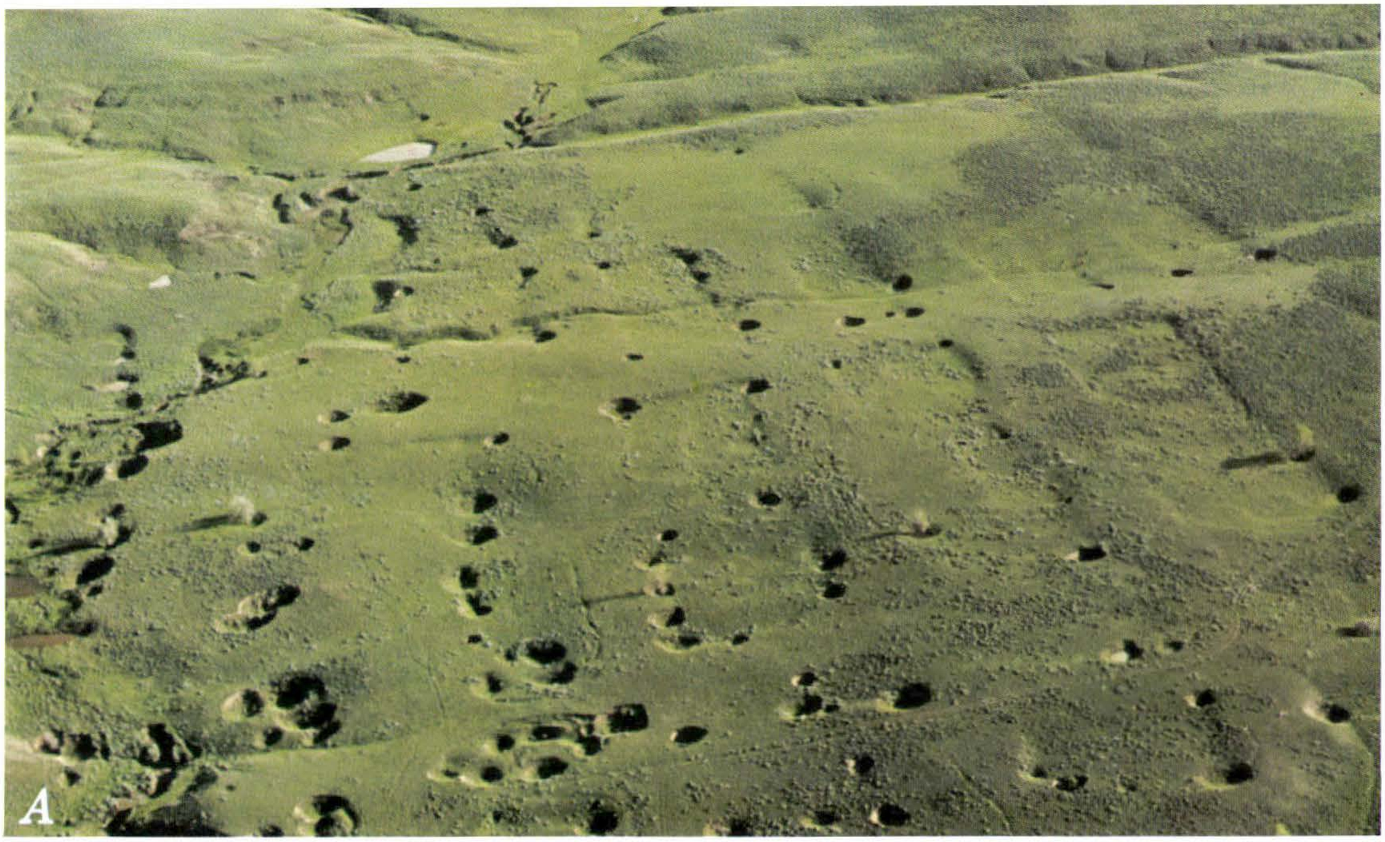
Exhibit 47

EFFECTS OF COAL MINE SUBSIDENCE IN THE SHERIDAN, WYOMING, AREA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1164

COVER.—Effects of past and present coal mining in the western Powder River Basin, as discussed in this report.

EFFECTS OF COAL MINE SUBSIDENCE
IN THE SHERIDAN, WYOMING, AREA



FRONTISPIECE.—Aerial oblique views showing surface subsidence effects above abandoned coal mines 10–15 km north of Sheridan, Wyo. *A*, Aerial oblique view of subsidence depressions and pits above the Old Monarch mine in operation from 1904 to 1921 (May 1978). Rectangular depressions, some of which are bounded by pits or locally include pits, are evident at right. Some of the pits are sealed at the bottom and provide sufficient moisture to support trees (foreground). Overburden thickness is estimated to be approximately 10–15 m. The depressions occur where much of the coal is removed and the remaining coal cannot support the weight of the overburden. Pits at the margins of the depressions commonly are caused by piping failure and the local flow of surface water to underground mines via subsidence cracks. *B*, Subsidence pits and troughs, above the Dietz coal mines (October 1976). The Dietz mines were operated from the 1890's to the 1920's. Coal was mined from three different beds. The mine workings, which were abandoned in the early 1920's, are locally superimposed. The overburden comprises weak claystones, shales, and local thin, soft sandstones. Its thickness is estimated to range from about 5 m along the margins of the subsidence area (right side of photograph) to as much as 45 m (Darton, 1906, p. 111). Pits and troughs located in draws draining into Goose Creek (near background) disrupt or divert surface water to old mine workings. Bighorn Mountains are in far background.

Effects of Coal Mine Subsidence In the Sheridan, Wyoming, Area

By C. RICHARD DUNRUD *and* FRANK W. OSTERWALD

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1164

A summary of geology, subsidence, and other effects of past and present mining as related to the environment, coal resource management, and land use

Supplemental information is included from Beulah, N. Dak., Decker, Mont., Somerset, Colo., and Raton, N. Mex.

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CONTENTS

ILLUSTRATIONS

METRIC-INCH-POUND EQUIVALENTS

Metric unit	*Multiply by*	*To give inch-pound equivalent*
Centimeter (cm)	0.39	Inch (in.)
Meter (m)	3.28	Feet (ft)
Kilometer (km)	.62	Mile (mi)
Calories per gram (cal/g)	1.8	British thermal unit per pound (Btu/lb)
Meganewton per square meter (MN/m^2)	145	Pounds per square inch (psi)
Grams per cubic centimeter (g/cm^3)	62.4	Pounds per cubic foot (lb/ft^3)

EFFECTS OF COAL MINE SUBSIDENCE IN THE SHERIDAN, WYOMING, AREA

By C. RICHARD DUNRUD and FRANK W. OSTERWALD

ABSTRACT

Analyses of the surface effects of past underground coal mining in the Sheridan, Wyoming, area suggest that underground mining of strippable coal deposits may damage the environment more over long periods of time than would modern surface mining, provided proper restoration procedures are followed after surface mining. Subsidence depressions and pits are a continuing hazard to the environment and to man's activities in the Sheridan, Wyo., area above abandoned underground mines in weak overburden less than about 60 m thick and where the overburden is less than about 10–15 times the thickness of coal mined. In addition, fires commonly start by spontaneous ignition when water and air enter the abandoned mine workings via subsidence cracks and pits. The fires can then spread to unmined coal as they create more cavities, more subsidence, and more cracks and pits through which air can circulate.

In modern surface mining operations the total land surface underlain by minable coal is removed to expose the coal. The coal is removed, the overburden and topsoil are replaced, and the land is regraded and revegetated. The land, although disturbed, can be more easily restored and put back into use than can land underlain by abandoned underground mine workings in areas where the overburden is less than about 60 m thick or less than about 10–15 times the thickness of coal mined. The resource recovery of modern surface mining commonly is much greater than that of underground mining procedures. Although present-day underground mining technology is advanced as compared to that of 25–80 years ago, subsidence resulting from underground mining of thick coal beds beneath overburden less than about 60 m thick can still cause greater damage to surface drainage, ground water, and vegetation than can properly designed surface mining operations.

This report discusses (1) the geology and surface and underground effects of former large-scale underground coal mining in a 50-km^2 area 5–20 km north of Sheridan, Wyo., (2) a ground and aerial reconnaissance study of a 5-km^2 coal mining area 8–10 km west of Sheridan, and (3) some environmental consequences and problems caused by coal mining.

INTRODUCTION

Thick coal deposits, representing hundreds of billions of tons of low-sulfur subbituminous coal, are present in the Powder River Basin of Wyoming and Montana (fig. 1). The coal occurs beneath overburden composed of weak bedrock and surficial deposits that range in thickness from a few meters to as much as 900 m. A controversy currently exists over the relative merits of mining strippable coal deposits by underground and surface methods. Many mining and land-use planners contend that the many billions of tons of strippable coal in the Powder River Basin can be mined more safely and much more completely by surface methods than by underground methods, particularly in areas where thick coal beds occur beneath soft bedrock and surficial material less than 60 m thick. On the other hand, environmental groups are concerned that surface mining might be more damaging to the environment than would underground mining.

Surface mining operations disturb the total land surface of the mining area during the mining cycle (figs. 2, 3). The topsoil and remaining overburden commonly are removed by earth-moving scrapers or by large draglines; the coal is then removed by draglines or power shovels, and trucks. In modern surface mining operations, in contrast to those of the past, the overburden is replaced and graded, the topsoil is replaced, and the land is revegetated (figs. 2, 3). In a few years or a few decades, depending on the climate and on

