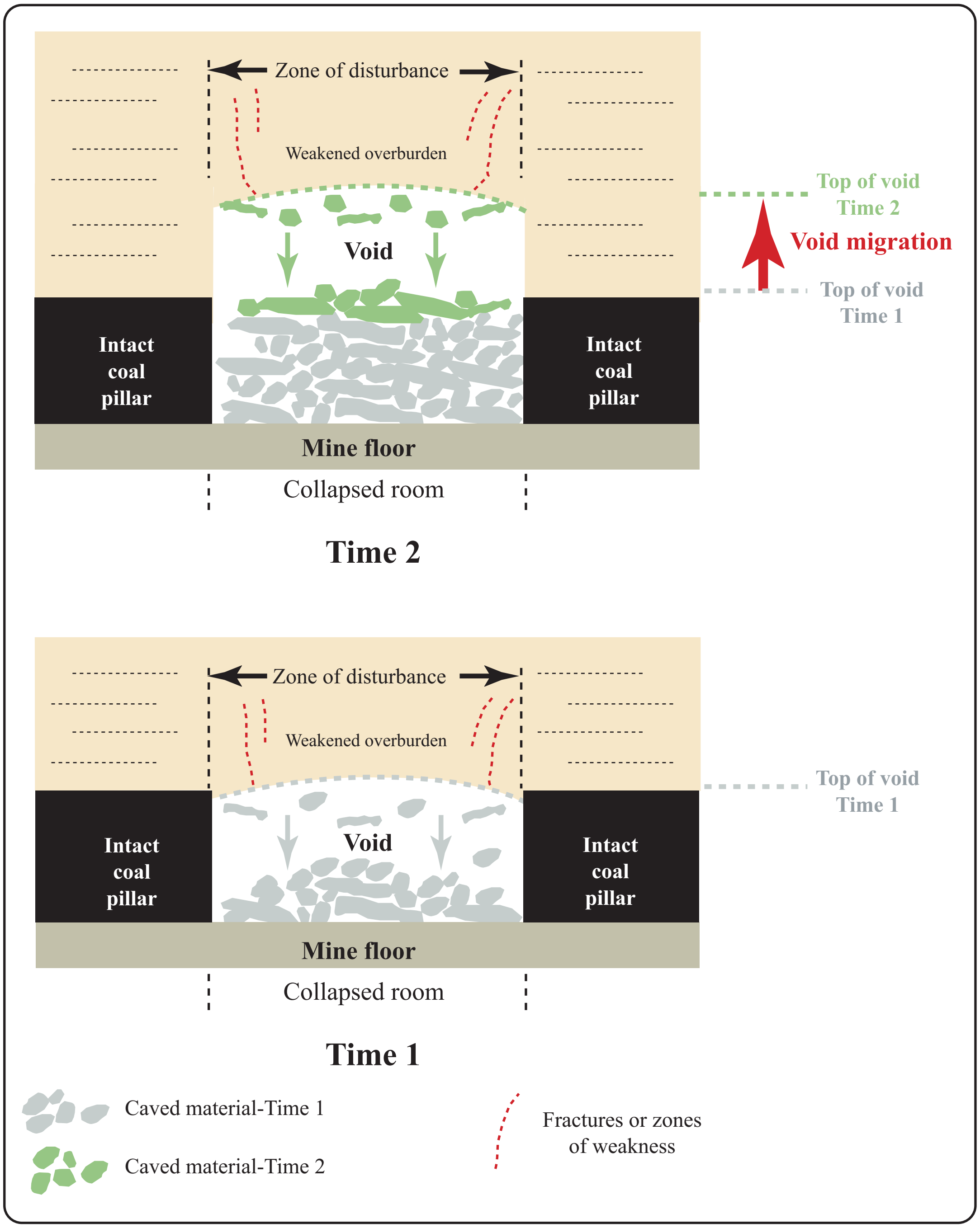


Figure 18. Schematic diagram showing the process and results of roof and overburden collapse (chimney subsidence) into an abandoned room of an underground coal mine. From time 1 to time 2, progressive failure (collapse) of weakened roof rock or overburden above the mine room results in the accumulation 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 may be subject to downward sagging or separation as the effects of mine collapse are propagated upward. Diagram not to scale.

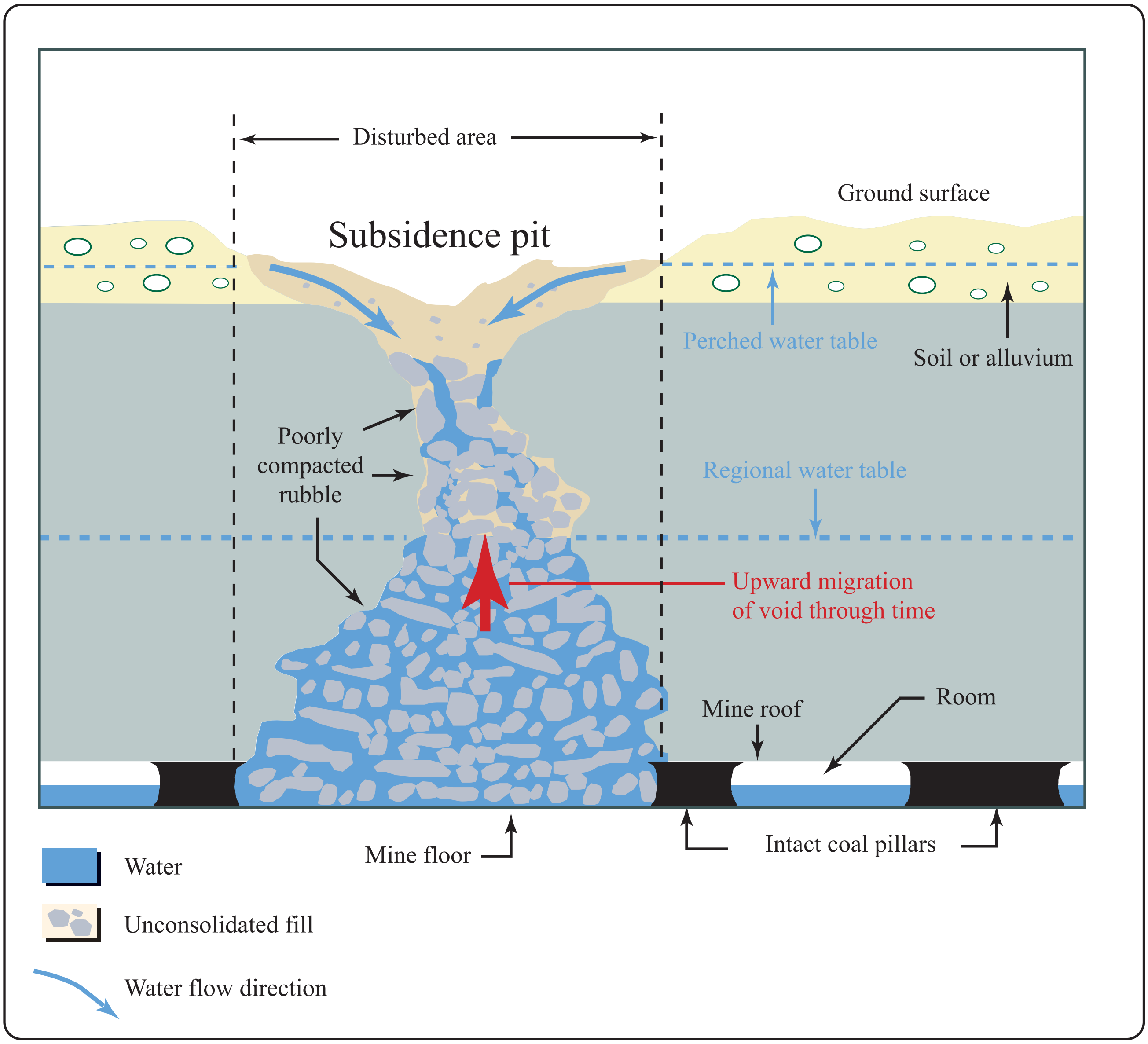


Figure 19. Schematic diagram depicting the chimney subsidence process and its potential effects. Overburden collapse and upward void migration above an abandoned room in an underground coal mine has resulted in the development of a subsidence pit (sinkhole) on the ground surface. In chimney subsidence, 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 is increased as shallow waters wash loose surface material downward through the caved rubble into the collapsed mine room. Diagram not to scale. Modified from Turney (1985).

