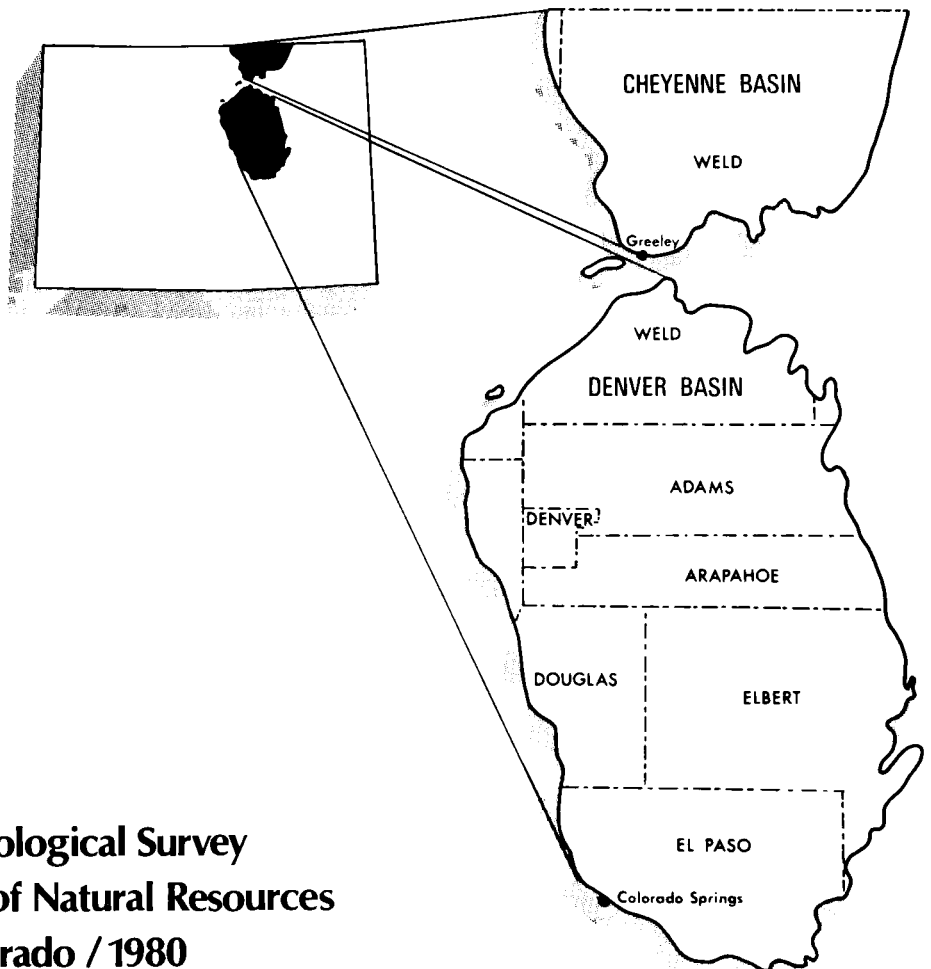
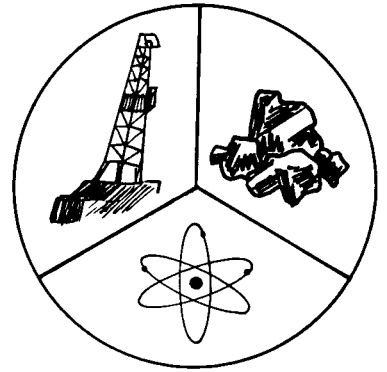


Energy Resources of the Denver and Cheyenne Basins, Colorado

Resource Characteristics, Development Potential, and Environmental Problems

by Robert M. Kirkham and L. R. Ladwig



Colorado Geological Survey
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- Plate 2. Oil and gas fields in the Denver and Cheyenne Basins, Colorado, between T15S to T12N and R57W to R71W.

ABSTRACT

Economically significant deposits of coal, lignite, uranium, oil, and gas occur in the Denver and Cheyenne Basins of Colorado. Coal, ranging in quality from subbituminous B to lignite A, occurs in the lower 275 ft (82.5 m) of the Upper Cretaceous Laramie Formation. Maximum individual coal bed thickness usually ranges from 5 to 15 ft (1.5 to 4.5 m) but occasionally exceeds 20 ft (6 m). Generally, individual Laramie coal beds are more abundant, much thicker, laterally more persistent, and of greater economic interest in the Denver Basin than in the Cheyenne Basin.

Early Paleocene lignite beds occur in the upper 500 ft (150 m) of the Denver Formation in the Denver Basin. Evaluation of lignite beds in this investigation was mainly restricted to regions where the lignite zone is shallow, generally at strippable depths. In this region two lignite-bearing areas are recognized, a northern and southern lignite-bearing area. Individual lignite beds are thicker and laterally more persistent in the northern area than in the southern area. It is unknown if these recognized lignite-bearing areas extend into nearby areas where the lignite zone is at depths greater than 200 to 300 ft (60 to 90 m). Many lignite beds contain partings or are adjacent to beds of kaolin, a potential source of alumina.

Medium- to small-sized uranium roll-front deposits occur in the Upper Cretaceous Laramie Formation and the Fox Hills Sandstone in the Cheyenne Basin. These deposits, initially discovered in the 1970s, are not rich in uranium, but, nonetheless, they are economically important. In situ solution mining is the primary mining method likely to be used on these deposits, although other types of mining may be feasible for some deposits.

Oil was first produced in the study area in 1901 from fractured, sandy zones in the Upper Cretaceous Pierre Shale at Boulder field. Several additional fields were discovered during ensuing years, but production was at low levels until the 1950s when major oil and gas discoveries were made in the D and J Sandstone members of the Lower Cretaceous Dakota Group and the Permian Lyons Sandstone. To date, most oil and gas has been recovered from the Dakota Group, but significant quantities have also been produced from the Lyons Sandstone and Sussex and Shannon Sandstone members of the Upper Cretaceous Pierre Shale.

Recorded coal mining in the Denver and Cheyenne Basins dates back to the 1860s. Over 130 million tons (118 billion kg) of coal and lignite have been mined from the area, with peak production occurring in the 1920s and 1930s. Production has steadily decreased since this time and currently no coal mines operate in the study area. However, we anticipate increasing coal mining activity in the study area, a result of the pressing energy situation. Two proposed Laramie coal strip mines have been permitted and initiated mine construction. Additional mines, either in the permitting process or planning stages, are scheduled to mine Laramie coal for power plants and other usage. Both surface and in situ gasification of Denver lignite and Laramie coal is also feasible. It is

possible that this type of development, at least at a pilot scale, will occur before the end of this decade. This is especially likely in view of the Federal push towards alternate energy sources (i.e. coal gasification and liquefaction). Denver lignite will probably not be used in power plants in the near future because of the relative abundance of better quality coal nearby. It may, however, be suitable for other types of innovative uses.

About 20,397 lb (9,260 kg) of uranium were mined in the study area in the 1950s, principally from the Dakota Group. These deposits were very small and similar deposits are not of great economic importance today. Known economically significant deposits are restricted to the Laramie Formation and Fox Hills Sandstone in the Cheyenne Basin. Most exploration concentrates on these two formations in the Cheyenne Basin, but these formations, the Dawson Arkose and the Arapahoe Formation, are also being evaluated in the Denver Basin. One of the known uranium deposits, the Grover deposit, has been tested on a pilot scale using in situ solution mining techniques. Another deposit, the Keota deposit, is scheduled to be solution mined. This project is presently in permitting stages and mining should initiate within the next year or two. It is likely that up to 0.5 to 1.0 million lb (0.23 to 0.45 million kg) of U308 may be produced annually from the study area in the near future.

Oil and natural gas production in the study area, as of January 1, 1979, totals over 203 million barrels of oil and 681 billion cubic feet of gas. Conservative estimates suggest future production will at least equal past production. Many new fields will be discovered in the Dakota Group and, possibly, in other formations. Existing fields will continue to produce significant quantities of oil and gas. Estimates by several different individuals suggest just one field, Wattenburg, contains gas reserves that exceed the present cumulative gas production of the entire study area.

Energy resource exploration and development in the Denver and Cheyenne Basins of Colorado may cause environmental problems. Some of these impacts are unavoidable to a certain extent, but many can be minimized and some even eliminated by proper planning, operation, and abandonment of recovery facilities and adequate plugging of abandoned drill holes. The primary environmental problems relate to changes in various hydrologic factors which affect surface- and ground-water quantity and quality.

Oil and gas recovery generally impacts the environment less than coal and uranium mining activities, but overflow or seepage from brine retaining pits and leakage through damaged or improperly completed well casing may contaminate ground and surface water. Uranium mining in the study area has a higher potential for ground-water problems than coal mining, primarily because uranium deposits are usually within major aquifers and any mining activity poses a direct hazard to the host aquifer. Surface mining of coal or uranium may contaminate ground and surface water and disrupt aquifer and stream flow paths. Underground mining has a somewhat lower potential for damaging the hydrologic

environment than does surface mining, but severe mine subsidence may cause serious environmental problems. Non-conventional resource-recovery techniques, such as underground coal gasification and in situ uranium solution mining, offer many economic and environmental advantages over conventional methods. These new techniques, however, may pose serious potential threats to ground-water quality and quantity unless recovery activities are carefully planned, operated, and abandoned.

It should be emphasized that many of the environmental impacts associated with energy resource exploration and development can be reduced, if not eliminated, by carefully examining the environmental aspects of each project and incorporating the appropriate protection measures.

INTRODUCTION

PURPOSE AND METHOD OF INVESTIGATION

This report presents the results of a 32-month study of the geologic characteristics, development potential, and environmental problems related to the exploration for and development of energy resources in the Denver and Cheyenne Basins, Colorado. Coal, lignite, uranium, oil, and gas are evaluated in this investigation. Other energy resources exist in the study area, including solar, geothermal, biomass, and wind, but these are not considered either because of their non-geological nature or their limited development potential. This investigation is a cooperative study conducted by the Colorado Geological Survey and partly funded by the Energy Lands Program of the U.S. Geological Survey through U.S.G.S. Grant No. 14-08-0001-G-487.

A primary goal of our investigation involves the development of a thorough understanding of potential environmental problems that may result from the exploration for and extraction of energy resources in the study area. Environmental aspects of resource beneficiation, processing, and utilization, such as uranium milling, coal beneficiation, surface gasification and liquefaction of coal and lignite, oil and gas refining, and electric power generation were not studied.

Because our study covers a wide range of geologic elements and a large geographic area, an in-depth, detailed evaluation of all relevant factors is far beyond the project scope. Our approach involves a somewhat generalized and regional, rather than a site-specific assessment of pertinent geologic, hydrologic, and environmental components. If it appears that we have allotted an unusually large number of pages in this report to the environmental aspects of in situ uranium solution mining, it is not because we believe there are more environmental problems with solution mining than with other mining methods. Solution mining is more thoroughly discussed because it is a relatively new mining technique that is widely misunderstood by or unknown to the general public, government decision-makers, and many geoscientists. Furthermore, in situ solution mining will probably be the primary mining method used to recover uranium in the study area.

Complete evaluation of the geology and development potential of an energy resource deposit or the hydrology and environmental problems of a particular recovery site can only be accomplished through a combination of general regional studies and local detailed evaluations. We hope our report provides valuable, regional background data to mineral exploration and development organizations and government agencies to promote development of Colorado's valuable energy resources and protection of its desirable environmental qualities.

Our investigation began in August, 1977. During the first few months, available data sources were analyzed and the most efficient method of study was selected. Discussions were held with representatives from state and regional planning agencies to ascertain the types of information

most valuable to them. Results of this part of the study are available in C.G.S. open-file report 77-1: "Preliminary investigation and feasibility study of the environmental impact of energy resource development in the Denver and Cheyenne Basins, Colorado."

Coal and lignite resources were evaluated during the following year. Extensive compilation and review of data on past and present coal mining, existing coal analyses, and published coal reports were followed by interpretation of data from over 1,500 drill hole logs that we were able to obtain from industry, other governmental agencies, and private individuals. Several reports resulted from this phase of study, including C.G.S. open-file report 78-8: "Location map of drill holes used for coal evaluation in the Denver and Cheyenne Basins, Colorado," open-file report 78-9: "Coal mines and coal analyses of the Denver and Cheyenne Basins, Colorado," and Resource Series 5: "Coal resources of the Denver and Cheyenne Basins, Colorado."

Four months were dedicated to a brief evaluation of uranium resources and familiarization with uranium mining methods that will probably receive extensive use in the study area. A part of this research was published in C.G.S. Environmental Geology 11: "Promises and problems of a new uranium mining method--In situ solution mining." Only one month was spent studying oil and natural gas resources and the environmental problems associated with their recovery because 1) existing published reports adequately describe the regional geologic aspects and development potential of oil and gas resources, 2) it would require years of detailed study by us to make a significant contribution to current knowledge on oil and gas in the study area, and 3) environmental problems related to oil and gas exploration and recovery are minimal when compared to those associated with coal and uranium.

Five months of research was directed toward furthering existing knowledge of ground-water resources in both basins. Most work concentrated on the Cheyenne Basin, because minimal data are publicly available on ground water in this area. Two hydrogeologic reports that primarily contain analyses of well waters resulted from part of this investigation phase. They are C.G.S. Information Series 12: "Hydrogeologic and stratigraphic data pertinent to uranium mining, Cheyenne Basin, Colorado" and Information Series 13: "Chemical analyses of water wells in selected strippable coal and lignite areas, Denver Basin, Colorado." The final seven months of our study concentrated on the environmental problems of coal and uranium exploration and mining, and on preparation of this final report which summarizes the results of the entire grant-funded investigation.

STUDY AREA LOCATION

The outline of the study area is shown in Figure 1. Approximately 14,000 mi² (36,400 km²) of northeastern Colorado are within the study area, which is roughly defined as the area between T12N to T15S and R57W to R71W. Part of the mountainous Front Range is within this area, but the Precambrian rocks in the Front Range were not studied. Only sedimentary

rocks in the designated area were evaluated in this report. All or parts of Adams, Arapahoe, Boulder, Denver, Douglas, Elbert, El Paso, Jefferson, Larimer, Lincoln, Morgan, and Weld Counties are within the study area. Many of Colorado's larger cities, including Denver and the Denver metropolitan area, Colorado Springs, Boulder, Greeley, Fort Collins, and Fort Morgan are within the study area.

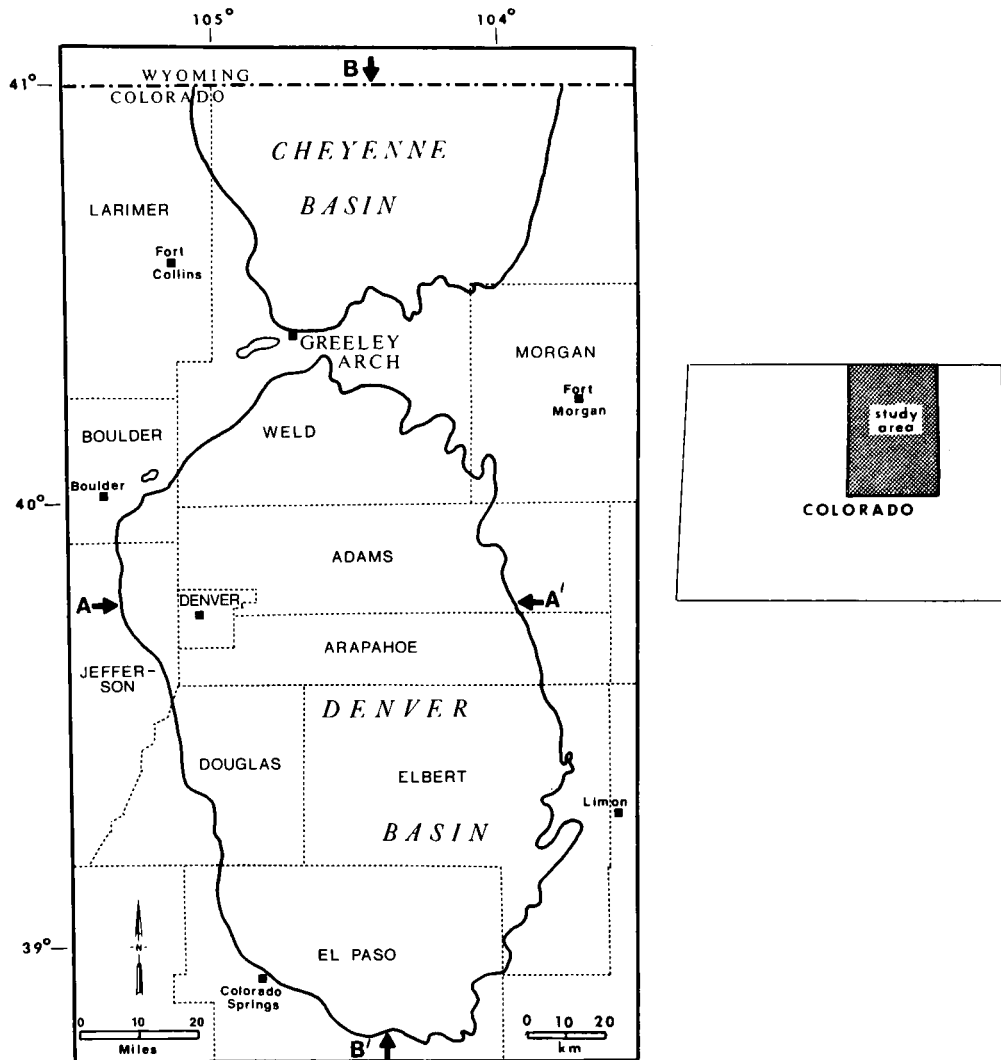


Figure 1. Location map of the study area. (from Kirkham and Ladwig, 1979).

Land in the study area is used for a variety of purposes. Areas near major cities are largely urbanized. Most types of energy resource development are virtually prohibited in these urban areas because of environmental, social, and political constraints. Most of the remaining land is used for agricultural activities, either farming or ranching. Both irrigation and dry-land farming are common in the study area. Most irrigated farming is conducted in the South Platte River valley or in the valleys of its main tributaries. Some irrigation above valley floors is accomplished by pumping large volumes of ground water or through extensive irrigation ditch systems. Wheat and hay are grown on many dry-land farms, but some of this farm land is being returned to range land uses. Most ranches run only cattle, but sheep are not uncommon. Some of the environmental problems associated with energy resource development in the study area relate to land-use conflicts. This aspect is described in a later section on "Land-use conflicts related to energy resource development."

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GENERAL GEOLOGY

REGIONAL GEOLOGY AND GEOGRAPHY

The study area encompasses a large part of northeastern Colorado. It lies just east of the Southern Rocky Mountain province and is almost entirely within the Great Plains physiographic province of the Interior Plains (Fenneman, 1931). Hammond (1964) places most of the study area within the Rocky Mountain Piedmont physiographic province of the Interior Division. A small part that is underlain by the Ogallala Formation near the Colorado-Wyoming line is within the High Plains province of Hammond (1964).

The U.S. Geological Survey (1970) recognizes two general classes of land forms in the study area. The northern part is classified as irregular plains with 50 to 80 percent of the areas gently sloping. Average local relief ranges from about 100 to 300 ft (30 to 90 m) and about 50 to 80 percent of the gentle slopes are within lowlands. They describe the southern part of the area as tablelands with moderate relief in which 50 to 80 percent of the area is gently sloping. 50 to 70 percent of the gentle slopes are in upland areas and local relief averages 300 to 500 ft (90 to 150 m).

Figure 2 illustrates the major regional topographic and tectonic features of the Southern Rocky Mountain province and adjacent basins. The depositional and structural history of the study area is directly tied to the geologic history of the South Rocky Mountain province. This mountainous province is an area of complex geology and changing topography. It has experienced three major periods of mountain building since the Precambrian. The "Ancestral Rockies" were high, abrupt mountain ranges that were uplifted during the Pennsylvanian and later extensively eroded. New mountains, some of which roughly coincided geographically

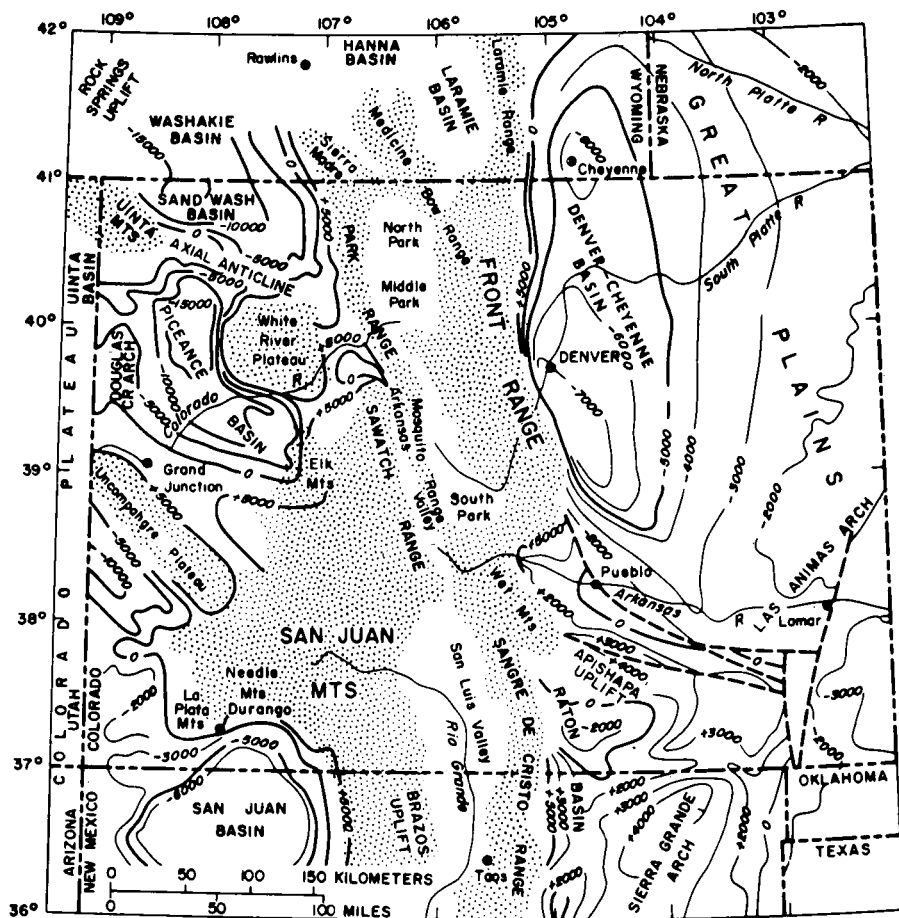


Figure 2. Principal topographic features and tectonic units in the Southern Rocky Mountain province and adjacent basins. (after Tweto, 1975)

with the Ancestral Rockies, were developed during the Late Cretaceous-Early Tertiary Laramide orogeny. These mountains apparently were not as high and abrupt as the Ancestral Rockies or present-day mountains. By the Late Eocene, they were eroded and leveled to the general elevation of adjoining basins (Epis and Chapin, 1975). The modern Rocky Mountains began to form during the Miocene and have experienced continued tectonic and erosional modification to the present. Sediments have been eroded from these mountains and deposited in the study area. Evidence of the extensive mountain-building episodes is preserved in the

sedimentary rocks of the study area. This evidence will be discussed in a later section on stratigraphy.

STRUCTURE AND BASIN NOMENCLATURE

Figure 2 indicates that much of northeastern Colorado and adjacent parts of Wyoming and Nebraska are within a large regional basin herein called the Denver-Cheyenne Basin. The study area is entirely within this large basin. The Denver-Cheyenne Basin is of great interest to the petroleum industry and has been studied in detail for potential hydrocarbon accumulations. A variety of names have been applied to the basin by the petroleum industry, including the Denver, D-J, or Denver-Julesburg Basin, but the name Denver-Cheyenne Basin is preferred for this study.

A structure contour map of the Denver-Cheyenne Basin based on the top of the Precambrian surface is shown in Figure 3. The basin is an asymmetrical, doubly plunging syncline with its long axis extending in a nearly north-south direction. A series of anticlinal arches form topographically subtle boundaries around much of the basin. These structures include the Hartville Uplift on the northwestern flank, the Chadron Arch on the northeastern flank, the Las Animas Arch on the southeastern flank, and the Apishapa Uplift on the southwestern flank. Along these arches, bedding generally dips gently toward the basin center, except where disrupted by local faulting or by small folds. The western basin margin is unlike the other basin margins in that it is marked by abrupt topographic relief and a major structural zone, the Front Range structural zone. This complex zone is up to 4 mi (6.4 km) wide and consists of basement-controlled, moderate-to high-angle reverse faults and monoclines. Many earth scientists believe the monoclines become faults at depth and that the entire structural zone is a single, complex fault zone at depth. Within the Front Range structural zone individual beds dip steeply eastward, locally are vertical or overturned, and may be offset up to 9,000 ft (2,700 m) by faulting. Two prominent structural lows mark the structural center or deepest parts of the basin (Figure 3), one near Denver and a second near Cheyenne. Elevation differences on the top of the Precambrian in these areas and in the mountains to the west indicate over 21,000 ft (6,300 m) of structural relief. Over 13,000 ft (3,900 m) of sedimentary basin-fill deposits are preserved in these deeper areas.

The Denver-Cheyenne Basin can and should be subdivided into two distinct smaller basins when coal, uranium, or ground water is studied. This practice, to the best of the authors' knowledge, was first used in the literature by Childers (1974) and later re-emphasized by Kirkham and Ladwig (1979). Figure 1 illustrates the outline of these two smaller basins, the Denver and Cheyenne Basins, as defined by the outcrop or subcrop of the Fox Hills Sandstone.

Justification for this subdivision into two smaller basins is based on several factors. Virtually all important coal and uranium deposits and most potable ground water are contained in the Fox Hills or younger formations and are within the two smaller basins. A structural high, the

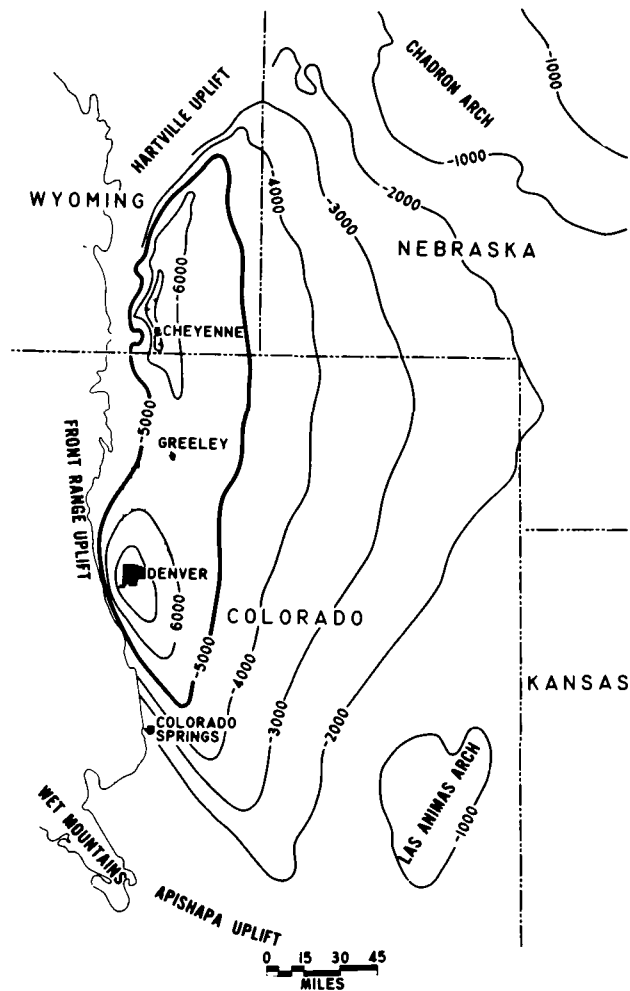


Figure 3. Structure contour map (in feet) on the top of the Precambrian surface in the Denver-Cheyenne Basin. (after Matuszcak, 1973)

Greeley Arch, separates the two basins. The Greeley Arch trends approximately east-west, has over 1,000 ft (300 m) of structural relief since the Late Cretaceous, and is a complex anticlinal structure which has smaller folds superimposed on it. Drillers' logs from water wells over the center of the arch suggest alluvial gravels overlies Pierre Shale, indicating the Laramie Formation and, at least locally, the Fox Hills Sandstone have been eroded off the arch.

The two basins also have major stratigraphic differences. Many of the Paleozoic and Mesozoic formations mappable throughout much of eastern

Wyoming extend into the Cheyenne Basin, but are not found south of the Greeley Arch in the Denver Basin. Several Cretaceous formations, especially the Niobrara Formation (Weimer, 1978), are influenced by the arch. Appreciable formational thinning and changes in sedimentological characteristics are common in certain formations. The Laramie Formation, an important coal- and uranium-bearing formation, is markedly different in both basins. An 1,800 to 4,700-ft (540 to 1,410-m) thick section of strata containing the Arapahoe Formation, Denver Formation, and Dawson Arkose occurs in the Denver Basin, but is apparently absent from the Cheyenne Basin.

Both basins are oval shaped with their long axes approximately north-south. The deepest part of the Denver Basin is southeast of Denver near Cherry Creek Reservoir, and the deepest part of the Cheyenne Basin is near Cheyenne, Wyoming. In both areas the top of the Precambrian surface is over 7,000 ft (2,100 m) below sea level. The overall structure of the two basins is similar, but structural details, especially on the western basin margin, are quite different.

Figure 4 is a generalized north-south cross section through the study area. In this view the Denver Basin appears symmetrical and only the southern flank of the Cheyenne Basin is shown. The structural high between the two basins is the Greeley Arch. Note the Laramie and Fox Hills have been eroded off the arch. A generalized east-west cross section through the Denver Basin at about the latitude of Golden is illustrated in Figure 5. The asymmetrical character of the basin is obvious in this view. The Golden Fault dominates the structure on the western basin margin at this location. Sediments on the west side of the fault dip 30° to 35° east, whereas sediments directly on the east side of the fault are often vertical or overturned. Much of the western basin margin, especially the area from just south of Boulder to near Monument, is similar to that shown in Figure 5. From Boulder north, the structural zone is dominated by complex, basement-controlled faulting that is expressed in the sedimentary section by sharp folding (Matthews, 1976). The Ute Pass fault, widely believed to be a low-angle (approximately 40° to 60°), west-dipping, reverse fault, is the main structural feature of the western basin margin near Colorado Springs.

On the southern, eastern, and northern margins of the Denver Basin, beds dip gently towards the structural center of the basin and are only locally deformed by small folds and faults. Dips ranging from less than 1/2° to about 3° are common in these areas and on the southern and eastern flanks of the Cheyenne Basin. The eastern margin of the Cheyenne Basin is only approximately located through subsurface studies. A major angular unconformity truncates the Laramie and Fox Hills in this basin, but surface exposures of this erosional feature are rare.

Major faults are not common outside of the Front Range structural zone. The only other area which has numerous large faults is along the northwest flank of the Denver Basin (Figures 6 and 7). Seismic and stratigraphic studies by Davis and Weimer (1976) suggest part of these faults are basement-controlled while others are listric growth faults

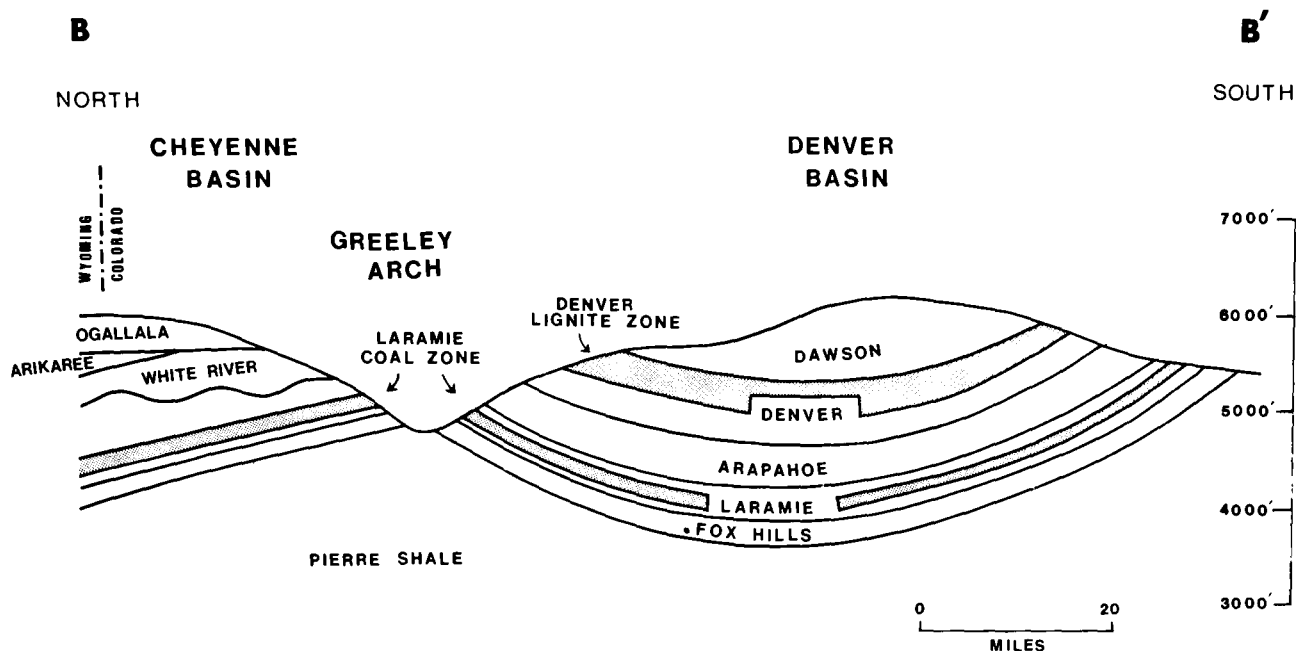


Figure 4. Generalized north-south cross section through the Denver Basin and the south flank of the Cheyenne Basin showing the Pierre Shale and younger formations. (after Kirkham and Ladwig, 1979)

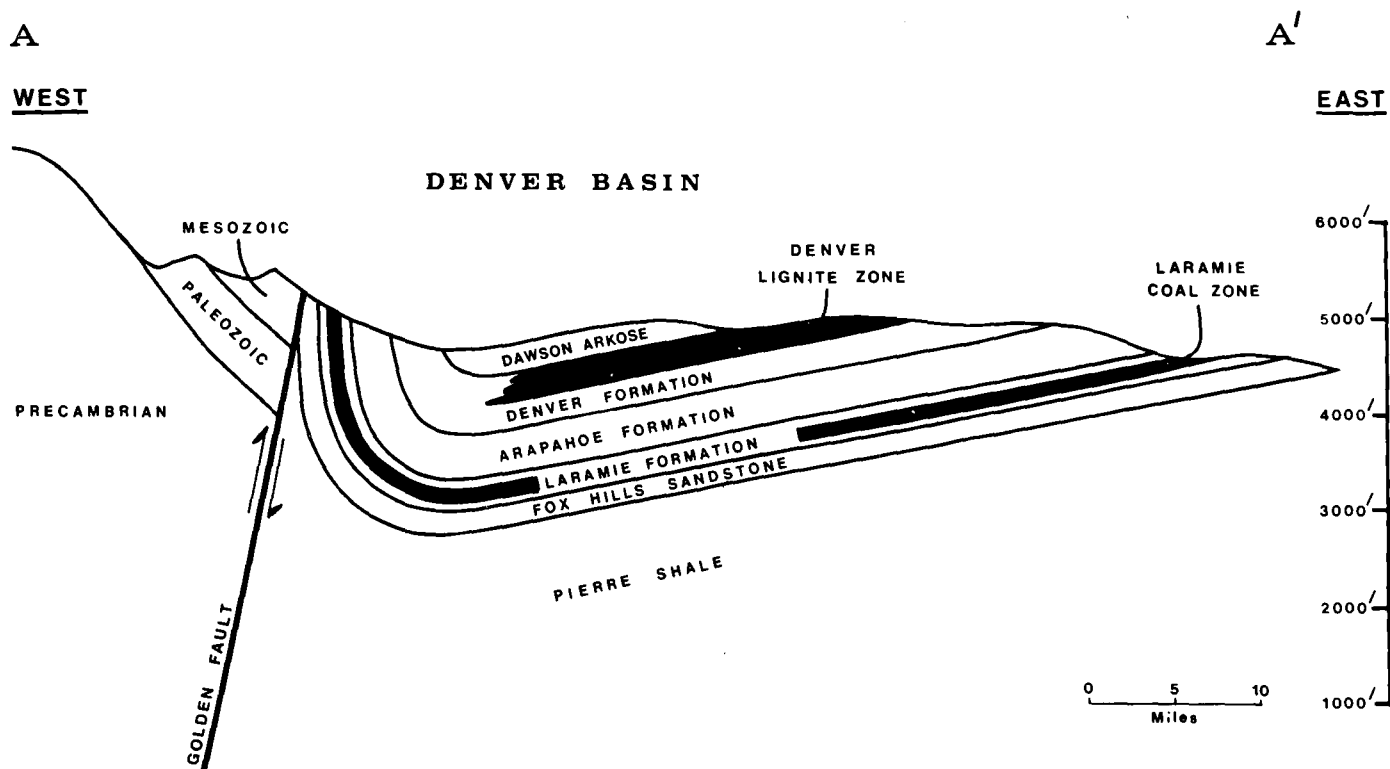


Figure 5. Generalized east-west cross section through the Denver Basin showing the Pierre Shale and younger Formations. (from Kirkham and Ladwig, 1979)

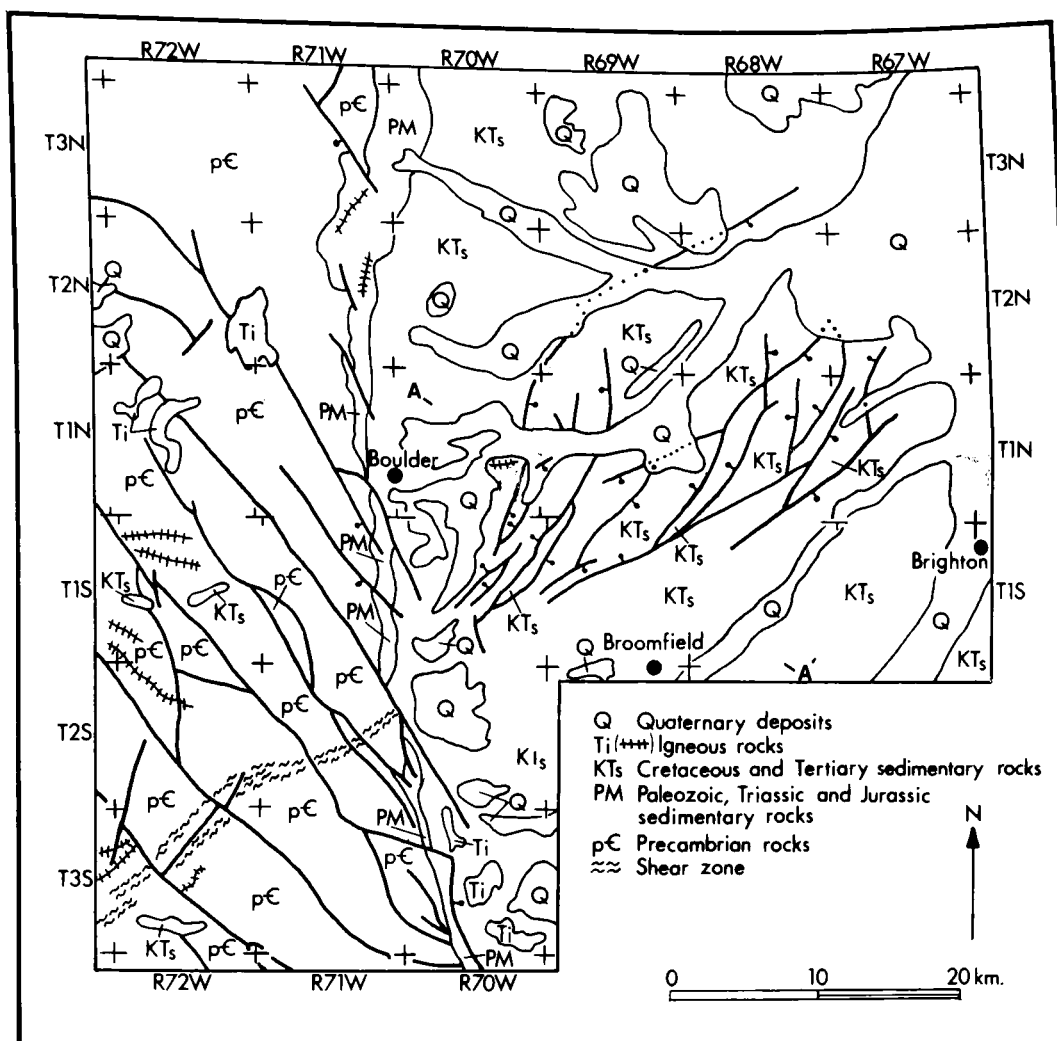


Figure 6. Generalized map showing the larger faults along the northwest flank of the Denver Basin in the Boulder-Weld coal field. (after Kirkham and Rogers, 1978)

which die out in the Pierre Shale. Tectonic faults in this area generally are high-angle normal at the surface and form a series of horst and graben blocks with individual fault displacements ranging up to about 300 ft (90 m). We have also observed several small-displacement, high-angle reverse faults in outcrops in the West Bijou Creek area. They are especially common along Station Gulch, where a lignite bed exposed along the creek is repeatedly offset a maximum of about 3 ft (0.9 m) by several reverse faults. The orientation and relation to underlying lignite beds suggest the faults are related to sediment deformation due to compaction and lithification. Similar small displacement faults may also be common in other areas.

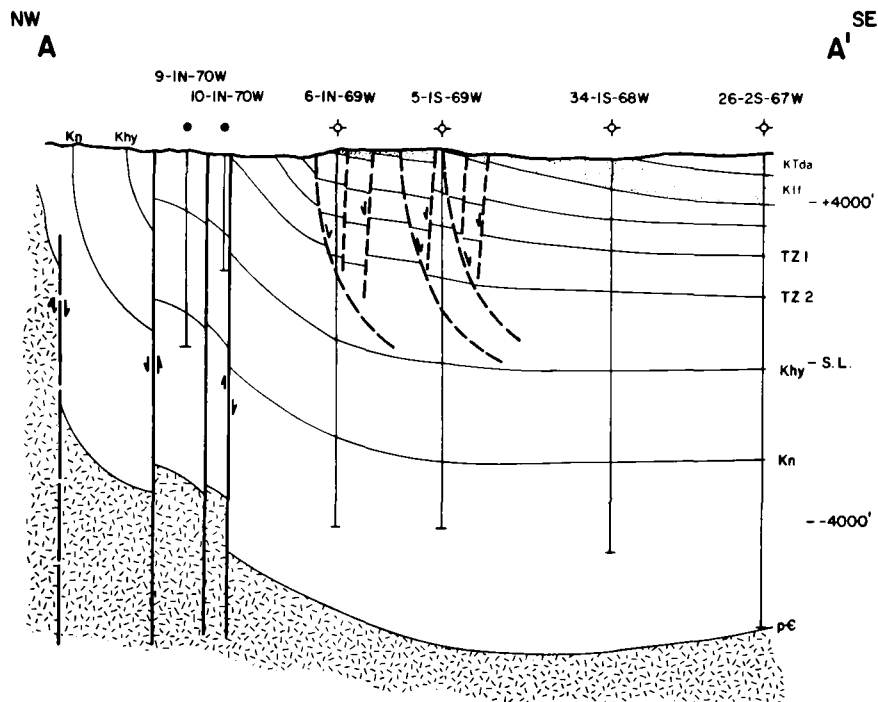


Figure 7. Northwest-southeast structure section through the Boulder-Weld coal field showing high-angle normal and listric faults. (from Davis and Weimer, 1976)

BEDROCK STRATIGRAPHY

Up to 14,000 ft (4,200 m) of consolidated and unconsolidated sediments fill the deepest parts of the Denver and Cheyenne Basins. These deposits range in age from Cambrian to Holocene and are underlain by Precambrian igneous and metamorphic rocks. Only the consolidated, pre-Quaternary sedimentary rocks are described in this report. Unconsolidated, Quaternary sedimentary deposits are important to energy resources for a variety of reasons, but they are not discussed in detail in this section. Potential water-producing Quaternary aquifers are briefly described in a later section on surface water and alluvial aquifers.

Lower Paleozoic Rocks

Lower Paleozoic rocks occur only to a limited extent in the study area. Because of their limited distribution, they will be only briefly described. The only surface exposures of lower Paleozoic rocks are found near Colorado Springs and immediately to the north. In this area the

Upper Cambrian Sawatch Sandstone, the oldest sedimentary formation in the study area, lies unconformably on Precambrian igneous and metamorphic rocks. The Sawatch Sandstone is overlain, in ascending order, by the Upper Cambrian Peerless Dolomite, Lower Ordovician Manitou Limestone, Middle Ordovician Harding Sandstone, Mississippian (Devonian?) Williams Canyon Limestone, and Mississippian Leadville Limestone. Total thickness of the lower Paleozoic section near Colorado Springs ranges from about 200 to 450 ft (60 to 124 m). These rocks do not extend very far northward along the outcrop from this area, and their eastward extent into the subsurface is uncertain. None of these rocks contain economically significant energy deposits in the Colorado Springs area. It is possible that the Mississippian oil- and gas-producing formations in Kansas and southeastern Colorado extend into the southeasternmost part of the study area, but the authors are not aware of any published information which document the presence or stratigraphy of these rocks in the subsurface within the study area.

Pennsylvanian, Permian, Triassic, and Jurassic rocks

In the Colorado Springs area the lower Paleozoic rocks are overlain by the Permian and Pennsylvanian Fountain Formation. To the north, near Denver and in the Cheyenne Basin, the Fountain Formation rests on a major unconformity cut on Precambrian rock. The formation was deposited in a bajada complex adjacent to the "Ancestral Rocky Mountains" (Mallory, 1972), an actively rising complex of mountains west of the study area. It consists of reddish-brown arkosic conglomerate, yellowish-gray arkosic sandstone, and interbedded thin layers of light green and reddish-brown shale and ranges from 800 to 4,400-ft (240 to 1,320-m) thick. Thickest accumulations of the Fountain occur in the Colorado Springs area. The lower 100 ft (30 m) of the formation includes the Glen Eyrie Shale member. Excellent outcrops of the Fountain Formation are exposed at the Garden of the Gods, Perry Park, Roxborough Park, Red Rocks Park, and Flatirons near Boulder. The Fountain Formation is roughly equivalent to the Casper Formation found in Wyoming.

In the western part of the Cheyenne Basin the Lower Permian Ingleside Formation overlies the Fountain Formation (Braddock and Cole, 1978). Gray-white sandstone and crinoidal limestone beds characterize the 100 to 130-ft (30 to 39-m) thick Ingleside Formation. In the Denver Basin the Fountain is overlain by the Permian Lyons Sandstone, a white to red, fine- to medium-grained, quartzose sandstone with local conglomerate, siltstone, and mudstone (Romero, 1976; Braddock and Cole, 1978; Bryant and others, 1978). The Lyons overlies the Ingleside in the Cheyenne Basin. Thickness of the Lyons Sandstone ranges from about 30 ft (9 m) near Golden to 800 ft (240 m) near Colorado Springs (Romero, 1976; Scott and Wobus, 1973). Detailed studies by Walker and Harms (1972) and Weimer and Land (1972) suggest the depositional environment of the Lyons varies geographically. An eolian origin can be demonstrated for the flagstone beds of the Lyons in Boulder County, whereas in part of Jefferson County the Lyons was deposited in a fluvial environment. The Lyons Sandstone is one of the major oil-bearing formations in the study area and has produced about 21 million barrels of oil or about 10 percent of the total oil production in the study area.

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

Several Permian, Triassic, and Jurassic formations occur in the Cheyenne Basin, but not the Denver Basin. They include the Lower Permian Satanka Formation, Upper Permian Forelle Limestone, Upper Triassic Jelm Formation, Triassic Chugwater Formation, and Upper and Middle Jurassic Sundance Formation (Braddock and Cole, 1978). The Satanka is a 100 to 300-ft (30 to 90-m) thick unit composed of red-brown marine mudstone, siltstone, and minor sandstone, limestone, and gypsum. The Forelle Limestone is a reddish, dolomitic, marine limestone interbedded with thin, red mudstone and gypsum. The formation is about 20-ft (6-m) thick and is only found north of Lyons. Buff-red, cross-bedded, arkosic, continental sandstone characterize the 200-ft (60-m) thick Jelm Formation. The Chugwater Formation ranges in thickness from 300 to 800 ft (90 to 240 m) and primarily consists of red sandstone, siltstone, and shale, and locally contains gypsum. Buff, eolian sandstone ranging from 100 to 200-ft (30 to 60-m) thick characterizes the Sundance Formation.

In the Denver Basin the Upper Jurassic Ralston Creek Formation overlies the Lykins Formation. It rests on a regional unconformity, consists of varicolored limestone, claystone, and gypsum interbedded with thin beds of sandstone, and is 2 to 110-ft (0.6 to 33.0-m) thick (Romero, 1976; Bryant and others, 1978). The Upper Jurassic Morrison Formation overlies the Ralston Creek Formation in the Denver Basin and the Sundance Formation in the Cheyenne Basin. Locally the Morrison may unconformably rest on older rocks. It consists of varicolored, continental shale, siltstone, and claystone, and may be interbedded with thin beds of sandstone, limestone, and conglomerate. Formation thickness ranges from about 200 ft (60 m) in the Colorado Springs area to about 400 ft (120 m) near Kassler (Romero, 1976). The formation crops out just west of the Dakota hogback and comprises the lower part of the "geologic point-of-interest" at the I-70 roadcut. In most areas, however, outcrops are covered by colluvial, debris-flow, sheetwash, and landslide deposits.

Lower Cretaceous Rocks

Early Cretaceous time in the study area was characterized by a complex sequence of beach, delta, and near-shore marine sediments deposited over the continental Morrison Formation in a transgressing seaway. These rocks are included in the Lower Cretaceous Dakota Group. Early workers who studied outcrops divided the Dakota Group into two units. Recent study of geophysical logs from oil and gas drill holes indicate the group is much more complex than outcrop data suggest.

The two units defined by surface studies in the Denver area are the Lytle Formation and overlying South Platte Formation. The Lytle is 30 to 100-ft (9 to 30-m) thick and composed of yellowish-gray, fine- to medium-grained, locally conglomeratic sandstone. The South Platte Formation consists of 200 to 350 ft (60 to 105 m) of interbedded fine- to medium-grained gray sandstone and dark gray, silty shale. In the Colorado Springs area, Scott and Wobus (1973) and Scott and others (1976) divide the Dakota Group into the Dakota Sandstone (upper part) and Purgatoire Formation (lower part).

Subsurface stratigraphic studies related to petroleum exploration reveal a somewhat different stratigraphy. Haun (1963) divides the Dakota Group into a sequence of individually named shales and sandstones which thicken, thin, pinch-out, and split laterally. Major Dakota sandstone units in the study area are the D and J Sandstone members. These are separated by the Huntsman or Mowry Shale. The J Sandstone is believed to correlate in part with the Muddy Sandstone of Wyoming. The Colorado Oil and Gas Conservation Commission (1979) apply the Muddy Sandstone nomenclature to some of the oil and gas producing sands in the northern part of the study area. The D, J, and Muddy Sandstones collectively have produced about 75 percent of the oil and 83 percent of the gas from the entire study area. The lowermost sand in the Dakota Group, the Lakota Sandstone, is in part equivalent to the Cloverly Formation or Cheyenne Sandstone of adjoining areas. It is separated from the J Sandstone by the Skull Creek Shale. Waage (1961) and Weimer (1960) believe the Lakota Formation and Lytle Formation are equivalent, and the D and J Sandstones, respectively, correlate with the upper and lower members of the South Platte Formation.

The Dakota Group forms a prominent, linear, topographic high, the Dakota hogback, along the entire western flank of the Denver-Cheyenne Basin, except where it has been cut out by faulting. Generally the South Platte Formation forms the crest and dip slope of the hogback, and the Lytle is exposed west of the hogback crest and in road cuts and water gaps.

In some parts of Colorado, for instance the San Juan Region (Landis, 1959), the Dakota Group contains economic coal deposits. In the study area, however, Dakota coal beds are thin, very lenticular, generally very deep, and are not economically important. Uranium is known to occur in the Dakota Group, and a small quantity was mined from the formation during the 1950s. Most deposits are extremely small and the potential for future discovery of significant deposits is low.

Upper Cretaceous Rocks

The Upper Cretaceous Colorado Group conformably overlies the Dakota Group throughout the study area. It consists of the Benton Shale (lower part) and Niobrara Formation (upper part). The Benton Shale is 300 to 500-ft (90 to 150-m) thick and composed of dark gray, marine shale and interbedded limestone, bentonite, and calcarenite (Romero, 1976; Van Horn, 1976). Bentonite layers serve as excellent time lines in this part of the

stratigraphic section. Locally the Benton Shale can be subdivided into three members, the Graneros Shale (lower), Greenhorn Limestone (middle), and Carlile Shale (upper). Recognition of these three members depends on the presence of the Greenhorn Limestone. The Codell Sandstone, an oil-bearing sandstone generally less than 10-ft (3-m) thick, is included in the upper part of the Carlile Shale.

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

The marine Pierre Shale conformably overlies the Colorado Group. It consists of 3,750 to 7,833 ft (1,125 to 2,350 m) of shale with interbedded siltstone, sandstone, bentonite, and thin, lenticular limestone. Nolte (1963) divides the Pierre into four units, which, in ascending order, are the Rusty, Sharon Springs, Hygiene, and Transition Zones (Figure 8, left side). The Hygiene Zone, approximately equivalent to the Mesaverde Group (Weimer, 1960), can be further subdivided into the Richard, Larimer, Rocky Ridge, Terry, and Hygiene Sandstone members. In most of the study area, the Larimer and Rocky Ridge members apparently merge into one unit. Field terminology used by oil and gas operators for these sandstone units is, in descending order, the Teapot, Parkman, Sussex, and Shannon Sandstone members.

Kitely (1976, 1978) developed a somewhat different nomenclature for the Pierre Shale. It is shown on the left side of Figure 8. Major changes involve 1) eliminating the use of the Hygiene Zone and granting equal rank to the sandstone units formerly within the Hygiene Zone, 2) recognizing and naming several sandy units within the Transition Zone and a shale unit between the Sharon Springs and Hygiene members, and 3) changing the name of the Rusty Zone to the Gammon Ferruginous member. Kitely (1976) also discourages the use of field terms (Teapot, Parkman, Sussex, and Shannon) because of apparent age differences between the so named units in the type area and in the Denver-Cheyenne Basin.

Over 10 percent of the oil and gas produced in the study area is from the Sussex and Shannon (or Terry and Hygiene) Sandstone members of the Hygiene Zone of the Pierre Shale. A few thin coal beds are reported in the Transition Zone of the Pierre Shale in some parts of Colorado, but none are of economic significance in the study area.

Figure 9 is a regional stratigraphic column of the Pierre Shale and younger formations in the Denver and Cheyenne Basins. Figure 10 illustrates the typical geophysical response of uppermost Cretaceous and

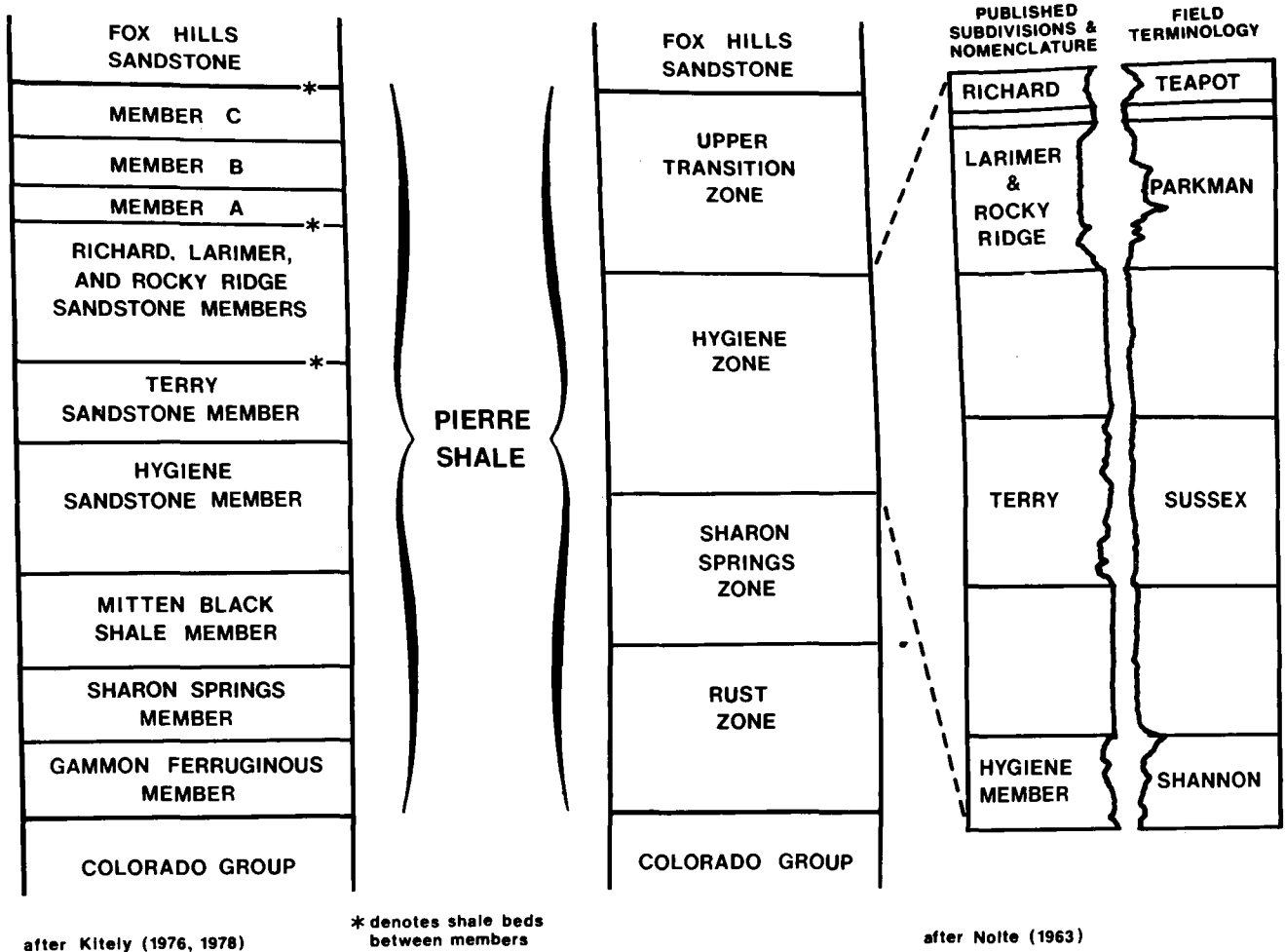


Figure 8. General stratigraphic relationships of the members of the Pierre Shale.

lower Tertiary rocks on petroleum exploration drill hole logs in the Denver Basin. The logged interval begins in the upper part of the Transition Zone of the Pierre Shale and continues upward through the Fox Hills Sandstone, Laramie Formation, Arapahoe Formation, Denver Formation, and into basal Dawson Arkose. Figure 11 is a geophysical log that illustrates the response of part of the stratigraphic units in the Cheyenne Basin. This log begins near the top of the Pierre Transition Zone, extends through the Fox Hills Sandstone and Laramie Formation, and terminates in the lower part of the White River Group. These logs and indicated stratigraphic picks are representative of the stratigraphic characteristics and formational boundaries used in this investigation.

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

Figure 9. Generalized regional stratigraphy of the uppermost Cretaceous and younger formations in the Denver and Cheyenne Basins, Colorado. (after Kirkham and Ladwig, 1979)

The marine Upper Cretaceous Fox Hills Sandstone conformably overlies the Transition Zone of the Pierre Shale. The contact between the two formations is not always sharply defined and in many areas it is transitional. Generally, the contact is picked at the base of the first upward-coarsening sandstone sequence overlying the dominantly shale section of the Pierre. Formation thickness ranges from about 25 to 450 ft (7.5 to 135.0 m). Thick sandstone beds and interbedded shales characterize the Fox Hills, and thin, carbonate-rich units occasionally cap the formation. Individual sandstone beds usually coarsen upwards or are uniformly graded, but fining-upward beds are occasionally present. In the Denver Basin most sandstone units within the Fox Hills coarsen upwards, although uniformly graded and fining-upward sandstones do locally occur. In the Cheyenne Basin the Fox Hills can be divided into an upper and lower member (Ethridge and others, 1979; Kirkham and others, 1980). The lower member contains three to seven upward-coarsening sandstone beds overlain by zero to five massive sandstones in the upper member. The massive sandstones appear "blocky" on geophysical logs. Lenticular, iron-rich concretions are common in the upper member of the Fox Hills (Wacinski, 1979).

Brownlie, Wallace, Armstrong,
and Bander
Rampart Range No. 1
SE SE sec. 13 T6S R67W

Clark — Canadian Exploration
Company
Seidensticker No. 1
NE NE sec. 32 T8S R66W

National Associated Petroleum
Company
1 State
NE NW SE sec. 36 T9S R66W

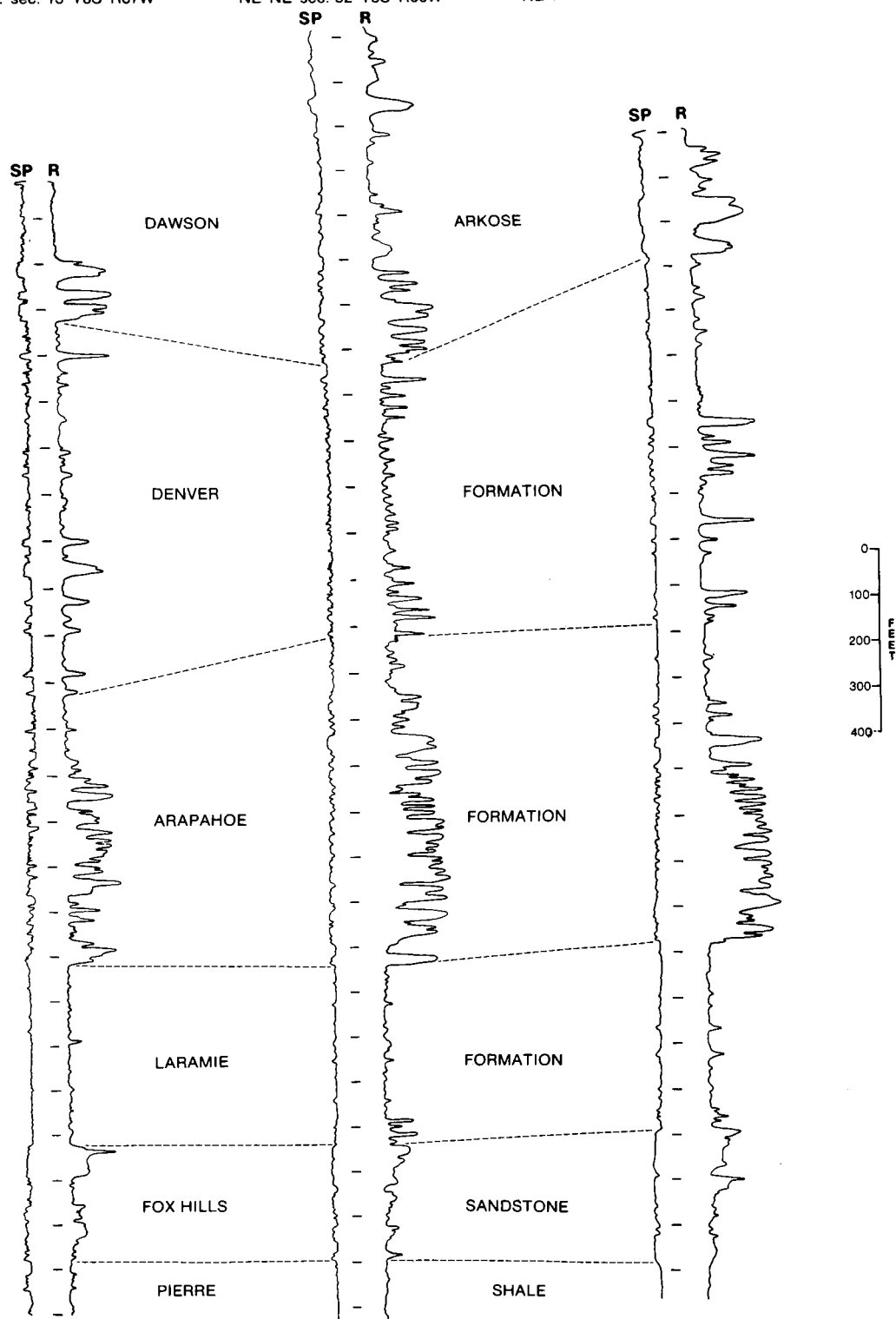


Figure 10. Geophysical logs of petroleum drill holes that illustrate typical geophysical responses and stratigraphic characteristics of uppermost Cretaceous and lower Tertiary formations in the Denver Basin. (from Kirkham and Ladwig, 1979)

Amoco Production Company
Champlin 279 A No.1
NE NW sec. 27 T12N R66W

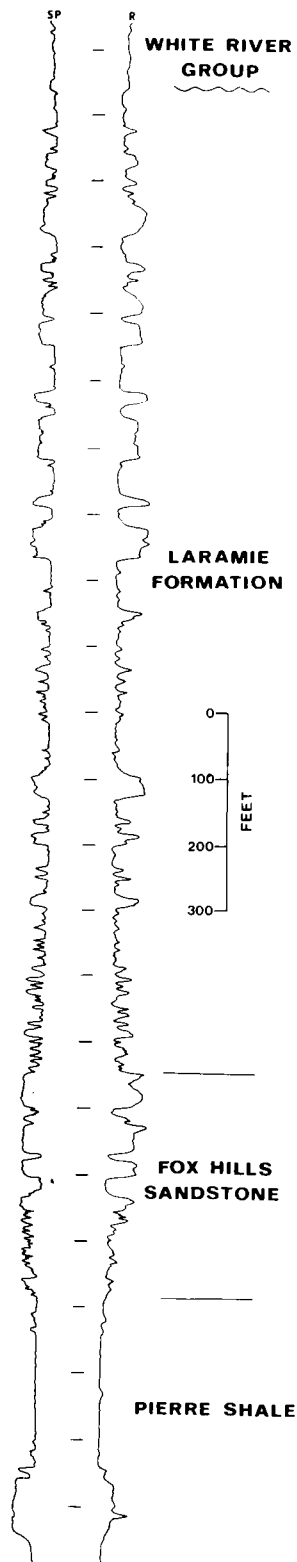


Figure 11. Geophysical log of a petroleum drill hole showing general stratigraphic characteristics and formation boundaries of uppermost Cretaceous and middle Tertiary formations in the Cheyenne Basin, Colorado. (from Kirkham and others, 1980)

Weimer (1973) suggests the Fox Hills in the Golden-Boulder area of the Denver Basin was deposited in a delta-front environment. Reconnaissance studies throughout the Denver Basin conducted during this investigation indicate the Fox Hills was deposited in both delta-front and barrier bar systems, although the barrier bar system is only present in some areas. Regional stratigraphic studies by Ethridge and others (1979) in the Cheyenne Basin and local studies by Shepard and Summer (1979) suggest the sequence of upward-coarsening sandstones in the lower Fox Hills were deposited in a wave-dominated delta-front system and that the massive sandstones of the upper Fox Hills were deposited in a barrier bar system. Local studies in the Cheyenne Basin by Kirkham and others (1980) support the subdivision of the Fox Hills into two units in this basin and generally agree with depositional environments proposed by Ethridge and others (1979) and Shepard and Summers (1979).

Thin, lenticular coal beds are reported within the upper part of the Fox Hills in the Denver Basin (Trimble, 1975; Zawistowski, 1978, pers. comm.), but none are of economic importance. Several economically important uranium roll-front deposits occur in the upper member of the Fox Hills in the Cheyenne Basin. One of these, the Keota deposit, is scheduled to be mined using in situ solution mining techniques. Small oil and gas shows are reported from the Fox Hills in the deeper parts of the Denver Basin, but it is unlikely the formation will ever produce petroleum on a commercial scale in the study area.

The Fox Hills Sandstone is a key stratigraphic horizon related to energy resources in the Denver and Cheyenne Basins, Colorado. Virtually all coal, lignite, and uranium of economic importance and most potable water are within the Fox Hills and younger formations. The only major energy resources within older formations are oil and gas.

The non-marine, Upper Cretaceous Laramie Formation overlies the Fox Hills Sandstone. For this investigation the contact between the two formations is placed at the top of the uppermost, thick, marine sandstone in the Fox Hills, just below the coal, claystone, and thin sandstone beds of the lower Laramie. In some locations a thin coal bed rests directly on the top of the uppermost thick sandstone in the Fox Hills. This coal bed is included in the Laramie. The Laramie Formation typically consists of interbedded, brackish-water and fluvial beds of shale, claystone, coal, and fining-upward sandstone. There appear to be major differences in the Laramie between the two basins. In many ways the Laramie Formation in the Cheyenne Basin more closely resembles the Lance Formation of Wyoming than the Laramie Formation of the Denver Basin. Further detailed stratigraphic studies may conclude that the Laramie Formation terminology should be used only in the Denver Basin and that Lance Formation terminology should be applied in the Cheyenne Basin.

In the Denver Basin the Laramie Formation often can be divided into two members which range in combined thickness from 350 to 700 ft (105 to 210 m). The lower part is 50 to 275-ft (15.0 to 82.5-m) thick and predominantly is shale, claystone, coal, and lenticular, channel sandstone. The top of the lower Laramie is defined by Kirkham and Ladwig

(1979) as the top of the uppermost coal bed in the lower part of the formation. The lower Laramie coal zone thus generally corresponds to the lower member of the Laramie Formation.

Some workers have named the lower Laramie sandstones in the Denver Basin the A, B, and C sandstones. These units should not be confused with the A, B, and C sandstones described in the Pierre Shale by Kitley (1976, 1978). The lower Laramie sandstones are very lenticular, and our work suggests these names should only be used locally where they were first described, unless a definitive correlation can be made by study of closely spaced drill holes and outcrop data. The upper member of the Laramie Formation in the Denver Basin is 250 to 600-ft (75 to 180-m) thick and consists primarily of shale, claystone, and siltstone, with only very minor amounts of sandstone.

In the Cheyenne Basin the entire Laramie Formation, where preserved intact, is as much as 1,600 to 1,800-ft (480 to 540-m) thick. In general the Laramie contains fewer and thinner coal beds and more and thicker sandstone beds in the Cheyenne Basin than the Denver Basin. Numerous 10 to 125-ft (3.0 to 37.5-m) thick sandstones occur throughout the Laramie and are especially common in the upper two-thirds of the formation. Several of the thicker and laterally persistent sandstones have been informally named by the uranium industry. They include the Grover, Porter Creek, and Sand Creek Sandstone members.

Most workers believe the Laramie is dominantly a fluvial deposit. Weimer (1973) and Kirkham and Ladwig (1979) indicate that a delta-plain model best fits the Laramie of the Denver Basin. Ethridge and others (1979) suggest delta-plain sedimentation was responsible for the lower part of the Laramie in the Cheyenne Basin, whereas the upper part of the formation was probably deposited in a lower alluvial plain environment. There is some evidence for a minor transgression of the Cretaceous seaway during deposition of the Laramie. The Grover Sandstone member of the Laramie may have been deposited in a marine bar or beach environment (Childers, 1979, pers. comm.; Krukar, 1980, pers. comm.)

Initiation of the Laramide orogeny and regression of the Cretaceous seas are recorded in the upper Pierre Shale Transition Zone, Fox Hills Sandstone, and Laramie Formation. Orogenic activity continued during deposition of the Arapahoe Formation, Denver Formation, and Dawson Arkose. Weimer (1973) developed a delta-sedimentation model to relate the regressing Cretaceous seaway to the sediments preserved in the Denver Basin (Figure 12). The uppermost part of the Pierre shale was deposited in an off-shore, deep-marine environment. As regional uplift began and the sea regressed, an extensive deltaic system developed, and extended into the marine environment. Sediments were eroded from the highlands, which some authors propose was the Sawatch Anticline, transported downstream, and redeposited in delta-front, delta-plain, and barrier bar systems. The Fox Hills was deposited in delta-front and barrier bar environments, and the Laramie was deposited in a delta-plain environment. These depositional conditions persisted until continental sedimentation in meandering and braided streams and in flood basins became dominant.

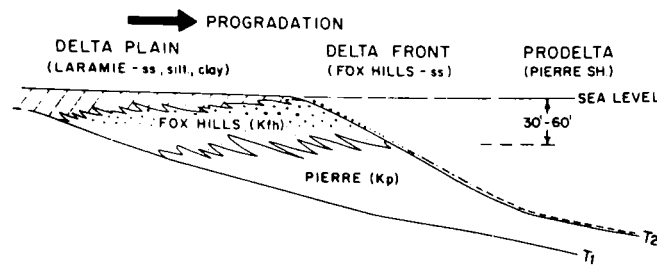


Figure 12. Delta-sedimentation model that relates the regression of the Late Cretaceous seaway to the facies and depositional environments of the Denver Basin. (from Weimer, 1973)

As shown in Figure 9 the depositional histories of the Denver and Cheyenne Basins are markedly different. In the Denver Basin the Upper Cretaceous Arapahoe Formation, Upper Cretaceous-Paleocene Denver Formation, and Eocene Dawson Arkose overlie the Laramie Formation. In the Cheyenne Basin the Oligocene White River Group, Miocene Arikaree Formation, and Miocene Ogallala Formation were deposited over a major unconformity or series of unconformities cut on the Laramie Formation. Several possible explanations have been proposed for the apparent missing section of Upper Cretaceous, Paleocene, and Eocene rocks and the anomalous thickness change in the Laramie Formation. They have been in part discussed by Kirkham and others (1980) and will not be restated or further discussed in this report.

The Arapahoe Formation overlies the Laramie Formation in the Denver Basin. It is 200 to 1,000-ft (60 to 300-m) thick and averages about 600-ft (180-m) thick. Basal Arapahoe near the mountain front is very coarse, often containing thick sequences of interbedded, chert-rich conglomerate and sandstone, as indicated on the geophysical log in Figure 10. The upper part of the Arapahoe is usually much finer-grained, typically consisting of claystone, siltstone, and thin, fine-grained sandstone. The overall geometry of the unit is that of a wedge deposit. The formation is thickest along the mountain front and thins eastward and southward. Textures also generally become finer-grained to the east. Formation characteristics suggest the Arapahoe was deposited in a bajada complex near the mountain front and grades eastward into a meandering stream environment. The Arapahoe-Laramie contact is readily apparent on geophysical logs in the western part of the basin, as shown in Figure 10, but it is difficult to determine the contact in the eastern part of the area due to the fine-grained textures of both formations.

Cenozoic Rocks

The Upper Cretaceous-Paleocene Denver Formation overlies the Arapahoe Formation in the Denver Basin. The Cretaceous-Tertiary boundary has been recognized paleontologically on South Table Mountain (Brown, 1943) and near the intersection of Broadway and County Line Road by Middleton (1980, pers. comm.). Palynology may be beneficial to help establish the Mesozoic-Cenozoic boundary within the Denver Formation in areas where macro-fossils are absent.

Some workers (Richardson, 1915; Dane and Pierce, 1936; Scott, 1962, 1963; Scott and Wobus, 1973; Morse, 1979; Trimble and Machette, 1979) map the Arapahoe, Denver, and Dawson as one formation or at least as in part age-equivalent facies. Other workers (Reichert, 1956; Soister, 1972, 1978b; Romero, 1976, 1978b, pers. comm.; Soister and Tscudy, 1978; Kirkham and Ladwig, 1979) believe the formations are distinct stratigraphic formations that can and should be mapped throughout the area. In most areas formational boundaries can be recognized in outcrop and through regional subsurface studies using geophysical logs. Only in the southern and southeastern areas is it difficult to pinpoint contacts. One of the problems with picking formation contacts in these areas is a lack of reliable subsurface data and the virtual absence of outcrops.

In general the Denver Formation consists of 600 to 1,580 ft (180 to 474 m) of medium-yellow to light-gray, olive, and gray-green claystone, siltstone, very fine- to medium-grained sandstone, andesitic conglomerate, and lignite. Several andesitic lava flows are interbedded with the upper Denver near Golden, and a dike of uncertain origin (Miller and others, 1979) cuts the Denver Formation at the Rocky Mountain Arsenal. The distinguishing characteristics of the Denver Formation are andesitic conglomerates, thick lignite beds and color. Andesitic conglomerates are common along the mountain front and thick lignite beds are prevalent in the upper 500 ft (150 m) of the formation in the eastern part of the basin. Emmons and others (1896) define the base of the Denver Formation by the first appearance of andesitic eruptive material in the sedimentary section. Unfortunately andesitic material is scarce on the east flank of the basin. The Denver-Arapahoe contact can only be defined by detailed regional, drill hole correlation in the eastern part of the basin, and in some areas it is still difficult to precisely assign a contact.

The top of the formation in the eastern part of the basin can be picked as the base of the first thick, arkosic sandstone or conglomerate above the uppermost lignite bed in the Denver lignite zone. This pick cannot be used in the central or western part of the basin because the lignite beds are either lower in the formation or are absent in this area. Morse (1979) suggests the change from andesitic to arkosic mineralogy should be used to establish the contact along the mountain front.

The Paleocene-Eocene Dawson Arkose unconformably overlies the Denver Formation. Soister (1978b) divides the Dawson into a lower and upper member. The lower member is a mixed unit, 200 to 400-ft (60 to 120-m) thick, containing both andesitic and arkosic material ranging from

claystone to conglomerate. Usually, the base is marked by a 10 to 20-ft (3 to 6-m) thick arkosic conglomerate. Soister (1978b) and Soister and Tscudy (1978) describe thin, non-economic lignite beds in the lower member of the Dawson. Pollen samples from the lower member are Late Paleocene in age (Soister and Tscudy, 1978).

Varicolored claystone and deeply weathered sandstone and conglomerate cap the lower member. Good exposures of this interval can be seen in the clay pit in SE 1/4 SW 1/4 sec. 14, T6S, R66W near Parker. Soister (1978b) believes this weathered horizon is a paleosol and represents a period of non-deposition in the basin during Late Paleocene and Early Eocene. The paleosol appears to rise within the Dawson westward. Morse (1979) describes a silcrete in the southern part of the Denver Basin which he correlates with the paleosol. In the east part of the basin the paleosol is near the base of the lower member of the Dawson, whereas in the west part of the basin there is as much as 330 ft (100 m) of lower Dawson between the paleosol and the top of the Denver Formation. Soister suggests the Green Mountain Conglomerate may be equivalent to the lower Dawson. Trimble (1978, pers. comm.) believes the paleosol may possibly be equivalent to the Eocene paleosol described by Pettyjohn (1966) in South Dakota, Wyoming, and Nebraska.

Above the paleosol is the 800 to 1,400-ft (240 to 420-m) thick upper member or main body of the Dawson. It is 70 to 90 percent arkosic sandstone and conglomerate interbedded with 10 to 30 percent sandy claystone (Soister, 1978b). Pollen analyses and regional correlations suggest the upper member is of Eocene age (Soister and Tscudy, 1978).

The Arapahoe Formation, Denver Formation, and Dawson Arkose in part record the middle and late episodes of the Laramide orogeny. Sedimentological characteristics of the Arapahoe suggest a provenance of Paleozoic and Precambrian rocks either within the Front Range or perhaps from as far as the Sawatch Range. Along the mountain front the Denver Formation consists of andesitic units ranging from conglomerate to mudstone. Morse (1979) suggests the andesitic rocks in the Denver Formation in the southern part of the area were deposited in a point bar system of a major meandering stream whose source was far beyond the Front Range, possibly from near Salida (Epis and others, 1976). An alternate interpretation could involve uplift of the Front Range during Denver time with the andesitic material being eroded from volcanic flows preserved on the top of the uplifted Front Range block. This meandering system grades eastward into the flood-basin deposits that contain the thick lignite deposits of the Denver Formation.

Major uplift of the Front Range and accompanying erosion is suggested by the presence of coarse arkosic material in the Dawson Arkose derived from the Pikes Peak Granite and by the braided stream environment typical of the Dawson near the mountain. This braided system appears to grade into a meandering environment eastward (Morse, 1979). Extensive erosion of the Front Range occurred throughout Dawson time and by the late Eocene the uplifted block had been eroded to the general elevations of the adjoining basins. Major stream channels extending from South Park to the Denver Basin were cut on this surface.

A rhyolitic ash-flow tuff, locally called the Douglas Rhyolite, flowed down one or possibly more of these paleo-stream channels into the Castle Rock area. Epis and Chapin (1975) correlate the Douglas Rhyolite with the Oligocene Wall Mountain Tuff, which is believed to have erupted in the Mount Princeton area. The Castle Rock Conglomerate overlies the Wall Mountain Tuff and, where the tuff is absent, the Dawson Arkose. Clasts of Oligocene andesitic material from the Thirtynine Mile volcanic field are contained in the conglomerate and Oligocene mammals have been found in the formation (Robinson, 1980, pers. comm.). The Castle Rock Conglomerate consists of up to 300 ft (90 m) of andesitic conglomerate with individual clasts up to 4 ft (1.2 m) in diameter and arkosic and andesitic coarse sandstone.