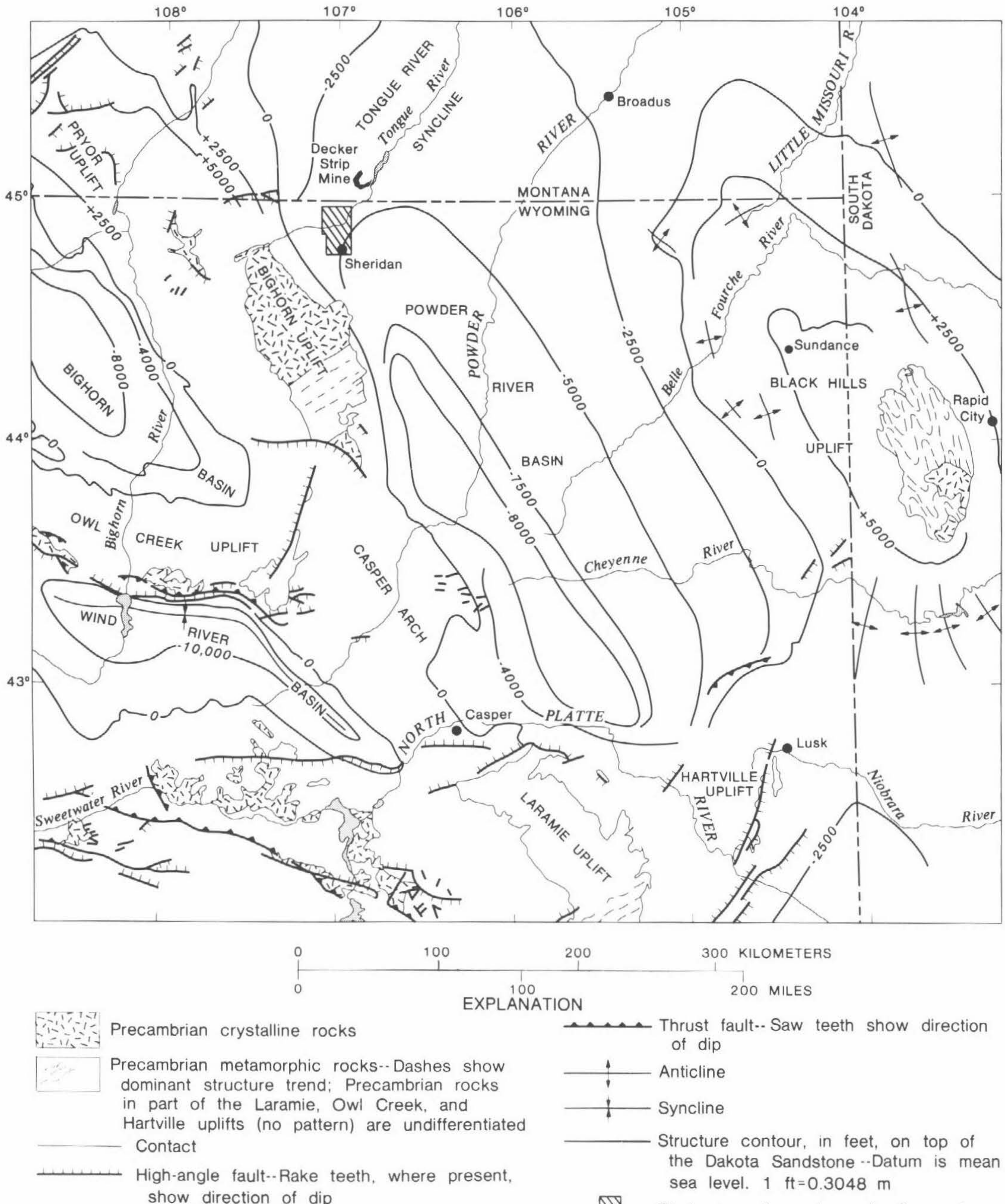


FIGURE 1.—Map of the Powder River Basin and adjacent areas. Modified from the tectonic map of the United States (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961).

FIGURE 2.—Present and past mining in the Big Horn mine area. *A*, Eastward oblique aerial view of the Big Horn surface mine (April 1976). Coal from two, and locally three, separate beds totaling 15–18 m in thickness is removed by power shovels and trucks after the overburden has been stripped by earth-moving scrapers. The highwall (near background), which is about 50 m high after coal is removed, ultimately will be as much as 75 m high in the active mining cycle. Note the variable thickness in rocks separating the coal beds. Geotechnical tests on core were made from drill holes located in left and middle background of photograph. Haul roads and spoil, in early stages of reclamation and revegetation, can be seen in the foreground. *B*, View of an underground mine opening of the abandoned Dietz No. 8 mine (fig. 4) in the Monarch coal bed (one of the beds mined in the Big Horn surface mine (right middle ground of *A*)), December 1971. Only about 2 m of a 17-m-thick coal bed was removed in past underground mining. Photograph (July 1972) courtesy of Big Horn Coal Co.

the physico-chemical and geotechnical properties of the overburden, the land surface normally can be restored to its original use or it can be used for other purposes (Hardaway, 1976, p. 1–76).

Underground mining, on the other hand, appears at first to disturb only a small part of the mining area. Mine portals, coal processing and loading facilities, and mine support buildings occupy only a small part of the area underlain by mine workings. However, beneath the surface the mine workings comprise a labyrinth of underground entries and rooms that are connected by coal haulageways and airways to mine portals or shafts at the surface (cover). The unmined coal pillars may be left to support the overburden, or they may be extracted near the end of the mining cycle, which causes a local lowering of the ground surface. In modern mining operations, the pillars are extracted where possible, in order to make more efficient use of energy resources.

In the western Powder River Basin and in other areas, such as in underground mining areas in the Williston Basin of western North Dakota, studies by the authors revealed that the long-range effects of past underground mining, which include a local lowering of the land surface and attendant deformation, collectively termed subsidence, can cause environmental problems. In addition, coal fires in abandoned mine workings have locally damaged the land surface more severely than

FIGURE 3.—Southward aerial view of the west Decker strip mine near Decker, Mont. (May 1978). The overburden is removed by large draglines. The coal, which is about 17 m thick, is removed by power shovels and trucks. The topsoil is removed by earthmoving scrapers and is stockpiled prior to stripping. The spoil is graded, covered with topsoil, and revegetated (green strips). The overburden comprises soil, colluvium, and soft bedrock of the Tongue River Member of the Fort Union Formation and ranges in thickness from 8 to 37 m. Coal is hauled by trucks along radially oriented haul roads to the unit-train loading facility at left. Production of low-sulfur subbituminous coal from this mine totaled 9.3 million t (metric tons) in 1977, or about 1.5 percent of the total coal production of the United States in 1976 (based on a total of 609 million t (World Almanac, 1978, p. 97)). Bighorn Mountains and Cloud Peak are in right background.

have surface mining activities on nearby land. Subsidence continues to be a problem many years or many decades after the mine workings were driven.

The purpose of this report is: (1) to discuss and evaluate the subsidence effects caused by past coal mining in the Sheridan, Wyo., area in underground mines that were worked beneath weak bedrock and surficial deposits 5-60 m thick; (2) to compare some of the long-range environmental effects of the underground and surface mining methods in these areas; and (3) to make this information a matter of public record in order that future mining activities may benefit from this knowledge.

These investigations are part of a series of engineering geologic studies of the western Powder River Basin, in connection with the U.S. Geological Survey's environmental studies of Energy Lands. Detailed subsidence investigations of a 50-km^2 area 5-20 km north of Sheridan, Wyo. (fig. 4), were supplemented by a ground and aerial reconnaissance study of a 5-km^2 mining area 8-10 km west of Sheridan along Big Goose Creek and an aerial reconnaissance of 65 km^2 of land impacted by underground and surface mining near Beulah, N. Dak. Other investigations were made of strip mines in the northern Great Plains, particularly of the Decker strip mine in southern Montana. Some results of subsidence studies are included from currently operating coal mines near Somerset, Colo., and Raton, N. Mex., where the overburden is thicker than 60 m.

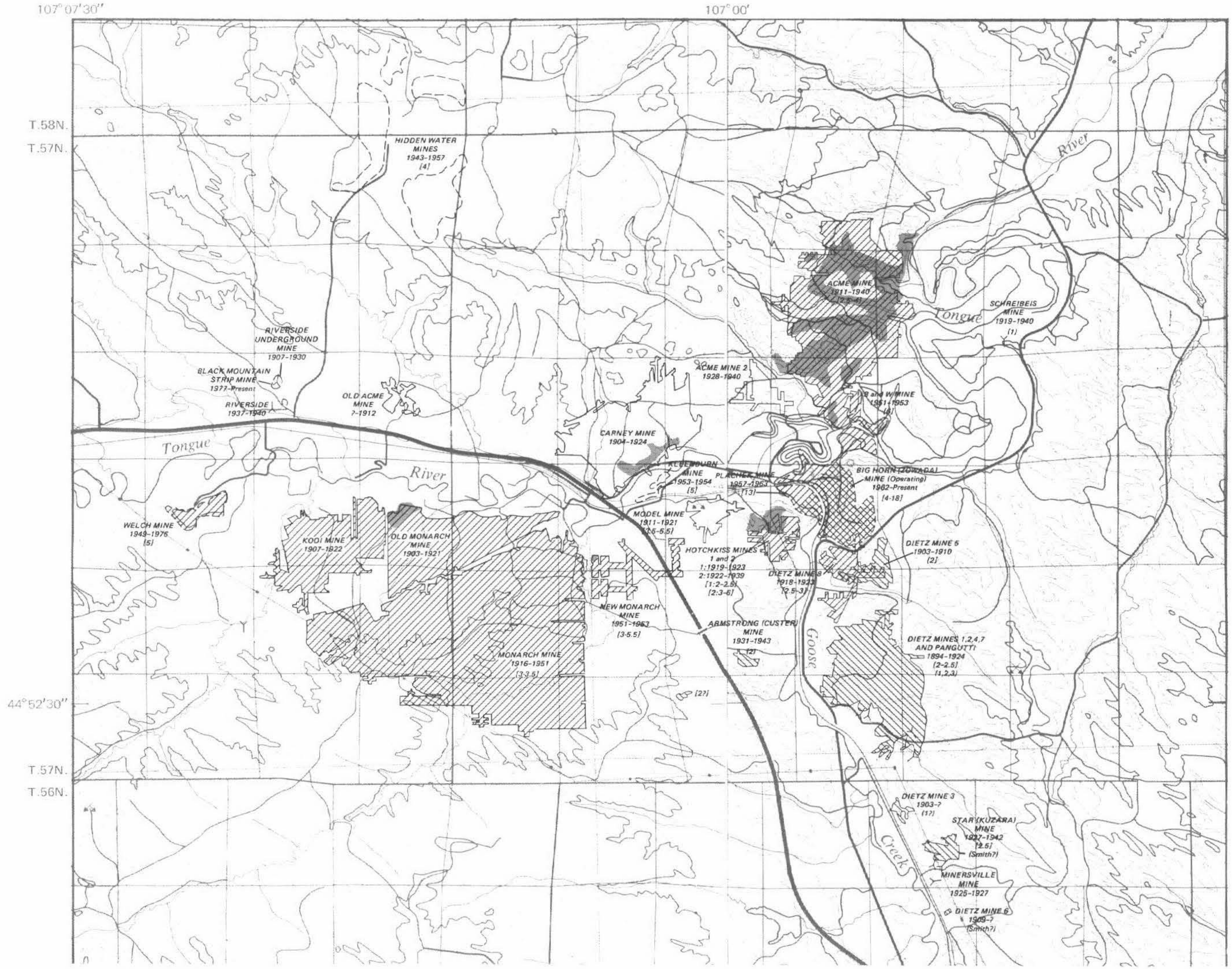
Large areas near Sheridan are underlain by abandoned mine workings in the Carney, Monarch, and Dietz coal beds located between about 5 and 60 m beneath the ground surface (fig. 4). Underground mining began in about 1892 (Kuzara, 1977, p. 55) and ended in 1953. The old mining towns or camps of Acme, Monarch, Kooi, Riverside, Kleenburn (Carneyville), and Dietz (Higby) are abandoned, demolished, or in the process of being demolished. In 1907 the population of the mining towns of Dietz, Kleenburn (Carneyville), and Monarch was about 2,000, 1,400, and 700 respectively; and the towns of Kooi and Riverside were established. About 1,600 men were employed at the Dietz, Carney, and Monarch mines (Taff, 1909, p. 125). Many of the personnel employed at the current surface mines at Big Horn and Decker now reside in Sheridan and other nearby communities.

The terms subsidence, overburden, and coal mine openings, as used in this report, require clarification. Subsidence is defined as the local lowering of the Earth's surface caused by subsurface removal or compaction of material. Coal mine subsidence includes the local lowering of the ground surface and all deformation processes within the overburden and at the surface that are produced by the movement of rock and surficial material into underground coal mine openings. Subsidence processes therefore include downward vertical movement, local depressions, pits, horizontal compressive and tensile strains produced by flexure of strata, compressive strain associated with compression arching, shearing across lithologic boundaries due to flexure of strata, and even upward movements that locally occur near depressions. The term overburden means all earth material that overlies the coal bed being mined. Coal mine openings include all underground cavities, entries, or workings created as coal is removed.