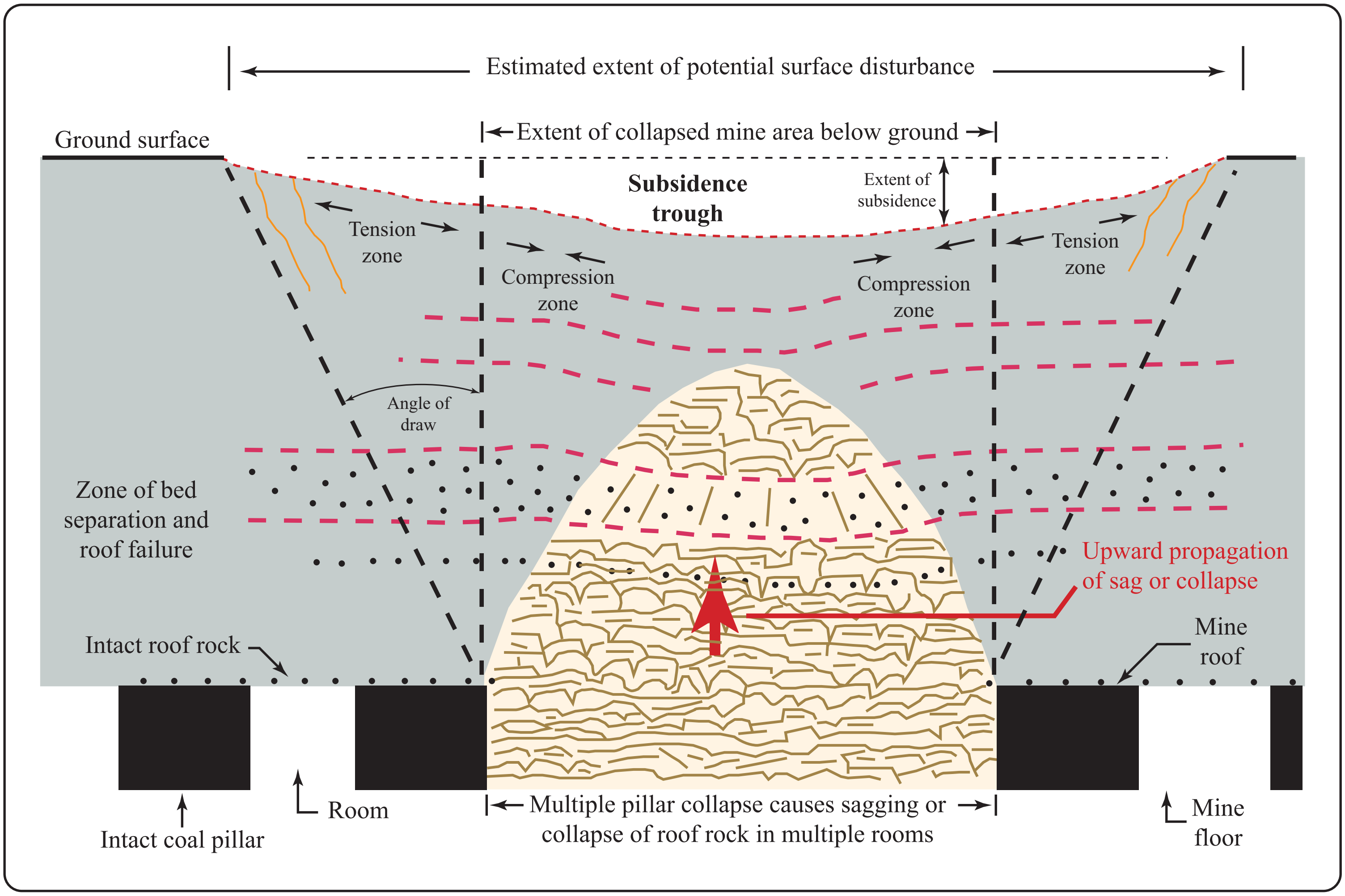


Figure 20. Schematic diagram depicting the process and potential ground surface effects of trough subsidence. In this scenario, the collapse of multiple coal pillars separating adjacent mine rooms results in the development of a large underground void. Overlying strata are weakened, and sag or collapse into the underlying void. As this sagging/collapse propagates upward, a subsidence trough can develop on the ground surface. The areal dimensions of the subsidence trough on the ground surface exceed the areal dimensions of the underground cavity. Red dashed line and black dots highlight the effect of subsidence on bedding planes and ground surfaces. Diagram not to scale. Modified from Turney (1985).

example, Turney, 1985; Matheson and Bliss, 1986). Troughs are larger in areal dimension than subsidence pits, and may be hundreds to thousands of feet in breadth (Matheson and Bliss, 1986). A single trough may actually include numerous subsidence pits (see, for example, Dunrud and Osterwald, 1980). Troughs can develop over areas where continuous, high-extraction mining of a coal bed has generated a large, open cavity with little or no roof support, or where multiple coal pillars in an abandoned coal mine have collapsed simultaneously or in rapid succession, also resulting in the development of a large open void. In the latter example, the chain reaction of pillar failure can be initiated when the weight of the overburden exceeds the strength of the existing coal pillars (Turney, 1985). Coal mine fires can also facilitate the process of trough subsidence by burning multiple pillars of coal as the fire propagates through the mine, resulting in weakening and collapse of the burned pillars and mine roof. As the mine roof sags or collapses into the void, the overlying overburden may collapse or sag correspondingly. Ultimately, a trough of depression can form on the ground surface as the sag is propagated upward to the ground surface (fig. 20) (Myers and others, 1975). In contrast to subsidence pits, the surface disturbance resulting from trough subsidence usually exceeds the areal dimension (breadth) of the underground void (see, for example, Myers and others, 1975).

In addition to subsidence features caused by chimney and trough subsidence, there is also the potential for the sudden, rapid collapse of abandoned mine shafts and steeply sloped entryways. In many coal fields, vertical or near vertical shafts were used for access to coal mines at depth, as well as for ventilation. Upon abandonment of the mine, these shafts may have been backfilled with unconsolidated mine material and waste in attempts to seal the entries. Through time, this unconsolidated material might fail downward, allowing the shaft to reopen. Additionally, inclined slope entries (adits) may be present close to the ground surface. If these entries opened in poorly consolidated surficial material, there is a potential for the collapse or caving of the ground surface overlying these shallow adits (Turney, 1985).

Although the processes of subsidence are reasonably well understood, difficulty arises when trying to accurately predict when and where subsidence will occur. Numerous analytical techniques aimed at determining the subsidence potential in undermined areas have been developed, and the reader is referred to studies by Myers and others (1975), Hynes (1984), Dames and Moore (1985), Matheson and Bliss (1986) and Roenfeldt and Holmquist (1986) for detailed information on mine subsidence investigations in Denver Basin coal fields. The processes of chimney and trough subsidence described above, generally serve as the 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 because differences in mining techniques, overburden characteristics, and data availability may necessitate modification to the models on a site-specific basis. In all cases, it is critical to have a foundation of accurate map data depicting such elements as mine elevation, orientation, room and pillar locations, major and minor haulage ways, entries, and shaft locations, in order to proceed with subsidence investigations. Most or all of the abandoned underground mines in the Denver Basin are now inaccessible, so improvements of, or additions to, the existing map information is usually not feasible. Maps for some of the older mines, which may have been abandoned since the late 1800s or early 1900s, are highly variable in terms of accuracy and completeness. Because these mine maps are key to analyzing the potential for subsidence, attempts at subsidence prediction in some areas may be hampered significantly if the available maps are of poor quality.

Numerous models have been devised to aid in the prediction of surface subsidence in areas of abandoned underground mines. In Denver Basin subsidence studies, the prediction of surface depressions resulting from chimney subsidence is generally based on the bulking characteristics of the roof rock and overburden in the area of concern. If a model for prediction of the potential surface disturbance is constrained within a framework of bulking characteristics alone, the theory of harmless depth is applied (Hynes, 1984). According to Hynes (1984), the harmless depth theory relies on the idea that as a caving void migrates upward, the volumetric increase due to 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 appreciably, both vertically and laterally, within a fairly small area. Bulking characteristics can be determined through laboratory experiments, and from these, a bulking factor (bulking coefficient) can be calculated that reflects the percentage increase in the volume of rubble generated by the collapse of a specific rock-type (see, for example, Hynes, 1984; Herring and others, 1986). Hynes (1984) reports bulking factors ranging from 1.25 to 1.30 (25 to 30 percent volume increase) for sandstone and siltstone, and 1.1 to 1.2 (10-20 percent volume increase) for shale and claystone in the northeastern part of the Boulder-Weld coal field. These bulking factors can 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 (see, for comparison, Herring and others, 1986). An application of this formula is as follows. If a bulking factor of 1.1 (10 percent volume increase), and a mined void thickness of 10 ft were assumed, then 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, 1984). 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 assumes essentially flat-lying coal beds, and for this reason, may not be universally applied in all areas of the Denver Basin. An additional model, which incorporates bulking aspects described here coupled with a stable arch concept, may also be useful in subsidence prediction over room and pillar mines (see Hynes, 1984, for details). Because bulking properties are so critical to interpretations of potential surface subsidence using these models, extensive drilling and sample analysis may be required to accurately assess these properties.