In the Cheyenne Basin, the fluvial Oligocene White River Group overlies a major angular unconformity or series of unconformities cut on the Upper Cretaceous Laramie Formation, Fox Hills Sandstone, and Pierre Shale. The White River Group may, at least in part, correlate with the Castle Rock Conglomerate. The group contains two formations, the Upper and Middle Oligocene Brule Formation and the Lower Oligocene Chadron Formation. Scott (1978) describes the Brule as 200 to 500-ft (60 to 150-m) thick and composed of light-colored, sandy or clayey, ashy siltstone. Lenticular channel sandstones or siltstones containing siltstone clasts and granitic gravel occur sporadically throughout the lower part of the formation. The Chadron consists of 100 to 250 ft (30 to 75 m) of predominantly clayey, blocky, ashy siltstone and montmorillonitic claystone (Scott, 1978). Channels of calcite- and silica-cemented sandstone and conglomerate which often occur at the base of the Chadron are scattered throughout the formation. These coarse-grained units are more common in the Chadron than in the Brule. Both the Chadron and the Brule contain thick, altered volcanic ash beds derived from volcanic centers to the west.

Unconformably overlying part of the White River Group is the fluvial Lower Miocene Arikaree Formation. In the study area the Arikaree occurs only to a limited extent as channel sandstones and conglomerates cut into the White River Group. Beyond the study area to the east and north, the Arikaree is more of a blanket-type deposit. The Arikaree was deposited in response to renewed uplift of the Southern Rocky Mountains during the early phase of a period of Neogene tectonic activity.

Continued, episodic tectonic activity resulted in deposition of the Miocene Ogallala Formation. It unconformably overlies the Arikaree and White River Group, and where these deposits are absent, it overlies the Laramie and older formations. The Ogallala is 50 to 600-ft (15 to 180-m) thick and consists primarily of conglomerate and sandstone beds interbedded with siltstone, limestone, and volcanic ash (Scott, 1978).

HYDROGEOLOGY

Surface Water And Alluvial Aquifers

Surface water supplies a major part of the water used for irrigation and municipal water systems in much of the Denver and Cheyenne Basins. The study area lies within two major drainage systems, the South Platte and the Arkansas (Figure 13). About 4/5 of the area is in the South Platte River drainage basin, and about 1/5 is in the drainage system of the Arkansas River. The headwaters of both drainage basins extend far beyond the study area to the Continental Divide. Both drainage basins also continue far beyond the eastern limit of the study area and eventually empty into the Mississippi and Missouri River systems.

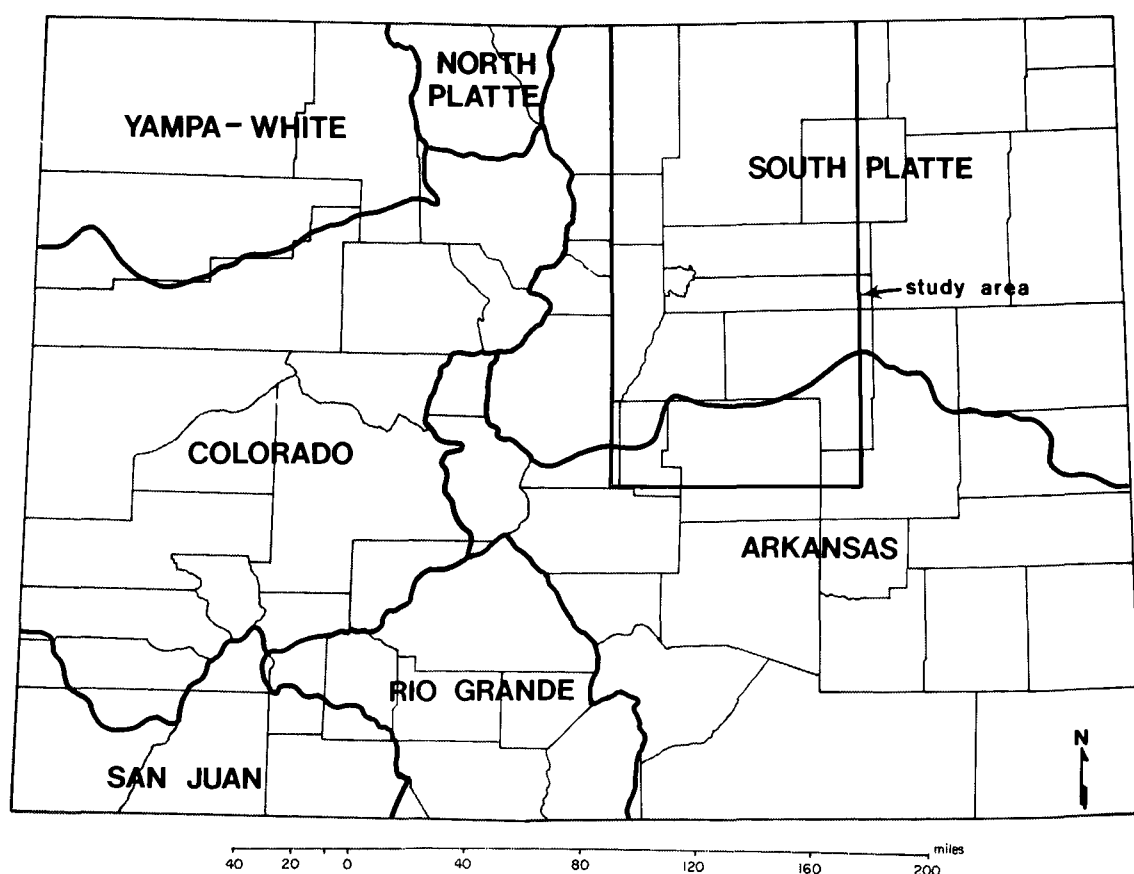


Figure 13. Major drainage basins of Colorado. (after Pearl, 1974)

Figure 14 illustrates major rivers, streams, and tributaries of the Denver and Cheyenne Basins. The alignment of individual stream courses is very interesting. The South Platte River enters the plains near Kessler, runs almost due north to Greeley, and then abruptly changes course and runs eastward, nearly paralleling the apparent axis of the Greeley Arch. Most tributaries of the South Platte in the central and eastern parts of the Denver Basin run nearly due north, while those in the Cheyenne Basin run south or southeast. In the southern part of the Denver Basin, creeks drain to the south or southeast toward the Arkansas River. The only exception is the anomalous route of Big Sandy Creek. It runs east-northeast to near the east edge of Elbert County separating the two groups of oriented drainage systems. At this point it makes an abrupt right-angle bend and then parallels the streams draining southeast towards the Arkansas.

Most perennial streams in the study area, such as Fountain, Deer, Bear, Clear, Boulder, and St. Vrain Creeks, and the South Platte, Big Thompson, and Cache la Poudre Rivers, originate in the mountains. Streams with headwaters in the plains are dominantly ephemeral, although short reaches of individual streams, particularly those which head in the Black Forest, may flow year-round.

The alluvial aquifers associated with modern streams are an integral part of the surface-water system. The ground water within alluvial aquifers is considered as part of the surface stream system by the Colorado State Engineer and is administered by the priority system of water rights. Figure 15 shows the distribution of "probable" and "possible" water-bearing, alluvial deposits (alluvial aquifers) in the study area. Probable alluvial aquifers include the Wisconsin age and younger alluvial deposits and possible alluvial aquifers include the pre-Wisconsin, Quaternary alluvial deposits shown by Tweto (1979). "Probable," as used in these definitions, means most designated deposits are alluvial aquifers. "Possible" means some of the deposits may be alluvial aquifers.

Many of the small, ephemeral streams in the area have deposited thick sequences of valley-fill alluvium. These deposits carry large volumes of water, even during the hot, dry, summer months. The authors have dug test pits into the bottom of several dry creek beds in August and have encountered fresh, alluvial water within 0.2 to 2.0 ft (0.06 to 0.6 m) of the surface.

A large region in the southeastern part of the study area is shown on Figure 15 to be underlain by possible alluvial aquifers. Older gravel deposits are known to occur extensively throughout this area, but in most places wind-blown sand blankets the surface. Much of the area covered by eolian sands is underlain by older gravels, as is indicated on Figure 15, but bedrock may underlie some areas within this designated region. Furthermore, little is known about hydrologic characteristics of these deposits. Detailed studies in these areas are needed to precisely ascertain the stratigraphy beneath the eolian sand and the ground-water potential.

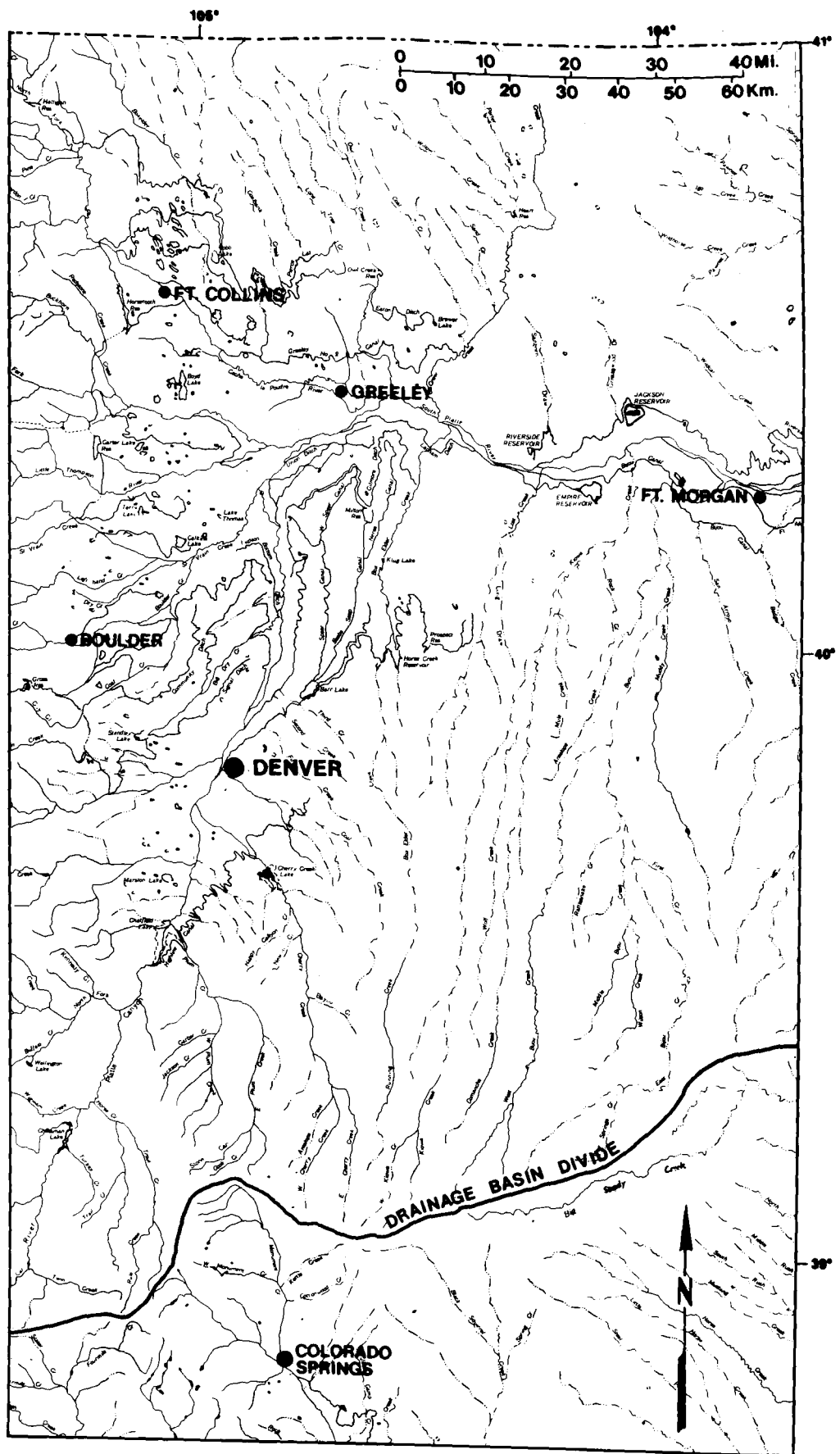


Figure 14. Rivers, streams, and tributaries of the Denver and Cheyenne Basins, Colorado.

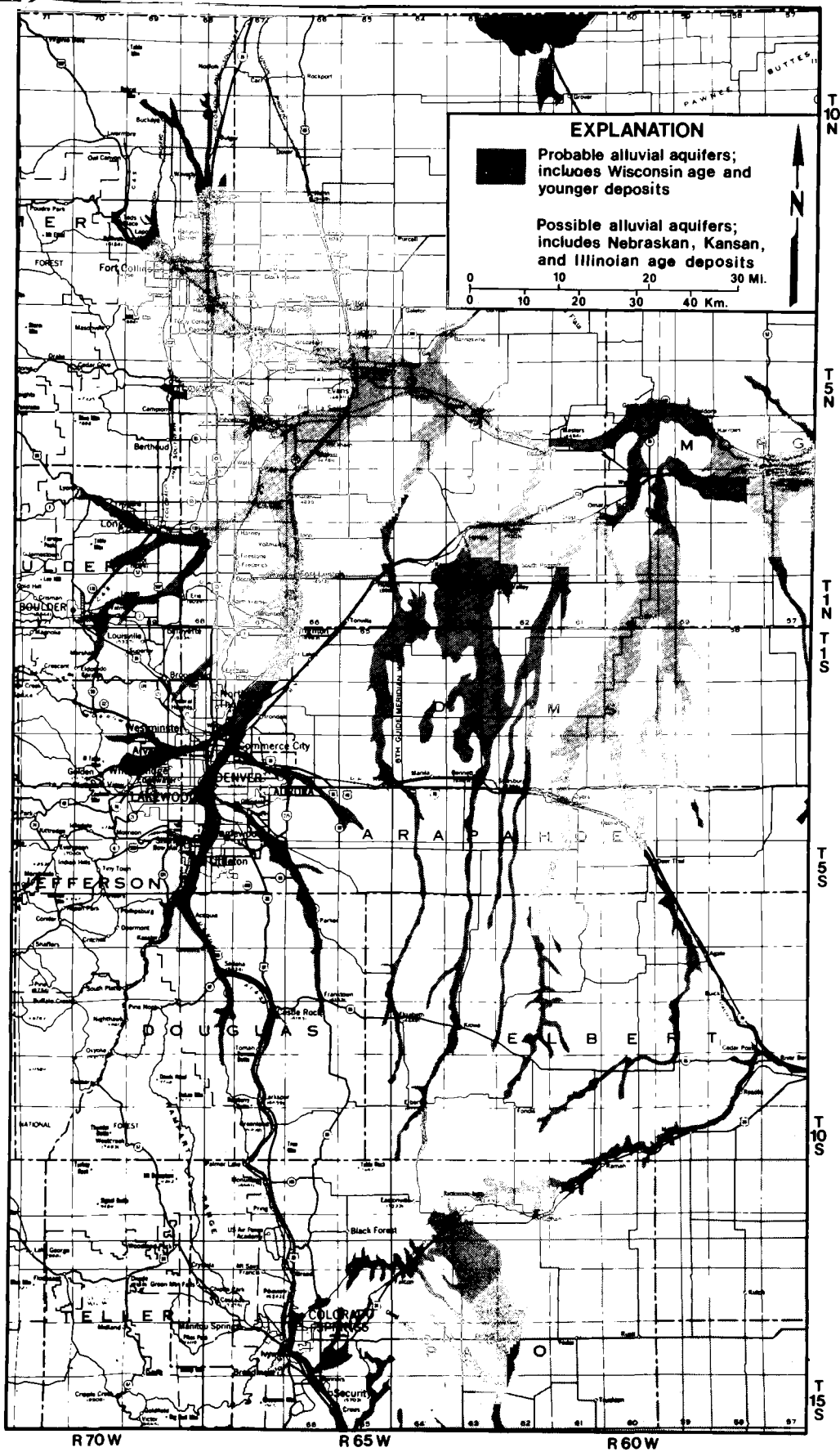


Figure 15. Generalized distribution of alluvial aquifers in the Denver and Cheyenne Basins, Colorado. (modified from Tweto, 1979)

Public Law 95-87 states that alluvial valley floors must be protected from coal surface mining. In other words, either no surface mining is allowed on an alluvial valley floor, or any mining in these areas must be carefully planned, conducted, and reclaimed to avoid impact on the alluvial valley floor. Obviously, it is important to recognize the extent of alluvial valley floors when conducting coal exploration programs. The definition of alluvial valley floors according to Public Law 95-87 has been interpreted in several ways. We believe the distribution of probable alluvial aquifers, as shown on Figure 15, generally coincides with the distribution of alluvial valley floors as defined by Public Law 95-87. Part of the area shown as possible alluvial aquifers may also be classified as alluvial valley floors. Thus, Figure 15 can be used as a general guide to the distribution of alluvial valley floors, but precise outlines can only be determined by detailed studies of individual mine sites. This evaluation should be an integral part of the environmental study of a particular mine site.

Surface water in any particular area directly relates to the local hydrologic cycle or hydrologic regime. Figure 16 graphically illustrates the hydrologic cycle. The cycle involves water movement and storage in a certain area and is not a static phenomenon. There are constant changes both over the long term and short term in the inflow to, storage in, and outflow from a particular hydrologic unit. Man and nature play important roles in the hydrologic cycle by controlling or influencing precipitation,

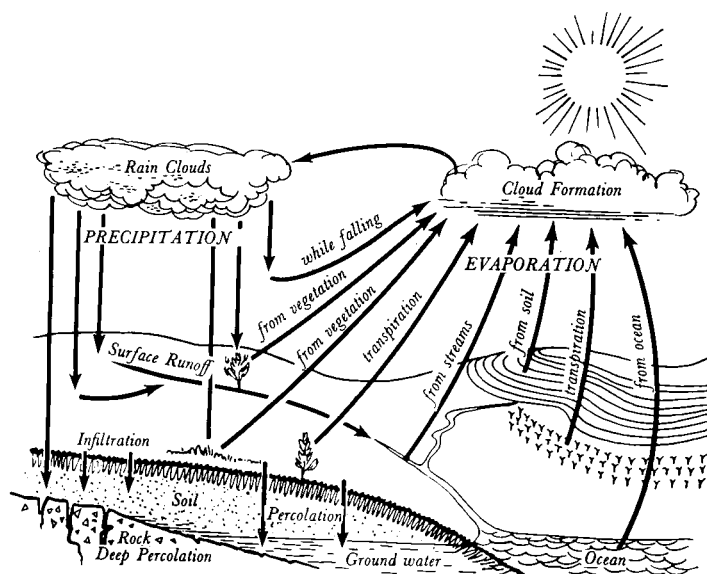


Figure 16. Hydrologic cycle. (from U.S. Department of Agriculture, 1955)

evapotranspiration, runoff, infiltration, and contaminant concentrations. The Office of Surface Mining define the hydrologic cycles or regime as "the entire state of water movement in a given area. It is a function of the climate and includes the phenomena by which water first occurs as atmospheric water vapor, passes into a liquid or solid form, falls as precipitation, moves along or into the ground surface, and returns to the atmosphere as vapor by means of evaporation and transpiration."

Surface water is a key element in the hydrologic cycle. Factors that influence the volume of available surface water include precipitation (which in the study area varies from about 11.0 to 18.5 in/yr; Hansen and others, 1978), amounts of infiltration and percolation (recharge) into soil, shallow aquifers, and deep aquifers, runoff characteristics, discharge from shallow and deep aquifers, transpiration rates, and evaporation rates, which in the study area range from about 50 to over 70 in/yr (Hansen and others, 1978). Any land disturbance that affects infiltration, percolation, and runoff rates, and any disruption of aquifers (such as that by mining) may also affect discharge rates. Specific ways in which surface water may be affected by energy-related activities are discussed in later sections.

Ground Water in Bedrock Aquifers

Ground water is a major source of water in the study area for domestic, irrigation, stock, industrial, and municipal purposes. It occurs in many of the formations in the Denver and Cheyenne Basins, but most readily accessible ground water is within the Fox Hills or younger rocks. Of the older rocks only the Fountain Formation, Lyons Sandstone, Dakota Group, and upper Transition Zone of the Pierre Shale contain appreciable amounts of ground water that can be economically tapped in the study area. Of the younger rocks the Fox Hills, Laramie, Arapahoe, Denver, Dawson, White River, and Ogallala all contain important ground water supplies. Pre-Pennsylvanian rocks near Colorado Springs are not considered important aquifers. Some of these formations may contain water, but their lateral extent is apparently very limited, and in the subsurface they are too deep to be economically used. Only the principal aquifers are described in this report.

Historic use of ground water in the Denver and Cheyenne Basins dates back to 1883. Over 400 artesian wells existed in the Denver area by 1895. By the turn of the century most of the artesian wells had stopped flowing and pumps had to be installed (Romero, 1976). During the early part of the century surface water received increased usage for domestic and municipal purposes. Extensive ground-water development occurred during the 1940s and 1950s for industrial, commercial, domestic, and municipal supplies throughout the study area. Major trans-mountain diversion projects developed during the 1950s and 1960s reduced the need for ground water in much of the urbanized area, but not in some surrounding subdivisions and communities. Continued pumping of ground water has caused over-development of many of the ground-water aquifers, especially in heavily subdivided areas. The Laramie-Fox Hills, Arapahoe and Dawson aquifers have locally experienced serious declines in water levels, in

some cases up to 600 ft (180 m) during the period of record (Romero, 1978a, 1978b, pers. comm.).

In the Cheyenne Basin the Fountain, Ingleside, and Lyons are grouped together to form the lowermost significant aquifer. In the Denver Basin the Fountain and Lyons constitute the lowermost significant aquifer. These aquifers are suitable for use along the western margin of the study area near the mountain front. Eastward, the formations are at great depths and ground-water extraction is not economically feasible. None of these aquifers have been extensively developed in the study area. Romero (1976) states that only 25 to 35 wells tap these aquifers in the Denver Basin. Probably fewer than 100 wells tap these formations in the entire study area. Generally these formations yield small to moderate amounts of water, ranging from 1 to 60 gpm (0.06 to 3.8 l/s) and averaging 5 to 10 gpm (0.3 to 0.6 l/s).

In the Cheyenne Basin the Fountain, Ingleside, and Lyons aquifers are overlain by a sequence of interbedded sandstones, shales, and limestones that include the Lykins Formation, Satanka Formation, Forelle Limestone, Jelm Formation, Chugwater Formation, and Sundance Formation. The Jelm and Sundance Formations contain relatively thick sandstone beds that locally are aquifers, but very little is known about their potential for supplying large volumes of good quality water. Along the western margin of the study area they occur at shallow depths and may be used as local water supplies. Throughout most of the study area, however, these formations are too deep to be economically tapped.

The Dakota Group contains thick water-yielding sandstones in both basins, but is generally utilized only along the western basin margin because of excessive depths and deterioration of water quality to the east. Wells which tap the Dakota Group yield from 2 to 50 gpm (0.1 to 3.2 l/s) and average 15 gpm (1.0 l/s) (Romero, 1976). The Pierre Shale contains several porous and permeable horizons in parts of the Cheyenne Basin, including the Richard, Larimer, Rocky Ridge, and Hygiene Sandstone members and sandstone and siltstone in the upper Transition Zone. The first four sandstone members provide some water in the northwest part of the study area, but they contain varying amounts of oil and gas in some areas and water quality near these areas is often very poor. Sandstone and siltstone in the upper Transition Zone of the Pierre Shale may locally contain significant amounts of potable ground water. These aquifers are often tapped by wells east of the study area, but they were not studied during this investigation. Throughout most of the study area, aquifers within the Pierre Shale are too deep to be economically utilized. Generally, shallower aquifers that are more readily available can be tapped.

The Fox Hills is one of the more reliable bedrock aquifers in the study area. The formation generally contains thick sandstone beds throughout much of the area. In the Denver Basin, Romero (1976) believes the Fox Hills and the lower Laramie sandstones should be grouped together into the Laramie-Fox Hills aquifer. This practice has not been adopted in the Cheyenne Basin because the lower Laramie in this area generally contains few water-producing sands. Major sandstone aquifers in the

middle and upper part of the Laramie in the Cheyenne Basin are usually separated from the Fox Hills by at least 100 ft (30 m) of relatively impermeable strata. Stratigraphic differences in the Laramie Formation between the two basins discourage use of the Laramie-Fox Hills terminology in the Cheyenne Basin.

Figure 17 shows the lateral extent and structure contours on top Laramie-Fox Hills aquifer in the Denver Basin and the Fox Hills aquifer in the Cheyenne Basin. A large part of the study area is underlain by these aquifers at relatively shallow depths. The Fox Hills Sandstone in the Cheyenne Basin and the Laramie-Fox Hills aquifer in the Denver Basin have well yields generally ranging from 2 to 100 gpm (0.32 to 6.36 l/s). Some Laramie-Fox Hills wells produce up to 200 gpm (12.7 l/s) (Romero, 1976). The lower part of the Fox Hills contains a large number of low permeability beds, and the lower Laramie sandstones, though locally prolific, usually are thin and laterally discontinuous even in the Denver Basin. Romero (1976) states the Laramie-Fox Hills water is one of the most heavily mineralized aquifers in the Denver Basin. Analyses presented by Kirkham and others (1980) in the Cheyenne Basin suggest the Fox Hills water quality is highly variable and generally more mineralized than other aquifers. Their data in the Cheyenne Basin may be somewhat biased by the close proximity of most sampled Fox Hills wells to known uranium deposits.

Two major factors play important roles in causing serious quality problems in Laramie-Fox Hills wells in the Denver Basin and Fox Hills wells in the Cheyenne Basin: 1) the presence of coal beds or mineralization within the general aquifer zone, and 2) faulty well construction practices such as poor logging control, open-hole construction, improper grouting, improperly placed or deteriorated casing, and failure of seals. Such factors can allow a variety of contaminants from coal beds and mineralized zones to enter a well. Coal gas or methane contamination has also been documented in the Denver Basin (Kirkham and Ladwig, 1979). One sampled well contained such high levels of methane that water from a faucet would burn when a flame was applied to it. Coal beds are less abundant in the Cheyenne Basin, but this type of problem may still occur. Pyrite-rich horizons locally cause iron contamination in both basins. A serious quality problem in the Cheyenne Basin relates to the highly mineralized water near uranium deposits (Kirkham and others, 1980).

The Laramie Formation is a major aquifer in the Cheyenne Basin, but only the lowermost part of the formation produces water in the Denver Basin. In the Cheyenne Basin, the middle and upper parts of the formation often contains numerous, prolific water-producing sandstones ranging from 10 to 125-ft (3.0 to 37.5-m) thick (Kirkham and others, 1980). The lower part of the formation contains fewer and thinner sandstones and potentially contaminating coal beds. This part of the formation may produce a minor amount of good quality water if the coal beds are properly isolated from the producing aquifer. Figure 18 illustrates the lateral extent of the Laramie Formation in the Cheyenne Basin. In the Denver Basin the lowermost part of the Laramie locally contains a few sandstones that are grouped with the Fox Hills into the Laramie-Fox Hills aquifer. The remaining upper part of the Laramie contains very little water in the Denver Basin (Romero, 1976).

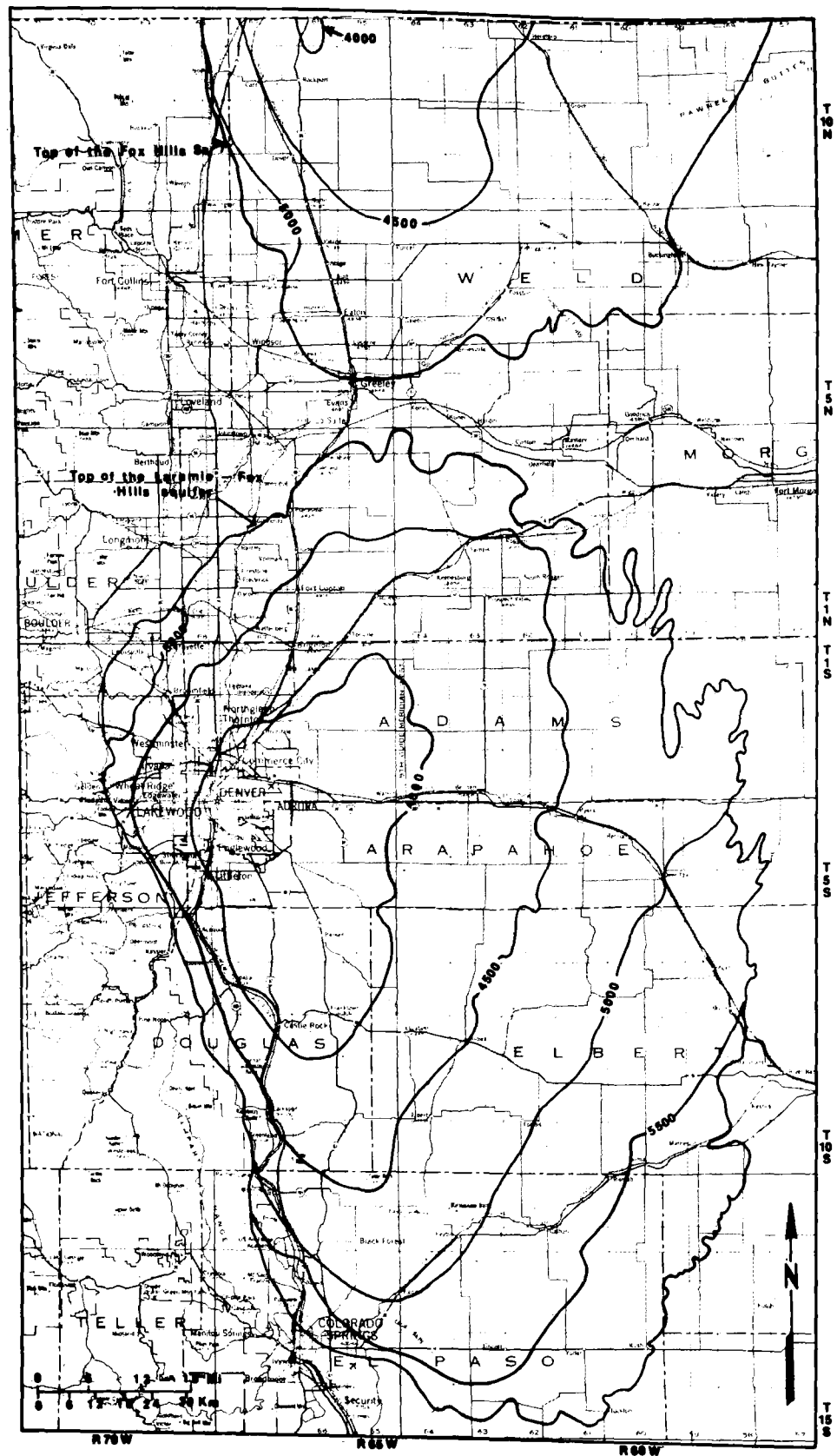


Figure 17. Structure contour map on the top of the Laramie-Fox Hills aquifer in the Denver Basin and the Fox Hills Sandstone in the Cheyenne Basin, Colorado. (modified from unpublished maps prepared by the Colorado Division of Water Resources, Ground Water Investigations Branch; and Ethridge and others, 1979)

The Arapahoe Formation is a major aquifer in the Denver Basin. A structure contour map of the top of the formation and the lateral extent of the formation are shown in Figure 19. As seen in Figure 10 the lower and middle parts of the formation generally contain more sandstone and water than the upper part. Near the mountain front the formation is about 60 to 70 percent sand and conglomerate. Sand percentages decrease eastward and in the eastern outcrop area, only 10 to 20 percent of the formation is sand. Yields up to 400 to 500 gpm (25.2 to 31.5 l/s) may be obtained from the Arapahoe (Romero, 1976). Water quality generally is very good in the Arapahoe.

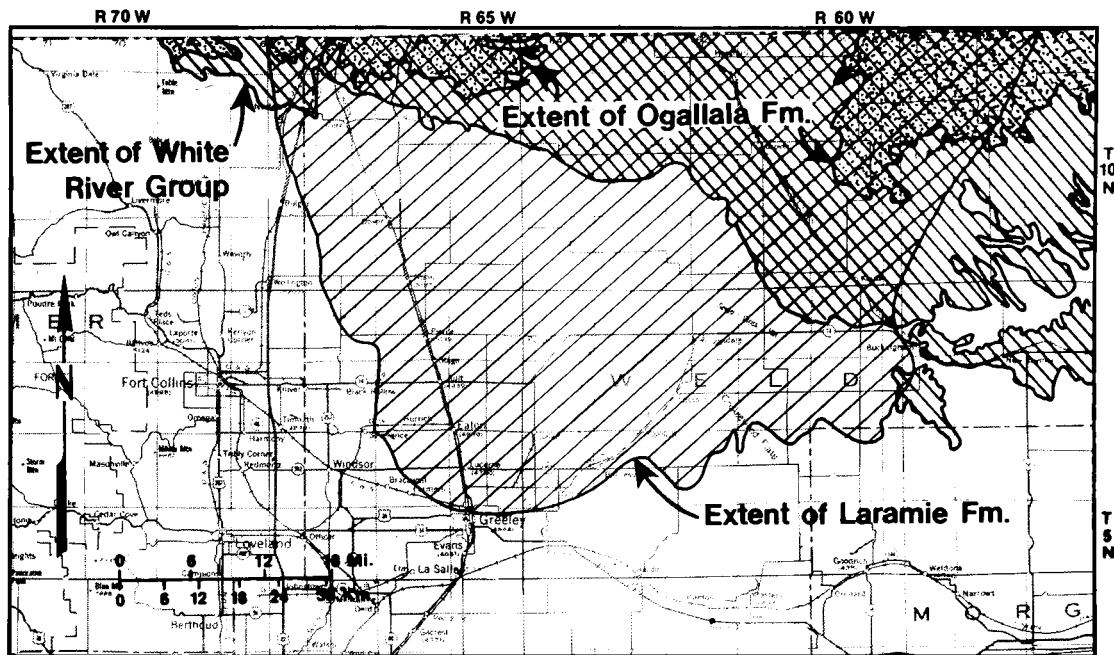


Figure 18. Extent of the Laramie Formation, White River Group, and Ogallala Formation, Cheyenne Basin, Colorado. (modified from Tweto, 1979)

Unlike the Arapahoe, the Denver Formation is not a major aquifer. Locally the formation contains some thin and lenticular sandstone aquifers particularly in its lower part. Occasionally individual sandstone beds up to 50-ft (15-m) thick are present, but they are rare. The upper part of the formation generally is less suited for ground-water production than is the lower part, but locally it may yield some water. Figure 20 illustrates the extent of the Denver Formation and presents a structure contour map on the top of the formation.

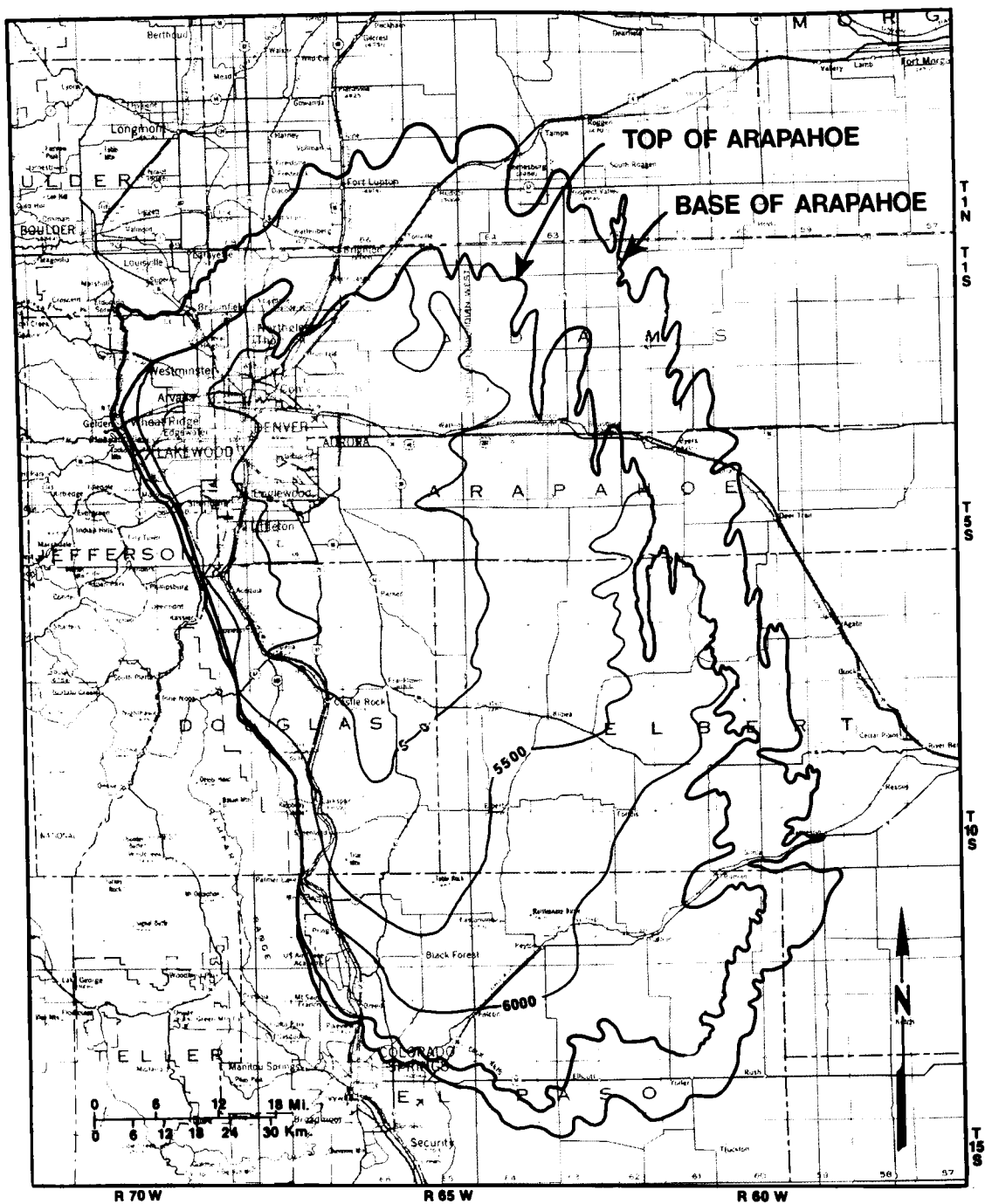


Figure 19. Structure contour map on the top of the Arapahoe Formation. (modified from unpublished maps prepared by the Colorado Division of Water Resources, Ground Water Investigations Branch)

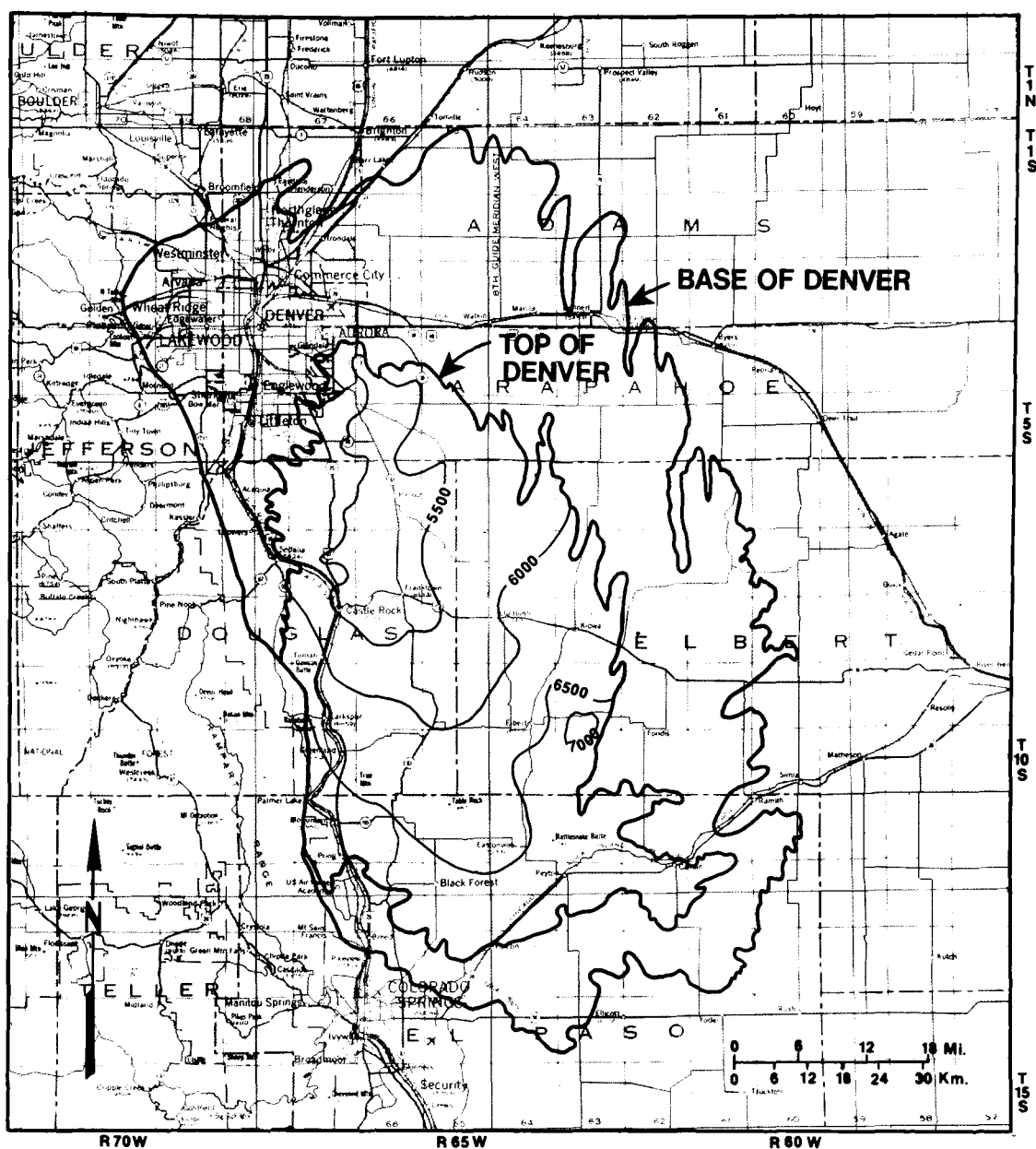


Figure 20. Structure contour map of the top of the Denver Formation. (modified from unpublished maps prepared by the Colorado Division of Water Resources, Ground Water Investigations Branch)

The Dawson Arkose is the uppermost major aquifer in the Denver Basin. In most areas the formation contains numerous thick sandstones and conglomerates that may yield up to 400 to 500 gpm (25.2 to 31.5 l/s) (Romero, 1976). Locally, the formation may be predominantly claystone, but even in these areas the formation usually has enough ground water for low- to medium-yield domestic wells. Water quality typically is very good. The Dawson rivals the Arapahoe Formation for having the highest quality water in the Denver Basin. Figure 21 shows the extent of the Dawson in Denver Basin.

The White River Group overlies the Laramie Formation in the Cheyenne Basin. Lenticular, water-bearing, coarse sandstones and conglomerates randomly occur throughout much of the formation. Wells that tap these units generally produce enough water for domestic and stock-watering uses, and occasionally enough for irrigation. The remaining part of the formation is dominantly siltstone that has moderately low permeability and produces little water. Fractures, pipes, solution cavities, and vertical clastic dikes, however, may locally have great influence on the hydrologic characteristics of the siltstone (Lowry and Crist, 1967; Crist and Borchert, 1972; Wacinski, 1979; Kirkham and others, 1980). The influence of these features is not well understood, but the fractures may carry important small amounts of water and pipes and solution cavities may locally provide large volumes of water. As shown in Figure 18, the White River Group extends through much of the Cheyenne Basin.

The Ogallala Formation occurs over a small part of the Cheyenne Basin (Figure 18). The underlying Arikaree Formation is included with the Ogallala in Figure 18 because of its limited extent in the study area. The Ogallala underlies much of the High Plains in many adjacent States and has been extensively used for irrigation. Reports of excessive pumping and water-level declines are common. Some farmers who at one time irrigated with Ogallala water have been forced to revert to dryland farming because of this problem. Since the Ogallala underlies only a limited part of the study area, it was not studied in detail in this report.

Very little is known about the direction of ground-water flow in bedrock aquifers in the study area. Romero (1976) has published the only regional potentiometric surface map for the Denver Basin. His map, reproduced in Figure 22, shows the approximate configuration of the potentiometric surface for the Laramie-Fox Hills aquifer in 1970 and possible recharge and discharge areas. Ground water within the Laramie-Fox Hills aquifer generally moves northward, towards the South Platte River. Romero (1976) believes potentiometric maps constructed for overlying aquifers would have a similar configuration. Romero (1976) cites evidence to indicate that ground-water withdrawal from the Laramie-Fox Hills aquifer and also most other Denver Basin aquifers is significantly affecting local, ground-water flow paths and that large cones of depressions exist in areas of high ground-water usage.

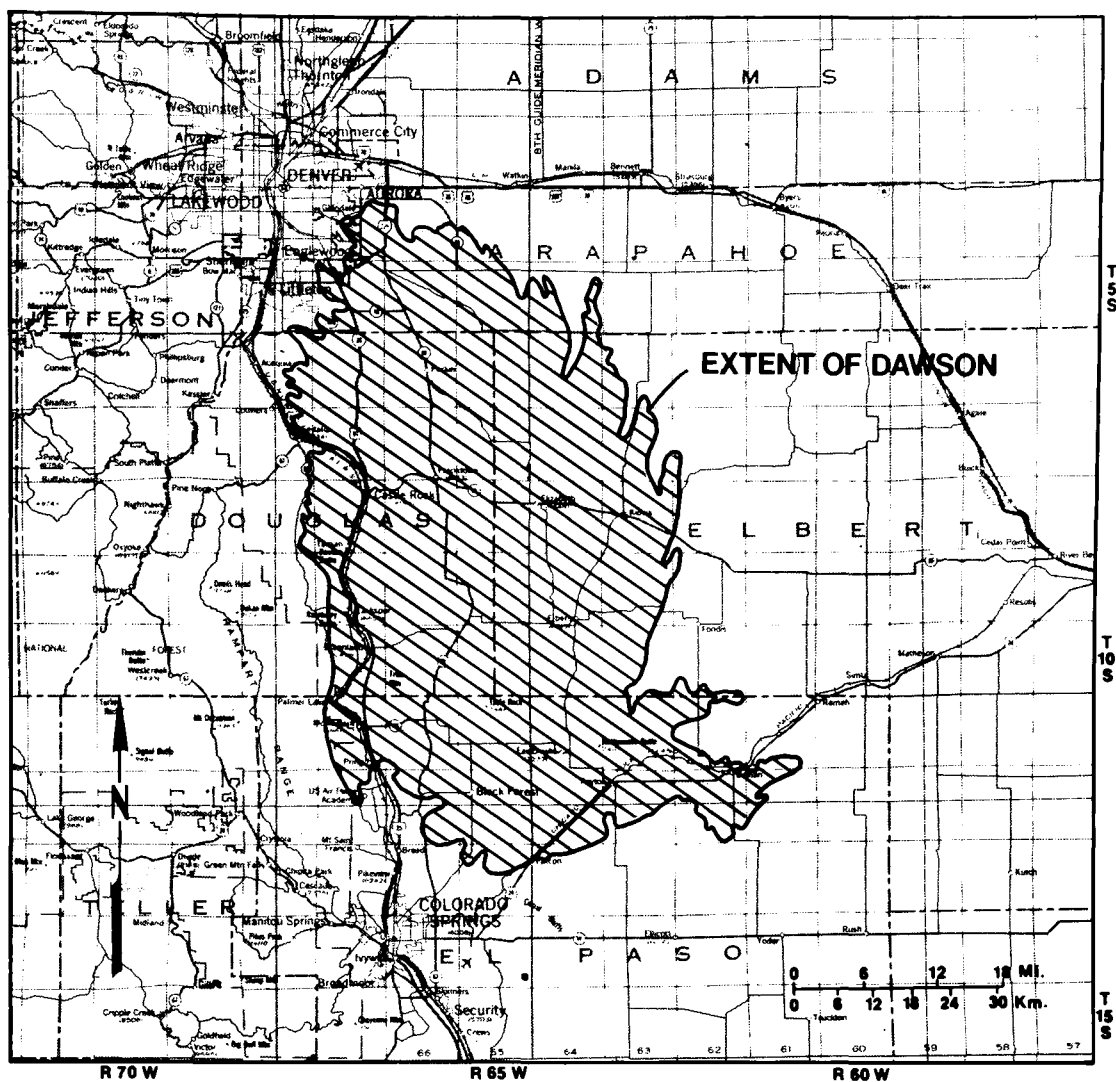


Figure 21. Extent of the Dawson Arkose. (modified from unpublished maps prepared by the Colorado Division of Water Resources, Ground Water Investigations Branch)

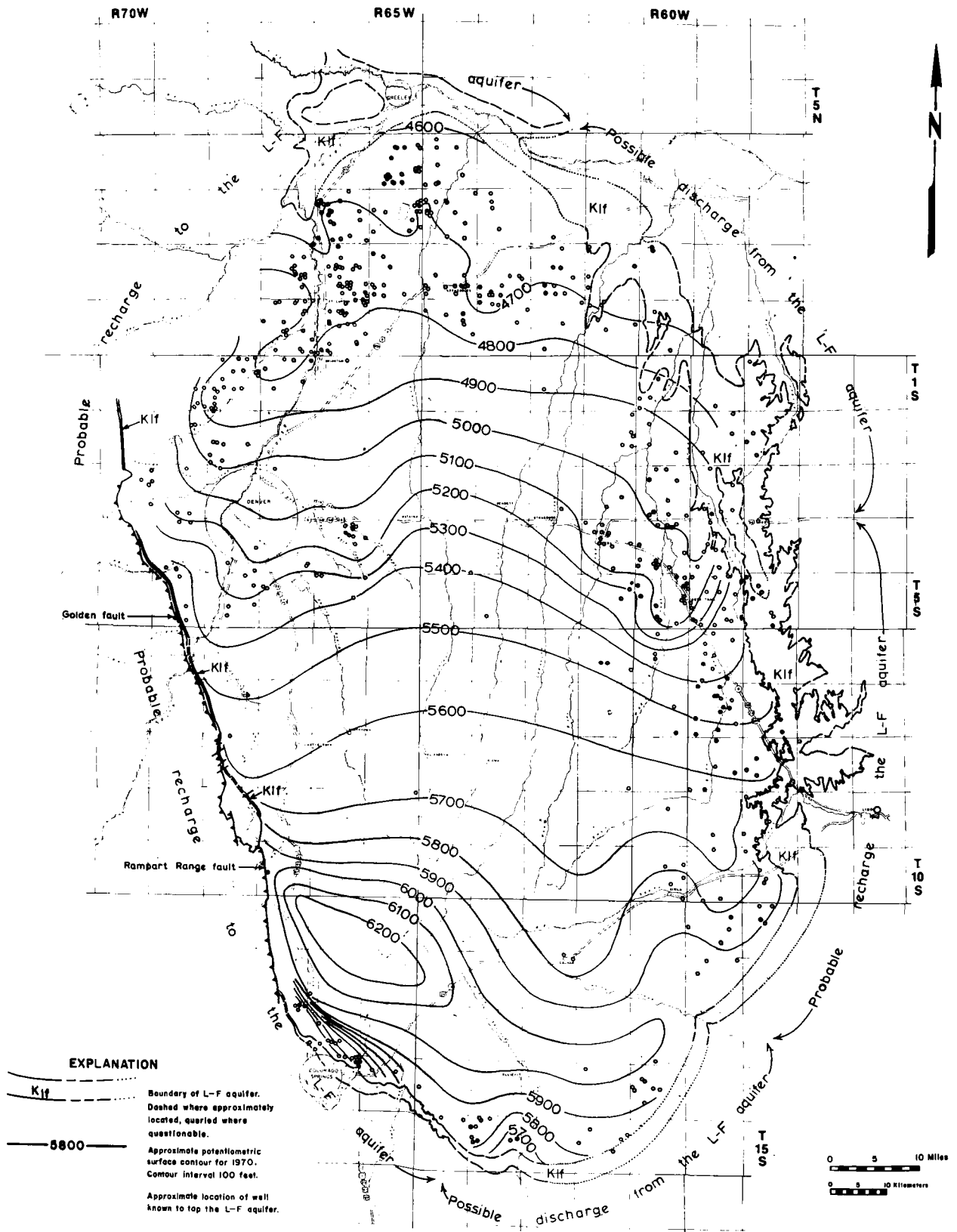


Figure 22. Approximate configuration of the potentiometric surface in the Laramie-Fox Hills aquifer, Denver Basin, and possible recharge and discharge areas. (from Romero, 1976)

Figure 23 is a contour map showing water-table elevations in the Cheyenne Basin. This map was prepared by Kirkham and others (1980) by contouring the elevations of water levels in wells tapping a variety of aquifers. It is not a potentiometric map of a particular formation, but it does suggest that ground water generally moves southward or southeastward towards the South Platte River. The location of springs in the area supports this interpretation. Kirkham and others (1980) attempted to prepare a potentiometric map of the Fox Hills, but their results were unsatisfactory for numerous reasons cited in their report. Wacinski (1979) prepared a water-table map for part of the Cheyenne Basin. His map also suggests water movement to the southeast.

Ground-water quality aspects of the various aquifers in the study area are very complex. For this reason no attempt will be made to summarize water quality in this report. If additional quality information other than that described in previous paragraphs is desired, refer to sources such as Romero (1976), Kirkham and others (1980), Schneider and Hershey (1961), Weist (1964), Bjorkland and Brown (1957), Jenkins (1961, 1964), McConaghly and others (1964), McGovern and Jenkins (1966), Smith and others (1964), and Schneider (1962).

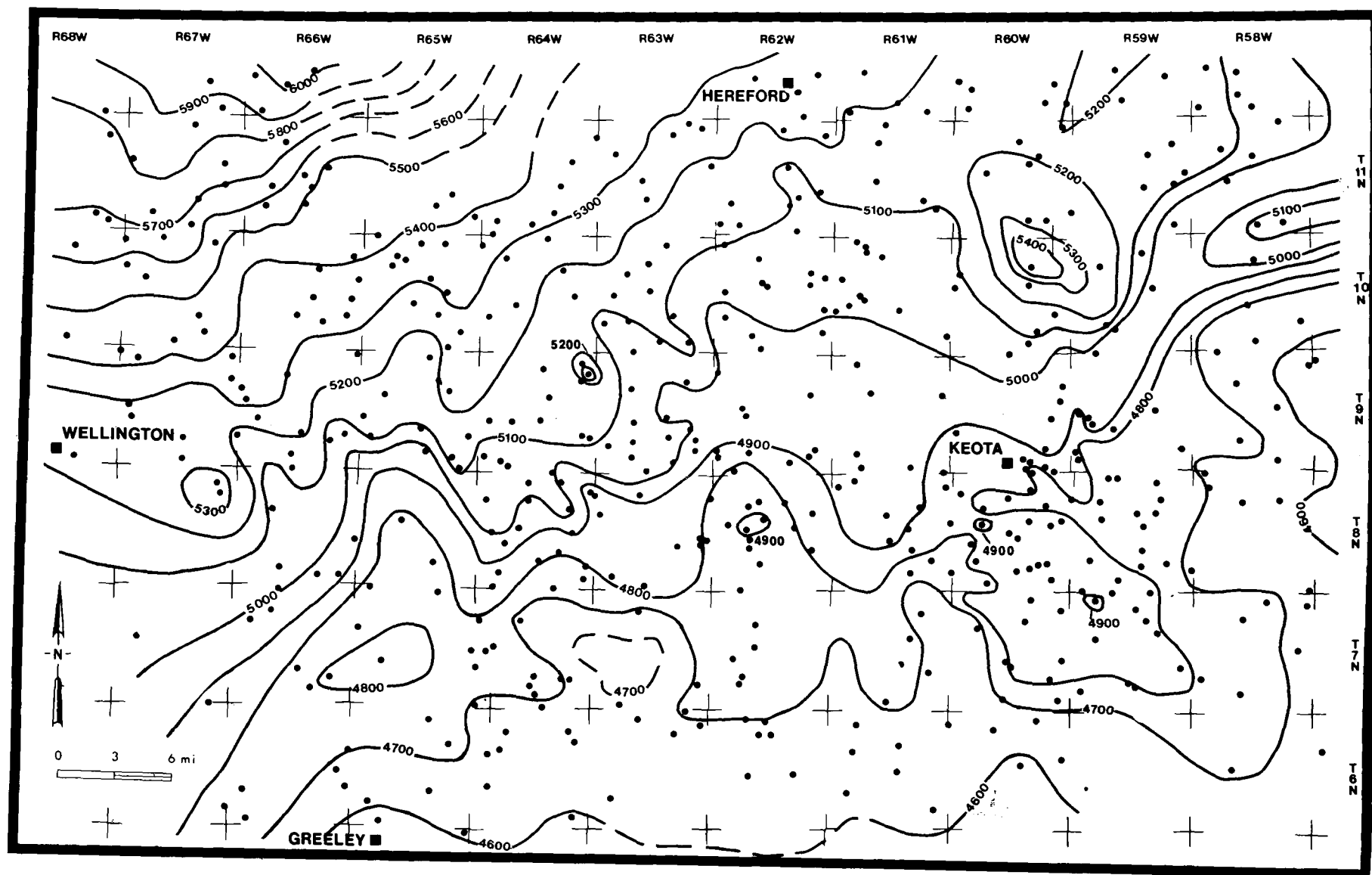


Figure 23. Water-table elevation map, Cheyenne Basin. (from Kirkham and others, 1980)

COAL RESOURCES

RESOURCE CHARACTERISTICS

Coal is a readily combustible rock containing carbonaceous material in amounts exceeding 50 percent of the total rock weight and more than 70 percent of total rock volume. It is formed by compaction and lithification of physically and chemically altered plant remains, such as those in peat. Originally, plant remains were deposited in a variety of environments, examples of which include overbank flood basins, lagoons, delta plains, and abandoned stream channels. In order for peat to accumulate and be preserved, the depositional setting must be in a reducing environment to prevent oxidation of the organic materials.

Coal is primarily classified by rank and quality. Rank depends upon fixed carbon, volatile, and heat content, and is calculated on a dry, mineral-free basis. Coal ranks, in order of increasing fixed carbon and heat content, include lignite, subbituminous coal, bituminous coal, and anthracite. Generally, higher rank coal results from exposure of the altered peat to higher temperature and pressure for longer periods of time. Coal quality depends on the content of sulfur, ash, and other undesirable constituents. In the study area, coal rank ranges from lignite to subbituminous B coal. Some bituminous coal may occur in the deepest part of the Denver Basin, but no sample analyses are available from this area. All coal and lignite in the study area is low in sulfur content.

Use of coal has changed with time. At one time coal was the principal fuel used for space heating in the United States. Oil, gas, and electricity eventually replaced coal for space heating needs. Currently there is a noticeable trend toward increased utilization of coal and wood to heat private homes. Both authors use coal and wood to supply at least part of their home heating needs. This increased utilization for space heating is important, but most coal presently mined is burned in power plants to generate electricity. A relatively new use of coal and lignite in the United States involves coal conversion to synthetic gas and petroleum products. Conversion technology has long been known, but economically feasible production is still in its infancy. As petroleum and natural gas supplies dwindle, costs increase, and the need for decreased dependence on foreign oil becomes obvious, surface and underground coal conversion will become increasingly important.

Within the study area economically significant coal and lignite deposits occur in the Laramie and Denver Formations. Several published reports describe the regional and local aspects of these coal and lignite beds. Kirkham and Ladwig (1979) is one of the more regionally comprehensive reports. Much of the following generalized information is adopted from these publications.

Laramie Formation Coal

A sequence of strata containing economically significant coal and lignite occurs in the lower 50 to 275 ft (15.0 to 82.5 m) of the Upper Cretaceous Laramie Formation over much of the Denver and Cheyenne Basins. This sequence, the lower Laramie coal zone, consists of interbedded coal, claystone, shale, siltstone, and sandstone. The exact stratigraphic position of the lower Laramie coal zone is debated among geologists who have studied it in local investigations. Our regional study indicates the general stratigraphic position of the coal zone is relatively uniform through the Denver Basin but is less predictable in the Cheyenne Basin. Usually the base of the lower Laramie coal zone coincides with the base of the Laramie Formation. In the Denver Basin the top of the lower member of the Laramie corresponds with the top of the uppermost coal bed in this lower Laramie coal zone (Kirkham and Ladwig, 1979).

In the Cheyenne Basin the Laramie coal zone is less predictable. Generally coal beds are restricted to the lower 200 to 300 ft (60 to 90 m) of the Laramie. However in a small area north of Purcell and east of Nunn, up to six coal beds that are a maximum of 1.5-ft (0.45-m) thick occur several hundred feet above the base of the Laramie Formation.

Stratigraphic details of the lower Laramie coal zone may vary markedly throughout both basins. Unlike many of the coal beds found in the eastern part of the United States, individual Laramie coal beds are often relatively lenticular, do not extend laterally for any greater distance, and vary considerably in thickness geographically.

Figure 24 illustrates the lateral extent of the Laramie coal zone in the study area. Approximately 7,500 sq mi² (19,500 km²) of the study area are underlain by the Laramie coal zone. Our investigation reveals that some areas within this designated coal-bearing area contain only thin coal beds or are barren of coal. Approximately 75 to 85 percent, or 5,600 to 6,400 mi² (14,600 to 16,600 km²) of this outlined area is actually underlain by Laramie coal. Kirkham and Ladwig (1979, plate 1) indicate that less than 10 percent of the area contains coal beds 5-ft (1.5-m) thick or greater. This map could be somewhat misleading in that very little drill hole data are available for the lower Laramie coal zone over much of the study area. We estimate that about one-third of the Denver Basin and perhaps one-sixth of the Cheyenne Basin are underlain by Laramie coal beds 5-ft (1.5-m) thick or greater.

Laramie coal distribution and stratigraphy can be interpreted through use of deltaic sedimentation models. Figure 25 illustrates the theorized environment of deposition for the lower Laramie Formation. Areas free of Laramie coal were probably channel and channel-margin environments. Fine- to coarse-grained sandstones were deposited in channel environments, light gray, massive claystones were deposited in the well-drained swamps, and light-colored silts and clays were deposited on the levees. The coal beds developed from peat layers which, along with dark-gray, organic-rich claystones, accumulated in poorly drained swamps in overbank or flood-basin areas. Some Laramie coal beds may have developed from peat

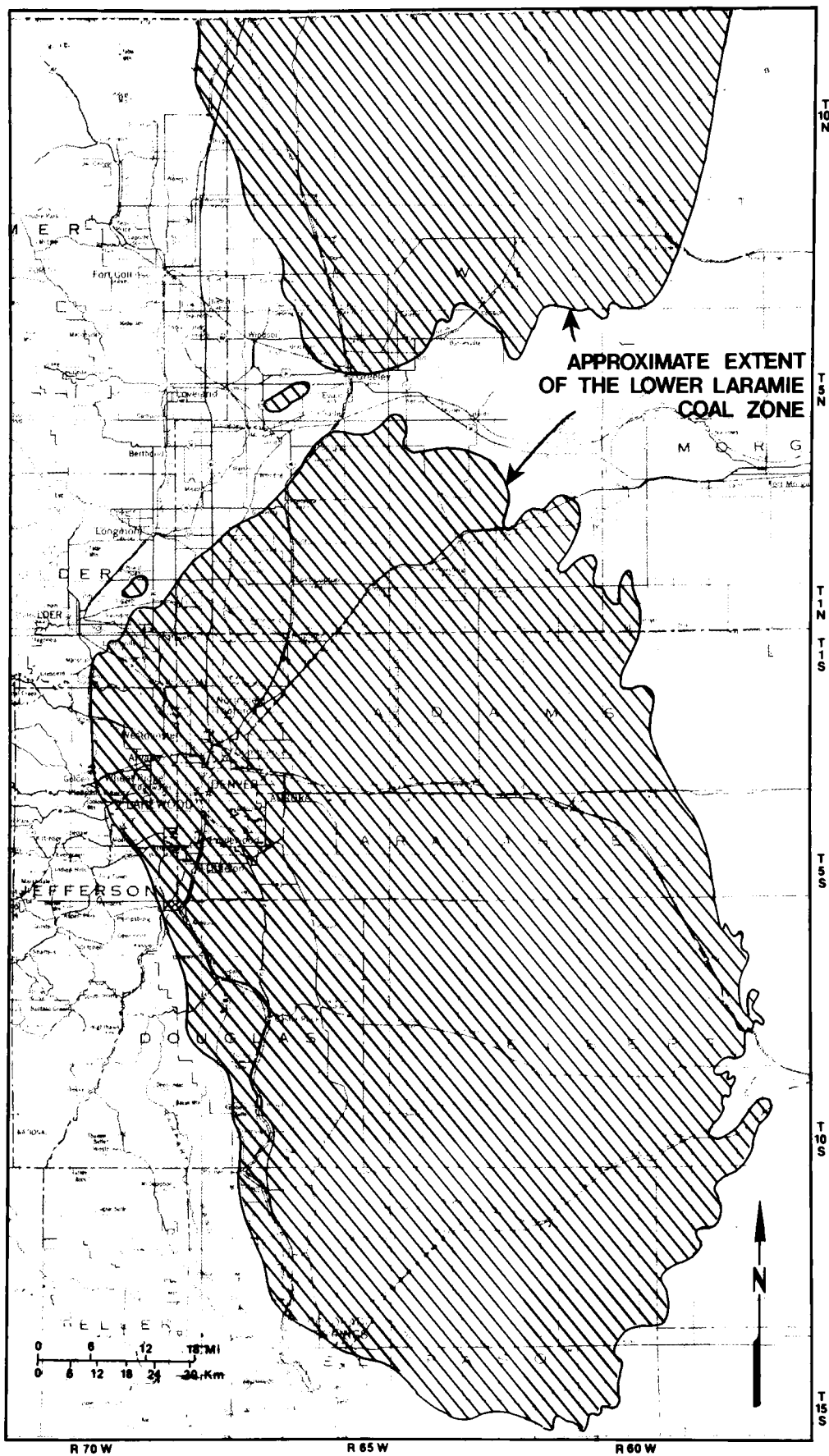


Figure 24. Lateral extent of the Laramie coal zone.

deposits in abandoned channels. The thickest coal beds formed in the more stable parts of the swamp. Coal beds that are laterally continuous over relatively large areas, such as those in the eastern part of the study area, were deposited in broad swamp areas. Sandstone partings within a coal bed may have resulted from crevasse splays breaking through levees and depositing fine- to medium-grained sand in the overbank areas.

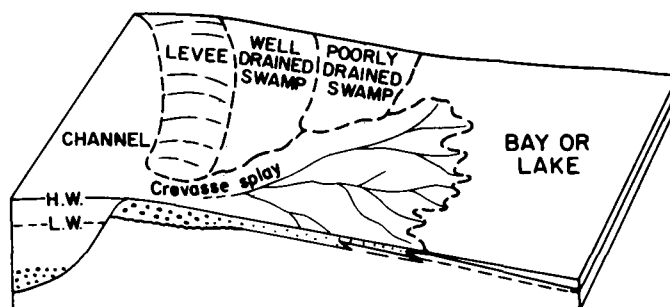


Figure 25. Environments of deposition of the Laramie Formation. (from Weimer, 1973)

Stratigraphic details of the lower Laramie coal zone vary considerably. In some areas it contains up to 16 individual coal beds, and in other areas, as previously mentioned, it may contain little or no coal. The thickest Laramie coal bed is usually 10 to 100 ft (3 to 30 m) above the top of the Fox Hills Sandstone, often at or near the top of the Laramie-Fox Hills aquifer. Several minable coal beds may also occur above this stratigraphic horizon. Lowrie (1966) describes four coal beds that locally are of minable thickness above the Laramie-Fox Hills aquifer in the Boulder-Weld coal field. Zawistowski (1978, pers. comm.) observed 12 coal beds, some of which were of minable thickness, above the Laramie-Fox Hills aquifer from core samples in the central part of the Boulder-Weld coal field.

Coal beds may also occur within the Laramie-Fox Hills aquifer. Geophysical logs of drill holes indicate a coal bed occasionally occurs directly on top of the Fox Hills Sandstone. Trimble (1975) reports an 8-in (20-cm) thick coal bed within the Fox Hills Sandstone in the Niwot Quadrangle. Four thin coal beds within the Laramie-Fox Hills aquifer were recorded by Zawistowski (1978, pers. comm.) in a core hole in the central part of the Boulder-Weld coal field. Lowrie (1966) described two coal beds, locally of minable thickness, within the Laramie-Fox Hills in the Boulder-Weld field. Several coal beds, including some of minable thickness, in the Colorado Springs area are within the Laramie-Fox Hills aquifer (Goldman, 1910). Our investigation found numerous, usually thin coals interbedded with the Laramie-Fox Hills aquifer in much of the study area. Only in a few areas, however, such as the Colorado Springs field,

Foothills district, and locally in the Boulder-Weld field, are the beds economically significant.

Overburden thickness above a coal bed is an important factor when considering minability. Laramie coal beds crop out or are very shallow in parts of the study area, but are also present at depths up to about 3,000 ft (900 m) in other parts of the area. Amount of overburden above a coal bed depends on structural configuration of the basin and surface topography. Topography can have great local and regional effects. Local topography such as hills, buttes, and eroded stream channels may cause local variations in overburden thickness of up to 400 ft (120 m) in less than one mile (1.6 km). Regional topography may influence overburden thickness by more than 1,000 ft (300 m).

Both the Denver and Cheyenne Basins are doubly plunging synclines. The Laramie coal zone has been deformed along with other rocks into this same configuration. The coal zone crops out along the basin margins and is deepest in the structural centers of the basins. Within the Denver Basin, just southeast of Cherry Creek Reservoir, the top of the Laramie coal zone is at an elevation of about 3,800 ft (1,140 m) above sea level and about 1,700 ft (510 m) below land surface. In T9S, R66W near Black Forest the top of the coal zone is at an elevation of only 4,100 ft (1,230 m), but there is about 2,900 ft (870 m) of overburden. This comparison exemplifies the importance of regional topography on overburden thickness. Figure 26 illustrates the depth to the top of the Laramie coal zone in both basins. This map should be considered approximate, especially in the southern, western, and central parts of the Denver Basin and in the central and western parts of the Cheyenne Basin, because drill hole control in these areas is very limited.

The stratigraphy of the lower Laramie coal zone is very complex, a direct result of the depositional setting of these coals. Because of this problem and because of the lack of detailed information in much of the study area, no attempt will be made to summarize the overall Laramie coal zone stratigraphy for the entire area. Short descriptions of the stratigraphy for a few areas will be presented.

One of the better known areas, an area where extensive past mining was conducted, is the Boulder-Weld coal field. Several workers, including Spencer (1961), Lowrie (1966), Amuedo and Ivey (1975), Zawistowski (1978, pers. comm.), and Kirkham and Ladwig (1979), have studied the area and described the Laramie coal zone stratigraphy. A summary of the stratigraphic findings of these workers is presented in Figure 27.

In the Boulder-Weld coal field the lower Laramie coal zone is up to 265-ft (79.5-m) thick and contains up to 16 coal beds. Seven of these coal beds are locally minable. Lowrie (1966), named these beds, in ascending order, the nos. 1 through 7 coal beds. This practice has been adopted by most geologists who have worked the area, and it will be utilized for this investigation. Much of the following descriptions of individual coal beds are from Lowrie (1966) and Kirkham and Ladwig (1979).

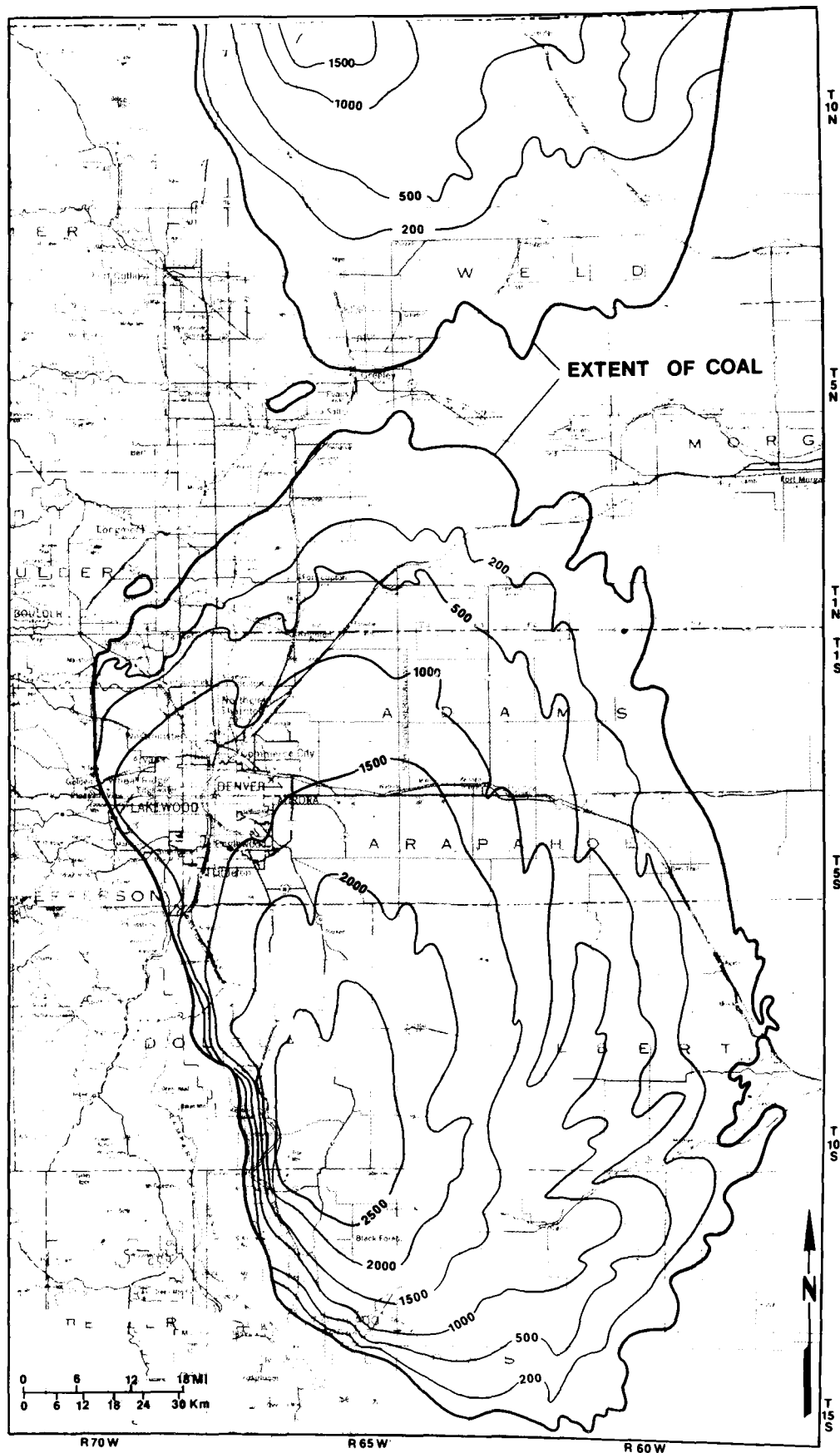
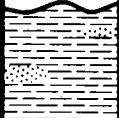
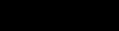


Figure 26. Approximate depth to the top of the lower Laramie coal zone.
(from Kirkham and Ladwig, 1979)

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

*thickness not to scale

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

Figure 27. Generalized stratigraphy of the lower Laramie coal zone, Boulder-Weld coal field. (from Kirkham and Ladwig, 1979)

Coal bed no. 1, the lowermost minable bed, is only 1 to 3-ft (0.3- to 0.9-m) thick and is very limited in lateral extent. It reaches maximum thickness in secs. 13, 14, 22, and 23, T1N, R68W. Coal bed no. 2 lies 20 to 65 ft (6.0 to 19.5 m) above the no. 1 bed. The sequence of strata between the two beds often is a thick, upward-fining, channel sandstone, locally called the "A" sandstone, and is part of the Laramie-Fox Hills aquifer. Because the no. 2 coal bed is 10 to 45 ft (9.0 to 13.5 m) below the extensively mined no. 3 coal bed, it is known as the "sump seam." In many areas coal bed no. 2 is greater than 2.5-ft (0.75-m) thick and in sec. 20, T1N, R68W, it is over 8-ft (2.4-m) thick.

Coal bed no. 3 is the thickest and laterally most continuous coal bed in the Boulder-Weld coal field. It is 10 to 45 ft (3.0 to 13.5 m) above coal bed no. 2. Locally the intervening strata contain a thick, upward-fining, channel sandstone, the "B" sandstone. Coal bed no. 3, also called the "main or Gorham seam", ranges from about 2 to 14-ft (0.6 to 4.2-m) thick. The coal bed may coalesce with the no. 4 coal bed, as it does in secs. 34 and 35, T1N, R69W. Coal bed no. 4 is as much as 35 ft (10.5 m) above coal bed no. 3 and ranges from 1 to 11-ft (0.3 to 3.3-m) thick. It is thickest in the central and southwestern part of the coal field. About 20 to 50 ft (3 to 15 m) of shale and sandstone separate coal bed nos. 4 and 5. The intervening sandstone, the "C" sandstone, is developed only in the Marshall area. Coal bed no. 5, also known as the "middle seam", is 1 to 10-ft (0.3 to 3.0-m) thick and has been extensively mined in several areas. Coal bed no. 5 reaches its maximum thickness in secs. 25, 34, and 35, T2N, R68W.

The "upper seam", coal bed no. 6, ranges from 1 to 8-ft (0.3 to 2.4-m) thick and lies 20 to 75 ft (6.0 to 22.5 m) above the no. 5 coal bed. It has been mined using both surface and underground mining methods. Coal bed no. 7 is very lenticular, occurring only in the eastern and southeastern parts of the Boulder-Weld coal field. It ranges from 2 to 5-ft (0.6 to 1.5-m) thick, with maximum thickness in sec. 8, T1N, R67W, and lies 30 to 100 ft (9 to 30 m) above coal bed no. 6. Coal bed no. 7 is the uppermost minable coal bed in the Boulder-Weld field.

The coal beds in the Boulder-Weld coal field are believed to have been deposited in a delta plain on the northern margin of a delta system whose distributary channels were in the Golden-Leyden Ridge vicinity (Rahmanian, 1975; Weimer, 1977). Presence of a second delta system in the White Rocks area north of the Boulder-Weld coal field (Weimer, 1973, 1976) and occurrence of oyster Ostrea glabra and highly burrowed beds suggesting a brackish-water environment (Rahmanian, 1975) support this hypothesis.

South of the Boulder-Weld field along the mountain front lies the Foothills district. Camacho (1969) studied the north end of this district and described the coal beds, which he called beds A and B. Van Horn (1976) reported one to six coal beds in the central part of the Foothills district in the Golden Quadrangle. In the Littleton Quadrangle in the southern end of the district, Scott (1962) found four coal beds. Kirkham (1978b) indicates the thickness of the mined coal beds in the Foothills district ranges from about 4 to 15 ft (1.2 to 4.5 m). Figure 28 summarizes the Fox Hills and lower Laramie stratigraphy from Leyden Ridge to Golden (Camacho, 1969; Weimer, 1973). Two distributary channels occur in the area. The A and B coal beds described by Camacho (1969) were deposited on the north side of the older channel and were locally eroded out when the younger channel developed. Coal beds described by Scott (1962) and Van Horn (1976) were deposited south of the older channel.

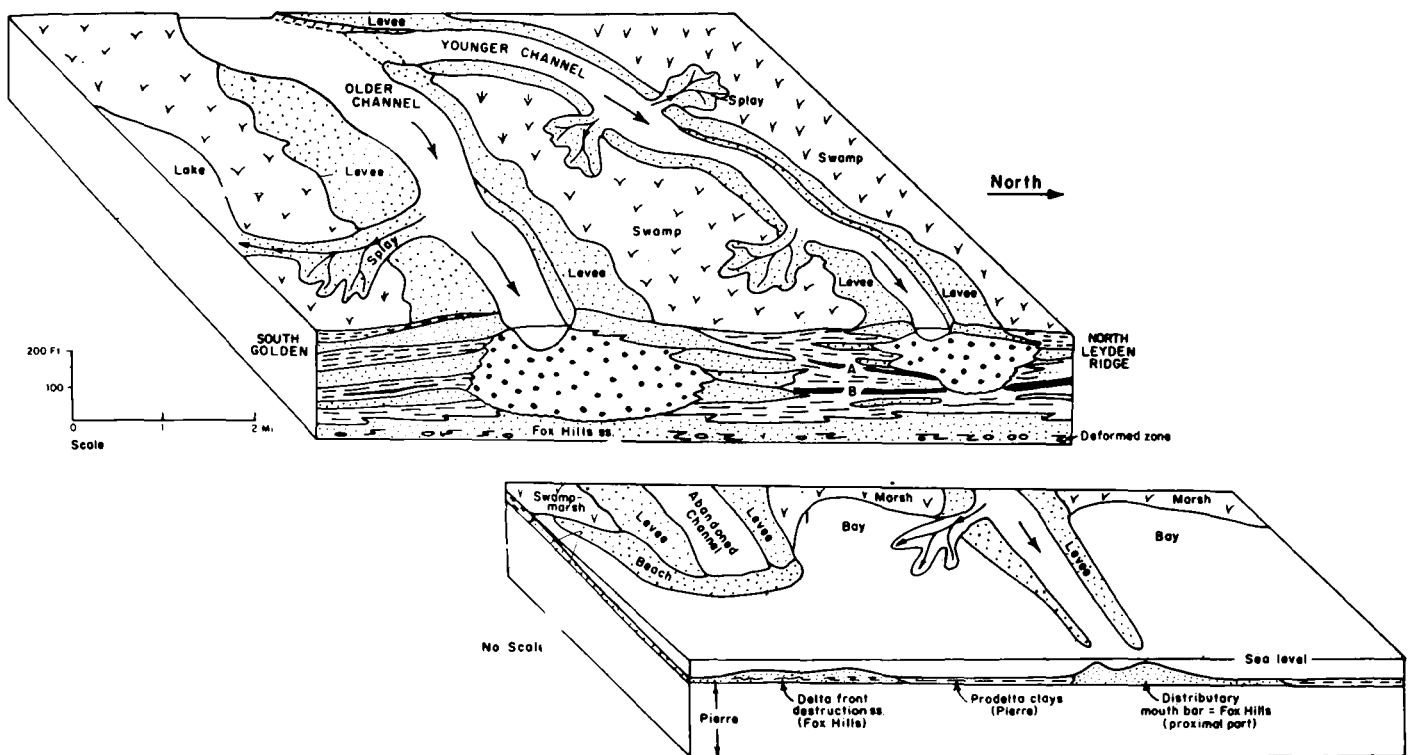


Figure 28. Block diagrams of stratigraphic relationships and environments of deposition in the lower Laramie Formation from Leyden Ridge to Golden (upper diagram) and the hypothesized environment directly east (lower diagram). (from Camacho, 1979 and Weimer, 1973)

From the Foothills district to the Colorado Springs field the lower Laramie coal zone is displaced by faulting and folding in the Front Range structural zone. In this region very little is known about the Laramie coal zone. No coal crops out in this area and the few drill holes that provide reliable data indicate the coal zone is present on the east side of the structural zone at depths of 500 ft (150 m) or more.