ACKNOWLEDGMENTS

The authors' work was aided by many individuals, organizations, and companies. Access to the field area and information was granted by Dan Scott and B. J. Spear of the Padlock Ranch Co., Dayton, Wyo. Personnel of Peter Kiewit Sons' Co., and the Big Horn Coal Co., Sheridan, Wyo., particularly T. P. Wollenzien, J. F. Ratchye, E. W. Temple, and W. M. Rosewarne provided drill core for geotechnical testing, maps, charts, and other useful information. Valuable information, mine mapping, and assistance in locating and identifying old coal mines were provided by S. A. Kuzara, Ray Bottomly, and W. F. Welch. Information on subsidence and coal mine fires was given by G. L. Mooney, Department of Environmental Quality, State of Wyoming; H. F. Alley, United Mine Workers of America, district 15; and D. L. Donner, U.S. Bureau of Mines, Denver, Colo.

Geologic information on the western Powder River Basin was provided by W. J. Mapel, S. P. Kanizay, B. E. Law, and B. E. Barnum, U.S. Geological Survey. Subsidence information from New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HIDDEN WATER MINES 1943-1957 [4]
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ACME MINE 1911-1940
Tongue
SCHREIBEIS MINE 1919-1940 [1]
RIVERSIDE UNDERGROUND MINE 1907-1930
BLACK MOUNTAIN STRIP MINE 1977-Present
RIVERSIDE 1937-1940
OLD ACME MINE ?-1912
ACME MINE 2 1928-1940
CARNEY MINE 1904-1924
Tongue
River
WELCH MINE 1949-1976 [5]
KOOI MINE 1907-1922
OLD MONARCH MINE 1903-1921
MODEL MINE 1911-1921
HOTCHKISS MINES 1 and 2 1:1919-1923 2:1922-1939 [1:2-2.5] [2:3-6]
BIG HORN MINE (Operating) 1962-Present [4-18]
DIETZ MINE 5 1903-1910 [2]
NEW MONARCH MINE 1951-1953 [3-5.5]
ARMSTRONG (CUSTER) MINE 1931-1943
Goose
MONARCH MINE 1916-1951 [3-3.5]
DIETZ MINES 1,2,4,7 AND PANGUTTI 1894-1924 [2-2.5] [1,2,3]
[27]
DIETZ MINE 3 1903-? [1?]
STAR (KUZARA) MINE [2.5] (Smith?)
Creek
MINERSVILLE MINE 1925-1927
DIETZ MINE 6 (Smith?)

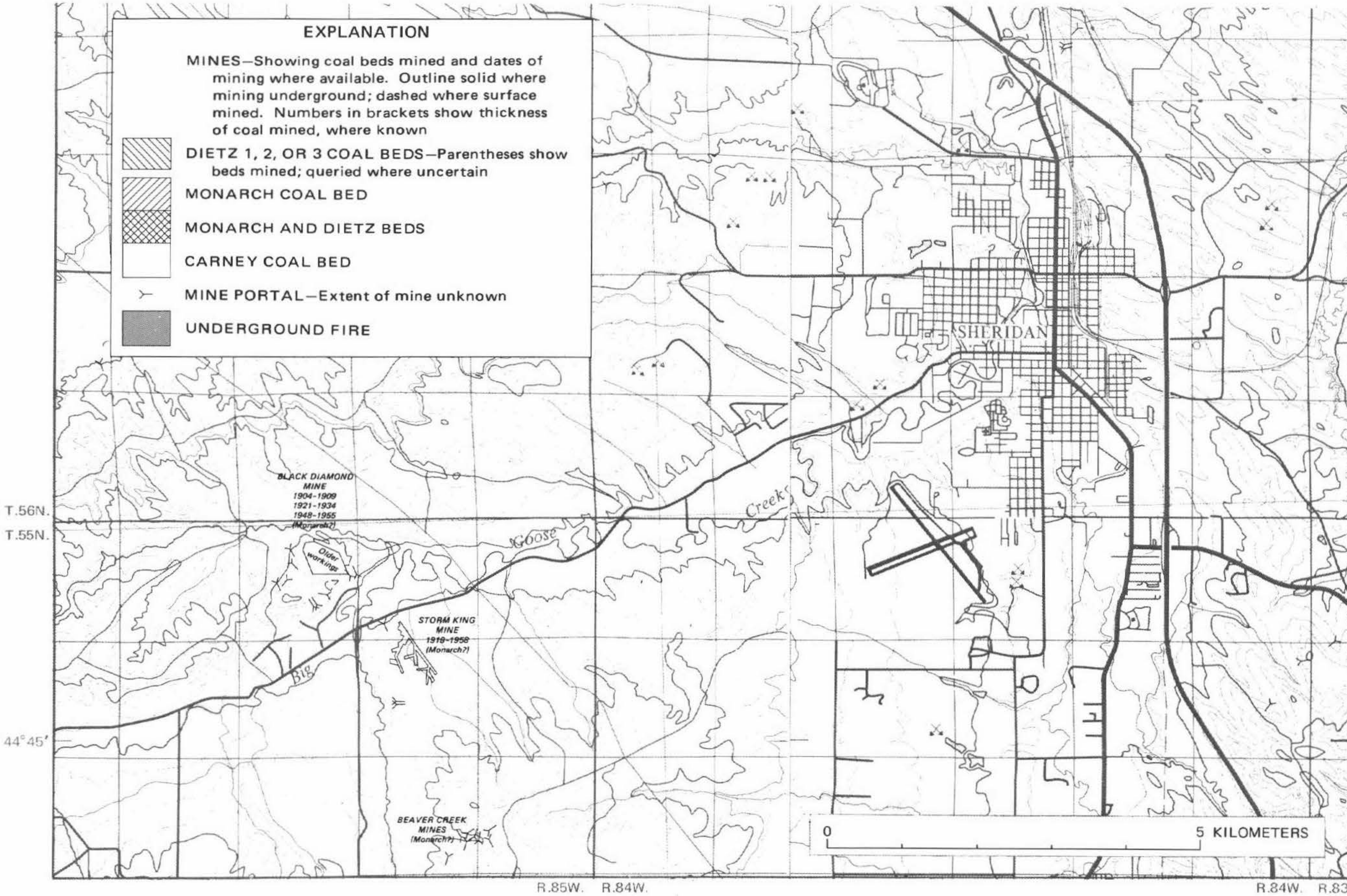


FIGURE 4.—Locations of underground and surface mines in the Sheridan, Wyo., area. Overburden thickness ranges between about 5 and 60 m. Estimated thickness of coal mined is 2–3 m, except where known more accurately and indicated (in meters, shown in brackets). Period of mining is included where available. At mines where coal bed correlation is questionable or where coal bed is not symbolized in explanation, coal bed name shown in parentheses with query. Subsidence depressions, cracks, and pits are locally common above the mine workings. Underground fires were mapped from a March 1978 aerial and ground survey of bare ground surrounded by deep snow. Mine mapping and periods of operation from various sources including U.S. Geological Survey (unpub. data, various dates), Coal Mine Inspector, State of Wyoming (unpub. data), U.S. Bureau of Mines (unpub. data, various dates), Darton (1906, p. 111–112), and Kuzara (1977). Base from U.S. Geological Survey 1:100,000, Sheridan, Burgess Junction, 30′×60′ series, 1979.

Mexico was made available to the authors by D. W. Gentry, and J. F. Abel, Jr., Colorado School of Mines, Golden, Colo.

Valuable suggestions were given by D. D. Dickey, S. P. Kanizay, and J. R. Smith, U.S. Geological Survey, and J. E. Hardaway, U.S. Office of Surface Mining.

GEOLOGY AND PHYSIOGRAPHY

The Powder River Basin, as defined by Keefer and Schmidt (1973), is a northwest-trending structural and topographic basin located in northeastern Wyoming and southeastern Montana (fig. 1). Structurally, the basin is strongly asymmetric, the deepest part being to the southwest only a few kilometers northeast of the Bighorn Mountains (Osterwald and Dean, 1961, p. 348). It is about 320 km long and 130 km wide and is bounded by elongate, blocklike uplifts of Laramide age, with minor younger movements, that commonly trend northwestward and are bounded by high-angle normal and reverse faults or folds (Osterwald and Dean, 1961, p. 338).

The Powder River Basin is bounded on the west and southwest by the Pryor uplift, the Bighorn uplift, and the Casper arch; on the east by the Black Hills uplift; and on the south by the Laramie and Hartville uplifts. Structural relief of the uplifts relative to the basin exceeds 5,500 m (U.S. Geol. Survey and Am. Assoc. Petroleum Geologists, 1961). Erosion has exposed crystalline and metamorphic rocks of Precambrian age in most of the cores of the uplifts. Paleozoic and Mesozoic rocks are exposed along the flanks of the uplifts; then they warp downward into the basins, where they are covered by thick sequences of rocks of early Tertiary age.

The topography of the Powder River Basin is characterized by low-rolling grass-covered hills with craggy, clinker-covered crests that are separated by intermittent and locally perennial streams. Five major streams drain the Powder River Basin: the Powder River and Tongue River to the north, the Belle Fourche River to the northeast, the Cheyenne River to the east, and the North Platte River to the southeast (fig. 1). Many tributaries of these major streams trend northwest and meander along extensive alluvial valley floors. This pattern tends to produce a pronounced ridge-and-valley topography oriented in a northwesterly direction. In some areas within the basin, however, the tributaries trend predominantly northeastward, northward, or westward. In these areas the ridges and valleys are oriented in these directions.

Elevations in the Powder River Basin range from about 910 m near the northern and northwestern margins of the basin to about 1,620 m in the Pumpkin Buttes area in the south-central part of the basin and about 1,560 m at Casper in the southwestern part of the basin. In the Sheridan area, elevations range from about 1,100 m at the former town of Acme to about 1,220 m near the Sheridan airport.

Precipitation—an important factor controlling restoration of surface-mined lands—is variable both locally and regionally in the Powder River Basin. On a regional basis, according to the U.S. Weather Bureau, the 30-year (1931–60) mean annual precipitation in the Powder River Basin ranges from 42 cm in the northwestern part, to 36 cm in the northeastern and central parts, to about 30 cm in the southwestern part. Most of the Powder River Basin therefore has a semiarid climate. In the Sheridan area, according to a local rancher (Dan Scott, oral commun., 1975), the mean annual precipitation ranges from about 25 cm at Acme to about 40 cm at Ranchester, 20 km northwest of Sheridan.

BEDROCK AND COAL DEPOSITS

The bedrock in the western Powder River Basin comprises predominantly weak rocks of the Fort Union Formation of Paleocene age. Rocks of the overlying Wasatch Formation, which crop out farther east of the subsidence study area, commonly are lithologically similar to the rocks of the Fort Union except that they are somewhat softer and coarser and characteristically underlie more rounded hills and ridges and broader valleys (W. J. Mapel, U.S. Geol. Survey, oral commun., 1975).

The Fort Union Formation consists of soft siltstones, mudstones, shales, silty claystones, lenticular sandstones, and locally thick subbituminous coal beds. It is subdivided into three members by most workers in the area. They are: (1) the Tullock Member at the base, (2) the Lebo Shale Member, and (3) the Tongue River Member in ascending order (Barnum, 1974). The Tullock

Member, which is exposed about 6.5 km west of Ranchester, Wyo., is composed of interbedded mudstone and sandstone with some coal (Barnum, 1974). The Lebo Shale Member consists of soft mudstones, shales, and claystones, with interbedded discontinuous coal beds and thin soft sandstone lenses. Rocks of the Tongue River Member in the Acme area, which contain the major coal deposits in the area, consist of soft, argillaceous siltstones, mudstones, coal, and friable, lenticular sandstones totaling about 365 m (B. E. Law, U. S. Geol. Survey, oral commun., 1976; fig. 5).