Models used to analyze larger-scale, trough subsidence potential are primarily based on studies of subsidence above longwall mines. One of the primary trough subsidence models utilizing longwall mining/subsidence data was devised by the National Coal Board (NCB) of Britain. This NCB model has served as the basis for interpretations of trough-type subsidence in studies of Denver Basin coal fields (see, for example, Myers and others, 1975; Hynes, 1984; Turney, 1985). 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 actively being mined. Coal extraction by this method typically approaches 100 percent recovery in each longwall panel (Lee Osmonson, U.S. Geological Survey, personal communication, 2001). Subsidence over longwall mines is commonly immediate, and can take place as mining progresses. The NCB model is based on the principal that the continuous extraction of coal, and corresponding loss of roof support in a longwall panel, causes the roof and overlying rock to sag into the void caused by mining. The sag is propagated upward resulting in the development of a trough of depression at the ground surface; the depth of the depression can be no more than the thickness of the mined coal bed (Myers and others, 1975). Basically, this model was designed to determine vertical and horizontal displacement, horizontal ground strain, ground surface tilt and curvature, and the magnitude of these features relates to the width, depth and height of the extraction zone (Hynes, 1984). After the mining has ceased, subsidence can continue in a steady manner, or stop for a period of time, and then resume during subsequent failure and collapse of the overburden (Myers and others, 1975). The primary basis of the NCB model is that subsidence is induced by the development of an open, completely unsupported underground void during the process of coal extraction. An important consideration related to the application of this model for subsidence prediction in the Denver Basin is that the majority of coal mining in the Front Range area was completed using room and pillar techniques. Even if coal pillars were pulled in existing rooms during the process of mining retreat, it is likely that all pillars and manmade supports were not removed, and thus, could continue to provide roof support for an indeterminate amount of time. For this reason, the development of subsidence troughs would not follow as orderly and predictable a pattern as would be expected in longwall mines (Myers and others, 1975).

Stop 4: Interlocken Office Park—Changing Land Use

At this stop we will discuss urban growth and the changes in population in Front Range counties as an introduction to subsequent stops where urbanization is occurring in areas of past, present, and potentially future energy production.

Dramatic growth has been documented in Colorado by the 2000 Census. In fact, Colorado's population increased from about 3.3 million people in 1990 to more than 4.3 million in 2000, a 30.6 percent increase (Colorado Department of Local Affairs, 2001). Much of the increase occurred in counties along the Front Range, including Adams, Arapahoe, Boulder, Denver, Jefferson, Larimer, and Weld (table 1). These seven counties contain more than over 61 percent of the state's population (Colorado Department of Local Affairs, 2001), or more than 2.6 million people. By the year 2025, projections are that these same seven counties will be home to more than 3.7 million people (Colorado Department of Local Affairs, 2001).

This stop at Interlocken Office Park serves as an example of the intense urbanization that has occurred in the Front Range in just the last decade. The town of Superior, part of which is in view from this stop (fig. 21), has grown from 255 people in 1990 to 7,400 people in 2000 (table 2) and is even larger today. Much of this growth has occurred on land that was previously undeveloped, and much of the new development occurs on land that overlies abandoned coal mines of the Boulder-Weld coal field (see fig. 16). The growth in Superior serves as an example of what has happened in many other small towns or cities in the Front Range (table 2), some of which we will visit later in this trip. These small communities have also seen growth measured in orders of magnitude. Nevertheless, the Front Range has been and is projected to be the focal point of much of the urban growth in the state.

Projections for growth in the Front Range area estimate that an additional 2 million people will move to Colorado by the year 2025 (Colorado Department of Local Affairs, 2001), with many of those new residents choosing to live in these same seven counties. Thus, issues related to growth such as traffic congestion, increased air pollution, diminished quality of life, and a greater need for resources (for example water, sand and gravel, aggregate, and energy), will likely intensify in the next 25 years.

Accommodating an additional 2 million people in Front Range communities will be a challenge not only in terms of quality of life issues but also in terms of the impact that increasing urbanization will have on production of energy resources. Much of the growth anticipated for the Front Range is expected to occur in areas of energy production, past, present, and/or future. In the past, the production of energy resources in the Front Range occurred principally in rural areas, largely removed from urban centers (fig. 22). The dramatic urban and commercial growth that has occurred in the last few decades has caused the encroachment of urban and commercial development on regions of energy production (figs. 23 and 24). Urban growth models predict that much of the growth in the Front Range will be along the Interstate 25 corridor north of Denver (see fig. 6 for location), as well as along the proposed Colorado State Highway 470 corridor, again north of Denver (DRCOG, 1999). This area of potential new growth is in large part coincident with the Boulder-Weld coal field and the GWA (see figs. 6 and 24 for location). Thus, more people will not only be living in areas underlain by abandoned coal mines, but they will also be living in areas that already have a large number of oil and gas wells in existence and also have high potential for future oil and gas exploration and production (T. Cook, U.S. Geological Survey, written commun., 2001). An expected consequence would be

Table 1. Population growth for selected counties in the Front Range of Colorado and for the State of Colorado. Populations for 1990 and 2000 from census data (from Colorado Department of Local Affairs, 2001), whereas the population of counties and state for 2025 are projections from Colorado Department of Local Affairs (2001). The most significant population growth (percentage change) for those counties shown is expected to be in Adams, Boulder, Larimer and Weld Counties.

County	Population, 1990	Population, 2000	Projected Population, 2025	Percent Change, 1990-2000	Percent Change, 2000-2025
Adams	265,708	336,909	602,565	+ 27	+ 78
Arapahoe	393,284	497,310	612,445	+ 26	+ 23
Boulder	226,014	286,460	409,141	+ 27	+ 43
Denver	467,854	541,835	671,016	+ 16	+ 24
Jefferson	439,885	527,790	634,848	+ 20	+ 20
Larimer	187,081	243,414	368,465	+ 30	+ 51
Weld	131,946	179,965	394,262	+ 36	+ 219
Colorado	3,304,042	4,250,110	6,427,169	+ 29	+ 51

Table 2. Population growth and the percentage change in population from 1990-2000 for selected cities in the Front Range of Colorado. Populations for 1990 and 2000 from census data (from Colorado Department of Local Affairs, 2001).

City	Population, 1990	Population, 2000	Percentage Change 1990-2000
Boulder	83312	91606	+ 10.0
Brighton	14186	22382	+ 57.8
Broomfield	24638	37117	+ 50.6
Dacono	2228	3015	+ 35.3
Erie	1258	6406	+ 409.2
Firestone	1358	1908	+ 40.5
Frederick	988	2467	+ 149.7
Golden	13116	15309	+ 16.7
Greeley	60454	76930	+ 27.3
Lafayette	14548	23028	+ 58.3
Louisville	12361	20005	+ 61.8
Morrison	465	844	+ 81.5
Northglen	27195	31041	+ 14.1
Superior	255	7399	+ 2801.6
Thornton	55031	79952	+ 45.3

Figure 21. Photograph of part of Superior, Colorado. Virtually all of the development seen in this photo has been built in the last 5-10 years.