Goldman (1910) studied the geology and coal mining history of the Colorado Springs coal field. Much of the information reported here was compiled from Goldman (1910), Colorado Division of Mines (1978a), Kirkham (1978b), and Kirkham and Ladwig (1979). Three coal beds present in the lower Laramie in the Colorado Springs field are termed the A, B, and C beds. The names applied to individual coal beds in this field do not correlate with coal beds similarly named in the Foothills district or elsewhere. Mine data held by the Colorado Division of Mines (1978)

indicate production also occurred from a fourth coal bed, the Fox Hill bed. We believe this bed probably is the same coal bed as coal bed A described by Goldman. Most coal produced in the Colorado Springs field was mined from coal bed A, although many mines worked coal bed B to a limited extent. Over half the total field production is from one mine, the Pikeview or Carlton mine, which worked coal bed A.

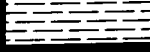
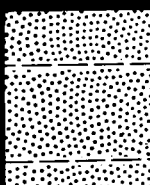
Coal bed A lies about 50 ft (15 m) above the top of the Fox Hills Sandstone. West of Monument Creek coal bed A is poorly developed, but to the east it is up to 20-ft (6-m) thick. Massive sandstone beds similar to those that cap Pope's Bluff commonly overlie and underlie coal bed A. Thin claystone or shale beds are locally present, but rapidly give way to massive sandstone. Coal bed B lies 20 to 30 ft (6 to 9 m) above bed A. It ranges up to 13-ft (3.9-m) thick. Generally the interburden between beds A and B is predominantly massive sandstone. Coal bed C is very lenticular and not found throughout the field. Where coal bed C is present, it is separated from coal bed B by 20 to 50 ft (6 to 15 m) of claystone and sandstones. Thickness of coal bed C rarely exceeds 2 ft (0.6 m).

The Laramie coal zone is thinner on the east flank of the Denver Basin than on the west flank, but individual coal beds are often laterally more persistent on the east flank. Typically the coal zone in this area is up to 150-ft (45-m) thick and consists of one to seven coal beds. Figure 29 summarizes the stratigraphy of the Laramie coal zone near Buick and Matheson. The lowermost of the two prominent coal beds, informally called the A bed, often lies directly on the top of the Fox Hills Sandstone and ranges from 1 to 6-ft (0.3 to 2.0-m) thick. The main coal bed, the B bed, commonly is 8 to 10-ft (2.4 to 3.0-m) thick, but ranges from 1 to 17-ft (0.3 to 5.1-m) thick and locally splits into as many as five thinner beds. Thin, lenticular coal beds may occur above this main bed. Recent work by Brand (1980b, pers. comm.) and a coal exploration company in the northeastern part of the basin near Deer Trail suggest the coal zone in this area is similar to that reported by Kirkham and Ladwig (1979) in the Buick-Matheson area, but that there are usually three major beds present in the Deer Trail area and these may locally split into additional beds.

Lower Laramie coal beds in the Cheyenne Basin generally are thinner, less numerous, and more lenticular than those in the Denver Basin. Because of these factors, the development potential in the Cheyenne Basin is much lower than in the Denver Basin. A few mines in the Wellington field have reported coal beds greater than 5-ft (1.5-m) thick (Colorado Division of Mines, 1978), and drill hole information in this area indicate a 4 to 6-ft (1.2 to 1.8-m) thick coal bed extends over much of the Wellington area. Numerous scattered drill holes throughout the rest of the Cheyenne Basin encounter several coal beds within the lower Laramie, but very few are over 5-ft (1.5-m) thick.

Little is known about the distribution and thickness of lower Laramie coal beds in the deeper parts of the Denver and Cheyenne Basins. The only information is from geophysical logs of oil, gas, or water wells. Unfortunately these logs are usually run at fast speeds and/or do not

include gamma and density readings. Thus, it is difficult to accurately pick coal beds on these logs. Driller's logs from water wells provide a small amount of data, but are often unreliable. What little data are available suggest several areas where lower Laramie coal beds are 5-ft (1.5-m) thick or greater. A relatively large area in T5 and 6S, R62 and 63W is underlain by Laramie coal beds up to 10 to 20-ft (3 to 6-m) thick at depths of 800 to 1,300 ft (240 to 390 m). Similar coal beds probably exist in other parts of the Denver Basin and await discovery.

GEOLOGIC FORMATION		GRAPHIC LITHOLOGY	THICKNESS* (FT.)	DESCRIPTION
LARAMIE FORMATION	UPPER MEMBER		200 - 400	shale and thin sandstone and lignite lenses
			1 - 17	lignite, locally splits into as many as five beds
	LOWER MEMBER		10 - 25	shale
			1 - 6	lignite
	FOX HILLS SANDSTONE		30 - 110	sandstone, thin shale

*thickness not to scale

Figure 29. Generalized stratigraphy of the lower Laramie coal zone, Buick-Matheson area. (from Kirkham and Ladwig, 1979)

Quality of Laramie coal varies from subbituminous B coal to lignite A. Figure 30 illustrates the variation in average as-received heat values. Table 1 lists average as-received analyses from various parts of the study area. Highest quality coal occurs in the Boulder-Weld field, Foothills district, and Colorado Springs field. Coal averages 8,500 to 9,500 Btu/lb and ranks as subbituminous C and B coal in these areas. Within the Boulder-Weld field quality generally decreases from southwest to northeast. Lowest quality coals occur on the eastern flanks of both basins. In the southeastern part of the Cheyenne Basin, a limited number of analyses suggest an average of about 7,200 Btu/lb. Laramie coal

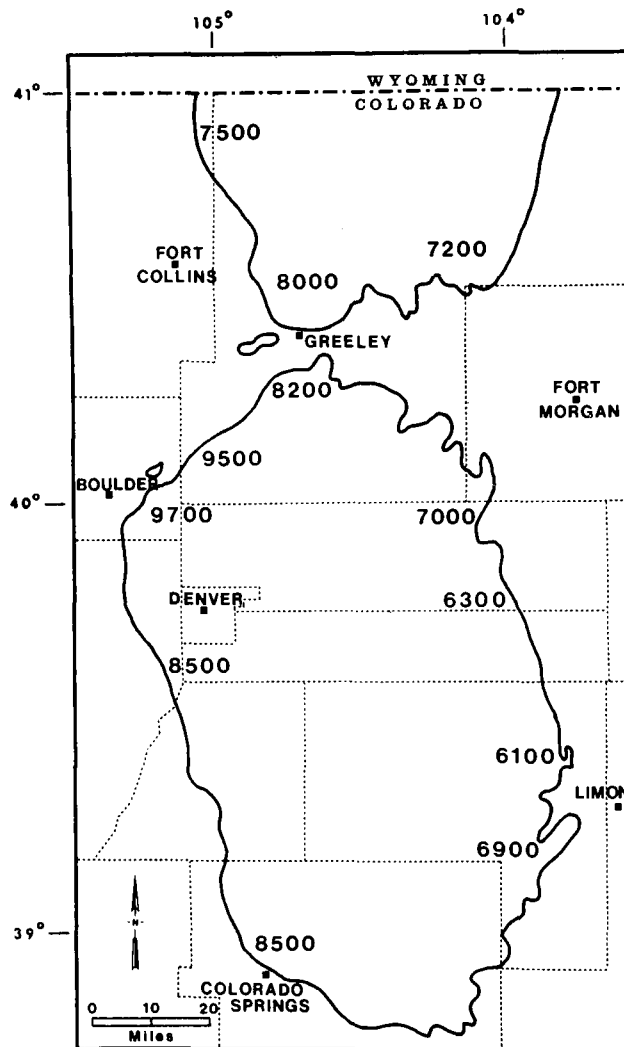


Figure 30. Average as-received heat value for lower Laramie coal. (from Kirkham and Ladwig, 1979)

averages 6,000 to 7,000 Btu/lb as-received in the eastern part of the Denver Basin. Some Laramie coal in the Buick-Matheson area ranks as lignite A. Sulfur content is usually less than 1 percent, although analyses from the Wellington field average 1.7 percent sulfur. The lateral extent of this moderately high sulfur coal is unknown.

Methane content of Laramie coal beds is not well known. Three Laramie coal cores have been desorbed by the Colorado Geological Survey as a part of a Department of Energy-funded investigation (Tremain, 1980, pers. comm.). Their desorption analyses indicate very low methane contents. These cores, however, are from shallow depths where gas leakage is not uncommon. Other lines of evidence suggest there is some methane in Laramie coal beds. Fender and Murray (1978) note several Laramie coal mines that report gas occurrences. Table 2 lists these mines, their locations, and the type and year of gas occurrence. Several water wells tapping the Laramie-Fox Hills aquifer have been contaminated by methane from coal beds in the Denver Basin (Kirkham and Ladwig, 1979; Slyter, 1978, pers. comm.). These occurrences indicate the Laramie coal beds, at least locally, contain significant amounts of methane. The desorption tests indicate the methane does not occur in Laramie coal throughout the study area in a blanket-like manner but the local reports of methane suggest that some sort of trapping mechanisms may control methane accumulations.

Landis (1959) estimated that 649 mi² (1,687 km²) of the study area contained 4.3 billion tons of coal within the Laramie Formation. Hornbaker and others (1976) revised this estimate by assuming two-thirds of the Denver and Cheyenne Basins to be underlain by coal beds similar in thickness and number to coal beds in the areas studied by Landis. Their revised estimate suggests 29.8 billion tons of Laramie coal in the Denver and Cheyenne Basins. Myers and others (1978) document 2.3 billion tons of Laramie coal in just Jefferson County. Kirkham and Ladwig (1979) suggest the study area as a whole contains less coal per square mile than the specific areas described by Landis (1959). They estimate the total remaining in-place resources in Laramie coal beds greater than 2.5-ft (0.75-m) thick at depths less than 3,000 ft (900 m) to be 20 to 25 billion tons.

Denver Formation Lignite

Lignite was first discovered in the study area in outcrops along Coal Creek in Sec. 20, T4S, R65W. These beds were originally believed to be in the Laramie Formation and equivalent to the coal beds later mined near Marshall. Eldridge (in Emmons and others, 1896) described the Scranton lignite mines that operated northwest of Watkins, but incorrectly correlated the lignite beds with the "upper shaly division of the Laramie Formation". Richardson (1915), the first to recognize that the lignite beds were in the Denver Formation, traced them from Fondis and Calhan to near the Scranton mines. This field evidence, combined with fossil data and one poorly logged drill hole, convinced Richardson that the lignite beds mined at Scranton were in the Denver Formation, not the Laramie. Further more detailed studies of the Denver lignite zone have been completed by Soister (1972, 1974, 1978a), Kirkham (1978a, b), and Kirkham and Ladwig (1979). Much of the information presented in this section is summarized from these sources.

Table 1. Average as-received analyses of Laramie Formation coal. (from Kirkham and Ladwig, 1979)

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

Table 2. Gas occurrences in mines, Denver and Cheyenne Basins, Colorado. (from Kirkham and Ladwig, 1979)

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

Thick lignite beds occur in the upper 300 to 500 ft (90 to 150 m) of the Upper Cretaceous-Paleocene Denver Formation. Palynological and paleontological evidence indicate the lignite zone is of Early Paleocene age (Soister and Tscudy, 1978; Middleton, 1980, pers. comm.; Brown, 1943). The base of the Denver lignite zone is 800 to 1,500 ft (240 to 450 m) above the top of the Laramie coal zone. The Denver Formation and included

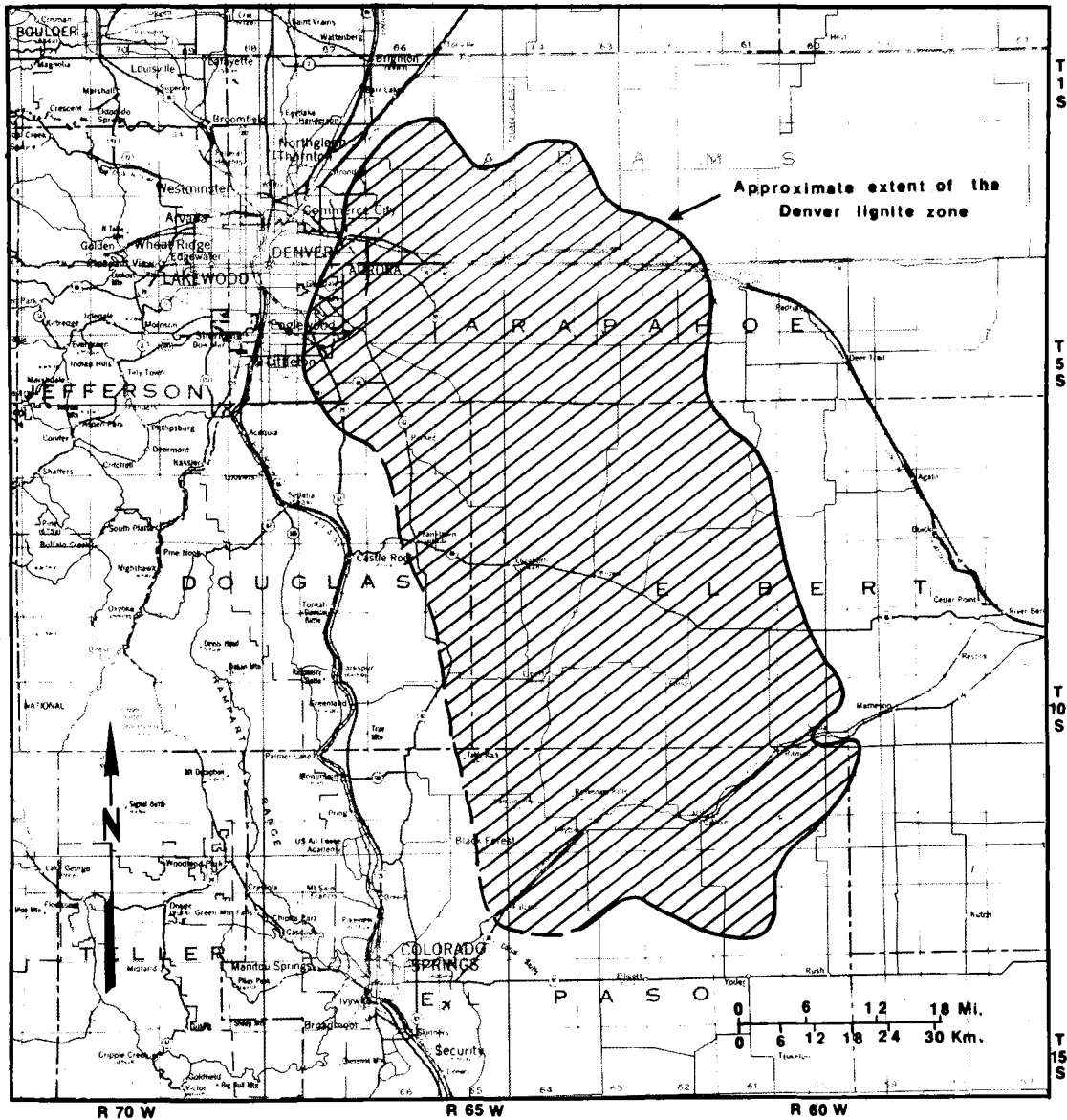


Figure 31. Approximate lateral extent of the Denver Formation lignite zone. (from Kirkham and Ladwig, 1979)

lignite zone are restricted to the Denver Basin (Figure 31) and are absent from the Cheyenne Basin. The area of occurrence extends over a roughly kidney-shaped region encompassing about 1,700 mi² (4,400 km²) from north of Watkins to several miles south of Calhan. Best exposures of individual lignite beds are in West Bijou Creek valley and along Kiowa Creek south of Bennett in stream and road cuts. One lignite bed can be traced in outcrop for about 1.5 mi (2.4 km) in Station Gulch. Additional excellent exposures occur nearby in Big Gulch.

More data on the original distribution of lignite beds come from the study of burnt lignite beds. Several hills in West Bijou Creek valley and elsewhere are capped by baked and fused rock, commonly known as clinker. The clinker formed when burning lignite beds heated or baked overlying strata. Within West Bijou Creek valley the burning probably occurred during the Pleistocene, after initial development of the valley.

In the northern, southern, and eastern parts of the area, the lignite zone consists of three to ten lignite beds of variable thickness, several carbonaceous beds, and interbedded claystone, siltstone, and sandstone beds. Little is known about the lignite zone in the central and western parts of the Denver Basin. The Denver Formation crops out along the western basin margin but in this area the formation contains no known lignite. Available data suggest the number and thickness of lignite beds within the lignite zone decrease westward, especially west of the structural center of the basin. A few, relatively thick lignite beds occur in some of the deeper parts of the basin (Brand, 1980b, pers. comm.), but in general they are less abundant and less persistent than those beds in the northern, eastern, and southern areas. In the eastern part of the basin the top of the lignite zone is at or very near the top of the Denver Formation. Westward, the top of the lignite zone lies farther below the top of the formation.

Many of the lignite beds contain numerous non-coal partings. Parting thickness ranges from less than 0.1 in (0.25 cm) to over 2 ft (0.6 m). Partings may comprise 5 to 30 percent of the total lignite bed thickness. Figure 32 shows an outcrop along Kiowa Creek of a lignite bed with several prominent partings. Some partings are fine- to very fine-grained sandstone, siltstone, and claystone, typical of overbank flood deposits that entered a peat swamp. Most partings, however, are kaolin, a kaolinite-rich rock. Kaolinite is a pale, yellowish-brown mineral that weathers to a light or white color and commonly occurs in both fine- and coarse-grained hexagonal crystalline habits that often appear as "worms". Soister (1978a) has traced a thick parting for about 3 mi (4.9 km) in drill holes in the Strasburg NW Quadrangle. Thin partings in a lignite bed exposed in Station Gulch can be traced in outcrop for over 1 mi (1.6 km). In some areas kaolin beds ranging up to 5-ft (1.5-m) thick overlie and underlie certain lignite beds.

Origin of the partings in the Denver lignite beds have not been studied in detail. Kirkham and Ladwig (1979) suggest that at least a few of the partings are altered volcanic ash layers. These partings are valuable marker beds useful for stratigraphic correlations and depositional-environment guides.



Figure 32. Photograph of a Denver Formation lignite bed that contains four partings along Kiowa Creek.

Thick kaolinitic partings may also be valuable as a potential source of alumina. The U.S. Bureau of Mines has demonstrated that alumina can be recovered from kaolinite, but the process is not yet economic. Table 3 lists the typical parting composition. Alumina (Al_2O_3) is a major constituent of the partings, averaging about 24 percent by weight. Alumina extraction from kaolinite may become commercially feasible in the near future, especially if aluminum prices soar and availability becomes limited.

Kirkham and Ladwig (1979) suggest the Denver Formation lignite zone can be divided into two lignite-bearing areas that are separated by an area nearly barren of lignite. They propose these lignite-bearing areas should be called the northern and southern lignite areas. Their work concentrated in areas where the lignite zone is at strippable depths, therefore, it is unknown whether these lignite areas are recognizable and distinct where the lignite zone is at greater depths.

Figure 33 illustrates the stratigraphy of the northern and southern lignite areas, as proposed by Kirkham and Ladwig (1979). Soister (1972) described and named five thick lignite beds in the Strasburg NW Quadrangle in the northern lignite area. In descending order they are the A, B, C, D, and E lignite beds. Kirkham and Ladwig (1979) adopted this nomenclature

Table 3. Typical analysis (in percent) of kaolinite-rich partings in Denver Formation lignite beds. (from Hand, 1978a; Kirkham, 1979)

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

because these same beds extend throughout much of the northern area and further described a series of unnamed lignite beds below the E lignite bed. The E lignite bed, also informally known as the Watkins bed, can be traced for at least 24 mi (38.4 km) across most of the northern lignite area. It is the thickest lignite bed in the entire study area, commonly ranging between 20 and 30-ft (6 to 9-m) thick and up to a maximum of 54.5-ft (16.4-m) thick near Watkins in sec. 29, T3S, R64W. Lignite beds A through D usually are up to 10 to 15-ft (3.0 to 4.5-m) thick, but locally are over 30-ft (9-m) thick. The B and C lignite beds, respectively, are also known as the Lowry and Bennett lignite beds. In strippable areas the lignite beds that underlie the E bed are thin. Some evidence suggests these underlying beds may locally thicken in the deeper parts of the basin. Brand (1980b, pers. comm.) believes the stratigraphy of the E lignite bed and other beds is much more complex than that suggested by Kirkham and Ladwig (1979). In many areas, the beds split and coalesce rapidly, making correlations using widely spaced drill hole logs tenuous.

Major lignite beds in the southern area, in descending order, are the Wolf, Comanche, Upper Kiowa, Middle Kiowa, Lower Kiowa, and Bijou beds. These bed names were mainly adopted from industry terminology. Lignite beds in the southern area generally are thinner than those in the northern area. The Wolf bed is the thickest lignite bed in the southern area, ranging from 18 to 28-ft (5.4 to 8.4-m) thick. It lies 25 to 75 ft (7.5 to 22.5 m) below the top of the Denver Formation in the eastern part of the basin. The four underlying named lignite beds are usually 5 to 10-ft (1.5 to 3.0-m) thick, but locally are over 15-ft (4.5-m) thick. Other lignite beds lie below the Bijou bed, but in areas where these beds are strippable, they generally are very thin.

The depositional environment of the Denver Formation lignite beds is poorly understood. A detailed evaluation was beyond the scope of this

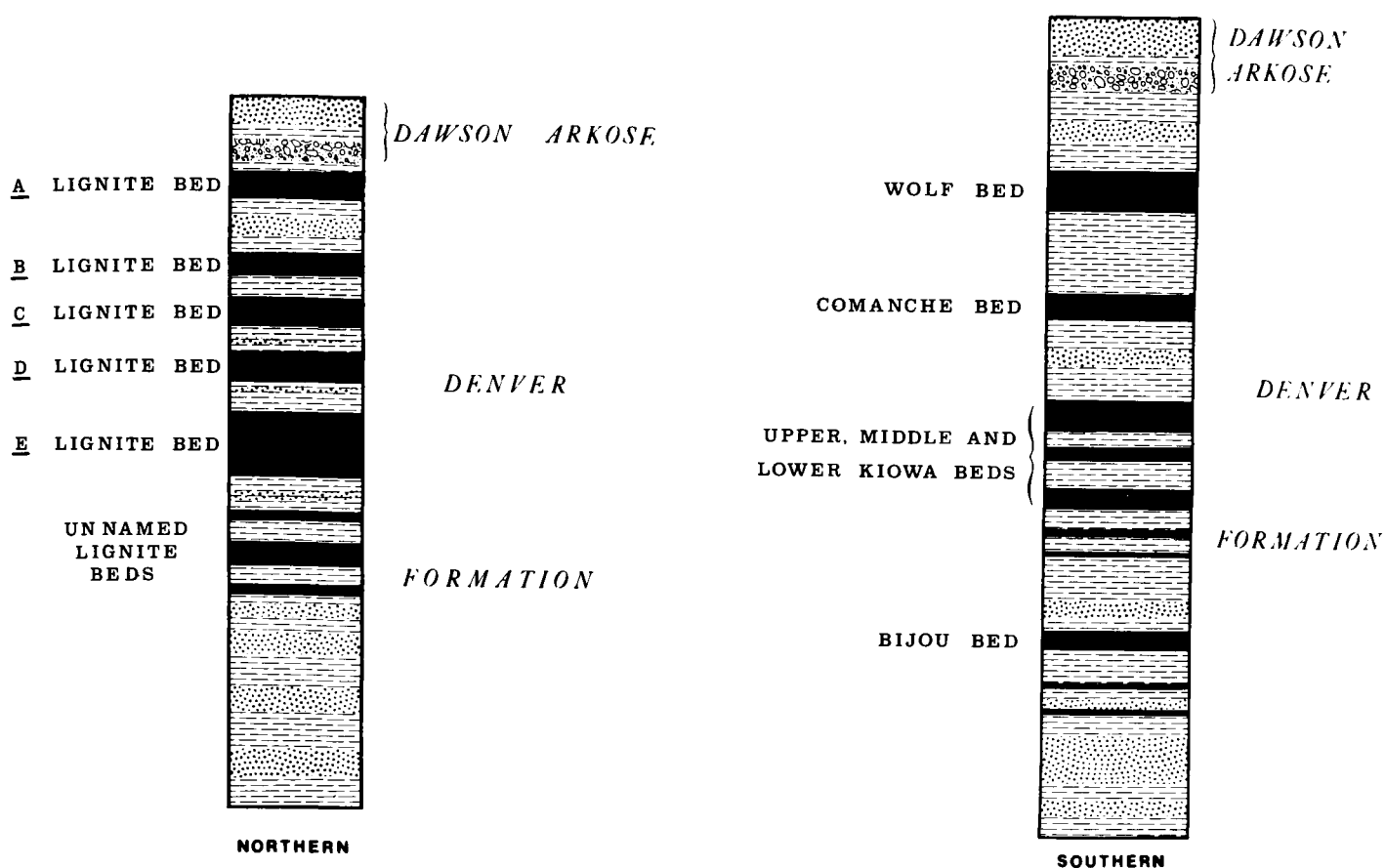


Figure 33. Generalized stratigraphy of the northern and southern lignite areas in the Denver Formation. (from Kirkham and Ladwig, 1979)

investigation, therefore, only a limited description will be presented. The Denver Formation was deposited in a continental environment consisting of meandering stream systems, large overbank flood basins, and, at least locally adjacent to the mountain front, braided stream or alluvial fan complexes. There is much debate as to whether or not the Front Range was a positive element during the Early Paleocene. The authors prefer the interpretation that the Front Range was episodically active to a limited extent during deposition of the Denver Formation. It was not a towering mountain range similar to the present-day Front Range, but probably consisted of gently rolling uplands that were 1,000 to 2,000 ft (300 to 600 m) above the adjacent plains. Rivers that crossed this upland from west to east probably carried more water than the present South Platte River. These rivers brought andesitic material possibly from as far away as Salida. Andesitic flows may have capped the Front Range at this time, and uplift and accompanying erosion would have added additional andesitic

material. Locally, andesitic mud flows were deposited in the Golden-Green Mountain area. The source of these materials was probably high in the Front Range.

A piedmont depositional complex developed along the east flank of the mountain range. In this area meandering stream systems coincided with major drainages and braided streams or alluvial fan complexes and were probably restricted to limited areas directly adjacent to the mountain front between the major drainages. To date, no evidence of major river systems have been described in the eastern part of the basin in the Denver Formation. Numerous small channel sands are present, suggesting several small stream systems rather than one large river system. Most of the eastern part of the basin must have been characterized by widespread, gently subsiding overbank flood basins and peat swamps separated by small stream systems, as evidenced by the extensive, thick lignite deposits, interbedded claystone, and channel sandstones. With time, the piedmont complex along the mountain front extended farther east, forcing a general eastward migration of the coal swamps. Much remains to be learned about the depositional environment of the Denver Formation and included lignite beds. This proposed depositional scenario may be significantly altered as new investigations bring forth additional data.

Quality of the Denver Formation lignite varies due to the number and thickness of non-coal partings and the physical character and rank of the pure lignite. Most analyses indicate the lignite ranks as lignite A. Thin intervals within a thick bed, however, may rank as high as subbituminous C coal. Table 4 lists the typical range of as-received analyses of Denver lignite. For specific analyses, refer to Kirkham (1978b) and Brand (1980a). Ash content varies from 8 to 30 percent and is primarily a function of the non-coal partings. Most lignite beds have at least one or two thin partings and some have many partings. Sulfur content is usually well below 1.0 percent.

Table 4. Typical range of as-received analyses of Denver Formation lignite. (from Kirkham and Ladwig, 1979)

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

The only available methane data on Denver lignite beds are from core desorption tests by the Colorado Geological Survey (Tremain, 1980, pers. comm.). A total of four cores have been tested and all contained very little methane. Recent nationwide methane studies indicate methane content is often directly related to coal quality: the higher the coal quality, the higher the methane content (Tremain, 1980, pers. comm.). In light of these general findings and the four desorption analyses, we believe most Denver lignite beds probably contain very low amounts of methane.

Landis (1959) estimated a total of 0.9 billion tons of Denver lignite in a 187 mi² (486 km²) area of the Denver Basin, primarily in the

Scranton district and Ramah-Fondis area. Soister (1974) estimated about 20 billion tons of lignite in beds 4-ft (1.2-m) thick or greater within 1,000 ft (300 m) of the surface. Hornbaker and others (1976) revised the estimates of Landis (1959) and suggested that over 12 billion tons of Denver lignite lay in the Denver Basin. Soister (1978b) restated his resource estimate at "more than 10 billion short tons" of lignite in beds 4-ft (1.2-m) thick or greater within 1,000 ft (300 m) of the surface. Kirkham and Ladwig (1979) indicated 10 to 15 billion tons of lignite in the Denver Basin in beds at least 4-ft (1.2-m) thick within 1,000 ft (300 m) of the surface and probably less than 1 billion tons of lignite at depths greater than 1,000 ft (300 m).

Mining History

The earliest records of coal mining in the Denver and Cheyenne Basins were reported by Hayden (1868), Hodge (1872), and Marvine (1874). The Marshall mines in the Boulder-Weld coal field were probably the first mines to operate in the study area. Hayden (1868) indicates the mines were producing coal four or five years before he visited them, thus indicating production initiation in 1863 or 1864. Marvine (1872) reports that the Marshall mines began operations in 1863. Small unrecorded ranch-type mines may have operated a few years before 1863, but production undoubtedly was limited.

In 1883 the Colorado State coal mine inspector began keeping extensive, state-wide records of coal-mining activities. These valuable, unpublished records are held by the Colorado Division of Mines, Department of Natural Resources, at 1313 Sherman Street, Denver, and are available for public inspection. Over a dozen mines were producing coal by 1883 when the State coal mine inspector began keeping records. From 1883 into the 1920s, the number of mines and total production gradually increased. Production activity slowed in the late 1920s and early 1930s and has continued to decrease ever since. There currently are no active mines in the study area. The most recently active mine was the Lincoln mine, located in the Boulder-Weld field. It was closed in 1979 because of a fire. The present energy and economic situation is forcing a return to coal as a source of energy throughout the United States. This affects the mining potential of the study area, and large increases in coal production are foreseen for the near future. A complete discussion of the anticipated coal mining activity is presented in a following section on development potential.

Over 130 million tons of coal and lignite have been mined in the Denver and Cheyenne Basins since 1883 (Colorado Div. Mines, 1979). Table 5 lists cumulative coal and lignite production by county as of December, 1979. Of the total recorded production 130,159,777 tons (99.95 percent) were mined from the Denver Basin and only 66,974 tons (0.05 percent) were mined in the Cheyenne Basin. Only 39,376 tons (0.03 percent) of the total is lignite from the Denver Formation, whereas 130,187,375 tons (99.97 percent) is from the Laramie Formation. 129,972,228 tons (99.80 percent) were produced from underground mines and only 254,523 tons (0.20 percent) were from surface mines.

Table 5. Cumulative coal and lignite production by county through December, 1979 in the Denver and Cheyenne Basins, Colorado. (from Kirkham, 1978b; Boreck, 1979; Deborski, 1979; Colorado Div. Mines, 1979)

<u>COUNTY</u>	<u>PRODUCTION (short tons)</u>
Adams	37,112
Arapahoe	470
Boulder	41,327,996
Douglas	25,667
Elbert	108,948
El Paso	16,164,310
Jefferson	6,622,522
Larimer	54,611
Weld	65,881,085
TOTAL	130,226,751

Figure 34 shows the general outline of coal and lignite mining areas described by Landis (1959). Table 6 lists production totals and producing formation for each area. The Boulder-Weld field has produced the greatest amount of coal, but significant tonnages were also produced at the Colorado Springs field and Foothills district. All other designated areas produced only small amounts of coal or lignite. Additionally, a very small amount was also mined in isolated, unnamed areas and is not included in these figures.

Development Potential

Development potential of the coal and lignite resources of the Denver and Cheyenne Basins is high. Currently no mines are active in the study area, but several mines have been recently proposed. They are either in the permitting process or have obtained all necessary permits and initiated mine construction. There are also several mining projects in various planning stages. In light of the energy and economic situation facing our country and the Federal impetus toward development of coal and alternative sources of energy, particularly coal gasification and liquefaction, any forecast must anticipate increased utilization of coal over the long term throughout the country. The coal and lignite deposits in the study area are not the highest quality deposits in the country, nor are they the easiest or most economical to mine. But the fact that they are very near major population centers and may be suitable for both steam coal and many alternative uses tends to balance out their unfavorable characteristics. Increased utilization of the coal and lignite resources of the Denver and Cheyenne Basins, over the next 10 to 20 years is likely.

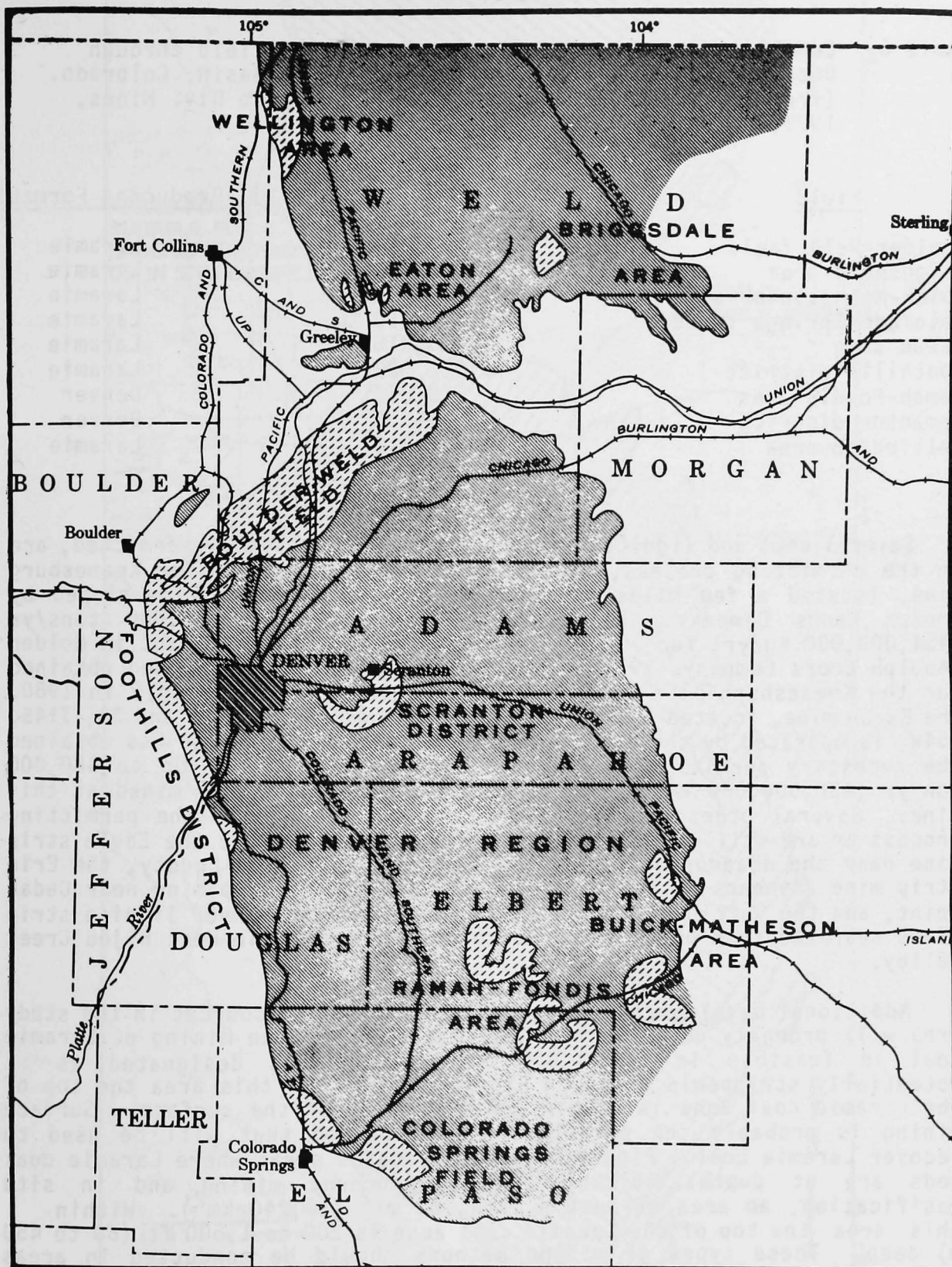


Figure 34. Coal and lignite mining areas in the Denver and Cheyenne Basins.
(from Landis, 1959)

Table 6. Cumulative coal and lignite production by field through December, 1979 in the Denver and Cheyenne Basin, Colorado. (from Kirkham, 1978b; Boreck, 1979; Colorado Div. Mines, 1979; Deborski, 1979)

<u>Field</u>	<u>Production (short tons)</u>	<u>Producing Formation</u>
Boulder-Weld field	107,196,718	Laramie
Briggsdale area	3,229	Laramie
Buick-Matheson area	106,740	Laramie
Colorado Springs field	16,164,310	Laramie
Eaton area	8,018	Laramie
Foothills district	6,622,522	Laramie
Ramah-Fondis area	3,047	Denver
Scranton district	35,789	Denver
Wellington area	54,611	Laramie

Several coal and lignite mining projects are presently permitted, are in the permitting process, or are in planning phases. The Keenesburg mine, located a few miles north of Keenesburg, is being developed by Adolph Coors Company. They plan to produce about 500,000 tons/yr (454,000,000 kg/yr) for use as steam coal at their power plant in Golden (Adolph Coors Company, 1979). All necessary permits have been obtained for the Keenesburg mine and mine construction initiated early in 1980. The Bacon mine, located east of Colorado Springs in secs. 29 and 30, T14S, R64W, is operated by the A. T. Massey Coal Company. It also has obtained the necessary permits and initiated mine construction. Up to 480,000 ton/yr (436,000,000 kg/yr) of Laramie coal will be strip mined at this mine. Several other proposed and planned mines are in the permitting process or are still on the drawing board. These include the Eagle strip mine near the abandoned underground Eagle mine in Weld County, the Erie strip mine adjacent to the town of Erie, the Limon strip mine near Cedar Point, and the Watkins project, which could involve Denver lignite strip mines near the town of Watkins, south of Watkins and in West Bijou Creek valley.

Additional development of the coal and lignite resources in the study area will probably occur in the near future. Surface mining of Laramie coal is feasible in the 1,850 mi² (4,810 km²) designated as potentially strippable areas on Figure 35. Within this area the top of the Laramie coal zone is within 200 ft (60 m) of the surface. Surface mining is probably the principle mining method that will be used to recover Laramie coal. Figure 35 also indicates areas where Laramie coal beds are at depths suitable for underground mining and in situ gasification, an area of just over 4,000 mi² (10,240 km²). Within this area the top of the Laramie coal zone is 200 to 1,500 ft (60 to 450 m) deep. These types of mining methods should be conducted in areas unlikely to be urbanized or at such depths that surface subsidence will be minimal.

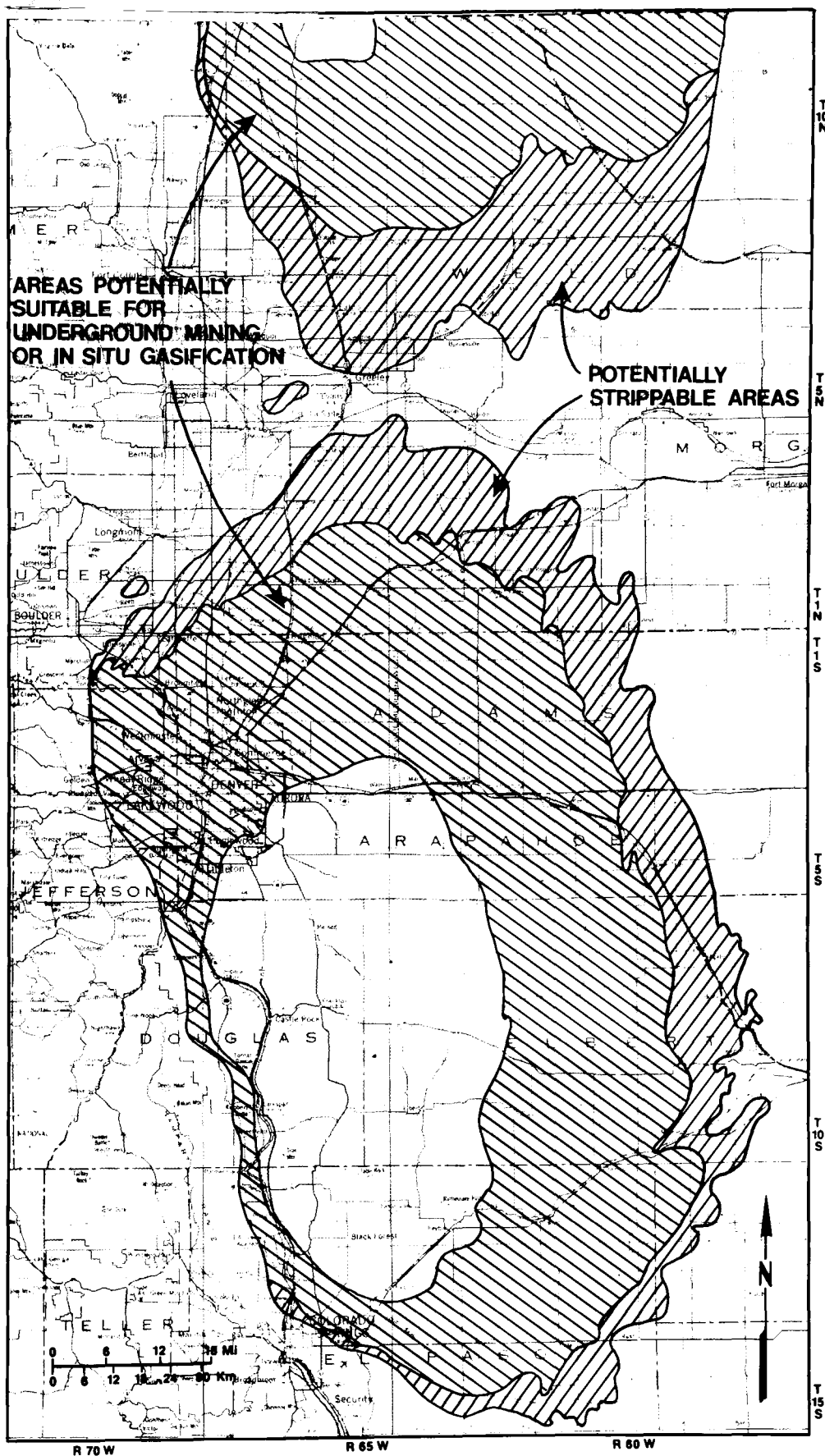


Figure 35. Areas in which Laramie coal beds are potentially suitable for strip mining, underground mining, and underground gasification.

Widespread underground mining of Laramie coal in the near future is considered unlikely. Underground coal mines are very expensive to construct and operate. Unless a coal bed is of high quality or strippable coals do not exist in the region, underground mining is not usually economically competitive. Underground mining of Laramie coal, however, should not be totally ignored. Some companies are presently interested in it, and as the economic and technological situation evolves, underground coal mining may once again become competitive.

In situ coal gasification is a relatively new recovery technique in the United States. If this technology receives widespread usage, it may be utilized for Laramie coal in the eastern part of the study area where the coal is lignite and has relatively high permeabilities, or along the mountain front where techniques used to gasify steeply dipping beds may be employed.

Figure 36 indicates areas where the Denver lignite zone is potentially strippable. In the designated potentially strippable area the top of the Denver lignite zone is within 200 ft (60 m) of the surface. The potentially strippable area extends over about 980 mi² (2,500 km²) of the Denver Basin. It is highly unlikely that Denver lignite beds will be mined underground because of hazardous working conditions and economic problems. Generally roof rock above Denver lignite beds is very weak. Mine cave-ins and squeezing problems would probably be very common. Denver lignite beds may be strip mined and used as feedstock for electric power plants or surface gasification and liquefaction plants. Denver lignite may also be suitable for other types alternate energy technologies. A power plant would have to be specially designed to burn Denver lignite. The abundance of nearby, higher quality coal in Colorado and Wyoming limits the potential use of Denver lignite in power plants. The potential for use in surface gasification plants, such as that proposed for the Watkins area, however, is high. Surface gasification and/or liquefaction plants could require several million tons of lignite per year. Although no test results are publicly available, Denver lignite appears to be well suited for in situ gasification. If in situ gasification becomes a viable mining method, it probably will be used on the deeper Denver lignite beds and could become the most feasible method of utilizing Denver lignite.

Methane occurs in Laramie coal beds in several areas. Until further testing for methane content is completed, the potential for methane extraction from Laramie coal is uncertain. Existing analyses indicate Denver lignite beds contain little methane. The potential for methane in Denver lignite thus appears to be low.

One of the major factors limiting coal and lignite development in the study area is water availability. Virtually all surface and tributary water in the study area is appropriated and in many cases it is over-appropriated. If tributary water is needed for a project, it would be necessary to obtain suitable water rights or implement an innovative source of waste water, possibly similar to that proposed for the Watkins project (Hand, 1978b). Non-tributary ground water is available in several

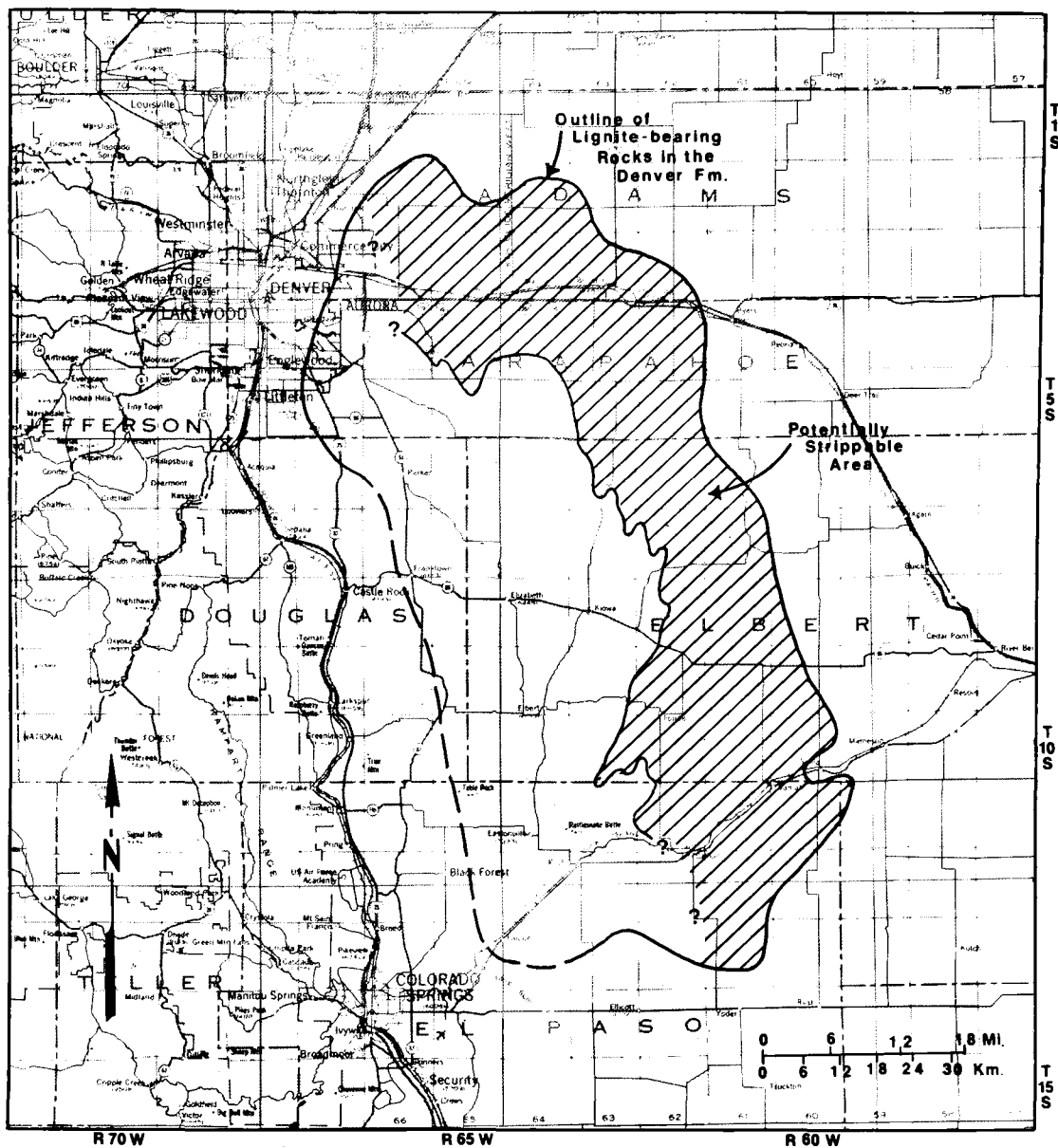


Figure 36. Potentially strippable areas, Denver Formation lignite.

formations in the study area, but it is limited in quantity. The State Engineer, Division of Water Resources, restricts what ground water and how much ground water can be withdrawn by a particular user. Most conventional surface and underground mines and in situ gasification facilities would not be seriously affected by this water-supply problem, but large water-consuming projects such as surface gasification and liquefaction plants would have to deal with it (Romero, 1978a).

An important factor controlling the location of future surface mines is the distribution of alluvial aquifers that may be classified as alluvial valley floors according to Public Law 95-87. Figure 15 illustrates the general distribution of probable and possible alluvial aquifers in the study area. A significant part of the area is underlain by these deposits. Most of the probable alluvial aquifers and a small part of the possible alluvial aquifers may be classified as alluvial valley floors. Detailed studies will be required to determine the extent of alluvial valley floors at individual mine sites.

MINING METHODS

After discovery and evaluation of a coal deposit, a mining method must be selected that can physically and economically recover the coal in an environmentally acceptable manner. Most coal is mined by one of two mining methods: surface or underground mining. Several new, non-conventional coal recovery techniques are also being developed, but have not been utilized on a commercial scale. Primary factors that must be considered in the mine selection process are the amount of overburden, bed thickness, deposit size, overburden characteristics, ratio of overburden thickness to coal thickness, and coal quality. Modern technology allows surface mining of coal to great depths, as is currently practiced in some parts of Europe, but economic factors generally limit surface mining in the western United States to depths of 200 to 300 ft (60 to 90 m). In certain cases where extremely thick coal beds are present, surface mines utilizing open-pit methods may be up to 500-ft (150-m) deep.

Other factors to consider when selecting a mining method or designing a mine for a particular site are mine safety, production capacities, nature and strength of roof and floor rock, discontinuities or irregularities of the coal bed and overburden, dip, cleat, methane content, coal hardness, and surface and subsurface hydrologic conditions (Schroder, 1973). Generally, surface mining of relatively shallow coal beds is preferred by industry over underground mining because surface mines have 1) lower manpower requirements, 2) shorter lead time to production initiation, 3) fewer safety problems, 4) higher recovery rates, and 5) the ability to easily transfer equipment to other operations when the mine is abandoned (Train and others, 1975).

Two relatively new coal utilization techniques are presently being extensively experimented with by the Federal government and industry. In situ or underground coal gasification differs from conventional surface and underground mining in that the coal is not removed from the subsurface. It is burnt in situ (in place) and the resulting products are brought to the surface. Hydraulic borehole or slurry mining involves a series of drill holes into which a borehole tool with cutting jets is lowered. Water is forced through the jets at high pressures to break the coal into small particles and the coal-bearing slurry is piped to the surface. These techniques have not been commercially utilized in the United States. Because of this the eventual applicability of the methods is not precisely understood, and little is known about environmental problems associated with full-scale projects.

Historically most coal production throughout the United States, including Colorado, has been from underground mines. Surface mining has accounted for less than 0.25 percent of the total coal production in the study area. These figures are somewhat misleading in that current mining trends are toward increased surface mining. Figure 37 illustrates the U.S. production of bituminous coal and lignite by type of mining. At the turn of the century virtually all coal was mined underground. Surface mining was seldom used until the 1920s and 1930s. Several surface mines initiated operations at this time in the study area, including the Barker,

Cox, Jordan, Stimson, and Wright. From this time on, however, surface mining has enjoyed increased usage in the United States, primarily a result of the growing availability of giant surface mining equipment. By the mid-1970s, U.S. coal production from surface mining exceeded production from underground mines. Much of the anticipated future coal production in the study area and throughout our country will probably be from surface mines. Underground coal gasification, should it become economically and technologically feasible, could be widely used in the U.S. and in the study area. Zukor and Burwell (1979) estimate that underground coal gasification could quadruple the usable coal resources of the U.S.

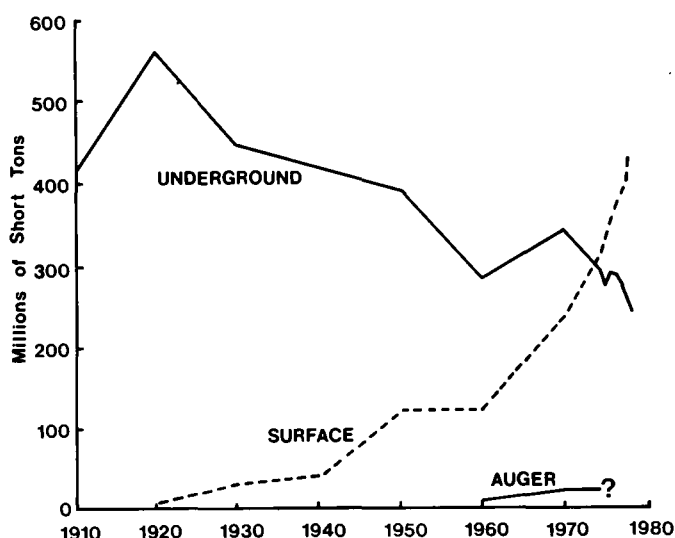


Figure 37. U.S. bituminous coal and lignite production by mining method. (after Hebb and Morse, 1976; Coal Age Mining Informational Sources, 1979; and U.S. Bureau of Mines)

Surface Mining

MINING PROCEDURE

Several types of surface mining methods commonly are employed in the United States: area mining, contour mining, open-pit mining, and auger mining (Phelps, 1973). Area mining, also known as strip mining, is used in level to gently rolling terrain where coal beds are relatively flat-lying. In such a situation depth to the coal remains fairly constant

over a large area. Area mines can produce tremendous quantities of coal at low costs. The mine consists of a series of parallel, excavated pits up to several thousand feet long. The initial pit is usually opened up where the overburden is thinnest, and additional pits are excavated in adjoining areas where overburden is progressively thicker. A typical view of an area mine is shown in Figure 38. Before any actual mining takes place, the surface must be prepared. Access roads and personnel, maintenance, and production facilities must be constructed. Utilities must be brought to the site, and vegetation, such as trees and bushes, must be removed. After vegetation removal the topsoil is removed and stockpiled for later use in site reclamation.

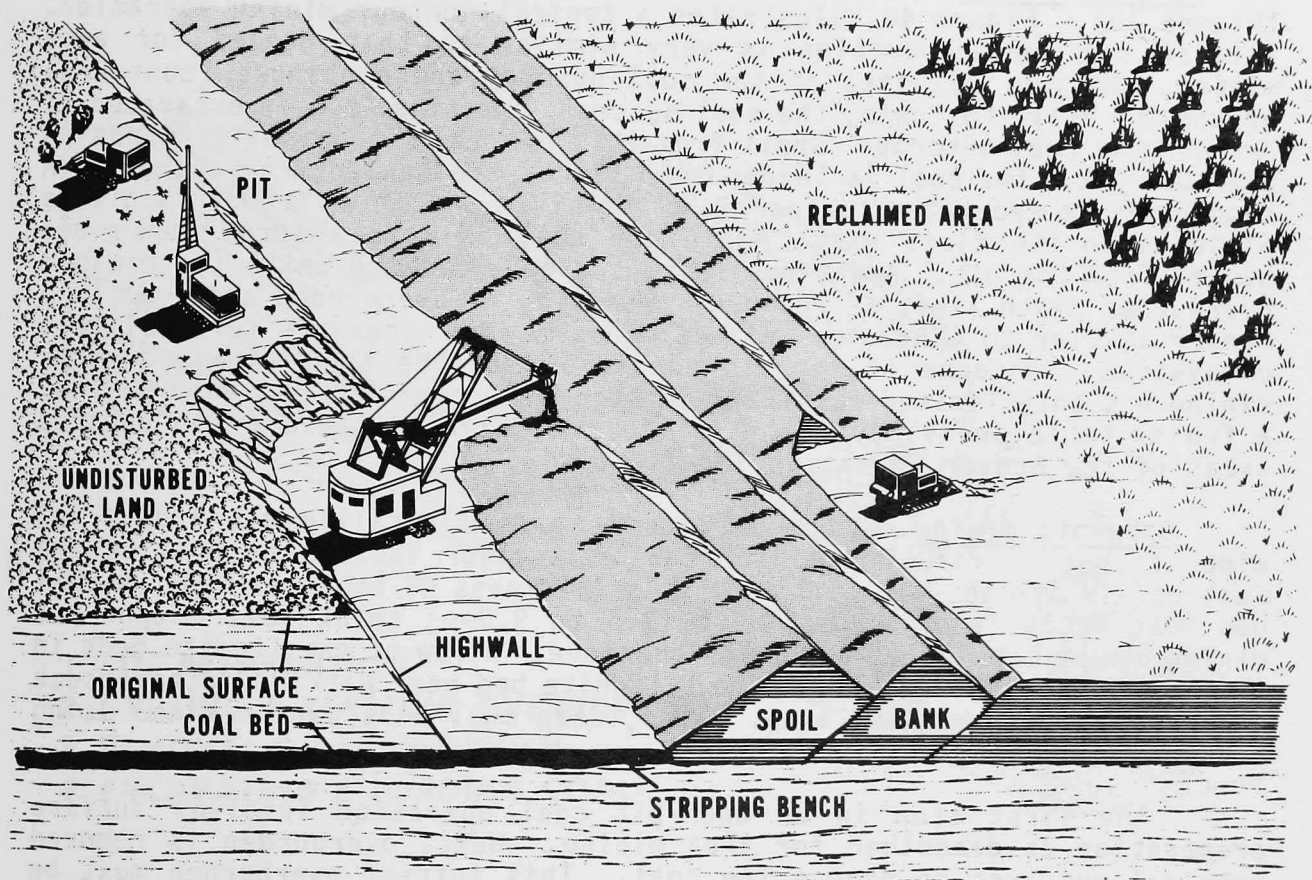


Figure 38. Area surface mining of coal. (from Grim and Hill, 1974)

Mining begins by making an initial box-cut or trench extending across the area. Overburden spoil from the initial pit is placed on the ground surface and the coal is removed and hauled to market. The initial pit is backfilled by spoil from the second pit. Adjacent pits are mined and backfilled in a similar way. In many mines it is necessary to blast the overburden and/or the coal to facilitate excavation. Blasting holes, commonly 0.5 ft (0.15 m) in diameter, are drilled in a grid pattern with 15 to 30-ft (4.5 to 9.0-m) spacing. A mixture of ammonium nitrate and fuel oil is often used for the blasting charge and is detonated by an electric blasting cap. Coal recovery rates range from about 80 to 95 percent for area mining, with losses mainly due to spillage during loading and hauling.

Contour mining is used on coal beds in mountainous or hilly terrain (Figure 39). Figure 40 illustrates a typical contour mining operation. Initial surface preparation is very similar to that needed for area mining. Mining initiates at the coal outcrop and continues (contours) around the hill, following the coal outcrop. The first pit is excavated at or near the coal outcrop. Spoil from this cut is cast downhill, exposing the coal bed. The coal is loaded into trucks and hauled from the pit. A second pit is excavated further into the hill, and spoil from this pit is placed into the first pit. Again the coal is loaded into trucks and hauled from the pit. Additional pits can be excavated until the maximum overburden depth limit is reached. Blasting of overburden and coal in a manner similar to that used in area mines may be necessary to facilitate excavation. Because of terrain conditions in the study area, contour mining has only limited applicability in the Denver and Cheyenne Basins. A few suitable areas may exist in the Boulder-Weld field or in outcrop areas of the Denver Formation lignite beds.

Open-pit mining is commonly used to mine metallic and industrial minerals but is rarely used for coal. A major factor controlling the feasibility of open-pit coal mining is thickness of the coal bed. A coal bed must be at least 25 to 30-ft (7.5 to 9.0-m) thick before open-pit mining can be considered a viable technique. A few of the lignite beds in the Denver Formation, such as the E lignite bed near Watkins, attain such thicknesses in the study area. Also, deep coal beds can be mined using open-pit methods.

The first step in an open-pit coal operation involves surface preparation as described for area mining. Next, overburden is removed over a large area to expose the coal. This initial overburden must be hauled from the mine and stored, at least temporarily, on the surface. After the coal is removed from this cut, additional overburden created by mine expansion can be cast into areas where coal has been extracted, thus avoiding haulage of spoil out of the pit. Pit walls may have to be benched to aid stability. After completion of mining the open pit is often left unreclaimed.

Auger mining is often used to complement or complete a conventional surface mining operation and occasionally may be employed as the primary mining technique. After a surface mining operation has reached a point

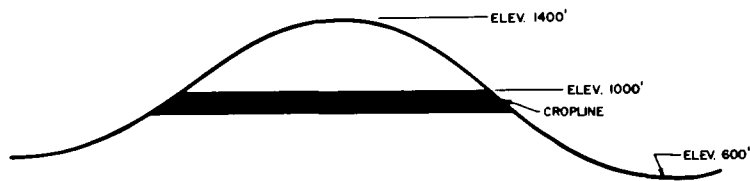


Figure 39. Example of the type of terrain suitable only for contour mining.
(from Phelps, 1973; courtesy of A.I.M.E.)

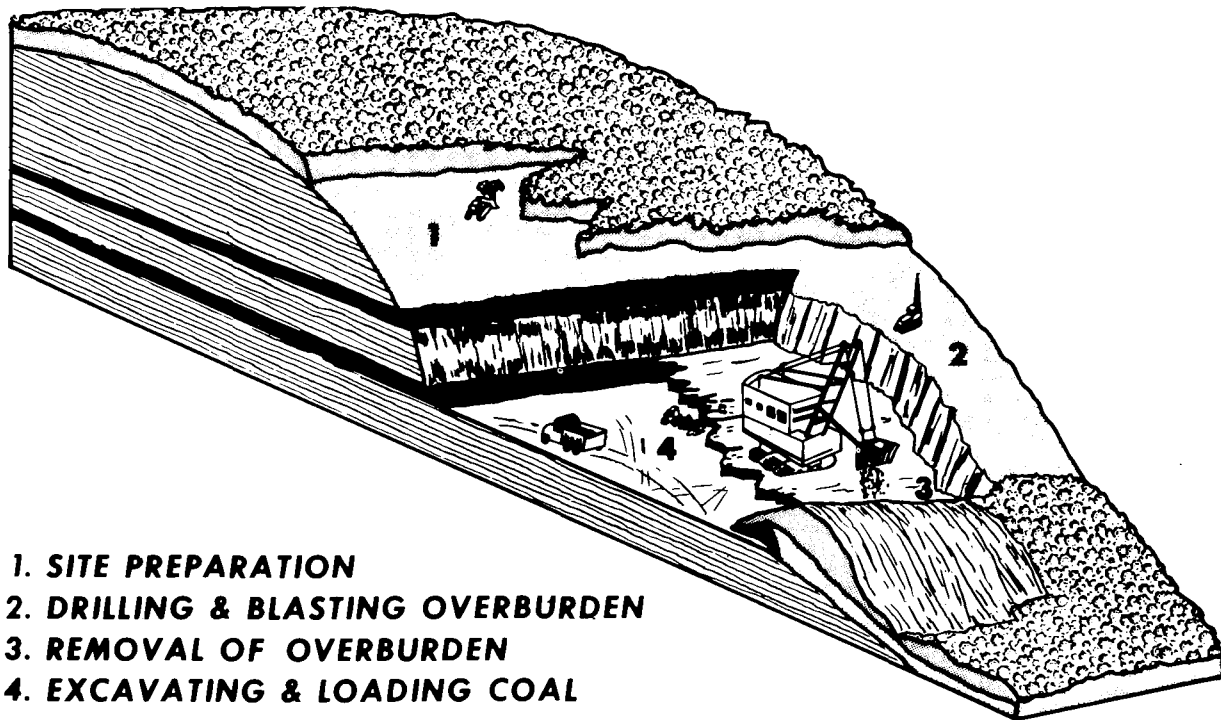


Figure 40. Cross section through a typical contour mining operation. (from Phelps, 1973; courtesy of A.I.M.E.)

where it is no longer capable of economically mining a coal bed (because the high wall is too high), a coal bed remains exposed at the bottom of the high wall. If a large quantity of coal remains, an underground drift mine can be developed into the high wall. In many cases, however, tonnage reserves are too small to justify development of an underground mine, the coal bed is too thin for economic underground mining, or abandoned underground mine workings exist which create safety hazards. In such a situation auger mining may be applicable. Augers can often recover coal that is economically impossible to recover using any other mining technique. Figure 41 illustrates use of auger mining as a complimentary method of contour mining.

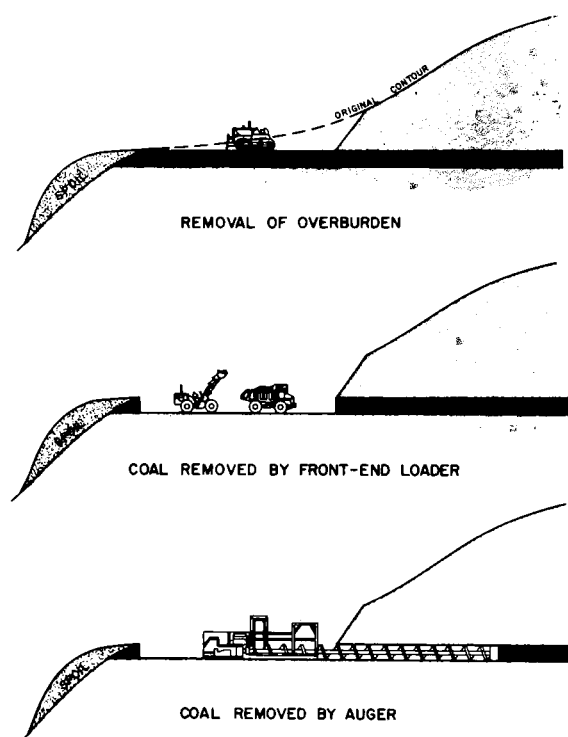


Figure 41. An example of using auger mining to complement a contour mining operation. (from Phelps, 1973; courtesy of A.I.M.E.)

Auger mining involves drilling a horizontal hole into a coal bed. The auger rotates, advances forward, and backs the coal cuttings out of the hole by the spiraling action. Coal is discharged at the mouth of the auger hole and is loaded onto a conveyor system or a truck for transportation. Auger penetration up to 200 ft (60 m) beyond the outcrop is possible and is accomplished by adding additional auger lengths to the

cutting head drifts into overlying or underlying strata, encounters a previous hole, or until the maximum penetration distance is achieved (Phelps, 1973). Additional auger holes are drilled by moving the augering machine along the high wall and drilling new holes. Coal varying in thickness from 0.5 to 3.0 ft (0.15 to 0.9 m) must be left between holes (called webs, ribs, or fins) and at the top and bottom of the coal bed. High wall instability and squeezing of holes may necessitate leaving barrier pillars between groups of augered holes. Because of these factors, total recovery for auger mining usually averages less than 30 percent. Auger mining generally produces coal at a lower cost per ton than do other mining methods.

Types of heavy equipment used at surface mines to mine and haul the coal and overburden include mobile tractors and trucks, power shovels, draglines, and bucket-wheel excavators. Most operations use combinations of this equipment, but one or two types usually dominate the operation. Bulldozers, scrapers, front-end loaders, and heavy haul trucks are types of tractors and trucks used for surface mining. They are often used for the removal, loading, and hauling of coal and top soil, road and bench construction, leveling spoil piles, and, at small mines, removing and transporting overburden. Principal advantages of this type of equipment are maneuverability, capacity to work on steep grades, and relatively low cost. Large electrical- or diesel-powered shovels commonly are used to remove and load overburden at small mines and load coal at large mines.

Draglines (Figure 42) are the most popular type of equipment used for overburden removal at large surface mines. They are preferred for a number of reasons, including 1) great flexibility to handle overburden, 2) ability to mine thick overburden, 3) capacity of digging deep box cuts or initial cuts, 4) ability to operate out of the pit, 5) low cost relative to mining capacity, and 6) low maintenance (Phelps, 1973). A dragline operates by casting its bucket into the overburden and loads the bucket by dragging it toward the machine. The dragline then lifts the bucket, rotates, and dumps the load on the spoil pile.

The bucket-wheel excavator (Figure 43) is commonly used in Europe, but to date has not been successfully used in the United States. The machine has a rotating bucket wheel at the end of a boom that is used to mine overburden. The wheel is up to 50 ft (15 m) or more in diameter with equally spaced buckets on it that hold from 1/3 to over 6 yd³ (0.25 to 4.58 m³) of material. The bucket-wheel excavator differs from conventional excavators markedly. Conventional excavators must dig, lift, swing, and dump. Each action must be performed separately. The bucket-wheel excavator continuously digs overburden and performs all actions simultaneously. The overburden is transferred by a series of conveyor belts within the machine to a spoil pile behind the machine. It can dig overburden faster than any other type of excavator, but it has one major drawback--it can only dig relatively soft rock. Throughout most of the United States this problem limits the applicability of the bucket-wheel excavator, although it could be successfully used in combination with a shovel at some mines. Within the study area the bucket-wheel excavator may be suitable for removal of overburden above



Figure 42. Photograph of a drag line, at a coal strip mine in Routt County, Colorado. (photograph by J. M. Soule)

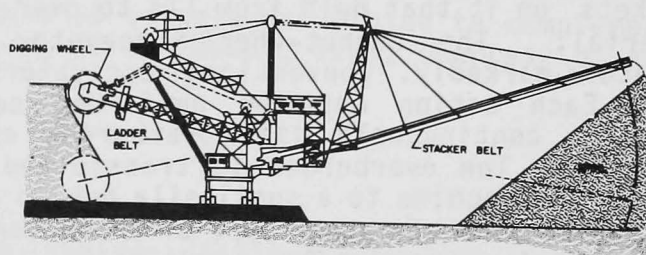


Figure 43. Side view of a bucket-wheel excavator. (from Phelps, 1973; courtesy of A.I.M.E.)

Denver Formation lignite beds, because this overburden generally is not well indurated. It may also eventually be used for the actual digging of the lignite.

WASTES AND EFFLUENTS

Atmospheric Emissions

Surface coal mines may produce atmospheric emissions from several sources, including 1) fugitive dust, 2) vehicular emissions, and 3) combustion of waste piles. Fugitive dust results from the blasting, loading, and hauling of overburden and coal, vehicular traffic on dirt roads, wind erosion of exposed spoil piles and broken rock within the mine, and regrading of spoil piles during reclamation. Diesel- and gasoline-fueled heavy equipment used in the mining operation emit carbon monoxide, nitrogen and sulfur oxides, unburned hydrocarbons, and particulates. Waste piles containing coal may ignite spontaneously and burn, releasing products of combustion and unburned materials into the atmosphere. Table 7 summarizes the atmospheric emissions of a typical surface coal mine producing 12 million tons/yr (10.9 billion kg/yr) of coal. Mines of this size may be developed to exploit Denver Formation lignite beds, but Laramie coal mines will probably produce significantly less coal and have corresponding lower emission rates.

Table 7. Atmospheric emissions from mining and reclamation phases of a typical 12 million ton/yr (10.9 billion kg/yr) area coal mine. (from White and others, 1979a)

EMISSION SOURCE	PRODUCTION RATE	EMISSION RATE (lbs/hr)					
		Particulates	CO	NO _x	SO ₂	Hydrocarbons	CO ₂
Diesel Engines	250 gal/hr	6	23	100	8	8	5500
Fugitive Dust							
Mining	1375 tons/hr	1100	--	--	--	--	--
Reclamation	180 acres	600	--	--	--	--	--

Solid Wastes

The only significant solid waste from surface coal mining is overburden, or spoil, which must be removed to expose the coal bed. The amount of solid waste generated by surface mining depends on the types of mining and reclamation methods utilized. Most overburden is usually used

in subsequent reclamation efforts and, therefore, is not considered a waste product. Generally open-pit mining creates the greatest volume of solid waste. During initial construction of the pit, all overburden must be hauled from the pit to allow for mine expansion and access to the coal bed. Once coal removal has been initiated, additional overburden may be used to backfill mined-out areas, thus minimizing the amount of overburden that must be hauled from the pit.

An open-pit mine with an initial pit opening in excess of 25 acres (101,000 m²) and an overburden thickness of 100 ft (30 m) could generate about 100 million ft³ (2.8 million m³) of solid waste before any spoil could be used as backfill in the mine. An area surface mine may need only 10 acres (40,000 m³) for this initial box cut. If overburden thickness is again 100 ft (30 m), only about 40 million ft³ (1.1 million m³) of spoil would be generated. A contour mining operation would create even less solid waste, but it also would not produce large quantities of coal.

Physical and chemical characteristics of the spoil depend upon the characteristics of the overburden. Throughout most of the study area, overburden above coal and lignite beds is poorly indurated claystone that will readily break into small clasts and fine-grained material and can be easily compacted. Occasional sandstone beds may be encountered, but generally only those above Laramie coal beds are well indurated and break into large blocks. Minimal information is available on overburden chemistry in the study area.

Liquid Wastes

Liquid wastes associated with surface coal mining primarily result from water that enters the mine and must be removed in order to continue mining. Such water may originate as precipitation that falls into the mine, ground water that leaks into the mine from aquifers penetrated by the mine, and surface water that flows into the mine. The water usually incorporates suspended solids, and after coming into contact with the exposed coal and overburden in an oxidizing environment, it often gains dissolved solids. Potential pollutant parameters in contaminated water may include acidity, the dissolved solids of iron, aluminum, nickel, manganese, sulfate, ammonia, nitrate, fluoride, strontium, zinc, arsenic, copper, and lead, and total suspended solids (Train and others, 1975; White and others, 1979a). Specific contaminant concentrations will, of course, depend on coal and overburden chemistry at a particular mine. Generally acidity and iron are not serious problems in the west because of the low amounts of iron sulfides associated with the coal beds. Mine water from many western mines is actually alkaline (White and others, 1979a).

The volume of liquid waste from a surface coal mine depends upon local precipitation and evaporation rates and amounts of ground and surface water that enter the pit. Throughout the study area precipitation is low and evaporation rates are high. Only after exceptionally large precipitation events will significant liquid waste be generated in this manner. Amounts of surface-water inflow is site dependent. If a mine is

situated in the flood plain of a major stream, a large volume of water may flow into the mine during periods of flooding. Stream diversion channels are necessary to minimize surface-water inflow into the mine and allow for continuity of the stream below the mine site. If a mine is located on a hillslope, surface runoff in small drainages and sheetwash may enter the mine. Diversion ditches along the upslope side of the mine will divert this water and minimize its inflow into the mine.

Any aquifer penetrated by the mine may leak ground water into the mine. Fortunately, most coal and lignite beds in the study area that are suitable for surface mining are not overlain by major aquifers. In some areas of the western United States the coal beds themselves are major aquifers that produce water into the mine, but no evidence in the study area indicates the coal and lignite beds are significant aquifers. The coal and lignite beds may carry some water, but they certainly are not major aquifers. In a few areas in the Denver and Cheyenne Basins important aquifers overlie surface-minable coal and lignite beds. Lenticular channel sandstones in the Laramie Formation occur in such a position, for instance, in the Boulder-Weld field, northern Foothills district, Colorado Springs area, and parts of the Cheyenne Basin. Some of the uppermost lignite beds in the Denver Formation lie within 200 ft (60 m) of the base of the Dawson Arkose, a major aquifer. Should a mine disrupt one of these aquifers, a considerable amount of ground water could flow into the mine and require removal.

Underground Mining

MINING PROCEDURE

Underground mines are classified according to the manner in which the coal bed is entered. There are three basic types of underground mines: drift, slope, and shaft mines. Figure 44 illustrates in cross section how these mines compare. In a drift mine the mine opening is driven into a coal outcrop along a hillslope, usually into a fairly flat-lying coal bed. This type of mine offers the easiest and least expensive method to initiate an underground mine, primarily because no or little rock excavation is necessary. Near the portal of a drift mine overburden is usually thin, but thick overburden is encountered as a mine works further into a hill or mountain. In a slope mine an inclined opening provides access to the coal bed. The inclined opening may dip up to 30° from the horizontal, but usually dips are much less. Generally slope mines are not used on deep coal beds because the great depth necessitates a very long and expensive opening. In parts of western Colorado the above described terminology is somewhat revised. A mine entry that follows a dipping coal bed may be called a slope mine. A vertical opening is used for shaft mines, and a elevator, skip, or cage is used to haul equipment, supplies, personnel, and coal to and from the surface. Shaft mines are preferred for coal beds that lie far below the land surface and do not crop out. Some mines may utilize more than one type of opening.

In all three types of entries, adequate protection techniques must be used to prevent roof and wall cave-ins and to provide ventilation. Generally, a concrete liner is used for shafts. Numerous factors must be

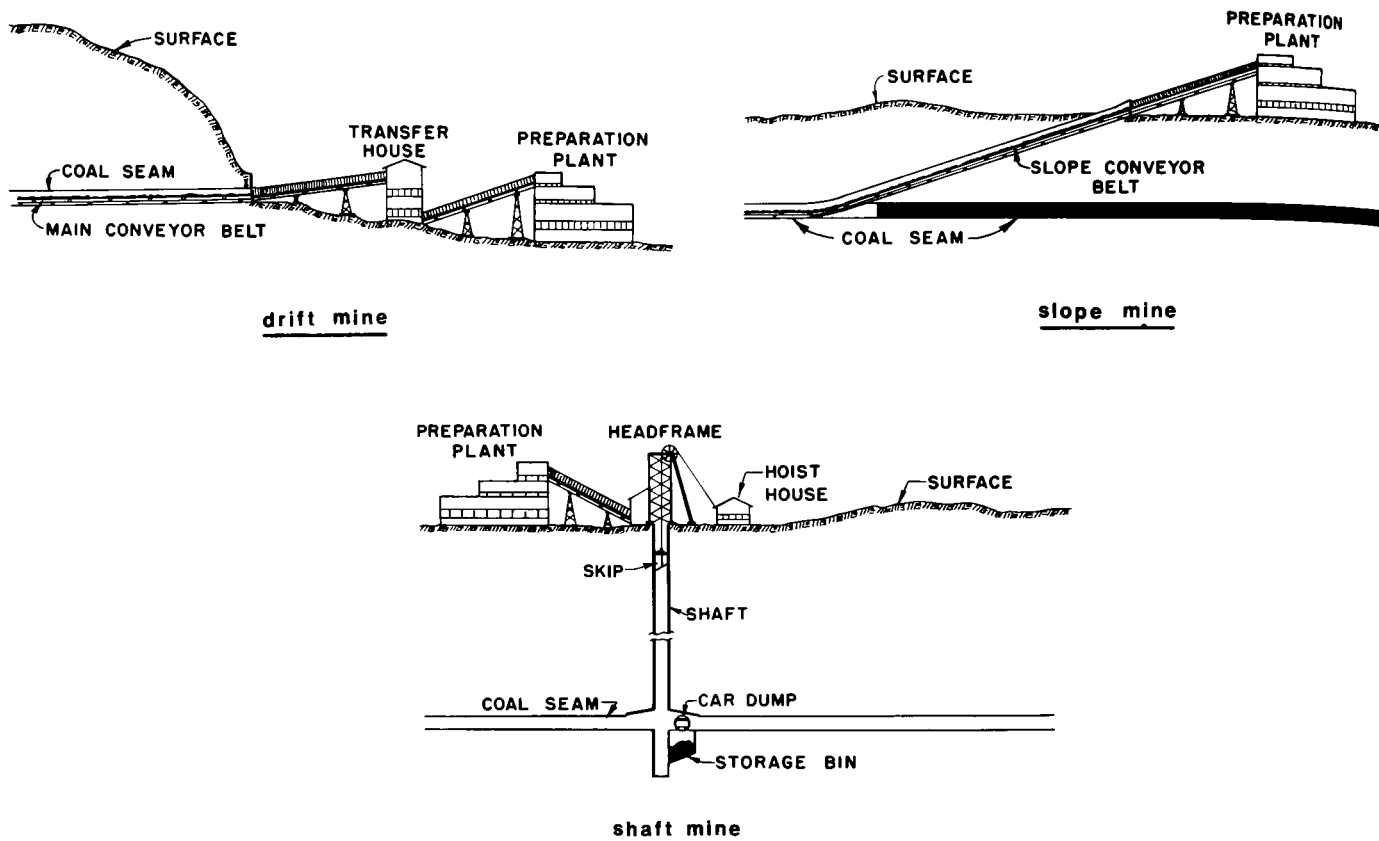


Figure 44. Cross sections through various types of underground coal mines.
(from Schroder, 1973; courtesy of A.I.M.E.)

considered in designing roof support systems for slopes and drifts. They include opening length, roof-rock conditions, hydrologic conditions, use of the opening, and life expectancy of the mine. Roof bolting, timbering, and cribbing may suffice in many areas, but sprayed cement coatings may be needed in areas of spalling and poured concrete liners will protect badly fractured and overstressed rock. Aquifers that are penetrated by slope mines may need to be sealed to prevent excessive water inflow.