The coal beds, which are of subbituminous rank and contain low percentages of sulfur, thicken and thin within short distances and are separated by rocks that range in thickness from about 1 m to as much as 50 m. The coal beds vary in thickness from less than 1 m to about 17 m, and in some areas the rock interval between two coal beds varies in thickness from about 1 m to about 10 m within short lateral distances.

Coal beds in the western Powder River Basin, which were extensively mined by underground methods near the old towns of Acme, Dietz, Kleenburn (Carneyville), and Monarch from the early 1890's to the early 1950's (fig. 4), include the Carney, Monarch, Dietz 3, Dietz 2, and Dietz 1 in ascending order (Taff, 1909, p. 129–130). Most of the coal has been produced by surface methods since the 1940's. Currently active or planned large-scale surface mines are located where a coal bed is locally thick or where two or more coal beds are locally thick and the intervening rocks are thin (figs. 2, 3).

SURFICIAL DEPOSITS

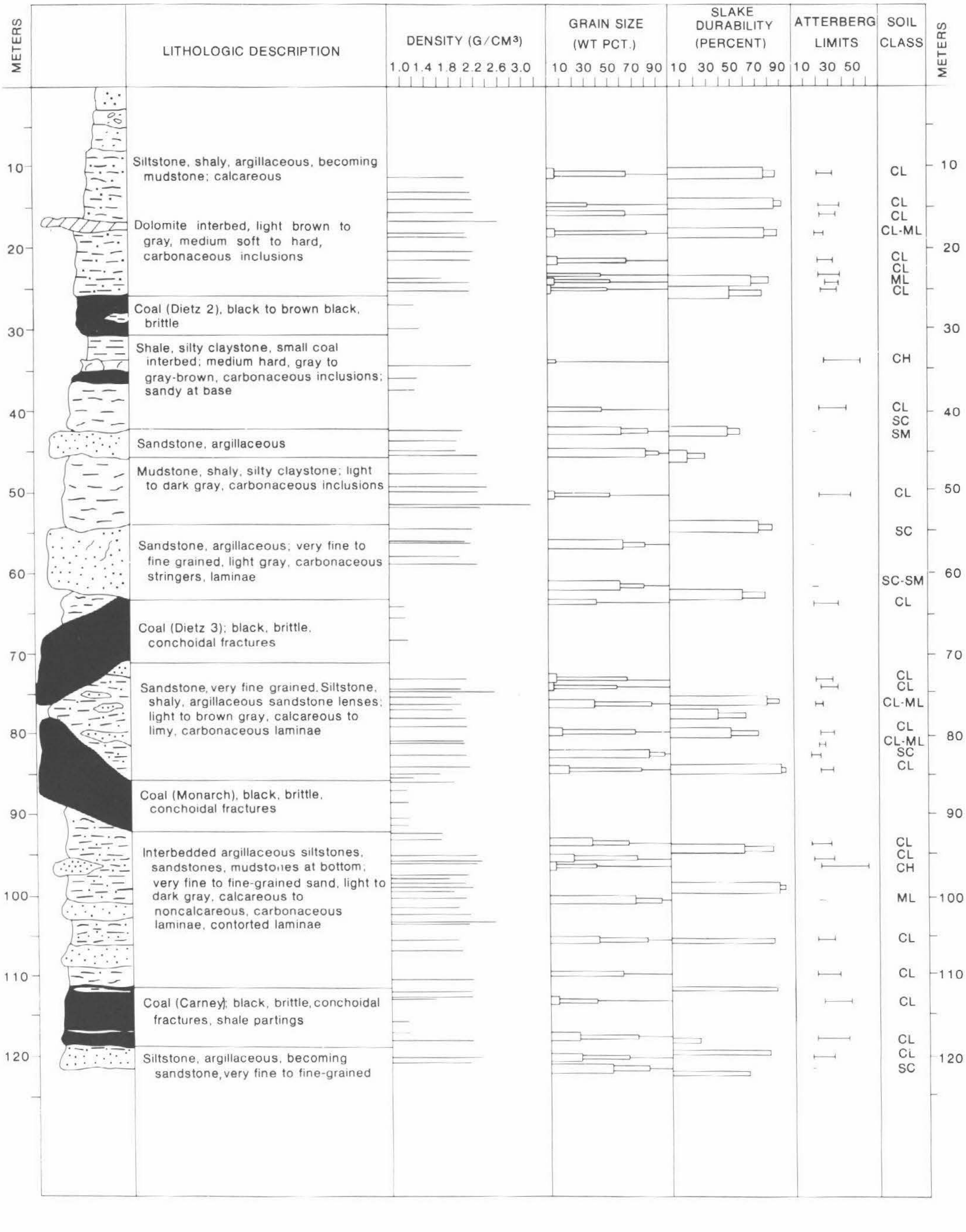
The surficial deposits in the Sheridan area consist of Holocene and Pleistocene colluvium, alluvium, and local pediment deposits with thin to moderately thick soil profiles developed on them (Barnum, 1974). The colluvium, which includes weathered clays, silts, and sands from bedrock of the Fort Union Formation and rounded to irregularly shaped granules, pebbles, and cobbles from adjacent uplifts and outcrops of pre-Tertiary rocks, is concentrated locally on breaks in slope, in draws, and on valley margins.

The alluvium comprises clays, silts, sands, granules, and cobbles derived from Fort Union rocks, from Precambrian rocks in adjacent uplifts, from resistant pre-Tertiary rocks adjacent to the uplifts, and from colluvium. Alluvium, ranging from about a meter to about 15 m thick, blankets the valley bottoms and local terraces above the valley bottoms along major perennial streams and also the bottoms of draws containing small or intermittent streams. The upper portion of the alluvium along the Tongue River near the subsidence study area is predominantly clay, silt, and sand that is overlain by an organic soil that supports hay meadows and local grain fields.

BEDROCK STRUCTURE

Rocks of the Fort Union Formation generally dip 1°-3° eastward in the Acme area. However, local undulations and local changes in thickness of lithologic sequences in short distances cause the rocks to dip more steeply, to dip in the opposite direction, or to dip in directions other than the general attitude. The rocks locally are dis-

FIGURE 5 (overleaf).—Composite geologic section and geotechnical properties of the bedrock and coal in the Tongue River Member of the Fort Union Formation from two core drill holes near the Big Horn coal mine. The Big Horn mine is located about 13 km north of Sheridan, Wyo., in the major coal-bearing portion of the Tongue River Member of the Fort Union Formation of Paleocene age. Grain-size distribution—sand-size (wide bar), silt-size (narrow bar), and clay-size (line) particles—is shown graphically in percent of total disaggregated weight. Slake durability (Franklin and Chandra, 1972, p. 325–338) is in percent of material retained in drum after the first cycle of rotation at 20 rpm for 10 minutes (narrow bar) and percent of material retained in drum after second cycle of rotation at 20 rpm for 20 minutes (wide bar). Atterberg limits of disaggregated core samples, which include plastic limit (smallest value of horizontal line) and liquid limit (largest value), are in percent of water relative to the dry weight of sample. Soil classification terms are described in Lambe and Whitman (1969, p. 35) in terms of plasticity (the numerical difference between liquid limit and plastic limit) as follows: (1) CL—inorganic, silty clays of low plasticity; (2) ML—silts with slight plasticity; (3) CH—inorganic clays of high plasticity; (4) SC—clayey sands, poorly sorted sand-clay mixtures; and (5) SM—silty sands, poorly sorted sand-silt mixtures. In MN/m^2 (meganewtons per square meter), $I_s \parallel$ and $I_s \perp$ are point-load strength indices parallel and perpendicular to bedding, respectively.


METERS
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SLAKE
DURABILITY
(PERCENT)
10 30 50 70 90
ATTERBERG
LIMITS
10 30 50
SOIL
CLASS
METERS
Siltstone, shaly, argillaceous, becoming mudstone; calcareous
Dolomite interbed, light brown to gray, medium soft to hard, carbonaceous inclusions
Coal (Dietz 2), black to brown black, brittle
Shale, silty claystone, small coal interbed; medium hard, gray to gray-brown, carbonaceous inclusions; sandy at base
Sandstone, argillaceous
Mudstone, shaly, silty claystone; light to dark gray, carbonaceous inclusions
Sandstone, argillaceous; very fine to fine grained, light gray, carbonaceous stringers, laminae
Coal (Dietz 3); black, brittle, conchoidal fractures
Sandstone, very fine grained. Siltstone, shaly, argillaceous sandstone lenses; light to brown gray, calcareous to limy, carbonaceous laminae
Coal (Monarch), black, brittle, conchoidal fractures
Interbedded argillaceous siltstones, sandstones, mudstones at bottom; very fine to fine-grained sand, light to dark gray, calcareous to noncalcareous, carbonaceous laminae, contorted laminae
Coal (Carney); black, brittle, conchoidal fractures, shale partings
Siltstone, argillaceous, becoming sandstone, very fine to fine-grained
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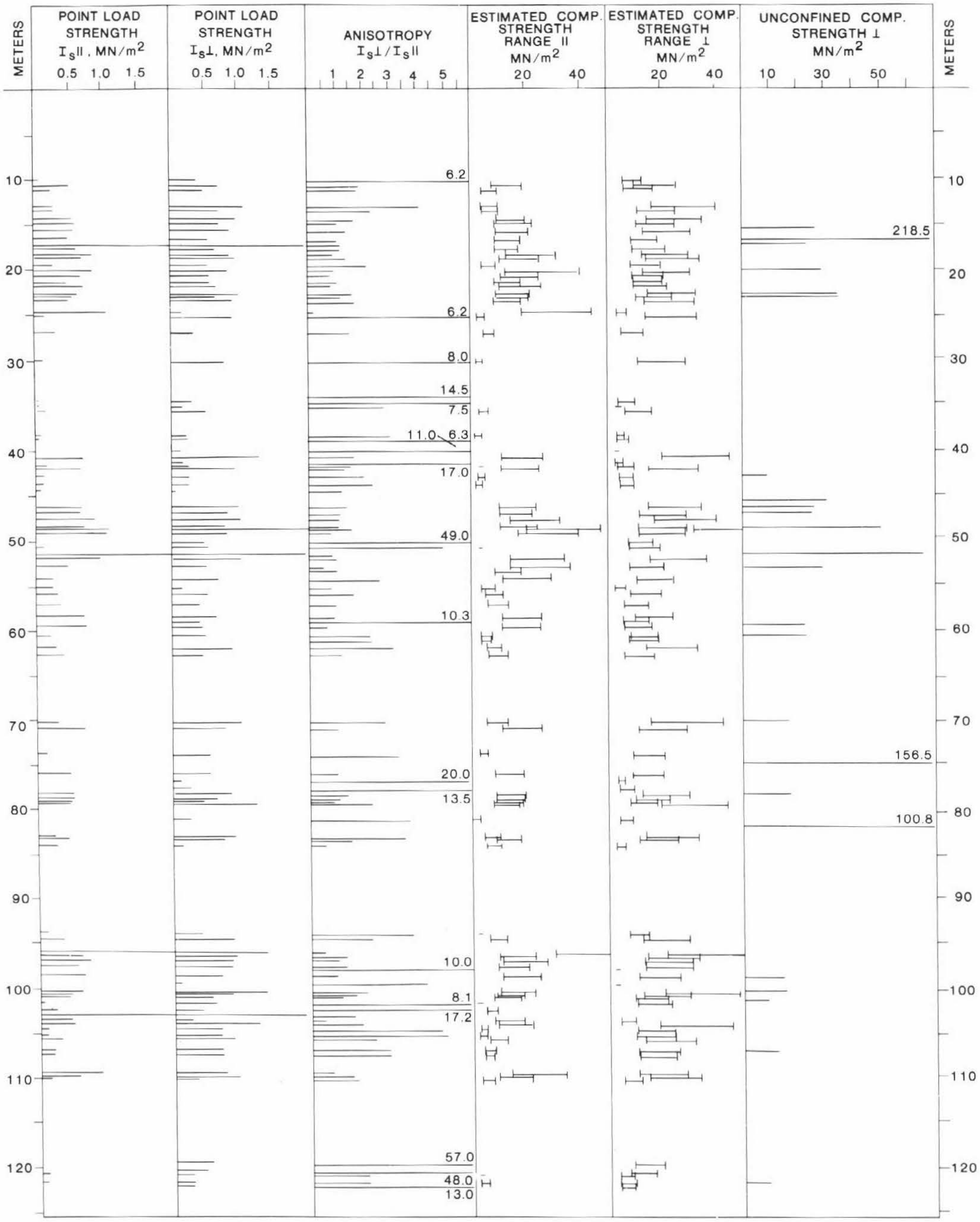
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100.8