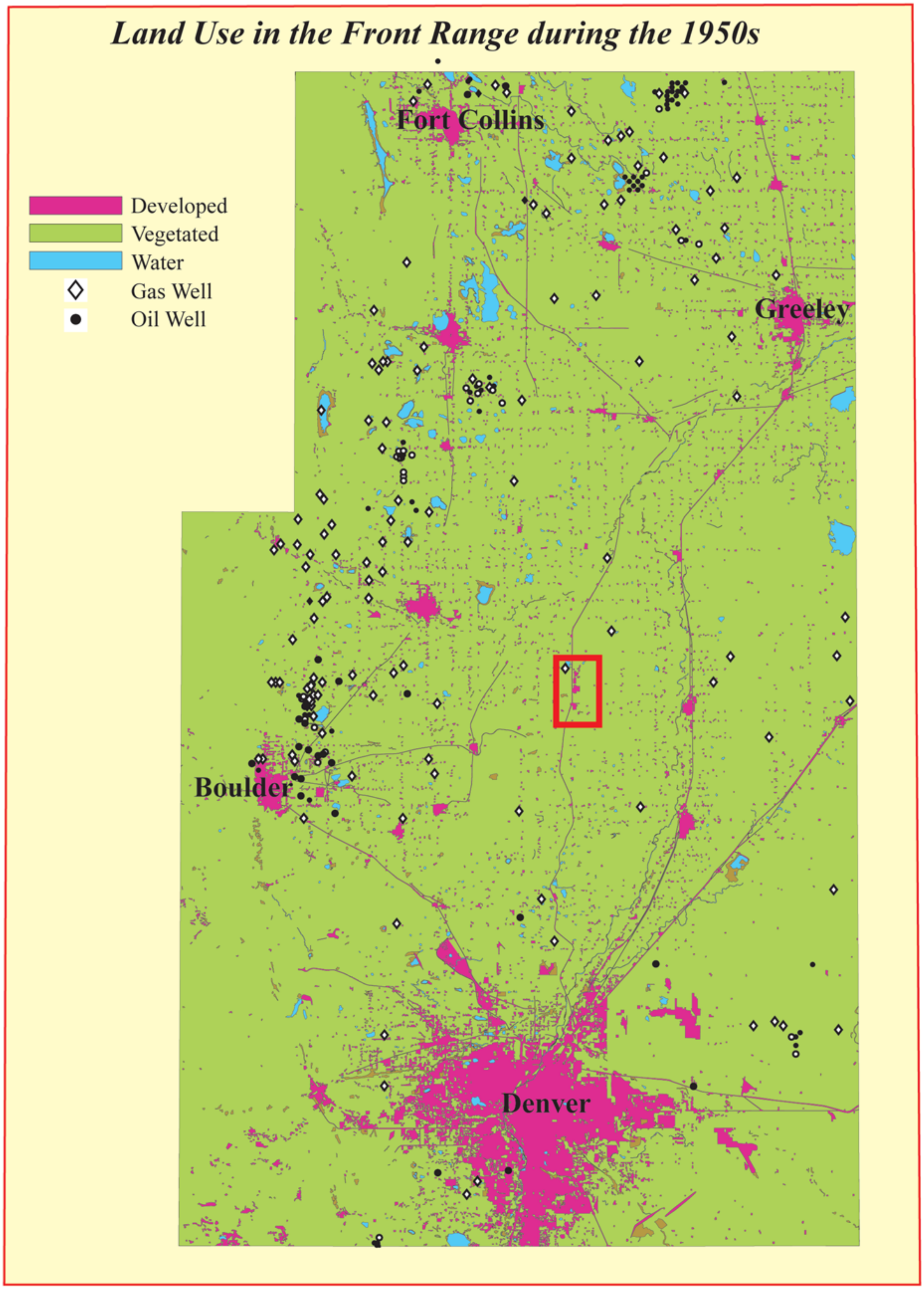


Figure 22. Map showing land use and land cover characteristics (LULC) for part of the Front Range during the 1950s. The large developed area at the bottom of the map is Denver and the developed area in the upper right corner is Greeley. Note that oil and gas wells were principally removed from urban development. LULC data from C. Mladinich (U.S. Geological Survey, written commun., 2001).

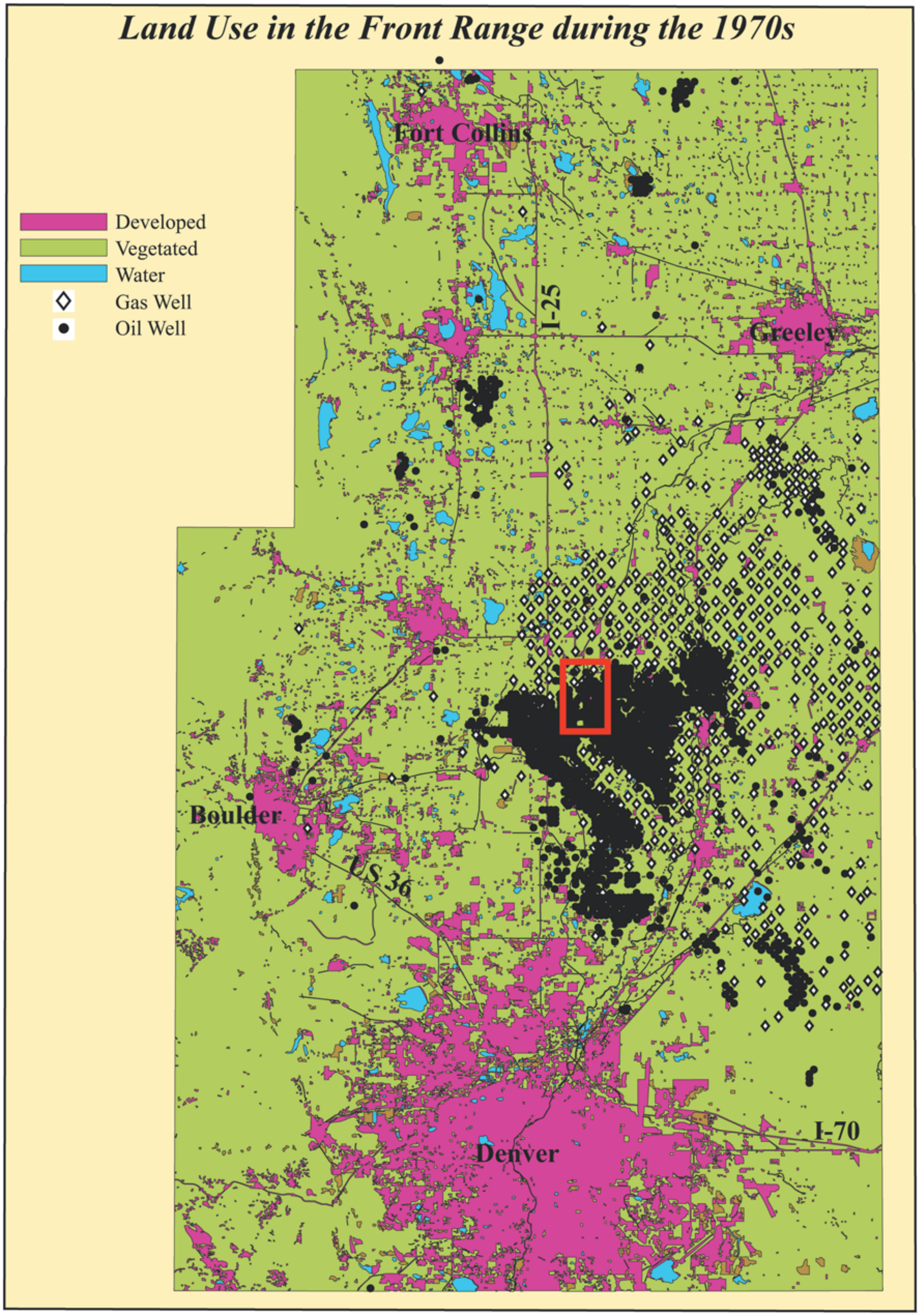


Figure 23. Map showing LULC characteristics for part of the Front Range during the 1970s. Many more oil and gas wells existed in the 1970's than before, but they are still concentrated in areas away from development. LULC data from C. Mladinich (U.S. Geological Survey, written commun., 2001)

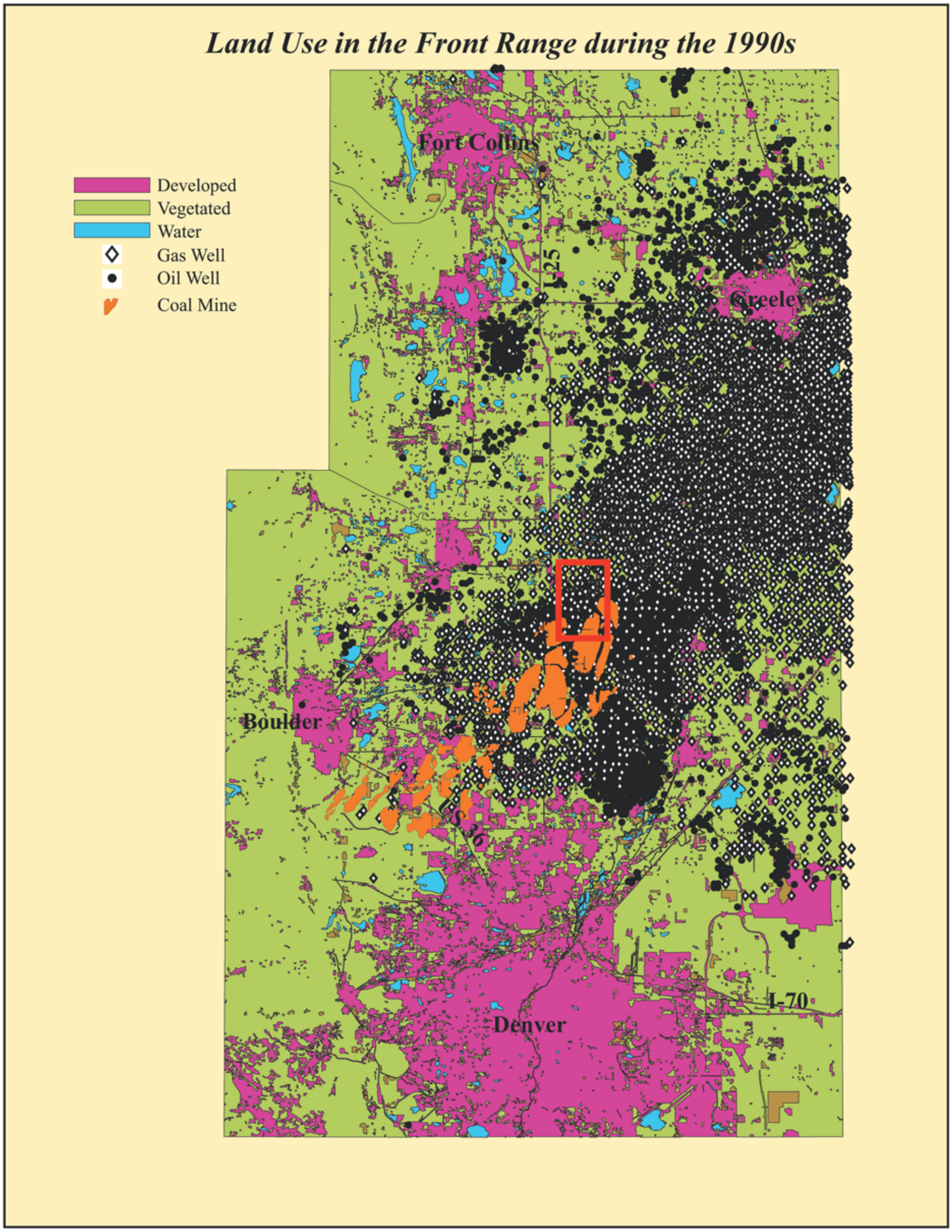
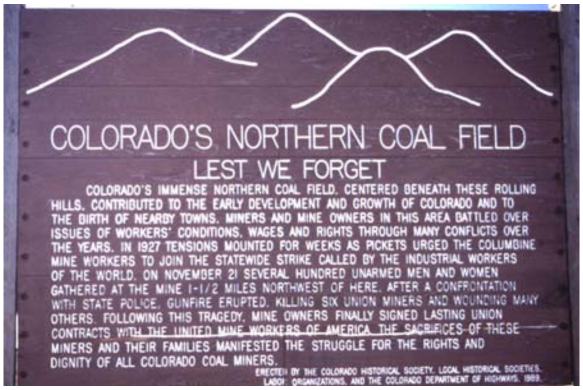