Two primary types of underground coal mining methods are used to recover coal: room-and-pillar mining and longwall mining. Room-and-pillar mining has been the time-honored method of extraction in the United States, but longwall mining is rapidly becoming accepted. A third method, shortwall mining, is being tested and may become important in the future. For all types of underground mining, initial mine development is basically identical; main tunnels or headings are driven from the point of entry.

But the similarity ends here. With room-and-pillar mining a secondary set of entries is driven perpendicular or at an angle to the main headings. Rooms are driven from the secondary entries in a systematic manner on both sides of the entries. Secondary entries and associated rooms are commonly called panels. Usually rooms on one side of the panel are cut on advance and rooms on the other side are mined while retreating from the panel. Pillars of coal are left intact between mined-out rooms to prevent roof and floor problems and surface subsidence. Cuts between entries or rooms are usually termed crosscuts. During retreat from a panel, pillars are often "split" or divided into smaller pillars by additional mining to improve coal recovery.

Figures 45 and 46 illustrate typical plan views of room-and-pillar mines. The mined-out area of a midwestern mine that used 90° angles between entries, rooms and crosscuts is shown in Figure 45. Main entries are indicated by "A", secondary entries by "B", and rooms by "C". Less than 50 percent of the coal was extracted from this mine, because of poor roof conditions, active oil wells around which large buffer zones are needed, and surface subsidence problems. Figure 46 illustrates an active mine that employs angled crosscuts and angled rooms to facilitate equipment movement and coal haulage. As in Figure 45, "A" designates main mine entries and "B" marks the secondary entries. "C" indicates rooms mined during panel advance and "D" denotes areas where rooms will be driven during panel retreat. Mined-out and sealed panels are indicated by "E".

Coal in room-and-pillar mines is extracted using one of two types of mining systems: conventional or continuous. Conventional systems have long been employed in room-and-pillar mines, but during the past two decades continuous mining systems have experienced increased utilization. By 1985 over 60 percent of all coal produced from underground mines may be extracted using continuous mining systems (Merritt and Davis, 1977).

In a conventional mining system coal is mined through a sequence of steps, each of which requires specialized equipment. First, the coal is under-cut, center-cut, or over-cut by a cutting machine which resembles a large chain saw on wheels. It may also be necessary to shear-cut the coal face. Next, holes are drilled into the coal face, loaded with explosives, and detonated to break the coal. The coal is then loaded by hand or by a loading machine into a shuttle car which carries the coal to a belt conveyor or a mine-car loading point.

A continuous mining system uses a single operation and single machine to continuously mechanically break the coal and load it for transport. Maximum single advance of a continuous mining machine is about 20 ft (6 m) or the length of the machine because the machine operator must be under supported roof at all times. If a roof bolting machine could be mounted on a continuous miner or the miner controlled by remote control, the distance of advance per cut would only be limited by ventilation requirements.

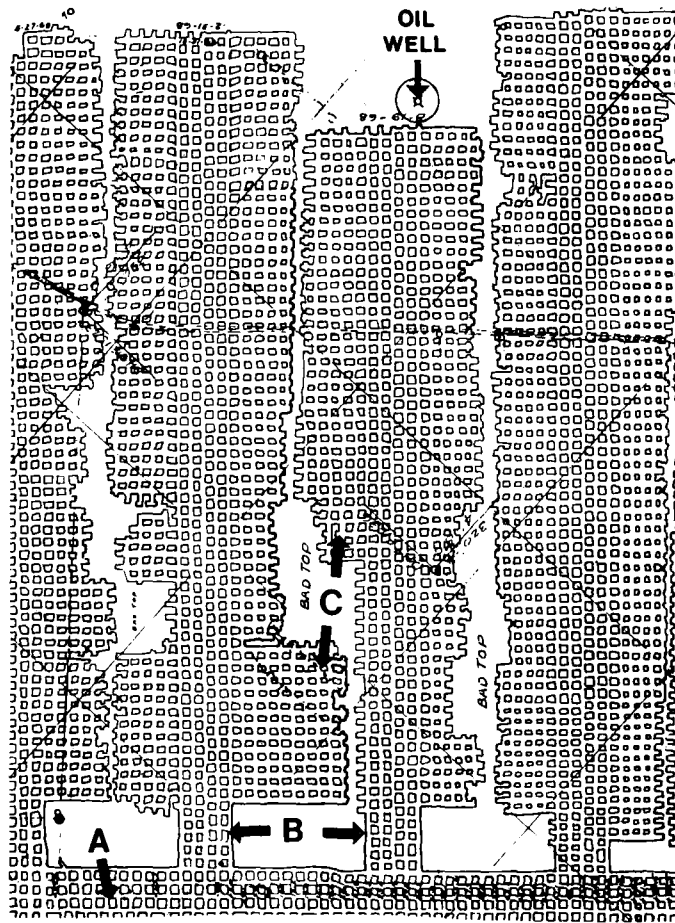


Figure 45. Plan view of part of a typical room-and-pillar coal mine. (from Schroder, 1973; courtesy of A.I.M.E.)

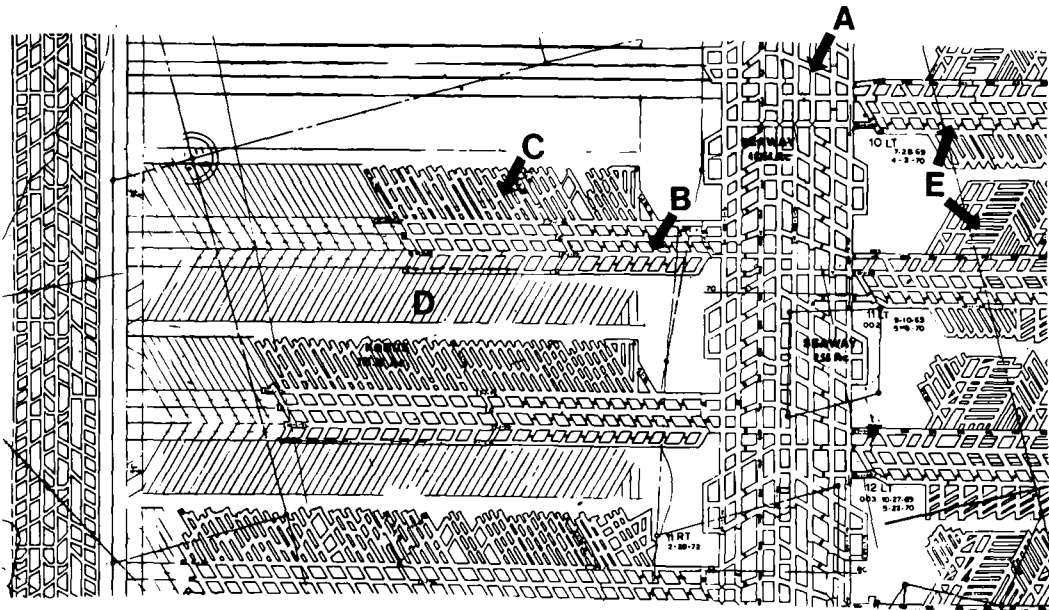


Figure 46. Plan view of part of a typical room-and-pillar coal mine that utilizes angled room to facilitate easier equipment movement and coal haulage. (from Schroder, 1973; courtesy of A.I.M.E.)

There are three types of continuous miners: boring-type, ripper-type, and drum-type. Boring-type miners break the coal by the scraping action of an arm or arms that rotate flat against a coal face. A boring miner produces arched entries, advantageous to roof support, but the entry width and height are restricted by the dimensions of the machine, a serious problem for coal beds of varying thickness. Ripper miners employ the sawing or ripping action of cutting chains to break the coal free. Square or rectangular entries of variable size (height and width) are cut by a ripper miner, but it produces a great deal of fine coal dust. A drum-type miner utilizes a drum-shaped cutting head that rotates parallel to the coal face. An arched roof can be cut by using a tapering drum, thus incorporating the beneficial aspects of a boring miner. The drum miner also has the flexibility of a ripper miner for cutting entries of variable size, but produces much less dust. It is the most popular continuous miner currently in use.

Longwall mining offers many advantages over room-and-pillar mining. These include increased productivity, higher recovery rates, safer mining conditions, and uniform or more predictable surface subsidence. Longwall mining has received widespread use in Europe for many years, but only recently has become popular in the United States. Presently less than 20 percent of all coal mined underground in the United States is extracted using longwall techniques, but it is possible that longwall production may equal production from continuous mines by the year 2000 (Merritt and Davis, 1977).

Longwall mining differs from room-and-pillar mining in the manner in which panels off the main entries are mined. Two types of longwall methods can be used: retreat and advance longwalling. Retreat longwall mining is the most commonly used method in the United States. Figure 47 shows a plan view of a retreating longwall face. It is necessary to first drive a series of entries along the flanks of the longwall panel to provide for ventilation, escapeways, and equipment and coal haulage. These entries are referred to as headgate and tailgate headings. In retreat mining these entries must be driven to the end of the panel before longwalling can initiate.

Retreat longwall mining begins at the far end of the panel and retreats towards the main entries. Within the panel all coal is removed, but a barrier of coal is left between the panel and the main entries. The roof in the mined-out area, or gob area, is not supported in any way and is allowed to collapse. Advancing longwall mining, as shown in Figure 48, differs from retreat mining in that the headgate and tailgate entries are developed as the panel progresses. The longwall face moves away from the main entries towards the far end of the panel. This procedure has some advantages over retreat mining. In many mines where retreat mining is used, development of the secondary openings takes longer than the actual longwalling operation. Careful planning and scheduling of overall mine development work is needed to prevent delays in longwalling new panels.

Longwall mining machines work back and forth across the exposed coal face (Figure 49). The miner operator is protected from roof-fall problems

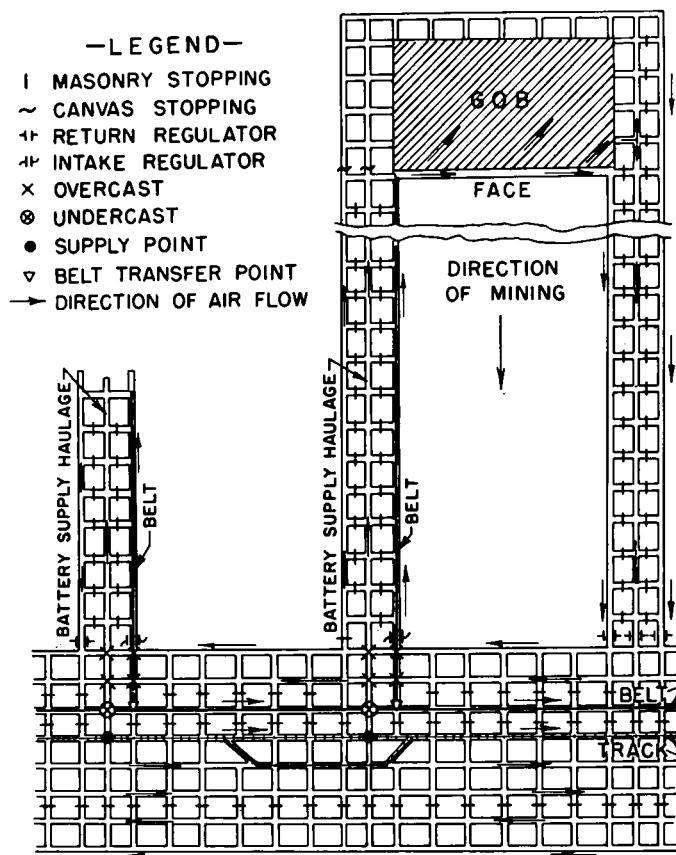


Figure 47. Plan view of a retreating longwall mining system. (from Schroder, 1973; courtesy of A.I.M.E.)

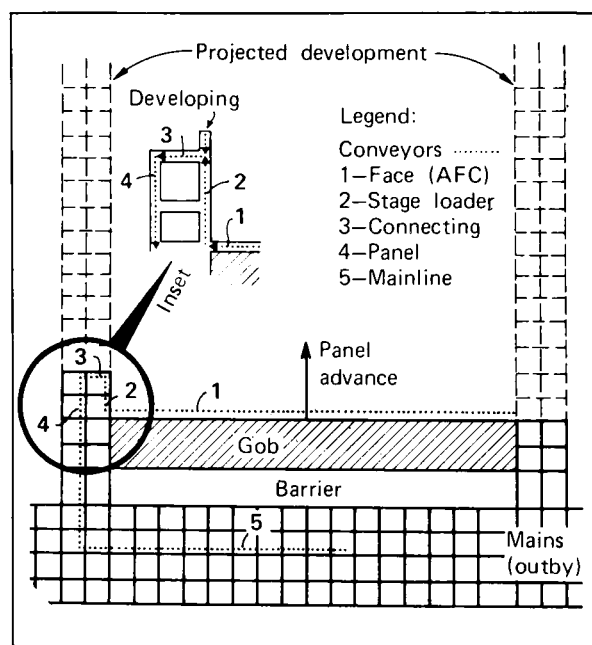


Figure 48. Plan view of an advancing longwall mining system. (from Chironis, 1977a; courtesy of Coal Age Mining Informational Services)

by a series of hydraulic, self-advancing roof supports along the entire face. As the coal is removed and the mining machine advances, the roof support system follows. Unsupported strata in the gob area are then allowed to cave-in behind the support units. Longwall mining machines are of two general types: plows and shears. A plow miner consists of an arrangement of fitted bits or a saw-toothed edge that is pulled back and forth along the coal face by a heavy chain and breaks the coal and plows it onto a conveyor system. Most plows can cut while traveling in either direction. A shearing machine works similar to a plow miner except a rotating drum replaces the plow to cut and push the coal onto the conveyor.

Shortwall mining is a new mining method recently introduced to the United States from Australia. It involves a combination of continuous and longwall mining systems. Figure 50 shows a plan view of a shortwall mining panel. The panel development is similar to development work required for retreat longwall mining. A series of entries is driven along the sides of the panel to be mined to provide ventilation and access. The mining face is a short-length longwall face supported by specially designed, self-advancing roof supports that provide a protective steel canopy over the miner operator. Coal is cut by a continuous miner.

Shortwall mining offers several advantages over other types of mining methods. It has many of the same advantages over conventional and continuous mining that longwall mining offers. In comparison with longwall mining, shortwall mining is more flexible to changing local conditions, has lower initial capital outlays when converting from continuous mining, and has shorter personnel training periods because fewer pieces of new equipment are needed.

WASTES AND EFFLUENTS

ATMOSPHERIC EMISSIONS

Atmospheric emissions from operating underground coal mines are generally very low. Small amounts of fugitive dust and vehicular emissions may be released during construction of surface facilities, but emission rates are even lower after construction completion. Moderate quantities of coal dust are generated underground by blasting or cutting, loading, and hauling the coal. Dust concentrations may locally become high at a working face, but the dust is rapidly dispersed by the mine ventilation system and generally does not escape into the above-ground atmosphere in high concentrations. Most underground coal mines use electric-powered equipment that generate no vehicular emissions. Diesel-powered machinery is employed at a few mines, and they emit typical vehicular emissions.

Any emissions released in the underground mine are vented to the atmosphere by the mine ventilation system. This would include vehicular emissions and methane emanating from the coal. Coal beds with high methane contents could release large volumes of methane into the atmosphere. Existing data, though scant, suggest Denver lignite beds have

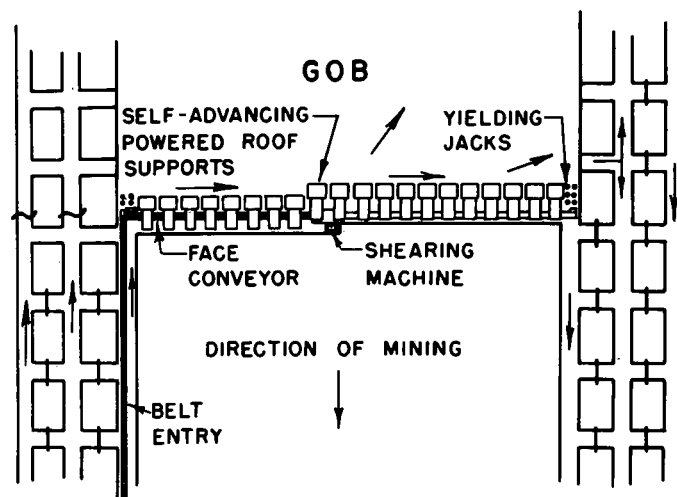


Figure 49. Detailed plan map of the longwall face shown in Figure 47. (from Schroder, 1973; courtesy of A.I.M.E.)

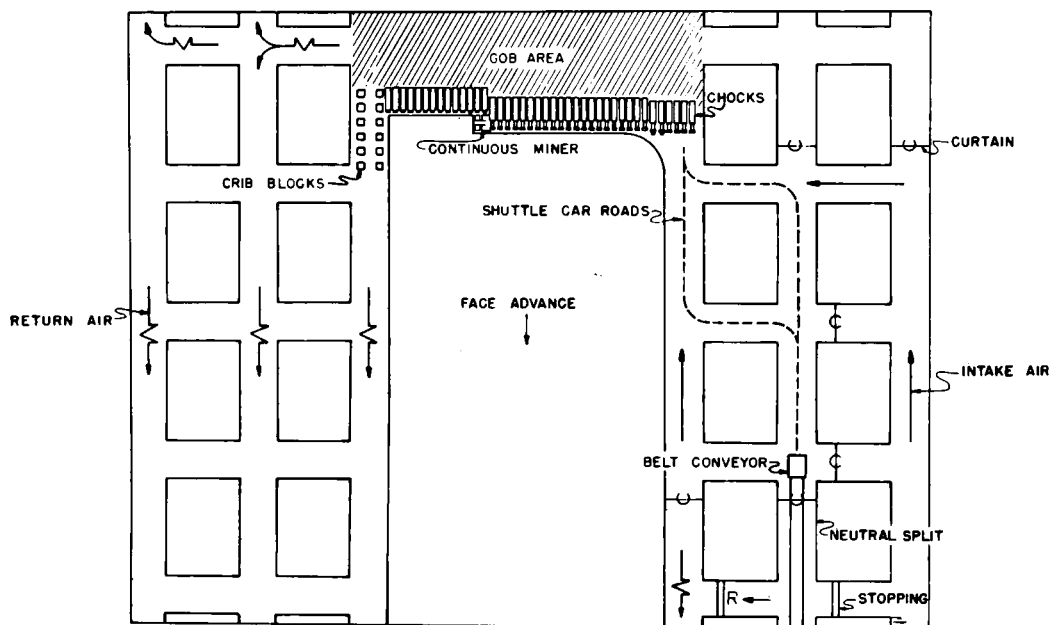


Figure 50. Plan view of a shortwall mining system. (from Schroder, 1973; courtesy of A.I.M.E.)

very low methane content, but Laramie coal beds, at least locally, contain moderate amounts of methane (Kirkham and Ladwig, 1979; Tremain, 1980, pers. comm). A reasonable estimate of the maximum methane content of Laramie coal beds might be on the order of 50 to 100 ft³ (1.4 to 2.8 m³) per ton of coal. Thus, a mine producing 200,000 tons (181 million kg) of coal each year would release 10 to 20 million ft³ (280,000 to 560,000 m³) of methane per year.

Another potential source of atmospheric pollution is underground mine fires, especially fires that burn out of control. Mine fires, unfortunately, are all too common in both active and abandoned mines. Several active mines in the study area have caught fire and had to be abandoned. The last two operating underground mines in the study were closed because of uncontrollable fire. The Eagle mine, which caught fire in October, 1978, released large, billowing, black clouds of smoke from its main shaft, before the shaft was backfilled. An abandoned mine near Marshall continues to burn today, causing not only atmospheric contamination, but the associated subsidence also affects the land surface.

SOLID WASTES

Underground coal mining creates a very small amount of solid waste. The largest volume of solid waste results from construction of shafts and slopes to gain access to the mine. These openings are driven into strata such as claystone, shale, and sandstone that overlie the coal bed. A shaft 20-ft (6-m) wide and 500-ft (150-m) deep generates about 150,000 ft³ (4,200 m³) of waste rock that must be disposed of. A 20-ft (6-m) wide slope dipping at 10° to a coal bed 500-ft (150-m) deep would remove over 900,000 ft³ (10,000 m³) of solid waste. Additional solid waste may be created during the mining process when floor or roof rock is accidentally mined along with the coal, when roof falls are cleaned up, and when geologic features such as clastic dikes or channel cut-outs are encountered and removed.

LIQUID WASTES

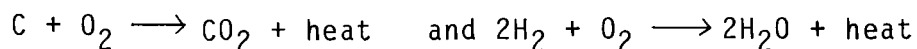
Underground coal mines usually produce small volumes of liquid waste if all shafts and slopes are properly sealed to prevent ground-water inflow from penetrated aquifers. Liquid waste will result from ground water in the coal bed and overlying and underlying formations leaking into the mine. In the study area little evidence indicates that coal beds carry significant amounts of water. Most mine water will probably seep from overlying and underlying formations through faults and fractures, some of which may result from subsidence and floor heave. No quantitative data are available on seepage rates into mines nor on dewatering rates in the study area. Many of the old, now abandoned underground mines did have significant dewatering problems, and most of the abandoned mines with which the authors are familiar have at least partially filled with water since abandonment. Types of potential pollutants in underground mine water may include dissolved solids of iron, manganese, aluminum, nickel, strontium, zinc, arsenic, copper, fluoride, ammonia, nitrate, and sulfates. High alkalinity or acidity and suspended solids may also occur.

Underground Gasification

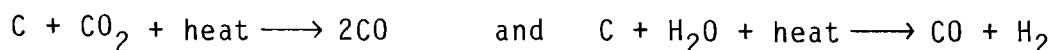
MINING PROCEDURE

Over the past few years there has been growing speculation that in situ or underground coal gasification (UCG) may become economically and technologically feasible to recover energy from deep coal beds, many of which are unminable using conventional techniques. UCG is not a particularly new technology. The Soviet Union began developing the method in the 1930s and they currently operate two commercial-scale mines, each which produces sufficient gas to generate 100 MW of electricity (Thompson, 1978). Some pilot-scale testing was conducted in the United States and Britain during the 1940s and 1950s, but these experiments were halted, primarily because the technique could not economically compete with the cheaply priced oil and natural gas readily available at that time. Changing economic conditions have now fueled increasing interest in UCG as a non-conventional source of energy.

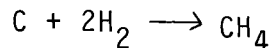
Figure 51 illustrates a schematic cross section through a single gasification chamber. A full-scale operation would consist of many such chambers. Air or oxygen is blown down the injection well, the coal is ignited at the bottom of the well, and gases resulting from the combustion are withdrawn from the production well. Coal combustion in UCG involves a complex series of reactions. A simplified model, such as the one described by Thompson (1978), will suffice for this report. Two basic oxidizing reactions are involved:



These hot gases are incombustible and have little value from an energy standpoint once they lose their heat content. Therefore, it is necessary to allow these gases to remain in contact with the coal along the gasification chamber after all oxygen has been consumed. Two secondary reducing reactions will then occur:



The resulting combustible gas can be used as a fuel. Part of the hydrogen will combine with the coal to produce methane according to the reaction:



If air is used as the gasifying agent, the resulting gas composition may average 10 percent CO, 12 percent H₂, 2 percent CH₄, 15 percent CO₂, and 60 percent N₂ (Thompson, 1978), and have a heating value ranging from 100 to 150 British thermal units per standard cubic foot (Btu/scf) (Stephens and Hill, 1978). The gas has a high nitrogen content, a result of initial nitrogen in the injected air. By using pure oxygen rather than air, the nitrogen content can be lowered and the heating value raised. Tests using oxygen indicate the produced gas will have a heating value in the 250 to 300 Btu/scf range, over twice the value achieved using just air (Cena and Minkel, 1978).

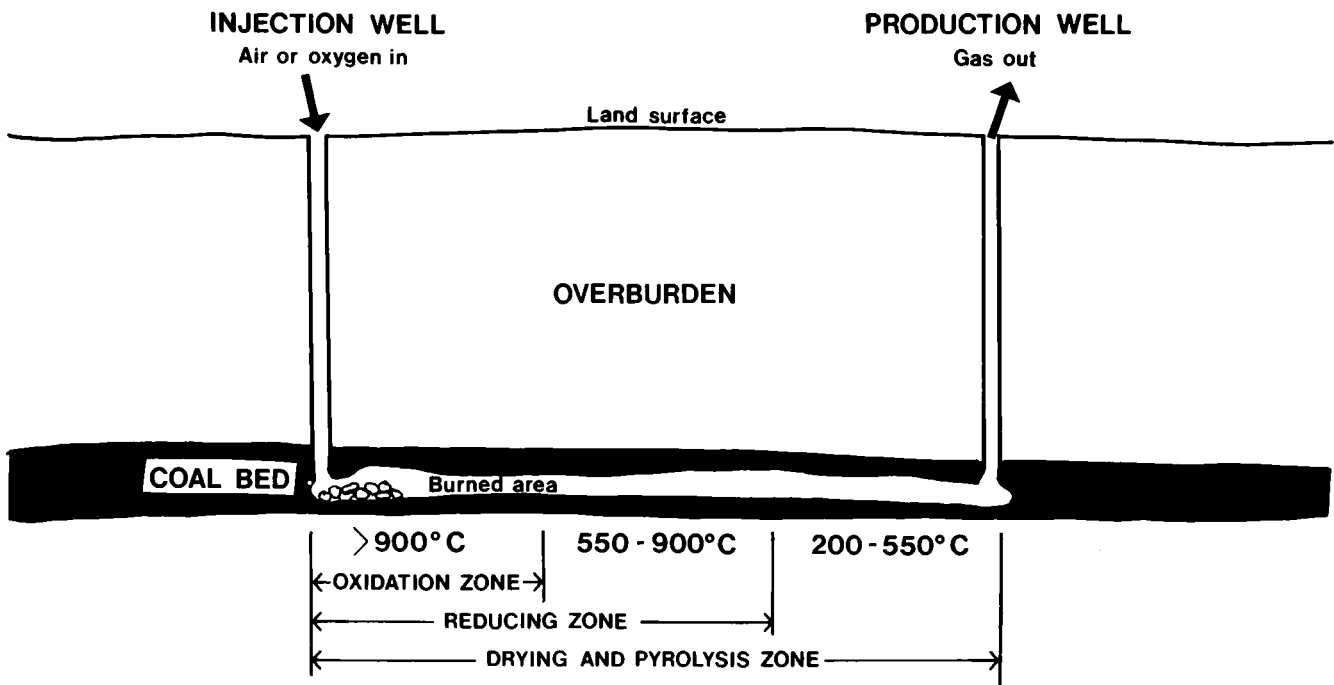


Figure 51. Cross section through a simplified underground coal gasification system. (after U.S. Department of Energy, 1979)

Prior to gasification it is necessary to establish a linkage channel between the two wells to allow the combustion front to burn in the proper direction. Such a channel may be created in several ways. Methods include hydrofracturing, electro-linkage, pneumatic linkage, explosive linkage, reverse combustion, and directional drilling. Hydrofracturing involves injection of water under high pressures to force open natural fractures. Usually some sort of sand or beads are introduced into the fractures and serve to prop open the fractures after cessation of water injection. Electric currents are used in electro-linkage. Electrodes are placed at the bottom of the wells, and a high voltage current is passed between them. This first dries the coal and then carbonizes it, creating a permeable conduit of coke between the holes. High-pressure air is injected in one well during pneumatic linkage. The air passes through the coal to the second well and forms an enlarged air passage. Explosive linkage involves the detonation of charges at the bottom of the wells. This method was tested during Hoe Creek I, by Lawrence Livermore Laboratory, but proved to be ineffective (Brandenburg, 1979; Hill and others, 1978). During reverse combustion air is injected into the coal bed through the production well and the coal bed is ignited at the bottom

of this well. After the coal is ignited, the direction of air flow is reversed, with air injected through the injection well and withdrawn through the production well. A small combustion front is drawn towards the production well from the injection well, thus generating an open channel along the coal bed. Directional drilling involves drilling a hole down to the coal bed, which is "whipstocked" so that it will follow the coal bed and physically connect the two wells. The most promising linkage method involves a combination of directional drilling followed by reverse combustion.

There are two basic types of gasification systems. One depends entirely upon drilling from the surface and the other involves preliminary mining to establish an area underground from where the drilling takes place. Because of problems with having workers underground, most projects favor drilling from the surface. Several methods using surface drilling have been tested. The most popular method uses a modified version of the linked vertical drilling program developed by the Soviet Union.

Figure 52 illustrates in plan view how the linked vertical drilling method works. Wells are drilled along Row 1. Air is injected into well 2, and the coal is ignited at well 1. Reverse combustion creates a combustion channel between wells 1 and 2. Reverse combustion is repeated for wells 2 and 3 and wells 3 and 4 to establish combustion channels along the entire row. Wells in Row 2 are linked to wells in Row 1 by reverse combustion in a similar manner. Gasification can then be conducted between wells in Row 1, followed by gasification between Rows 1 and 2. Additional combustion chambers can be linked between Rows 2 and 3.

Deep coal beds over 50-ft (15-m) thick may be gasified using the packed bed process. In this method chemical explosions produce a rubblized underground reaction chamber. The top of the fractured zone is ignited, and oxygen and steam are injected into it. The coal is gasified in a vertical manner, and gas is recovered from the bottom of the rubblized zone and pumped to the surface.

The longwall generator involves a series of parallel wells (Figure 53) drilled into a thin coal bed. First, a directionally drilled well is drilled into the coal bed and extends along the coal bed to the opposite side of the gasification chamber. A vertical well is drilled to connect the first well with the surface. Parallel wells are drilled in a similar manner on both sides of the initial well. Air is injected into the middle well and the coal is ignited. Gas is recovered from the surrounding wells, forcing the expansion of reaction zone or gasification chamber.

The Soviet Union has also tested UCG on steeply dipping coal beds, such as those found in the western part of the study area. Figure 54 illustrates one way to gasify steeply dipping coal beds. Initially a production well is drilled along the coal bed to the top of the intended gasification chamber and an injection well is drilled into the footwall of the coal bed at the bottom of the chamber. The two wells are linked using

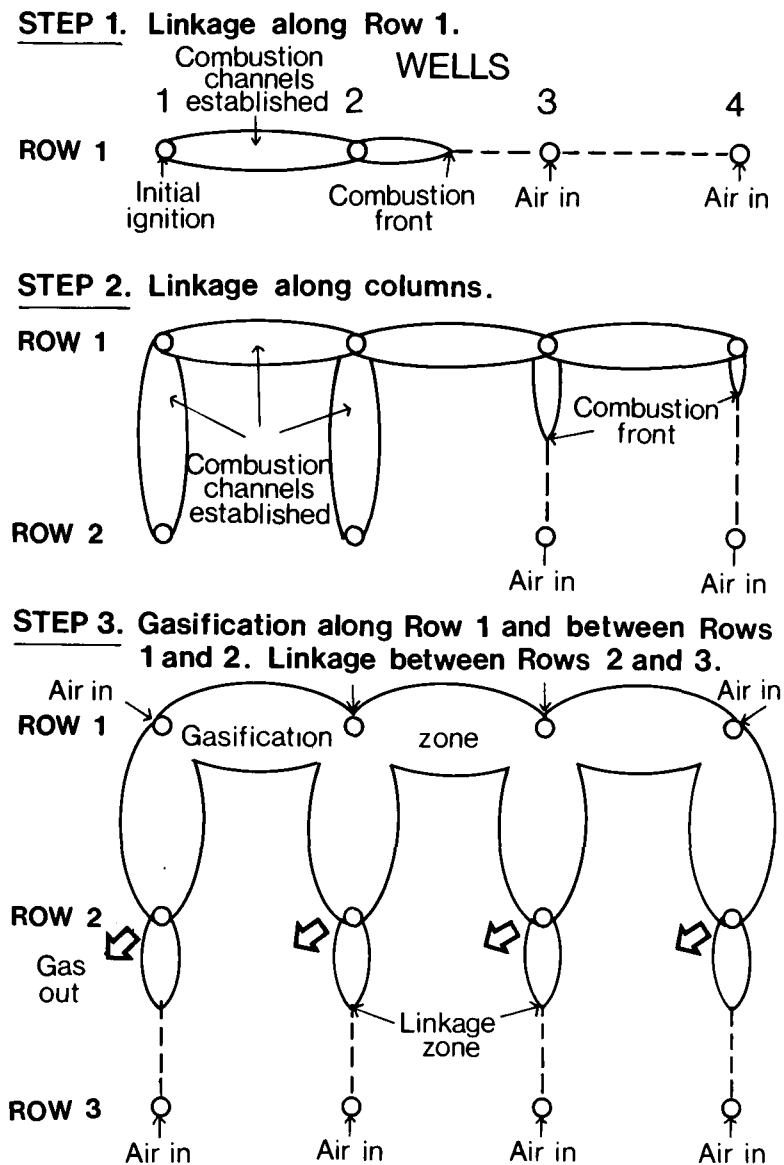


Figure 52. Plan view of an underground coal gasification system using linked vertical drilling. (modified from Thompson, 1978)

one of the previously described linkage techniques. The coal bed is ignited at the bottom of the chamber and burns up dip. As gasification proceeds upward, burnt coal and ash drop to the bottom of the chamber and may eventually plug the initial injection well. Secondary injection wells must then be drilled to enter the coal bed above the plugged zone. A series of parallel wells are drilled into the coal bed along the strike of the beds, and gasification is accomplished as described above.

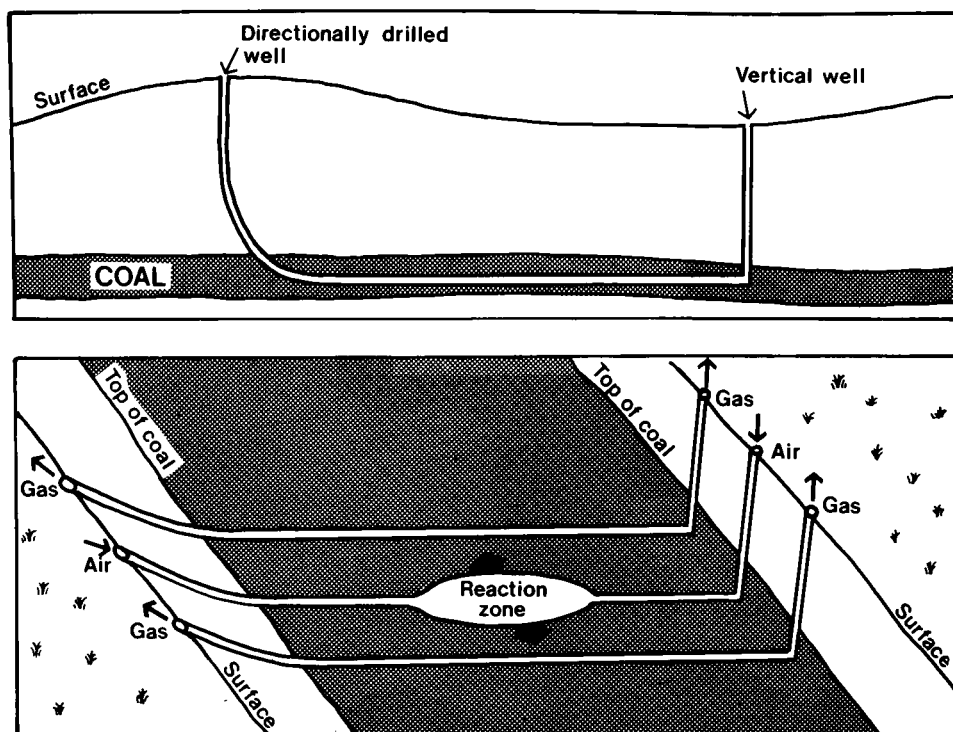


Figure 53. A conceptual underground coal gasification system using the longwall generator system. (modified from Thompson, 1978)

UCG is feasible only for certain types of coal deposits. Numerous factors, such as physical properties of the coal and geologic setting of the coal bed and adjacent formations, influence the suitability of a particular site for UCG (U.S. Dept. Energy, 1978). Important coal properties that affect suitability for UCG include rank, proximate and ultimate analysis, trace element chemistry, reactivity, shrink/swell behavior and permeability. The following discussion is summarized from several sources, primarily the U.S. Dept. Energy (1978).

Lower rank coals, especially subbituminous coal and lignite, are more suitable for UCG than higher rank coals. Higher rank coals commonly swell upon heating and release viscous tars that seal natural and artificial permeable channels, thus inhibiting gasification. Existing tests also suggest subbituminous coal generates a higher Btu gas than does bituminous coal. High ash content generally causes a decrease in the heating value of the product gas, but thick lignite beds may contain up to 60 percent ash and still produce an acceptable quality gas. Trace element chemistry is important because gasification reactions may be inhibited or enhanced by trace elements. Furthermore, corrosion problems may be stimulated by

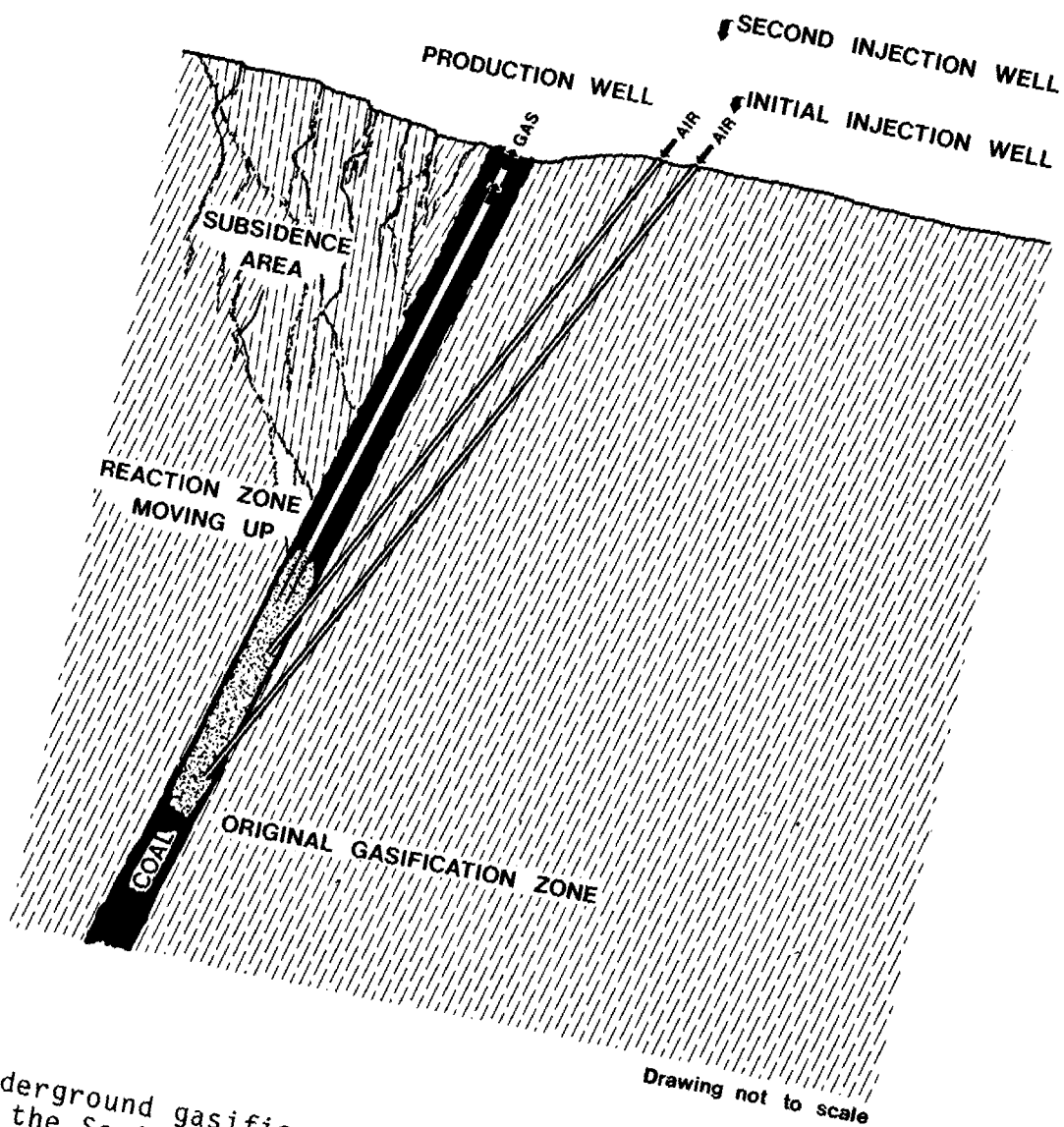


Figure 54. Underground gasification of steeply dipping coal beds, as tested by the Soviet Union. (after Buder, 1978)

certain trace elements. A great deal more research and testing is needed before specific relationships can be ascertained.

Coal reactivity is one of the most important factors influencing stability for UCG. Highly reactive coals, such as lignite and bituminous coals, readily ignite and efficiently burn at lower temperatures. Coal permeability is also very important. High

permeabilities are desirable to allow high flow rates at relatively low pressures. Within a coal bed initial permeability is heavily influenced by cleat characteristics. Faulting and fracturing also play important roles in controlling permeability and will be further discussed in later paragraphs. During gasification, permeability is affected by shrink/swell behavior and tar release. Shrinkage and low levels of tar generation are favorable for UCG. In most cases, coal bed permeabilities must be artificially increased by linkage between wells to assure successful gasification.

Geologic factors such as bed thickness, depth, continuity, and dip, presence of partings, overburden lithology, thickness, and tightness, roof stability, structural setting, and hydrogeologic setting all play important roles influencing suitability for UCG (U.S. Dept. Energy, 1978; McCurdy, 1977). Generally, coal bed thickness must exceed 5 ft (1.5 m) to prevent significant heat loss into surrounding rock. A coal bed should be between 200 to 1,500 ft (60 to 450 m) deep to be acceptable for UCG. Surface mining is preferable for beds less than 200 ft (60 m) deep, and drilling costs are presently prohibitively high for beds greater than 1,500 ft (450 m) deep. As the economic situation evolves, deeper beds may become suitable for gasification. Severe subsidence problems may accompany UCG of coal beds in the 200 to 500 ft (60 to 150 m) depth range and may prohibit UCG in certain areas. Conventional coal mining is restricted to beds that dip less than 30°, but only high rank coal can be economically mined at such a dip. Most conventional coal mines are limited to dips of 8° to 10°. UCG is feasible for steeply dipping beds and in many ways steep dips enhance favorable recovery for UCG. Some workers believe the optimum dip for UCG is between 35° and 65° (U.S. Dept. Energy, 1978).

Overburden characteristics affects UCG in several ways. Obviously, the greater the thickness, the higher the drilling costs are. From an environmental standpoint, however, thick overburden is advantageous. Fracturing and subsidence resulting from roof collapse are less likely to extend to the surface if overburden is thick. Overburden lithology also influences fracturing and subsidence. Competent rock such as sandstone and limestone may limit these problems. Roof collapse also affects the gasification operation. Since the initial linkage between wells is placed at the bottom of a coal bed, it is beneficial for overlying coal to fracture, break loose, and fall into the rubblized zone. Further collapse of overlying non-coal roof rock is detrimental because it can obstruct gas flow, cause bypassing of oxygen around the reaction zone, and damage wells.

Structural features are important from several aspects. Coal bed continuity is affected by faulting and folding. Faults may truncate a bed, thus dividing a coal deposit into individual, distinct blocks of coal. Obviously, a gasification chamber could not extend across a fault that displaces a coal bed against non-coal strata. Folding may make linkage between wells difficult and allow for wastage of much of the deposit. Fracturing and jointing play an important role in controlling bed permeability. Gasification chambers should be aligned parallel to

fracture patterns, not perpendicular to them. A possible explanation of some technological problems experienced by the most recent Hanna gasification tests may be related to the orientation of their burns to local fracture patterns (Gardner, 1980, pers. comm.).

The hydrogeologic setting of a UCG site is important from operational and environmental standpoints. Water plays a crucial role in the gasification process and either too little or too much water may cause serious problems. Too little water impedes the gasification reaction, resulting in low quality gas. It is also more difficult to control the burn when water is scarce. Additional water can be injected into the gasification chamber, but this results in undesirable consumptive use of water supplies. If too much water is present, much of the heat of combustion is expended on water vaporization and in some cases excess water may flood the burn zone and extinguish the ignited coal. The presence of major supplies of ground water within either the gasified coal bed or overlying formations is also important because of potential impacts on water quality and quantity. This topic is discussed in a later section.

From the above discussion it appears that many coal and lignite deposits in the Denver and Laramie Formations may be suitable for UCG. Site specific studies are required to determine the feasibility of gasifying a particular deposit and identification of associated environmental problems.

WASTES AND EFFLUENTS

Because UCG has never been attempted on a full scale in the United States, the actual wastes and effluents from a large mine are not well known. Past pilot-scale tests, such as those at Hanna by the Laramie Energy Research Center and at Hoe Creek by Lawrence Livermore Laboratory, do provide some insight into this aspect of UCG. In general the total volume of wastes and effluents from UCG are less than that from conventional coal mines.

UCG facilities operating under normal conditions are expected to produce low amounts of atmospheric emissions. The primary air pollutants will result from construction and drilling activities. Fugitive dust and vehicular emissions will constitute the most significant air pollutants. UCG is expected to produce vehicular emissions and fugitive dust in volumes fairly similar to those that result from underground coal mining. Because surface coal mining involves overburden handling and extensive use of heavy equipment on the surface, it will release significantly larger amounts of air pollutants than UCG. Beneficiation of gas recovered by UCG is accomplished in surface treatment plants. Waste products accompanying this aspect of UCG are not considered in this investigation.

Ground subsidence related to UCG, and attendant rock fracturing may provide conduits for the upward escape of gaseous and possibly liquid substances from the gasification chamber. Such an escape may be undesirable from both environmental and economic aspects. Composition of

leaking gas would depend upon where the leak developed within the gasification chamber. Escape of gases through subsidence cracks has been documented at UCG facilities in the Soviet Union (Gregg, 1977). It is possible that escaping gases and fluids may chemically react with overburden and in part be "purified" by sorption on clay particles in the overburden (Humenick and Mattox, 1977). Another type of potential accidental contamination could result from surface rupture of pipelines extending from the gasification site to the treatment or beneficiation plant or from leakage around well casings due to poor completion techniques or casing deterioration. Obviously, leaks in pipelines carrying air or oxygen to the injection wells would not cause any serious environmental problems, but leakage from production pipelines or from production wells would allow for escape of the low Btu gas and any included contaminants.

UCG will generate a very low, almost insignificant volume of solid waste. Solid waste will result from surface excavations for foundations, pipeline trenches, and road construction, and from cuttings from drill holes. When compared to either underground or surface coal mining, the amount of solid waste from UCG is negligible.

Most UCG facilities will produce very few or no liquid wastes. (Again, remember that this report does not deal with surface processing or beneficiation of recovered gases). In certain instances, however, it may be necessary to dewater a coal bed prior to and during gasification. This is especially true for highly fractured coal beds that carry a great deal of water. Water removed by dewatering is a liquid waste that may or may not contain undesirable elements.

Liquid waste containing harmful substances should be treated prior to release or disposed of in evaporation ponds or deep disposal wells. Available data indicate the coal and lignite beds in the study area usually do not contain much ground water; therefore, dewatering prior to gasification is unlikely. Some liquid waste may also be withdrawn by the production wells during certain phases of gasification. This water may be contaminated with organic and inorganic compounds during gasification and, if contaminated, should be properly treated before release, placed in evaporation ponds, or injected into deep disposal wells.

Other Methods

A variety of new coal mining techniques are being designed and tested to reduce mining hazards to the environment and to miners while increasing productivity. One of these new methods, hydraulic borehole mining, is very briefly described in this report.

Hydraulic borehole mining involves the use of water to cut the coal. First, a vertical hole is drilled into a coal bed. A downhole unit containing a high-pressure hose, water jets, and a pump system is lowered into the hole. Water is jetted from the unit to cut the coal, and the eroded coal is slurried to the surface by swiveling the unit around in the hole. A large cavity up to 30 ft (9 m) in diameter (Savanick, 1979) can be cut into the coal bed. A series of such boreholes would constitute a mine.

ENVIRONMENTAL IMPACTS AND IMPACT MITIGATION

Exploration Activities

Exploration for coal deposits basically consists of 1) determination of areas likely to contain desirable coal deposits and 2) drilling of prospects. In certain cases geophysical exploration techniques such as seismic reflection and refraction may be employed. Drilling of prospects is generally the only phase of exploration that may impact the environment, although drill holes may be required for some geophysical exploration, and these also may contribute to environmental problems.

A very small amount of atmospheric pollutants is generated by coal exploration activities. Vehicular emissions from drilling rigs and associated equipment and fugitive dust from vehicular travel on dirt roads and from the actual drilling are the primary air contaminants. Vehicular emissions can be minimized by using air pollution control devices on vehicles and by limiting the number of miles traveled through transportation planning and carpooling. Fugitive dust is the most visible form of air pollution. It may cover local vegetation, reduce growth rates, and make the vegetation less desirable as fodder. Precipitation will wash fugitive dust from the vegetation. Amounts of fugitive dust can be lowered by restricting vehicular travel on unpaved roads, by watering, paving, or chemically treating unpaved roads, and by using fluids to drill with. In general atmospheric impacts associated with coal exploration are very low and are restricted to the immediate vicinity of exploration activities.

Coal exploration may slightly affect the land surface. New roads may be needed to provide access to drilling sites. A drill site in rough terrain may need to be leveled to allow for setting up the rig. Spilled oil and fuel may cause local problems. Land impacts associated with coal exploration are generally low and can be easily minimized or eliminated by immediate reclamation and revegetation of roads and drill sites. Surface disturbance can also be reduced by avoiding drilling activities at times when the ground is wet and can easily be rutted, compacted, and otherwise damaged.

Surface water may be affected by construction of access roads and drilling pads, and by mud pits. Erosion of these features may contribute to sediment loads in streams. Stream flow and runoff may be diverted or locally ponded by exploration-related construction. In some cases precipitation infiltration may be increased or decreased by construction activities associated with exploration and cause changes in runoff characteristics. Surface water impacts caused by coal exploration usually are low and can be further minimized or eliminated by immediate reclamation and revegetation of disturbed areas.

Probably the most serious potential environmental problem related to coal exploration involves ground-water quality and quantity. Water from different aquifers penetrated by a drill hole may commingle in unplugged, abandoned exploration holes. In many cases aquifers contain water of

differing quality and any commingling will degrade the better quality aquifer. The quantity of water within an aquifer may also be affected by improperly abandoned drill holes. For instance, a shallow aquifer penetrated by a drill hole may lose water into the hole, and a small cone of depression may develop in the aquifer around the drill hole. Artesian aquifers could lose water to overlying dry formations or possibly flow onto the surface through improperly abandoned drill holes. An individual, improperly abandoned exploration hole may not have a great effect on an aquifer, but the cumulative effect of hundreds of improperly abandoned holes can be significant.

Proper abandonment of exploratory drill holes by plugging with cement, heavy muds, or other approved sealants would eliminate future quality and quantity problems caused by the drill holes. Colorado now has legislation and proposed regulations which address coal exploration drill hole abandonment. House Bill 1223 (1979) and the proposed rules and regulations of the Colorado Mined Land Reclamation Board require appropriate plugging and abandonment of coal exploration drill holes.

Mining Activities

AIR-QUALITY IMPACTS AND MITIGATION MEASURES

The primary air-quality impacts from coal mining result from vehicular emissions of diesel- and gasoline-powered equipment and fugitive dust. Escape of gases from UCG operations may also locally affect air quality. Generally surface mining releases greater amounts of fugitive dust and vehicular emissions than does underground mining, UCG, or hydraulic borehole mining. None of the mining techniques seriously affect regional air quality, but fugitive dust from surface mining and escape of gases during UCG may cause some local temporary problems. Surface facilities that clean or beneficiate coal and those that clean or upgrade the quality of gas produced from UCG may also impact air quality, but these aspects are not discussed in this report.

Sources of fugitive dust in coal mining include vehicular traffic on unpaved roads both within and outside of the mine, mine construction, mining activities such as drilling, blasting, loading, and hauling coal and overburden, and wind erosion of exposed spoil piles, coal stock piles, and disturbed land. Fugitive dust will consist of fine-grained particles of coal and overburden material.

Because all mining activity associated with surface mines takes place at the surface, and any disturbed land is readily exposed to wind erosion, surface mining of coal generates more fugitive dust than do other types of coal mines. Fugitive dust problems can be minimized in several ways. Heavily traveled dirt roads can be paved, oiled, or watered. Exposed spoil piles should be rapidly reclaimed and revegetated. Coal stockpiles can be located in areas protected from high winds. Disturbed land should be revegetated as soon as possible.

Surface coal mines usually generate more vehicular emissions than do other types of coal mines, because surface mining takes place at the

surface and it requires a great deal of heavy equipment to blast, load, and haul the coal and overburden. Use of air pollution-control devices and maximum utilization of electric-powered equipment will reduce vehicular emissions. Drag lines and most underground mining equipment are especially well adapted for electricity. Some shovels may also be powered by electricity, but any surface equipment that travels considerable distances are not readily adaptable to electric power. Reduction of the number of miles travelled will also reduce vehicular emissions. This can be accomplished by designing the mine for minimal travel, eliminating unnecessary travel within the mine, and by car- or van-pooling to and from the mine.

Gaseous emissions may be released by UCG facilities in three ways: 1) leakage through subsidence cracks, 2) leakage from surface pipelines, and 3) leakage from around wells. Subsidence may be associated with many UCG facilities. In some cases subsidence will be limited only to strata directly overlying a gasified coal bed. In other cases subsidence and attendant cracks may extend to the surface. Subsidence cracks provide excellent conduits for transmission of gases from the gasification chamber to the surface. Such leakage has been detected at several UCG facilities in the Soviet Union (Gregg, 1977). Escaping gas would primarily consist of carbon monoxide, hydrogen gas, nitrogen gas, carbon dioxide, nitrogen oxides, methane, and sulfur oxides, but it could also contain small amounts of a variety of pollutants, including radioactive gases. The gasified coal bed must contain radioactive material for the escaping gases to be radioactive and significant amounts of radioactive minerals do locally occur in the coal of the study area. The Leyden mine in Jefferson County is well known for the coffinite-bearing coal mined there (Sims and Sheridan, 1964; see Appendix 1 of this report). Escaping gases may in part be purified by sorption of pollutants on clay as the gas passes through cracks in the overburden.

Rupture or deterioration of surface pipelines that run to and from the wells could also allow for escape of gases into the atmosphere. The amount of escaping gas would depend upon the time lag between when the leak occurred and when it was repaired. Gas composition will depend on whether the pipeline carries injected or recovered gases. Injection gases are primarily air or oxygen, and no significant impact would result from their release. Recovered gases probably would have a chemistry similar to gases escaping through subsidence cracks, as described in the preceding paragraph.

A small amount of gas may also leak from around the wells. Faulty completion practices, poor construction methods, and deteriorated or damaged casing potentially allow gas to escape. The volume of gas that escapes is again dependent on detection and repair lag time, and the gas composition is a function of whether the well is used for injection or recovery.

Gas leakage from UCG operations can be minimized to a certain extent. Fortunately the potential atmospheric impacts of these releases are not great and are generally limited to the facility site. Leakage through subsidence cracks can be eliminated if the cracks do not reach the

surface. The deeper a coal bed is, the less likely it is that subsidence cracks will extend to the surface. Another possible way to minimize leakage involves sealing subsidence cracks with clay liners and spreading a layer of clay over subsided areas. Leakage from pipelines and wells can be reduced by proper construction and maintenance and by regular flow pressure monitoring to allow for rapid leak detection. Wells should also be pressure tested before usage to detect potential problems.

A thorough meteorological survey should be conducted of any mining site prior to initiation of construction to determine climatic and wind conditions. At this same time air samples should be collected and analyzed for fugitive dust and any other critical pollutants to establish baseline air-quality conditions. During mine construction and operation air-sampling stations should be regularly monitored to document any changes in air quality at and around the mine.

LAND IMPACTS AND MITIGATION MEASURES

Land in the study area that is underlain by coal-bearing rocks is currently used for several purposes, the most widespread uses being for agriculture and urban areas. Agricultural uses include livestock grazing, dry-land farming, irrigation farming, and feed lots. Urbanization is rapidly overtaking much of the land surrounding the Denver metropolitan, Fort Collins, Boulder, Greeley, and Colorado Springs areas. Rural subdivisions are spreading over a much wider area. In most cases urban development will probably preclude the future recovery of any coal under the urbanized area. Thus, a part of the valuable coal and lignite resources is being lost to urbanization. This problem is further discussed in the final section of this report.

Coal mining may affect the land by construction of the mine pit, roads, mine buildings, and waste piles. Surface subsidence associated with underground coal mining and UCG may also seriously affect the land surface. Mining operations may alter existing land forms, drainage patterns, and land slopes. One serious problem related to surface gasification, surface liquefaction, or power generation, that of ash disposal, is not discussed in this report because it is not directly related to mining.

Historic and archaeological sites and natural landmarks within a mine site may be affected by the mining operation and should be protected. Locations and descriptions of landmarks and historic places are contained in the National Registry of Natural Landmarks and the National Registry of Historic Places. The Colorado State Archaeologist, Colorado Natural Areas Program, and the Colorado State Historical Society should also be contacted for up-to-date information on landmarks, historic places, archaeological sites, and natural areas. Significant archaeological sites in the mine area must be studied. Recovery of historical and archaeological information is required by the Historic and Archaeologic Preservation Act of 1974 (Public Law 93-291). A few very important fossil localities have been discovered in the Denver Formation that also warrant protection. These localities contain some of the best assemblages of Early Paleocene (Puercan) mammal fossils in the United States (Middleton,

1980, pers. comm.). Descriptions of specific localities may be obtained from the Colorado Geological Survey or the University of Colorado Museum.

The major land impacts associated with coal mining result from land disturbance and topographic changes in surface mining and surface subsidence in underground mining and UCG. A large area of land, ranging from a few hundred acres to thousand's of acres, is disturbed by mining operations at typical open-pit and area surface mines. Additional land may be occupied by associated surface facilities, including railroad tracks, roads, and buildings, and by spoil piles. Underground coal mines occupy a relatively small surface area. Spoils result from shaft, slope, or drift construction and rock waste from mining. UCG facilities may cover large areas, but land disturbance is minimal because this type of coal recovery does not involve overburden removal.

Permanent land disturbance can be minimized at all types of mines by utilization of appropriate reclamation techniques in accordance with the requirements of the Colorado Mined Land Reclamation Board. Reclamation activities may include, among other things, extensive site regrading, replacement of topsoil, revegetation, re-establishment of drainages, and stabilization of highwalls. In certain case local landowners may request that specific roads or buildings remain intact for post-mining use. These arrangements should be made in advance among the landowner, mining company, and Colorado Mined Land Reclamation Board.

The reclamation program should be an integral part of a mining operation. Pre-mining studies are necessary to determine natural land conditions, including not only topography and stream drainages, but also active surface processes and surficial geology. During mining, removal and stockpiling of topsoil is required before stripping of overburden. Most mining projects initiate reclamation before completion of the entire mining project. Area surface mining, as illustrated in Figure 38, is especially well suited for simultaneous mining and reclamation. Overburden is cast into a previously mined cut and is graded to the desired contour. Topsoil is replaced over the overburden and the surface is revegetated. Successful revegetation may be difficult to achieve in the study area because of the semi-arid, dry climate. Irrigation may be necessary in some areas to establish a satisfactory initial vegetative cover.

Current regulations require that mined land be reclaimed as near to original topographic conditions as is feasible. This entails extensive pre-mining studies and overburden regrading. It is virtually impossible to achieve 100 percent restoration because features such as cliffs and rock outcrops are difficult to reproduce and sometimes not desirable. Also, removal of the coal may cause a general, overall change of the topographic elevation at the mine. Overburden will expand as it is loosened and broken during mining and replacment. The expansion factor or bulking will vary depending on the characteristics of the overburden. Keefer and Hadley (1976) indicate soft sandstone and shale commonly increases 20 to 25 percent in volume. We anticipate overburden above Denver lignite beds and Laramie coal beds in the study area to have similar bulking characteristics, although no tests were conducted to

substantiate these numbers. Thus, for a coal or lignite bed 20 to 25-ft (6.0 to 7.5-m) thick with 100 ft (30 m) of overburden, there would be little change in the average elevation of reclaimed land. If the overburden thickness remains constant and coal bed thickness increases, a lower land surface would result, whereas a thinner coal bed would result in higher land surfaces. Some consolidation of reclaimed land will probably occur during the years following completion of reclamation.

At some mines overburden removed to make the initial box cut is disposed of on the surface. Such an overburden pile should be placed, graded, and contoured to best fit existing topographic and hydrologic conditions. It should be recontoured, reclaimed, and revegetated as soon as possible to prevent excessive erosion and increased sediment loads in nearby streams.

Surface subsidence associated with underground coal mining, UCG, and hydraulic borehole mining may severely impact surface topography (Figures 54 and 55). Subsidence, in simple terms, results as coal is extracted underground, either through mining or burning, and overlying strata cave, collapse, or bend into the mined void. Surface subsidence occurs when the disturbed strata extend to the surface. Surface expressions of subsidence may include gentle depressions, abrupt collapse cavities, and ground cracking. Subsidence is a very complex phenomenon involving many factors. For this reason subsidence mechanics and characteristics will not be

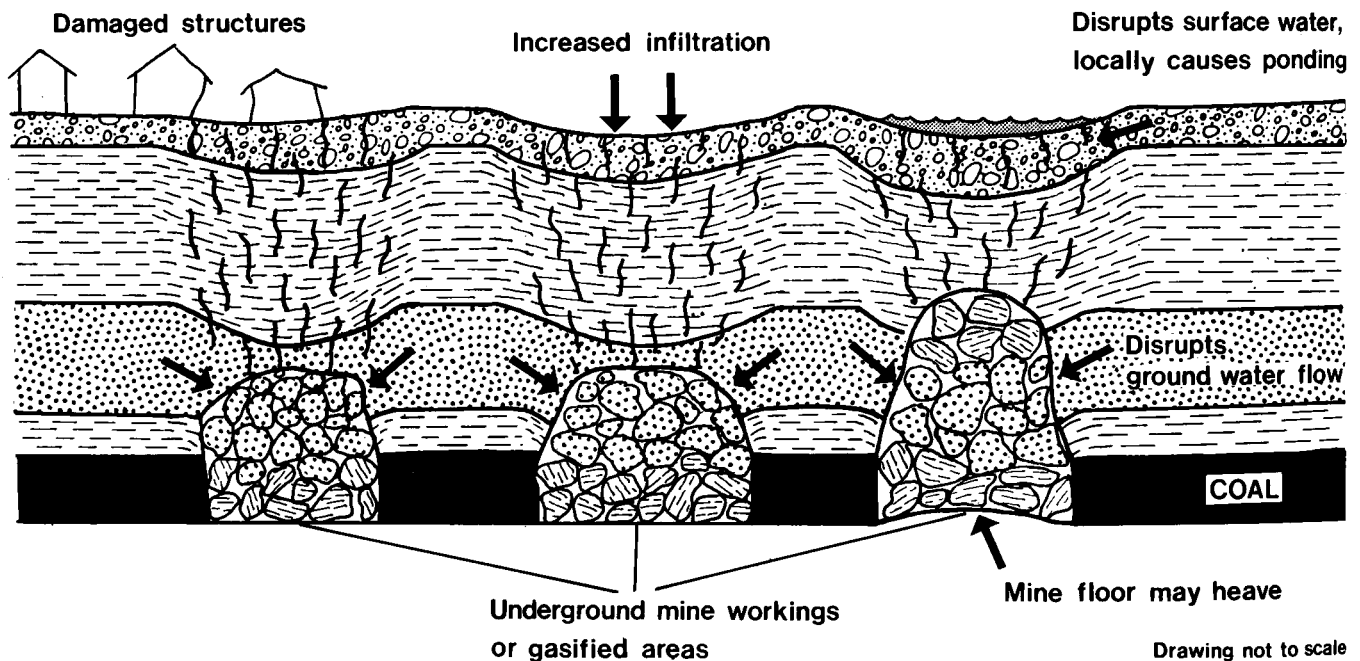


Figure 55. Potential environmental effects of subsidence over underground coal mines and underground coal gasification facilities.

discussed in this report. See Amuedo and Ivey (1975), Gregg (1977), Greenlaw and others (1977), Zwartendyck (1978), Dunrud (1976), and National Coal Board (1966) for references on this subject.

Abundant evidence indicates shallow underground Laramie coal mines may experience severe subsidence problems in the study area. Amuedo and Ivey (1975) document numerous cases of subsidence in the Boulder-Weld coal field. The Colorado Springs Planning Department (1967) describe subsidence problems in the Colorado Springs field. Recent newspaper articles and field investigations by the authors point to continued subsidence problems in these two fields and in the Foothills district. Less evidence of subsidence over underground Denver lignite mines is publicly available, primarily because only a few small underground mines have worked this formation. Physical characteristics of strata overlying the Denver lignite beds and a limited description of roof fall and subsidence problems by Soister (1974) indicate a great potential for subsidence over underground operations that mine or burn Denver lignite.

Existing small-scale UCG experiments in the United States have created only small amounts of subsidence, but full-scale operations in Russia have caused serious surface subsidence problems (Gregg, 1977). Many workers believe subsidence and related aspects are among the main environmental concerns with UCG (Mead and others, 1978; Gregg, 1977; U.S. Department of Energy, 1979; Greenlaw and others, 1977; McCurdy, 1977). Subsidence is also believed to be a serious potential environmental problem for hydraulic borehole mining (Savanick, 1979).

Figures 54 and 55 illustrate some of the potential environmental problems caused by surface subsidence. Ground cracks or fractures may extend from the subsidence cavity to the surface. The land surface may be deformed into depressions above the caved parts of the mine. Man-made structures such as buildings, bridges, roads, powerlines, and pipelines may be seriously damaged by these subsidence phenomena.

Subsidence hazards can be minimized at least temporarily in several ways. For instance mined-out workings can be backfilled, or large blocks of coal can be left intact as pillars to support overburden. Mining in areas with a high potential for surface subsidence should be carefully conducted and in certain cases completely avoided. The effects of subsidence on structures can be decreased by prohibiting or requiring special construction in potential subsidence areas. Unfortunately most hazard reduction techniques are often undesirable from economic, technological, or land-use aspects.

SURFACE-WATER IMPACTS AND MITIGATION MEASURES

Most surface-water impacts related to energy resource development are either directly or indirectly caused by disturbance of the hydrologic balance. The Office of Surface Mining defines the hydrologic balance as "the relationship between the quality and quantity of water inflow to, water outflow from, and water storage in a hydrologic unit such as a drainage basin, aquifer, soil zone, lake, or reservoir. It encompasses

the dynamic relationships among precipitation, runoff, evaporation, and changes in ground and surface water storage." Mining activities are now required by Federal and State regulations to be conducted and abandoned in such a way that their effect on the hydrologic balance is minimized. Proper reclamation is essential to reduce the long-term effects of surface mining on surface water.

The hydrologic balance is naturally in a constant state of change, depending on precipitation and evapo-transpiration rates and variations in runoff, infiltration, and percolation capacities. Coal mining may contribute artificial changes by altering runoff patterns, infiltration, percolation, and stream courses, by vegetation removal, and by exposing rocks and minerals that may react with water and pollute surface waters. In the following paragraphs a few of the more common ways that coal mining can affect the hydrologic balance are illustrated. No attempt is made to completely cover this complex subject because many of the impacts are dependent on site-specific conditions that must be evaluated as part of the environmental studies for a particular mine site. Furthermore many aspects of the interrelationships between mining and surface water are as yet poorly understood or poorly documented.

Surface mining of coal has a greater potential for altering surface water than do other types of coal mining. The primary reason for this is rather obvious because surface mining involves considerably more land disturbance than do other mining methods. During mining, open cuts may collect and temporarily store precipitation on the surface. Such impoundments are common at area mines, occurring in the mine pit and between spoil piles, and may allow for increased evaporation or infiltration of precipitation. Runoff that enters surface mines usually must be diverted around the mine through a series of diversion ditches and settling ponds. If runoff enters the mine, it may be impounded and allowed to evaporate, or it may infiltrate into the spoil and be stored underground. If any water is temporarily stored in sedimentation ponds, evaporation rates will tend to be higher. Thus, during mining the local hydrologic balance is altered in many ways because of changes in runoff, infiltration, and evaporation.

Normal runoff from a mining area may contain increased suspended and dissolved solids. Suspended solids can be removed before the water leaves the mine site by use of sediment-catch basins. Chemical contamination may or may not be a problem. Acid mine drainage, a serious problem associated with the high sulfur coals found in the east, will probably not be a problem with the low sulfur coals in the study area. However, certain minerals in the overburden may be leached from spoil piles and carried from the mine site by runoff and infiltrating ground water (Hounslow and others, 1978; Curtis, 1979).

Research in the eastern United States suggests the highest erosion rates and sediment loads usually occur during the first six months after completion of mining (Curtis, 1979). Once a good vegetative cover is established, the erosion rates lower considerably. Since vegetation growth is much slower in the study area, high erosion rates and sediment loads would persist for a longer period of time. Terracing reclaimed

areas may aid erosion control (Curtis, 1971a).

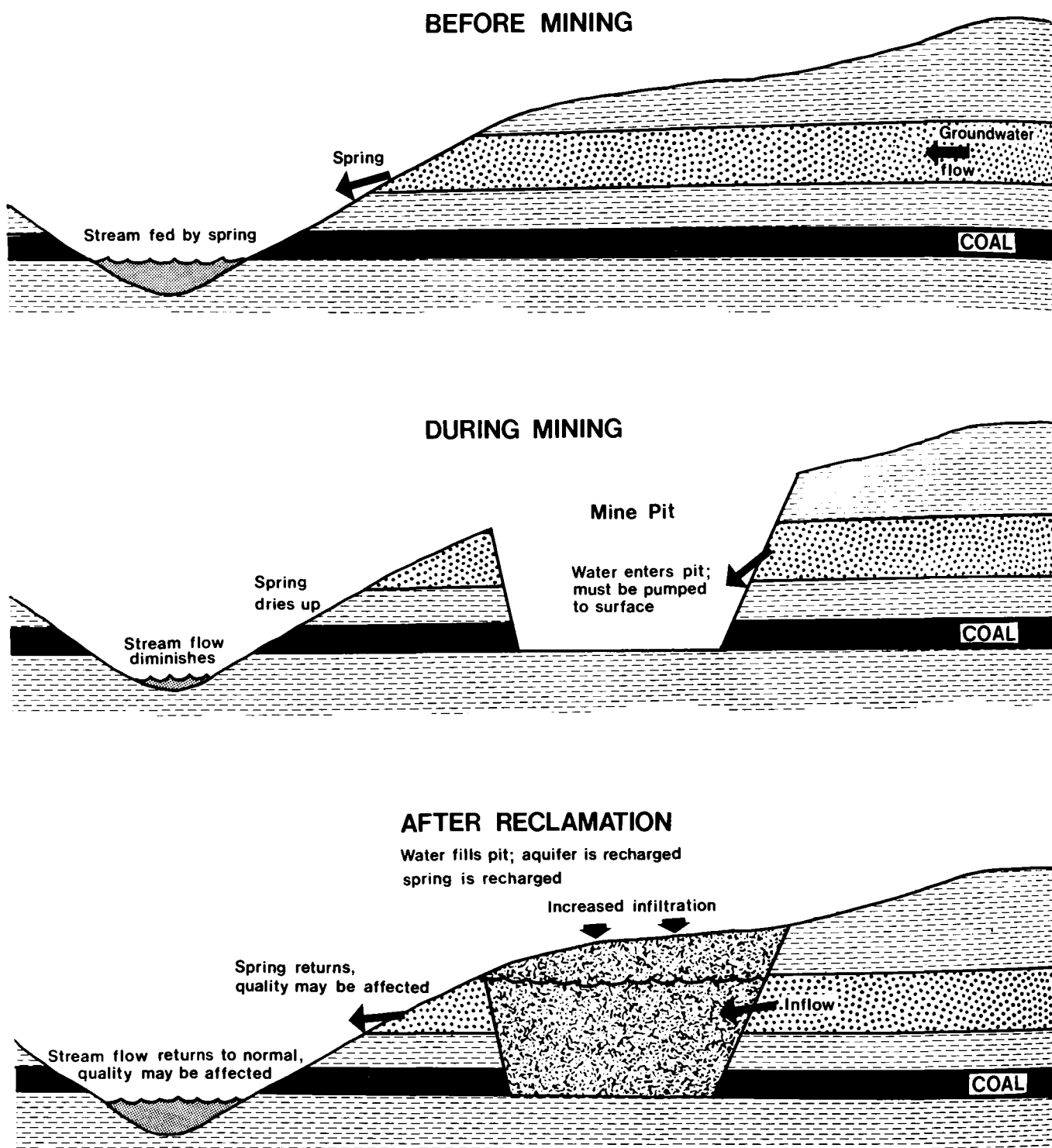
Surface mining may disrupt shallow aquifers and in certain cases cause springs to dry up and affect stream flow. Figure 56 illustrates a situation where the mine penetrates a shallow aquifer. Ground water from the aquifer enters the pit on the up-gradient side, and aquifer recharge on the down-gradient side of the pit is interrupted. The spring dries up, and stream flow diminishes. After completion of mining and reclamation, the replaced overburden may act as a large, relatively homogenous, fractured aquifer. Ground-water inflow and surface-water infiltration may eventually saturate the replaced spoil and allow the spring to be rejuvenated, although flow rates and water quality may differ from pre-mining levels. Suspended and dissolved solids in the spring and stream may increase after mining.

It is also possible to create new springs because of mining and reclamation. As shown in Figure 57, a reclaimed pit has been backfilled with replaced overburden that has a high fracture porosity. The pit may fill with infiltrating surface water (and in some cases ground water) and eventually discharge water to the surface as a spring. Increased water retention by disturbed land can also play an important role in controlling peak stream flow during high precipitation events. Studies in the eastern U.S. by Curtis (1977b) indicate the increased water retention capabilities of disturbed land may reduce peak flow by retaining part of the runoff in temporary underground storage.

Surface mining may also indirectly affect surface-water quantity and quality in adjacent drainage basins by altering the recharge areas of ground-water aquifers that discharge to streams in adjacent drainage basins. Surface mining may increase or decrease recharge capacities and have a corresponding effect on the amount of water in an aquifer and its discharge rates. If recharge water leaches ions from the spoil, the water quality within the ground-water aquifer and in streams that receive the discharged ground water may be affected.

Figure 58 illustrates a situation where the recharge area of an aquifer is disturbed by mining. The aquifer discharges into a stream in an adjacent drainage. During mining aquifer discharge is decreased, stream flow diminishes, and the stream may lose some water to the aquifer. After completion of mining and reclamation, the aquifer recharge is re-established and aquifer discharge to the stream and streamflow eventually stabilize. Because the water in the recharge area now percolates through broken spoil, the total dissolved solids in the aquifer and stream may increase.

Surface mines that penetrate ground-water aquifers may experience considerable ground-water inflow into the mine. A dewatering system consisting of sump pumps, graded drainage ditches, or dewatering wells may be used to remove water from the mine or prevent it from entering the mine. Water from the dewatering system must be disposed of, generally on the surface. If the water is of acceptable quality, it may be discharged directly into the surface-water system. If the water is of poor quality, it must be treated prior to release, evaporated in holding ponds, or



Drawing not to scale

Figure 56. An example of potential hydrologic effects of surface coal mining on springs.

injected into deep disposal wells.

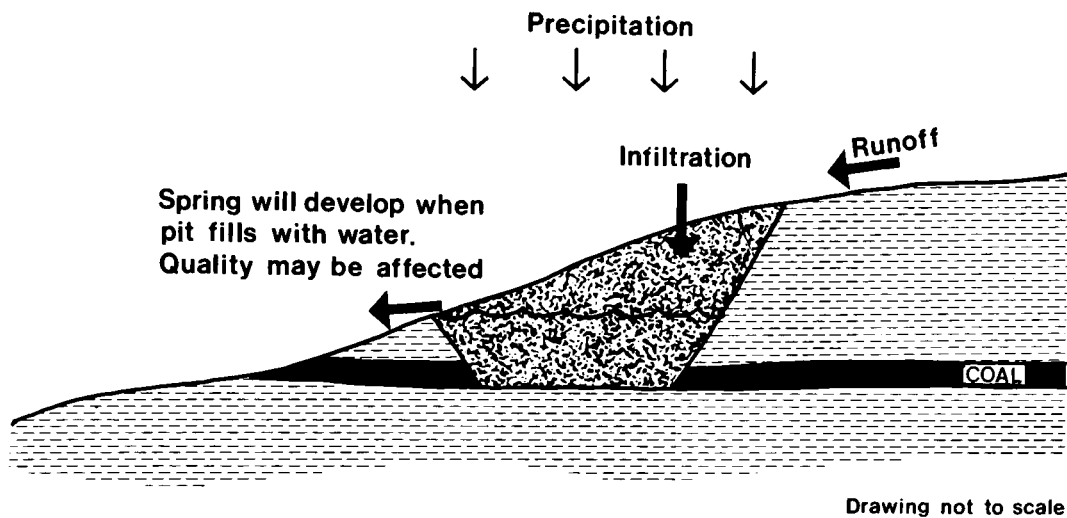


Figure 57. A potential way in which springs or seeps may be generated as a result of the reclamation of a surface coal mine.

As can be seen from these few simplified examples, surface coal mining can affect the hydrologic balance in many ways and potentially impact surface water at the mine site and in nearby drainage basins. Most effects, such as increased sediment load, salinity and evaporation, and decreased average stream flow, are detrimental, but some aspects, such as decreased peak stream flow during rain storms, may be beneficial.

Underground coal mines, hydraulic borehole mines, and UCG facilities all affect the hydrologic balance to lesser degrees than does surface mining. Underground mining generally will cause less impact on surface water than UCG and hydraulic borehole mining because it disturbs only a very limited area near the mine openings. All three types of operations will affect infiltration and runoff by construction of roads, buildings, and other structures, but these land disturbances are small when compared to surface mining. Subsidence and its associated phenomena may, however, cause additional surface-water impacts, and all three of these mining methods may cause subsidence. Surface subsidence may create local closed depressions that could trap or divert stream flow and runoff (Figure 55). Impounded water could be subjected to high evaporation rates if the water stands for long periods of time, or it could infiltrate into the subsurface through permeable units and subsidence-induced ground cracks.