placed by discontinuous faults that commonly dip steeply to vertically and trend east-northeastward (B. E. Law, oral commun., 1976).

Joints and lineaments in the bedrock are expressed as individual fractures on outcrops or by the trends in stream drainage, and are revealed as lineaments on aerial photographs. Dominant trends are northwest, east-northeast, west, and north. Based on studies of the trends of drainages on aerial photomosaics and faults and joints mapped by high-resolution photogrammetric plotters, a close correlation exists among (1) the trends of joints and faults in the Fort Union rocks within the Powder River Basin, (2) the dominant trends of the uplifts, anticlines, and flexures adjacent to the Powder River Basin, and (3) the trends of foliation and joints and faults within the Precambrian rocks of the Bighorn uplift (fig. 1).

GEOTECHNICAL STUDIES

The geotechnical and geological properties of rock above and below the coal beds are important factors to consider in planning mining activities, because they control the behavior of the bedrock in response to surface or underground mining and also the behavior of the stripped overburden or spoil after restoration of surface-mined lands. The properties of the rocks at the outcrop commonly are so altered from their natural state that geotechnical test results on rock samples from outcrops can be misleading. Most weak, soft siltstones, shales, mudstones, and coal in outcrops are not preserved well enough to be tested and appear much weaker than core samples, whereas most outcropping sandstones are cemented more completely by near-surface ground water and therefore are stronger at the outcrop than in unaltered bedrock. Therefore, it is often necessary to test drill cores in order to obtain realistic geotechnical results (fig. 5). Some geotechnical properties of the coal and rock mass also can be determined from calibrated, downhole geophysical logging that includes gamma density, caliper, and sonic velocity measurements.

Rock masses commonly are much weaker than strength tests on core samples indicate, because bedding planes, joints, and faults weaken the rocks greatly. Cohesion across most of these discontinuities is zero, or nearly zero. Therefore, bedded, jointed, and faulted rock masses derive strength only by confining stress and the resultant friction along the various fractures. This confining stress commonly is greatly reduced or altered by surface and underground mining activities.

Other factors that tend to weaken rock masses, particularly over periods of years or decades, are the effects of weathering, wetting, and drying by fluctuation and movement of ground water and exposure to air. An example of how rock masses are weakened by the movement of surface and ground waters can be seen in surface mining operations in the western Powder River Basin. Highwalls ranging from 7.5 m to more than 30 m high commonly stand nearly vertical for periods of weeks or months in operating surface mines (figs. 2, 3), but they weaken and fail by rockfalls, landslides, or other mass-gravity movements over periods of years or decades under the effects of alternate wetting, drying, freezing, and thawing of water along fractures and bedding surfaces (fig. 6).

The stable slope angle of fractured and jointed bedrock on strip mine highwalls ultimately may be less than the stable slope angle of a broken-up pile of the same rock, because open joints and tension fractures behind the rims of highwalls provide avenues for water to flow, as well as to freeze and thaw, whereas the broken counterpart of the bedrock in spoil piles at the angle of repose appears to be less permeable and therefore less susceptible to the effects of water. Graded spoil material, however, might absorb surface water readily and fail, unless the graded slopes are designed in accordance with soil engineering properties of the broken-up and mixed overburden material (Terzaghi and Peck, 1967, p. 31–35; Lambe and Whitman, 1969, p. 33–38). Results of these tests should be considered, in addition to in-place soil properties, potential land use, and existing climatic conditions, before benching and final grading requirements of highwalls and requirements for grading restored spoil in surface mines are specified.

As an aid in evaluating the behavior of the Fort Union bedrock in response to past, present, and future coal mining, field and laboratory tests were conducted on cores from two drill holes in

FIGURE 6.—Westward aerial oblique view of the highwall at the abandoned Plachek surface mine near the Big Horn mine (April 1978). Rockfalls, landslides, and mass wasting caused by wetting, drying, freezing, and thawing may ultimately reduce the highwall slope below the angle of repose of the rocks of similar lithology and structure when broken up and mixed by surface mining. A coal fire, located in the black area near the west end of the highwall (middle ground at the right), started in about 1975 by spontaneous combustion. Since then, the fire has spread southward and eastward into coal near the base of the highwall.

the Big Horn mine area in March 1976 (figs. 2, 4, 5). The core, which was made available for testing by Peter Kiewit Sons' Co., was stored in unsealed core boxes a few weeks prior to testing. The core had dried out some and locally was broken up by freezing and thawing.

Results of the field and laboratory tests on the Big Horn cores showed that the bedrock was weak to very weak, except for local thin lenses of dolomite. Characteristically the bedrock might be classified as overconsolidated muds, clays, and sands rather than rocks. Results of tests on core from a drill hole at Sheridan, Wyo., in the spring of 1975 (R. A. Farrow, written commun., 1977) revealed the same thing.

Few tests were conducted on the coal from the Big Horn cores, because the coal was broken up and put in bags before geotechnical testing began. Taff (1909, p. 133) described the fresh coals in the study area as laminated to massive with a black, shiny luster, which break into small angular blocks and fragments with hackly to conchoidal surfaces when mined. The coal, however, turns a dull-black to gray color and breaks readily into small fragments and dust when exposed to moisture and air. According to E. W. Temple (Big Horn Coal Co., oral commun., 1976), piles of coal commonly heat and ignite spontaneously when exposed to air and water, unless the fine dust is removed. Analyses of coal samples, on an as-received basis, collected by Taff (1909, p. 135) from the Carney, Monarch, and Dietz coal beds, reveal that the coal is subbituminous in rank with heat values of about 5,000–5,400 cal/g (9,000–9,700 Btu/lb). Sulfur and ash contents ranged from about 0.2 to 0.8 percent and 3 to 6.5 percent by weight, respectively, for the Carney and Monarch coal beds, and from about 0.4 to 1.2 percent and about 4.5 to 8 percent by weight, respectively, for the Dietz coal beds.

The field tests, which were conducted in a mobile laboratory, included lithologic identification, point-load strength index, and slake durability tests (fig. 5). The point-load strength index test (Broch and Franklin, 1972, p. 669–693) is a simple, inexpensive method of estimating the tensile and compressive strengths of rocks. The point-load strength index approximates the tensile strength of the rocks, whereas an unconfined compressive strength can be estimated by multiplying the point-load strength by 15 and 35, based on tests by D'Andrea, Fischer, and Fogelson (1965, p. 7), Broch and Franklin (1972, p. 690), and on various tests run by the authors. Point-load index strength tests were run parallel and perpendicular to bedding in order to determine

FIGURE 7 (above and facing page).—Southward aerial oblique view of subsidence depressions, pits, and cracks above the south part of the abandoned room-and-pillar Acme mine (May 1976). The mine was operated from the early 1900's to 1943. The location and geometry of subsidence depressions and pits correspond to mining areas and to individual mine openings. *A*, General view of subsidence features (foreground), abandoned strip mine (left background), and currently operating Big Horn surface mine along the Tongue River (center and left background). Dragline-dumped spoil piles in old abandoned strip mine are stable at the angle of repose; the vertical highwall in alluvium also is stable. Note that depressions enclosing pits (left middle ground) are rectangular in form near the abandoned strip mine, where overburden is about 12 m thick, to elliptical in form in left foreground, where the overburden is about 25 m. Some pits (left center and right center of photograph) are deeper than the reported anisotropy or the ratio of strength perpendicular to bedding to strength parallel to bedding. The slake durability index test is designed to simulate, in an accelerated way, the wetting, drying, and abrasion of rocks subjected to weathering, erosion, and transport by streams. Two cycles were run on most samples to more accurately simulate wetting and drying.

Characteristically, the point-load strength indices of the siltstones ranged from 0.01 to 1 MN/m^2 perpendicular to bedding, with an anisotropy of 2 to 10; the sandstones, 0.5 to 1 MN/m^2 parallel and perpendicular to bedding, with an anisotropy of approximately 1 (fig. 5). The slake durability indices of the siltstones, mudstones, and shales, when subjected to repeated test cycles, ranged from 30 to 90 percent in the first cycle and 15 to 80 percent in the second cycle; the sandstones ranged from 25 to 85 percent in the first cycle and 15 to 75 percent in the second cycle (fig. 5). Slake durability indices, according to Franklin and Chandra (1972, p. 337) of bedrock range from very low to high.

Laboratory tests conducted at U.S. Geological Survey laboratories in Golden, Colo., included grain-size distribution, density, unconfined com-

thickness of coal mined. On cold mornings steam is visible above many cracks and pits, indicating underground fires. The subsidence and fire that occurred above ground on January 22, 1979, were located a few meters to the right of the road along the spoil where the road curves to the right. The grass is greener in depressions and pits where moisture accumulates. *B*, Closer view of subsidence depressions containing pits and bounded by tension cracks. Pits of markedly different ages are present, ranging from bowl-like depressions blanketed by green grass, many years or decades old, to small pits with vertical or overhanging walls, only a few months or years old. Subsidence depressions, pits, and cracks occur sporadically on road in left foreground and present problems to stock and to vehicle travel.