Figure 24. Map showing LULC characteristics for part of the Front Range during the 1990s. All urban (developed) areas have grown significantly since the 1970s (see fig. 23). Note there are many more oil and gas wells than in previous times (see figs. 22 and 23) and that developed areas are now encroaching upon areas of hydrocarbon production (urban growth has continued since these LULC data were acquired so encroachmentat present is even more significant than shown here). Also note how Greeley (developed area in upper right corner) is virtually surrounded by wells, although no wells exist within the developed area. Also included is the distribution of coal mines in the Boulder-Weld coal field. LULC data from C. Mladinich (U.S. Geological Survey, written commun., 2001).

increased competition for use of the land surface between owners of the surface estate and owners of the underlying mineral estate; commonly these are different individuals, companies or governments (state and federal).

Stop 5: Colorado 7 and Interstate 25—Coal-bed methane



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 causing 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 viable 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 on the order of 49.9 trillion cubic feet (Tcf) (U.S. Geological Survey National Oil and Gas Assessment Team, 1996).

Methane is typically the dominant component of the natural gases within coal beds, although other hydrocarbon gases (for example, ethane and propane), and varying amounts of nitrogen and carbon dioxide may also be present (see, for example, Rice and others, 1993; Johnson and Flores, 1998). The generation of gas in coal beds takes place during coalification, the process by which accumulated plant material (peat) is transformed to coal. Coal-bed gas is either biogenic or thermogenic in origin (see, for example, 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. 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 (see, for example, Rice and others, 1993; Johnson and Flores, 1998). In contrast, thermogenic gas is generated during the latter stages of coalification, as greater depths of burial result in increased heat and pressure, and cause the release of gases rich in methane and carbon dioxide. Because the rank of the coal beds in the Laramie Formation is subbituminous, it is assumed that coal-bed gas in this formation is primarily biogenic despite the absence of confirming thermal maturity and gas composition data. Nevertheless, because biogenic gas consists mainly of methane (Rice et al, 1993), we also assume that the dominant component of coal-bed gas in the Laramie Formation is methane.

There is no current coal-bed methane production in the Denver Basin. The recent rapid development of this resource in the Powder River Basin (Wyoming and Montana), as well as relatively recent production from coals in the San Juan Basin of New Mexico and the Piceance Basin in Utah, have stimulated interest in the potential for coal-bed methane development in the Denver Basin. The Powder River Basin is perhaps the best analogue to the Denver Basin because methane-rich coal in the Powder River Basin is comparable in rank and depth to coal beds in the Laramie

Formation of the Denver Basin. Additionally, the Gas Research Institute (GRI) (1999) estimated that there might be as much as 2 trillion cubic feet (Tcf) of coal-bed methane (in-place) within the Denver Basin. Of this total, GRI (1999) suggests that some 0.3 Tcf of coal-bed methane may be a recoverable resource.

A small-scale pilot study was undertaken to gain some perspective on the coal-bed methane potential in the Laramie Formation in the GWA, northern Denver Basin (Roberts and Fishman, 2000) (fig. 25). The GWA incorporates about 2,900 mi^2 and includes most of the Boulder-Weld coal field, and additional (Eaton and Briggsdale) areas (fig. 7) where Laramie Formation coal has been mined in the past. In the GWA, commingled gas production from all Cretaceous units is allowed, and recently relaxed drill-spacing requirements (spacing of less than 40 acres) might encourage re-completion efforts to tap into additional pay zones. Potential coal-bed methane resources in the Upper Cretaceous Laramie Formation overlie targets of current natural gas production in deeper, older Cretaceous strata, and could be considered a shallow, “behind-pipe” resource in existing gas wells. For this reason, and because a well-developed infrastructure (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 of coal core samples from three drill holes (Tremain and Toomey, 1983), and (2) reports of mine fires, gas explosions, and gassy mines in the Boulder-Weld coal field (Fender and Murray, 1978) (fig. 26). At least 8 coal mines experienced mine fires or explosions during their history, and an additional 8 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, where more than 7,000 cubic ft of gas per day (28 cubic ft of gas per ton of mined coal) was emitted during the first quarter of 1976 (Fender and Murray, 1978). This volume of gas emitted from the Eagle mine is comparable to the desorbed coal-bed methane content (24 cubic ft/ton) reported for the upper coal bed in drill hole CGS-5C (Tremain and Toomey, 1983) (fig. 26). However, whether or not these values are indicative of the overall methane content that might be anticipated for Laramie Formation coal in the basin is unknown, particularly given the absence of significant gas observed in other desorbed coal samples.

Another key factor for determining the coal-bed methane potential in the Laramie Formation relates to coal characteristics, such as coal thickness and distribution. In the Denver Basin part of the GWA, subsurface data from 74 coal exploratory drill holes (Kirkham, 1978a) 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 Formation ranges from a few feet or less (traces of coal) to as much as 35 ft in T. 1 S., R. 69 W. (fig. 27). 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 and the number of coal beds varies from 2 to 12.