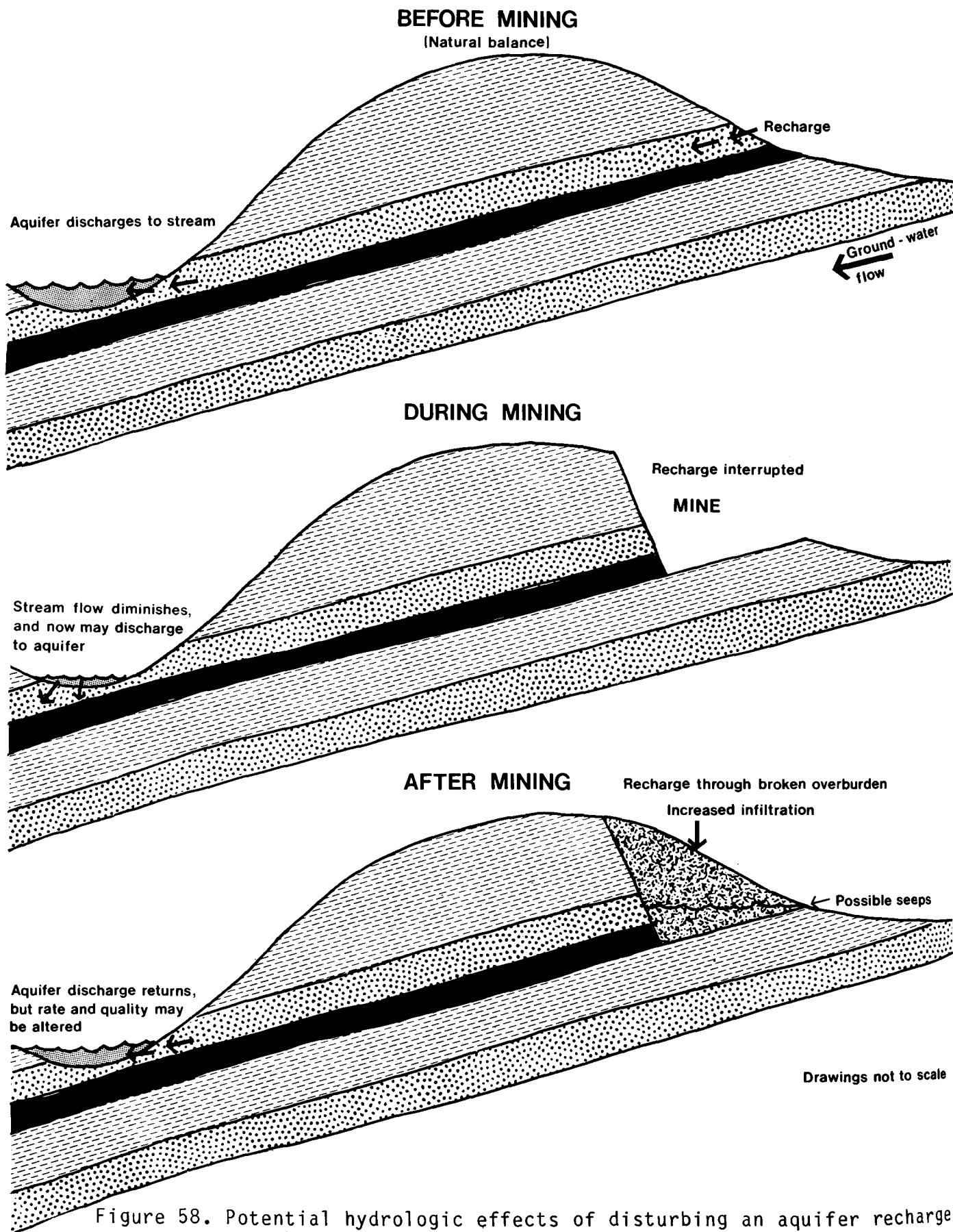


Figure 58. Potential hydrologic effects of disturbing an aquifer recharge area by surface coal mining.

Dewatering systems associated with underground mines, UCG facilities, and hydraulic borehole mines may generate water that must be disposed of on the surface. Recovered water may be discharged into surface streams with little effect, assuming the water chemistry and added flow rates are environmentally acceptable. If the extracted water is of poor quality, it may require treatment before release or it may have to be evaporated in holding ponds or injected into deep disposal wells. Dewatering systems at UCG operations are more likely to produce poor quality water that will require special handling than will underground and hydraulic borehole mines. Such water may contain high concentrations of inorganic and organic species, a result of the burning of coal and leaching of ash in the gasification chamber.

Baseline water-quality and flow data is required prior to the initiation of coal mining activities at any mine site. During mining repeated measurements should be taken to evaluate the effects of mining on the quality and flow. Detection of serious problems may warrant the need for corrective action. For instance, undesirably high suspended solid loads in streams may signal a need for sediment-catch basins and/or revision in reclamation plans. Surface-water monitoring should continue after mining until the mine site has been satisfactorily reclaimed.

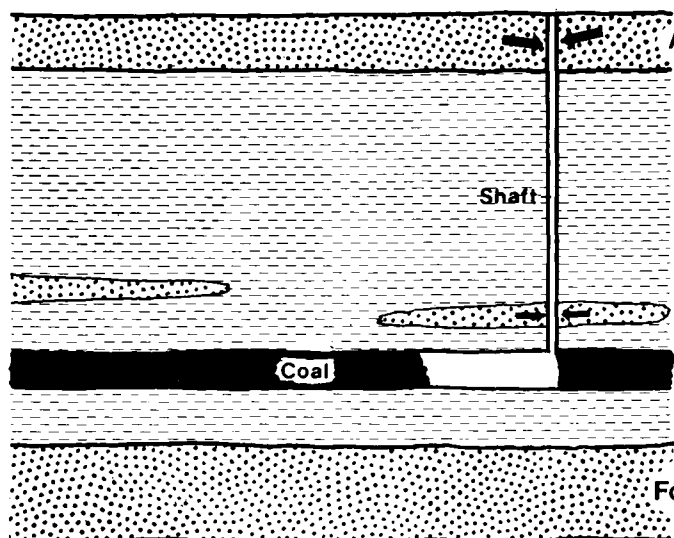
GROUND-WATER IMPACTS AND MITIGATION MEASURES

Coal mining may cause significant effects on ground-water quality and quantity. Aquifer disruption caused by mining or subsidence and disturbance of recharge areas are the primary ways in which the quantity and flow paths of ground water are affected. Ground-water quality may be impacted by escape of gases and fluids from UCG operations and by migration of contaminants leached from exposed coal and rock in underground mines and from replaced overburden in surface mines.

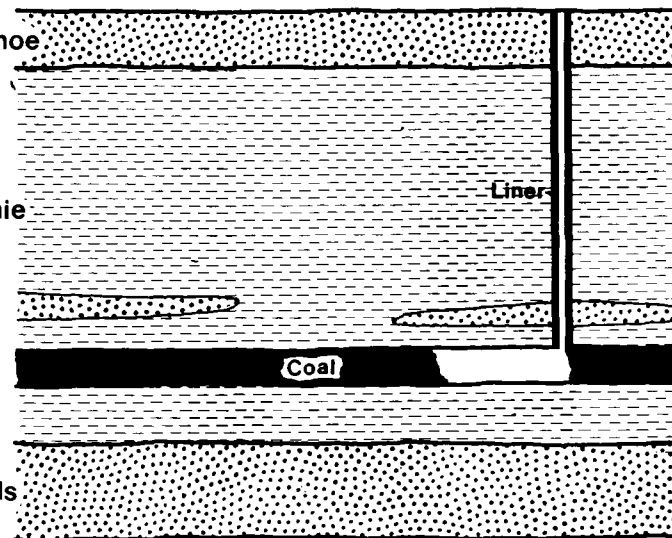
Conventional underground coal mining generally impacts the ground-water regime less than other types of coal mining methods. Unfortunately, underground coal mining will probably not receive widespread use in the near future in the study area for a variety of reasons previously described in this report. One potential ground-water problem that is related to underground coal mining involves leakage from aquifers penetrated by a shaft or slope. Such leakage could create a cone of depression in the potentiometric surface of any affected aquifer. Nearby water wells that tap an affected aquifer could experience declines in water levels if they are within the cone of depression and in extreme cases may go dry. Leakage through shafts or slopes can be minimized by proper sealing of penetrated aquifers exposed in the openings. Most mining companies normally line shafts and slopes to prevent ground-water incursion and stability problems as a regular part of mine construction.

Figure 59 illustrates conceptual examples of the potential hydrologic effects of open, unlined shafts and slopes. In the upper illustrations a shaft penetrates the Arapahoe Formation and a lenticular channel sandstone in the lower Laramie Formation. Both aquifers may leak into the shaft. In the lower illustrations a slope down to a Denver lignite bed penetrates sandstone aquifers in the Dawson Arkose and a lenticular channel sandstone in the Denver Formation. Both aquifers may leak into the unlined slope. Proper lining of the openings will prevent leakage problems in both situations.

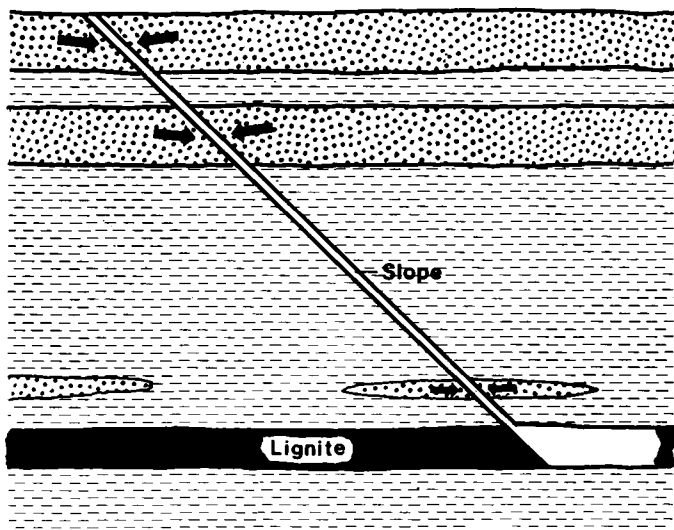
Unlined shaft may allow leakage from Arapahoe Formation and channel sandstones in Laramie Formation



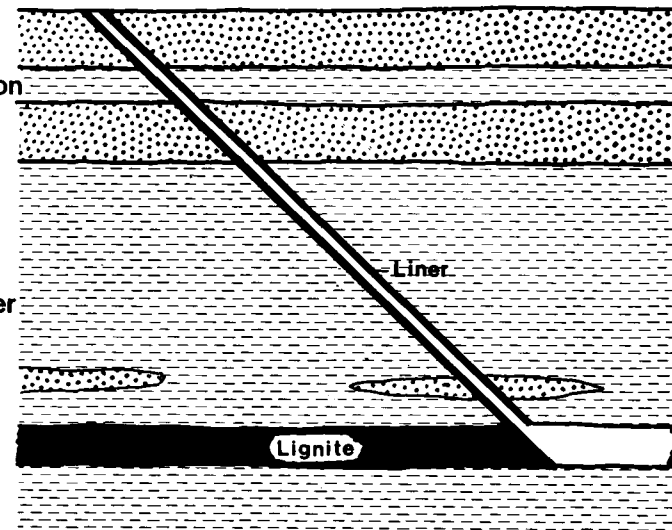
Shaft lined to prevent leakage



Unlined slope may allow leakage from Dawson Arkose and Denver channel sandstones



Slope lined to prevent leakage

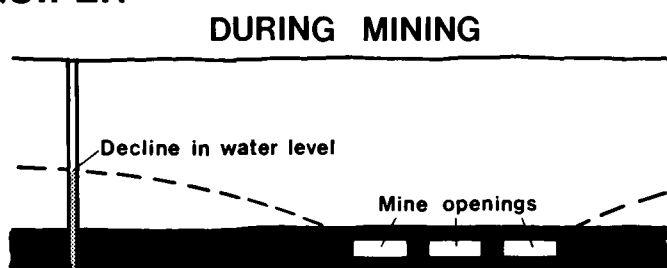
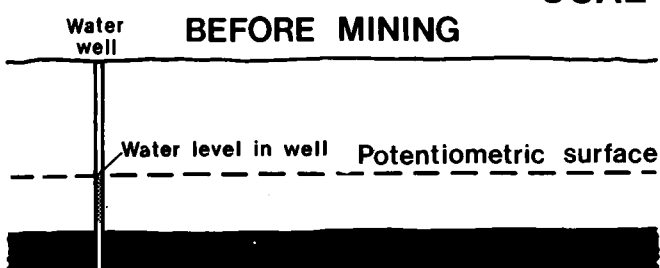


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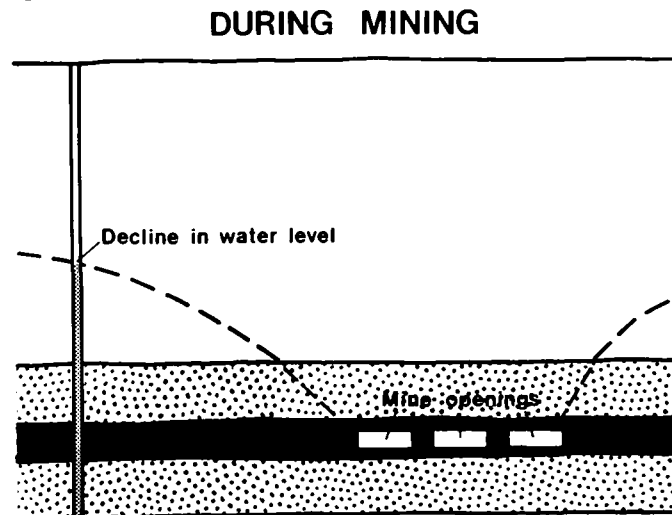
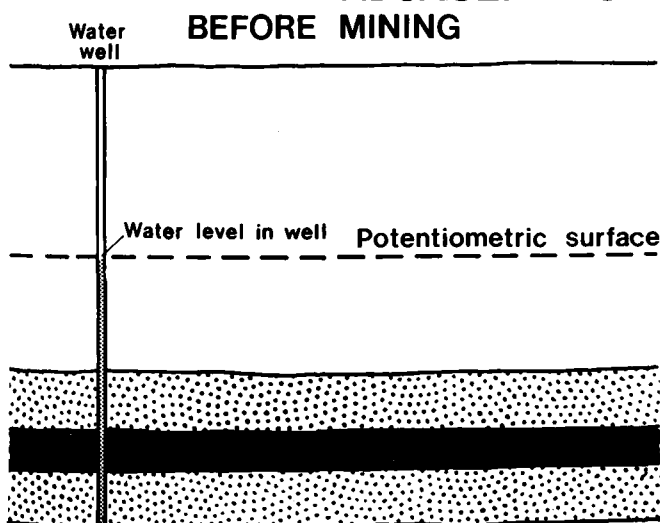
Figure 59. Theoretical examples of the potential hydrologic effects of shafts and slopes of underground coal mines and ways to mitigate the effects.

Coal beds are major aquifers in some coal-bearing areas of the west. Underground mines within a coal bed that is an aquifer may experience a large amount of ground-water inflow that must be removed from the mine. The upper part of Figure 60 illustrates a situation where a water well that is perforated in a coal aquifer could be affected by coal mining. The dewatering system of the mine may withdraw large amounts of water from the coal aquifer to keep the mine dry. This causes a cone of depression to develop in the potentiometric surface of the coal aquifer and may cause declines in the water levels of nearby wells. After completion of mining the mine openings should fill with water, and water levels and the potentiometric surface should approximately return to pre-mining conditions. Water quality, however, may be somewhat altered.

COAL AQUIFER



ADJACENT SANDSTONE AQUIFERS



Drawings not to scale

Figure 60. Potential hydrologic effects of underground coal mining when the coal bed is an aquifer or when aquifers directly overlie or underlie a coal bed.

Existing data suggest the coal and lignite beds in the study area are not major aquifers, but they may contain some water. In many areas, however, minable Laramie coal beds are overlain or underlain by major aquifers. These aquifers may be affected by mining of the coal beds, as is shown in the lower part of Figure 60. Adjacent aquifers could leak into the mine, with the resulting water loss causing a cone of depression in the disturbed aquifers around the mine site. Thin shale or claystone beds may separate the aquifers from the coal beds in some areas and effectively prevent leakage. These confining units, however, may be disturbed by roof fall and floor heave, thus allowing for leakage into the mine. Water intrusion problems can be mitigated by installing a series of dewatering wells around the mine to prevent inflow into the mine or by removing the water by sump pumps or a system of drainage ditches.

Mine subsidence may also allow for ground-water leakage from overlying aquifers both during and after mining (Figure 55). The mass of subsided rock will probably be intensely fractured. Ground water in penetrated aquifers may readily leak into the subsidence zone, migrate downward, and enter the mine.

Ground-water quality may be somewhat affected by underground coal mining. Water entering the mine may react with coal and overburden in an oxidizing environment and allow for certain undesirable ions to be leached from the coal or rock. A small amount of water may migrate back into the ground-water system during mining, but the greatest contamination may occur after mine abandonment. As shown in Figure 61, ground water will flood the mine workings after abandonment, and the potentiometric surface eventually should approximately return to pre-mining conditions. Water within the mine may react with the exposed coal and rock and leach certain undesirable ions from it. The contaminated water will migrate through the aquifer in the direction of ground-water flow and water quality in nearby wells may be affected. The chemistry of the escaping water will depend on the chemistry of the leached solution and on the ability of the host rock to purify the water. Coal often acts in a manner similar to activated carbon, and water quality may markedly improve as it moves through the undisturbed coal bed due to sorption. This is especially true for organic contaminants.

Ground-water quality may also be affected by subsidence. As previously described, overlying aquifers disturbed by subsidence may leak water into the subsided area during and after mining and allow for commingling of water from the various aquifers. Should an overlying aquifer contain poor quality water, the mixing could cause an overall decrease in the water quality of other aquifers with which it commingles. Surface water may be diverted underground through subsidence cracks. If the surface water is of poor quality, commingling may allow for degradation of ground-water quality.

UCG and hydraulic borehole mining may affect ground water in much the same way that underground mining does. The vertical and slanted drill holes used in these recovery techniques may be compared to the shafts and slopes of underground mines and the gasified or hydraulically mined areas

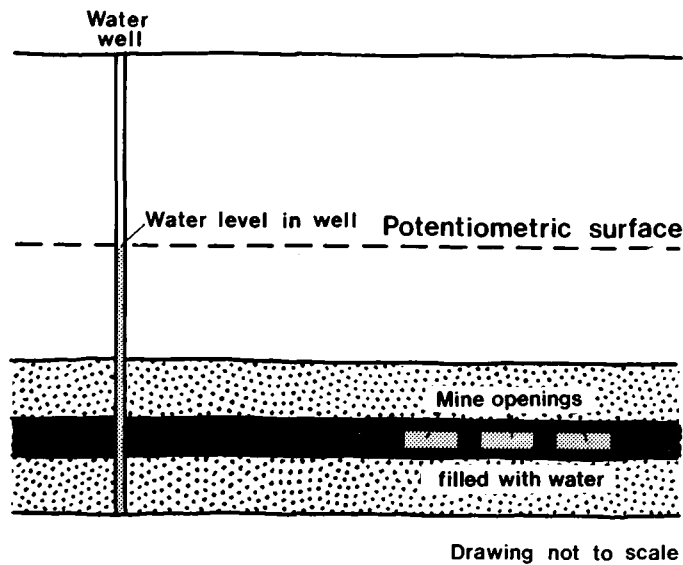


Figure 61. An example of how the potentiometric surface returns to pre-mining conditions after completion of underground coal mining.

are comparable to the underground mine workings. Individual drill holes, of course, are much narrower in diameter than are shafts or slopes, but hundreds of drill holes are required for full-scale UCG and hydraulic borehole mining, and only a few shafts or slopes are needed for an underground mine.

Ground water in aquifers penetrated by drill holes may leak into an uncased drill hole or into the annulus between the edge of the drill hole and the well casing. Such leakage from one drill hole may be relatively insignificant, but leakage in many holes may have noticeable cumulative effects on the ground water of disturbed aquifers. Slopes and shafts should be properly lined to prevent aquifer leakage and drill holes should be properly completed to minimize leakage. With UCG, aquifer leakage through drill holes is not only an environmental problem, but also may cause technological problems by allowing too much water to enter the gasification chamber and possibly extinguishing the burn.

If the mined coal bed is an aquifer or if it is adjacent to aquifers, the ground water in these aquifers may be affected by UCG or hydraulic borehole mining. During gasification ground water within the mined coal bed is usually forced away from the gasified area because gases are at high pressures within the chamber. A cone of depression in an aquifer's potentiometric surface may temporarily be created around a UCG facility because of this high pressure. Ground-water inflow rates, however, may be so high that excessive amounts of water may still flow into the

gasification area and cause technological problems. This is especially possible if the coal bed is a major aquifer or if it is adjacent to a major aquifer. Aquifer dewatering through a series of wells may be needed to limit ground-water movement into a gasification area. Aquifer dewatering may contribute to additional decline in the potentiometric surface during gasification, but water levels should ultimately nearly return to pre-mining conditions after completion of the project and termination of dewatering activities. Excessive ground-water inflow into a cavity being mined using hydraulic borehole techniques may inhibit the cutting action of the high pressure cutting jets. Aquifer dewatering will also alleviate this technological problem, but again it may also cause water level declines during mining.

Subsidence occurring at UCG facilities and hydraulic borehole mines may induce ground-water problems similar to those caused by subsidence at underground coal mines. Aquifer disruption and leakage of ground water from disturbed aquifers into the burnt or mined cavities are the primary effects of subsidence induced by UCG and hydraulic borehole mining. Subsidence, as previously described, may cause both water quantity and quality problems.

Hydraulic borehole mining may somewhat affect ground-water quality. Water that enters the mined out cavities may react with exposed material, mainly coal and any subsided overburden. Most contaminants leached in this manner will probably be the standard cations and anions, such as sodium, calcium, sulfate, and chloride, although some trace heavy metals and organic compounds may also go into solution.

Perhaps the greatest potential environmental problem associated with UCG involves ground-water contamination (Phillips and Muela, 1977; Humenick and Mattox, 1977; Campbell and others, 1978). This problem has been studied extensively at the Hoe Creek experiments by Lawrence Livermore Laboratory and at other test facilities, but much remains to be learned about the ground-water effects of full-scale gasification. The following paragraphs summarize the state-of-the-art knowledge concerning ground-water quality problems associated with UCG. The data is primarily from Campbell and others (1978) and from test results reported at the 5th Annual Underground Coal Conversion Symposium held at Alexandria, Virginia, during 1979. It should be emphasized that this information was developed from laboratory and pilot-scale tests and that the pilot-scale results are principally from one geologic environment. Also, this summary is highly generalized. Extension of these findings to full-scale operations in differing geologic settings may not be totally accurate.

During gasification injection pressures are maintained at a level approximately equal to or slightly greater than hydrostatic pressures. This allows some of the injected gases to migrate radially into the coal bed and adjacent formations. The gas is mostly N₂, CO, CO₂, and CH₄, but it also contains a variety of organic compounds produced during pyrolysis of the coal. In general the more volatile organic compounds (or lighter molecular weight compounds) migrate farther than do less volatile organic compounds. Most ash created during gasification remains isolated from the

ground water because of injection pressures that prevent ground-water inflow. Thus, gasification creates little increase in non-volatile inorganics. As gasification proceeds, cracking and subsidence of the overburden may occur. Gases and contaminants within the gasification chamber may escape into overlying strata and aquifers.

After gasification is completed injection pressures decrease, and ground water begins to enter the gasified cavity. Initially, most invading water is vaporized because of high temperatures, but eventually the cavity fills with water. Ash remaining in the cavity is leached by the water, resulting in increased pH and higher concentrations of many inorganic elements and compounds. Some evidence indicates the non-volatile inorganic contaminants are initially transported radially into the surrounding formations (Campbell and others, 1978). Natural ground-water flow through the gasified area is eventually re-established, and a pollution plume in the direction of flow develops. The dimensions, extent, and characteristics of the plume will depend on flow direction and velocity, dispersion properties, and the adsorption and reaction that occurs between the contaminants and host rock.

Considerable evidence has been documented that indicates subbituminous coal and lignite beds are highly sorptive and may cleanse contaminated water of many organic compounds, ammonia, and certain other inorganic species. Other contaminants, particularly light metal ions and most anions, are only weakly sorbed, and they may migrate considerable distances from the site with the natural ground-water flow. Laboratory testing indicates some claystones may also adsorb significant amounts of contaminants, but clean, clay-free sandstones generally have low sorption capacities. Thus, contaminated water in adjacent or overlying aquifers may be transported away from a UCG facility at a rate approximately equal to the rate of ground-water flow.

A detailed ground-water monitoring system must be an integral part of any proposed UCG project in the study area. Such a system should provide the necessary data to allow evaluation of ground-water quality problems and determination of the need to restore contaminated aquifers. Although ground-water restoration is not currently a standard procedure for UCG experiments, it may become a necessary part of a full-scale UCG operation if major ground-water aquifers are affected. Many of the restoration techniques that may be used with UCG are generally discussed in a later section of this report on ground-water restoration at in situ uranium solution mines. The problem of organic contamination, however, is unique to UCG and specific restoration techniques may have to be developed specially for UCG.

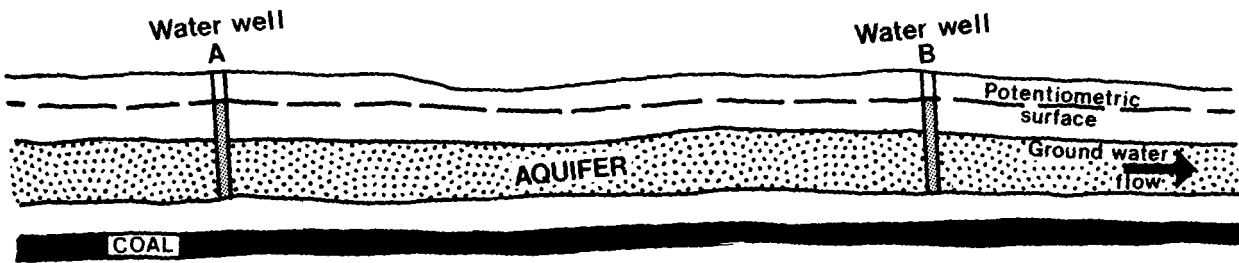
Surface coal mining may have serious effects on ground-water flow paths and quantity, and it may have some effect on ground-water quality. Most problems result from aquifer disruption, disturbance of recharge areas, and leaching of replaced overburden. Any aquifers penetrated by the surface mine may lose ground water into the pit. This includes both overlying aquifers and the mined coal bed, if it is an aquifer.

Figure 62 illustrates a general situation where a surface mine disrupts an aquifer that supplies water to nearby wells. The upper diagram shows the natural conditions prior to mining. Two wells tap a major sandstone aquifer that lies above a coal bed. In the middle diagram a surface mine has penetrated the aquifer to get to the coal bed. The disrupted aquifer discharges water into the mine. Some mines may use dewatering wells to prevent ground-water incursion and the problem of having to remove water from the pit. The result, in either case, is that a small cone of depression is created around the mine, and recharge into the aquifer on the down-gradient side is restricted. Water wells around the mine may experience declines in water levels and in extreme cases may go completely dry. After completion of mining (lower diagram), the pit is back-filled with overburden that will probably have high fracture permeability. Water will enter the pit from the aquifer and from infiltrating surface water, and recharge to the aquifer on the down-gradient side of the pit should be eventually re-established. The potentiometric surface may ultimately return to near original levels, but the altered infiltration rates and locally high evaporation rates may prevent complete restoration to original hydrostatic conditions. Because certain ions may be leached from the replaced, broken overburden, the water quality in well B may be altered, primarily by an increase in total dissolved solids.

Figure 63 illustrates typical situations in the study area. The upper diagrams show a common hydrogeologic setting in areas where Laramie coal beds are strippable and the lower diagram shows a possible setting where Denver lignite beds are strippable. The major aquifer in the upper diagram is the Fox Hills, although channel sandstones in the Laramie may locally supply ground water. Well A taps only the Fox Hills aquifer. It should experience no serious problems with declining water levels because of the mine, unless there is hydrologic connection between the mined coal bed and the Fox Hills. Well B taps only a Laramie channel sandstone that is disturbed by the mine. The water level in this well may be lowered during the mining operation and it may go completely dry. Well C also taps the disrupted Laramie channel sandstone, but it also extends down through the Fox Hills. Well C may experience some water level decline, but the Fox Hills should still provide sufficient water to keep the well operating in a satisfactory manner. Thus, wells which penetrate the entire Laramie-Fox Hills aquifer or just the Fox Hills should be affected less than wells which only tap Laramie channel sandstones that are disrupted by a surface mine. After completion of mining the water level in wells A and C should eventually approximately return to pre-mining conditions, but the hydrostatic conditions of the aquifer tapped by well B will probably never fully return to original levels. It may be necessary to replace well B with a well that extends to the Fox Hills.

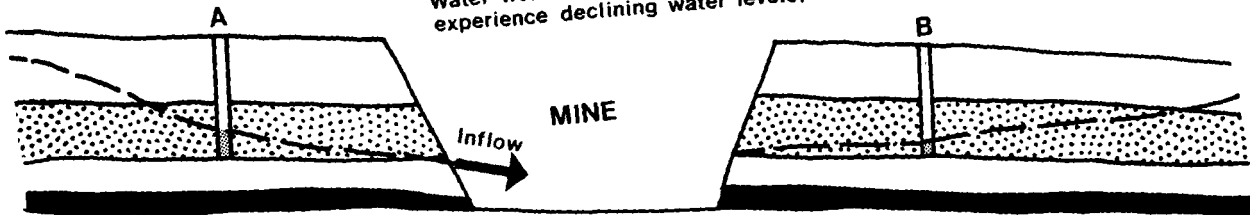
The lower diagrams in Figure 63 illustrate a hypothetical example of water wells near a Denver lignite mine. The Denver lignite zone is in the upper part of the Denver Formation. Only the lower part of the Denver contains regionally important sandstone aquifers (Romero, 1976). Wells that tap these lower sands, such as well D shown in Figure 63, should not be affected by surface mining operations. Locally, a few sandstone bodies

PRE - MINING



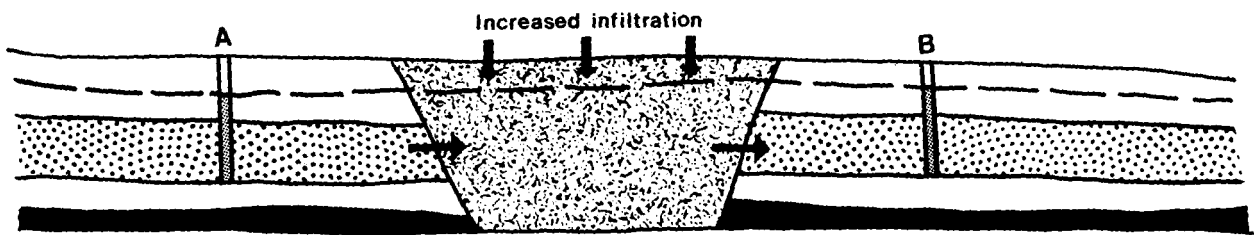
DURING MINING

Aquifer leaks water into the pit. Water wells near the mine may experience declining water levels.



AFTER MINING

Water levels approximately return to original conditions. Water quality may be altered in Well B.



Drawings not to scale

Figure 62. Possible hydrologic impacts of aquifer disruption by a surface coal mine.

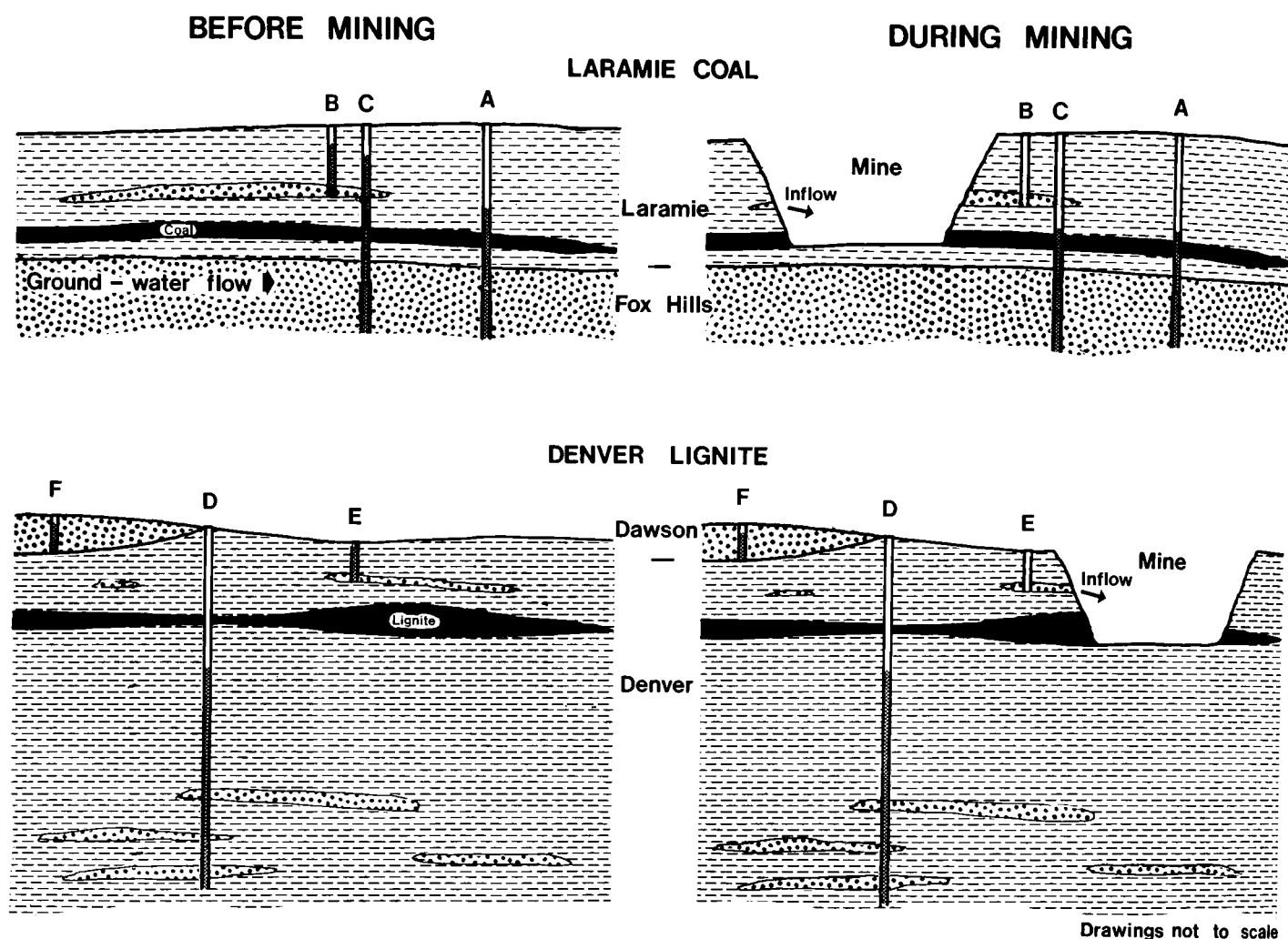


Figure 63. Theoretical examples of how water wells may be affected by surface mining Laramie coal (upper diagram) and Denver lignite (lower diagram).

within the lignite zone do provide small quantities of ground water for a limited number of wells in the study area. Should these water-bearing sandstones be disturbed by mining, any nearby wells that tap them, such as well E in the upper diagram, may experience water level declines during mining. A major aquifer of regional importance, the Dawson Arkose,

overlies the Denver lignite zone. If mining should penetrate the Dawson, ground water in the formation may be affected. In Figure 63 the mine does not disrupt the aquifer; therefore, well F should not be impacted by the depicted mine. After completion of mining and reclamation, the water level in well E will probably not return to pre-mining conditions because of the extent of aquifer disruption. It may need to be replaced with a well into the lower Denver sandstones or the Arapahoe aquifer.

Ground water may also be altered by surface mining operations that disturb recharge areas. Figure 58 illustrates a situation where the recharge area of a sandstone that overlies a coal bed is disturbed by mining. In this case the aquifer had been discharging into a stream. Because aquifer recharge is interrupted, the aquifer no longer discharges to the stream, and now the stream may lose water to the aquifer. In the study area mines that recover Laramie Formation coal may impact overlying channel sandstones in this manner. Denver lignite mines could, in certain cases, alter Dawson Arkose recharge areas.

Water that percolates through replaced overburden may leach certain ions from the broken rocks as it migrates. If this water re-enters a ground-water aquifer, as shown in Figures 58 and 62, it will alter the original quality of water within the aquifer. The degree of change and types of contaminants will depend on chemistry of the replaced overburden and reactions that occur after reclamation.

Baseline data on ground-water quality and water levels in nearby water wells should be collected prior to initiation of mine construction. During mining these same wells should occasionally be monitored to determine the extent of the impact of the mine on ground water. Severe problems may warrant a revision of the mining plan or environmental protection measures to minimize potential ground-water impacts. After completion of mining, wells should be regularly sampled to ascertain whether or not the mine abandonment and reclamation plan will achieve suitable long-term protection of the ground-water system.

URANIUM RESOURCES

RESOURCE CHARACTERISTICS

Uranium is the heaviest naturally occurring element known to exist. This dense metal is chemically very reactive and radioactive. Three uranium isotopes exist in nature: U-238 comprises about 99.3 percent of all natural uranium, U-235 about 0.7 percent, and U-234 less than 0.1 percent.

Nuclear power plants generate electricity through the fission of radioactive materials. Certain natural and artificial uranium isotopes are fissionable and are valuable for power generation. U-235 undergoes fission on exposure to neutron radiation. U-238 and Th-232 (natural thorium) are fertile materials that can be converted into fissionable materials by irradiation with neutrons. U-238 converts to plutonium and Th-232 converts to U-233. Besides being valuable for power generation, uranium and its associated isotopes are used in significant quantities for military weapons and production of radioisotopes utilized in medicine, chemistry, and industry. Minor amounts of uranium are used as purifying agents to produce inert gases, in electrodes and resistors in the electronics industry, as alloy additives in the metallurgical industry, and as coloring agents in the glass industry (Morse and Curtin, 1977; Griffith, 1967).

Uranium is one of the less common elements, constituting only about three parts per million of the earth's crust. It is more abundant than the precious metals and less abundant than the base metals. Uranium does not occur in nature as a free element, but it readily combines with other elements to form soluble and insoluble compounds or minerals. The mineralogy of uranium is quite complex and for this reason, will be discussed only briefly in this report. Uranium is a polyvalent element that occurs in +3, +4, and +6 forms. Because of its polyvalence, high chemical reactivity, atomic radius, and solubility, uranium occurs in very low concentrations in many diverse geologic environments and concentrations great enough to be an economic ore body are limited.

Over one hundred minerals contain uranium. These minerals can be divided into primary and secondary classes. Primary uranium minerals are deposited during the original ore-forming or rock-forming episode. Secondary uranium minerals develop through the alteration of primary uranium minerals. The most common primary mineral is uraninite, whose simplified chemical composition is UO_2 . It is found in sedimentary rocks, granites, pegmatites, and vein deposits. One common form of uraninite called pitchblende, is a sooty, fine-grained, colloform variety. Uranium may also combine with silicates to form another common primary mineral, coffinite. Secondary uranium minerals may be hydrated oxides, sulfates, phosphates, vanadates, silicates, and carbonates. The best known secondary mineral is carnotite, a hydrated potassium uranium vanadate. Other similar-looking yellow uranium minerals, including tyuyamunite and metatyuyamunite, are often incorrectly identified as carnotite.

Economic uranium deposits occur in a variety of geologic environments. Bailey and Childers (1977) devised a classification useful for uranium exploration based on the principal control of the mineralization. In their classification uranium deposits are divided into three general categories: 1) strata-controlled deposits, 2) structure- or fracture-controlled deposits (vein-type), and 3) intrusive-controlled deposits.

Strata-controlled deposits may be subdivided by the type of host rock into 1) sandstone-conglomerate hosts, 2) carbonate hosts, and 3) lignite, black shale, or phosphate hosts. Sandstone or conglomerate host deposits can occur in the form of 1) trend deposits, 2) roll-front deposits, 3) stack deposits, and 4) reworked Precambrian-age heavy-mineral placer deposits. Roll-front deposits are the primary type of uranium deposit in the Denver and Cheyenne Basins. Fractured and brecciated host rocks with mineralization filling voids, coating fracture surfaces, and partly replacing the host rock are typical of the structure- or fracture-controlled deposits. The Schwartzwalder mine, which is just outside the study area in Jefferson County, typifies this type of uranium deposit. Intrusive-controlled, finely disseminated uranium exists in many felsic igneous rocks. Deposits of this type also occur adjacent to the study area in bostonite dikes of the Front Range.

As mentioned previously, the primary type of uranium deposit in the Denver and Cheyenne Basins is the roll-front deposit. The term "roll-front" was first used by the uranium-vanadium miners in the Colorado Plateau to describe the character of the ore bodies which they mined (Bailey and Childers, 1977). Figure 64 illustrates a typical cross section through a roll-front deposit. The host rock for roll fronts is usually medium- to coarse-grained sandstone or pebble conglomerates. Roll fronts are deposited when uranium-enriched, oxidized ground water flowing

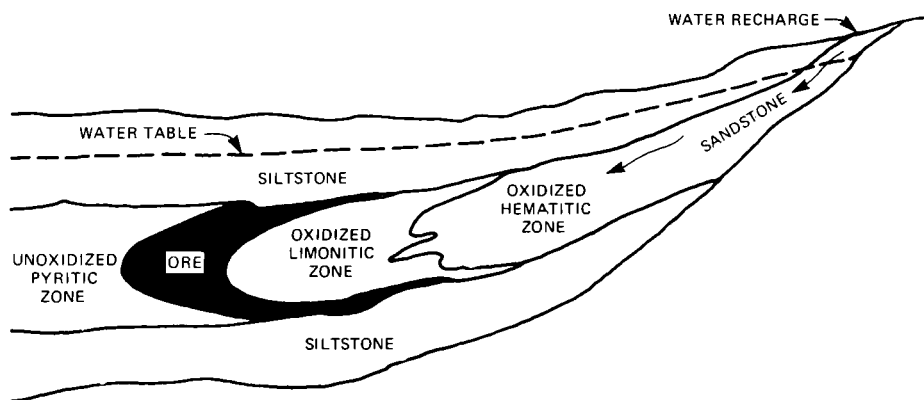


Figure 64. Generalized cross section through a uranium roll-front deposit. (from Adler, 1974)

through the host rock encounters a reducing environment. The uranium precipitates out in the interstitial pore space at the reducing-oxidizing boundary.

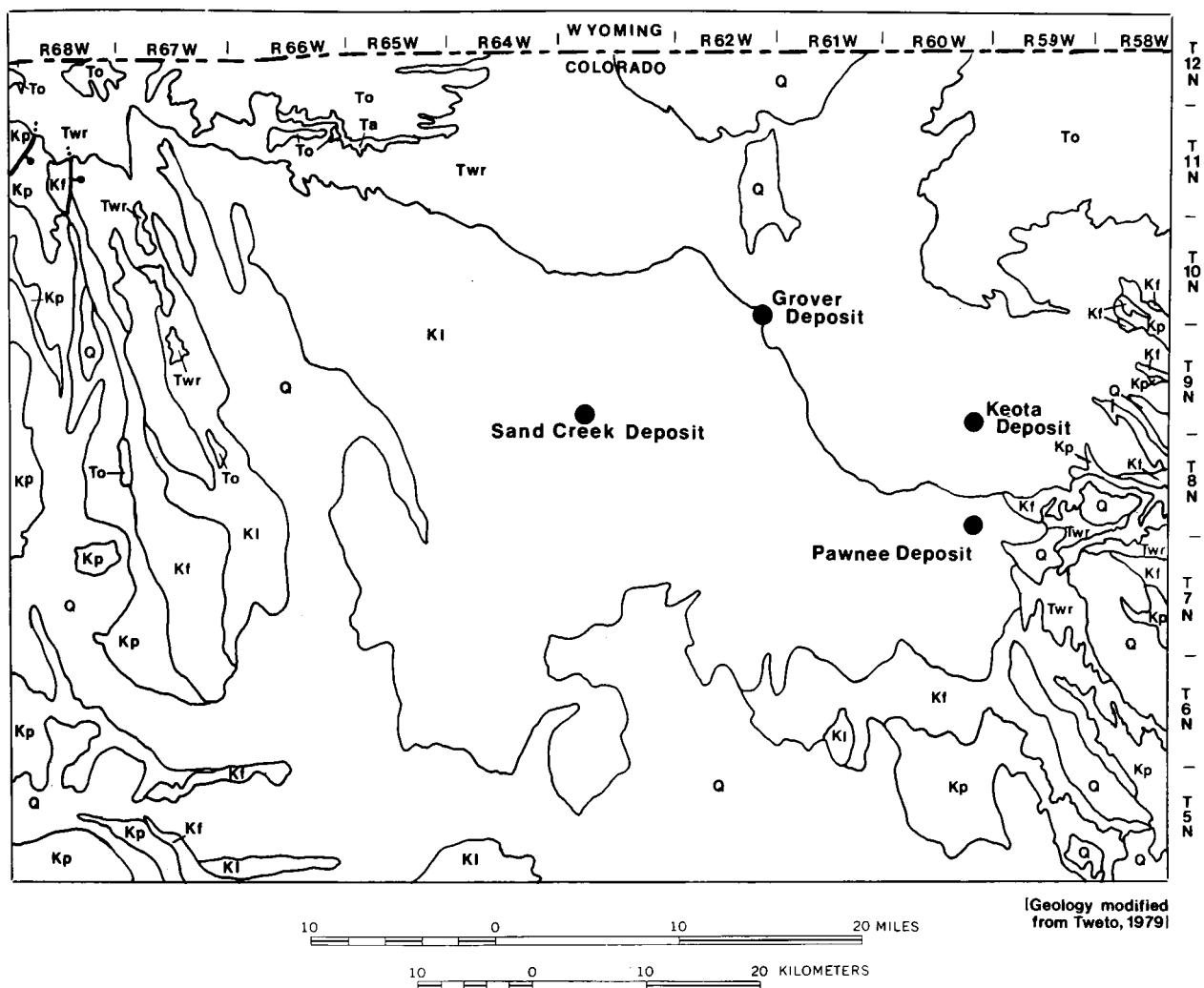
Known Deposits And Occurrences

Existence of uranium in the Denver and Cheyenne Basins has been recognized since the early 1950s (Nelson-Moore and others, 1978). About 20,397 lb (9,260 kg) of U3O8 was produced from the study area during the 1950s. At this time, however, most known deposits were very small in extent and limited in reserves. Renewed interest in the uranium potential of the area was generated in 1970 when a Weld County rancher, Solomon Schlagel, noticed anomalous uranium showings in Laramie Formation drill cuttings from a seismic-shot drill hole (Reade, 1976). His discovery stimulated regional exploration of the Laramie Formation and Fox Hills Sandstone in the Cheyenne Basin. Several significant low-grade uranium deposits were found during ensuing exploration efforts by industry.

Presently, four economically significant uranium deposits (Reade, 1978; Wyoming Mineral Corporation, 1978) and over 50 radioactive mineral occurrences (Nelson-Moore and others, 1978) are known to exist in the Denver and Cheyenne Basins. Plate 1 indicates the geographic locations of these deposits and occurrences. The four significant uranium deposits are roll fronts in the Laramie Formation and Fox Hills Sandstone in the Cheyenne Basin and the radioactive mineral occurrences are scattered throughout both the Denver and Cheyenne Basins in a variety of host rocks. Hundreds of additional occurrences and several significant roll-front deposits have been discovered by uranium exploration companies, but this information is not publicly available. Additional important uranium deposits almost certainly exist in the Cheyenne Basin and await discovery. It is also possible that additional economic deposits exist in the Denver Basin.

Reade (1978) describes three of the economically significant uranium deposits, the Grover, Pawnee, and Sand Creek deposits. Wyoming Mineral Corporation operated a pilot-scale in situ solution mine at the Grover deposit from 1977 to 1978. Power Resources Corporation and Union Oil Company of California plan to develop an in situ solution mine at a fourth deposit, the Keota deposit. Much of the following descriptions are from Reade (1976, 1978), Wyoming Mineral Corporation (1976, 1978), and Kirkham and others (1980). Locations of these deposits and a regional geologic map of the Cheyenne Basin are shown in Figure 65. The reserve estimates are from Reade (1978), unless indicated otherwise. His estimates may be somewhat high, because he may have used incorrect density values (Conroy, 1980, pers. comm.).

The Grover deposit occurs in T10N, R61 and 62W about four miles southwest of the town of Grover. It was discovered in November, 1970 during the regional exploration program stimulated by the Schlagel discovery. The program was conducted by a joint venture group composed of Getty Oil Company, Phelps Dodge Corporation, and Trend Exploration Limited. Uranium mineralization occurs as a roll-front deposit in the



EXPLANATION

- | | |
|------------|--|
| Q | Quaternary deposits, undifferentiated |
| To | Miocene Ogallala Formation |
| Ta | Miocene Arikaree Formation |
| Twr | Oligocene White River Group |
| Kl | Upper Cretaceous Laramie Formation |
| Kf | Upper Cretaceous Foxhills Sandstone |
| Kp | Upper Cretaceous Pier |
| | Fault; dotted where concealed; ball on downthrown side |

Figure 65. Generalized geologic map of the Cheyenne Basin, Colorado, showing known significant uranium deposits. (geology modified from Tweto, 1979)

Grover Sandstone member of the Upper Cretaceous Laramie Formation. Orientation of the roll front suggests the uranium-rich ground water moved in a northeasterly direction. Reade (1976, 1978) describes the Grover Sandstone member as a lenticular channel sandstone deposited in a delta-plain environment. Other workers (Childers, 1979, pers. comm.; Krukar, 1980, pers. comm.) believe the sandstone may be of marine origin and represents a minor transgression of the Late Cretaceous seaway during Laramie time. Gray, quartzose, micaceous, slightly carbonaceous, and medium- to fine-grained sand typifies the lithology of Grover Sandstone member. Thickness of this sandstone member ranges from 25 to 125-ft (7.5 to 37.5-m) thick and averages 80 to 90 ft (24 to 27 m) in the areas of concentrated mineralization. Depth of the Grover Sandstone member near the Grover deposit ranges from 200 to 400 ft (60 to 120 m) below land surface.

The top of the Fox Hills Sandstone lies 200 to 350 ft (60 to 105 m) below the Grover Sandstone member in this area. Claystone, shale, siltstone, and thin lignite and sandstone beds comprise the lower Laramie between the Grover Sandstone member and the Fox Hills Sandstone. A thin claystone bed, 8 to 55-ft (2.4 to 16.5-m) thick, is believed to separate the Grover Sandstone member from the overlying Porter Creek Sandstone member. The Porter Creek Sandstone member is 15 to 75-ft (4.5 to 22.5-m) thick in the Grover area, but often splits into two or three sandstone beds which are considerably less thick.

Grade of the Grover deposit averages 0.14 percent eU308, with the strongest mineralization occurring in areas of rapid sandstone thinning or at a constriction in the thickest part of the sandstone (Reade, 1978). Reserve estimates reported by Reade (1978) suggest the deposit contains a total of 1,007,000 lb (457,000 kg) eU308, using a cutoff grade of 0.05 percent eU308.

The Pawnee deposit was discovered in secs. 25 to 28, T8N, R60W during November, 1971. Uranium mineralization occurs as a roll-front deposit in the upper Fox Hills Sandstone, locally called the Pawnee Sandstone member. It ranges from 30 to 40-ft (9 to 120-m) thick and is fine-grained, well-sorted, and quartz-rich. The Pawnee roll front is very linear and trends approximately east-west. Orientation of the roll front and its associated chemical alteration suggests ground water moved southward during uranium deposition. Mineralized sandstone for the entire deposit averages 0.07 percent eU308 and contains 1,060,000 lb (481,000 kg) eU308 (Reade, 1978) in-place. The richest part of the deposit runs about 0.20 percent eU308.

Uranium mineralization at the Keota deposit in secs. 35 and 36, T9N, R60W, occurs in multiple roll fronts in both the Keota and Buckingham Sandstone members of the upper Fox Hills Sandstone. The Buckingham Sandstone member splits from the top of the Keota Sandstone member in the eastern part of the Keota area. Thickness of the Buckingham Sandstone member ranges up to about 50 ft (15 m), whereas the thickness of the Keota Sandstone member ranges from about 80 to 175 ft (24 to 52.5 m). A 10 to 25-ft (3.0 to 7.5-m) thick claystone lens separates these two sands

members in the eastern part of the Keota area.

Power Resources Corporation and Union Oil Company of California plan to mine the Keota deposit using in situ solution mining techniques beginning in 1980 or 1981. Production is anticipated at about 150,000 lb (68,100 kg) of U308 during the first year, about 250,000 lb (114,000 kg) in the second year, and about 500,000 lb (227,000 kg) annually for following years (Wyoming Mineral Corporation, 1978). Mining activities should continue for 10 to 20 years, resulting in a total production on the order of 5,000,000 to 10,000,000 lb (2,270,000 to 4,540,000 kg) of U308 during the life of the mine.

The Sand Creek deposit lies in secs. 19, 20, and 29, T9N, R63W, just northeast of the Hyland pit where uranium was first discovered in Weld County. Discovery of this deposit occurred in June, 1971 as a part of a subsurface investigation of a 50-ft (15-m) thick channel sandstone, the Sand Creek Sandstone member of the Laramie Formation. This sandstone unit is approximately 1,000 ft (300 m) above the base of the Laramie (Reade, 1978). The frontal zone of the Sand Creek deposit is very narrow, generally less than 50-ft (15-m) wide, but it is unusually rich in uranium for a sandstone deposit. Analysis of one core sample through the frontal zone indicates ore grades range up to 0.41 percent U308 (Reade, 1978). In-place reserve estimates using the block method and a cutoff grade of 0.05 percent eU308 are calculated at 154,000 lb (69,900 kg) with an average grade of 0.08 percent eU308 (Reade, 1978).

Sixty radioactive mineral occurrences are reported in the Denver and Cheyenne Basins. Appendix 1 lists these occurrences alphabetically by county and the location of each occurrence is plotted on Plate 1. Radioactive mineral occurrences are recorded in Boulder, Douglas, Elbert, El Paso, Jefferson, Larimer, and Weld Counties within the study area. Radioactive mineralization occurs in a variety of host rocks, ranging in age from Pennsylvanian to Quaternary. The following descriptions are largely adapted from Nelson-Moore and others (1978).

Anomalous radiation readings are reported in Boulder County at outcrops of the Fox Hills Sandstone and Dakota Group. In Douglas County, the Jarre Creek fault juxtaposes Precambrian granite and Pennsylvanian Fountain Formation. Carnotite mineralization occurs in this fault zone and extends into both rock types. An airborne survey in this same county detected radioactive minerals in the Dawson Arkose. Thorium, reportedly deposited in a heavy mineral placer in the Laramie Formation, occurs in Elbert County. Several radioactive mineral occurrences are reported in El Paso County in the Dawson Arkose, Fox Hills Sandstone, Dakota Group, and Fountain Formation. 108 tons (98,100 kg) of ore, averaging 0.13 percent U308 and containing 277 lb (126 kg) U308 were mined in El Paso County from the Dakota Group at the Mike Doyle carnotite deposit in 1955.

In Jefferson County, radioactive minerals occur in the Dakota Group and Laramie and Morrison Formations. Uranium has been produced in this county at two mines, the Mann and Leyden mines. From 1955 to 1961 15,579 lb (7,073 kg) of U308 were produced from 2,893 tons (2,627,000 kg) of ore from the Dakota Group averaging 0.27 percent U308 at the Mann mine. From

1954 to 1956 the Leyden mine, a Laramie Formation coal mine, produced as a by-product 4,533 lb (2,058 kg) of U308 from 645 tons (586,000 kg) of ore containing 0.35 percent U308. Only one radioactive mineral occurrence is reported in Larimer County, but it has produced a small amount of uranium and vanadium. In 1955 six tons (5,448 kg) of ore, averaging 0.07 percent U308 and 0.05 percent V205 were mined from the Dakota Group in Larimer County and yielded 8 lb (3.6 kg) U308 and 6 lb (2.7 kg) V205.

Thus, a total of 20,397 lb (9,260 kg) of U308 have been produced in the study area to the present. All production was from very small uranium mines or was a by-product of coal mining during the 1950s.

Development Potential

Currently there is one proposed uranium mine in the Denver and Cheyenne Basins, Colorado. Power Resources Corporation and Union Oil Company of California plan to mine the Keota deposit using in situ solution mining. This project is anticipated to produce 500,000 lb/yr (227,000 kg/yr) of yellowcake with a total production on the order of 5,000,000 to 10,000,000 lb (2,270,000 to 4,500,000 kg). No mining activities are proposed for other known deposits at this time, but it is possible that they may be developed in the near future. Other significant uranium deposits have been discovered in the Laramie Formation and Fox Hills Sandstone in the Cheyenne Basin, but details of these deposits are not publicly available.

Current exploration efforts are concentrated in the Cheyenne Basin, with the primary exploration targets being uranium roll-front deposits in the Laramie Formation and Fox Hills Sandstone. Some interest is also expressed in the Dakota and White River Groups. Several companies are also active in the Denver Basin, with exploration efforts centering on the Dawson Arkose, Laramie Formation, Fox Hills Sandstone, and Arapahoe Formation. Several small uranium deposits have already been discovered in the Dawson Arkose in the central part of the basin and there is considerable interest in the Laramie Formation and Fox Hills Sandstone in the northern and northeastern parts of the Denver Basin.

Uranium discoveries in both basins most likely will be made in areas where the host sandstones are at depths less than 500 to 1,000 ft (150 to 300 m). Uranium deposits may well occur at greater depths, but the mining of deep, low grade deposits is currently not economic. Because uranium occurs in several formations, a large part of the study area is underlain by potential host rocks at suitable depths. In that most exploration is concentrating on the Fox Hills and younger rocks, it is probable that any future discoveries will be made in the area outlined by the outcrop or subcrop of the Fox Hills, as shown on Figure 17.

As is suggested by the known uranium occurrences (Appendix 1), radioactive minerals occur in the Fountain Formation, Morrison Formation, Dakota Group, Fox Hills Sandstone, Laramie Formation, and Dawson Arkose. Significant uranium deposits may exist in any of these formations in both basins. Throughout much of the study area, however, the Fountain, Morrison, and Dakota are much too deep to be of economic interest. Future

significant uranium discoveries, for the most part, will be concentrated along basin margins, except for discoveries in the Dawson Arkose, which could occur in the central part of the Denver Basin, and for Laramie discoveries, which could be throughout most of the Cheyenne Basin. No radioactive mineral occurrences are publicly recorded in the Arapahoe Formation, but the formation does contain suitable uranium host rocks that are relatively unexplored. The lower and middle parts of the Arapahoe consist of thick, coarse sandstone and conglomerate which may be mineralized and certainly deserve further evaluation.

Most roll-front deposits in the study area are relatively low-grade and are small- to medium-sized. Because of this, they will probably be mined using in situ solution mining techniques. A few shallow, high-grade deposits may possibly be mined using open-pit methods. It is highly unlikely that underground mining will be used to mine any of the deposits in the study area. Because it is a relatively long haul to the nearest existing mill, ore from an open-pit mine in the study area would probably be heap leached.

The Denver and Cheyenne Basins do contain economically important uranium deposits, but the area will not become one of the major uranium-producing areas in the United States. It is almost certain, however, that a significant amount of uranium will be mined from this area, complementing the total uranium production of our country.

MINING METHODS

After discovery and evaluation of a uranium deposit, a mining method must be selected that can physically and economically recover the uranium in an environmentally acceptable manner. Factors which must be considered in the selection of a mining method include the size, shape, attitude, depth, grade and location of the ore body, physical, mechanical, and chemical characteristics of the host rock and overburden, surface and subsurface hydrologic characteristics of the site, environmental factors, and economic conditions.

Uranium may be recovered using either conventional or non-conventional methods. Both underground and surface (open-pit) mining are considered conventional techniques. In situ solution and heap leach mining, bacterial leaching, hydraulic borehole mining, and by-product recovery from phosphate and copper operations are non-conventional uranium recovery methods. The greatest production in the United States to date is from conventional methods. Of a total of 14,000 tons (12,700,000 kg) of U308 mined in 1976, only about 500 tons (454,000 kg) were produced from non-conventional sources. An estimated 1,500 tons (1,362,000 kg) and 3,000 tons (2,724,000 kg) were produced from non-conventional methods in 1977 and 1978 (U.S. Energy Resources and Development Administration, 1976; 1977). As can be seen from these production figures, however, an increasing amount of yellowcake is being recovered by non-conventional methods every year. Much of the future uranium recovery activity in the study area likely will utilize non-conventional methods, primarily in situ solution mining.

Surface Mining

MINING PROCEDURE

Surface mining of uranium primarily employs open-pit techniques. Open-pit uranium mining is similar to open-pit mining of coal, although open-pit uranium mines generally extend to greater depths and cover less surface area. Uranium ore bodies up to 500-ft (150-m) deep may be mined using open-pit methods, although 300 ft (100 m) is a more commonly used maximum mining depth. In certain cases, open-pit mines may be deeper than 500 ft (150 m).

The first step in open-pit mining involves removal of topsoil from the mine site. Topsoil must be stockpiled for later use during reclamation. Next, overburden above the ore body must be removed. Scrapers and power shovels are commonly used for overburden removal. Blasting or ripping may be required for removal of well indurated overburden. A series of benches are usually cut into the walls of the open pit to aid pit wall stability and provide access into the pit.

The mineralized ore body is usually blasted or loosened with rippers. Broken ore is loaded by backhoes, front-end loaders, or power shovels on to trucks and hauled from the pit to the mill or ore stockpiles. Ore recovery usually is in excess of 90 percent. The mill is designed to

process ore of a particular grade range. Grade of an ore body commonly varies significantly across the deposit, and waste rock may be occasionally loaded with ore into the haul trucks. Oftentimes, each ore truck is scanned with a scintillometer to determine the average grade of the truck load. If the grade is suitable for direct milling, it is sent to the mill. If the grade varies significantly from the required grade, the truck is sent to a stockpile area, where the ore is blended to meet appropriate grades.

Layout of the open pit is determined by ore body characteristics, fracture orientation, stripping ratio, equipment availability, slope stability, and required production rates. Figure 66 illustrates a typical cross section and plan view of an open-pit uranium mine. Generally about 15 to 30 tons (13,600 to 27,200 kg) of overburden must be removed for every ton (908 kg) of ore mined. Stripping ratios may be as high as 80:1.

Open-pit mines may experience problems with ground-water inflow. Water which enters the pit is usually drained by a series of ditches into a sump area. The water is pumped out of the mine and may be discharged into a stream, used to control dust on roads, placed in settling or evaporation ponds, or used as mill process water. An alternative water control technique involves a series of dewatering wells placed around the periphery of the mine. These wells pump water from aquifers penetrated by the mine and reduce water influx into the pit.

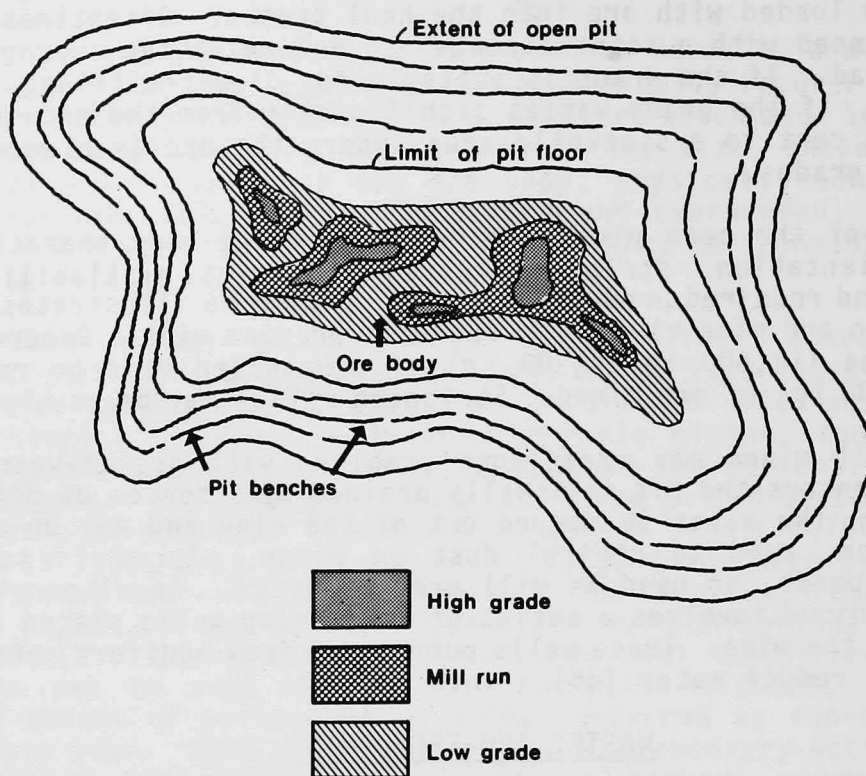
WASTES AND EFFLUENTS

ATMOSPHERIC EMISSIONS

Potential sources of atmospheric emissions from open-pit uranium mines include vehicular emissions, fugitive dust, and radon-222 emanating from the exposed ore body, spoil piles, and evaporation ponds containing fluids dewatered from the mine. Vehicular emissions from gasoline- and diesel-powered heavy construction equipment, drilling rigs, and mine personnel transportation vehicles include particulates, carbon monoxide, nitrogen oxides, unburned hydrocarbons, and sulfur oxides. Table 8 lists the estimated amounts of vehicular emissions from 1,500 ton/day (1,360,000 kg/day) open-pit and underground mines. Vehicular emissions from ore mining and overburden stripping operations at open-pit mines are significantly higher than emissions from underground mines. Additional gaseous pollutants similar to these vehicular emissions may be generated at a mine if oil, gas, or coal is burned to generate electricity at the mine.

Fugitive dust releases result from pre-mining site preparation, operational activities such as scraping, blasting, loading, transporting, and dumping of overburden and ore, and wind erosion of disturbed areas, unvegetated spoil piles, and ore stockpiles. The dust may include radioactive materials, primarily ore minerals such as uraninite and coffinite. Gaseous radon-222 will emanate from the exposed ore body and ore stockpiles. Other radiologic releases may occur if mine dewatering is needed. Water from the dewatering system that is placed in evaporation ponds may emit radon-222.

PLAN VIEW



CROSS SECTION

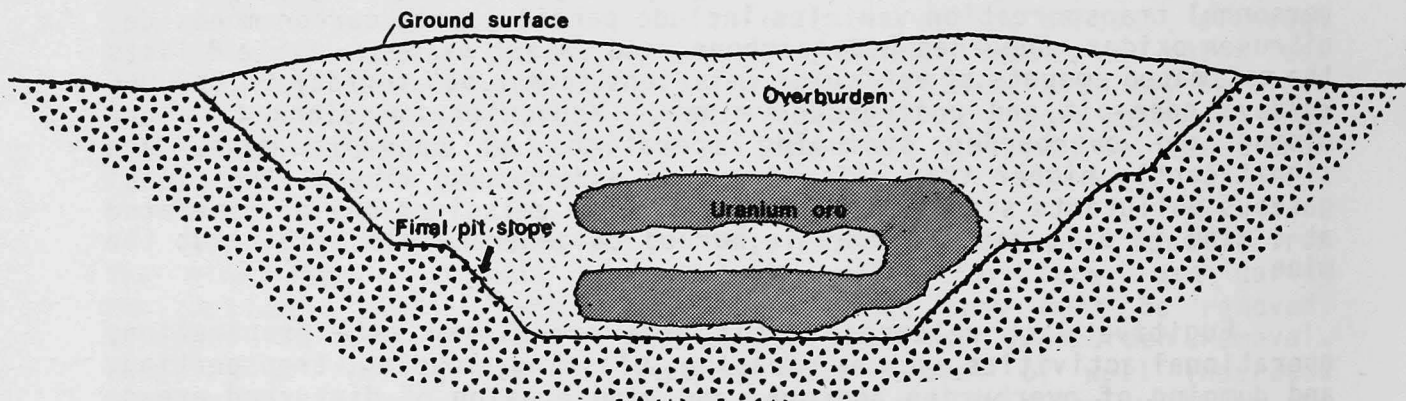


Figure 66. Typical plan view and cross section through an open-pit uranium mine. (from Loutens, 1977; courtesy of Dames & Moore)

Table 8. Estimated vehicular emissions from heavy equipment at 1,500 ton/day (1,360,000 kg/day) surface and underground uranium mines. (from Reed and others, 1976 and Stone and Webster Engineering Corporation, 1978).

POLLUTANT	EMISSIONS (kg/day)		
	<u>Mining</u>	<u>Surface Mine Stripping</u>	<u>Underground Mine</u>
Carbon Monoxide	294.2	327.4	41.9
Unburned Hydrocarbons	48.2	53.8	6.9
Nitrogen Oxides	484.6	538.4	68.1
Sulfur Oxides	35.4	39.3	5.0
Suspended Particulates	7.0	18.9	2.4

SOLID WASTES

The primary solid waste from open-pit uranium mining is the material excavated for construction and operation of the mine. This material includes overburden above the ore body and the very low grade ore not suitable for processing. Mill tailings are the most significant solid waste from conventional mining and milling techniques, but tailings are not considered in this report because they are associated with milling, not mining. Some suspended solids may be carried from the mine site by surface water which drains the area. A small amount of solid waste such as cuttings or mud pit sludge may result from drilling bore holes. This waste may require special disposal in, for instance, a licensed tailings pond.

The amount of excavated material is a function of the pit size, depth, and final slopes. A greater amount of waste rock comes from deep pits and pits that occupy large surface areas. The pit slope should be at maximum grade to minimize the amount of solid waste generated and to reduce the area of surface disturbance. Maximum pit wall slope is limited by stability and operational factors.

Solid waste generated from mining may be placed in spoil banks on the surface outside of the pit area or it may be returned to the pit and used as backfill. If the waste is placed in spoil piles, the piles should be rapidly revegetated and reclaimed to prevent excessive release of fugitive dust and water erosion.

LIQUID WASTES

Significant amounts of liquid waste may be generated by open-pit mining if the pit penetrates any alluvial or bedrock aquifers and

dewatering is necessary. Excavation of a pit through an aquifer will result in an influx of ground water into the pit. Sump pumps may be utilized to remove ground water from the pit or a system of dewatering wells may be used to prevent water inflow. Dewatering wells are placed around the pit, with the number of wells, location, and pumping rates controlled by hydrologic characteristics of the penetrated aquifer. The volume of water produced from dewatering operations will depend on characteristics of the aquifer and the dewatering system. Up to 5,000 gpm (1,900 l/m) of water may be produced by a dewatering system at an open-pit mine.

Water produced during dewatering activities must be properly used or disposed in accordance with government regulations. Part or all of the water may be used as make-up mill water or in dust control. The water may also be directly released to surface streams if it contains acceptable levels of dissolved and suspended solids. The water, however, often contains high levels of suspended and dissolved solids, radiologic elements, or toxic substances. In these cases it must be treated in settling or treatment ponds before being released to surface streams. Dissolved solids can be induced to precipitate and suspended solids will settle to the floor of the ponds. Addition of barium chloride and flocculents to the water will facilitate rapid precipitation and settling. All or part of the treated water may then be discharged into the surface-water system. If contaminated water is not used at the mine or is not treated, it must be disposed of in evaporation ponds or deep disposal wells. Sludges from settling ponds may require special disposal at, for instance, a licensed tailings pond.

Underground Mining

MINING PROCEDURE

Underground mining methods may be employed when uranium ore bodies are too deep to be economically surface mined. Underground mining is advantageous in that the ore removal process is selective and minimal waste rock is extracted. However, roof support is necessary and up to 20 to 30 percent of the ore body may be left underground as pillars.

Unlike surface mining, underground mining requires an extensive labor force because of confined work space and small capacity machinery. Access routes and haulage systems require special attention to assure a smooth mine operation. Adequate ventilation is also important for safe mining. Radon, a common gas in underground uranium mines, must be kept at low levels by providing adequate ventilation.

Access to an underground uranium mine is similar to that for underground coal mines (Figure 44). Either a series of shafts, a sloped incline, or a relatively level tunnel or drift is used. Drift mining is preferred, because of lower mine construction costs, better drainage, and easier haulage. However, the topography in the Denver and Cheyenne Basins and the geologic setting of the uranium deposits are not conducive to drift mining. An underground mine in the study area would probably have

to utilize an inclined slope or, more likely, a vertical shaft.

Three types of mining methods are commonly used to recover uranium ore. Room-and-pillar mining is suitable for tabular, relatively flat-lying ore bodies. Open rooms with random pillars are used for narrow, lenticular, flat-lying deposits or for tabular deposits if the overlying roof rock is exceptionally competent. Steeply dipping and vein-type ore bodies are generally mined by shrinkage stoping. Figure 67 illustrates a typical room-and-pillar uranium mine. Rooms and pillars are uniformly sized and equally spaced if the ore body is geometrically symmetrical and of constant grade. Areas of thinning or thickening, barren zones, and hazardous roof conditions can be dealt with by altering the room and pillar distributions. Some ore pillars may be recovered before abandonment of the working area.

WASTE AND EFFLUENTS

ATMOSPHERIC EMISSIONS

Atmospheric emissions from underground uranium mines consist of a small amount of vehicular emissions, fugitive dust, and radon-222 emanations. Vehicular emissions result from diesel- and gasoline-burning heavy construction and mining equipment, underground transportation vehicles, and drilling rigs which operate during both construction and mining phases. Table 8 lists the estimated vehicular emissions for a 1,500 ton/day (1,360,000 kg/day) underground uranium mine. Vehicular emissions from an underground mine average at least one order of magnitude less than emissions from a surface mine.

Sources of fugitive dust include exhaust air from the mine and surface activities such as construction of mine facilities on the surface, ore transporting and stockpiling, waste rock transporting and dumping, and vehicular travel on gravel and dirt roads near surface facilities. The dust is primarily fine-grained silicate particles, although a part of the fugitive dust may contain significant quantities of radioactive minerals such as uraninite and coffinite. The total amount of fugitive dust released from underground uranium mines is more than ten times less than that from surface mines.

Significant amounts of radon-222 emanate from radioactive minerals exposed during the mining operation. Miners working underground are directly exposed to this potentially hazardous radioactive gas. Proper ventilation minimizes radon concentrations within the mine, but hazardous levels may still be encountered near the active working faces of a mine. All radon from underground sources is eventually removed from the mine and exhausted into the atmosphere by the ventilation system. Relatively high concentrations of radon may locally occur near exhaust air vents. Radon-222 is also released directly into the atmosphere from ore stockpiles and waste rock containing minor amounts of radioactive minerals. Another potential source of radon-222 are evaporation ponds that hold water pumped from the mine dewatering system.

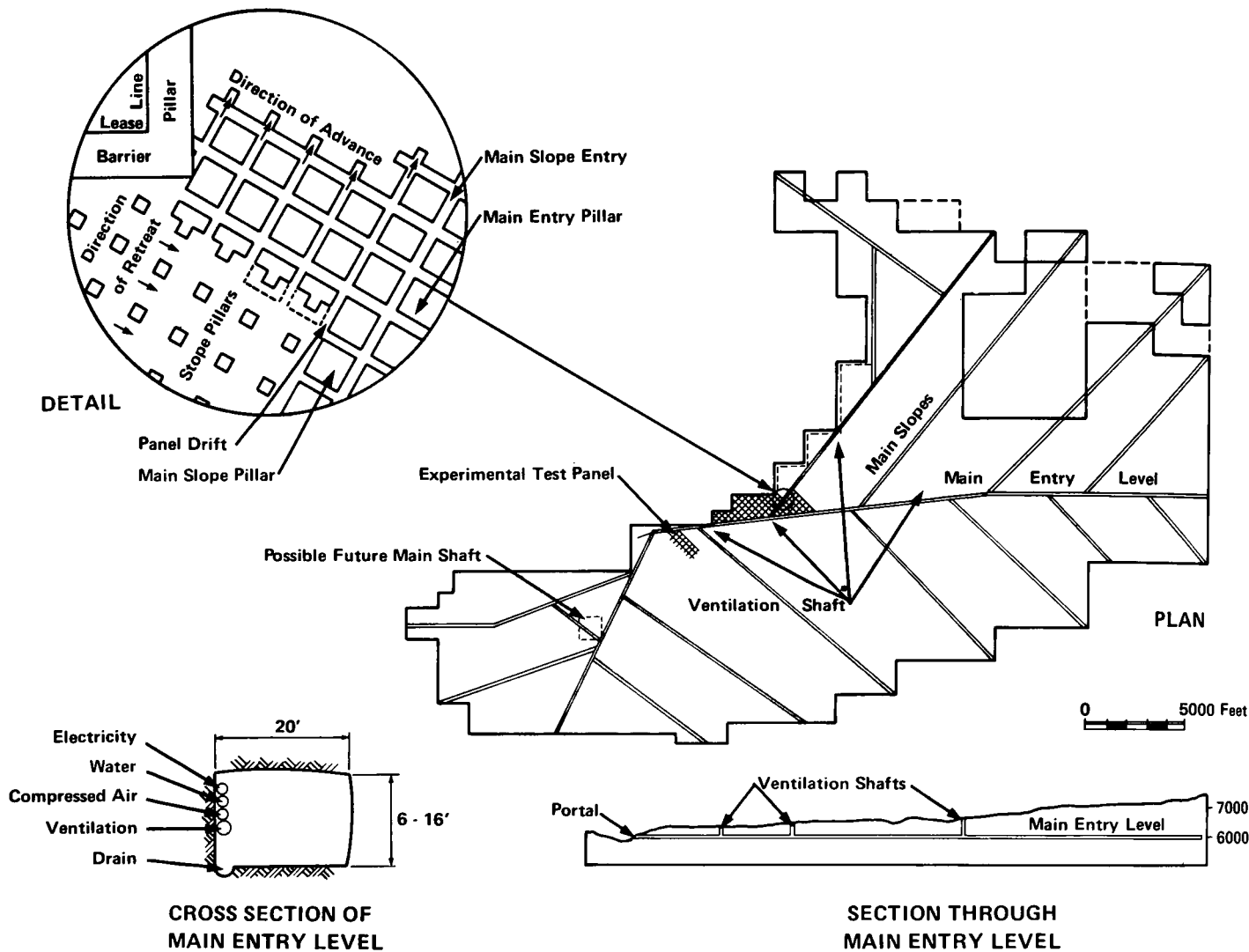


Figure 67. Plan and cross sectional views through a hypothetical room-and-pillar uranium mine. (from Loutens, 1977; courtesy of Dames & Moore)

SOLID WASTES

The only significant solid waste from an underground uranium mine is waste rock from the construction of shafts, adits, and other developmental access routes in the mine. In certain cases, low grade mineralized rock, not suitable for milling, may need to be disposed of. A small amount of solid waste may also be generated in the evaporation ponds by settling or

precipitation of solids on the pond floor. By far, the largest volume of solid waste associated with underground uranium mining and accompanying milling is mill tailings. This type of waste is not discussed herein because it is not an integral part of the mining phase.

Waste rock consists predominantly of silicate minerals. Low grade, mineralized waste rock will contain some radioactive minerals and possibly some heavy metals or toxic elements such as arsenic, selenium, vanadium, and molybdenum. Suspended solid waste that settles to the bottom of the evaporation ponds will be mostly silicate minerals, but it may also include some of the radioactive and toxic elements described above. Disposal of this sludge in secure storage sites may be required.

LIQUID WASTES

Most liquid wastes are generated by the mine dewatering system. If the ore-bearing host rock contains significant ground water, large amounts of water may enter the mine and necessitate implementation of a dewatering system. Additional water may enter the mine from shafts or slopes which penetrate overlying aquifers. As shown in Figure 59, these openings should be lined to prevent ground-water inflow. A dewatering system may involve a series of wells around the mine perimeter to prevent ground-water incursion, as described in the section on open-pit mining, or some type of system within the mine to provide for water removal. Sump pumps are usually employed in shaft or slope mines and a series of drainage ditches are often used in adit mines to allow for gravity drainage.

Liquid waste from the dewatering system may be used as make-up process water at the mill, for dust control, or it may have to be disposed of at the site. The volume of water produced from the dewatering system of an underground mine is generally less than that from open-pit mines because leakage from overlying aquifers can be avoided by underground mining. The water may contain high levels of radioactive and toxic elements and therefore may need to be treated prior to release to surface streams. Evaporation ponds or deep disposal wells may be utilized for liquid waste disposal if treatment is not desired.

In Situ Solution Mining

MINING PROCEDURE

In situ solution mining is a relatively new mining method that is very relevant to this investigation. Many of the future uranium mines in the Denver and Cheyenne Basins may utilize this extraction method. Solution mining consists of three phases of operation: (1) mining, (2) solution processing, and (3) aquifer restoration.

In the mining phase uranium is recovered from the host rock without actually removing the host rock. A series of injection and recovery wells are drilled into the ore deposit. A solution containing a lixiviant and oxidizing agent are introduced into the host sandstone through the injection wells. This solution circulates through the ore deposit and

mobilizes the uranium as a soluble complex. The uranium-bearing, "pregnant" solution is pumped back to the surface by the recovery wells and is piped to the process plant area.

During solution processing the uranium-bearing solution is usually passed through an ion exchange operation to recover the uranium. Ion exchange consists of two steps: 1) a loading or adsorption step and 2) an elution step. During the loading step, the complexed uranium ions are sorbed from the solution to the ion exchange resin, displacing anions sorbed to the resin. The resulting uranium-barren solution is then refortified with leach chemicals and oxidants and recycled. In some operations the recovered solution is saturated with calcium carbonate and it is necessary to cycle the solution through a calcium control unit to prevent calcite precipitation. Such precipitation could plug well openings and pipelines and reduce hydraulic conductivities in the ore body.

The uranium-loaded resin is transferred to the elution circuit and an equal volume of eluted resin is returned to the loading circuit. Some facilities employ a fixed bed system, so these transfer operations are continuously performed. During elution the resin is stripped of uranium by a chemical solution which typically consists of ammonium chloride, sodium chloride, ammonium bicarbonate, or other similar eluents. The resulting aqueous uranium complex is further treated and transferred to a precipitation circuit. The precipitate is then dried, converted to yellowcake, and packaged. Figure 68 illustrates a flow diagram of a typical in situ solution mining operation.