FIGURE 8.—Southeastward aerial view showing the surface effects of past and present coal mining along the Tongue River (July 1977). Subsidence pits, troughs, depressions, and cracks have formed above the south part of the Acme mine. Dam in right foreground across Hidden Water Creek ruptured due to subsidence. The water now is diverted into subsidence depressions, pits, and cracks upstream from the dam. Garbage from the town of Acme was dumped into the large pit at the left of the photograph. Subsidence pits and troughs in middle of photograph are in alluvium. Note that the pits near the road and left of the draw do not occur in any noticeable depression; these pits are located above collapsed areas in the main haulageway or in spur haulageways of the Acme mine, where adjacent coal pillars are strong enough to support the overburden. Alluvium is being stripped at the Big Horn surface coal mine to extract the coal (background). Grading is beginning near the river (right background).

pressive strength, and Atterberg limits (fig. 5). Grain-size and density test results showed that the rocks are primarily argillaceous siltstones, claystones, shales, and local sandstones with densities ranging from about 1.7 to 2.3 g/cm^3. The density of the coal ranged from 1.1 to 1.3 g/cm^3. Results of the unconfined compressive strength tests reveal that, with the exception of the local, strong dolomite beds and a few other beds, compressive strength of the remaining bedrock ranged from 10 to 50 MN/m^2. Many of the weaker rocks, which were tested for point-load strength, were too weak even to be prepared for the unconfined compressive strength test; such rocks were treated as strong soils.

Liquid limits and plastic limits were measured on ground up samples of the core. Plasticity indices, which are the numerical difference between liquid limit and plastic limit, provide a basis for the unified soil classification (fig. 5; Lambe and Whitman, 1969, p. 33–38). Based on this classification, the siltstones and mudstones contained clays of from slight plasticity (ML) to low to medium plasticity (CL), the local shales and claystones beneath the coal beds contained clays of high plasticity (CH), and the sandstones comprised poorly graded sand-clay mixtures (SC) and sand-silt mixtures (SM).

SURFACE SUBSIDENCE EFFECTS

SHERIDAN, WYOMING, AREA

Surface subsidence effects caused by underground mining in the western Powder River Basin comprise local depressions, pits, troughs, tension cracks, and compression bulges (cover; frontispiece *A*, *B*; figs. 7, 8). These effects also were observed and recorded in the Illinois coal fields in the early 1900's by Young (1916) and in the United Kingdom, for example, by Piggott and Eynon (1978, p. 749–780). The depressions overlie a number of rooms in room-and-pillar mining areas, where the remaining coal was not strong enough to support the weight of the overburden either because the coal pillars were partly removed or because the initial coal pillars were too small to support the load. In areas where the overburden is less than about 15 m thick, the depressions range in depth from about 30 cm to 2.5 m; in plan view many are square or rectangular (frontispiece *A*) with rounded corners that outline the extent of the former mining areas. In overburden thicker than about 25 m, the corners of the depressions become more rounded, and the general outline of the depressions is more circular or elliptical in plan view. The areas encompassed by the surface depressions appear to be slightly larger than the mining areas beneath the depressions.

Tension cracks occur at the margins of subsidence depressions as a result of convex bending and associated stretching of the ground surface (figs. 7, 8, 9*A*; Dunrud, 1976a, p. 4–5). Compression ridges or bulges occur in the depressions where the ground surface is subjected to concave bending and attendant shortening of the ground surface (fig. 9*B*; Young, 1916, p. 36), although this damage is not as evident as the tension cracks because the soft bedrock and alluvium compress with less visible effect and compression features are not enhanced by erosion. Holes measuring 5 cm to as much as 3 m wide are present locally in soil and colluvium above tension cracks a few centimeters to a few meters wide that occur in the shale and claystone overburden rocks below the soil and colluvium (fig. 10). In these areas the soil and colluvium stretched without fissuring, as the bedrock cracked in response to tensile stresses along the margins of local subsidence depressions. Consequently, soil and colluvium cover the underlying fissures except where holes were initiated by local piping or by the activities of man or animals. At the surface these holes look very much like the initial pits above individual mine cavities; however, below ground the initial pits commonly widen out into large cavities and are 3–4 m deep. The holes continually enlarge with time under the forces of erosion and small mass gravity movements, until the slope becomes stable or until the cracks are filled with material.

Subsidence pits and troughs occur above individual mine openings or above the intersections of mine openings. Field evidence indicates that the pits result from intermittent, sequential collapse of the overburden or an upward stoping process that is initiated by the collapse of mine roofs. In some areas the upward stoping process can be observed in subsidence pits that are adjacent to underground cavities. The roofs of these cavities commonly comprise arches and the floors consist of caved, broken rock or unconsolidated material (fig. 11). The cavities migrate upwards as roofs collapse and the caved material accumulates on the floor of the cavities. Troughs, which occur above elongate mine openings or rooms, probably form by the coalescence of individual pits. Collapse of mine roofs is governed by the width of mine openings, the strength of mine roofs, and the adequacy of roof support system used.

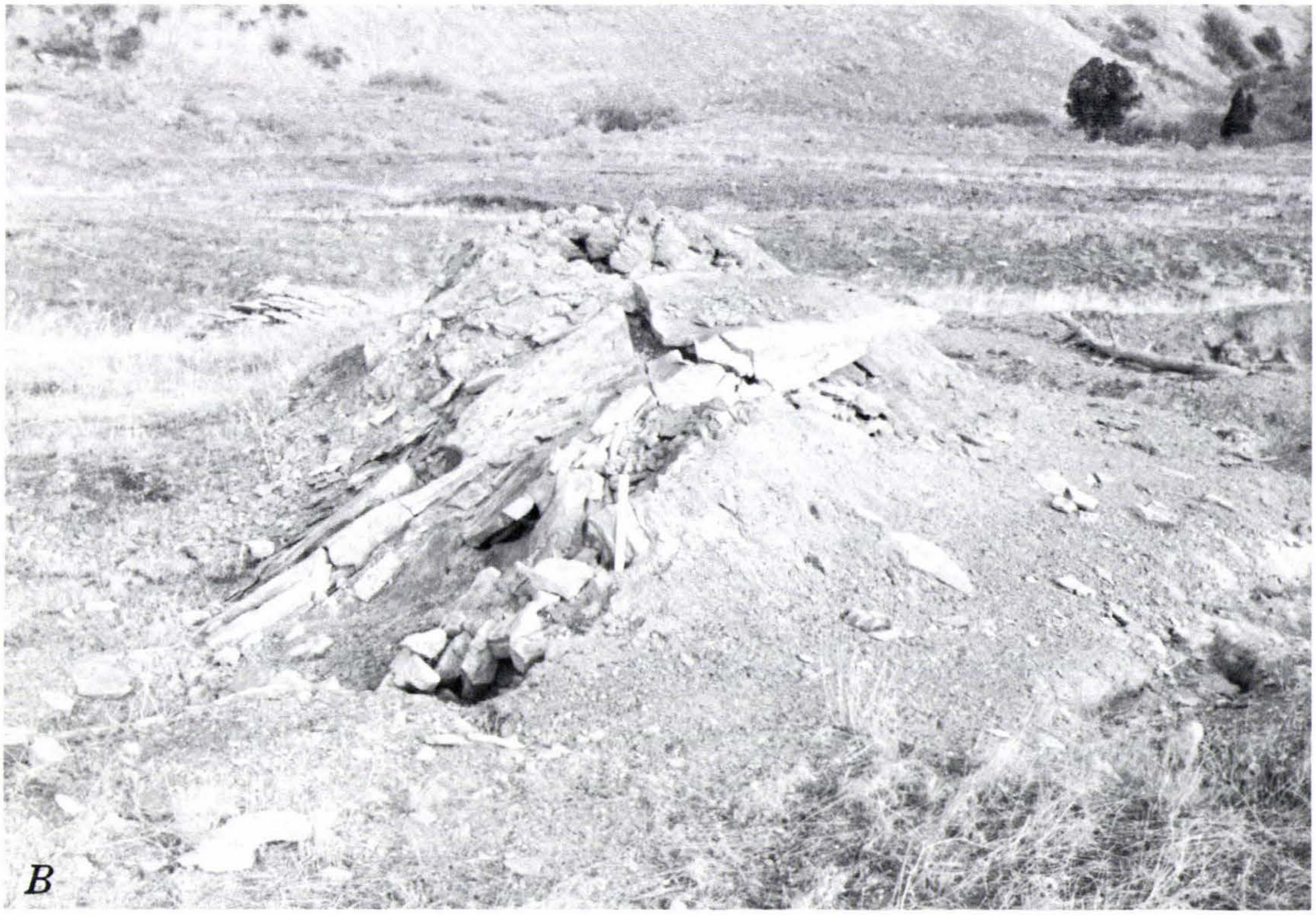
The occurrence of pits at the surface, therefore, depends on the time necessary for mine roofs to fail, on the thickness and strength of overburden materials, and on the width of mine openings. In the Acme area, the overburden consists of weak shales, mudstones, and local sandstones ranging in thickness from about 5 to 60 m. Pits commonly are more abundant in areas where mine openings trend northwest or northeast, parallel to the predominant trends of joints in the bedrock. New pits may form among old pits many years or many decades after initial pit formation (fig. 7). The occurrence of pits at the surface, even where overburden is of constant thickness and strength,

FIGURE 9 (above and facing page).—Ground views showing tensile and compressive features caused by subsidence. *A*, Northwestward view of a large tension crack at the margin of a subsidence depression. Local pits to the right of the crack occur above individual underground mine openings. Snow and water accumulate in the larger cracks, which in turn enlarges the cracks by erosion. *B*, View of buckled and bulged siltstone and mudstone in the eastern part of the Acme mine above an underground fire. The bulge is about 1.5 m high. The effects of shortening are most pronounced in subsiding ground above coal mine fires because subsidence amounts are greater where more of the coal is removed than in past mining. The bedrock was stained a maroon color by oxidation of iron caused by heat from the fire below.

tends to be sporadic because collapse of mine roofs is sporadic.

The initial pits caused by sequential collapse of mine roofs commonly are nearly circular holes 1-3 m wide and 2-5 m deep which have vertical to overhanging sidewalls (example of appearance in figs. 10, 14*A*). The pits widen and the slope angle becomes smaller through the processes of erosion, mass wasting, and deposition. In this area, these processes may continue for 10-25 years or more, depending on geologic conditions and geotechnical properties of the overburden. The bases and walls of the pits support range grass, vines, and woody plants a few years or decades after formation of the initial pits, depending on the nature of the near-surface material.

The geotechnical properties of the material in which the pits, troughs, and cracks form control the behavior of the rims and walls and their rate of failure. Pits, troughs, and cracks in sandstone or in alluvium, consisting of well-drained sands and gravels commonly exhibit vertical rims and walls for many years or even decades. However, the rims and walls of pits and cracks in poorly drained siltstones, mudstones, claystones, and shales—that contain clays of medium to high plasticity—may slake, slab, slough, or flow readily. These failures occur by mass gravity move-



ments and mass wasting until pits and cracks attain a saucer shape or flattened trench shape in a few years or decades and begin to support vegetation.

Subsidence pits are present in the local depressions as well as in areas above room-and-pillar mine workings where no noticeable depression exists—or at least where depressions cannot be detected without making precise, periodic surface measurements (figs. 7, 8). Most pits within the depressions are not as deep as pits outside the depressions. The total depth of the depressions and the pits within them is roughly equal to the depths of pits that are present where no noticeable depression exists. On the basis of mine reports, the total depth of both types of these surface collapse features commonly is nearly equal to the thickness of coal mined. Locally, however, the total subsidence is greater than the reported thickness of the coal mined. In these areas some of the collapsed material probably spreads, or is transported, laterally into adjacent mine openings or compacts more than the original state of the material, aided by the presence of water. Most pits caused by roof collapse occur where the overburden is less than about 10 times the original height of the mine workings, an upper limit suggested by studies in the United Kingdom by Piggott and Eynon (1978, p. 764–765). However, pits might occur in overburden as much as, or more than, 15 times the height of the mine workings in areas where the caved material moves laterally.