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

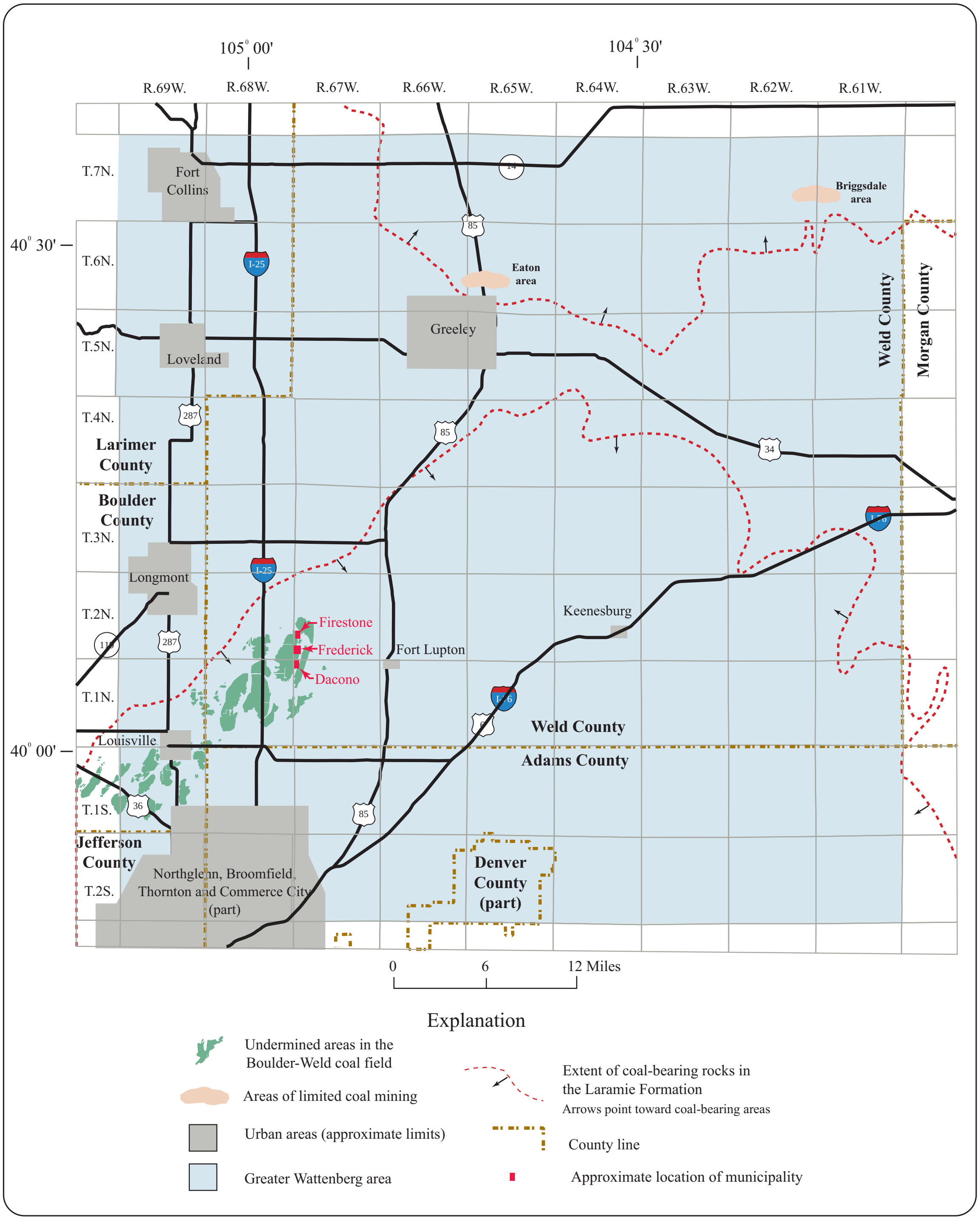


Figure 25. Index map showing the greater Wattenberg area in the Front Range of Colorado.

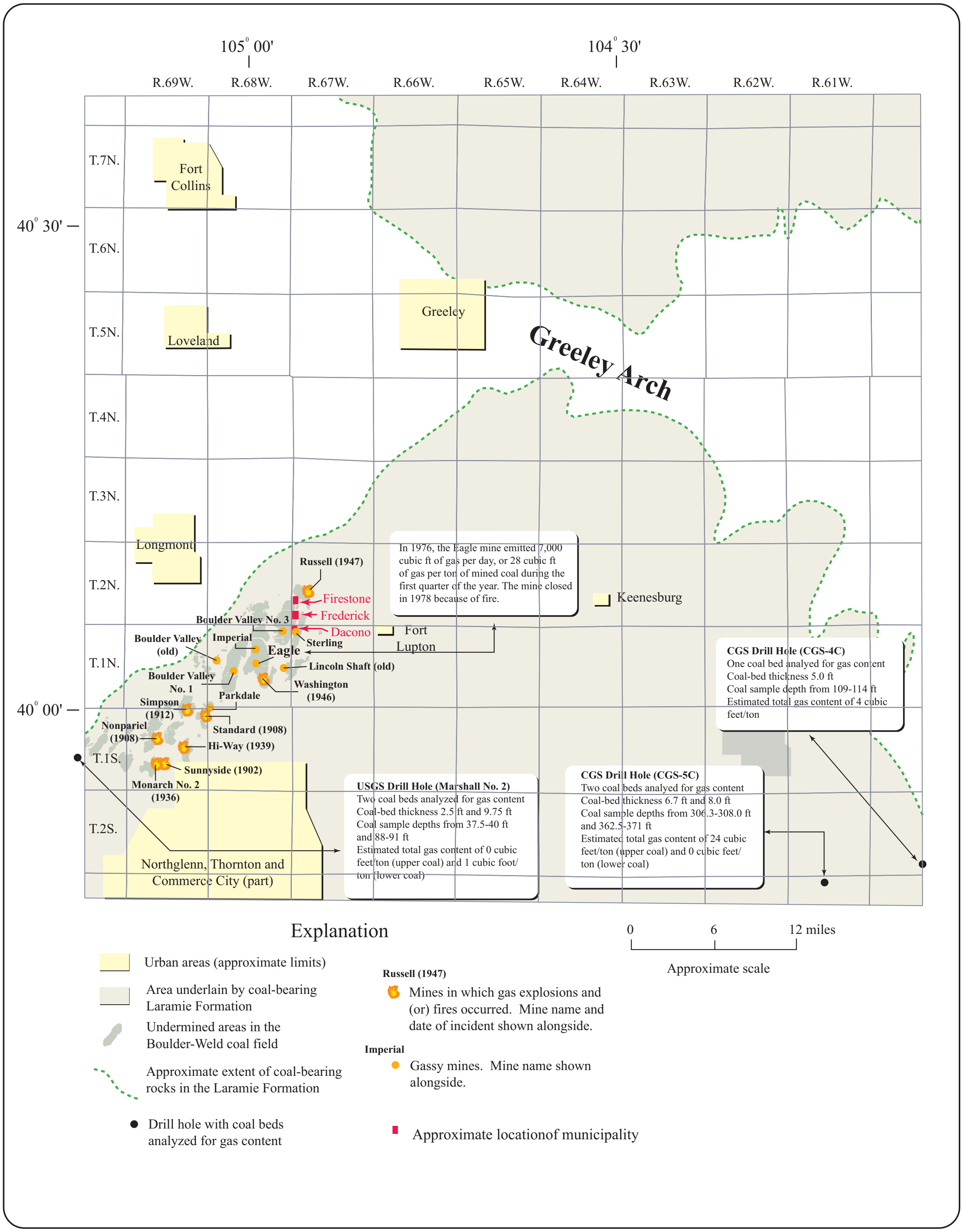


Figure 26. Map showing the locations of gassy coal mines, or coal mines that experienced fires or gas explosions, and the locations of drill holes in which Laramie Formation coal beds were analyzed for total gas content in the northern part of the Denver Basin, Colorado. Mine data from Fender and Murray (1978). Data on coal-bed gas content from Tremain and Toomey (1983).