Choice of the proper lixiviant is based on factors such as ability to selectively dissolve uranium, recirculation suitability, environmental considerations (especially restoration aspects), and maintenance of hydrologic properties. Both alkaline and acidic lixiviants are used. Popular types of alkaline lixiviants include ammonium, sodium, or alkaline-earth carbonate-bicarbonate solutions. Sulfuric acid is the only acidic lixiviant currently used. Hydrogen peroxide or gaseous oxygen are often used as the oxidizer.

Table 9 lists the chemical reactions involved in uranium mobilization for a few selected alkaline and acid leach processes. Other elements besides uranium are also mobilized by the lixiviants. Ammonia lixiviants, for instance, may form stable aqueous amine complexes of arsenic, copper, zinc, cadmium, and mercury. Acidic lixiviants are generally more reactive than alkaline lixiviants and may enable better recovery, but they also mobilize more undesirable ions than alkaline lixiviants. A partial list of elements which are mobilized during the solution process is given in Table 10. Natural mechanisms that limit the mobility of these ions are also indicated in this table.

Injection and recovery wells at a solution mine are grouped into production cells. Production cells are grouped into a well field. Typically, a full-scale mine consists of several well fields. Several types of production and well-field patterns may be employed at in situ

Table 9. Chemical reactions involved in the mobilization of uranium by alkaline and acidic lixiviants at in situ solution mines. (from Larson, 1978)

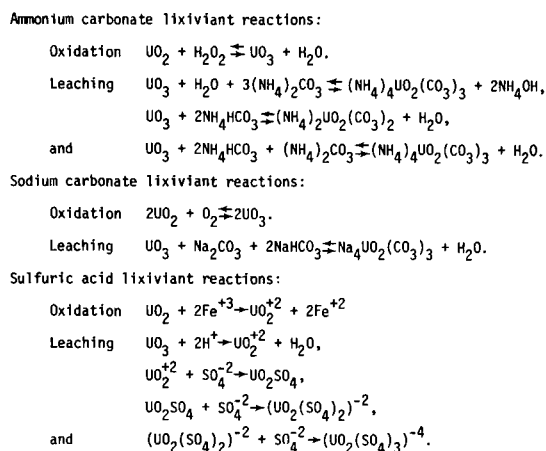


Table 10. A partial list of ions mobilized by weak acidic and alkaline lixiviants and natural mechanisms that limit their mobility. (after Thompson and others, 1978)

Mechanism	Ions Mobilized	Ions Immobilized
<u>Mildly Acid Lixiviants</u>	Mo, Se, As, V, Ba, Ra Na, Ca, Mg, $N(NH_4^+)$, U V, Mn, Fe, Cu, Pb, Zn Cd, Hg	
Reprecipitation		$S(SO_4^{-2})$, Mo, Se, As, V, Ba, Ra
Ion Exchange		Na, Ca, Mg, $N(NH_4^+)$, U, V
Adsorption		$S(SO_4^{-2})$, Mn, Mo, Se, As
Reduction		$S(SO_4^{-2})$, U, Fe, Mo, Se, As, Cu Pb, Zn, Cd, Hg
<u>Mildly Alkaline Lixiviants</u>	$C(CO_3^{-2})$, $S(SO_4^{-2})$, V, U, Ra, Fe, Mn, Se, As, Cu, Pb, Ba, Zn, Hg, Cd, Mo, Ca, Mg Na, $N(NH_4^+)$, F	
Reprecipitation		Ca, Mg, $C(CO_3^{-2})$, $S(SO_4^{-2})$, U Fe, Mn, Se, As, V, Cu, Pb, Ba F, Ra
Ion Exchange		Na, Ca, Mg, $N(NH_4^+)$, U, V, Cu Pb, Zn, Hg
Adsorption		$S(SO_4^{-2})$, U, Mn, V, Cu, Pb, Zn Ba, Cd, Hg
Reduction		$S(SO_4^{-2})$, U, Fe, Mo, Se, As, Cu Pb, Zn, Cd, Hg

uranium solution mines. Examples are illustrated in Figure 69. A commonly used pattern is the five-spot pattern (Figure 70). It consists of four injection wells located on the corners of a square or rectangular production cell with one recovery well in the center of the cell. Dimensions of the production cell and well field depend on the hydrologic and chemical properties of the ore-bearing aquifer and the characteristics of the ore body. A properly designed well field is designed and operated to extract the maximum amount of uranium with minimal solution flow.

A generalized cross section through a production cell is illustrated in Figure 71. Well completion techniques are very critical. Both injection and recovery wells are perforated only in the mineralized part of the drill hole to centralize solution movement in this part of the section. The annulus of all wells must be cemented from the top of the mineralized zone to the surface to ensure containment of solutions. The amount of leach solution injected into the well field should equal or be slightly less than the amount of recovered uranium-bearing solution. This balance is significant from both economic and environmental standpoints to contain the lixiviant flow within the well field.

There are many advantages and a few disadvantages to solution mining (Kirkham, 1979). Solution mining is usually less expensive than other mining methods and requires fewer mining stages. Table 11 lists the various stages required for production of U3O8 from surface, underground, and in situ solution mines. Only ten stages are needed for solution mining, as opposed to 16 for open-pit mines and 18 for underground mines. Table 11 also indicates stages which have environmental problems that affect land surfaces, water quality, and personnel safety or radiation exposure. Solution mining has significantly fewer stages that present environmental problems. These environmental problems will be discussed in detail in a later section.

Primary advantages of solution mining over conventional mining methods include 1) minimal surface disturbance, 2) reduced personnel exposure to radiation, 3) lower capital costs and improved cash flow, 4) less solid waste generation and corresponding waste and tailings disposal needs, 5) ability to mine low grade or small, scattered deposits that are otherwise uneconomic, 6) shorter lead time to production initiation, 7) lower manpower requirements, 8) minimal air pollution, 9) smaller radiological release, and 10) recycling of process chemicals. Possible disadvantages include the potential for ground water contamination and a relatively low level of uranium recovery. Furthermore, many uranium deposits are not amenable to solution mining.

WASTES AND EFFLUENTS

In situ solution mining of uranium generates only a small amount of atmospheric emissions and solid wastes, but a considerable volume of liquid waste results from well-field overpumping during mining and post-mining aquifer restoration. Part, but not all of these wastes and effluents are radioactive and/or toxic. Most of the following

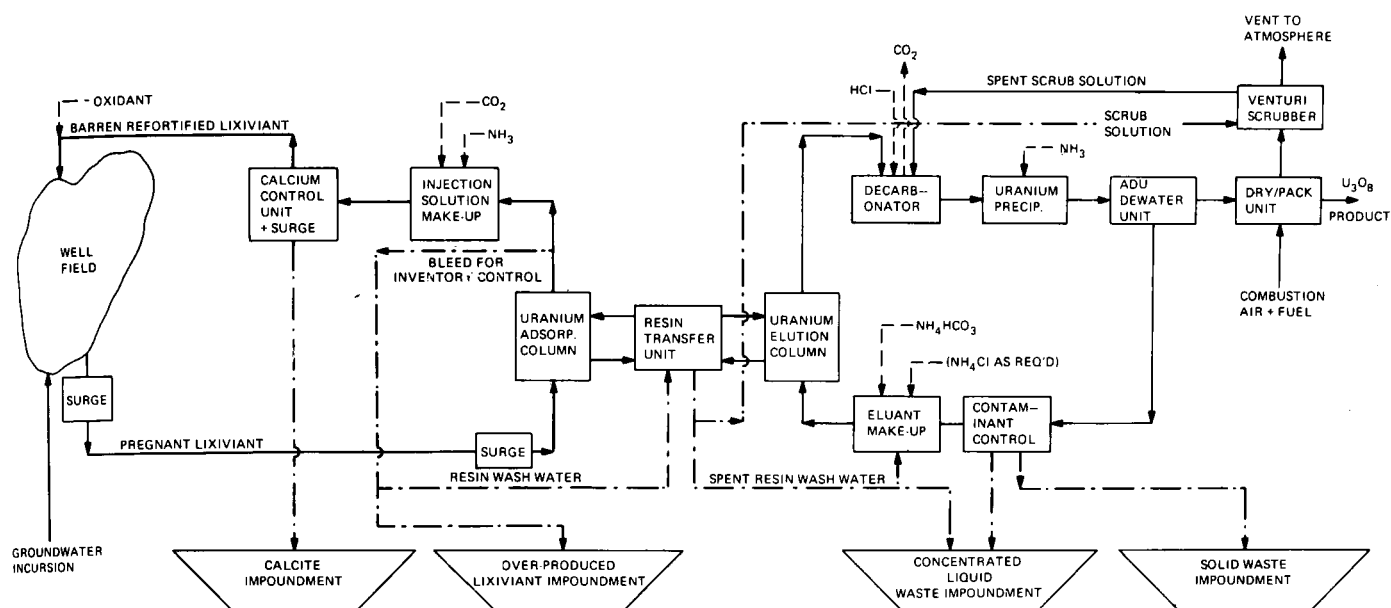


Figure 68. Flow diagram of a typical in situ uranium solution mine. (from U.S. Nuclear Regulatory Commission, 1978a)

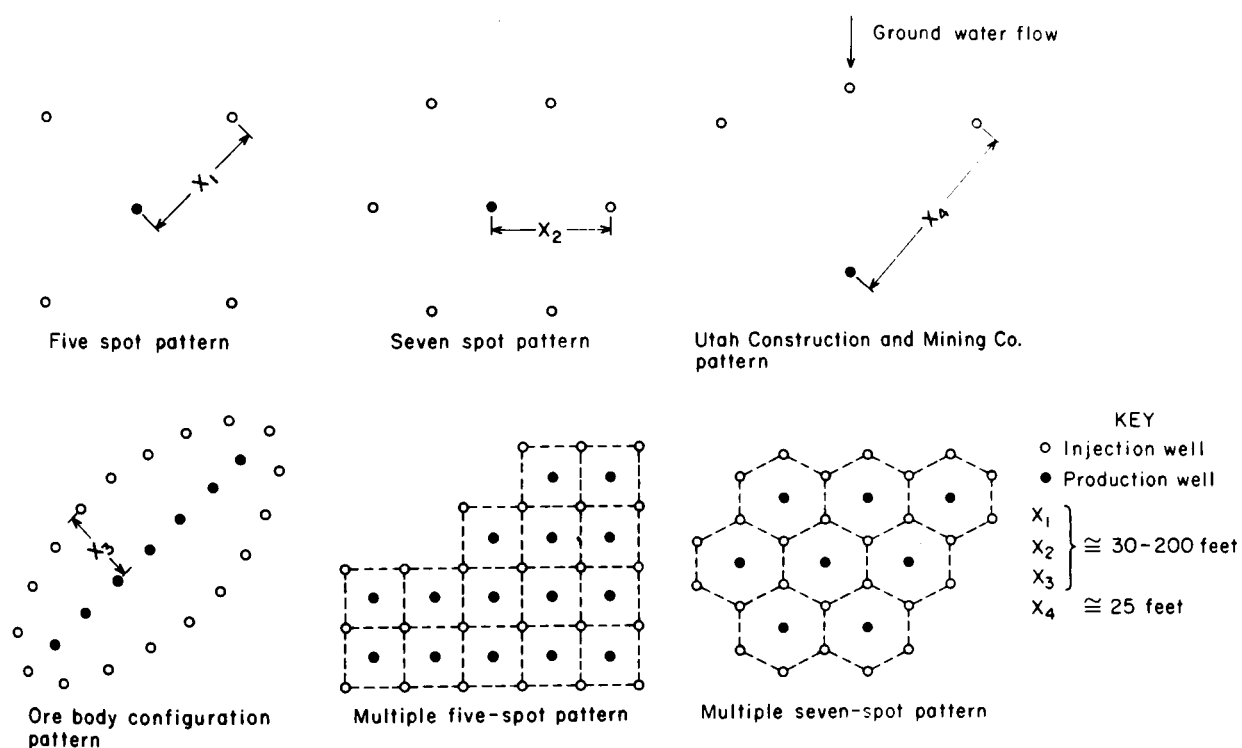


Figure 69. Plan views of the common well-field patterns used for in situ solution mining of uranium. (from Larson, 1978)

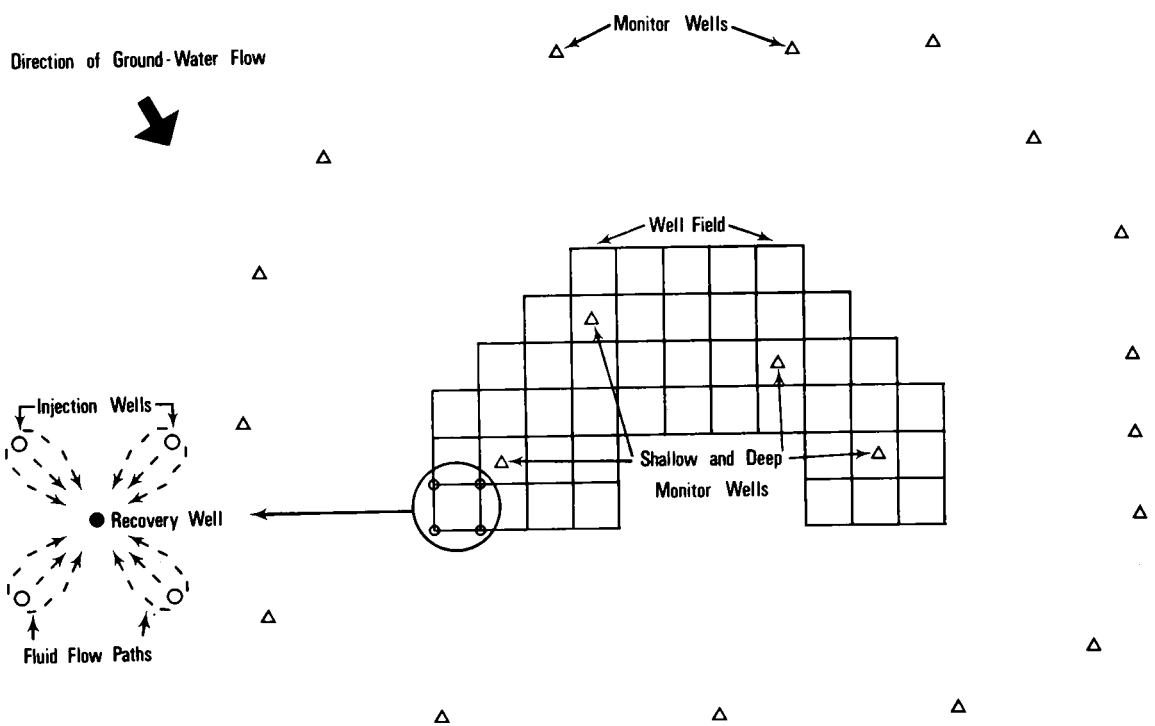


Figure 70. Typical five-spot well-field pattern. (after Stone and Webster Engineering Corporation, 1978)

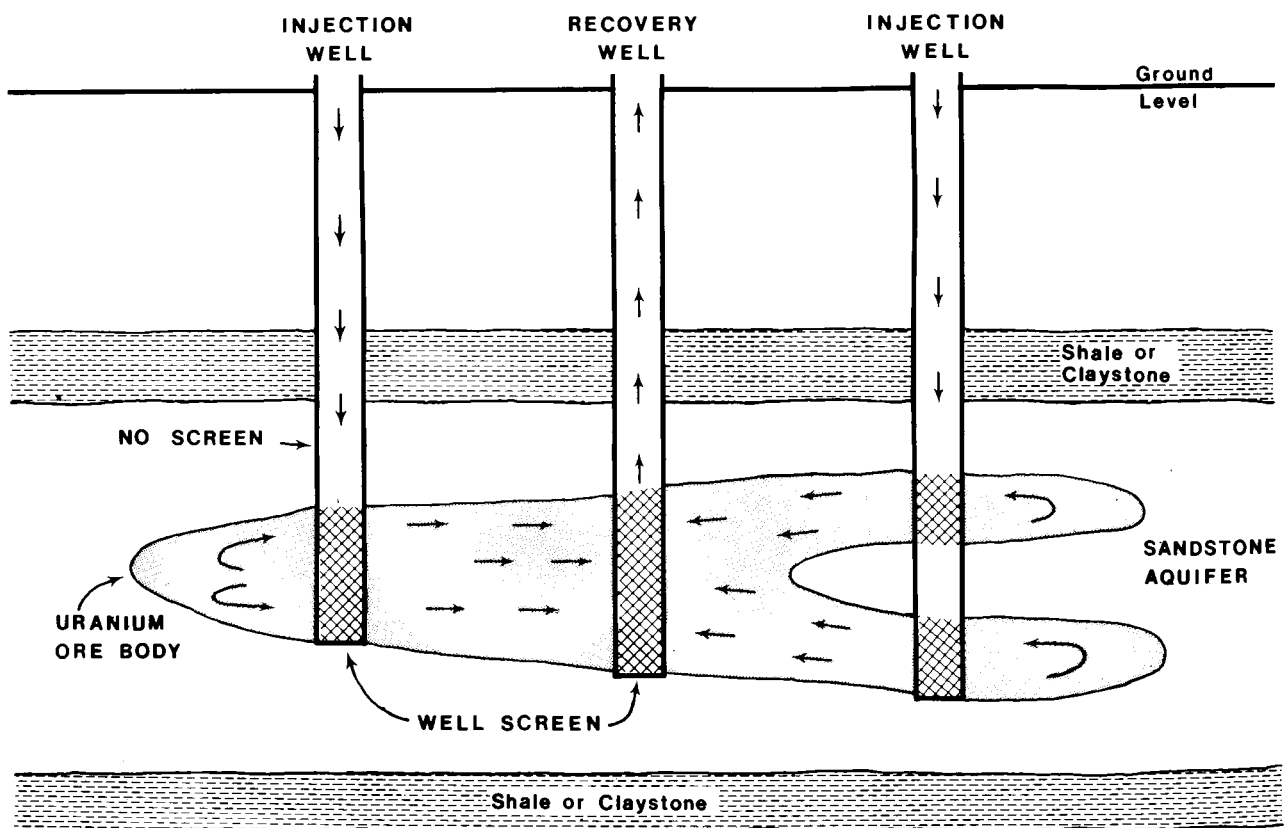


Figure 71. Schematic cross section through a production cell. (from Wyoming Mineral Corporation, 1977; courtesy of Wyoming Mineral Corporation)

Table 11. Major process stages of open-pit, underground, and in situ solution mining and milling of uranium. (from Hunkin, 1975)

OPEN-PIT MINES	UNDERGROUND MINES	SOLUTION MINING
Development drilling	Development drilling	Development drilling
Stripping*	Shaft sinking*	---
Mine waste*	Development drifting	---
Waste dump*	Waste dump*	---
Develop ore faces	Develop stopes	Drill wells
Drill, blast*	Drill, blast	Leach uranium*
Load	Muck out	---
Haul	Haul	---
---	Hoist	---
---	Haul to mill	Pump solution to plant
Crush*	Crush*	---
Grind*	Grind*	---
Leach uranium	Leach uranium	---
Liquid-solid separation	Liquid-solid separation	Uranium extraction
U ₃ O ₈ concentration	U ₃ O ₈ concentration	U ₃ O ₈ concentration
Precipitate, dry, package	Precipitate, dry, package	Precipitate, dry, package
Tailings dam* operations	Tailings dam* operations	Recirculate leach solutions Aquifer restoration*
Reclamation	Reclamation	Reclamation
Stages to produce saleable product	16	10

NOTE:

* Denotes stages generally producing significant changes in or affecting land surfaces, water quality, personnel safety or radiation exposure.

descriptions of these wastes and effluents are adapted from the U.S. Nuclear Regulatory Commission (1978a,b), Thompson and others (1978), Cooperstein (1978), Stone and Webster (1978), Wyoming Mineral Corporation (1978), and Reed and others (1976).

ATMOSPHERIC EMISSIONS

Atmospheric pollutants that may be released by in situ solution mines result from vehicular emissions, fugitive dust, and atmospheric emanations from waste storage ponds, exposed well-field surge tanks, and the recovery process area. Vehicular emissions originate from diesel- and gasoline-burning heavy construction equipment, drilling rigs, and mine personnel transportation vehicles. The greatest amount of vehicular emissions will occur during construction of well fields and a limited amount may be released during mining. Construction of the processing plant and associated buildings, roads, pipelines, and drilling pads will generate moderate amounts of fugitive dust. Minimal amounts of fugitive dust are released during the mining phase. Solution mines generate far less fugitive dust and vehicular emissions than open-pit mines.

Most emissions at a solution mine are from the recovery process plant, waste storage ponds, well field surge tanks, calcium removal unit, and yellowcake drying and packaging units. Although most of these emissions are from the processing phase, they will be briefly discussed. Atmospheric emissions from the recovery plant may include a variety of gases such as ammonia, ammonium chloride, sodium chloride, and carbon dioxide, depending on which lixiviant is used. Waste storage ponds may emit radon-222, ammonia, ammonium chloride, sodium chloride, sodium sulfate, carbon dioxide, and water, again dependent on which lixiviant is used. Emissions from the calcium removal unit are also dependent on the selected lixiviant, but may include radon-222, ammonia, ammonium chloride, sodium chloride, carbon dioxide, and water. Well field surge tanks may emit radon-222. Some particulate yellowcake may escape through the scrubbers of the packaging unit. Typical atmospheric emissions from the recovery circuit of a 500,000 lb/yr (227,000 kg/yr) solution mine using an ammonium bicarbonate lixiviant are shown in Table 12. It should be noted that these emissions herein described for solution mining include both mining and processing phases. Emission characteristics previously described for conventional mining techniques do not include milling phases.

SOLID WASTES

Radioactive and non-radioactive solid wastes, though limited in volume, may be generated by four principal sources at a solution mine: 1) calcium removal unit, 2) contaminant control unit in the process plant, 3) precipitated waste in liquid waste storage ponds, and 4) water treatment methods used in post-mining aquifer restoration. Two of these sources are related to the actual mining or restoration phase, while the other two sources are associated with processing. The total volume of solid waste from solution mining and processing is several orders of magnitude less than that generated by conventional mining and milling. Although tailings

Table 12. Atmospheric emissions from the recovery circuit of a 500,000 lb/yr (227,000 kg/yr) uranium solution mine using an ammonia bicarbonate lixiviant. (after U.S. Nuclear Regulatory Commission, 1978a)

SOURCE	Emission Rate ^a (thousands of lb/yr)				Radioactive Releases ^b (Ci/yr)	
	NH ₃	CO ₂	NH ₄ Cl	H ₂ O	U-238	Rn-222
Uranium Recovery Process Facility (excluding calcium control unit and waste storage ponds)	6-9	1500-3000	30-54	-	0.141	-
Calcium Control Unit (based on 1,000 ft ² of exposed solution surface containing 0.75g NH ₄ , 1.5g total CO ₃ , and 0.75g Cl/L)	2-4	6-9	0.06-0.09	390-470	-	0.04
Calcite storage pond (based on complete evaporation of 2.04 gpm of supernate containing 0.75g NH ₄ , 1.5g total CO ₃ , and 0.75g NH ₄)	2.5-3.5	9-10	9.5-10.5	~8000	-	1.36
Liquid waste storage ponds (based on 1 acre of exposed solution surface containing about 7.0g NH ₄ , 1.0g total CO ₃ , and 16g Cl/L)	9-11	7-8	27-31	~9300	-	-
Well field Surge Tanks	-	-	-	-	-	76

a) based on data supplied by WMC and a net evaporation rate of 42 in/year

b) NRC estimates

disposal is one of the major environmental problems facing conventional uranium mining and milling, this is not a serious problem with solution mining since there are no actual tailings and other solid wastes are volumetrically small.

Precipitated solids resulting from evaporative concentration of impounded waste solutions must be disposed properly. This waste may consist of a variety of contaminants including ammonium and alkaline chlorides, sulfates, and carbonates and likely contains radioactive materials. Additional precipitated solid waste results during the restoration process. Contaminated waters withdrawn during ground-water

sweeping may be placed in evaporative liquid waste ponds. Solid waste will accumulate at the bottom of these ponds. Water purification during restoration also produces solid waste. Water from the restoration process may contain up to 10 to 20 g/l total dissolved solids, primarily high concentrations of salts such as ammonium chloride, sodium chloride, and sodium sulfate. The brine may also contain radium in excess of 100 pCi/l and small quantities of uranium, molybdenum, selenium, arsenic, and other trace elements. These elements will concentrate or precipitate with the solid waste as the brine evaporates.

Calcite (CaCO_3) precipitated from the calcium removal unit is another of the major solid wastes of the solution mining process. Estimates suggest that at some mines 1 lb (0.454 kg) of calcite is produced for every 1 to 3 lb (0.454 to 1.36 kg) of U308 recovered. A 500,000 lb/yr (227,000 kg/yr) solution mine could produce up to 166,000 to 500,000 lb (75,000 to 227,000 kg) of calcite every year. The precipitated calcite may contain by weight up to 2 percent U308 and from 500 to 1,500 pCi of radium-226 per gram of calcite. Additional non-radioactive contaminants may also co-precipitate with the calcite. The calcite should be temporarily stored in an adequate waste storage pond with a liquid seal to prevent dispersion to the atmosphere. Permanent disposal should be in an approved tailings pond at a licensed active mill.

The contaminant control unit in the elution and precipitation circuit may also generate solid wastes. High concentrations of sulfate and vanadium may build-up in the eluant and it may become necessary to remove these contaminants. Removal can be accomplished by vanadium adsorption on activated carbon and by sulfate precipitation utilizing barium salts. The resulting solid wastes, vanadium-saturated activated carbon and barium sulfate, must be placed in solid waste storage ponds with liquid seals or stored in metal drums. Later burial in an approved tailings pond or licensed burial site may be necessary should the wastes contain significant levels of radioactive or toxic materials.

Rotary drilling of the numerous injection, production, and monitor wells results in a small volume of rock cuttings. Most cuttings are from rock units overlying the ore-bearing formation and are non-radioactive. Unless these cuttings contain hazardous trace elements or heavy metals, they may be disposed of by being scattered on the ground and then revegetated. Radioactive cuttings or cuttings that contain hazardous materials, though usually very limited in volume, should be temporarily placed in on-site solid waste storage ponds or permanently disposed in an approved disposal site.

LIQUID WASTES

The principal liquid wastes related to solution mining are from 1) ground-water restoration, 2) well field overpumping, 3) monitor well sampling, 4) well cleaning, 5) resin wash water in the contaminant control unit, 6) building and equipment cleaning, 7) eluant bleed for contaminant control, 8) sanitary water, 9) yellowcake slurry washwater, and 10) water softening brine. The first four types of waste result from mining phases and the remaining six are from processing.

By far, the largest volume of liquid waste results from the ground-water restoration program. Estimates by the U.S. Nuclear Regulatory Commission (1978a,b) suggest about 20.5 to 65.0 acre-ft (25,000 to 80,000 m³) of liquid waste will be produced for every acre (4,047 m²) mined. Obviously, these numbers will vary depending on factors such as aquifer thickness and porosity, mining methods, lixiviant chemistry, and restoration problems. Waste water from the restoration program may contain ammonium, sodium, calcium, and magnesium bicarbonates, carbonates, and sulfates, depending on the lixiviant used. Trace contaminants such as selenium, molybdenum, and arsenic may also be present. Uranium concentrations may exceed several parts per million. Radium-226 concentrations greater than 50 pCi/l may also occur. Thorium-230 may be present in concentrations of 50 to 150 pCi/l. Waste water from the restoration operation may be processed or used in the mill or it must be impounded in sealed evaporative waste storage ponds or injected into deep disposal wells.

Additional waste water results from well field overpumping, resin wash, eluant bleed, well cleaning, building and equipment cleaning, monitor well sampling, yellowcake slurry washing, and other sources. The U.S. Nuclear Regulatory Commission (1978a) estimates a 500,000 lb/yr (227,000 kg/yr) solution mine may produce about 21 acre-feet (25,700 m³) of liquid waste annually. This water may contain varying amounts of ammonium, sodium, calcium, and magnesium chlorides, sulfates, bicarbonates, and carbonates. These waste waters may also contain significant levels of uranium, radium, and thorium. Waste water from these sources should also be disposed of in sealed waste storage ponds.

Hydraulic Borehole Mining

MINING PROCEDURE

Hydraulic borehole or slurry mining of roll front uranium deposits is a type of in situ mining similar in certain aspects to solution mining. A series of wells are drilled into the ore body. A borehole mining device, which includes a high-pressure hydraulic cutting nozzle, is lowered down the drill hole. Water under high pressure is forced through the nozzle and mechanically disaggregates the ore deposit. The resultant uranium-bearing slurry is pumped to the surface and sent to a conventional mill for processing. One of the big differences between this type of in situ method and solution mining is that the uranium-bearing slurry from the borehole mining method must be treated using conventional milling procedures on the surface.

Hydraulic borehole mining is economically and environmentally desirable for many of the same reasons that solution mining is. Tailings disposal, however, is still a major problem associated with milling of the uranium-bearing slurry. One solution to this problem involves returning the tailings to the borehole cavity. This particular mining method has not yet been commercially proven. Pilot studies suggest the method may be physically and economically feasible for sandstone ore, but problems because of its relative lack of selectivity and incomplete recovery must be considered.

WASTES AND EFFLUENTS

ATMOSPHERIC EMISSIONS

Atmospheric emissions from hydraulic borehole mines primarily consist of vehicular emissions and fugitive dust. Radioactive emissions generally are not associated with this type of mining because the ore slurry is enclosed in pipelines and not exposed to the air. Some radioactive emissions will occur at the mill where ore slurries are treated and from mill-associated disposal ponds, but these are not discussed in this report.

Vehicular emissions result from personnel- and equipment-transporting vehicles and from drill rigs and hydraulic borehole equipment. Types of emissions are similar to those from gasoline and diesel-powered machinery described in preceding sections. Fugitive dust is generated by vehicular traffic on unpaved roads and by preparation of drilling and mining equipment pads. Since the ore and back-fill material are slurried to and from the mine site, minimal dust is created by the actual mining process.

SOLID WASTES

A large volume of solid waste (tailings) results from milling the uranium-rich slurry produced by hydraulic borehole mining. The amount produced is similar in volume to that resulting from milling the ore from underground or open-pit mines. Since this waste is not from the mining phase, it will not be further discussed.

The actual mining phase generates only a very small amount of solid waste, primarily rock cuttings from drilling activities. Cuttings that are radioactive or contain hazardous elements, such as those from the mineralized zone, should be temporarily placed in on-site solid waste storage containers or permanently disposed in approved tailings ponds. Other cuttings may be spread on the ground near the drill hole and revegetated.

LIQUID WASTES

The only important liquid wastes from hydraulic borehole mining are water used in the mining and transporting of ore and water from dewatering, if necessary. From 300 to 500 gpm (1100 to 1900 l/m) of water is used per borehole tool to cut and slurry the ore to the surface. Since no commercial mines use this method at full-scale levels, it is difficult to estimate the total volume of waste water which may result from full-scale mining. The need for dewatering will depend on each site. Some mines may not require any dewatering while others may. The amount of water removed by the dewatering system also is very dependent on site characteristics. Part or all of this waste water may be used for mining, milling, and dust control.

A very rough estimate of the amount of water needed for mining can be calculated by assuming it requires 15 to 20 boreholes to mine out one acre of mineralized ore and that the mining rates given by Savanick (1979) are

approximately correct. Such a calculation suggests 20 to 44 acre-ft (24,000 to 53,000 m³) of water are required to mine and transport ore from every acre mined.

Other Methods

Other mining methods have been commercially proven or used in pilot-scale studies to extract uranium. Several of these methods are actually better classified as milling procedures. For this reason, or because of their limited applicability to the uranium deposits of the Denver and Cheyenne Basins, they will be described only briefly.

Heap leaching involves the leaching of uranium from ore by gravity flow of a solvent solution through an open ore pile or by flooding a confined ore pile. Low-grade dumps, small, isolated ore bodies a great distance from a mill, and abandoned mill tailings may be suitable for heap leaching. The leaching pad is prepared on a leveled site covered with an impermeable clay liner or plastic sheeting. Cement or treated cement may also be used. The pad slightly slopes in one direction to allow for drainage. Collection pipes are placed on the pad to centralize solutions. A layer of gravel is spread over the pad and the ore is placed above the gravel. Weak sulfuric acid is sprayed or ponded on the ore. The solution reacts with the ore and leaches the uranium. The uranium-bearing, pregnant solution is collected at the base of the pad in the system of pipes, drains into a collection trough, and flows to a sump. Ion exchange or solvent extraction is used to remove the uranium from the pregnant solution.

Heap leaching eliminates mill construction, ore haulage, and the costly grinding steps required by conventional milling. The ore, however, must be mined and usually crushed to some extent before leaching. Heap leaching takes several months for maximum extraction, considerably longer than conventional milling times. Recovery is usually limited to 60 to 70 percent. Heap leaching might be used in the study area on ore from small, isolated open-pit mines.

In certain cases water drained from uranium mines or pumped from dewatering wells may contain high levels of uranium. These waters can be processed to extract uranium. Wet underground mines generally have greater potential for this type of uranium production. However, most development in the Denver and Cheyenne Basins will be in situ or surface facilities and for this reason, minimal production of uranium from this type of method is foreseen.

Uranium may also be recovered as a by-product from copper and phosphate ore processing. In that neither copper nor phosphate occur in economic quantities in the study area, these methods will not be discussed.

ENVIRONMENTAL IMPACTS AND IMPACT MITIGATION

Potential environmental problems may be associated with uranium exploration, mining, and milling. Degradation of air and water quality, disturbance of the ground surface, and disruption of surface and ground-water flow paths are the major environmental concerns. Uranium mining presents a unique hazard, in that radioactive materials are involved. Radiation exposure to mine personnel and potential radiological and non-radiological contamination of the air, water, and earth must be closely evaluated and minimized.

Radionuclides, such as uranium, radium, and their daughter products may enter the environment from several pathways (Figure 72). The atmosphere may be contaminated with radionuclides by exhaust air from underground mines, by fugitive dust from ore stockpiles, exposed tailings, and surface mining activities, and by mill stack effluents. Water contamination may result from water discharge and commingling of waters at surface and underground mines, from excursions and incomplete aquifer restoration at in situ solution mines, from improperly controlled drainage through ore and waste stockpiles, and from leakage of tailings ponds and evaporation ponds. Radionuclides enter humans and other animals by ingestions of food and water or inhalation of air that is contaminated.

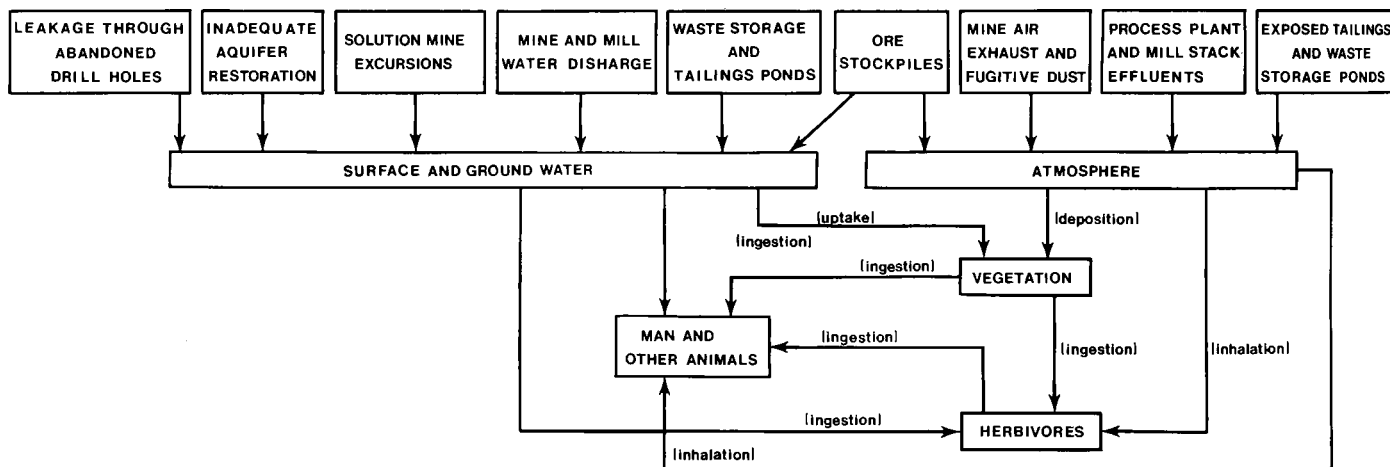


Figure 72. Major pathways for the transport of radionuclides during uranium exploration, mining, and milling. (modified from Morse and Curtin, 1977)

Potential environmental impacts associated with uranium exploration and mining are described in this section. Many aspects of uranium milling

may also impact the environment and in many situations, uranium milling and related waste disposal present a much greater environmental threat than do uranium exploration and mining. A detailed description of the environmental problems associated with uranium milling and waste disposal is beyond the scope of this report. If the reader is interested in the environmental problems of uranium milling and processing, refer to Stone and Webster Engineering Corporation (1978), Kaufman and others (1975), Morse and Curtin (1977), Reed and others (1976), and the environmental reports listed in the bibliography which were prepared by the U.S. Nuclear Regulatory Commission.

Exploration Activities

Exploration for uranium deposits in simple terms consists of 1) determination of areas geologically favorable to contain significant uranium deposits, 2) airborne and ground radiation surveys, 3) water and stream sediment analyses, and 4) drilling of prospects. Extensive drilling is the only phase of uranium exploration activities that may cause significant impact to the environment.

A small amount of atmospheric pollutants are generated during uranium exploration programs by drill rigs, trucks, backhoes, and other equipment. Exhaust emissions, including carbon monoxide, unburned hydrocarbons, sulfur and nitrogen oxides, and particulates, are the primary air contaminants. The total amount of exhaust emissions is not great, but it can be lowered by using pollution control devices on all equipment and by minimizing the number of miles traveled. Fugitive dust is created from vehicles traveling on unpaved roads and, to a certain extent, from drilling operations. It may be minimized by decreasing vehicular speed and amount of travel on unpaved roads, and by drilling with fluids. Fugitive dust is the most visible form of air pollution from uranium exploration. The greatest impact of fugitive dust is upon local vegetation. In limited areas dust may completely cover individual plants and impair growth.

The impact of uranium exploration activities on the atmosphere is generally low and is restricted to the immediate vicinity of drilling rigs and access roads. Most effects also are of very short duration. Emission pollutants readily dissipate into the atmosphere and fugitive dust is washed from vegetation by precipitation.

Uranium exploration may also slightly impact the land surface. New roads or trails are sometimes needed to provide access to remote areas. It may be necessary to bulldoze new access roads in rough terrain. A drill rig and associated equipment require a small area for setting up and operating. This immediate area will be impacted to a certain extent by various activities associated with drilling. Vegetation may be disturbed and drill cuttings and drilling muds may be left on the surface. Once vegetation has been removed from a road or drill pad, wind and water may rapidly accelerate erosion of the land surface. Spilled or discarded oil and fuel may cause short-term impacts. Cuttings from the drill holes should be scattered on the ground surface after they have been examined,

not left in piles. If the cuttings contain significant amounts of radioactive or hazardous materials, they may need to be transported to an active tailings pond for disposal.

The impact of uranium exploration activities on the land surface is generally low, although small amounts of grazing land may temporarily be damaged. Most land impacts can be readily minimized by reclamation and revegetation of roads and drill pads immediately following exploration activities.

Uranium exploration may affect surface water, although impacts generally are minimal. The most significant potential impact results from increased erosion of land disturbed by drilling pads and access roads. Erosion of access roads, drilling pads, and associated cuttings piles and mud pits may increase the concentration of suspended solids in the surface-water system. Rapid site reclamation will minimize surface-water impacts from exploration activities.

One of the more important potential impacts of uranium exploration activities relates to local ground-water conditions. Abandoned, unplugged exploration drill holes may contribute to both ground-water quality and quantity problems. Aquifers penetrated by a drill hole may leak water into the hole if it is not properly plugged when abandoned. Within the drill hole water from the various penetrated aquifers freely commingle. This mixing may alter the quality of water in penetrated aquifers around the hole. The impact of this commingling in a single drill hole may not be significant, but the cumulative effects of dozens or hundreds of holes may be. The amount of water in an aquifer or the aquifer head may also possibly be affected by unplugged exploration holes, depending on hydrologic conditions. For instance, shallow aquifers may lose water to drill holes and deep aquifers may experience increased or decreased heads. Artesian aquifers could lose water to overlying dry formations, or it could flow onto the surface. Again, the effect of a single hole may be low, but the cumulative effects of many holes may be important. Improperly abandoned exploration holes are also troublesome in areas where in situ solution mining or UCG may be conducted, because the holes can readily transmit leach solutions or gases to other formations, causing both economic and environmental problems.

There is no published information available that the authors are aware of that documents the potential effects of unplugged, abandoned drill holes on ground-water aquifers. Therefore, it is difficult to summarize what types of impacts may result from this problem. Several exploration companies, however, have recognized the importance of properly abandoning drill holes and now routinely plug their exploration holes in an effective manner. Other companies, however, have abandoned drill holes without plugging them or only use a shallow, surface plug of limited value. The Colorado legislature has recently passed legislation that addresses proper abandonment of exploration drill holes. House Bill 1195 (1980) requires that exploration drill holes be plugged with concrete or other appropriate substances to prevent artesian flow to the surface and commingling of aquifers.

Mining Activities

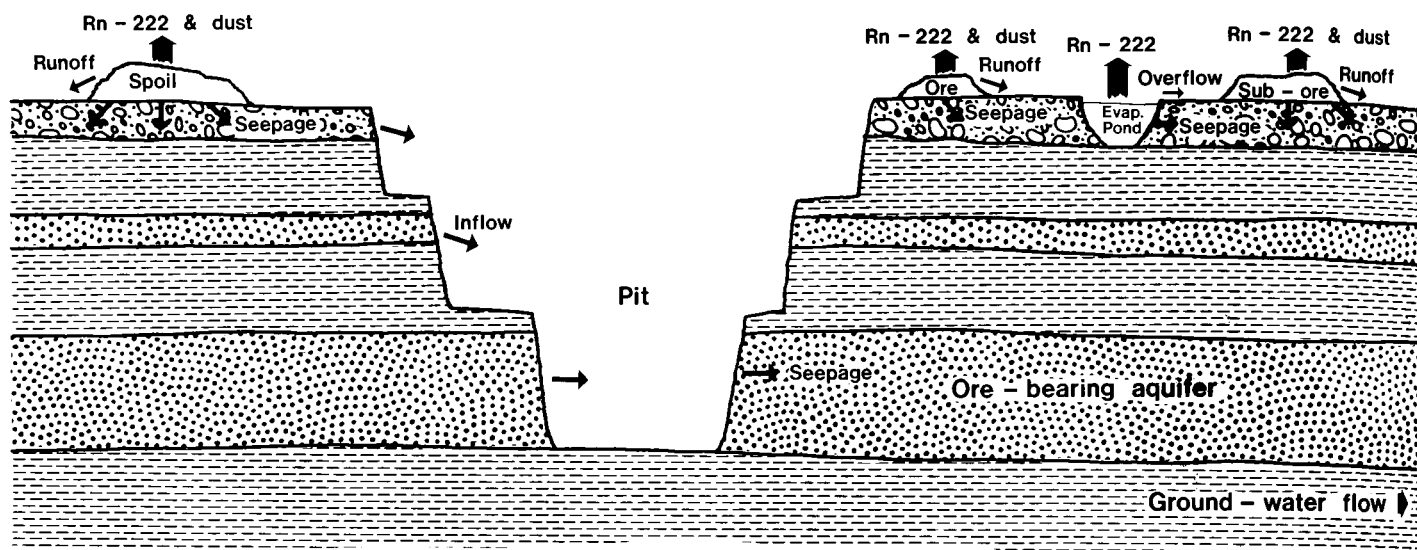
AIR-QUALITY IMPACTS AND MITIGATION MEASURES

All uranium mining methods impact air quality to various degrees. Generally, surface mining has greater atmospheric impacts than other types of mining. Except in rare cases, none of the mining techniques seriously impact regional ambient air quality. Typically, all mining methods will impact air quality to some degree at the mine site, but only during adverse meteorologic conditions will off-site atmospheric contamination occur. Milling and processing uranium ore or uranium-bearing solutions may impact air quality in several ways. Air impacts may be caused by atmospheric emissions from liquid and solid waste storage ponds, tailings ponds, yellowcake drying and packaging units, and recovery process plants. Impacts associated with milling are not, however, discussed in this report.

Primary atmospheric pollutants resulting from uranium mining include fugitive dust, vehicular emissions, and radon gas. Sources of fugitive dust include vehicular travel on dirt roads, construction of mine facilities (including buildings, roads, drill pads, etc.), mining activities (including blasting, loading, and hauling overburden and ore), and wind erosion of exposed overburden, ore stockpiles, and unreclaimed, disturbed land. Fugitive dust is comprised of fine-grained rock particles and may include radioactive materials. Figures 73 and 74 illustrate some of the typical ways in which open-pit and underground uranium mining may impact the atmosphere.

Surface mining generates the greatest amount of fugitive dust of any of the uranium mining methods, mainly because all mining activities take place at the surface. Main sources of fugitive dust at a surface mine include blasting, loading, and hauling of the overburden and ore, and wind erosion of ore, sub-ore, and overburden stockpiles. In situ solution mining, underground mining, and hydraulic borehole mining usually generate about an equal amount of fugitive dust and the volume of fugitive dust from these mines is much less than that created by surface mining. Fugitive dust sources at these facilities include vehicular travel on dirt roads and drilling activities, wind erosion of ore, sub-ore, and spoil piles, and exhaust air vented to the surface. Most dust generated at a mine site is restricted to the immediate vicinity and only during strong winds is a significant amount carried off-site. As dust is carried off-site, it mixes with clean air and dust concentrations are reduced with distance of transport. In many cases, uranium mines are located in relatively remote areas and miners must travel a number of miles on unpaved roads to get to work. It may also be necessary to haul ore on unpaved roads to a mill or process site several miles from the mine. Fugitive dust created by this "commuter" travel and/or ore haulage may be a nuisance to local people who live near heavily traveled roads.

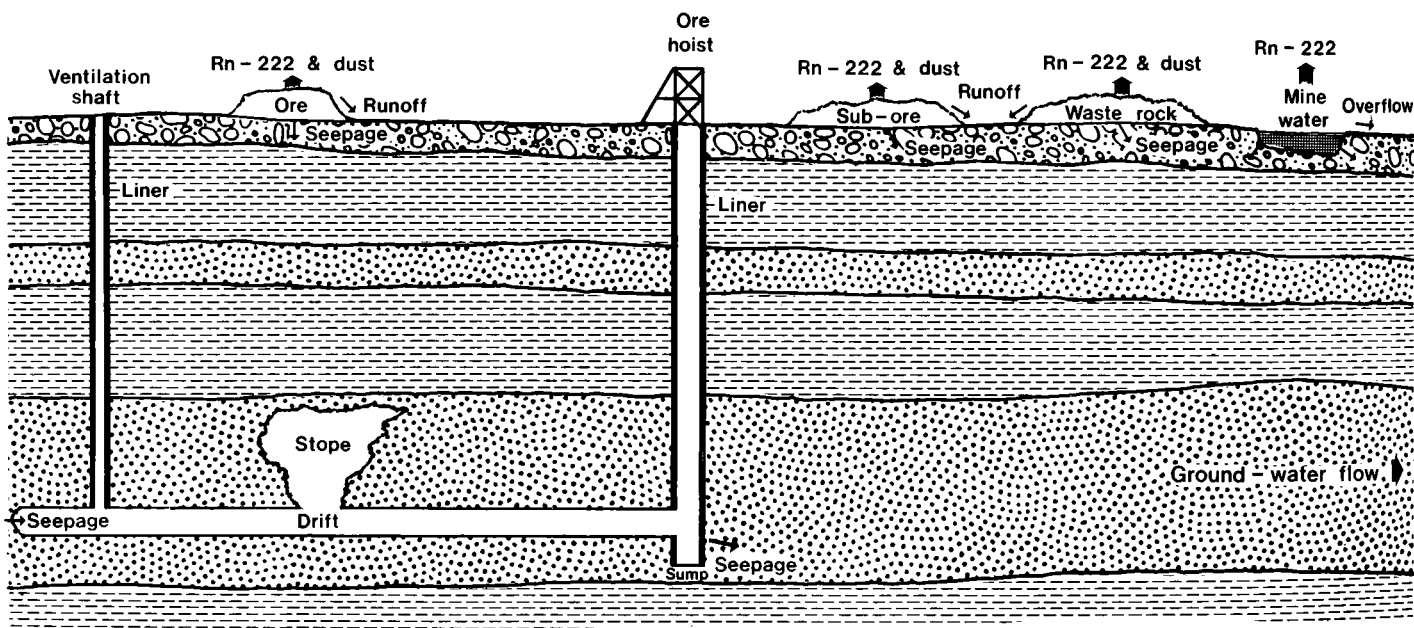
The main environmental problem with fugitive dust is its effect on vegetation. Dust covers leaf surfaces, reducing insolation to the leaves



After U.S.E.P.A., 1979

Drawing not to scale

Figure 73. Potential contamination sources from an active open-pit uranium mine located on an alluvial valley floor.



After U.S.E.P.A., 1979

Drawing not to scale

Figure 74. Potential contamination sources from an active underground uranium mine.

of plants, slowing growth rates, and diminishing the desirability and food value of forage for animals. This impact is usually of short duration, because precipitation washes the dust from the plants. Some fugitive dust may contain radioactive materials, thus adding an additional environmental hazard. Fugitive dust problems can be minimized in several ways. Heavily traveled roads can be paved, oiled, chemically treated, or watered. Exposed ore, sub-ore, and spoil piles should be covered or rapidly revegetated and stabilized. Ore trucks can be watered or covered before extensive haulage.

Vehicular emissions from gasoline- and diesel-burning drilling, construction, and heavy mining equipment will occur during mine construction, operation, and reclamation. Table 8 compares the amount of vehicular emissions from typical surface and underground mines. Surface mines generally release significantly more vehicular emissions than do other types of mines.

Vehicular emissions can be reduced by the proper utilization of pollution-control devices on all vehicles and equipment and by maximum use of electric-powered equipment. Decreasing the total miles traveled, both within the mine and in commuting to and from the mine, will also reduce vehicular emissions. This can be accomplished by car- or van-pooling, by limiting unnecessary traffic within the mine, and by designing the mine for minimal travel.

Radon gas emanation may be a problem at certain mines. Radon gas directly enters the atmosphere in surface mines, but it readily disperses and mixes with air, thus minimizing radon concentrations. Underground mines may have the most serious radon gas problems. Radon emitted from the ore mixes with air breathed by the miners in the underground workings. The ventilation system should be designed and operated to keep radon levels within the mine at safe levels. Any failure of the ventilation system, either a total shut-down or improper ventilation of a small area, may create hazardous conditions for miners. All radon entering an underground mine is eventually released to the atmosphere at an exhaust vent. Radon levels near the surface exhaust vent may reach hazardous levels and this area may need to be either fenced or posted. Radon vented to the atmosphere will readily mix with fresh air and be rapidly diluted to acceptable levels as it travels from the mine. Radon may also be emitted from evaporation ponds at all types of mines.

Prior to establishment of a uranium mine, a meteorologic survey of the mine site should be conducted to determine climatic and wind conditions. At this same time air samples should be collected and analyzed for uranium, thorium-230, radium-226, lead-210, and gross alpha to establish baseline air quality. Natural soil emanation of radon-222 should also be measured prior to initiation of mining activities. During mine construction, several air-quality monitoring stations should be employed to determine particulate and other critical pollutant concentrations. Air sampling stations should continue to be monitored during mining. Several stations should be located on the mine site and downwind from it. These stations should be sampled regularly for radium, thorium, uranium, and other pollutants, if necessary.

LAND IMPACTS AND MITIGATION MEASURES

Most land in the study area underlain by potential uranium-bearing rocks is currently used for agricultural purposes. Livestock grazing, dry-land wheat farming, and irrigation farming are the principal uses of this land. Uranium mining would remove between a few hundred to a few thousand acres from agricultural uses for each mine facility. Multiple, sequential land use concepts should be employed to assure the return of mined land to a usable condition.

Uranium mines impact the topography by construction of mining pits or areas, roads, spoil piles, waste storage ponds, and buildings. Mining operations may cause changes in land forms, drainage patterns, and land slopes which may sharply alter existing conditions. One of the greatest long-term land impacts of uranium-recovery activities results from tailings disposal, a problem related to milling ore from open-pit, underground, and hydraulic borehole mines.

Historic and archaeologic sites and natural landmarks within a mine site may be affected by mining. They should be noted and may require special consideration. The National Registry of Natural Landmarks and the National Register of Historic Places contain locations and descriptions of landmarks and historic places. The Colorado State Historical Society, Colorado State Archaeologist, and the Colorado Natural Areas Program should be contacted for up to date information on landmarks, historic and archaeologic sites, and natural areas. Additional sites deserving protection should be evaluated during site specific studies. Protection procedures are documented in 36 CFR 800. Recovery of historical and archeological information is required by the Historic and Archaeologic Preservation Act of 1974 (Public Law 93-291). A few areas in the Denver Basin are underlain by important fossil localities in the Denver Formation. Some of the best assemblages of Early Paleocene mammal fossils in the United States are found in this area and should be evaluated prior to mining or protected and preserved for future scientific research (Middleton, 1980, pers. comm.). Descriptions of specific, critical fossil localities are held by the Colorado Geological Survey and by the University of Colorado Museum.

After termination of mining activities the land must be reclaimed in accordance with the Colorado Mined Land Reclamation Act, administered by the Mined Land Reclamation Board, Department of Natural Resources, State of Colorado. This may involve, among other things, extensive site regrading, drainage reconstruction, replacement of top soil, revegetation, and stabilization of highwalls. In certain cases local ranchers or landowners may desire that specific roads or buildings remain intact for future use. Such arrangements should be made in advance between the landowner, the mining company, and Colorado Mined Land Reclamation Board. Any buildings left standing should be fully decontaminated and decommissioned, and any remaining roads should be constructed in such a way as to minimize future environmental problems.

Surface or open-pit mining generally impacts the land greater than other mining methods. Three aspects of open-pit mining are responsible for most effects on the land: 1) construction of the open-pit, 2) disposal of overburden materials, and 3) disposal of water from the dewatering system. The open pit is a problem because it is a large excavation. Surface drainages may need to be diverted around the open pit or entire mine facility. Drainage rerouting may cause accelerated soil erosion and increased sediment loads in streams.

Dimensions of an open pit may exceed 2 mi (3.2 km) in maximum length. Pit excavation results in a tremendous volume of overburden or spoil which must be placed temporarily or permanently on the land surface. Overburden stripping rates commonly range from 1,000 to 10,000 tons/day (908,000 to 9,080,000 kg/day) and the total amount of overburden to be removed ranges from less than 4 to over 100 million tons (3.6 to 90.8 billion kg). Overburden may be placed in permanent storage on the land surface, usually in a natural low spot, or it may be used in the open pit as back-fill material. Should the overburden be left on the land surface, the open pit will remain after mining as a large void which may fill with water, depending on hydrologic conditions. Water in the pit may or may not be usable. It may contain high levels of hazardous materials which make the water unfit for drinking, livestock watering, or recreation. If the water is usable, pit walls should be reshaped to allow access to the water by potential users. The decision to back fill an open pit depends on site-specific concerns. If, for instance, the pit intercepts a natural, important drainage course, it may be necessary to back fill and re-establish the drainage course in a manner approximating original conditions. However, should the pit be located high on a drainage divide, it may be left open, rather than back filled.

If overburden is left on the land surface, it should be placed, graded, and contoured to best fit existing conditions. Pit walls in the abandoned open pit should be stabilized. In the past overburden often was placed in a natural drainage with no provisions allowed for proper re-establishment of the stream. Large precipitation events occurring every 25 to 100 years, and normal precipitation runoff erode such poorly placed overburden piles and add suspended sediment to stream loads. Overburden placement and rerouting of natural drainages must be carefully designed to harmonize with existing conditions to prevent future sedimentation problems. It may also be beneficial to regrade the waste pile in such a way so that precipitation runoff is slowed to allow for better water infiltration, rapid revegetation, and lower peak flows.

Underground uranium mining avoids many of the land impacts associated with open-pit mining. Problems caused by the presence of a large open pit are eliminated; only a few relatively small diameter shafts, slopes or drifts are needed for access into the mine. The only significant spoil material results from excavation of access routes and occasionally from underground development work. This spoil is placed on the surface and problems associated with spoil placement in open-pit mining also concerns spoil piles from underground mining. Differences in impacts result from the volume of spoil. Spoil from underground mining is typically orders of magnitude less in volume than that from open-pit mining.

An important potential land impact of shallow underground uranium mines involves land subsidence. A relative wealth of subsidence information is available for coal mines, but minimal information on uranium mine subsidence exists. This results from several factors: 1) uranium mines are generally less extensive than coal mines, 2) roof rock in uranium mines often is indurated sandstone, a better and more stable roof rock than the shale that commonly overlies coal beds, 3) coal mining often occurred beneath or adjacent to urban areas where subsidence and its effects on urban structures were easily observed and of greater interest than subsidence in the remote areas where most uranium mining takes place, and 4) uranium mines are commonly deeper than coal mines. Nonetheless, subsidence is associated with some underground uranium mines and it is a potential impact that must be considered when planning underground mining activities.

Within the study area, subsidence is a severe problem with shallow coal mines. It is anticipated that shallow underground mining of uranium in the Laramie or Fox Hills also could cause some subsidence problems, but underground mining in younger formations, such as the Dawson Arkose, would be of even greater concern because of the relatively unconsolidated state of the younger formations.

Hydraulic borehole mining, because it cuts large underground voids, also may have subsidence problems associated with it. It is possible that underground cavities resulting from borehole mining will be larger than those from underground mining and, correspondingly, the subsidence hazards may be greater. Subsidence potential can be reduced and effectively mitigated by back filling borehole cavities, as is suggested by Savanick (1980).

In situ solution mining does involve extraction of uranium in the subsurface, but it does not include removal of the host rock or overburden. Subsidence potential is virtually eliminated and mine spoil is minimal with solution mining. Both solution mining and borehole mining do require utilization of the land surface over the entire ore body (unlike underground mining which uses only a centralized area near the access and ventilation openings), but land impacts are primarily restricted to road, drill pad, waste storage pond, pipeline, and mine building construction. Reclamation and revegetation of borehole and solution mine sites are relatively simple compared to open-pit mines.

Drilling pads at in situ solution and hydraulic borehole mines should be reclaimed and revegetated to acceptable levels immediately after completion of the well. After successful aquifer restoration at solution mines and cavity back filling at borehole mines, drill holes should be plugged with concrete or an acceptable alternative substance, to within 3 to 4 ft (0.9 to 1.2 m) of the surface. From this depth upward, the well casing should be removed and the hole back filled with soil. Final reclamation and revegetation of the entire mine site follows proper drill hole abandonment.

SURFACE-WATER IMPACTS AND MITIGATION MEASURES

Uranium mining may affect the quantity and quality of surface waters both at and downstream from the mine (Wentz, 1974; Harp, 1978). In the study area most uranium mining will occur in drainage basins of ephemeral streams. Most perennial streams in the study area are not underlain by formations likely to contain economic uranium deposits. Only the South Platte River from near Kassler to Greeley flows over potential uranium-bearing rocks, and these rocks have only low uranium potential. Much of this area has also been heavily urbanized and uranium mining, even if significant deposits should be found, is highly improbable because of land-use conflicts.

As with coal mining most impacts to the surface-water system eventually add water to the surface system if relate to disturbances of the hydrologic balance. Mining may affect the hydrologic balance by altering stream courses, runoff patterns, infiltration rates, percolation rates, soil water-retention capacities, and vegetation distribution. Rocks and minerals exposed to the air by mining may be leached of certain ions that may contaminate surface water.

One of the obvious ways that the hydrologic balance may be affected is through disruption of runoff and natural drainages by a mine. Open-pit mining, because it disturbs a large land area, has greater potential to seriously interrupt stream courses and runoff patterns than do other types of uranium mines. In many open-pit operations it is necessary to divert surface runoff around the pit. This usually is accomplished through a series of diversion ditches and dikes which intercept runoff on the upslope side of the pit, bring it around the pit, and release it on the downslope side of the pit. If large drainages that have high potential for flooding are disrupted by the pit, the diversion system will have to be carefully designed to handle maximum flood waters. If a diversion system is included as part of a reclamation program, it may require periodic maintenance after mine abandonment to prevent disruption problems.

Some mines may allow runoff to enter the pit if it is of small amounts. Within the pit a system of graded ditches may drain runoff and infiltrating ground water to a centralized area where sump pumps may be used to remove the water from the mine. Pre-release treatment may be needed if the collected water has high undesirable concentrations of suspended and dissolved solids. Settling ponds can be effectively used to decrease suspended solids to acceptable levels, but it is difficult and expensive to remove dissolved solids. It is easier to prevent increases in dissolved solids than to try and remove them. Some structures associated with mining, such as buildings, waste storage ponds and piles, and roads, may cause local effects on surface-water flow paths, but this effect is usually small.

In situ solution mining and hydraulic borehole mining may slightly interrupt streams drainages and runoff. Both of these types of mining do occupy a sizable land area above the ore body for mining operations (although more land is usually required for open-pit mining), but the land

surface is not greatly disturbed. These operations should not seriously affect small drainages or runoff patterns. Underground mining rarely involves stream diversion because of the small land area required for the mine openings and associated surface facilities. Surface subsidence, however, should it result from underground or borehole uranium mining, could disrupt stream flow and runoff, and cause local ponding of water in subsidence-induced closed depressions. Water impounded in these closed depressions may be subjected to high evaporation rates or may rapidly infiltrate into the subsurface through subsidence cracks.

Disturbance of recharge areas may also affect surface water. For instance, an open-pit mine could disrupt the recharge area of an aquifer that discharges to a nearby stream. The volume of water in the stream could be seriously altered if discharge from the aquifer diminishes.

Infiltration and percolation rates and water-retention capacities of land disturbed by mining may also affect surface-water flow. Spoil from a mining operation commonly is more permeable and porous than the original rock before mining. Spoil may be capable of absorbing and holding a considerable amount of precipitation and runoff. This effect may be beneficial in that the additional water-retention capacity may serve to lower peak flows during large rain storms and spread the discharge over a longer time period. Open-pit mines generally cause greater changes in the overall infiltration and percolation rates of an entire site than do other types of mining, although surface subsidence and attendant ground deformation may cause important changes in infiltration rates above underground and hydraulic borehole mines.

The volume of flow in the surface-water system may also be affected by other mine-related activities. The most significant impact involves aquifer dewatering at open-pit, underground, and possibly hydraulic borehole mines. Dewatering systems at uranium mines often generate from 300 to 5,000 gpm (18.9 to 315.0 l/s) of water that must be removed from the mine, depending on the hydrologic setting of the mine. In general more water is produced from the dewatering systems of open-pit mines than from other types of mines, because overlying aquifers as well as the ore-bearing aquifer may need to be dewatered.

Figure 75 illustrates some of the possible uses and disposal methods of water from dewatering systems. Any excess water that cannot be beneficially used must be disposed. If the water is of acceptable quality or is treated before release, it may be discharged into nearby streams. In the study area this may cause an ephemeral stream to flow perennially. Such a change in flow regime may stimulate downstream erosion and accompanying sedimentation problems. It could also provide some benefits by making additional water temporarily available for downstream users and could aid recharge of alluvial aquifers.

Surface-water flow may also be affected by accidents at in situ solution mines (Table 13), such as overflow or leakage from evaporation ponds and by rupture of surface pipelines or spillage from tank trucks. Overflow may directly enter a drainage and increase flow volumes. Subsurface pond leakage may eventually add water to the surface system if

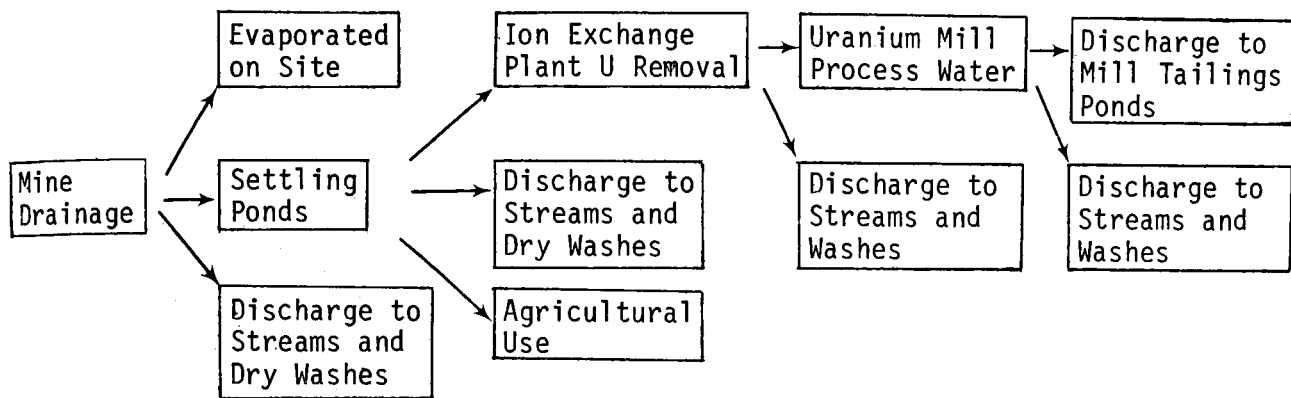


Figure 75. Possible uses or disposal methods of drainage water from active open-pit and underground mines. (from U.S. Environmental Protection Agency, 1979)

the leakage is into an aquifer with hydrologic connection to surface streams. Surface pipelines at in situ solution mines may rupture because of faulty construction practices, climatic factors, or physical impacts. Pipeline rupture may add to the total volume of flow in a stream. The degree of impact depends on the volume and flow rate of fluids in the pipeline and leak-detection lag time.

Surface-water quality may be affected by uranium mining in several ways. As mentioned previously, runoff collected by a system of ditches around a mine may gain suspended and dissolved solids. Water from a mine dewatering system may also be high in suspended and dissolved solids. Water pumped from dewatering wells usually does not contain significant suspended solids, but the dissolved solid content is typical of natural ground water near uranium deposits. It may or may not have high concentrations of undesirable ions. Dewatering systems that consist of a series of ditches within a mine may also release water high in suspended and dissolved solids. Soluble contaminants may be leached from exposed ore and overburden as the water runs through the mine. All water that leaves a mine and drains into the surface-water system should be of acceptable quality from both dissolved solids and suspended sediment standpoints. Suspended sediment loads can be lowered by the use of settling ponds. Some dissolved radioactive solids, though not uranium, may be removed by the addition of barium chloride to cause precipitation and allow removal in settling ponds. If the dissolved solid content is very high, chemical treatment may be necessary prior to release. In general, surface uranium mining has a higher potential for surface-water contamination than do other types of uranium mines.

Environmentally hazardous accidents may affect local surface-water quality at an in situ solution mine. Table 13 lists potential surface and subsurface accidents that could occur at a solution mine. Liquid and solid waste storage ponds may overflow directly onto the surface and mix

with surface water or the ponds may leak into alluvial aquifers containing water that readily commingles with surface water. During normal operations an acceptable freeboard should be maintained to prevent pond overtopping. Ponds should be designed for high rainfall events and lined to avoid subsurface leakage. The quality of the water in the pond and the amount released dictate the degree of impact on the surface-water system. Failure of well casings in alluvial aquifers, pipeline rupture, leachate excursions into alluvial aquifers, and leakage through improperly abandoned drill holes may also lead to contamination of surface water.

Table 13. Potential environmentally hazardous accidents at an in situ solution mine (from Kirkham, 1979).

<u>Subsurface Accidents</u>	<u>Surface Accidents</u>
subsurface pipeline rupture	surface pipeline rupture
waste storage pond leakage	failure of chemical storage tanks
well casing failure	overflow of waste storage ponds
leachate excursions	explosion and fires
production well failure	tornadoes
leakage through improperly abandoned drill holes	seismic effects
hydraulic fracturing	spillage from tank trucks

Many improperly abandoned, inactive uranium mines are known to contribute to surface-water problems (U.S. Environmental Protection Agency, 1979). All entries into abandoned underground mines should be sealed for human and animal safety, to prevent surface water from draining into the mine, and to keep mine drainage from escaping into surface streams. Open-pit mines usually should be back filled with spoil. An abandoned, unfilled pit may interfere with natural drainages and seriously disrupt stream flow. Such a pit should be back filled, graded, and recontoured to accommodate approximate original flow regimes. Solution mines and hydraulic borehole mines should be rapidly reclaimed and revegetated to prevent deleterious runoff problems.

Prior to initiation of any mining activities, all streams and nearby water impoundments should be sampled and analyzed to ascertain their baseline chemistry. Table 14 lists some of the physical and chemical parameters that may be measured. It may not be necessary to determine baseline values for all these parameters at all mines, but an appropriate suite of these parameters should be used. Additionally, baseline discharge rates for all flowing surface water and the water level of impoundments should be determined. During mining all surface water should be monitored regularly, or if the stream is ephemeral, after significant precipitation events. Stream flow and water levels of impoundments should also be monitored regularly.

Table 14. Physical and chemical parameters of surface- and ground-water monitoring programs (from U.S. Nuclear Regulatory Commission, 1978a).

Ammonia (as NH ₄)	Gross alpha and beta	Potassium
Arsenic	Hardness (as CaCO ₃)	Radium-226
Barium	Iron	Selenium
Bicarbonate	Lead	Silica
Boron	Magnesium	Silver
Cadmium	Manganese	Sodium
Calcium	Mercury	Sulfate
Carbonate (as CO ₃)	Molybdenum	Total dissolved solids
Chloride	Nickel	Thorium-230
Chromium, hexavalent	Nitrate	Vanadium
Conductivity	Nitrite	Uranium
Copper	pH	Zinc
Fluoride		

GROUND-WATER IMPACTS AND MITIGATION MEASURES

Probably the greatest potential environmental problems associated with uranium mining relate to ground-water quantity and quality. Much of the agricultural activity in the study area that occurs outside of major alluvial valleys is solely dependent on ground water as a source of water suitable for stock watering, irrigation, and domestic use. Proper mine planning, operation, and reclamation will minimize many of the potential ground-water impacts, but certain problems, particularly consumptive use of ground water, cannot be totally avoided.

One of the most important reasons why uranium mining has a high potential to impact ground water relates to the geologic occurrence of uranium. Uranium mineralization occurs within major aquifers in the study area. The known, economically significant deposits are in the Fox Hills Sandstone and the thick sandstones within the Laramie Formation in the Cheyenne Basin. These units also supply large volumes of ground water. Any mining conducted in a major aquifer has the potential to seriously impact ground-water quality and quantity.

OPEN-PIT MINING

One of the primary aspects of open-pit mining on ground water results from aquifer disruption. Any aquifers, either alluvial or bedrock types, penetrated by the open pit will produce water into the pit. Water that enters the pit may be removed by sump pumps within the mine and/or by a

dewatering well system that removes ground water before it flows into the pit. Pit walls could also be sealed to prevent inflow. In either case water-table elevations or potentiometric surfaces, reduce ground-water quantities, and affect ground-water flow paths. As much as 5,000 gpm (19 m³/min) of water may be withdrawn by a dewatering system. Water levels in wells that tap aquifers disrupted by the pit may decline markedly. Generally, the closer the well is to the pit, the greater the likelihood of declining water levels. In extreme cases nearby water wells may go dry as a result of the dewatering.

Aquifer disruption by open-pit mining may also result in water-quality impacts. Water in the pit may seep back into an aquifer. Water in the pit often is of poor quality due to leaching of ions from ore and overburden that is exposed to oxidizing conditions. It may have high dissolved solids content and contain high levels of radioactive and toxic elements and heavy metals. Seepage of mine water into aquifers may contaminate ground-water, but contaminant concentrations will decrease by dilution and adsorption as the plume moves away from the mine. Consumptive use of ground water by a dewatering system cannot be totally avoided in open-pit mines. If at all possible this water should be put to valuable use, possibly as mill make-up water or, if of suitable quality, used for irrigation, reclamation, or dust control.

Water quality in alluvial aquifers and, in certain cases, bedrock aquifers may also be affected by leakage from evaporation ponds and seepage of runoff from ore stockpiles and overburden piles (Figure 73). Unlined or poorly lined evaporation ponds may leak into underlying permeable formations. Depending on the chemistry of the impounded water and the volume of leakage, it may seriously contaminate infiltrated aquifers. Evaporation pond leakage can be minimized by proper construction techniques and adequate monitoring, as described in a following section.

Figure 76 illustrates some of the potential hydrologic effects of open-pit mines on nearby water wells. The upper diagram shows the pre-mining hydrologic conditions. Wells A and D tap a major aquifer that contains a uranium deposit. The water level in the wells is indicated by the heavy screen pattern. Quality of the water in this major aquifer may naturally be somewhat poor. Studies in the Cheyenne Basin by Kirkham and others (1980) indicate water quality of uranium-bearing aquifers is highly variable and water quality is often naturally very poor near uranium deposits. Wells B and E tap shallow alluvial aquifers and well C taps a thin, lenticular, channel sandstone overlying the uranium deposit.

The lower diagram in Figure 76 illustrates some of the potential effects that may result from open-pit mining. Water may flow into the pit from all three aquifers. The water level in Wells A, B, and D may drop severely. Well C will probably go dry, depending on the dimensions of the aquifer and its hydrologic characteristics. Water quality in well D may worsen if poor quality water seeps back in the ore-bearing aquifer from the pit. Well E may also experience a decline in water level, and if

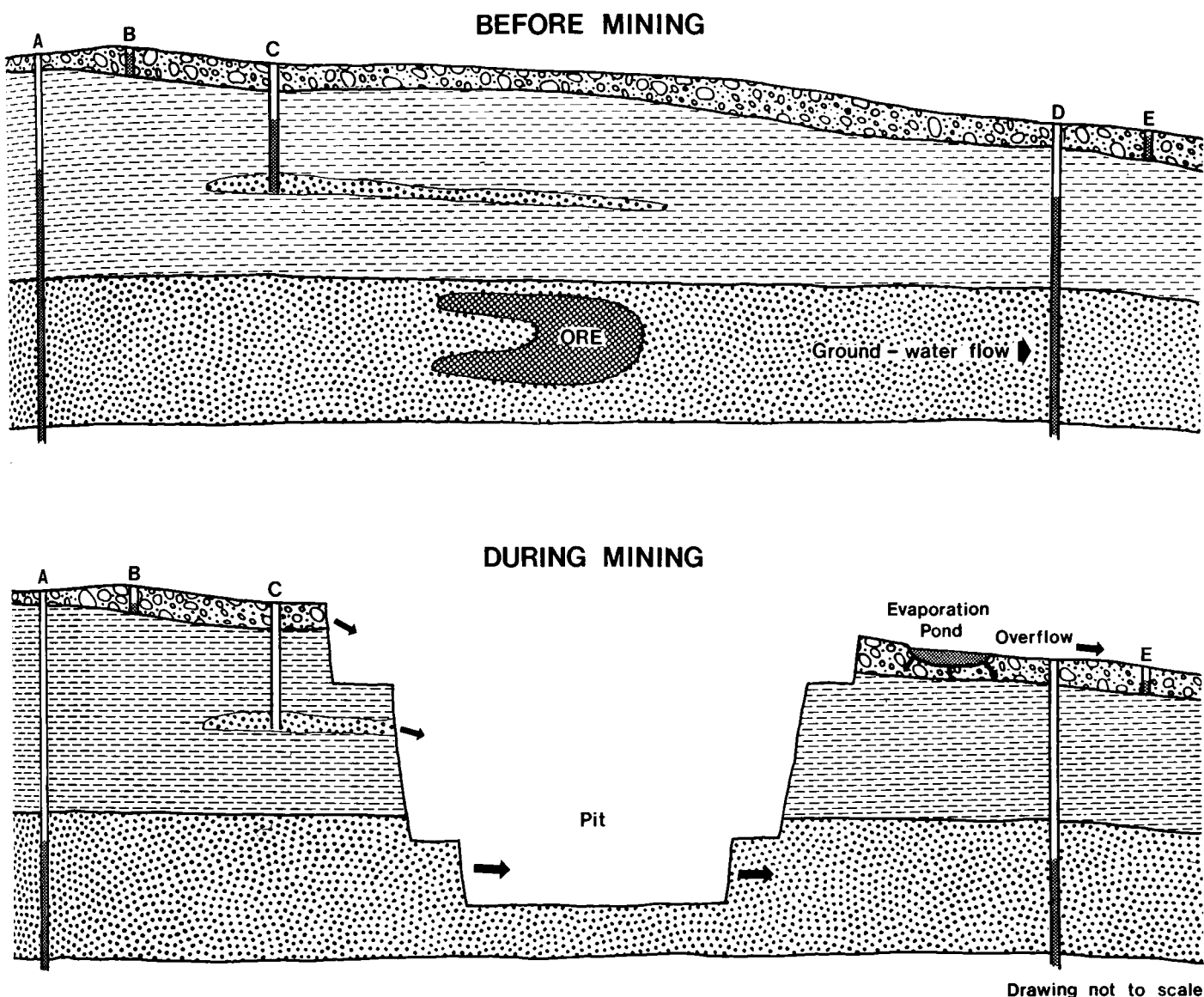


Figure 76. Potential hydrologic effects of an open-pit uranium mine.

contaminated water leaks from the evaporation pit into the shallow alluvial aquifer, it may produce poor quality water.

Runoff from overburden piles and ore stockpiles may infiltrate alluvial aquifers (Figure 73). Runoff may contain high levels of suspended solids, some of which may be radioactive or toxic, and, possibly, moderately high levels of undesirable dissolved ions.

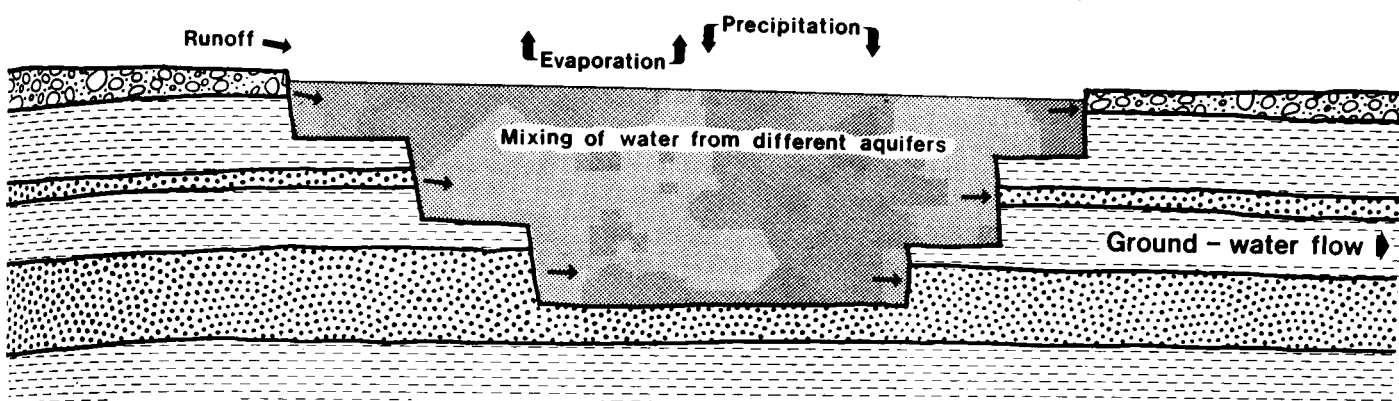
Generally, contaminated runoff is a greater hazard to surface water than to ground water, but if a site is underlain by a highly permeable alluvial aquifer, a significant amount of runoff may infiltrate into the subsurface.

After completion of an open-pit mining operation the pit may simply be allowed to fill with water or it may be back filled with spoil (Figure 77). If a pit is abandoned without back filling, and the dewatering system for that pit is abandoned or removed, ground water, precipitation, and surface runoff will continue to enter the pit. It will eventually partly or completely fill with water, depending on inflow and evaporation rates and aquifer conditions. Water from the various sources may be of differing quality. It will mix within the pit and result in a body of water that has relatively homogeneous quality characteristics which reflect the average quality of inflowing water. Within the pit additional ions may be leached from exposed ore and overburden, causing a decrease in water quality. Water in the pit may re-enter penetrated aquifers on the down-gradient side of the mine. This infiltrating water will probably be of different quality than natural water within the aquifers. In some cases it will be of poorer quality, but it may also be better than the natural water in poor quality aquifers.