Pits within the local depressions usually form many years or many decades after the depressions, depending on geologic factors and mining conditions previously discussed; therefore, local depressions can serve as warnings to possible future pit collapse within them (figs. 7, 8). However, the elevation of the ground surface may not noticeably change prior to pit collapse above mine openings that are bounded by pillars strong enough to support the overburden (figs. 8, 11). In these areas the ground surface may collapse suddenly with little or no advance warning unless it is periodically monitored for minute movement. Pits and cracks are only beginning in some parts of the Dietz mine area, where the overburden is about 45 m thick (Darton, 1906, p. 111) above mines that were worked from the early 1900's to the early 1920's (frontispiece *B*; fig. 4).

BEULAH, NORTH DAKOTA, AREA

Spectacular surface subsidence features occur above abandoned underground coal mines in western North Dakota, particularly in the Beulah area (fig. 12). The subsidence features look like those in the western Powder River Basin except that subsidence troughs are more common. The overburden is similar in lithology and age to the coal-bearing rocks near Sheridan, Wyo., except that the bedrock appears to be somewhat softer and that glacial deposits—comprising clays, sands, silts, gravels, and local erratic boulders—locally are present in the upper few meters (D. E. Trimble, written commun., 1977).

Room-and-pillar mines operated in lignitic coal beds 2.5–9 m thick from 1884 to 1966. The area shown in figure 12 was mined by underground methods from 1918 to 1952 (Parker, 1973, p. 40). The coal bed is about 5 m thick and the overburden thickness averages about 25 m (Pollard and others, 1972, p. 21). The geometry of the room-and-pillar mine workings is vividly portrayed by subsidence pits and troughs. As in the Sheridan, Wyo., area, the troughs are believed to overlie elongate rooms and apparently formed by coalescence of individual pits.

Much of the lignite in the Beulah area was produced by surface mining in the past; currently lignite is produced only by surface mining (fig. 13). Restoration of surface-mined lands, although not done in the past, is now underway (Hardaway, 1976, p. 107–112) in compliance with the Mined Land Reclamation Law, 1969, which essentially requires that land mined by surface methods be restored in a manner that will minimize adverse economic and aesthetic effects and will maximize the future use of the land (Pollard and others, 1972, p. 7–8). Based on an aerial reconnaissance study by the authors, operations appear to be hindered more by near-surface ground water than in similar surface mining operations in the Powder River Basin. Depressions may occur on restored land in the Beulah area, however, that could affect drainage because much of the land is nearly flat. There are fewer hills than in the Powder River Basin from which material can be used to compensate for the volume of coal removed (figs. 12, 13).

FIGURE 10.—Three holes in soil above a subsidence crack in bedrock. The holes are 30–45 cm in diameter and are located in soil and weathered bedrock approximately 1.2 m thick. Soil may initially bridge the tension crack without rupturing as fissure forms in bedrock below. Later, the holes form, either by natural piping associated with wetting and drying or by surface activities of animals. Note grass is greener and more prevalent on either side of crack than along it because crack dewaters soil and retards plant growth.

SUBSIDENCE PROCESSES

Studies of deformations within underground coal mine workings and at the surface in the United States (Peng, 1978, p. 1-280); in Utah and Colorado (Dunrud, 1976a, b; Osterwald, 1961, 1962); in Wyoming (Dunrud and Osterwald, 1978a, p. 175-190); in the Raton, N. Mex., area (Gentry and Abel, 1978, p. 191-220); in the Netherlands (Pöttgens, 1979, p. 267-282); and in the United Kingdom (National Coal Board, 1966, 1975; Shadbolt, 1978, p. 705-748) provide a basis for interpreting subsidence processes that are initiated when underground mining begins and that end with surface subsidence effects described in the previous section. In this section, stresses and deformations are briefly described (1) within and near the mine workings, (2) in the mine overburden, and (3) at the land surface, in order to relate surface subsidence to underground mining operations. Additional information is available, for example, in Peng (1978).

Analyses of the behavior of coal and rock in the mine roofs, ribs (walls), and floors of underground coal mines by the authors and others (Schoemaker, 1948, p. 4-7; Dunrud, 1976a, p. 17-30) show that stresses caused by overburden load and by any existing tectonic stresses must readjust to the presence of underground openings. Stress concentrations after mining are greater in

FIGURE 11.—Recent subsidence pit above the Old Monarch mine (fig. 4) showing connecting underground cavity. Fencepost, about 2 m long, was left dangling in mid-air by collapse. The road from which photograph was taken collapsed in 1974 and had to be filled and graded in order to be used again. The cavity is migrating upward by intermittent collapse (stoping) of the mine roof. Original mine workings are estimated to be about 10 m below the surface. Note that the ground above and behind the pit appears to be unaffected by a large cavity only 2 m below, except that plant growth within about 25 cm of the rim is retarded due to the effects of soil dewatering.

the coal and rocks near the mine openings than they were before any opening existed in order to bear the stress previously borne by the material removed from the openings.

The shapes of the mine openings—in addition to such factors as overburden thickness, lithologic and structural character of the coal and associated rocks, and hydrologic conditions—control the state of stress around them. For example, tensile stresses in the roofs and floors of common rectangular or trapezoidal mine openings, can be nearly as great as the overburden stress, whereas compressive stresses two to three times greater than the overburden stress can occur on the ribs (Schoemaker, 1948, p. 4). However, stresses around elliptical openings, where the long axis of the ellipse is oriented in the direction of maximum stress, are primarily compressive according to Fenner's analysis (presented in Schoemaker, 1948, p. 6–8). Elliptical openings therefore are much more stable than the common rectangular openings because, as shown in the geotechnical properties section (fig. 5), rocks are much stronger in compression than in tension.

Elliptical zones of compressive stress commonly occur around individual mine openings (fig. 14*A*). They also occur around larger cavities created by extraction of pillars in room-and-pillar mining areas (Dunrud, 1976a, p. 23–30) or by longwall mining unless the elastic limit of the coal or rock is exceeded and viscoelastic or plastic deformation occurs, or the cavities are sufficient-

FIGURE 12.—Oblique aerial view of subsidence features located 1.5–6.5 km north of Beulah, N. Dak., looking south (October 1976). Pits and troughs occur above elongate rooms in room-and-pillar mine workings in lignitic coal that was mined from 1918 to 1952. The overburden averages about 15 m thick and is composed of poorly consolidated claystones, siltstones, and lenticular sandstones overlain by local glacial deposits. The land surface above mine workings is of little use because of subsidence hazards. Wheat farming, the major industry in the area, is hazardous in the old mining areas because the vibrations and extra weight of equipment might trigger further collapse. Cultivated areas at right probably overlie areas of unmined coal.

FIGURE 13.—Eastward aerial view showing the effects of lignite mining near Beulah, N. Dak. (October 1976). Farmlands used for raising wheat are disrupted by subsidence pits and troughs (middle ground), spoil piles, and highwalls remaining from past underground and strip mining operations (foreground and background). Restoration, including grading and revegetation of spoil, has begun on later surface mining operations (background). Wheat is being grown between two abandoned strip mines in the foreground but not above underground mines (middle and near background).

ly wide so that the compression ellipses migrate to the ground surface (fig. 14*A*, *D*). Whittaker and Pye (1977, p. 306–307) discussed the transfer of overburden stresses above mine openings to adjacent coal by the presence of pressure arches and indicated that the height of the relaxed or destressed zone is approximately equal to the width of the mine opening.

Deformation of coal and rocks within the elliptical zones of compressive stress is controlled by such factors as (1) the height-to-width ratio of the openings, (2) the elastic and time-dependent geotechnical properties of the coal and rocks, (3) lithology and geologic structure of the roof and floor rocks, and (4) hydrologic conditions. Breaking and caving above mine openings are extensive where height-to-width ratios are near 1 (fig. 14*A*, enlarged view; 14*B*, *C*), whereas the rock strata may only break one to three mining thicknesses above mine openings with very small height-to-width ratios (fig. 14*D*). The strata commonly flex downward into mine openings as more or less continuous units only a few mining heights above mine openings, with very small height-to-width ratios, and recompress the fragmented debris below. The rate of downward movement of overburden rocks into mine openings, or the voids above the openings, commonly is not uniform, because elliptical zones of compressive stress around the mine openings migrate upward and downward from openings that are widened by mining. This, in turn, may cause separation of