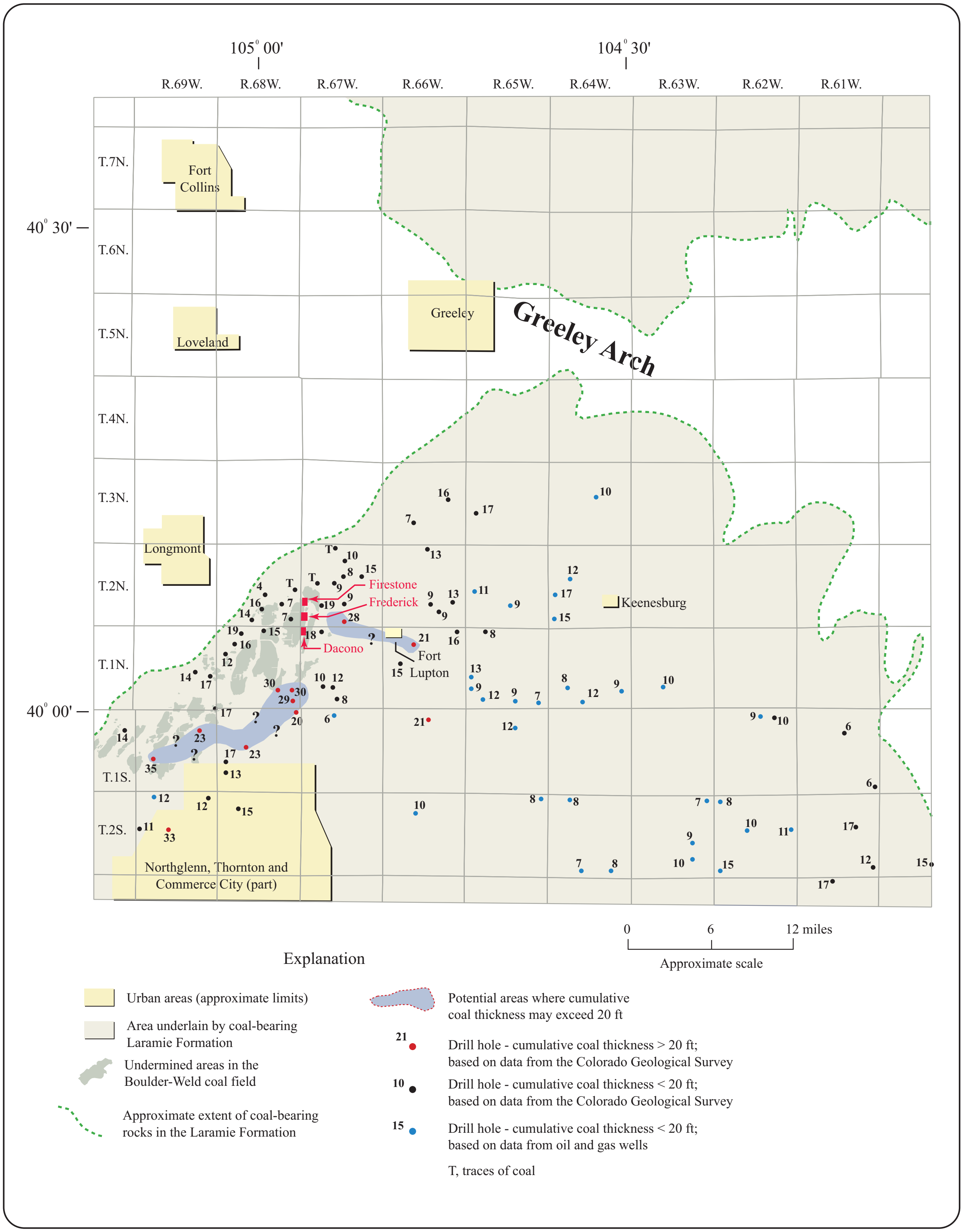


Figure 27. Map showing total coal thickness in drill holes penetrating the lower part of the Laramie Formation in the northern part of the Denver Basin, Colorado. Total coal thickness data based on interpretations of geophysical logs from oil and gas test wells, and from drill-hole data reported by Kirkham (1978a) and Brand (1980).

Formation coal. Average (arithmetic mean) as-received heat-of-combustion (Btu/lb) values for Laramie coal beds, based on analyses of coal mine samples (see, for example, Kirkham, 1978b) and coal core samples (Brand, 1980), range from 7,200 to more than 9,900 Btu/lb (fig. 28). Interestingly, average as-received Btu/lb values reported for coal beds in the Boulder-Weld coal field are the highest reported in the Denver Basin (see, for comparison, Kirkham and Ladwig, 1979; 1980) and are commonly in excess of 1,000 Btu/lb higher than heat-of-combustion values reported for Laramie Formation coal in all other areas. The higher BTU/lb values may be due to the fact that the Boulder-Weld coal field, in part, overlies the thermal anomaly (fig. 28) that has been identified in the GWA (see, for example, Meyer and McGee, 1985; Higley and Gautier, 1988). The anomaly is recognized by an unusually high temperature gradient and high, mean random vitrinite reflectance (Rm) values (fig. 28) determined for the Lower Cretaceous Muddy ("J") Sandstone and associated hydrocarbon source rocks in the Graneros, Mowry, and Skull Creek Shales. The apparent 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 (see, for example, Weimer, 1996; Meyer and McGee, 1985). Wrench faults and subsidiary faults at depth may have provided conduits for heat flow into overlying sedimentary units. Higher Btu/lb values observed in coal beds in the Boulder-Weld coal field might also relate to heat flow from intrusions at depth, although this concept is only speculative at this point. Regardless of the causal mechanism, higher BTU/lb values in the Boulder-Weld coal field likely relate to slightly higher coal ranks, and possibly give rise to a corresponding higher potential for coal-bed gas generation relative to the rest of the GWA. However, there is insufficient isotopic and compositional data on the coal-bed gas to indicate whether it was at least in part generated very recently (post mining) by biogenic methanogenesis related to the introduction of fresh groundwater in the coal beds that occurred after collapse of the mines and subsequent water infiltration.

Certain geologic factors characteristic of the GWA, however, might impede the development of a coal-bed methane resource. For example, in places where total coal accumulations exceed 20 ft, and where individual coal beds may be 8 ft or more in thickness, the lower Laramie coal zone is generally shallow (depths less than 500 ft). Additionally, many of the thick coal beds that may be a potential source of coal-bed methane 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 due to leakage into mined-out cavities (voids), or leakage to the surface via fault conduits or up-dip migration of gas to nearby outcrops. In addition, in the south-central part of the GWA, greater coal depths (more than 500 ft) might enhance coal-bed methane retention, but reported total coal accumulations are typically less than 20 ft, and are commonly less than 10 ft. The limited volume of coal in these areas could also diminish coal-bed methane resource potential.

Another factor that could influence coal-bed methane development in the Denver Basin is the close association of coal beds in the Laramie Formation with the Laramie-Fox Hills aquifer. This aquifer is pervasive throughout the basin, and is one of the primary sources of fresh water for residential, agricultural, and commercial use.

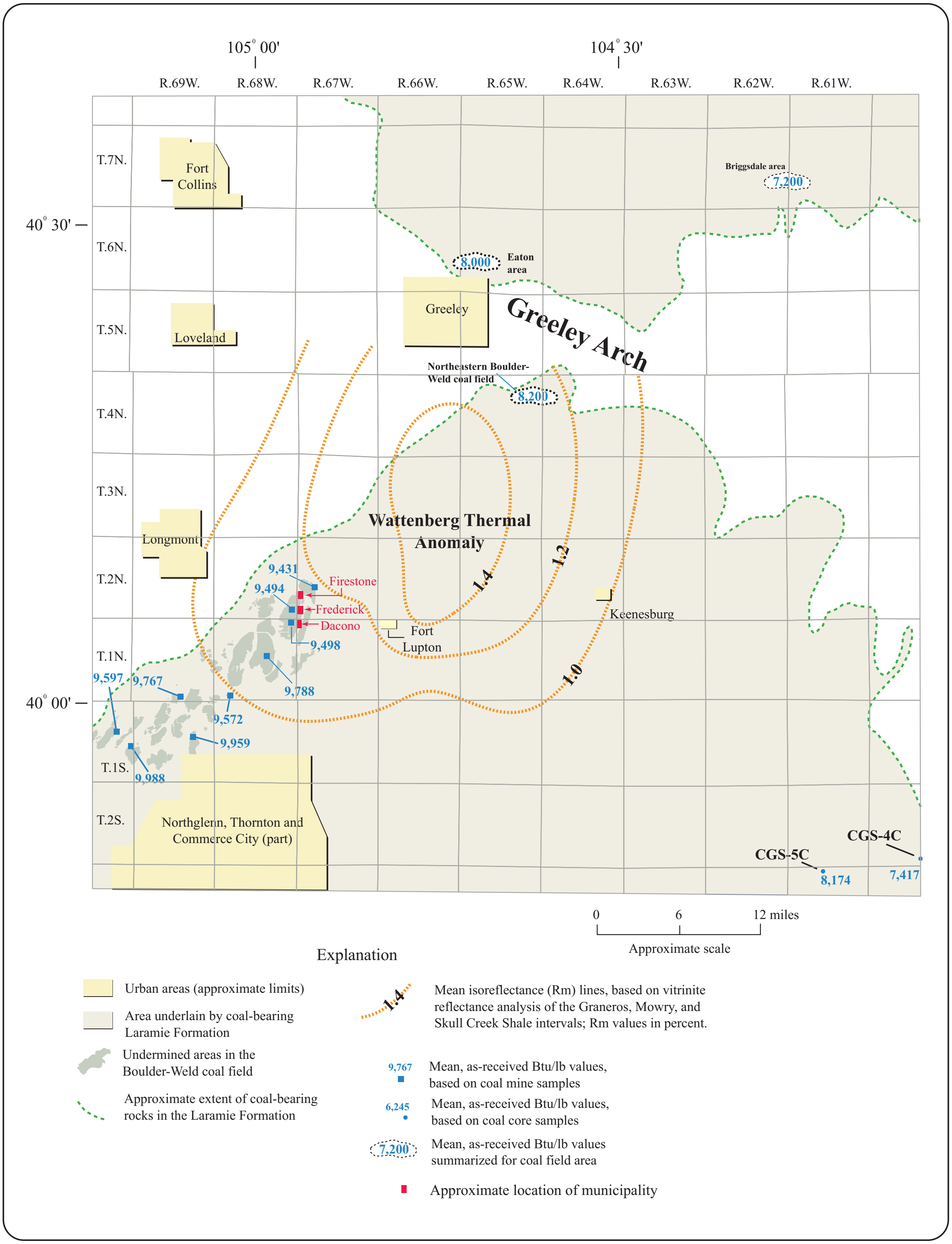


Figure 28. Map showing heat-of-combustion values for coal beds in the lower part of the Laramie Formation in the northern part of the Denver Basin and southern part of the Cheyenne Basin, Colorado. The position of the Wattenberg thermal anomaly is based on vitrinite reflectance data from the Graneros Formation, Mowry Shale, and the Skull Creek Shale intervals. Heat-of-combustion values are from Kirkham (1978b) and Tremain and Toomey (1983). Vitrinite reflectance data (isoreflectance lines) are from Higley and Gautier (1988) and Higley and others (1992).