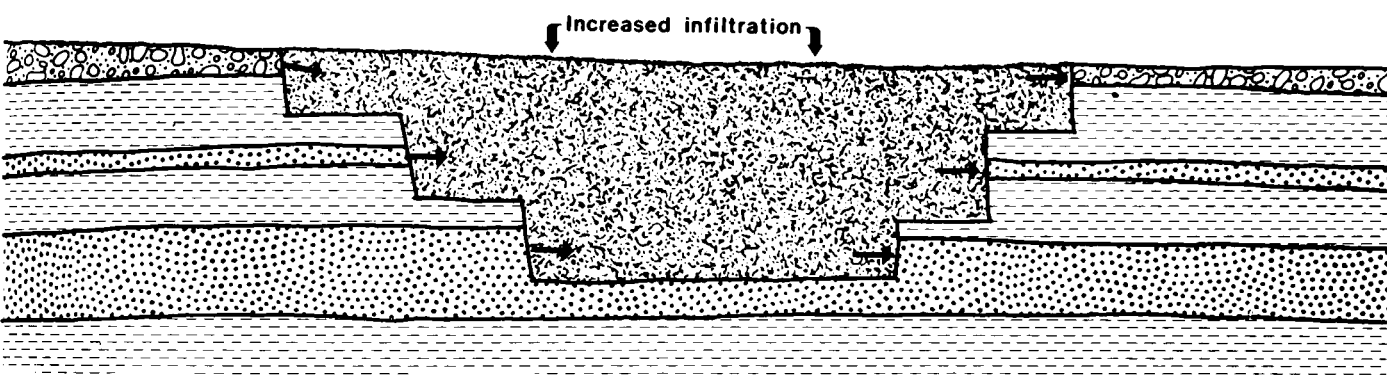
When a pit is back filled the replaced spoil loses most natural stratification and is a fairly heterogeneous mass of broken rock. Permeability of the replaced material may be high, and the continuity of individual aquifers will be interrupted. The lower diagram in Figure 77 schematically illustrates possible hydrologic consequences of pit back filling. Ground water in penetrated aquifers will continue to enter the pit, but it will not flow directly through the broken fill and re-enter the same aquifer from which it originated. It will migrate through the fractures and open pores, mix with water entering the fill from other aquifers and from surface infiltration, and then may re-enter any of the penetrated aquifers on the down-gradient side of the pit. Disruption of natural flow paths thus continues after completion of mining and reclamation. This may be a significant problem if the involved aquifers contain water of differing quality, if undesirable ions are leached from the replaced spoil as ground water and infiltrating surface water pass through it, or if altered flow paths are not desired. In operations where alluvial valley floors have been disrupted by mining, it may be beneficial to separately stockpile alluvial materials and then return the alluvial deposits to near original conditions by careful, selective pit back filling. This type of alluvial valley floor reclamation may be especially desirable in situations where the open-pit has removed a significant part of the alluvial valley floor and a return to natural hydrologic conditions with the alluvial aquifer is desired.

Open-pit uranium mining may also impact ground water by disturbance of recharge areas. During mining the recharge into an aquifer may be decreased and the amount of water within the aquifer lowered. Water wells that tap the disturbed aquifer may experience declining water levels during mining. After completion of mining recharge, may return if the pit is properly abandoned. The water in the aquifer, however, may

NO BACKFILLING – PIT FILLS WITH WATER



HETEROGENEOUS BACKFILLING



Drawing not to scale

Figure 77. Cross sections through abandoned open-pit uranium mines schematically illustrating potential effects of abandoned pits on the hydrologic environment.

have higher dissolved solids concentrations after mining due to leaching of exposed rocks. The effects of recharge area disturbance by open-pit mining is similar to those caused by surface coal mining, as previously described in this report and illustrated in Figure 58.

UNDERGROUND MINING

Underground uranium mining may impact ground water in several ways. The primary impacts are related to dewatering and to aquifer disruption caused by subsidence or construction of mine openings and workings. Vertical shafts and slopes associated with a mine may penetrate alluvial and bedrock aquifers. Water will leak into these openings and enter the mine. Penetrated aquifers may experience declines in water tables or potentiometric surfaces. Fortunately, most mining companies normally construct mine openings in such a way that leakage is minimized or eliminated by lining the opening or by sealing off the penetrated aquifers. In the study area uranium deposits are within thick sandstone aquifers. Mine workings, therefore, are also within these aquifers. Ground water may leak into the mine workings from the ore-bearing aquifer and cause operational problems. It must be pumped from the mine to the surface by one or more sump pumps or prevented from entering the mine by a series of dewatering wells. This water loss may cause a cone of depression to develop in the mined aquifer around the mine. As described in an earlier section on underground coal mining and shown in Figure 60, such a water loss may cause declines in the water levels of nearby wells. After completion of mining, however, water levels eventually should nearly return to pre-mining conditions.

The U.S. Environmental Protection Agency (1979) studied mines in the Colorado Plateau and found that underground uranium mines discharged an average of 734 gpm (2.78 m³/min). In other words over 1 million gallons (28,000 m³) of water are removed from ground-water aquifers at a typical underground uranium mine in the Colorado Plateau every day. The authors have not attempted any detailed hydrologic comparison of aquifers in the study area with those in the Colorado Plateau, but even if the average mine in the Denver and Cheyenne Basins discharged only one-tenth the volume of a Colorado Plateau mine, it still amounts to over 100,000 gallons (2,800 m³) of ground water per day.

If at all possible, water from a dewatering system should be put to beneficial use to avoid wasting a valuable resource or the expense of water disposal. Such uses may include irrigation, stock watering, mill process water, operational needs of the mine, and dust control. Unfortunately, in many cases the water in an ore-bearing aquifer near a uranium deposit naturally has high levels of undesirable dissolved solids. Additional contaminants may enter the water within the mine by leaching of exposed rock. Beneficial use of this water may be limited and surface disposal may be required. At some mines the water may be directly released to a surface stream, but often the water must be treated before release. If the water is of very poor quality or treatment is undesirable, it may have to be evaporated on site in ponds. These ponds should be properly constructed to prevent overflow and seepage into shallow underlying aquifers.

Following abandonment of a mine, the dewatering system will cease operating, and the mined-out area may fill with water, depending on hydrologic conditions and evaporation rates. Water filling the mine may

leach certain ions from the exposed host rock and ore. This water may re-enter the mined aquifer on the down-gradient side of the mine and a contaminant plume could develop. The chemistry and extent of the plume will depend on a number of factors, including the chemistry of the mine water, adsorption capacities of the host aquifer, ground-water flow rates and direction, and dilution factors.

As illustrated in Figure 78, mine subsidence may seriously impact ground-water flow paths in aquifers that overlie a uranium deposit, and in certain cases water quality may also be affected. Water in overlying aquifers may leak into subsidence cavities and fractures which penetrate it. A cone of depression may develop in the water level or potentiometric surface of a disrupted aquifer. Water levels in nearby wells that tap disrupted aquifers may lower. Water quality may be affected by commingling of water from overlying aquifers with water in the mined-out area.

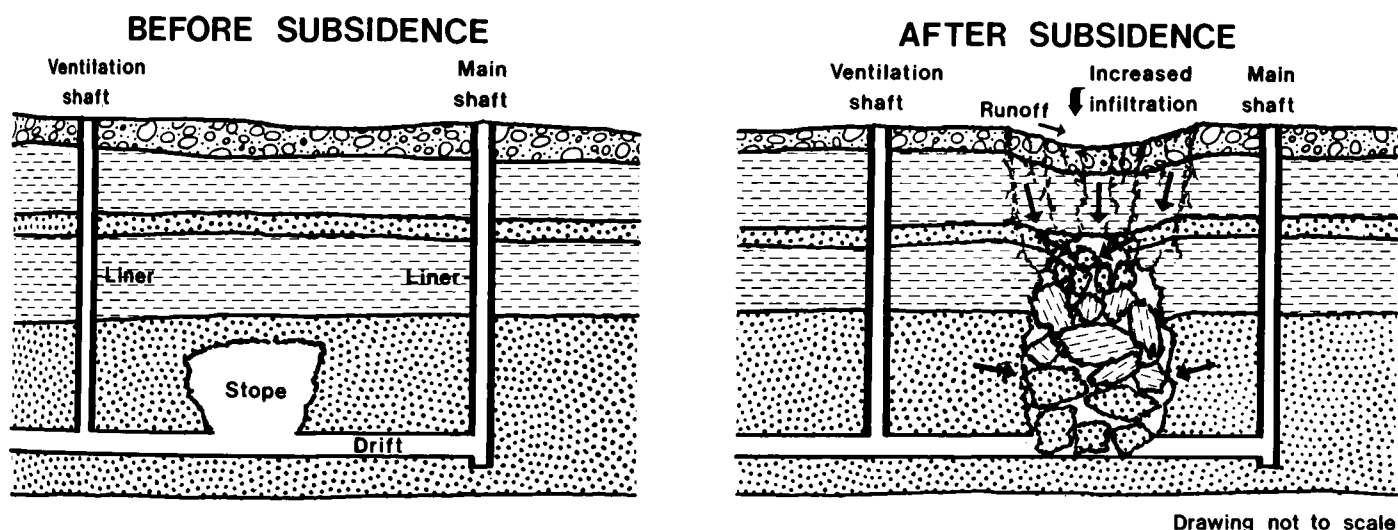


Figure 78. An example of potential hydrologic impacts resultant from subsidence at underground uranium mines.

IN SITU SOLUTION MINING

Contamination and consumptive use of ground water are probably the greatest potential impacts of solution mining. The mining process directly affects ground-water quality at the mine site by the injection of a leach solution into the ore-bearing aquifer. The injected leach solution contains foreign elements, and additional ions, including both radioactive and toxic species, are leached from the host rock by the lixiviant. Ideally, all contaminated water within the mining zone will be restored to near original conditions following completion of mining by extensive ground-water restoration.

Ground-water quality may also be affected by accidents such as horizontal and vertical excursions of contaminated ground water during mining, leakage through improperly plugged drill holes, rupture of well casings, rupture of pipelines, and leakage of storage ponds. These quality problems also can be effectively mitigated by proper restoration techniques. Large volumes of ground water may be consumed by well field overpumping and restoration activities. The amount of water used during restoration can be greatly reduced by "clean-water recycling." Problems may also result from the processing phases of solution mining operations, but these are not discussed in this report. Refer to Kirkham (1979) for a discussion of impacts associated with the processing of pregnant uranium-bearing solutions from in situ solution mines.

During the operation of a solution mine a lixiviant and oxidant are injected into the ore-bearing aquifer. The specific amount and type of chemicals injected depend on the characteristics of the selected lixiviant. Some of the commonly used chemicals include ammonium, sodium, calcium, and magnesium carbonates and bicarbonates, sulfuric acid, hydrogen peroxide, and oxygen. Besides uranium, the lixiviant may mobilize selenium, vanadium, thorium, and molybdenum. Lesser amounts of copper, iron, cadmium, lead, zinc, arsenic, nickel, mercury, and manganese may also be possibly mobilized, depending on the chemistry of the host rock and the lixiviant. A general example of the types of ions mobilized by the various lixiviants is indicated in Table 10. A specific example of the types of elements liberated by solution mining can be seen by comparing the pre-mining and post-mining water quality at the Grover test site (Table 15).

If no accidental contamination occurs and restoration of the ore-bearing aquifer is successful, contaminant levels should nearly return to pre-mining concentrations. Most potential contaminants are fairly amenable to removal by restoration. Ammonium, however, is one of the more difficult ions to clean up. Ammonium has a high ion exchange capacity with the clay minerals that occupy interstitial pore space within the host sandstone. Ammonium commonly replaces calcium, magnesium, and sodium ions that are bonded to the clay minerals during leaching. Restoration will successfully remove most ammonium in solution. This alters the equilibrium established between the ammonium in solution and that which is bonded to the clays, resulting in transfer of part, but not all of the adsorbed ammonium into solution. Existing restoration tests indicate the adsorbed ammonium is slowly released with time and that the desorption

Table 15. Restoration data from the Grover test site, Colorado. (from Wyoming Mineral Corporation; Webb, 1979, per. comm.)

Constituents	Pre-Mining Samples ^a	Post-Mining Samples ^b	Post-Restoration Samples ^c		Restoration Stabilization Period ^c			
			WMC	CDH	45-days		90-days	
					WMC	CDH	WMC	CDH
Calcium	9.1	75.8	11.5	-	10.1	-	9.9	-
Magnesium	1.1	22.4	2.2	-	2.2	-	2.3	-
Sodium	85.2	237.5	-	-	-	-	-	-
Bicarbonate	220.1	1127.3	-	-	-	-	-	-
Sulfate	38.3	311.0	-	-	-	-	-	-
Chloride	7.0	75.5	-	-	-	-	-	-
Nitrate	1.4	5.2	N/A	0.018	0.005	<0.003	0.009	<0.1
Fluoride	0.7	0.1	-	-	-	-	-	-
TDS	295.0	763.0	275	240	268	260	267	270
pH	8.45	8.07	8.2	8.7	7.3	8.5	8.4	8.55
Arsenic	0.01	0.01	-	-	-	-	-	-
Barium	0.03	0.16	-	-	-	-	-	-
Cadmium	0.002	0.004	-	-	-	-	-	-
Chromium	0.003	0.005	-	-	-	-	-	-
Copper	0.06	0.08	-	-	-	-	-	-
Iron	0.70	1.25	-	-	-	-	-	-
Lead	0.02	0.03	-	-	-	-	-	-
Manganese	0.02	0.16	-	-	-	-	-	-
Mercury	0.0002	0.000	-	-	-	-	-	-
Molybdenum	0.02	0.31	-	-	-	-	-	-
Nickel	0.20	0.02	-	-	-	-	-	-
Selenium	0.01	0.59	-	-	-	-	-	-
Silver	0.003	0.002	-	-	-	-	-	-
Zinc	0.04	0.06	-	-	-	-	-	-
Boron	0.10	0.16	-	-	-	-	-	-
Vanadium	0.03	0.30	-	-	-	-	-	-
Ammonia	0.25	304.00	14.9	14	14	16	11	15
Uranium	0.086	12.48	0.62	0.59	0.61	0.57	0.65	0.68
Ra226 (pci/L)	13.4	259.8±3.9	-	N/A	-	13.0	-	14.7
Potassium	4.43	13.10	-	-	-	-	-	-
Carbonate	4.31	11.60	-	-	-	-	-	-
Silica	5.45	13.03	-	-	-	-	-	-
Conductance (umho)	380.7	2705.0	530	520	546	580	565	540
Alkalinity	154.7	1692.8	189	180	165	190	203	200
Aluminum	0.537	0.05	-	-	-	-	-	-
Phosphorus	0.050	0.15	-	-	-	-	-	-
Gross Alpha (pCi/L)	87.67	5255±132.6	347±30	579±36	262±25	499±34	348±31	454±30
Gross Beta (pCi/L)	15.23	1256.6±124.8	27±57	99±18	79±167	92±19	63±67	247±25
Lead (pCi/L)	0.37	9.9±2.3	-	-	-	-	-	-
Thorium (pCi/L)	0.7417	10.6±1.4	-	-	-	-	-	-

a) based on the average of twelve analyses; in ppm unless indicated otherwise

b) based on the average of seven analyses; in ppm unless indicated otherwise

c) based on analyses of samples from well G-2; WMC designates analyses by Wyoming Mineral Corporation; CDH designates analyses by Colorado Department of Health; in mg/L unless indicated otherwise

rate decreases with decreasing adsorbed ammonium concentrations. In other words it becomes increasingly difficult to remove ammonium from the aquifer as the ammonium concentration decreases.

Ammonium is objectionable at elevated levels because of its odor and effect on chlorination. Little is known about ammonia toxicity to humans, but low concentrations of ammonium are toxic to fish (Willingham, 1976). Considerable controversy revolves around the establishment of acceptable ammonium limits in water and in allowable mine discharges. The details surrounding this controversial topic are beyond the scope of this report.

An additional potential hazard created by the presence of ammonium involves the formation of nitrite and nitrate. At or near the surface in the presence of oxygen, ammonium may be converted to nitrate and nitrite by nitrifying bacteria. A lack of oxygen, high pH, and other factors is thought to limit nitrite and nitrate formation within the aquifer, but this aspect is not well understood. Data reported by the U.S. Nuclear Regulatory Commission (1978a) suggest nitrification within the aquifer under normal reducing conditions is unlikely. Nitrifying bacteria could be re-injected with the fortified lixiviant into the subsurface, but conditions would be significantly different from what these acidic-soil-loving bacteria are used to thriving in. It is not known if the bacteria would survive in the subsurface. In the subsurface ammonium should travel only short distances before adsorbing to clay minerals, but mobility of nitrate and nitrite is much greater, and these ions may migrate with the flowing ground water. Their relative concentrations, however, would decrease with increasing distance of travel.

As is apparent from the previous descriptions, if aquifer restoration is successful and no accidents occur, minimal long-term impacts will result from the use of sodium or alkaline earth carbonate-bicarbonate lixiviants or from the use of sulfuric acid lixiviants. Long-term, offsite impacts could possibly occur, however, when ammonium carbonate-bicarbonate lixiviants are used. Because of this, the application of ammonium lixiviants is discouraged, unless the chemical and hydrological characteristics of the ore body and the mining economics preclude the use of other lixiviants or the hazard due to ammonium is proved to be lower.

As mentioned previously, serious environmental consequences may also result from accidents during mining and processing phases at solution mining operations. Table 13 lists the potential surface and subsurface accidents at a solution mine. Only the more significant types of these accidents that affect ground water are discussed in this section.

One of the more hazardous potential subsurface accidents that could affect ground water involves vertical or horizontal leachate excursions. Lateral excursion or migration of leachate within the ore-bearing aquifer from the well field is possible because of geologic inhomogeneities, anisotropic aquifer permeabilities, differential hydraulic gradients, poor well spacings, incorrect injection/recovery rates, and equipment failure. Vertical excursions into overlying or underlying formations are possible

because of natural vertical conduits such as faults or fractures, leaky confining beds, artificial fractures induced by high injection pressures, improperly abandoned drill holes, and well casing failures. One of the principal concerns at any solution mine is the shape, chemistry, and magnitude of potential excursions and the transportation attenuation rates of contaminants. Table 10 lists the types of ions mobilized by the various leach solutions and the natural mechanisms that limit their mobility. These mobilized ions and the chemicals within the lixiviant may be present in an excursion.

Several factors control the size, shape, and chemistry of an excursion (U.S. Nuclear Regulatory Commission, 1978a,b). These factors include 1) ability of the well field to confine and then remove leachate and mobilized constituents from the aquifer, 2) direction and rate of ground-water flow, 3) geochemical characteristics of the aquifer and the adsorptive and ion-exchange capacity of clay minerals in the aquifer, 4) mobility and chemical reactivity of contaminant ions, 5) lithologic and hydrologic variations of the aquifer, 6) excursion detection lag time, and 7) mitigation measures employed by the mine operator. Most excursions will be of limited extent and will only affect areas very near or within the mine site, if corrective actions are rapidly employed. In rare situations where faults or fractures act as hydraulic conduits, fluids may travel greater distances from the site. The relative concentration of many of the contaminating ions in an excursion decreases with distance of travel until a quasi-equilibrium is reached. The contaminated zone is somewhat stationary, but most individual contaminant species will stabilize at some point within the excursion.

Proper selection and implementation of a corrective action to reverse an excursion should enable containment of the leach solution and reversal of the excursion. The U.S. Nuclear Regulatory Commission (1978a,b) recognizes four factors that must be considered to assure proper selection of the corrective action: 1) monitor well spacing, 2) contaminant mobilities, 3) uniformity of measuring and reporting procedures, and 4) consistency of response measures with the detected release.

Primary corrective action procedures include well overpumping and reordering, reducing or halting injection, reducing leachate concentration, establishing a water fence, and, if all else fails, restoration (Wyoming Mineral Corporation, 1978; U.S. Nuclear Regulatory Commission, 1978a,b). These methods may be applied only to a few wells within a production cell, to several production cells, or to the entire well field. The mine operator may be required to drill detection wells to locate the extent of the excursion beyond the monitor well ring.

Another potentially hazardous accident involves waste storage ponds. Leakage of waste storage ponds may contaminate alluvial and shallow bedrock aquifers. Waste storage ponds may contain radioactive and toxic liquids from the mining, processing, and restoration phases of a solution mining operation and any seepage of these contaminants into the ground-water system is undesirable. If leakage occurs, the contents of the pond should be lowered or removed to another intact pond to allow repair of the leak. Liquid waste escaping from the pond will migrate

vertically and horizontally through the subsurface. Rate and direction of effluent flow depends on the geometry and hydraulic characteristics of the underlying materials. Detrimental effects of seepage may be naturally mitigated over a long period of time and long distance of transport. Cation exchange with clay minerals in the aquifer will remove part of the contaminants. As the seepage migrates this adsorption will reduce the volume and concentration of undesirable ions in the aquifer. In severe cases it may be necessary to restore aquifers contaminated by waste pond leakage.

Leakage can be minimized by proper construction techniques. Ponds should be constructed as basins in relatively flat, high areas with a continuous detention dike on all sides of the pond to prevent overflow. Construction of ponds on alluvial or bedrock aquifers should be avoided. Ponds should be lined with impermeable layers of clay and/or plastic membranes such as hypalon to eliminate leakage. Figure 79 illustrates the waste storage ponds proposed by Wyoming Mineral Corporation (1978). This particular design involves a built-in leak detection system that is discussed in a later section.

Leakage through cracked or improperly set well casing may contaminate aquifers and dry formations which overlie the ore-bearing aquifer. Leakage in recovery wells probably will not cause significant contamination because any fluids present behind the leaking casing should be drawn into the well by the pumping action and brought to the surface along with the pregnant lixiviant. Leakage in injection wells, however, could allow for contaminant escape because of injection pressures. Most leaks will likely be the result of poor well completion techniques, faulty construction materials, or accidental rupture. Leakage should occur almost immediately upon initiation of production. In order to detect such leaks, natural ground water should be circulated through the production cell and injection/recovery pressures and volumes closely monitored before bringing the production cell on line. Any leaks thus detected should be repaired and the well retested prior to production.

During production, well casings may develop leaks from chemical or physical degradation. Such leaks, if of large enough size, should be detected by close monitoring of injection pressures. Small leaks may not be discovered by pressure monitoring. Vertical leachate excursions into the first aquifer above the ore-bearing aquifer should be detected by the shallow monitor well system described later in this section. Excursions into other overlying aquifers may go undetected unless additional monitor wells are completed into those aquifers. Most existing regulations require monitoring of only the first aquifer that overlies the ore zone. If other significant aquifers are stratigraphically above the ore zone and first overlying aquifer, it may be necessary to monitor them as a part of the overall monitoring program to assure total water-quality protection.

If contaminant escape through cracked or improperly set well casing is detected, efforts should immediately be undertaken to determine which well casing is leaking and to correct the problem. Contaminated aquifers

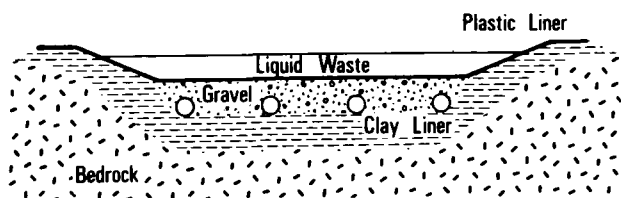
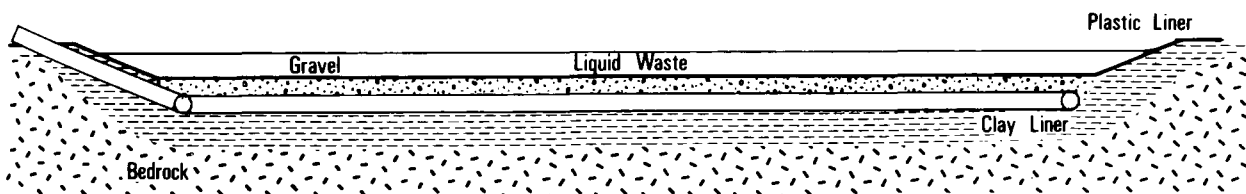
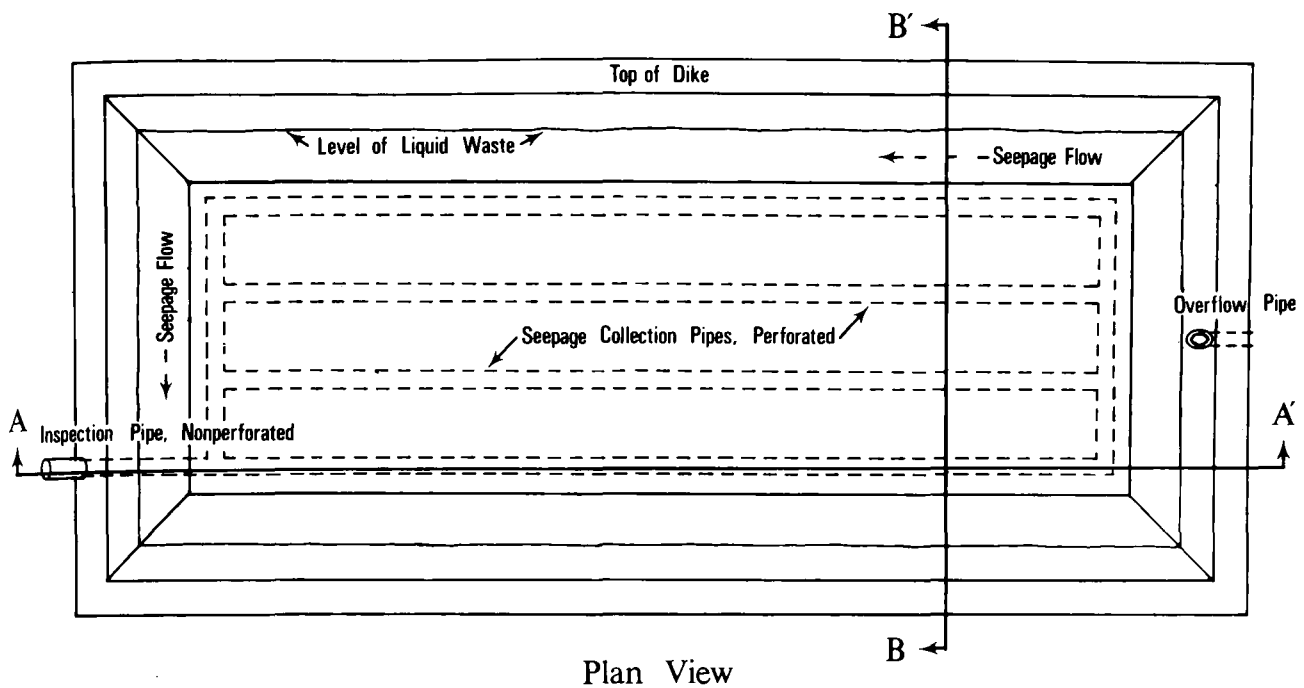


Figure 79. Waste storage pond construction details. (after Wyoming Mineral Corporation, 1978; Kirkham, 1980)

may need to be restored. This may involve drilling additional wells into the contaminated aquifer to facilitate restoration.

Failure of a production well to recover the pregnant lixiviant because of plugging or power failure could cause a localized fluid migration. Regular monitoring of injection and recovery flows should minimize lag time between failure and detection. Readjustment of injection pressures and flow rates of the well field should prevent further leachate migration and balance flows for the well field until the well can be repaired and put back in operation or replaced.

Migration of leachate through abandoned, improperly cased, or inadequately plugged drill holes may result in vertical excursions. Contaminated fluids may circulate within such a drill hole and mix with ground water in aquifers above and below the ore-bearing zone, depending on hydraulic conditions. In areas where this type of hole is anticipated it may be necessary to pump test production cells prior to production initiation to determine if leakage through abandoned drill holes occurs. During mining, water level and quality changes within monitor wells may indicate contaminant migration in aquifers tapped by monitor wells. Adjustment of flow rate, plugging or repair of the leaking well, and aquifer restoration are measures that should remedy the problem.

Improperly abandoned exploration drill holes are an example of this type of drill hole. Some of these holes will "self-plug" by squeezing of shale and bridging of the hole and some drilling muds aid in sealing drill holes. Other drill holes, however, remain open and serve as vertical conduits that allow commingling of water from different aquifers. Other types of abandoned drill holes, such as open-hole "homestead wells" and abandoned water or oil wells with leaky casing, may also allow commingling of aquifer waters.

Hydraulic fracturing of the ore-bearing aquifer may occur if injection pressures exceed formation fracturing pressures. Migration of leach fluids through such fractures could allow excursions into adjacent shale and mudstone layers or possibly even sandstone aquifers. Pilot-scale testing has shown that hydraulic fracturing may actually decrease uranium recovery at a solution mine and for this reason is economically undesirable. Mine operators should maintain injection pressures below fracturing pressures to avoid the environmental and technological problems associated with hydraulic fracturing.

Aquifer Restoration

If no accidents occur during the operation of a solution mine, the only contaminated ground water that will need to be restored after completion of mining is within the well field and possibly the area between the well field and the outer ring of monitoring wells. Following completion of mining, affected water must be returned to original baseline quality or to a quality level specified by mine permits, such as drinking water standards. Restoration may also be necessary to clean up aquifers contaminated by leachate excursions or other types of accidents that

affect water quality. Selection and implementation of a suitable restoration program is dependent on the characteristics of each mine site. Some of the restoration methods considered for use today include 1) natural restoration, 2) ground-water sweeping, 3) clean-water recycling, and 4) chemical restoration. Several of these methods have been used successfully at pilot-scale projects, but restoration of a full-scale mine has not yet been completed. Oftentimes a combination of these methods is used for a particular mine.

Establishment of restoration criteria is the initial step of any restoration program. Restoration, as defined by the U.S. Nuclear Regulatory Commission (1978a,b), consists of "the returning of affected ground water to a condition consistent with its premining use (or potential use) upon completion of leaching activities." Restoration must reduce concentrations of undesirable ground-water contaminants to acceptable levels.

There are three water-quality zones within an ore-bearing aquifer being solution mined: 1) the mining zone, 2) the containment zone, and 3) the undisturbed zone (Figure 80). The U.S. Nuclear Regulatory Commission (1978a,b) define the mining zone and containment zone as follows:

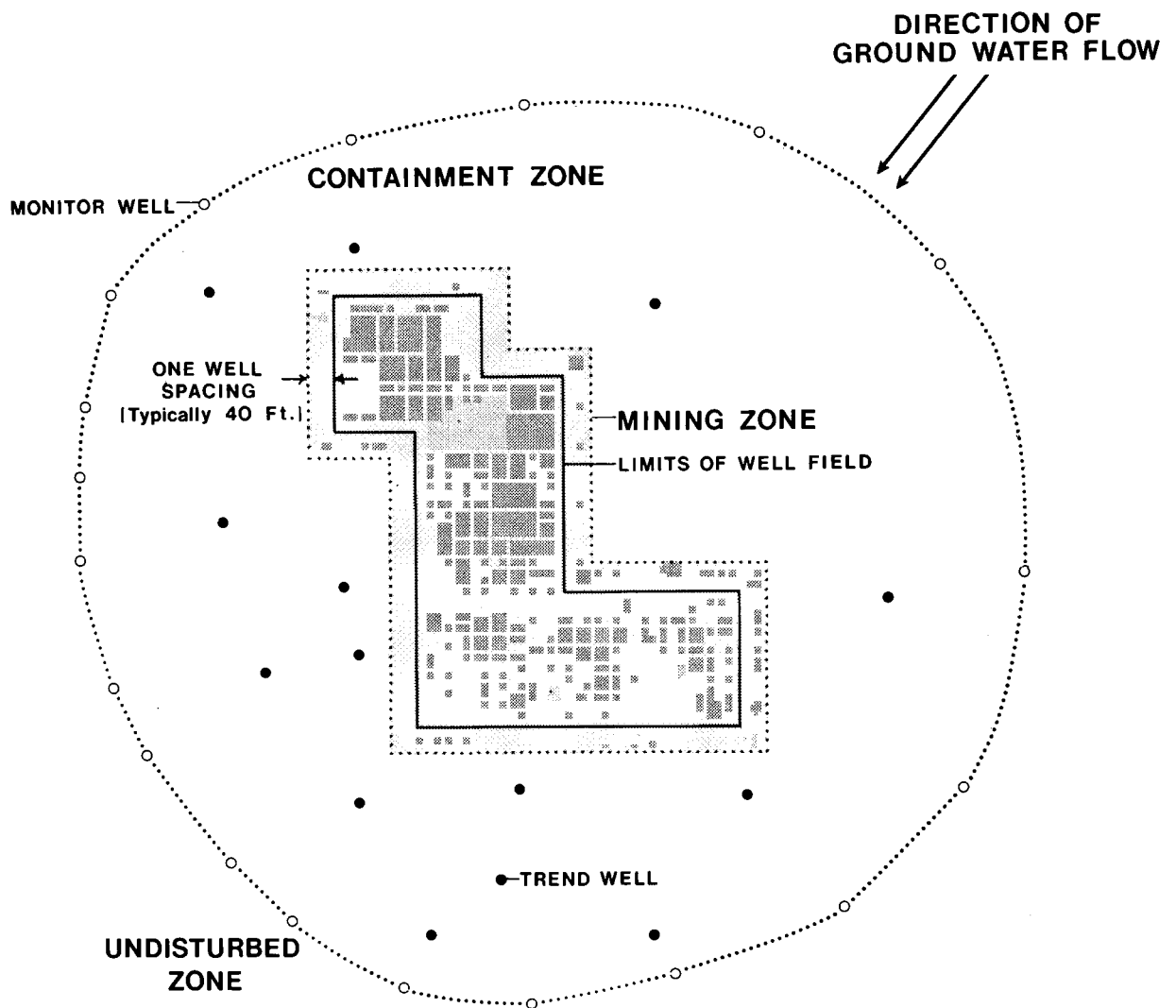
Mining Zone - the area within the mineralized (ore deposit) portion of the aquifer. The perimeter of this zone is defined as one well spacing (approximately 40 ft (12 m)) either beyond the outer injection wells or the limit of the ore deposit to be mined.

Containment Zone - the area, in the ore-bearing aquifer, from the perimeter of the mining zone to the nearest monitor well. The perimeter of this zone is defined by a line connecting the monitor wells surrounding the well field. Trend wells may be placed within this zone.

The authors define the undisturbed zone as the area in the ore-bearing aquifer outside the containment zone.

The original ground water within the mining zone often naturally exceeds drinking water standards for many constituents (U.S. Nuclear Regulatory Commission, 1978a,b; Wyoming Mineral Corporation, 1978) and may be unacceptable for either domestic or livestock use. This appears to be true for some areas in the Cheyenne Basin (Kirkham and others, 1980). Water in the mining zone will be affected by solution mining. Original ground water in the containment and undisturbed zones may or may not be fit for domestic and livestock use. Water in the containment zone may be affected by excursions during mining. Ideally, excursions should not extend into the undisturbed zone. Efforts should be made to minimize excursions and keep them within the originally defined containment zone.

Because the natural ground-water quality within each of these designated zones varies, it is often necessary to have separate



Drawing not to scale

Figure 80. Generalized plan map of water-quality zones in an ore-bearing aquifer at an in situ uranium solution mine.

restoration criteria for each zone. Ground-water quality within the undisturbed zone should not be altered by the mining project and therefore should not need to be restored. Ground water in the containment and mining zones may or may not meet drinking or livestock water standards. If the pre-mining water quality is within either domestic or livestock standards, the U.S. Nuclear Regulatory Commission (1978a,b) requires that the water be returned to appropriate State or Federal criteria. If the

pre-mining quality is not within either standard, the U.S. Nuclear Regulatory Commission believes the water should be returned to within 20 percent of the baseline concentration of each contaminant. Restoration to original baseline conditions may be desired in either case. For contaminants with no applicable standard a reasonable concentration level should be selected that satisfactorily protects present and potential water users.

Determination of baseline water quality and accompanying restoration criteria are ongoing efforts. Prior to any mining samples should be collected from selected wells within the mining zone, from all monitor wells, and from all existing water-supply wells near the mine site. These samples provide baseline quality data prior to any mining. Before mining proceeds into new areas, additional samples may need to be collected and analyzed to provide restoration criteria for areas added to the mining zone. Any new monitor wells should also be analyzed and taken into consideration for the restoration criteria of the containment zone.

Selection and regulatory approval of a suitable restoration program should be required prior to initiation of mining. Modifications to the restoration program may be made as mining and restoration proceeds. A restoration program may involve application of several treatment methods. Two general classes of restoration methods are recognized: 1) in situ methods, and 2) surface separation methods. An integral part of any restoration program also includes ultimate waste disposal.

In situ methods are characterized by ground-water restoration of the contaminated aquifer within the subsurface. Natural restoration is a type of in situ restoration which involves physical-chemical actions within the contaminated aquifer that occur naturally with no artificial influence. Theoretically, natural processes could eventually return a mined aquifer to baseline conditions. However, alterations caused by the mining operation are not well understood and it is not known if natural restoration is truly a viable technique which, by itself, can completely restore a mined aquifer. Riding and Rosswog (1979) note several advantages to natural restoration including 1) conservation of resources required for artificial restoration methods, 2) containment of contaminants in the subsurface which precludes contaminant entry into the atmosphere or onto the land surface, 3) conservation of waste disposal capacity, and 4) elimination of future contamination problems from leakage of surface waste storage ponds. To date no natural restoration program has, by itself, been approved for an entire site by a regulatory agency.

Most regulatory agencies require artificial restoration methods to aid natural processes. The most popular artificial restoration technique is ground-water sweeping. It involves pumping and extraction of contaminated ground-water from the ore-bearing aquifer. This withdrawal forces natural, undisturbed water from outside the containment zone towards the pumping wells. Migration of the natural water through the affected aquifer forces the contaminated water towards pumping wells where it is pumped to the surface. Disposal of this extracted water can be accomplished by evaporation, flood irrigation, or deep disposal injection. Contaminated water may be pumped from all or part of the wells in a

production cell. Ideally, all contaminated water will be replaced by uncontaminated natural water.

In certain cases, such as at the Highland, Wyoming, operation (U.S. Nuclear Regulatory Commission, 1978b), it has been shown that ground-water sweeping may, by itself, satisfactorily restore the water in the mined aquifer on a pilot-scale. At other operations, especially those using ammonium lixiviants, it has been necessary to employ additional techniques. Thompson and others (1978) cite several reasons why the exclusive use of ground-water sweeping may be unsatisfactory: 1) aquifer heterogeneity, 2) cation adsorption on clay minerals, 3) chemical disequilibrium, and 4) high consumptive use of ground water. Ore-bearing aquifers often are inhomogeneous and anisotropic. They commonly have preferential fluid flow paths. During restoration inflowing, uncontaminated water will be more or less "channelized" along these flow paths and inadequate removal of contaminants from areas having slow flow rates may occur. Another factor, cation adsorption on clay minerals, may limit successful restoration by ground-water sweeping. Several ions, especially ammonium, readily adsorb to clay minerals in the aquifer. During sweeping operations these ions desorb very slowly, and oftentimes may remain adsorbed after sweeping is terminated. Disequilibrium is important because it is virtually impossible to exactly re-establish equilibrium conditions after disturbance. Ground-water sweeping may also consume large volumes of ground water, an unacceptable action in areas such as the study area, where ground water is already in short supply.

To minimize the amount of liquid waste generated by restoration it may be necessary to employ surface separation methods such as clean-water recycling with the sweeping operation. Clean-water recycling involves the surface purification of withdrawn contaminated water and reinjection of the clean water into the aquifer being restored. Water purification may be accomplished by techniques such as reverse osmosis, electrodialysis, ion exchange, ultrafiltration, chemical precipitation, or ammonia air stripping. Chemical restoration may be needed to aid removal of ammonia or other ions that strongly adsorb to clay. This technique involves the addition of calcium, sodium, or magnesium to the purified water prior to reinjection. The injected ions replace the adsorbed ammonium. After ammonium levels are brought to desired concentrations a residual TDS reduction program is initiated. This encompasses reinjection of clean water to remove the calcium, sodium, or magnesium. In certain cases liquid from the restoration process may be processed or used at the mill.

The only restoration experiment to date in Colorado was conducted by Wyoming Mineral Corporation at the Grover test site. The experiment appears to have been successful, but certain aspects have not been completely resolved. Table 15 lists the results of the restoration experiment at Grover. The analyses indicate pre-mining, post-mining, and post-restoration measurements. Post-mining analyses indicate marked increases in the concentration of many ions, a result of the injected chemicals contained in the lixiviant and ions dissolved from the host rock by leaching. The Grover restoration program involved ground-water sweeping, clean-water recycling, chemical restoration, and residual TDS reduction, and appears to have been successful in restoring the mined

aquifer, at least for the monitored parameters. Unfortunately, post-restoration analyses for many of the trace elements have not been conducted and the successful removal of these ions is not documented. Post-restoration analyses at Grover suggest restoration stabilization was achieved for the monitored parameters.

Restoration of an entire commercial mine has never been attempted because none have yet been completely mined out. Many of the factors described above may contribute serious problems to restoration of a large mine site. Successful restoration of a commercial in situ solution mine is probably the greatest environmental question about solution mining that remains to be faced by the uranium industry.

Monitoring Programs

In order to detect accidental contamination of the ground water, it is necessary to know baseline water quality and to install several ground-water monitoring or surveillance systems. A general baseline water-quality study should be conducted prior to initiation of any mining activities. The physical and chemical parameters which may be measured for the baseline survey and in part during the monitoring program are listed in Table 14. In addition to these parameters, water levels in all wells should be measured.

There are two primary monitoring systems employed during mining. One monitors leakage from waste storage ponds and another monitors contamination of the ore-bearing, overlying, and underlying aquifers by excursions. All wells used in both systems should be sampled periodically prior to mining to establish natural water-quality fluctuations for baseline conditions.

Waste storage ponds should be designed and constructed to minimize the potential for leakage. Each pond or group of ponds should be equipped with leak detection monitoring systems. There are two types of leak detection monitoring systems: 1) built-in systems and 2) shallow monitoring well systems. A built-in leak detection system is constructed as an integral part of the waste storage pond. The system may be similar to the one proposed by Wyoming Mineral Corporation (1978) and illustrated in Figure 79. A gravel layer and series of perforated plastic pipes are placed at the base of the pond to collect seepage and serve as leak detectors. A layer of impermeable clay and/or a plastic, impermeable liner, such as a hypalon, overlies the detection system. Any leakage through the liner will collect in the pipes and can be observed and sampled in the inspection tube.

Shallow monitor wells may also be used to detect leakage from waste storage ponds. Such wells should be as close to the pond as possible and should monitor the formation into which the pond has been excavated or the first underlying aquifer.

The ponds should be monitored every shift for freeboard. The built-in leak detection system should be regularly monitored for the presence of any fluid, and if enough fluid is present it should be sampled

and analyzed to determine its source. If shallow monitor wells are used, water levels should be regularly checked and the water analyzed. If the pond leaks, appropriate steps should be taken to eliminate the problem. It may be necessary to transfer all or part of the contents of the pond to an adjacent, intact pond or temporary container and then repair the liner. Any contaminated aquifers should be restored to baseline conditions in the event of serious leakage.

To detect lateral and vertical excursions from the mine and to define an area of leachate containment, it is necessary to employ a well field monitoring system. This monitoring system represents the surveillance technique for initiating corrective actions, should a leachate excursion occur. The system consists of a series of monitor wells and, if desired by the mine operator, trend wells. Most monitor wells are completed only in the ore-bearing aquifer. Shallow and deep monitor wells may be completed in overlying or underlying formations. Monitor wells completed in the ore-bearing aquifer encircle the mine. The distance between these wells and the mine depends on the characteristics of each facility. Trend wells are a special type of monitor well used for operational purposes. They monitor the ore-bearing aquifer within the containment zone. The precise monitor well layout depends on the hydrologic conditions of each site. Shallow and deep monitor wells usually sample the first overlying and first underlying aquifers. In certain cases additional overlying aquifers may be monitored. All shallow and deep monitor wells should be located within the mining zone.

To minimize the environmental impact of leachate excursions, monitor wells must act affectively to detect and control the leachate within the containment zone. The U.S. Nuclear Regulatory Commission (1978a,b) has recognized three major factors which must be considered in the spacing of monitor wells:

- 1) site geological and hydrological variations must be evaluated, including (a) local variations in ground water flow rates and direction, (b) local variations in permeability zones of significant hydraulic conductivity, and (c) presence of sub-surface geologic features (channels, clay lenses, facies changes, etc.).
- 2) monitor wells should be spaced so that their respective zones of influence coincide.
- 3) monitor wells should be located at a distance from the well field so as not to intercept normal operating fluid flows: (a) the zone of influence during monitor well sampling must be considered and (b) sufficient distance should be available so that trend wells can be installed for normal operations.

As previously described, trend wells are a type of monitor well that is drilled within the containment zone to aid production control. Changes

in water quality in samples from trend wells might indicate a need for adjustment of production balances. Adjustment of injection and withdrawal pumping rates should correct a potential excursion. Use of trend wells thus will reduce the likelihood that an excursion will reach a monitor well.

Shallow and deep monitor wells sample the first aquifer directly above or below the mudstone or shale layers that confine the ore-bearing aquifer. The U.S. Nuclear Regulatory Commission (1978a,b) recommends that these wells be placed within the well field and that at least one shallow and one deep well be used for each five acres (20,200 m²) of well field. In certain cases where very thick confining beds underlie the ore-bearing aquifer, it may not be necessary to use deep monitor wells.

All monitor wells should be sampled every one to two weeks and analyzed for parameters such as pH, water depth, specific conductivity, chloride, bicarbonate, carbonate, and hardness. These particular analyses are useful because they are relatively easy and quick to obtain and they serve as lead indicators to an excursion. Other analyses, including uranium, radium, selenium, and ammonium, may be deemed necessary depending on the characteristics of the ore body and the lixiviant used. Prior to sampling a monitor well, it should be pumped so that at least one volume of water equal to the volume of water within the well bore is removed, or until the pH and conductivity of the water stabilize. Care is needed to prevent creation of an artificial excursion because of excess pumping.

To allow for natural fluctuation of ground-water quality an upper control limit (UCL) must be established for each selected indicator based on baseline quality determinations. A possible excursion and need for corrective action is signaled whenever two or more parameters exceed their designated UCL. An additional sample from the monitor well should be taken immediately after recognition of UCL exceedance. If this sample also indicates excessive values for two or more parameters, the cause of the high values should be determined. If it is determined that the high values are caused by an excursion, an appropriate corrective action should be selected and implemented as soon as is possible.

After completion of mining and restoration in all well fields a period of post-restoration monitoring is necessary to verify restoration stabilization. Monitor wells, including deep and shallow monitor wells, and the well field wells used to establish baseline water quality should be regularly sampled for at least one year after completion of restoration. If stabilization is not achieved, additional restoration may be necessary.

HYDRAULIC BOREHOLE MINING

Ground-water impacts associated with hydraulic borehole mining are not well understood, but they are believed to be similar to those caused by underground uranium mining. Ground water in aquifers penetrated by a borehole may seep into the borehole and drain into the mined area. Boreholes should be lined to prevent water inflow. The borehole cavity created by this mining process is similar to that from underground mining,

but in borehole mining the individual cavities are back filled after mining.

During mining it may be necessary to partly dewater the mined aquifer. Extracted water should be put to beneficial use unless the quality is poor. In this case the water must be properly disposed. The dewatering system may cause a cone of depression to develop in the mined aquifer around the mine site. Water levels in nearby water wells could be affected by this change. Subsidence over a hydraulically mined cavity could cause effects similar to those related to underground mining. Since borehole cavities will probably be back filled, subsidence problems should be minimal. A common disposal technique for extracted poor quality water involves placement in an evaporative waste storage pond. These ponds should be properly designed and constructed to prevent surface overflow and leakage into shallow underlying aquifers.

After completion of mining and cavity back filling ground water will re-enter the back filled cavity and water levels in nearby wells eventually should nearly return to pre-mining conditions. Water in the back filled cavity, however, may leach certain ions from the fill and then re-enter the aquifer on the down-gradient side of the cavity. Chemistry of the escaping water will depend on the chemistry of the fill and the leaching ability of the water.

OIL AND GAS RESOURCES

RESOURCE CHARACTERISTICS

Crude oil is a naturally occurring, complex mixture of hydrocarbons and oxygen, nitrogen, and sulphur derivatives of hydrocarbons or asphaltic compounds. Most crude oils also contain a variety of minor or trace elements, and its ash content commonly varies from 0.001 to 0.05 percent. The normal alkanes (hydrocarbons in which all carbon-carbon bonds are single bonds) that make up crude oil are liquid at one atmosphere of pressure and 25°C. They include pentane, hexane, heptane, octane, and others. Natural gas is a mixture of normal alkanes that are gaseous at one atmosphere of pressure and 25°C. These include methane, ethane, propane, and butane.

Most experts now believe that oil has an organic origin. As suggested by Hunt (1953) and others, the process of oil formation probably involves in part a degradation of raw organic materials and in part a preservation and concentration of hydrocarbons from the remains of plants and animals. As shown in Figure 81 an average shale contains approximately one percent organic matter. About 90 percent of the organic matter is the high molecular weight, insoluble, polymeric material called kerogen. The remaining organic matter is solvent soluble and is the bitumen factor.

Since kerogen accounts for about 90 percent of the organic matter in shales, small changes in its composition can produce large changes in the nature of the lower molecular weight, solvent extractable bitumens that

are generated from it. The formation of lower molecular weight hydrocarbons from kerogen is of particular importance because this is a critical process in petroleum generation. C₂-C₁₀ hydrocarbons are an important part of many crude oils. These particular hydrocarbons are absent in living organisms and recent sediments. They therefore must be made from some other carbonaceous material during petroleum generation. Kerogen is the most likely source for the C₂-C₁₀ hydrocarbons because of its ready availability and its response to changing thermal, chemical, and pressure conditions.

As kerogen is exposed to changing conditions in the subsurface, it begins to generate petroleum compounds. Its own chemical composition evolves in a process called "maturation." The chemical composition of kerogen and bitumin change systematically as depth increases (Figure 82). This results from increasing temperature and pressure, and duration of burial. Temperature increase is believed to be the most important factor, although it is possible to generate oil over a long period of time at relatively low temperatures.

Petroleum forms from a sequence of organic-rich source rocks. It migrates to a reservoir bed, a porous and permeable rock in which oil and gas can accumulate. Migration of petroleum from source beds to reservoir beds and final entrapment includes a number of possible mechanisms.

Hydrocarbons thermally generated from kerogen do not become important until depth of burial exceeds about 6,000 ft (1,800 m). As depth and temperature increase, the higher °API gravity crudes are formed. In the deepest part of a basin crude oil gives way to condensate and ultimately to gas. The overall process of migration and entrapment seems to be very inefficient. Less than one percent of the hydrocarbons in original source rocks eventually accumulates in reservoirs.

The chemical composition of a crude oil is not permanently fixed, but alters in response to changing conditions as shown in Figure 83. Evolution of a crude oil involves continuous and irreversible processes. This changes a heavy NSO-rich immature crude oil into mature crudes which are lighter in molecular weight. Crude oils are also altered by other processes, mainly water washing and bacterial degradation.

In order for petroleum to become localized or concentrated into significant deposits, it must migrate to traps within a reservoir bed. Traps can take a variety of forms, the most common ones being structural and stratigraphic traps, or a combination of these two forms. Petroleum exploration is the process of looking for and finding these traps and determining if they contain either oil or gas. Methods for locating these traps can be broken down into two general approaches--surface geology such as mapping of surface outcrops, stratigraphy and structure, and subsurface geology involving the use of information from both drill holes and various geophysical techniques. Seismic reflection and gravity surveys are the most commonly used geophysical methods.

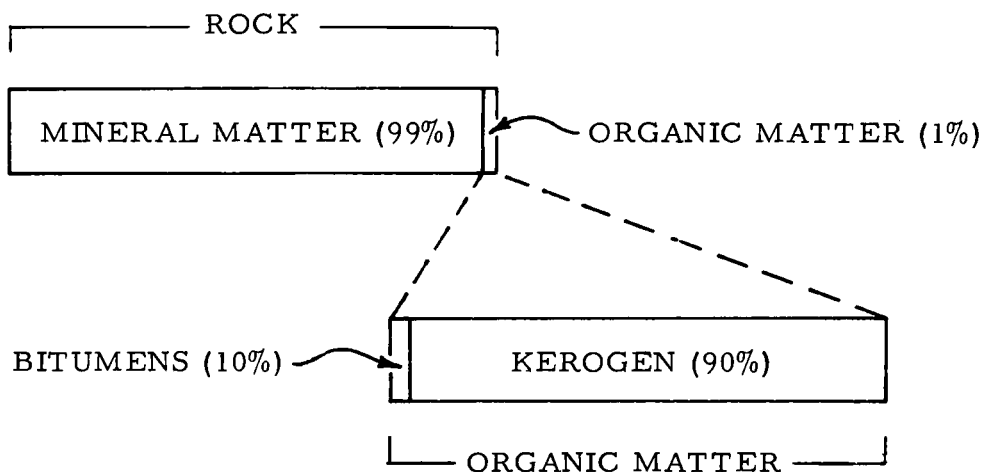


Figure 81. Kerogen and bitumen in average shales. (from Barker, 1979).

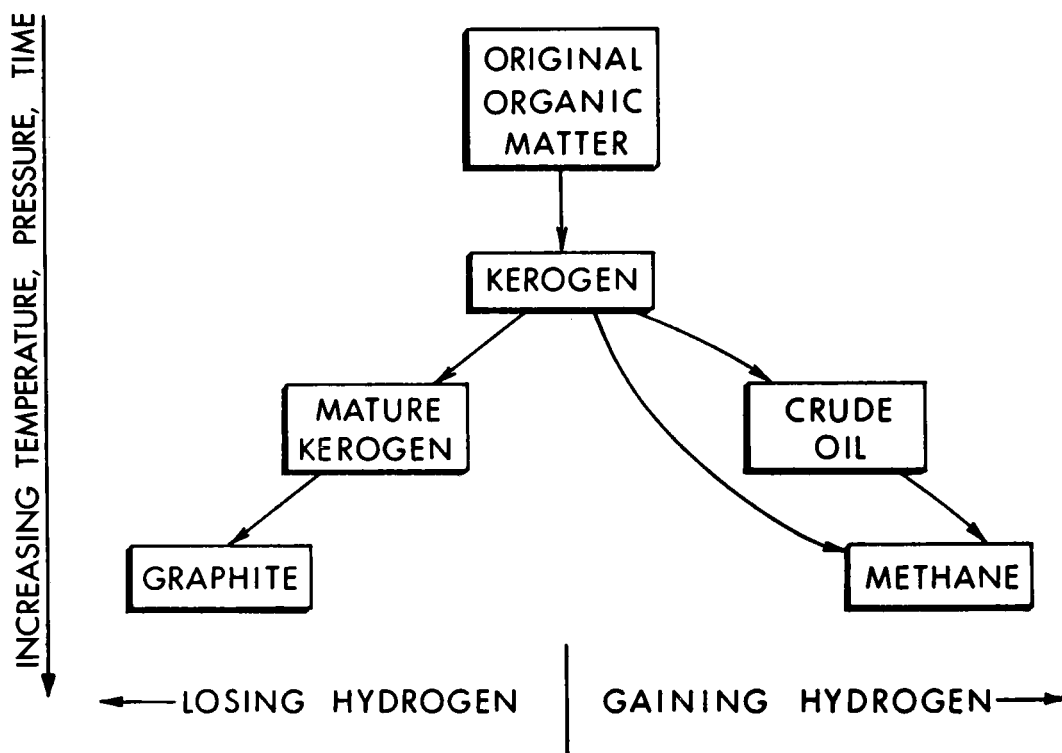


Figure 82. Changes in organic matter due to increase in pressure, temperature, and time. (after Barker, 1979).

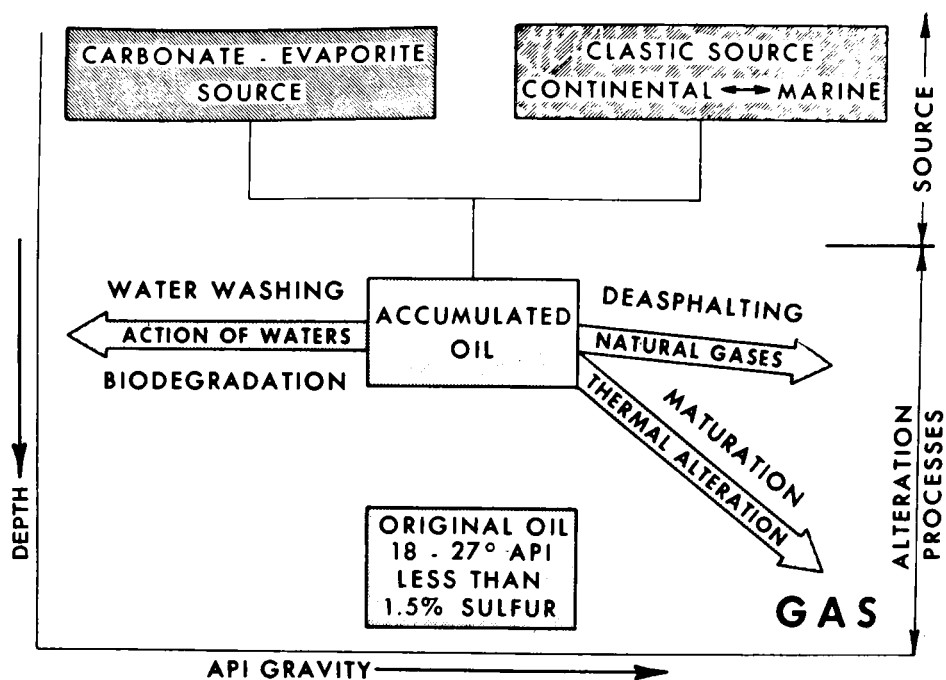


Figure 83. Alteration of petroleum after accumulation. (from Barker, 1979).

Once a prospect is defined, leases obtained, and the economics evaluated, drilling of an exploratory hole is the final and only definitive way to determine if petroleum is present in a postulated trap. The drilling process can take from a few days to over a year, depending on the depth of the hole, type of rocks encountered, and drilling problems. If oil or gas is discovered in commercial quantities, the next step would be production. This involves completion of the well and setting up a well pump and storage tank or pipeline system. If the hole is dry, it must be plugged and abandoned, and the drill site returned to its original use.

Production History

Oil and natural gas resources in the study area are an integral part of the resources of the large Denver-Cheyenne Basin which covers most of northeastern Colorado. This relationship exists because of geologic interrelationships between the entire Denver-Cheyenne Basin and the study area, and because the oil and gas exploration and development within the study area has direct ties with experience gained throughout the Denver-Cheyenne Basin. For these reasons, it is necessary to summarize the oil and gas history of the entire Denver-Cheyenne Basin in this report.

Producing, abandoned, and shut-in oil and gas fields in the study area are shown on Plate 2. Field locations outlined on this map are accurate as of 1977. New fields have been discovered since 1977, but they are not plotted on this map. Several existing fields have expanded beyond their boundaries shown on Plate 2. This is especially true for Spindle and Wattenburg fields, which cover much of the northern Denver area. Production statistics used in this report are from the Oil and Gas Conservation Commission (1979) and are listed for each field in Appendix 2. Included in this appendix are field name, location and year of discovery, cumulative production, producing formation(s), and production status. Producing formations indicated in this report are those cited by the Colorado Oil and Gas Conservation Commission (1979).

Oil was first produced from a well in Colorado during the spring of 1862, just two years after Colonel Drake completed his famous, world's first producing oil well near Titusville, Pennsylvania. The Colorado discovery well was sited near a live oil seep along Oil Creek, about six miles north of Canon City by A. M. Cassedy, one of Drake's associates from Pennsylvania. Located on the southwestern margin of the Denver-Cheyenne Basin, the discovery well produced from fractures in the Upper Cretaceous Pierre Shale at a depth of 50 ft (15 m), thus becoming the second oil-producing area in the United States. Additional wells drilled to depths from 50 to 90 ft (15 to 27 m) in this area also produced oil.

In 1876 Isaac Canfield drilled the discovery well for the Florence field just south of the town of Florence. The well was drilled to a depth of 1,187 ft (356 m) and oil again was found in joints and fractures in the Pierre Shale. Florence field produced 21,981 barrels of oil during 1978 for a cumulative production of 14,736,517 barrels.

Oil was first discovered within the study area in 1901. The McKenzie No. 1, discovery well for the Boulder field, was drilled on a structure exposed at the surface and completed in fractured, sandy zones in the Pierre Shale (Brainerd and Van Tuyl, 1954). This field produced 852 barrels of oil in 1978 for a cumulative production of 782,216 barrels.

Shortly before and during the 1920s considerable effort was expended by industry, the Colorado Geological Survey, and the U.S. Geological Survey to conduct regional stratigraphic and structural investigations in search of areas suitable for hydrocarbon accumulation, particularly anticlines with large closure. These efforts resulted in the discovery of numerous fields throughout Colorado, including a few discoveries on the west flank of the Denver-Cheyenne Basin. For instance, in 1923 a well drilled on the Wellington structure, resulted in the discovery of Wellington field. Production was from the Muddy Sandstone member of the Lower Cretaceous Dakota Group and was the first sandstone production in the State. Wellington field yielded 47,907 barrels of oil and 20,849 thousand cubic feet (Mcf) of gas during 1978 for a cumulative production of 14,383,452 barrels of oil and 23,157,513 Mcf of gas.

Another field still producing in 1980, the Fort Collins field, was discovered in 1924 on the Fort Collins structure. Original production

also came from the Muddy Sandstone member of the Dakota Group. Hydrocarbons were later discovered at this field in the Permian Lyons Sandstone and Upper Cretaceous Niobrara Formation. Fort Collins field produced 38,429 barrels of oil and 1,803 Mcf of gas during 1978 for a cumulative production of 3,809,873 barrels of oil and 462,034 Mcf of gas.

Berthoud field was discovered in 1927. It was drilled on the Berthoud structure and has produced from numerous pay zones, including the Niobrara Formation, D, J (Muddy), and Lakota Sandstone members of the Dakota Group, Codell Sandstone, and Lyons Sandstone. In 1978 Berthoud field produced 74,856 barrels of oil and 34,886 Mcf of gas resulting in a cumulative production of 1,047,495 barrels of oil and 438,419 Mcf of gas.

During the 1920s commercial quantities of oil and gas were discovered not only in the Dakota Group on the west flank of the Denver-Cheyenne Basin, but also in Wyoming, North Park, and northwestern Colorado. These discoveries generated considerable interest for several years in the oil and gas potential of the Dakota Group on the eastern flank of the Denver-Cheyenne Basin. Much of this region, however, is blanketed by a thick sequence of Tertiary sediments which conceal underlying, older geologic structures.

Greasewood field was one of the few fields found during this period. It was discovered in 1930 about 60 mi (96 km) east of the mountain front and was the first commercial development on the east side of the basin. The discovery well produced from the D Sandstone member of the Dakota Group and was drilled on a small structure exposed at the surface with very little or no closure. The trap was considered to be a stratigraphic type (Brainerd and Van Tuyl, 1954). This discovery sparked exploration interests, but the drilling of several dry holes nearby caused the interest to wane.

The Depression of the 1930s affected exploration activities by limiting the demand for hydrocarbons. During this period few fields were discovered in Colorado and existing fields produced at low levels. From 1938 to 1943 there were no field discoveries anywhere in the State. Increased utilization of geophysical techniques, primarily seismic methods, however, soon led to further discoveries. Clark Lake field was discovered in 1944 by drilling on a structure delineated by seismograph studies. Production was from the upper sandstones of the Dakota Group.

Interest in the east flank of the Denver-Cheyenne Basin escalated rapidly with discovery of commercial quantities of oil in the Dakota Group near Gurley, Nebraska during 1949. Within months, millions of acres were leased and geophysical prospecting and wildcat drilling grew to boom proportions in both southwest Nebraska and northeast Colorado. The first northeast Colorado discovery was made at Merino field in March, 1950. This discovery further heightened interest by establishing a southwesterly trend of fields extending from Gurley to Merino field. Exploratory drilling initially was largely confined to this trend or fairway (Brainerd and Van Tuyl, 1954). In the following years this belt has been extended far southwestward into Washington, Morgan, Adams, Arapahoe, and Elbert Counties (Plate 2).

Figure 84 illustrates the number of field discoveries per year in the study area from 1860 through 1978. The marked increase in discoveries beginning in 1950 corresponds to the boom on the east flank of the Denver-Cheyenne Basin initiated by the Gurley discovery. Numerous Dakota discoveries continue to be brought in at the present time. Significant amounts of Dakota oil and gas are produced in the study area today and will continue to be produced in the future.

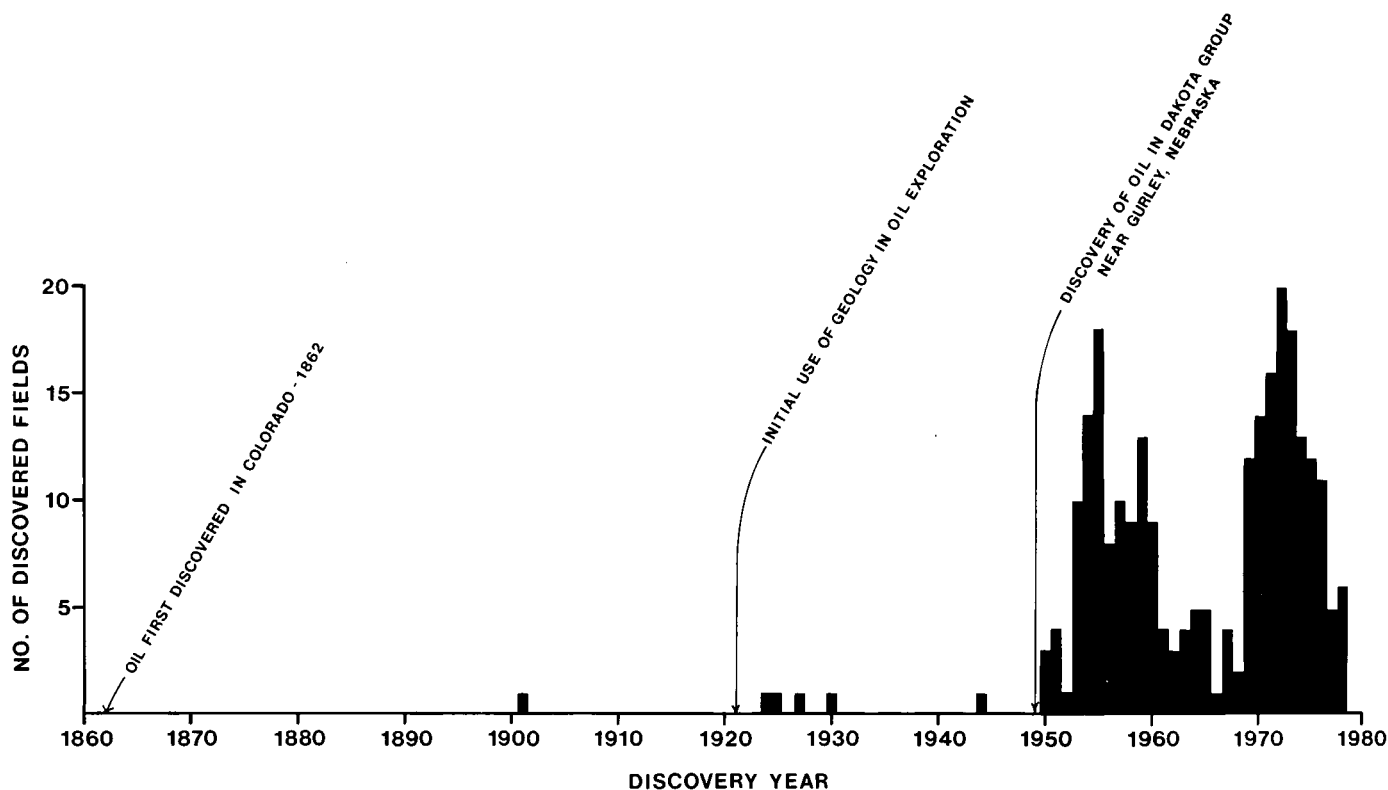


Figure 84. Graph showing number of discovered oil and gas fields in the study area versus year of discovery.

Commercial quantities of hydrocarbons occur in a variety of traps in the sandstone members of the Dakota Group in the Denver-Cheyenne Basin. Miller (1963) describes several of the trapping mechanisms responsible for hydrocarbon accumulations. They include 1) structural traps, primarily closed anticlines, 2) updip facies changes on the nose of an anticlinal structure, 3) sandstone lenses, 4) updip sandstone pinch outs, 5) channel sandstones, and 6) hydrodynamically-influenced traps.

Other formations have also produced significant quantities of hydrocarbons. During June of 1953, economically recoverable oil was discovered at Keota field on the east flank of the basin in the Permian Lyons Sandstone. Until this time most new commercial production and exploration activity concentrated on Dakota Group sandstones. The Lyons well at Keota produced only 12,816 barrels of oil before being plugged and abandoned. Five additional holes were drilled to the Lyons at Keota field, but all were dry (Nering, 1963). One month after the Keota discovery, during July of 1953, commercial quantities of Lyons oil were discovered at Black Hollow field. This discovery, a result of nine years of exploration, marked the first significant Lyons oil discovery in the basin. Black Hollow field produced 57,115 barrels of oil during 1978 for a cumulative production of 10,079,094 barrels.

Success at Black Hollow led to further Lyons exploration. Two years later Lyons oil was discovered at Pierce field. That same year, Lyons oil was also discovered at Fort Collins field, a previous Cretaceous producer. Additional Lyons oil has been recovered at New Windsor, Loveland, and Laporte fields. Nering (1963) describes two primary types of traps responsible for Lyons oil accumulation: 1) anticlinal structures of varying closure and 2) porosity loss due to updip increases in cementation. Stratigraphic interfingering may also in part be responsible for trapping hydrocarbons at Black Hollow field.

Several fields produce from sandstone members of the Pierre Shale, primarily the Sussex (Terry) and Shannon (Hygiene) Sandstone members. Most fields are small producers, with the exception of Spindle field (note: Surrey and Singletree fields are now included in Spindle). Spindle field ranks second in cumulative oil and gas production in the study area.

As of January 1, 1979 approximately 203.50 million barrels of oil and 681.17 billion cubic feet (Bcf) of natural gas have been produced in the study area from Cretaceous and Permian rocks. This represents a significant part of the entire production of the Denver-Cheyenne Basin. Table 16 compares production in the study area from the various reservoir rocks. The J Sandstone member of the Dakota Group has produced the most oil and gas in the area, followed by the D Sandstone member of the Dakota Group and the Sussex (Terry) and Shannon (Hygiene) Sandstone members of the Pierre Shale. Significant quantities of oil have also been produced from the Lyons Sandstone; it ranks fourth in oil production in the study area.

To date, the largest oil field in the study area is Adena field with a cumulative production of about 60.8 million barrels of oil from the upper sandstones of the Dakota Group. Spindle field has produced about 24.5 million barrels from the Sussex and Shannon Sandstone members of the Pierre Shale. About 11.8 million barrels have been recovered from the upper Dakota sandstones at Peoria field. Black Hollow field has yielded about 10.1 million barrels from the Lyons Sandstone.

By far, the largest gas field in the study area is Wattenburg field. Gas production from this field totals about 157 Bcf, principally from

Table 16. Oil and gas production by producing formation through January 1, 1979, in the Denver and Cheyenne Basins, Colorado.

Producing Formation(s) ¹		Production ²		No. of Producing Pools ³		Ave. Production per Pool	
		Oil (M-bbls)	Gas (Bcf)	Oil	Gas	Oil (M-bbls)	Gas (Bcf)
UPPER CRETACEOUS	Pierre Shale, undifferentiated	0.78	-0-	1	-0-	0.78	-0-
	Pierre Shale, Sussex sand	1.42	9.92	8	7	0.18	1.42
	Pierre Shale, Shannon sand	0.02	0.01	3	2	<0.01	<0.01
	Pierre Shale, Sussex & Shannon	24.50	97.60	1	1	24.50	97.60
	Pierre Shale, Hygiene sand (may correlate with Shannon)	<0.01	-0-	2	-0-	<0.01	-0-
	Niobrara Formation, undifferentiated	0.60	2.77	16	12	0.04	0.23
	Code11 Sandstone	0.03	<0.01	3	1	0.01	<0.01
LOWER CRETACEOUS	Greenhorn Limestone	<0.01	<0.01	3	1	<0.01	<0.01
	Dakota Group, undifferentiated	0.44	0.17	3	2	0.15	0.09
	Dakota Group, D sand	42.09	149.07	136	134	0.31	1.11
	Dakota Group, J sand	98.75	396.19	154	147	0.64	2.70
	Dakota Group, D & J sands	0.34	2.68	12	13	0.03	0.21
	Dakota Group, Muddy sand (may correlate with J)	12.04	19.50	4	4	3.01	4.88
	Dakota Group, Lakota sand	0.26	1.11	2	2	0.13	0.56
PERMIAN	Lyons Sandstone	21.02	0.84	7	4	3.00	0.21
	Commingled Reservoirs	1.21	1.31	12	8	0.10	0.16
Total		203.50	681.17	367	338	0.55	2.02

1) producing formation as assigned by the Colorado Oil and Gas Conservation Commission (1979)

2) M-bbls: million barrels; Bcf: billion cubic feet

3) a pool may produce both oil and gas and be counted once in each column

the J Sandstone member of the Dakota. Spindle field again places second in total gas production with just under 98 Bcf of gas from the Sussex and Shannon Sandstones. Adena field ranks third, having produced about 86 Bcf from the D and J Sandstones.

Production Potential

Future production of oil and gas in the study area and throughout the Denver-Cheyenne Basin is promising. Many existing fields will continue to produce significant amounts of hydrocarbons. Haun and others (1976) estimate the ultimate production of just Wattenburg field at over 33 million barrels of oil and 1,300 Bcf of gas. To date, Wattenburg has produced about 157 Bcf of gas, leaving gas reserves of over one trillion

cubic feet. Thus, more gas remains in the subsurface of one field than has been produced to date from the entire study area.

Many new fields will be discovered in the sandstone members of the Dakota Group, primarily the D and J Sandstone members. Future oil production from the Dakota Group probably will equal or exceed past production. This amounts to a future anticipated production of over 150 million barrels of oil from the Dakota within the study area. Additional oil and gas fields may also be discovered in the Lyons Sandstone and in the sandstone members of the Pierre Shale. These fields may add significantly to future production.

The Niobrara Formation currently produces vast amounts of natural gas from within the Denver-Cheyenne Basin east of the study area. Production is from the Beecher Island zone of the Smoky Hills member of the Niobrara. Lockridge and Scholle (1978) believe one of the principal geological characteristics required for porosity retention is shallow depth of burial, generally less than 4,000 ft (1,200 m). Unfortunately, the Niobrara has been buried by more than 4,000 ft (1,200 m) throughout most of the study area. Some gas may be recovered from the Niobrara where it is at shallowest depths in the study area, primarily in the southeast part of the Denver Basin. Other chalk beds in the study area may also produce biogenic gas, but this is doubtful.

In 1961 Rold (1961) and McLish and Ackman (1961) theorized extension of oil and gas production from pre-Pennsylvanian formations from Kansas into eastern Colorado. In 1965 Brandon field was discovered in eastern Colorado with production from Mississippian rocks. Several other pre-Pennsylvanian fields have been discovered in this part of the State and it is possible that some additional discoveries may even occur in the study area. However, pre-Pennsylvanian rocks are truncated by a major angular unconformity which limits the lateral extent of these rocks in the study area. Only a small part of the Denver and Cheyenne Basins, primarily the southern and southeastern parts, may be underlain by pre-Pennsylvanian rocks that possibly contain significant hydrocarbons.

Recovery Methods

The production of oil and/or gas from a particular well or field is a process that depends on a number of factors, all of which combined, dictate at what rate and for how long production will take place. After the discovery of commercial oil or gas the first step usually involves additional drilling to define the lateral extent of the field, the number of productive horizons, production characteristics, and reserves. This information will be used in designing the hydrocarbon recovery program and determining what equipment will be required to accomplish maximum recovery.

Some oil wells will flow under their own formation pressure, but most have to be pumped. A typical well installation will be made up of the well head, pump jack, pump motor, and a storage tank. If a number of wells are located close by, they may all pump into a common storage facility and therefore only have gathering lines running from the pump to the storage tank.

The physical characteristics of crude oil recovered by a well vary considerably. Most oil wells will "make" or produce along with the oil a certain amount of water. This water is usually saline and has to be separated from the oil by a separation facility. In colder climates the separator must be heated to prevent the water from freezing and breaking down the water/oil emulsion. A suitable disposal system for the separated brine may also be necessary. In some large fields the water is reinjected into a suitable, deeply buried formation that already contains poor quality water. If the volume of produced water is small, it may be placed in an evaporation retaining pit. After separation the recovered oil may be placed in a storage tank and later trucked or piped to a refinery. If hauled by truck, better than average roads are needed throughout the field. In either case access roads will be necessary for well maintenance.

The life expectancy of an oil or gas well can vary from a few months to many years. Higher oil and gas prices will prolong the economic life of a well. At some point in time the average oil reservoir will need help in maintaining production to increase field recovery. At this point a secondary recovery procedure may be implemented. This usually involves the injection of water, gas, miscible fluid, or microemulsion into the reservoir under high pressures. Secondary recovery methods extend the life of a reservoir and increase its ultimate oil recovery.

ENVIRONMENTAL IMPACTS AND IMPACT MITIGATION

Compared to most forms of energy resource extraction, oil and gas recovery presents minimal environmental problems. Nonetheless, certain environmental impacts can result from improper exploration, production, and site abandonment. Water contamination is the primary environmental concern, followed in importance by land surface impacts.

Exploration Activities

Two aspects of oil and gas exploration may impact the environment: seismic exploration and drilling of exploratory holes. Seismic exploration involves the introduction of vibrational energy into the ground by explosive or mechanical methods and detection of reflected and refracted energy by a series of vibration detectors or geophones. In certain cases, it may be necessary to construct temporary roads along which to run seismic equipment. Generally, this is not a major problem in the study area because there already are many roads. Seismic shot holes, in which explosives are detonated, are usually required as a part of seismic exploration unless some mechanical means of generating vibrational energy is utilized.

Exploratory drilling often requires construction of access roads and drilling pads similar to, but larger than those required by seismic exploration. All roads and drill pads should be reclaimed as nearly as possible to original conditions immediately after completion of the seismic exploration program or drill hole abandonment. If an exploratory or wildcat well encounters commercial oil or gas, the access road and

drill site likely will be used during production activities. In this case, surface reclamation should be conducted after well abandonment. The rules and regulations of the Colorado Oil and Gas Conservation Commission (COGCC) address the reclamation of roads and drill pads used for exploratory drilling. Roads and drill pads utilized for seismic exploration should be reclaimed in a similar manner.

Seismic shot holes generally range in depth from 2 to 300 ft (0.6 to 90.0 m). Exploratory drill holes in the study area may range in depth from about 3,000 to 15,000 ft (900 to 4,500 m). Improperly abandoned seismic shot holes and exploratory drill holes may allow intermixing of surface water and/or ground water from several aquifers within the hole. This may cause changes in the hydraulic heads and quality of penetrated aquifers. Shallow contaminated water may mix with deep potable water or, conversely, polluted deep waters may contaminate potable shallow aquifers. One individual hole may not cause significant environmental damage, but the cumulative affect of many holes may be great.

The COGCC (1978) requires that all wells be completed in such a way as to protect all fresh water aquifers encountered in the hole. This can be accomplished by setting and cementing surface casing through the fresh water zone or if the fresh water zone is too deep, the well owner may stage cement the production casing from the base of the aquifer up to the hole through the zone in question. Furthermore, Rule 331 of the COGCC (1978) requires that "A dry or abandoned well, seismic, core, or other exploratory hole, must be plugged in such a manner that oil, gas, water, or other substance shall be confined to the reservoir in which it originally occurred." Thus, all wells and drill holes used during oil and gas exploration must be properly completed or plugged and abandoned to assure protection of potable aquifers. In rare cases, however, corroded casing, insufficient surface casing, and inadequate cement jobs may allow inter-aquifer mixing.

In many cases, mud pits are required to drill exploratory wells. These pits are used as surface reservoirs for drilling fluids or muds used to lubricate the cutting bit, circulate cuttings, and prevent blowouts. A pit may also be used for temporary storage or disposal of any oil or water produced from the hole during exploratory drilling and testing. The COGCC does regulate the use of pits during production, but it does not regulate pits used during drilling. These unregulated pits may contain undesirable contaminants that could possibly overflow pit walls and pollute surface water. Mud pits used during exploration drilling should be constructed and maintained to prevent overflow.

Production Activities

Oil and gas production activities may impact the land surface and hydrologic environment. Construction of roads, drill and production sites, pipelines, and storage facilities all impact the land surface to varying degrees. Currently, the COGCC requires bonding to insure proper reclamation of abandoned production sites. Rules 304-b-1 and 304-b-2 state respectively: "Upon completion of drilling operations, such surface owner shall be paid for unreasonable crop losses or land damage resulting

from use of the premises by the lessee" and "Upon abandonment of the well, the surface of the land shall be restored as nearly as possible, to its condition at the beginning of the lease, or in accordance with a written agreement of the owner of the surface of such land." Bonds remain in force and in effect until the surface owner submits a release statement or the Director of the COGCC releases the bond. Land surface impacts resulting from oil and gas production have generally been satisfactorily mitigated in the study area by the bonding requirement.

Production activities may impact the hydrologic environment in several ways, primarily through retention or evaporation pits, insufficient surface casing and stage cementing, injection systems, abandoned production wells, and oil spills. Surface and subsurface leakage from evaporation pits is one of the more common ways in which oil and gas production may impact water resources.

Figure 85 illustrates a poorly constructed retaining pit. Water produced from a well or number of wells flows into the pit. This water sometimes is very saline, with a TDS ranging from 1,000 to 35,000 ppm. Ideally, all water evaporates from the pit, leaving behind a precipitated mixed residue of solids. Overproduction of water from the wells, heavy precipitation, or pit wall failure can cause the pit to overflow, thus contaminating nearby land and in some cases polluting surface waters. Leakage through the floor of an unlined or improperly lined pit, such as the one shown in Figure 85, may result in contamination of shallow ground-water aquifers.

Rule 328 of the COGCC (1978) requires that retaining pits that contain potentially contaminating, poor quality water "be constructed, maintained and operated so as to prevent any surface discharge that directly or indirectly may reach the waters of the State and also lined so as to prevent seepage where the underlying soil conditions are such as to permit such seepage reaching subsurface fresh waters." Figure 86 illustrates types of proper pit construction methods which minimize potential contamination problems.

Pit abandonment usually involves back filling and regrading of the pit area. Generally, this action adequately protects the environment, if the pit was initially properly constructed. The pit should be back filled with a relatively impermeable fill. Permeable material, such as sand or gravel could allow upward migration of salts.

Ground-water contamination may also result from insufficient surface casing and inadequate stage cement jobs. The COGCC (1978) requires that sufficient surface casing extend below all shallow, utilizable, domestic freshwater aquifers (Rule 317b). The annulus of such surface casing is cemented by the displacement method or another approved method to prevent fluid migration within the annulus. The COGCC also requires cementing the annulus of the production string to a height of at least 200 ft (60 m) above the top of the anticipated producing formation to prevent migration of hydrocarbons or salt water. Any deep, fresh-water aquifers encountered

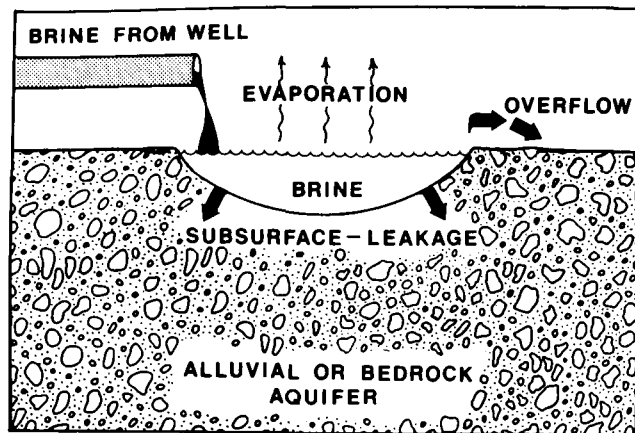


Figure 85. An example of a poorly constructed retaining pit.

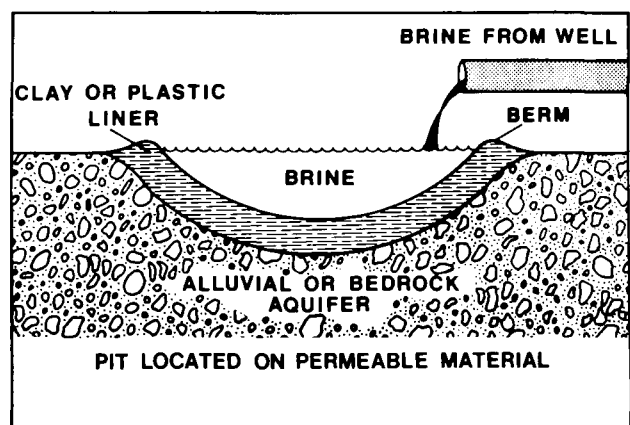
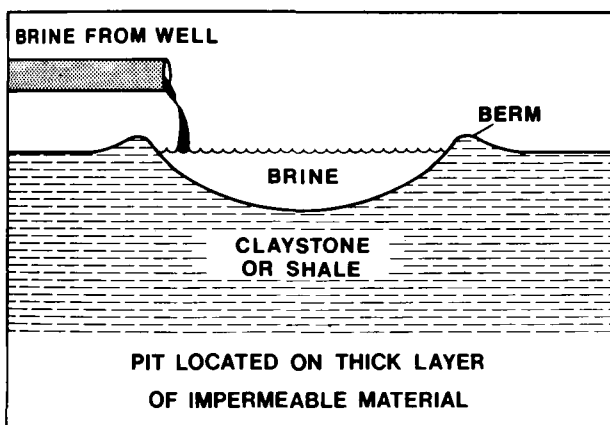


Figure 86. Proper construction methods for retaining pits.

encountered below the surface casing must also be protected and isolated by stage cementing the production string with a solid cement plug extending 50 ft (15 m) above and below the aquifer.

Injection systems used for waste disposal and water-flooding may, in certain instances, constitute a contamination hazard. Leakage through casing or cross-formational flow through natural or artificial fractures may allow injected fluids to enter formations other than the desired formation. High injection rates and large volumes of fluids contribute to the hazard. This type of pollution is not believed to have occurred in the study area.

Ground-water contaminants may also escape through improperly abandoned production wells. Wells should be abandoned in accordance with Rule 331 of the COGCC, which requires that the well be plugged to confine any oil, gas, or water to its host reservoir. Unfortunately, damaged casing and bad cement jobs may allow cross-formational flow. Casings may eventually deteriorate and fail, sometimes within 10 to 20 years, providing conduits for contaminant movement.

Oil spills in the offshore environment receive wide-spread press coverage. Oil spills on the land surface or in pits, ponds, or streams, also constitute a hazard. Rold (1971) described a situation in northeast Colorado where a game warden discovered 310 dead birds in 31 brine pits which contained spilled oil. This type of environmental problem is now addressed by the COGCC regulations and can be avoided by careful operation and maintenance activities.

In general, oil and gas production activities cause fewer environmental problems than most coal and uranium mining operations. The rules and regulations of the COGCC (1978) further reduce the potential environmental impacts associated with oil and gas recovery.

LAND-USE CONFLICTS RELATED TO ENERGY RESOURCE DEVELOPMENT

There are two general types of land use conflicts affiliated with energy resource development. One type involves the impact of energy resource development on adjacent property during and after recovery activities or on future use of the mined property. The second type encompasses the impact of current and proposed land use on future energy resource development. Part of this report has previously dealt with the various aspects related to the first type of conflict, but the second type of conflict is a problem with totally different perspectives.

It has been widely known for many years that energy resource development has high potential for affecting the atmosphere, land surface, ground water, and surface water. Careless resource recovery activities in the past have created numerous environmental problems that the general public usually recall when thinking about energy resource development. Obviously, these environmental problems played important roles influencing the types of activities that could be conducted adjacent to the mine both during and after mining and on the the mine property after completion of mining. The situation in regards to modern resource recovery has greatly improved, however. All proposed mining operations must go through extensive review and evaluation by a number of regulatory agencies to assure compliance with environmental laws and allow maximum protection of the environment. Many of the mining and oil companies have also realized that they have a responsibility to the public to minimize the impact of their energy resource projects.

We believe many of the potential environmental problems related to energy resource development that may affect land use can be minimized and in part eliminated by thorough pre-operational environmental studies, proper mine and recovery facility design, construction, and operation, adequate post-operational land reclamation, and, if needed, aquifer restoration. If these actions are satisfactorily conducted, land use conflicts on adjacent property during and after mining and those related to future use of the mined property will be held to a minimum. Certain environmental problems may be unavoidable, but society must accept these unless major lifestyle changes are made, energy consumption is drastically reduced, or new energy sources or recovery techniques are rapidly developed. We believe our technological society should strive towards increased development and utilization of renewable, relatively non-polluting energy sources. Our long-term future from both economic and environmental standpoints may depend on our ability to conserve energy and adapt to non-conventional energy sources.

The conflict between present and future use of adjacent land and the mined land itself is especially critical to surface mining of coal and uranium. These types of recovery activities have high potential for creating land use problems due to the large surface area disturbed and possible hydrologic problems. Underground mining, in situ solution mining, hydraulic borehole mining, and underground coal gasification generally have a lower potential for land use conflicts. One of the principal land impacts of these recovery methods is surface subsidence.

Oil and gas production usually generates few land conflicts, and these may be dealt with. In some situations urbanization and oil and gas recovery are not mutually exclusive. Oil and gas can be produced from an urbanized area by carefully designing the well field and individual wells to minimize environmental, visual, noise, and traffic problems. Likewise, urban development can occur in a producing field if it is planned such that oil and gas production is not inhibited.

The second type of land use conflict related to energy resource recovery is especially critical to the study area. Population growth in the Front Range Urban Corridor results in the need for a tremendous amount of new home, business, industrial, and transportation-related construction. Much of this urban-type growth occurs adjacent to current urbanized areas, but some takes place considerable distance from the cities in the form of small-town growth, suburban ranchettes, industrial parks, highways, airports, utility corridors, etc. This new development, unless carefully planned and conducted, may inhibit the future recovery of vital energy resource deposits. We believe all proposed projects that could affect energy resource recovery must be carefully evaluated by all involved decision makers to insure the protection of valuable resource deposits for present or future extraction. House Bill 1529 (1973) specifically addresses this problem and requires preservation of deposits for future recovery.

There can also be conflicts between the various types of energy resource recovery activities. For instance, if a coal deposit and an oil and gas field coincide, full recovery of both resources at the same time could be difficult or impossible. An underground coal mine could leave large pillars around the wells or surface mines could leave large blocks of coal around the wells unmined, but this type of mining is undesirable because of the amount of coal that could not be recovered. To assure maximum recovery of both resources it may be necessary to complete the recovery of one resources before initiating recovery of the second.

An even greater conflict can occur between uranium and coal. If, for instance, an open-pit mine worked a uranium deposit in the Fox Hills Sandstone, it would probably extend through the Laramie coal zone. Any economically significant coal beds should be recovered as the open pit is developed. Otherwise, the coal would be broken, mixed with other overburden, placed in the spoil pile, and lost for future recovery. This type of problem will probably not be severe in the study area, because the recovery of both resources would economically be beneficial to the mine operator.

SUMMARY

Coal, lignite, oil, gas, and uranium occur in economically significant deposits in the Denver and Cheyenne Basins, Colorado. Other types of energy resources, such as solar, geothermal, biomass, also exist in the area, but these were not evaluated in this investigation either because of their non-geologic nature or limited development potential.

Coal has long been mined in the study area, with recorded mining activity dating back to the 1860s. Over 130 million tons (118 billion kg) of coal and lignite have been mined from the area, with maximum production occurring in the 1920s and 1930s. Production has gradually decreased from this time and there presently are no operating coal mines in the study area. Demand for coal throughout the United States, however, is being rejuvenated and an increase in coal mining activity is anticipated for the Denver and Cheyenne Basins. Two surface mines have recently obtained all necessary permits and initiated mine construction. Production is scheduled to begin during 1980 or 1981. Additional surface coal mines are in the permitting process and will be brought into production in the near future.

Historical coal production has principally been from underground mines in the lower 50 to 275 ft (15.0 to 82.5 m) of the Upper Cretaceous Laramie Formation. Most Laramie coal beds are a maximum of 5 to 15-ft (1.5 to 4.5-m) thick, but some exceed 20-ft (6-m) thick. Generally, individual Laramie coal beds are more abundant, thicker, laterally more persistent, and of greater economic importance in the Denver Basin than in the Cheyenne Basin.

About 7,500 mi² (19,500 km²) of the study area are underlain by the Laramie coal zone. Approximately 1,850 mi² (4,810 km²) of this area are classified as potentially strippable areas where the top of the Laramie coal zone is within 200 ft (60 m) of the surface. Laramie coal quality varies markedly. As-received analyses in the Boulder-Weld field range up to about 10,000 Btu/lb. Lowest-quality Laramie coals, averaging 6,000 to 7,000 Btu/lb, are on the eastern side of the Denver Basin.

Early Paleocene lignite beds occur in the upper 300 to 500 ft (100 to 150 m) of the Denver Formation in the Denver Basin. These lignite beds are not found in the Cheyenne Basin because the Denver Formation is apparently absent from this basin. The lignite beds have been studied in the northern, eastern, and southern parts of the Denver Basin, primarily where the lignite-bearing zone is shallow. Recent work by Brand (1980a, 1980b) indicates some thick lignite beds extend into the central parts of the basin and may occur at depths in excess of 1,000 ft (300 m). Generally, however, individual lignite bed thickness and the total number of lignite beds decreases on the west side of the basin. The Denver Formation apparently contains no lignite beds where it crops out on the western basin margin.

Existing studies in areas of reasonable drill hole control (mainly in areas where the lignite zone is at strippable depths) have correlated

lignite beds in two general areas, called the northern and southern lignite areas. Lignite beds of the northern area are usually thicker than those in the southern area. In the northern area maximum individual lignite bed thickness ranges from 15 to 54.5 ft (4.5 to 16.4 m), whereas in the southern area the maximum known thickness is about 30 ft (9 m).

As-received analyses of Denver lignite range from 4,000 to 7,000 Btu/lb, 8 to 30 percent ash, 22 to 40 percent moisture, and 0.2 to 0.6 percent sulfur. Quality variation often is due to the number and thickness of partings within the bed. Many of the partings and some of the beds that immediately overlie or underlie a lignite bed are composed primarily of kaolinite. Testing by the U.S. Bureau of Mines indicates kaolinite is a potential source of alumina. Future lignite mining in areas where thick kaolinite-rich partings and beds are present could involve dual resource recovery.

Rough estimates of the remaining in-place resources in Laramie coal beds greater than 2.5-ft (0.75-m) thick and less than 3,000-ft (900-m) deep are on the order of 20 to 25 billion tons. Approximately 10 to 15 billion tons of lignite remain in the Denver Formation in beds at least 4-ft (1.2-m) thick and less than 1,000-ft (300-m) deep. Most Laramie coal will be used as steam coal and for domestic and industrial purposes, although some may be gasified in surface plants or in situ facilities. Because of its low quality and the availability of better quality coal, it is unlikely that Denver lignite will be used directly in power plants. Most Denver lignite will probably be gasified, liquefied, or used in some other type of alternate manner.

Oil and gas recovery in the study area initiated with production at the Boulder field in 1901 from fractured sandy zones in the Pierre Shale. During the 1920s, discoveries were made by drilling anticlinal closures detected by surface mapping. Most production from this period was from the Lower Cretaceous Dakota Group. Exploration activities decreased during the 1930s and early 1940s and very few fields were discovered in this period. Increased utilization of geophysical techniques, primarily seismic methods, led to several Dakota discoveries during the middle and late 1940s in the western part of the study area. Interest in the oil and gas potential of the east flank of the Denver-Cheyenne Basin was sparked by discovery of vast quantities of hydrocarbons in the Dakota Group in southwestern Nebraska in 1949. During the following years many additional fields were discovered in the Dakota Group, part of which are within the study area.

The Dakota Group is the major petroleum producing formation in the study area. Total Dakota oil production amounts to over 153 million barrels of oil or about 70 percent of the total production of the entire study area. Over 568 billion cubic feet or about 82 percent of the entire gas production is from the Dakota. Wattenburg field has accounted for about 156 billion cubic feet of gas and over 60 million barrels of oil have been recovered from Adena field. Both fields produce from the Dakota.

Significant quantities of oil and gas have also been produced from the Lyons Sandstone and Pierre Shale. The first major Lyons discovery

occurred in 1953 at Black Hollow field. Over 21 million barrels of oil have been produced from the Lyons in the study area as of January 1, 1979. Only a few fields produce from the sandstones within Pierre Shale, but one of these, Spindle field, ranks second in both oil and gas production. Spindle accounts for 24.5 million barrels of oil or over 94 percent of the total Pierre oil production and 97.6 billion cubic feet of gas or over 90 percent of the total Pierre gas production.

As of January 1, 1979 approximately 203 million barrels of oil and 68.1 billion cubic feet of gas have been produced from fields with discovery wells between T15S to T12N and R57W to R71W. Future production is very promising. Many existing fields will continue to produce significant quantities of oil and gas. One field, Wattenburg, is believed to still contain more gas in the subsurface than has been produced from the entire study area to date. Additional discoveries will also contribute to future production. Most discoveries will probably be in the D and J Sandstones of the Dakota Group, but significant finds could also occur in the Lyons Sandstone or in the sandstone members of the Pierre Shale. Conservative estimates suggest future oil and gas production from the study area will exceed the total past production.

Uranium occurs in many of the formations in the Denver and Cheyenne Basins. About 20,397 lb (9,260 kg) of U3O8 were mined in the study area during the 1950s from very small deposits. The only known significant uranium deposits currently of economic interest are within the Laramie Formation and Fox Hills Sandstone in the Cheyenne Basin. One of these deposits, the Grover deposit, has been tested on a pilot scale using in situ solution mining techniques. A second deposit, the Keota deposit, is scheduled to be mined in the near future, also using in situ solution mining techniques. Other economically significant deposits will probably be discovered in the study area, and some of these may develop into full-scale mining operations.

Environmental problems may result from energy resource exploration and development in the Denver and Cheyenne Basins. Some problems are unavoidable, but most can be minimized or eliminated by proper pre-environmental studies, comprehensive planning, appropriate operation, thorough reclamation and restoration, and adequate plugging of abandoned drill holes. Principal environmental problems relate to changes in the hydrologic balance that affect surface- and ground-water quantity and quality, but air quality and land resources may also be impacted.

Oil and gas recovery usually impact the environment less than coal and uranium mining, but overflow or subsurface leakage of retaining pits and leakage through damaged or improperly installed well casings may cause surface- and ground-water problems. Surface mining of coal or uranium may disrupt aquifers or stream flow paths and affect surface- and ground-water quality. Underground mining has a lower potential for damaging the hydrologic regime than does surface mining, but severe subsidence may cause environmental problems. In general uranium mining poses a greater threat to ground water than does coal mining, because many uranium deposits are within major aquifers and mining activity may directly affect

the natural condition of the host aquifer. Non-conventional resource recovery techniques, such as in situ uranium solution mining, underground coal gasification, and hydraulic borehole mining, offer many environmental and economic advantages, but such techniques must be carefully evaluated to avoid potential ground-water problems.

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Appendix 1. Radioactive mineral occurrences, Denver and Cheyenne Basins, Colorado. (modified from Nelson-Moore and others, 1978)

BOULDER COUNTY

Fox Hills Outcrop

LOCATION: 1 sec. 15, T. 1 S., R. 70 W.
MAP DENVER
DVEL Inactive coal mining district.
BKG .03 - .04 mr/hr
RNG .1 - .25 mr/hr
HOST Cretaceous Fox Hills Sandstone.
MNZ Abundant limonite.
DOI 1953
REF U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1966b.

Rose Mary 3

LOCATION: sec. 4, T. 3 N., R. 70 W.
QUAD Hygiene 7 1/2'
MAP GREELEY
BKG .04 mr/hr
RNG .04 to 17 mr/hr
HOST Cretaceous Dakota Group, conglomerate at base of formation.
STRC Mineralization is in overturned limb of isoclinal fold in and adjacent to small slips.
MNZ Sooty minerals (pitchblende) and limonite. Grab sample had a value of 0.13% U, a one ft channel sample had a value of 0.009% U.
DOI 1954
REF U.S. Bur. of Mines, 1977a; U.S. Geol. Survey, 1977; U.S. A.E.C. & U.S.G.S., 1966b; Sims and Sheridan, 1964.

DOUGLAS COUNTY

Highlands Ranch (Airborn Anomaly No. 1, Phipps Ranch)

LOCATION: sec. 12, T. 6 S., R. 68 W.
QUAD Highland Ranch 7 1/2'
MAP DENVER
BKG .03 mr/hr
RNG .03 to .4 mr/hr
HOST The host is a clay in the Paleocene/Eocene Dawson Arkose.
MNZ A yellow mineral was found in small amounts. The zone of radioactivity is about 4 in. thick and lies 12 in. below the surface.
DOI 1955
REF U.S. A.E.C. & U.S.G.S., 1966d.

Penley No. 1 Lease

LOCATION: SW 1/4 sec. 32, T. 7 S., R. 68 W.

QUAD Kassler 7 1/2'

MAP DENVER

DVEL One 120 ft shaft has been sunk. Four test pits and six holes were drilled.

BKG .017 mr/hr

RNG .017 to 1.0 mr/hr

HOST The host is Precambrian granite and the Pennsylvanian Fountain Formation.

STRC Radioactivity also occurs in the Jarre Creek fault zone between the rock types.

ALT The granite is described as being altered and radioactive.

MNZ A yellow mineral thought to be carnotite was observed with iron oxides.

RMKS An outcrop north of the shaft also had anomalous radioactivity.

DOI 1955, 1975

REF U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1966d.

EL PASO COUNTY

Airborne Anomaly 17

LOCATION: sec. 22, T. 12 S., R. 62 W.

LCRM From Calhan go west on U.S. 24 for 1.8 miles and turn left onto dirt road. Go for 1.0 mile and continue straight ahead at crossroad for 2.1 miles. Now turn right onto old dirt track road about 200 yds past house and go for 0.6 miles to the edge of the pit. The anomaly is in the pit.

QUAD Holcolm Hills 7 1/2'

MAP PUEBLO

DVEL There is an old pit that was mined for clay.

BKG .02 mr/hr

RNG To .05 mr/hr

HOST The deposit is in a sandstone of uncertain age with interclated multi-colored clay members and conglomerate. The sandstone is coarse-grained, loosely cemented, and white in color. A black, carbonaceous clay accounts for the radioactive anomaly.

MNZ Caliche, hardpan and iron staining.

RMKS Several small prospect pits were dug to determine if the radioactivity increases with depth, but the results were negative.

DOI 1954

REF U.S. A.E.C. & U.S.G.S., 1966f.

Burgess Claim

LOCATION: NE 1/4 sec. 22, T. 12 S., R. 66 W.

LCRM The occurrence is at the Reverse J. Diamond Ranch.

QUAD Pikeview 7 1/2'

MAP PUEBLO
DVEL A grade of 0.52% U308 has been reported.
HOST The host is the Paleocene/Eocene Dawson Arkose.
MNZ The ore occurs as a uraniferous limonite.
DOI 1973
REF U.S. Geol. Survey, 1977; Lovering and Beroni, 1956.

Drill Hole 1, Mobil Oil Corporation

LOCATION: NW 1/4 sec. 22, T. 15 S., R. 62 W.

LCRM There are offsets to the main hole to the north, south, east, and west.
QUAD Hanover NE 7 1/2'
MAP PUEBLO
DVEL Exploration holes have been drilled.
RNG 600 to 900 cps
HOST The Upper Cretaceous Fox Hills Sandstone is the host. Mineralization is near the top of the formation and is generally associated with coaly beds.
ALT No alteration or oxidation is present.
MNZ Three to six ft of the formation gave a count of 600 to 900 cps.
RMKS This deposit appears to be an impounded playa or similar feature rather than a roll front. It appears that mineralization is syngenetic.
DOI 1977
REF Holmes, 1977, pers. comm.

Drill Hole 2, Mobil Oil Corporation

LOCATION: SE 1/4 sec. 12, T. 15 S., R. 62 W.

LCRM This is the main hole. There are offsets to the north, south, east, and west.
QUAD Big Springs Ranch 7 1/2'
MAP PUEBLO
DVEL Exploration holes have been drilled.
RNG To 2,050 cps
HOST The Upper Cretaceous Fox Hills Sandstone is the host. Mineralization is near the top of the formation, and coaly beds are generally associated with it.
ALT No alteration or oxidation is present.
MNZ A section of the formation about 6 ft thick is mineralized, with count to 2,050 cps (0.01 to 0.02% eU308).
RMKS This deposit appears to be an impounded playa or some similar feature, rather than a roll front deposit. It is thought that the mineralization is syngenetic.
DOI 1977
REF Holmes, 1977, pers. comm.

Folbre 2

LOCATION: sec. 15, T. 17 S., R. 67 W.

QUAD Mt. Pittsburg 7 1/2'
MAP PUEBLO
DVEL One trench, 7 ft x 3 ft, has been opened in the side of the hill. It strikes S70°E.
HOST The radioactive zone is in a black shale about 12 in. thick and 5 ft wide at the top of the Jurassic Morrison Formation.

MNZ Uranium mineralization was detected.
DOI 1975
REF U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1966f.

Mike Doyle Carnotite Deposits (Lucky Ben Lease)

LOCATION: SW 1/4 sec. 2, T. 16 S., R. 67 W.
QUAD Cheyenne Mountain 7 1/2'
MAP PUEBLO
DVEL In 1955, 108 tons of ore were mined with an average grade of 0.13% U3O8 and containing 277 lbs of U3O8.
HOST The host is the Cretaceous Dakota Group.
MNZ Carnotite was the principal mineral noted.
RMKS Ore was shipped under name "Lucky Ben Lease".
DOI 1975
REF U.S. Geol. Survey, 1977; U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1971; King and others, 1953.

Rock View Claim

LOCATION: SW 1/4 sec. 10, T. 16 S., R. 67 W.
QUAD Mount Big Chief 7 1/2'
MAP PUEBLO
BKG .005 mr/hr
RNG To .012 mr/hr
HOST The deposit lies in a shale unit near the base of a red arkosic conglomerate of the Pennsylvanian Fountain Formation. The Fountain directly overlies Cambrian and Precambrian rocks in this locality.
MNZ No mineralization was visible.
DOI 1954
REF U.S. A.E.C. & U.S.G.S., 1966f.

Unnamed 2

LOCATION: sec. 2, T. 15 S., R. 67 W.
LCST Uncertain
MAP PUEBLO
RMKS Radioactivity reported where Morrison Formation overlies the Precambrian.
REF Reimer, 1977, pers. comm.

ELBERT COUNTY

Limon Locality

LOCATION: sec. 14, T. 8 S., R. 58 W.

LCRM Also sec. 23 and 32.

QUAD River Bend 7 1/2'

DVEL The anomalies were located in 1956 as part of a U.S. A.E.C. airborne radiometric program. Some shallow drilling was carried out on one anomaly.

PROD No production.

HOST Brown to black friable sandstone of the lower part of the Upper Cretaceous Laramie Formation. This bed was deposited as a heavy minerals beach placer in a regressive sandstone sequence similar to placer deposits of the same age in New Mexico and southwest Colorado.

MNZ Minerals include garnet, zircon, and magnetite. These minerals are concentrated in thin bands separated by sandstone with lesser amounts of minerals. Drill cuttings had the following values: %U308 .014-.020; %U308 .005; %Th2 .05-.07.

DOI 1959

REF R. C. Malan, 1978, pers. comm.

JEFFERSON COUNTY

Bray Lease

LOCATION: NE 1/4 sec. 12, T. 5 S., R. 70 W.

LCRM In Turkey Creek water gap through Dakota Hogback.

QUAD Morrison 7 1/2'

BKG .015 mr/hr

RNG .05 to .4 mr/hr

HOST Cretaceous Dakota Group and Quaternary alluvium.

MNZ Carnotite?

RMKS Other anomalous prospects nearby in Dakota Group.

REF U.S. A.E.C. & U.S.G.S., 1966g; Gottfried, 1956; Scott, 1957.

Lindsay Clay Mine

LOCATION: sec. 28, T. 2 S., R. 70 W.

QUAD Golden 7 1/2'

DVEL The mine has been worked for clay.

BKG .04 mr/hr

RNG .13 to .5 mr/hr

HOST A small 20 ft long pod of gray claystone in the Upper Cretaceous Laramie Formation. It is underlain by a thin coal and overlain by a thick sandstone.

STRC The formation strikes north and dips vertically.

MNZ A powdery carnary-yellow uranium mineral forms thin films on plant fragments in the claystone. A 3.5 ft channel sample had a value of 0.02% U308.

DOI 1954

REF U.S. A.E.C. & U.S.G.S., 1966g.

Mann Ranch (Mann Mine, Vanadium Queen)

LOCATION: SE 1/4 NE 1/4 sec. 12, T. 5 S., R. 70 W.
QUAD Morrison 7 1/2'
MAP DENVER
PROD During the period 1955-1961, 2,893 tons were mined at a grade of 0.27% U308, producing 15,579 lbs of U308.
HOST Cretaceous Dakota Sandstone.
STRC A fault striking N40 to 45°W and dipping 50°SW appears to have acted as a dam to mineralizing solutions.
MNZ The ore is an asphaltic material containing finely divided uraninite, accompanied by pyrite.
DOI 1975
REF U.S. Geol. Survey, 1977; U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1971; Sims and Sheridan, 1964; U.S. A.E.C. & U.S.G.S., 1959.

Morrison Lime

LOCATION: sec. 14, T. 4 S., R. 70 W.
LCST Uncertain
QUAD Morrison 7 1/2'
HOST Gray sandy limestone in the Morrison Formation. Average thickness is 5 ft.
MNZ 0.018% U308 assay from chip sample.
DOI 1952
REF U.S. A.E.C. & U.S.G.S., 1966g.

Old Leyden Mine (Old Leyden Coal Mine, Leyden Mine)

LOCATION: sec. 28, T. 2 S., R. 70 W.
QUAD Golden 7 1/2'
MAP DENVER
DVEL Past producing coal mine.
PROD Between 1954-1956, a total of 645 tons were mined at a grade of 0.35% U308, producing 4,533 lbs of U308. Drilling work published in a TEI estimated 17,500 tons of coal with a grade of 0.2% U308.
HOST Sandstone, coal, and carbonaceous claystone in the Upper Cretaceous Laramie Formation. The mineralization occurs as uraninite in siliceous material filling cracks in the coal.
MNZ Metatyuyamunite, autunite, uranophane, coffinite, uraninite, pyrite, and marcasite.
DOI 1971
REF U.S. Geol. Survey, 1977; U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1971; Sims and Sheridan, 1964; U.S. A.E.C. & U.S.G.S., 1959; Gude and McKeown, 1953; Breger and Deul, 1952; Gott, 1950.

Pallaora Lease (Morrison Mine, Four Corners)

LOCATION: S 1/2 sec. 1, T. 5 S., R. 70 W.
LCRM Also N 1/2 NE 1/4, sec. 12.
QUAD Morrison 7 1/2'
MAP DENVER
PROD During 1955-1960, 678 tons were mined at a grade of 0.20% U308 and 0.02% V205 producing 2,667 lbs of U308 and 256 lbs of V205.

HOST Lens in upper member of the Cretaceous Dakota Group.
STRC A fault appears to have caused a damming of the ore fluids.
The fault strikes N40°W and dips 30-55°SW.
MNZ The ore is an asphaltic material containing finely divided
uraninite, accompanied by pyrite.
DOI 1972
REF U.S. Geol. Survey, 1977; U.S. Bur. of Mines, 1977a; U.S.
A.E.C. & U.S.G.S., 1971; Sims and Sheridan, 1964; U.S. A.E.C.
& U.S.G.S., 1959.

Shale Prospect

LOCATION: SE 1/4 sec. 35, T. 4 S., R. 70 W.
QUAD Morrison 7 1/2'
HOST Black carboniferous shale in Cretaceous Dakota Group.
MNZ Small yellow grains (carnotite?) are visible in shale. Analysis
of 0.013% U.
RMKS Sandstone and shale are anomalous on both sides of gap of
Bear Creek.
DOI 1954
REF U.S. A.E.C. & U.S.G.S., 1966g.

Stevenson Prospect

LOCATION: sec. 2, T. 5 S., R. 70 W.
QUAD Morrison 7 1/2'
BKG .025 mr/hr
RNG .025 to 5 mr/hr
HOST Cretaceous Dakota Group, fine- to medium-grained, buff colored
with iron stains. Carbonaceous siltstone above and below.
MNZ Carnotite?
DOI 1954
REF U.S. A.E.C. & U.S.G.S., 1966g; Gottfried, 1956; Scott, 1957.

Unnamed No. 1

LOCATION: sec. 12, T. 5 S., R. 70 W.
LCRM Along Turkey Creek.
MAP DENVER
HOST Upper member of the Cretaceous Dakota Group.
MNZ Uranium.
DOI 1972
REF U.S. Geol. Survey, 1977.

Unnamed No. 2

LOCATION: sec. 2, T. 5 S., R. 70 W.
LCRM North end of Mt. Glennon near Bear Creek.
HOST Cretaceous Dakota Group.
MNZ Uranium.
DOI 1972
REF U.S. Geol. Survey, 1977; Rocky Mountain Assoc. of Geologists,
1955.

LARIMER COUNTY

Carter Lake

LOCATION: sec. 3, T. 4 N., R. 70 W.

QUAD Carter Lake Reservoir 7 1/2'

MAP GREELEY

MNZ Uranium minerals are present, with a sample value of 0.12% U308.

DOI 1972

REF U.S. Geol. Survey, 1977.

Schlagel Discovery

LOCATION: sec. 34, T. 9 N., R. 66 W.

QUAD Nunn 7 1/2'

MAP GREELEY

HOST Cretaceous Laramie Formation.

RMKS Uranium first discovered by Solomon Schlagel at this location.

DOI 1970

REF Reade, 1976, 1978.

Wahketa Lease (Wahketa Mine)

LOCATION: sec. 18, T. 8 N., R. 69 W.

LCST Uncertain

LCRM The P.R.R. indicates this is in sec. 13. The prospect is 1000 ft from the road across an irrigation ditch. The CRIB file lists this as sec. 13, T. 8 N., R. 70 W. A second CRIB reference verifies the location originally given above.

QUAD La Porte 7 1/2'

MAP GREELEY

DVEL The rim has been stripped at four places, with approximately 50 tons of rock broken.

PROD In 1955, six tons were mined at a grade of 0.07% U308, producing 8 lbs of U308, and 6 lbs of V205 at a grade of 0.05%.

RNG 0.06 to 0.7 mr/hr

HOST The deposit is in the Cretaceous Dakota Group along the prominent hogback rim formed by the sandstone. The formation strikes northerly and dips 30° to the west.

STRC The hogback appears to be the west limb of an anticline, the center of which has been eroded away.

MNZ Mineralization of a carnotite-type has been exposed at scattered points along the rim for approximately 0.2 miles. A weakly fluorescent mineral not distinguishable in ordinary light occurs in several of the pits.

RMKS An assay showed 0.16% U308. Autunite has also been identified.

DOI 1955

REF Finch, 1977, pers. comm.; U.S. Geol. Survey, 1977; U.S. Bur. of Mines, 1977a; U.S. A.E.C. & U.S.G.S., 1971; U.S. A.E.C. & U.S.G.S., 1966h.

WELD COUNTY

Eastman Basin

LOCATION: sec. 27, T. 9 N., R. 65 W.
LCRM Other anomalies in sec. 28, 33, 34.
QUAD Antelope Reservior 7 1/2'
MAP GREELEY
BKG 100 cps
RNG 1100 cps
HOST Upper Cretaceous Laramie Formation.
ALT Heavy Fe and Mn staining in the sands.
RMKS Radioactive anomalies in stream valleys and irrigation ditches.
REF Baker, 1977, pers. comm.

Grover Deposit

LOCATION: sec. 24, T. 10 N., R. 62 W.
LCRM See also sec. 23, 25, 36.
MAP GREELEY
DVEL Pilot in situ solution mining plant operated by Wyoming Mineral Corporation for one year during 1976-1977.
HOST Grover sandstone member of the Upper Cretaceous Laramie Formation, gray, medium- to fine-grained, quartzose, micaceous, in part carbonaceous.
ALT None identified. Sands reported to be similar on both sides of geochemical cell.
MNZ Grade of 0.14% eU308, gross reserves quoted as being 1,007,000 lbs U308 cutoff and a grade above 0.20.
RMKS Exploration was carried out extensively in this area 1970-1973 by Hyland Nuclear and Trend Exploration Limited. Several deposits reported found by drilling in the area. This deposit has been tested for possible solution mining.
REF U.S. Bur. of Mines, 1977a; Power Resources Corp., 1977, pers. comm.; Reade, 1976, 1978.

Indian Creek

LOCATION: sec. 19, T. 10 N., R. 67 W.
QUAD Carr SW 7 1/2'
MAP GREELEY
MNZ Uranium.
DOI 1975
REF U.S. Bur. of Mines, 1977a.

Keota Deposit

LOCATION: sec. 35, T. 9 N., R. 60 W.
QUAD Keota 7 1/2'
MAP GREELEY
DVEL Proposed 500,000 lbs U308 per year in situ solution mining facility operated by Power Resources Corporation and Union Oil of California.
HOST Buckingham and Keota sandstone members of the Upper Cretaceous Foxhills Sandstone.
DOI 1978
REF Wyoming Mineral Corp., 1978.

WELD COUNTY

Eastman Basin

LOCATION: sec. 27, T. 9 N., R. 65 W.
LCRM Other anomalies in sec. 28, 33, 34.
QUAD Antelope Reservoir 7 1/2'
MAP GREELEY
BKG 100 cps
RNG 1100 cps
HOST Upper Cretaceous Laramie Formation.
ALT Heavy Fe and Mn staining in the sands.
RMKS Radioactive anomalies in stream valleys and irrigation ditches.
REF Baker, 1977, pers. comm.

Grover Deposit

LOCATION: sec. 24, T. 10 N., R. 62 W.
LCRM See also sec. 23, 25, 36.
MAP GREELEY
DVEL Pilot in situ solution mining plant operated by Wyoming Mineral Corporation for one year during 1976-1977.
HOST Grover sandstone member of the Upper Cretaceous Laramie Formation, gray, medium- to fine-grained, quartzose, micaceous, in part carbonaceous.
ALT None identified. Sands reported to be similar on both sides of geochemical cell.
MNZ Grade of 0.14% eU308, gross reserves quoted as being 1,007,000 lbs U308 cutoff and a grade above 0.20.
RMKS Exploration was carried out extensively in this area 1970-1973 by Hyland Nuclear and Trend Exploration Limited. Several deposits reported found by drilling in the area. This deposit has been tested for possible solution mining.
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Indian Creek

LOCATION: sec. 19, T. 10 N., R. 67 W.
QUAD Carr SW 7 1/2'
MAP GREELEY
MNZ Uranium.
DOI 1975
REF U.S. Bur. of Mines, 1977a.

Keota Deposit

LOCATION: sec. 35, T. 9 N., R. 60 W.
QUAD Keota 7 1/2'
MAP GREELEY
DVEL Proposed 500,000 lbs U308 per year in situ solution mining facility operated by Power Resources Corporation and Union Oil of California.
HOST Buckingham and Keota sandstone members of the Upper Cretaceous Foxhills Sandstone.
DOI 1978
REF Wyoming Mineral Corp., 1978.

King Solomon

LOCATION: sec. 34, T. 9 N., R. 65 W.
QUAD Antelope Reservoir 7 1/2'
MAP GREELEY
MNZ Uranium, vanadium.
RMKS Federal lease.
DOI 1975
REF U.S. Bur. of Mines, 1977a.

Pawnee Deposit

LOCATION: sec. 25, T. 8 N., R. 60 W.
QUAD Keota 7 1/2'
MAP GREELEY
HOST Pawnee sandstone member of the Upper Cretaceous Fox Hills Sandstone, fine-grained, well sorted, quartzose sandstone
MNZ Average grade of 0.07 eU308; 1,060,000 lbs U308 reserves.
RMKS Also secs. 26, 27, and 28.
DOI 1978
REF U.S. Bur. of Mines, 1977a; Reade, 1978.

Sand Creek Deposit

LOCATION: sec. 19, T. 9 N., R. 63 W.
QUAD Baker Draw 7 1/2'
MAP GREELEY
HOST Sand Creek sandstone member of the Upper Cretaceous Laramie Formation.
MNZ Average grade 0.08 percent eU308 reserves calculated at 154,000 lbs eU308.
RMKS Also secs. 20 and 29.
DOI 1978
REF Reade, 1978.

Schlagel Discovery

LOCATION: sec. 34, T. 9N., R. R66W.
QUAD Nunn 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation
RMKS Uranium first discovered in Upper Cretaceous rocks in the Cheyenne Basin by Solomon Schlagel at this location.
DOI 1970
REF Reade, 1976, 1978.

Unnamed No. 1

LOCATION: NW 1/4 sec. 19, T. 9 N., R. 65 W.
QUAD Antelope Reservoir 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".

DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 2

LOCATION: NW 1/4 sec. 12, T. 9 N., R. 66 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 3

LOCATION: SW 1/4 sec. 7, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 4

LOCATION: NW 1/4 sec. 17, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 5

LOCATION: SE 1/4 sec. 6, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 6

LOCATION: SE 1/4 sec. 5, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".

DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 7

LOCATION: SE 1/4 sec. 4, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 8

LOCATION: SW 1/4 sec. 3, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 9

LOCATION: SW 1/4 sec. 22, T. 10 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 10

LOCATION: SE 1/4 sec. 19, T. 10 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 11

LOCATION: NE 1/4 sec. 15, T. 9 N., R. 65 W.
QUAD Chalk Bluffs SW 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".

DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 12

LOCATION: NW 1/4 sec. 34, T. 9 N., R. 65 W.
QUAD Antelope Reservoir 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS Pit.
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 13

LOCATION: SW 1/4 sec. 22, T. 9 N., R. 64 W.
QUAD Purcell 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 14

LOCATION: NE 1/4 sec. 27, T. 9 N., R. 64 W.
QUAD Purcell 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 15

LOCATION: SE 1/4 sec. 10, T. 8 N., R. 64 W.
QUAD Purcell 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 16

LOCATION: NW 1/4 sec. 24, T. 8 N., R. 64 W.
QUAD Purcell 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977

REF Holmes, 1977, pers. comm.

Unnamed No. 17

LOCATION: SE 1/4 sec. 28, T. 8 N., R. 64 W.
QUAD Purcell 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 18

LOCATION: NW 1/4 sec. 34, T. 8 N., R. 64 W.
QUAD Galeton 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 19

LOCATION: NW 1/4 sec. 24, T. 8 N., R. 64 W.
QUAD Purcell 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 20

LOCATION: NW 1/4 sec. 4, T. 9 N., R. 63 W.
QUAD Reno Reservoir 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 21

LOCATION: SE 1/4 sec. 10, T. 9 N., R. 63 W.
QUAD Reno Reservoir 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop with uranium showings".
DOI 1977

REF Holmes, 1977, pers. comm.

Unnamed No. 22

LOCATION: S 1/2 sec. 14, T. 9 N., R. 63 W.
QUAD Baker Draw 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop
with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 23

LOCATION: NE 1/4 sec. 4, T. 8 N., R. 62 W.
QUAD Briggsdale 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop
with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Unnamed No. 24

LOCATION: NW 1/4 sec. 10, T. 8 N., R. 62 W.
QUAD Briggsdale 7 1/2'
MAP GREELEY
HOST Upper Cretaceous Laramie Formation.
RMKS No radioactivity range given - merely noted as a "sand outcrop
with uranium showings".
DOI 1977
REF Holmes, 1977, pers. comm.

Wildhorse

LOCATION: sec. 20, T. 9 N., R. 63 W.
QUAD Baker Draw 7 1/2'
MAP GREELEY
MNZ Uranium.
DOI 1975
REF U.S. Bur. of Mines, 1977a.

1. Description of information headings:

LOCATION---Location. Given by section, township, and range.

LCST---Location Status. "Unlocatable" indicates there was a question as to the validity of the location. "Unsurveyed" means that the area where the occurrence is located has not been surveyed into the land-grid system; hence, there is a question as to its exact legal description. "Uncertain" was used when the location, the directions to the occurrence and/or the described geology did not correlate.

QUAD---Topographic Map Quadrangle. The name of the 7 1/2' or 15' U.S. Geological Survey topographic map quadrangle in which the occurrence can be found.

MAP--- 1° x 2° AMS Quadrangle. The name of the 1° x 2° map in which the occurrence can be found.

DEVL---Development. A short description of the type of mining or prospecting that has taken place at the site.

PROD---Production. The tons produced and grade of ore mined.

BKG--- Background Radioactivity---The normal range of the background radiation, reported in either mr/hr (milliroentgens per hour) or cps (counts per second) as measured with a radiation detection device.

RNG--- Range of Radioactivity. Range of the radioactivity that was found at the occurrence, from normal background to a maximum reading. This, like the background, is reported in mr/hr or cps.

HOST---Host Rock. Formation and lithology in which the occurrence is found.

STRT---Structural Controls. Any structure in the rock that may have significant control on the uranium mineralization.

ALT--- Alteration. Any change in the rock which may be due to emplacement of the uranium or have contributed to the emplacement.

MNZ--- Mineralization. The minerals found at the occurrence and any sample analysis data. The analysis is given as a percentage or as parts per million (ppm) of U (Uranium or U₃₀₈). The symbol for uranium is given as "U", "eU", and "cU". "U" stands for uranium in its elemental form. "eU" is the symbol for "equivalent uranium" which is the amount of uranium as measured on a radiation detection device such as a scintillometer or geiger counter. There is not necessarily any uranium at an occurrence that has "eU". The radiation seen on a counter can be caused by radon, radium, or other daughter products of uranium, or by thorium. "cU" means "chemical uranium", an

amount that has been measured chemically and is a true measure of uranium in the sample.

RMKS---Remarks. Any additional pertinent information.

DOI--- Date of information. Date that is applicable to most of the information given on the occurrence.

REF--- References. These are given in the short citation format of Author and Date. Using this citation, the reference can be found in the accompanying bibliography.

Appendix 2. Oil and gas production statistics for fields in the Denver and Cheyenne Basins with discovery wells between T15S to T12N and R57W to R71W. (from Colorado Gas Conservation Commission, 1979)

FIELD NAME	DISCOVERY WELL			CUMULATIVE PRODUCTION THROUGH 1/1/79		PRODUCING FORMATION(S) ²	STATUS ³
	LOCATION ¹	COUNTY	DATE	OIL (Bbts)	GAS (Mcf)		
Adena	20/01N/57W	Morgan	1953	60,766,614	86,414,996	Kd-D,J	P
Adena South	35/01N/58W	Morgan	1954	584,764	659,286	Kd-J	PA
Ambush	24/02S/65W	Adams	1973	234,702	2,748,879	Kd-J	P
Antelope	18/06N/66W	Weld	1957	2,541	0	Kp-Su	PA
Antler	22/05S/83W	Arapahoe	1973	95,254	146,391	Kd-D	P
Apollo	36/02S/57W	Adams	1964	1,813	0	Kd-J	PA
Aristocrat	04/03N/65W	Weld	1978	18,758	556,659	Kp-Su	P
Ashley	01/02N/59W	Morgan	1955	113,677	647,183	Kd-D,J	PA
Badger Creek	23/02S/57W	Adams	1953	6,310,928	2,547,345	Kd-J	P
Badger Creek-West	21/02S/57W	Adams	1953	522,623	256,497	Kd-J	P
Banner	11/02S/66W	Adams	1974	0	22,624	Kd-J	SI
Baxter Lake	30/04N/68W	Weld	1964	963	629	Kn	PA
Beacon	07/01S/57W	Adams	1955	1,204,769	3,966,747	Kd-D,J	P
Bear Gulch	32/02S/64W	Adams	1974	154,476	1,706,733	Kd-D,J	P
Bennett	20/03S/63W	Adams	1970	234,522	1,662,407	Kd-D	P
Berthoud	17/04N/69W	Larimer	1927	461,567	1,262,023	Kn;Kd;Kd-D,J, M,L;Kc;Pl	P
Beryl	05/02S/57W	Adams	1960	173,609	165,874	Kd-D,J	P
Big Bend	02/03S/61W	Adams	1975	35,708	173,491	Kd-D	P
Bijou	08/04N/59W	Morgan	1957	1,599,712	7,492,581	Kg;Kd-D	P
Bijou South	20/04N/59W	Morgan	1962	8,158	1,368,365	Kd-D,J	P
Bijou West	12/04N/60W	Morgan	1958	1,210,870	3,118,283	Kd-D	PA
Black Hollow	06/07N/66W	Weld	1953	10,079,094	329,320	Pl	P
Black Jack	09/04S/57W	Arapahoe	1967	977,939	85,748	Kd-J	P
Blue Bell	16/07N/58W	Weld	1975	36,847	3,150	Kd-J	P
Bombing Range	31/04S/63W	Arapahoe	1971	101,302	534,099	Kd-J	P
Bootjack	26/02S/58W	Adams	1973	7,158	3,620	Kd-J	PA
Boulder	21/01N/70W	Boulder	1901	782,216	0	Kp	P
Bounty	36/08N/57W	Weld	1963	87,064	67,852	Kd-J	P
Bow	31/01N/57W	Morgan	1959	106,061	1,372,941	Kd-J	P
Bowstring	27/01N/58W	Morgan	1971	7,464	27,508	Kd-D	P
Box Elder Creek	02/03S/65W	Adams	1974	4,849	59,849	Kd-J	P
Boxer	32/02N/58W	Morgan	1965	2,391,926	5,984,748	Kd-D	P
Bradbury	28/06S/61W	Elbert	1955	374	48	Kd-J	PA
Buckingham	33/08N/59W	Weld	1950	474,437	1,245,190	Kd-D	P
Buckingham West	25/08N/60W	Weld	1955	416,607	352,735	Kd-D	P

1) Location indicated by section/township/range.

2) Producing formations are assigned by the Colorado Oil and Gas Conservation Commission (1979) --
 Kp: Upper Cretaceous Pierre Shale, undifferentiated; Kp-Su: Sussex sandstone member of the Pierre;
 Kp-Sh: Shannon sandstone member of the Pierre; Kp-H: Hygiene sandstone member of the Pierre (may
 correlate with the Shannon); Kn: Upper Cretaceous Niobrara Formation, undifferentiated; Kn-Fh: Fort
 Hays limestone member of the Niobrara (also known as the Timpas limestone member); Kc: Upper Cretaceous
 Codell Sandstone; Kg: Greenhorn Limestone; Kd: Lower Cretaceous Dakota Group, undifferentiated;
 Kd-D: D sandstone member of the Dakota; Kd-J: J sandstone member of the Dakota; Kd-M: Muddy sandstone
 member of the Dakota (may correlate with the J sand); Kd-F: Fuson shale member of the Dakota;
 Kd-L: Lakota sandstone member of the Dakota; Pl: Permian Lyons Sandstone.

3) P: Producing field (only one well in entire field need still be producing); SI: shut-in field;
 PA: plugged and abandoned field.

FIELD NAME	DISCOVERY WELL			CUMULATIVE PRODUCTION THROUGH 1/1/79		PRODUCING FORMATION(S) ²	STATUS ³
	LOCATION ¹	COUNTY	DATE	OIL (Bbls)	GAS (Mcf)		
Buckskin	16/02N/60W	Adams	1960	22,053	2,800,005	Kd-J	P
Bugle	04/02S/66W	Adams	1974	316,420	663,483	Kd-D	P
Busy Bee	09/03S/60W	Adams	1955	283,969	415,341	Kd-D	P
Byers	01/04S/62W	Arapahoe	1970	207,432	150,675	Kd-J	P
Cabin Creek	16/03S/59W	Adams	1955	1,339	2,355	Kd-J	PA
Cactus	02/05N/58W	Morgan	1961	1,046	20	Kd-J	PA
Calico	34/01N/61W	Weld	1972	0	0	Kd-J	PA
Campana	12/02S/59W	Adams	1971	46,351	1,861,475	Kd-J	PA
Canal	34/04N/59W	Morgan	1959	0	3,822,234	Kd-D	P
Cannon	22/01S/59W	Adams	1976	3,496	0	Kd-J	P
Cartwheel	21/03S/61W	Adams	1973	4,121	8,588	Kd-J	PA
Chaparral	07/01N/58W	Morgan	1967	10,796	1,140,644	Kd-D	PA
Chieftain	10/02S/63W	Adams	1973	103,069	4,769,704	Kd-J	P
Chinook	30/05S/62W	Arapahoe	1976	52,546	87,925	Kd-D	P
Cinch	25/12N/57W	Weld	1969	20,735	13,865	Kd-J	P
Clark Lake	15/09N/68W	Larimer	1944	1,047,495	438,419	Kd-D,M	P
Comanche Creek	20/06S/62W	Elbert	1970	844,222	3,151,443	Kd-D	P
Cougar	30/01S/62W	Adams	1970	3,355	450,905	Kd-D,J	P
Crackerjack	23/06N/60W	Morgan	1976	2,400	38,090	Kd-D	P
Crow	27/08N/60W	Weld	1956	34,372	8,610	Kd-D	PA
Crystal	35/12N/57W	Weld	1969	23,877	17,500	Kd-D,J	PA
Cutlass	22/10N/57W	Weld	1969	7,893	619,393	Kd-J	PA
Dance	29/01S/60W	Adams	1969	57,089	404,779	Kd-D,J	P
Dance-South	06/02S/60W	Adams	1977	11,418	629,326	Kd-D	P
Dandy	16/04S/57W	Arapahoe	1976	15,573	0	Kd-J	P
Deadeye	08/06S/62W	Elbert	1976	224,684	337,783	Kd-D	P
Deer Trail	26/02S/60W	Adams	1960	369,205	9,258,415	Kd-D,J	SI
Dike	33/05N/60W	Morgan	1958	88,260	2,617,582	Kd-D	SI
Ditch	33/04N/58W	Morgan	1960	5,485	5,025	Kd-D	PA
Doherty	16/02S/65W	Adams	1957	74,282	2,515,011	Kd-J	P
Double Eagle	01/02S/63W	Adams	1973	71,498	98,231	Kd-D	P
Doubletree	02/06S/62W	Elbert	1973	59,531	1,792,645	Kd-J	P
Dragoon	04/05S/62W	Arapahoe	1971	1,249,236	6,171,681	Kd-D,J	P
Drifter	10/07N/59W	Weld	1977	1,317	55	Kd-D	SI
Dull Knife	20/06S/60W	Elbert	1970	15,537	0	Kd-J	PA
Eagle	16/05S/64W	Arapahoe	1974	10,310	7,750	Kd-J	P
Echo Canyon	35/06N/58W	Morgan	1970	16,099	26,214	Kd-D	SI
Egret	26/01S/61W	Adams	1976	189	15,159	Kd-J	SI
Empire	01/03N/61W	Weld	1953	3,013	0	Kg;Kd-J	P
Enigma	11/07N/57W	Weld	1978	740	792	Kd-J	P
Fairway	14/04S/63W	Arapahoe	1978	509	4,600	Kd-J	P
First Creek	21/02S/67W	Adams	1972	10,778	3,700	Kp-Su	P
Flag	35/07N/58W	Weld	1958	67,436	51,942	Kd-D	PA
Flint	18/03S/60W	Adams	1959	1,197	1,780	Kd-J	PA
Forge	07/02N/57W	Morgan	1960	112,647	38,207	Kd-D	PA
Fort Collins	30/08N/68W	Larimer	1924	3,809,873	462,034	Kn;Kd-M;Pl	P
Fort Morgan	19/03N/57W	Morgan	1954	158,574	9,729,497	Kd-D	SI
Fringe	29/12N/57W	Weld	1957	122,205	323,502	Kd-D	PA
Fury	33/12N/61W	Weld	1970	87,056	49,732	Kd-J	P
Goodrich	30/05N/60W	Morgan	1951	5,436	1,770	Kd-J	PA

FIELD NAME	DISCOVERY WELL			CUMULATIVE PRODUCTION THROUGH 1/1/79		PRODUCING FORMATION(S) ²	STATUS ³
	LOCATION ¹	COUNTY	DATE	OIL (Bbls)	GAS (Mcf)		
Graill	23/07N/58W	Weld	1957	142,484	170,025	Kd-D	PA
Greasewood	24/06N/61W	Weld	1930	1,014,892	912,182	Kd-D	P
Greasewood South	35/06N/61W	Weld	1954	175,988	704,077	Kd-D	P
Grover	20/11N/61W	Weld	1973	19,112	134,282	Kd-J	PA
Guidon	06/03S/63W	Adams	1974	1,234	127,738	Kd-J	SI
Gunsmoke	06/03S/58W	Adams	1969	29,310	955	Kd-J	PA
Hambert	19/04N/65W	Weld	1975	55,884	8,160,540	Kp-Su	P
Hawkeye	32/02S/63W	Adams	1971	24,066	46,490	Kd-J	SI
Hawthorne	20/05N/59W	Morgan	1960	7,140	2,390	Kd-D	PA
Hereford	34/12N/62W	Weld	1973	942	8,200	Kd-J	PA
Highland	04/03N/69W	Boulder	1956	1,199	0	Kp-H;Kn-Fh;Kc	PA
Holster	16/02S/66W	Adams	1972	264,488	1,924,755	Kp-Su;Kd-D,J	P
Hombre	32/03S/61W	Adams	1970	1,079,816	2,679,404	Kd-J	P
Homestead	13/01S/59W	Adams	1972	34,823	65,846	Kd-D	P
Igo Creek	35/10N/59W	Weld	1956	0	0	Kd-J	PA
Independence Creek	30/01N/66W	Weld	1975	830	1,170	Kp-Su	SI
Irondale	30/02S/61W	Adams	1972	1,228,841	5,037,046	Kd-D,J	P
Ironhorse	03/07S/63W	Elbert	1969	22,389	290	Kd-J	PA
Jackknife	32/05S/61W	Arapahoe	1975	4,705	23,000	Kd-J	PA
Jackpot	01/06N/59W	Morgan	1955	1,403,708	2,438,496	Kd-D	SI
Jackpot South	11/06N/59W	Morgan	1955	89,386	229,974	Kd-D	PA
Jackson	25/05N/60W	Morgan	1954	85,719	12,033	Kd-D,J	P
Jade	12/07N/59W	Weld	1964	163	0	Kn-Fh	PA
Jamboree	34/01S/58W	Adams	1970	240,493	3,591,570	Kd-D,J	P
Jasper	28/12N/57W	Weld	1959	328,677	1,350,961	Kd-D,J	P
Johnstown	04/04N/67W	Weld	1972	20,674	8,275	Kp-Sh	P
Kelim	02/05N/68W	Larimer	1965	653	0	Kn	PA
Keota	04/09N/61W	Weld	1951	1,222,426	598,576	Kd-J;Pl	P
Keystone	10/02S/57W	Adams	1968	13,403	6,302	Kd-D,J	P
Kiowa Creek	28/02N/61W	Weld	1955	34,658	3,322,270	Kn-Fh; Kc; Kd-D,J,L	P
Kitty	03/03S/62W	Adams	1972	59,842	144,302	Kd-J	SI
Knox	35/01S/59W	Adams	1954	46,562	49,418	Kd-D	PA
Lamb	16/03N/58W	Morgan	1956	119,000	3,037,042	Kd-D	P
Lamborn Draw	23/05N/59W	Morgan	1963	3,305	1,335	Kd-D	PA
Lantern	19/05S/58W	Arapahoe	1969	1,018	0	Kd-J	PA
Lanyard	18/02N/62W	Weld	1974	1,917,707	3,469,676	Kd-D	P
Laporte	28/08N/69W	Larimer	1959	141	0	Pl	PA
Lark	15/01N/59W	Morgan	1955	42,289	18,120	Kd-J	PA
Lasso	06/01S/58W	Adams	1955	2,156	10,800	Kd-J	PA
Latch String	25/02N/59W	Morgan	1975	6,315	12,795	Kd-D	P
Latigo	23/05S/61W	Arapahoe	1971	240,315	7,304,739	Kd-J	P
Leader	17/02S/59W	Adams	1954	158,231	1,320,760	Kd-J	PA
Leader East	27/02S/59W	Adams	1954	579	408,455	Kd-J	P
Lee	02/02N/57W	Morgan	1950	63,417	373,354	Kd-D,J	PA
Lido	36/01S/60W	Adams	1973	2,213	298,606	Kd-J	P
Little Beaver	01/02S/57W	Adams	1951	70,044	1,154,021	Kd-D,J	PA
Loam	31/07N/58W	Weld	1957	480,659	2,586,053	Kd-D	P
Lodestone	05/03N/59W	Morgan	1977	0	10,061	Kd-J	SI
Lone Tree	31/03S/59W	Adams	1974	1,716,566	2,347,276	Kd-J	P
Longbranch	22/02S/62W	Adams	1972	529,724	18,258,964	Kd-D,J	P

FIELD NAME	DISCOVERY WELL			CUMULATIVE PRODUCTION THROUGH 1/1/79		PRODUCING FORMATION(S) ²	STATUS ³
	LOCATION ¹	COUNTY	DATE	OIL (Bbls)	GAS (Mcf)		
Lost Creek	34/03N/62W	Weld	1957	924,505	7,050,967	Kn; Kd; Kd-D, J	P
Loveland	30/05N/68W	Larimer	1950	1,678,805	2,549,512	Kn; Kn-Fh; Kd; Kd-D, J, J, M, L; P ¹	P
Lowry	25/05S/65W	Arapahoe	1972	1,025,206	2,753,217	Kd-D, J	P
Malpais	02/08N/57W	Weld	1958	0	0	Kd-D, J	PA
Manila	21/03S/64W	Adams	1972	3,575	4,180	Kd-J	SI
Maple	19/05N/60W	Morgan	1963	6,917	463,745	Kd-D	PA
Maria	22/02S/64W	Adams	1973	19,205	128,418	Kd-D, J	P
Masters	25/05N/61W	Weld	1953	354,259	1,387,519	Kd-D	PA
Maverick	36/07N/61W	Weld	1959	8,841	31,395	Kd-D	P
Middlemist	20/02S/57W	Adams	1952	2,136,203	1,249,872	Kd-D	P
Midjay	19/01S/57W	Adams	1958	0	0	Kd-J	PA
Moccasin	02/02S/57W	Adams	1964	1,040,118	996,333	Kd-J	P
Monahan Lakes	08/03N/62W	Weld	1977	3,151	458,469	Kd-J	P
Moore	18/01S/59W	Adams	1959	4,233	2,513	Kd-D, J	PA
Morningside	07/07N/60W	Weld	1969	7,118	714,510	Kd-D, J	SI
Mosley	09/03N/57W	Morgan	1955	1,637	138,368	Kd-D	P
Mountain View East	21/01S/57W	Adams	1953	9,913	3,392	Kd-J	PA
Muddy Creek	27/01S/59W	Adams	1955	38,593	208,556	Kd-D, J	P
Musket	25/03S/57W	Adams	1972	45,995	0	Kd-J	P
Muskrat	15/04S/61W	Arapahoe	1974	0	0	Kd-J	SI
Mustang	31/12N/58W	Weld	1962	460,863	896,705	Kd-D	SI
Narrows	24/04N/59W	Morgan	1959	275	193	Kd-D	PA
New Raymer	02/07N/58W	Weld	1960	434,076	241,123	Kd-D, J	P
New Windsor	26/07N/67W	Weld	1956	1,037,938	39,599	Kp-Su; P ¹	P
Nile	18/01S/60W	Adams	1969	2,183,710	3,298,994	Kd-D, J	P
Noonen Ranch	24/03S/59W	Adams	1951	352,228	267,452	Kd-D, J	P
Omar	36/03N/61W	Weld	1972	348	6,937	Kd-J	SI
Onyx	24/04N/60W	Morgan	1959	696	5,119	Kd-J	PA
Opal	15/04N/58W	Morgan	1959	80,676	514,844	Kd-D	PA
Orchard	09/04N/60W	Morgan	1956	559,318	2,228,317	Kd-D, J	SI
Park	26/01N/59W	Morgan	1954	1,019,183	1,951,287	Kd-D, J	P
Peace Pipe	02/05S/62W	Arapahoe	1972	52,236	2,176,944	Kd-J	P
Peoria	14/04S/60W	Arapahoe	1970	11,758,883	16,710,722	Kd-J	P
Peoria North	15/04S/60W	Arapahoe	1970	583,957	1,547,655	Kd-J	P
Pierce	23/08N/66W	Weld	1955	9,657,890	483,256	P ¹ *	P
Pike	09/03N/61W	Weld	1975	542	0	Kn-Fh	P
Plainsman	05/06N/60W	Morgan	1963	68,868	237,033	Kd-D	PA
Poe	12/03N/59W	Morgan	1954	45,899	995,872	Kd-D	PA
Poison Spring	02/03S/58W	Adams	1959	136,128	54,479	Kd-D	P
Poncho	04/04S/59W	Arapahoe	1971	1,042,259	1,686,223	Kd-J	P
Poncho-South	10/04S/59W	Arapahoe	1973	26,931	13,169	Kd-J	P
Pony	02/03S/63W	Adams	1973	4,979	12,293	Kd-J	P
Pronghorn	16/05S/62W	Arapahoe	1972	55,582	328,059	Kd-J	P
Pronto	06/01S/61W	Adams	1975	35,226	59,839	Kd-D	P
Prospect	29/01N/62W	Weld	1971	7,504	195,533	Kd-D, J	P
Pyramid	08/01S/60W	Adams	1972	6,978	253,763	Kd-D	PA
Radar	35/02S/64W	Adams	1976	37,757	285,149	Kd-D, J	P
Rake	26/04N/60W	Morgan	1958	458,295	1,417,574	Kd-D	PA
Regent	06/02N/57W	Morgan	1955	153,341	215,447	Kd-D	P
Renegade	11/03N/58W	Morgan	1971	2,194	204,169	Kd-D	PA

FIELD NAME	DISCOVERY WELL			CUMULATIVE PRODUCTION THROUGH 1/1/79		PRODUCING FORMATION(S) ²	STATUS ³
	LOCATION ¹	COUNTY	DATE	OIL (Bbls)	GAS (McF)		
Reward	12/02N/61W	Weld	1972	9,041	18,642	Kd-D	P
Ridge	07/05N/58W	Morgan	1956	12,345	18,674	Kd-D	PA
Rimrock	23/02S/60W	Adams	1969	10,757	1,281,718	Kd-J	PA
Ringer	10/01S/63W	Adams	1970	1,021	17	Kd-J	PA
Rio	22/04N/58W	Morgan	1961	36,710	36,710	Kd-D	PA
Riverside	19/05N/61W	Weld	1955	0	3,891,613	Kd-J	PA
Roggen (Southwest)	12/02N/63W	Weld	1953	2,243,300	10,282,454	Kn-Fh;Kd-D,J	P
Roman Nose	03/04S/58W	Arapahoe	1967	282,901	79,409	Kd-J	P
Rosener	12/01S/59W	Adams	1954	319,515	1,301,505	Kd-D,J	P
Roundup	27/02N/60W	Morgan	1967	182,801	6,668,293	Kd-J	PA
San Arroyo	11/01S/58W	Adams	1954	0	9,747	Kd-J	PA
San Arroyo Creek	34/01N/58W	Morgan	1960	17,279	4,324	Kd-D	PA
Sawbuck	08/02N/58W	Morgan	1966	22,573	282,809	Kd-D,J	PA
Scabbard	08/01N/63W	Weld	1974	25,174	287,881	Kd-D,J	PA
Second Creek	08/03S/65W	Adams	1956	61,116	100,043	Kd-D,J	P
Sheehan	22/01N/63W	Weld	1975	157	10,634	Kd-J	P
Shelah	02/04N/58W	Morgan	1961	0	0	Kd-D	PA
Shivaree	36/09N/61W	Weld	1970	3,940	4,500	Kd-J	PA
Sidewinder	24/04S/62W	Arapahoe	1973	220,901	3,117,729	Kd-D,J	P
Simpson	34/02S/57W	Adams	1959	41,652	18,297	Kd-J	PA
Singletree	16/02N/66W	Weld	1971	Production included in Spindle		Kp-Su	P
Sloan	30/01N/63W	Weld	1974	14,850	4,912	Kd-D,J	P
Snowbird	02/04S/57W	Arapahoe	1973	9,482	0	Kd-J	P
Soda Lake	07/05S/69W	Jefferson	1955	15,275	3,820	Kn-Fh	PA
Songbird	01/07S/63W	Elbert	1976	102,274	350,978	Kd-D,J	P
Sooner	27/08N/58W	Weld	1969	29,467	1,398,615	Kd-D	P
Space City	31/01N/65W	Weld	1973	204,261	1,900,861	Kd-D,J	P
Spindle	33/02N/67W	Weld	1972	24,507,463	97,603,967	Kp-Sh,Su;Kc	P
Spurgin	13/11N/57W	Weld	1954	14,824	9,588	Kd-D	PA
Spurgin-North	12/11N/57W	Weld	1957	4,918	826	Kd-J	PA
Stage Stop	20/01N/68W	Weld	1975	7,851	49,084	Kn	P
Strasburg	21/03S/62W	Adams	1976	55,312	224,165	Kd-D	P
Strike	27/05N/60W	Morgan	1961	4,537	100,221	Kd-J	PA
Sun	01/02S/61W	Adams	1969	139,940	446,474	Kd-D,J	P
Supaha	11/01N/62W	Weld	1978	5,483	159,303	Kd-J	P
Surrey	33/01N/67W	Weld	1972	Production included in Spindle		Kp-Su	P
Superior	24/01S/70W	Boulder	1978	0	0	Kd	SI
Tampa	19/02N/63W	Weld	1965	450,378	3,561,404	Kd-D,J	P
Tempest	10/11N/61W	Weld	1962	1,408	5,128	Kd-J	PA
Tenderfoot	20/05N/58W	Morgan	1976	3,057	610	Kd-D	P
Terrace	12/10N/59W	Weld	1958	84,726	29,821	Kd-D	P
Third Creek	18/02S/65W	Adams	1971	3,394,669	20,092,292	Kd-J	P
Thunderbird	25/08N/58W	Weld	1972	12,496	5,572	Kd-J	SI
Titan	22/12N/57W	Weld	1975	15,230	16,570	Kd-D	P
Totem	17/02S/62W	Adams	1971	120,049	7,525,102	Kd-D,J	P
Track	30/05N/59W	Morgan	1960	177,174	682,005	Kd-D	SI
Trapper	06/02S/64W	Adams	1971	971,924	4,134,476	Kd-D,J	P
Travois	03/04N/59W	Morgan	1964	2,811	1,230	Kp-H;Kd-D	PA
Trend	35/05N/60W	Morgan	1958	370,134	3,482,900	Kd-D	P
Tribute	26/03N/62W	Weld	1973	871	2,910	Kd-J	SI

FIELD NAME	DISCOVERY WELL			CUMULATIVE PRODUCTION THROUGH 1/1/79		PRODUCING FORMATION(S) ²	STATUS ³
	LOCATION ¹	COUNTY	DATE	OIL (Bbls)	GAS (Mcf)		
Trigger	16/02S/61W	Adams	1971	239,566	500,728	Kd-D,J	P
Tumbleweed	23/12N/57W	Weld	1968	100,506	19,298	Kd-D,J	P
Turner	01/07N/59W	Weld	1955	454	0	Kd-D	PA
Vallery	23/03N/59W	Morgan	1954	185,785	9,374,719	Kd-D,J	P
Velvet	14/02N/59W	Morgan	1975	21,818	20,916	Kd-J	P
Vigor	31/12N/57W	Weld	1958	51,653	46,172	Kd-D,J	P
Vim	16/11N/58W	Weld	1957	120,606	498,986	Kd-D,J	SI
Vimy Ridge	03/06S/65W	Elbert	1972	1,150	567	Kd-J	PA
Voltage	02/07N/57W	Weld	1965	163,750	65,109	Kd-J	P
Waite Lake	01/03N/62W	Weld	1974	786	53,037	Kd-J	P
Warlock	30/02S/62W	Adams	1973	95,427	879,092	Kd-J	P
Wattenberg	26/01N/67W	Weld	1970	1,691,799	156,656,976	Kp-Sh; Su; Kd-D,J; Kc; Kn; Kn-Fh	P
Weldona	33/05N/59W	Morgan	1959	1,937	1,576	Kd-D	PA
Wellington	31/10N/68W	Larimer	1923	7,446,527	18,635,918	Kd-M	P
Wheeler Lake	27/03N/67W	Weld	1976	1,353	0	Kp-Sh	PA
Wigwam	32/01N/62W	Weld	1974	203,305	120,997	Kd-D	P
Wild Card	07/05S/63W	Arapahoe	1977	6,769	11,422	Kd-J	P
Wild Horse	09/07N/58W	Weld	1965	16,911	9,131	Kd-J	PA
Wildwood	26/09N/62W	Weld	1971	20,515	340	Kd-J	SI
Windy Hill	05/03S/57W	Adams	1954	449,417	124,453	Kd-J	P
Woodrow West	02/01S/57W	Adams	1953	274,427	236,646	Kd-D	P
Young	14/04N/58W	Morgan	1957	50,794	7,036,350	Kd-D	P
Yucca	26/05S/62W	Arapahoe	1971	1,245	460	Kd-J	SI
Zodiac	11/02S/57W	Adams	1978	601	303	Kd-D	P

BULLETINS

34-A--BIBLIOGRAPHY, COAL RESOURCES IN COLORADO, R. D. Holt, 1972, 32 p., \$1.00.

41--BIBLIOGRAPHY AND INDEX OF PUBLICATIONS RELATED TO COAL IN COLORADO, 1972-1977, H. B. Fender, D. C. Jones, and D. K. Murray, 1978, 54 p., \$2.00.

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80-9--GEOPHYSICAL AND LITHOLOGICAL LOGS FROM THE 1980 COAL DRILLING AND CORING PROGRAM, DENVER EAST 1/2° x 1° QUADRANGLE, K. E. Brand, and J. M. Caine, 1980, \$2.50.

MISCELLANEOUS

BULLETIN 37--BIBLIOGRAPHY AND INDEX OF COLORADO GEOLOGY, 1875 to 1975, American Geological Institute, 1976, 488 p., Softbound 7.50; Hardbound 10.00.

ENERGY RESOURCES MAP OF COLORADO--USGS and CGS, 1977, (scale 1:500,000). (USGS Misc. Geol. Inv. Map I-1039). \$2.00.

GEOLOGIC MAP OF COLORADO--USGS, Ogden Tweto, 1979, (scale 1:500,000). Over-the-counter or mailed folded, \$4.00; Mailed rolled, \$4.50.

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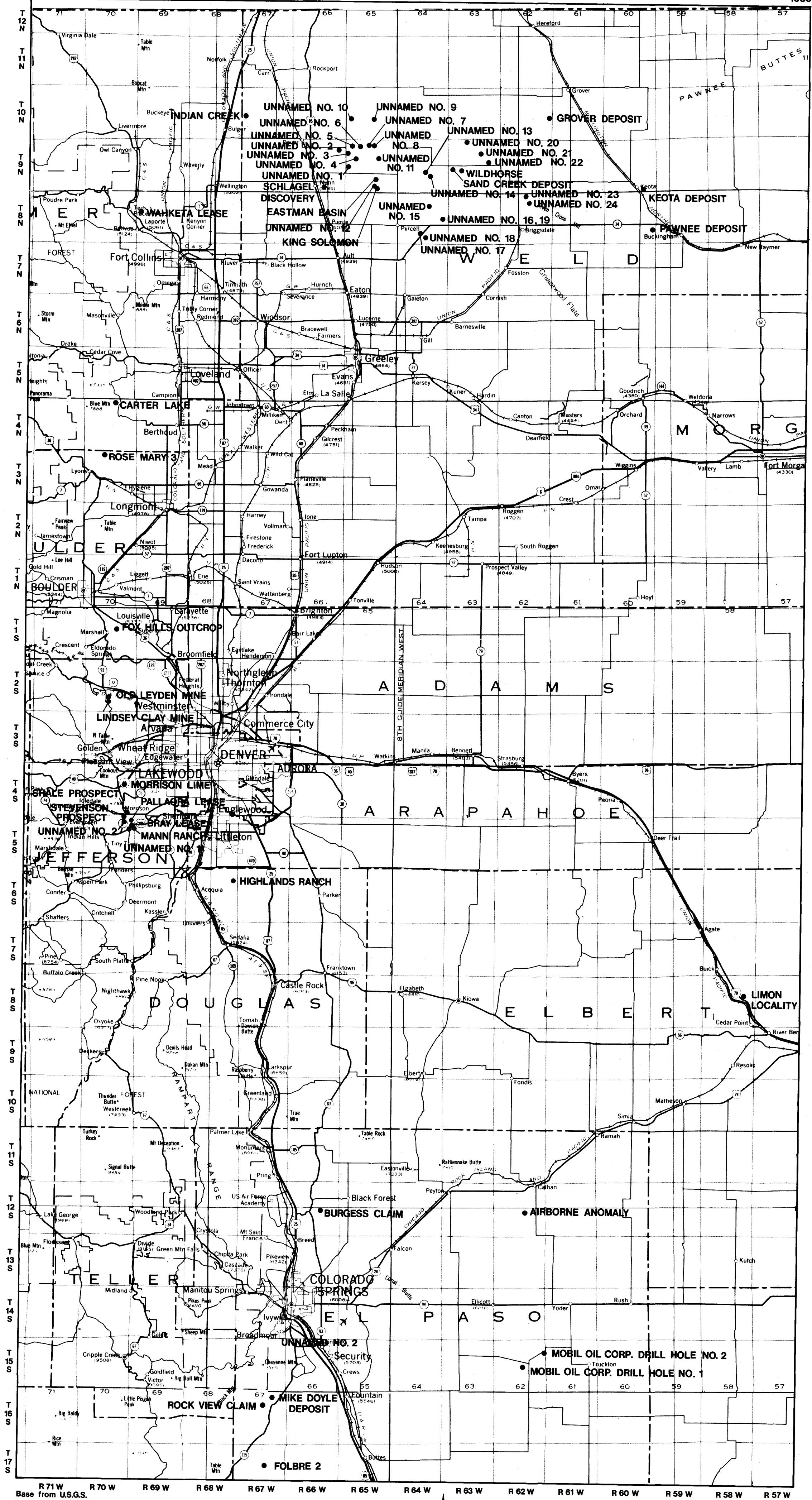
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COLORADO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES
JOHN W. ROLD, DIRECTOR

BY ROBERT M. KIRKHAM AND L. R. LADWIG

ENVIRONMENTAL GEOLOGY 12
PLATE 1 OF 2
1980



EXPLANATION

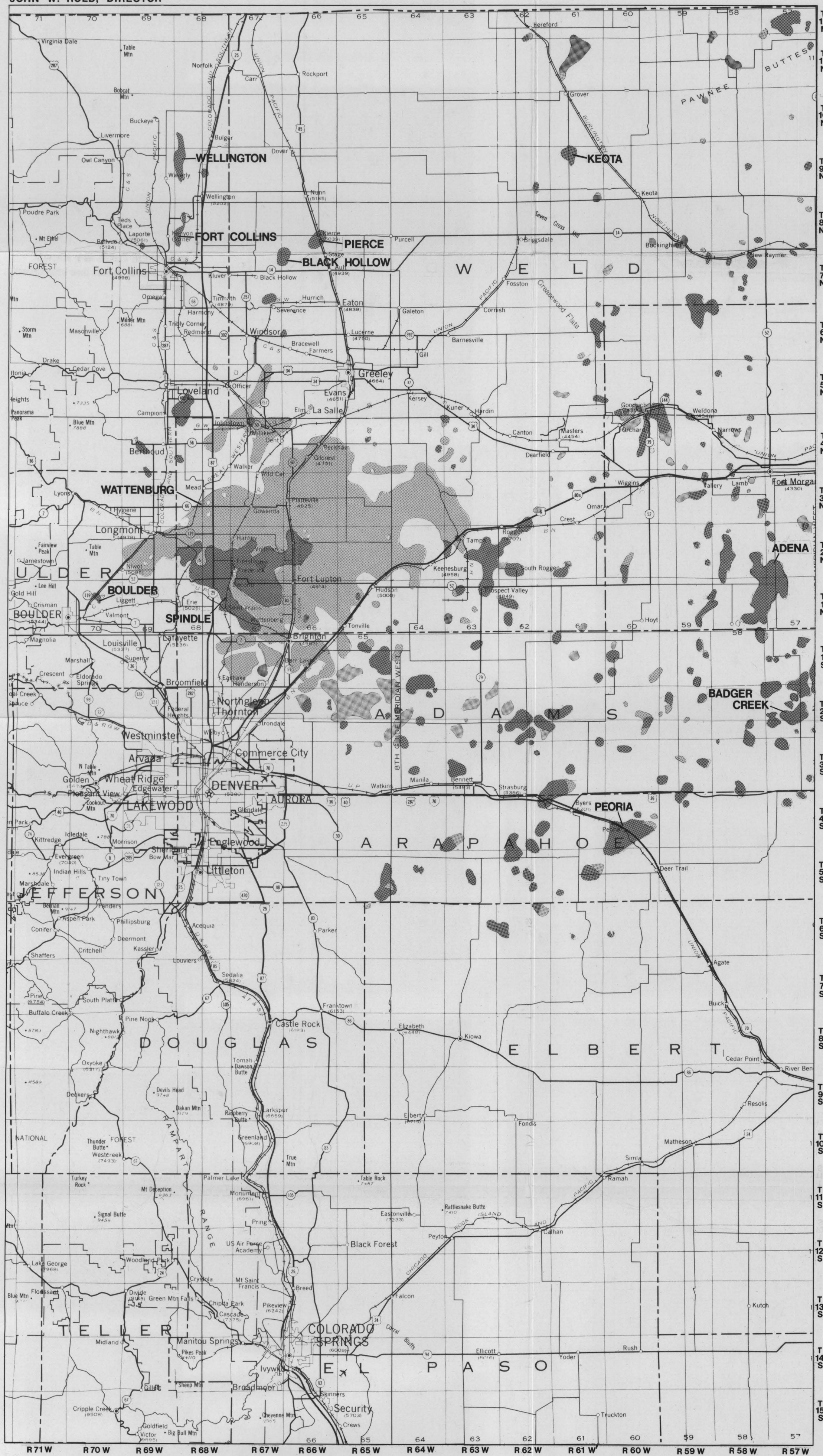
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OIL AND GAS FIELDS IN THE DENVER AND CHEYENNE BASINS, COLORADO
BETWEEN T15S TO T12N AND R57W TO R71W

BY
ROBERT M. KIRKHAM AND L.R. LADWIG

COLORADO GEOLOGICAL SURVEY
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ENVIRONMENTAL GEOLOGY 12
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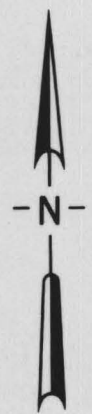


EXPLANATION

- OIL FIELD
- GAS FIELD

NOTE:

Gas fields may also exist where oil fields are shown. Only a few fields are identified by name.

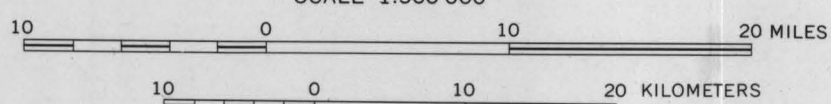


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