The Laramie-Fox Hills aquifer is present in basal sandstone units of the Laramie Formation, in sandstone and siltstone units of the Fox Hills Sandstone, and (less commonly), siltstone and sandstone units in the uppermost part of the Pierre Shale (Robson and others, 1981). The aquifer also includes the thicker coal beds historically targeted for mining in the Boulder-Weld coal field (see, for example, Kirkham and Ladwig, 1979). Successful development of a coal-bed methane resource generally involves a process of dewatering to remove in situ water from the coal bed and allow for the release (desorption) of methane from the coal matrix to a well bore for recovery (see, for example, Rice and others, 1993). Water yields related to coal-bed methane production can vary appreciably. For example, water production associated with coal-bed methane development in the Powder River Basin has ranged 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 draw down (lowering) 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 may be required to ensure that associated water production will not impinge on the quality or quantity of water in the aquifer.

In summary, the successful development of shallow, coal-bed methane resources from low rank coal in the Powder River Basin imparts some optimism that similar production in the Denver Basin might be feasible. The generally deeper and higher rank characteristics of coals in Utah and New Mexico make them less likely analogues to Denver Basin coals than are the coals in the Powder River Basin. Nevertheless, when comparing Denver Basin coals to those of the Powder River Basin, it is important to consider the overwhelming differences in coal thickness and coal resource volumes between these two basins. In the Powder River Basin in Wyoming, individual coal-bed thickness can exceed 200 ft (see, for example, Mapel, 1959; Roberts, 1986), and current coal-bed methane production commonly targets coal beds that are about 100 ft thick or greater (see, for example, Stricker and others, 2000). Most of the coal-bed methane production in that basin is from coal beds in the Wyodak-Anderson coal zone, which occupies a stratigraphic interval 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). Estimates of the total coal resources 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). In contrast, maximum thicknesses of individual coal beds in the Laramie Formation in the Denver Basin are only as much as 20 ft (Eakins, 1986), with most beds less than 10 ft thick. Coal resource estimates for Laramie Formation coal beds greater than 2.5 ft thick and at depths of less than 3,000 ft, are about 20 to 25 billion short tons (Kirkham and Ladwig, 1979). It is apparent that the great volume of coal associated with thick coal beds in the Powder River Basin, even though they are of low rank, has undoubtedly enhanced coal-bed methane production (in part) there because of the potential for large volumes of coal-bed gas per unit area of land (see, for example, Choate and others, 1984). Thus, even though gas contents of Laramie Formation coal beds are, to some degree, comparable to gas contents in coal beds of the Powder River Basin, there are marked dissimilarities in coal-bed thickness and coal resource volume that could limit the overall coal-bed methane potential in the Denver Basin.

Stop 6: Southern Weld County—Land Use Impacts on Energy Production

Recent urban development has been rapid in many parts of the Front Range, and in some cases development has overrun areas of oil and gas production (fig. 29). In Colorado, oil and gas operators, as owners or leasees of mineral rights, have the legal right to develop subsurface mineral accumulations, including oil and gas, whether or not they own the overlying land surface. In the past, access by mineral-rights holders to surface areas to explore for or produce petroleum required the oil and gas operators to work with surface owners (for example, farmers and ranchers), under guidelines provided by the State. Any conflicts that may have developed would probably have focused on issues such as 1) restoration of areas disturbed by exploration or production equipment, 2) timing of the disturbance relative to planting, harvesting, or irrigation, 3) contamination of land surface by operations, and 4) proper notification of intent to enter the land area in question.

Although these same issues still exist when exploring for or developing petroleum resources on agricultural or ranch land, the presence of new urban developments in the energy-rich part of the Front Range has created new challenges for petroleum operators. In addition to farmers or ranchers and county and state officials, operators now find they must also work closely with developers, city officials, and city residents in order to reasonably and safely develop petroleum resources. Furthermore, with annexation of land by various municipalities, and the subsequent adoption of new rules and regulations for land use by these municipalities, operators are presented with new or evolving challenges as they attempt to develop energy resources. The presence of a petroleum production infrastructure (such as pump jacks, well heads, tank batteries, and separators) in an urban development during regular production, maintenance and recompletion has also created a situation where safety for urban residents is more of an issue than ever. Thus, the economic side of petroleum exploration and production has also changed with increased urbanization.

There are already numerous examples of oil or gas wells, presumably experiencing marginal production, that have been abandoned in growing neighborhoods (fig. 30). In addition, the very existence of municipalities has inhibited, and in some cases has prevented the development and production of energy resources. Around the City of Greeley there has been intensive oil and gas production (see fig. 24); however, set-backs (buffers) and other restrictions have effectively eliminated oil and gas development within the city limits. Significant urban development elsewhere in

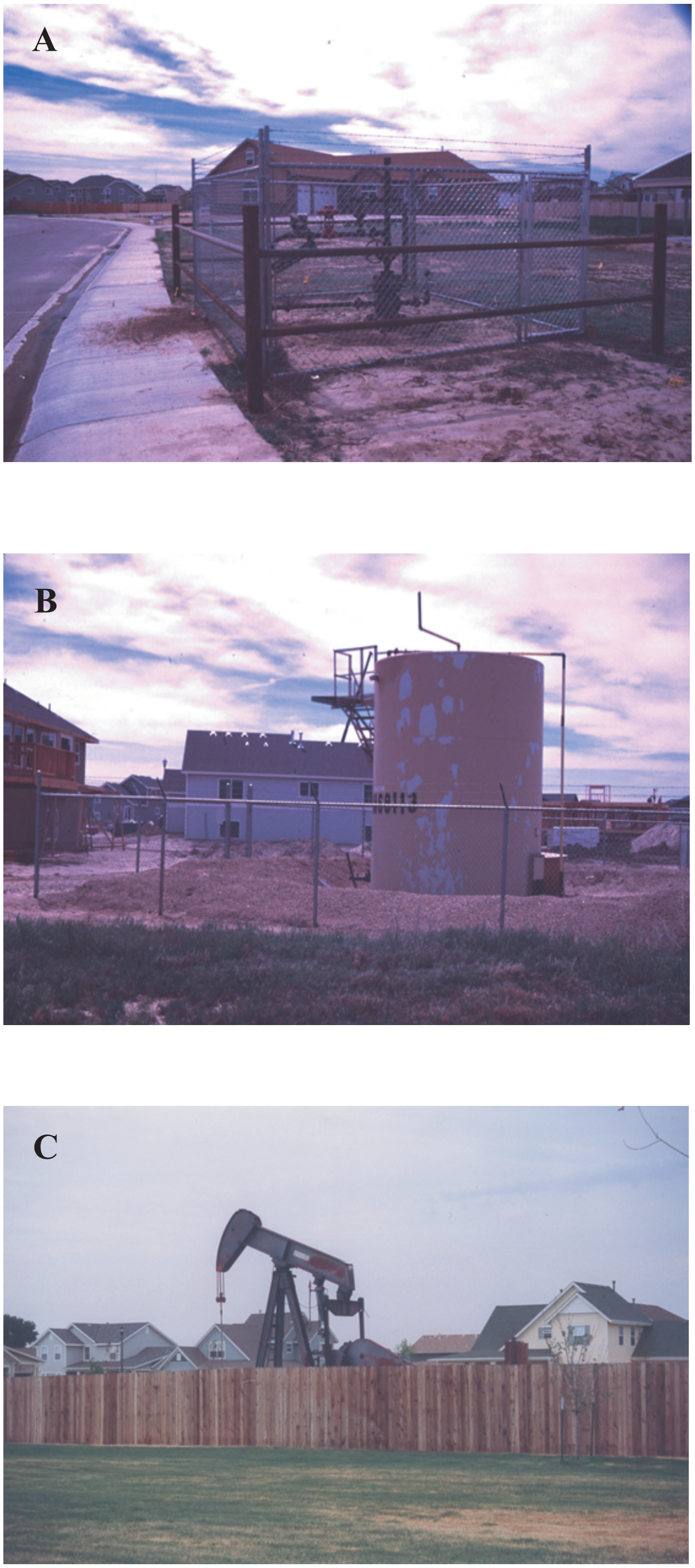


Figure 29. Photographs of housing development recently built around existing oil and gas production equipment in the GWA. A) Oil and gas well head next to sidewalk and newly-constructed home. B) Tank battery adjacent to house currently under construction. C) Pump jack in a recently completed housing development.

Figure 30. Photographs taken 3 years apart that document abandonment of oil wells in a growing urban development. A) Taken approximately 3 years ago with house in background under construction and an active pump jack producing oil from the Terry Sandstone. B) Taken recently of same locality as A, and showing completed house in background and the absence of the pump jack due to abandonment. Note that the former well site is being prepared for future construction.

the Front Range and within the GWA will likely result in similar circumstances.

The volume of potentially producible oil and gas resources and other commodities that have been or will be affected by urban development in the Front Range cannot be estimated. Truly informed decision making regarding land use will require careful and thorough analysis of all the critical issues involved in future planning for the Front Range corridor.

Acknowledgements

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