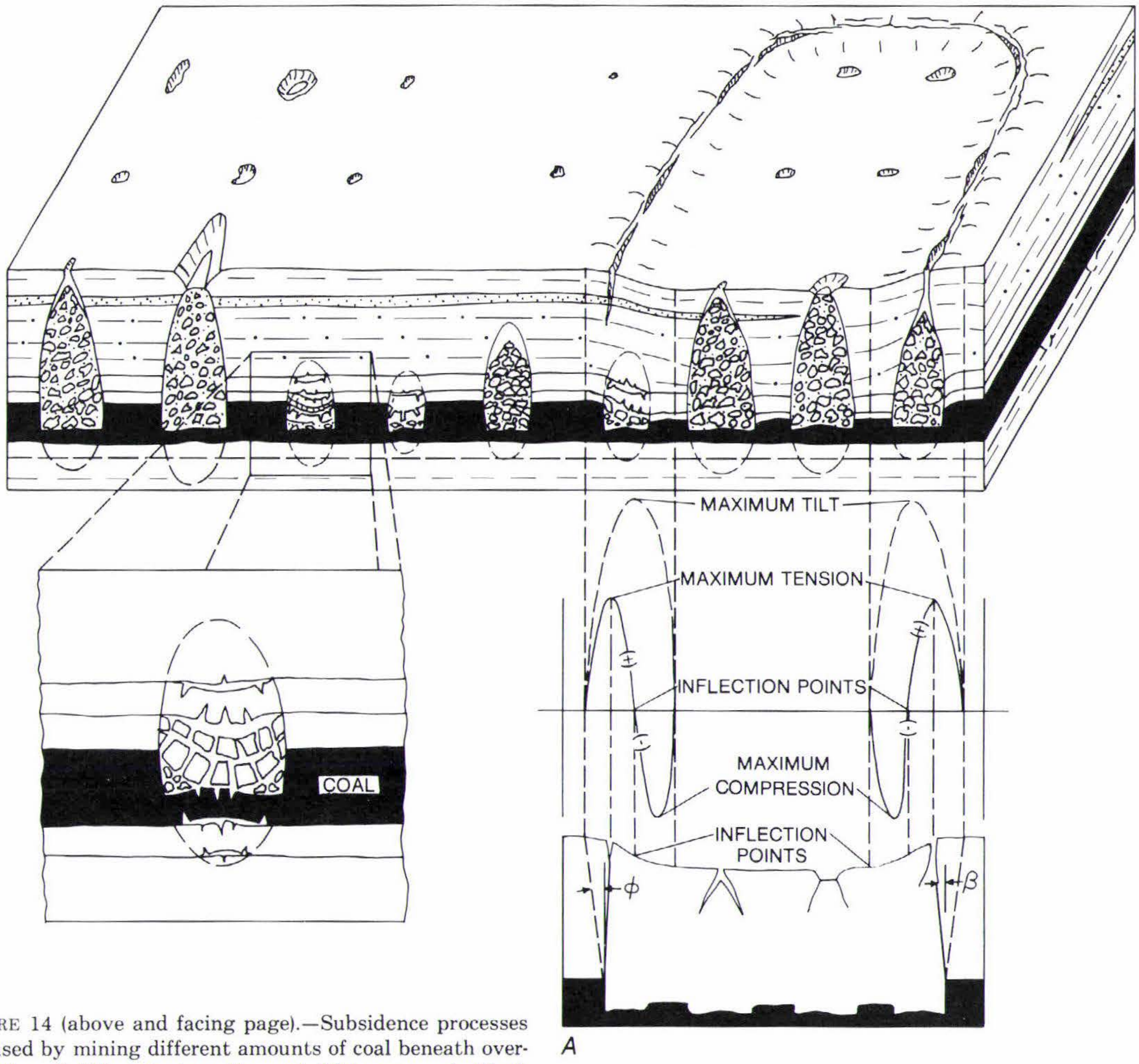
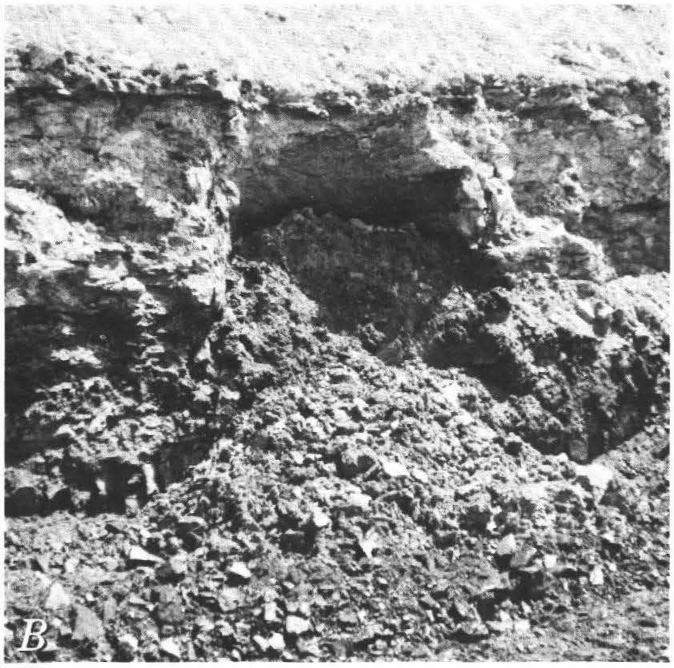
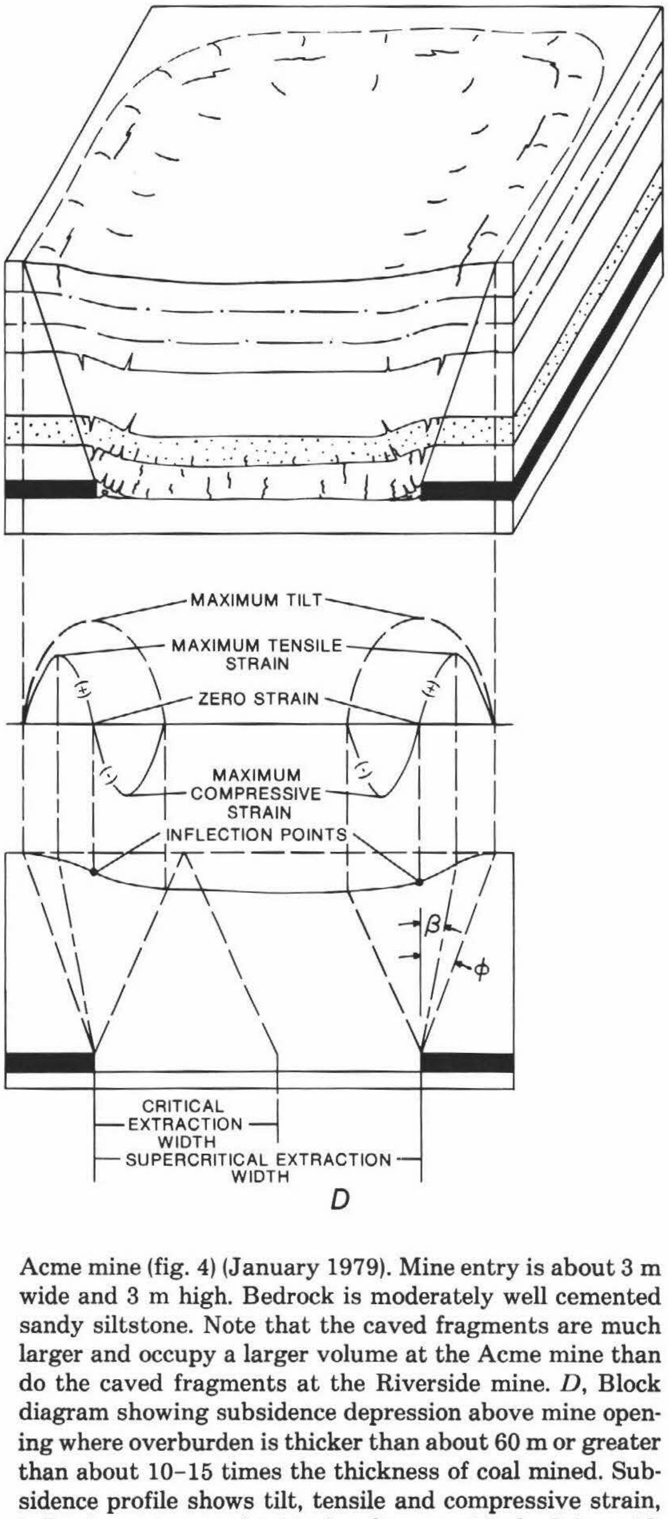


FIGURE 14 (above and facing page).—Subsidence processes caused by mining different amounts of coal beneath overburden of different strengths and thicknesses. *A*, Block diagram showing subsidence pits above caved mine openings where adjacent coal is sufficiently strong to support the weight of the overburden (left), and subsidence depressions and subsidence pits where the remaining coal yielded partially to the weight of the overburden (right). An enlarged view of the elliptical zone of compressive stress around a rectangular mine opening shows buckled and heaved floor and caved roof rocks that are common in zones of reduced stress within the zone of compression. Subsidence pits, which are the end result of successive collapse of the mine roofs, are deeper where no subsidence depression occurs than are pits within the depression. A plot of tilt, horizontal displacement, curvature, and strain caused by differential settlement is shown below the subsidence depression on right. ϕ , limit or draw angle; β , break angle; +, tensile strain; −, compressive strain. *B*, Caved opening above an entry in the Riverside mine (fig. 4) exposed on a surface mine cut (May 1978).Bedrock is soft, silty claystone with local thin carbonaceous zones. Entry is estimated to be about 3 m wide. The original height of the entries reportedly was about 2 m; the current limit of caving is about 9.5 m above the mine floor. *C*, Caved opening of an entry in the southern part of the





Acme mine (fig. 4) (January 1979). Mine entry is about 3 m wide and 3 m high. Bedrock is moderately well cemented sandy siltstone. Note that the caved fragments are much larger and occupy a larger volume at the Acme mine than do the caved fragments at the Riverside mine. *D*, Block diagram showing subsidence depression above mine opening where overburden is thicker than about 60 m or greater than about 10–15 times the thickness of coal mined. Subsidence profile shows tilt, tensile and compressive strain, inflection points, and critical and supercritical mining widths above an opening where the coal was completely removed.

the rock units that are within or above the compression zones from those that are the compression zone, in (fig. 14*A*).

Subsidence commonly occurs above these elliptical zones of compressive stress because the weaker material, such as the coal, shale, and mudstone within the zone, yields to the increased compressive stresses (Dunrud, 1976a, p. 22-25). Surface subsidence therefore commonly begins above mining areas before the elliptical zones of compressive stress reach the surface. The zones may migrate upward after all mining activities have ceased, because of either time-dependent failure of the rock or coal within the zone of compressive stress or failure due to wetting and desiccation of the coal and rock with seasonal and other cyclical fluctuations of the position of the water table. When the zones of compressive stress reach the surface, the ground surface either settles downward to form subsidence depressions (fig. 14*A*, *D*) or it collapses to form pits, depending on the height-to-width ratios of the underground cavities (fig. 14*A*, left). Pits eventually form at the surface in areas where these ratios are close to 1, unless the overburden is thick enough to contain cavities after they have become filled with caved debris (fig. 14*B*, *C*). Depressions commonly occur where the height-to-width ratios of the mine cavities are much smaller than 1 (fig. 14*A*, right; 14*D*).

The area mined necessary to cause maximum surface subsidence is called the critical area (fig. 14*D*; National Coal Board, 1975, p. 2-3). Critical area is dependent on overburden thickness. The thicker the overburden, the greater the mined area must be for the compression arch to reach the surface and allow maximum subsidence. Maximum subsidence commonly occurs when the horizontal dimensions of the mine cavities are greater than 0.8-1.2 times the overburden thickness (fig. 15). An area smaller than the critical area, where compression arches may still be present above the mine cavity, is called subcritical and a mining area larger than critical is called a supercritical area. The areas mined commonly are rectangular but most subsidence depressions are rounded (fig. 14*A*, *D*), apparently because of the formation of an elongate, horizontally oriented elliptical zone of compressive stress. Rounding of the corners of a rectangular mining panel was observed by Dunrud in western Colorado in 1976 as the roof rocks broke and collapsed behind the roof support jacks in a longwall coal mining operation.

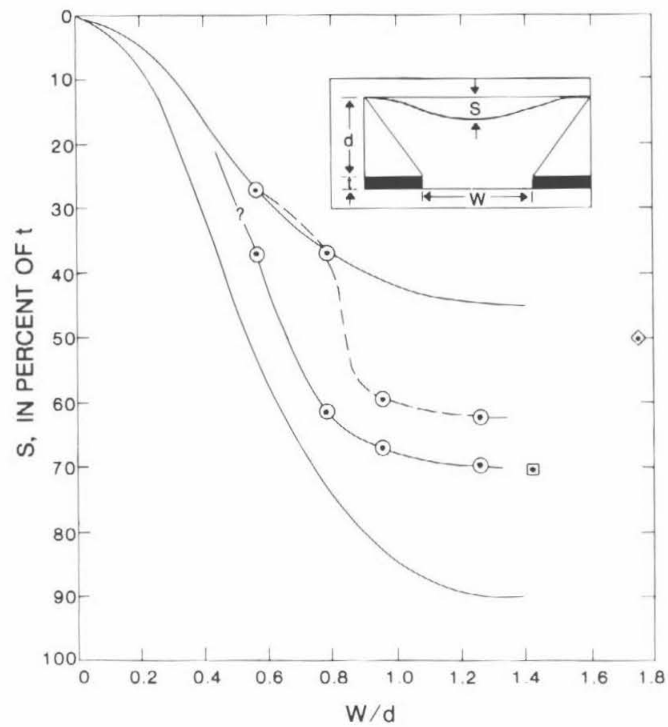


FIGURE 15.—Maximum subsidence for selected coal mining areas in the United Kingdom and in the Western United States. Graph shows maximum subsidence (S), in percent of thickness of coal mined (t), versus the ratio of mining panel width (W) to overburden depth (d) (see inset for details) for longwall mines in the United Kingdom (upper solid line for backfilled (stowed) mines; lower solid line for caved or strip-packed longwall mines; data from Bell, 1975, p. 116; Shadbolt, 1978, p. 729) and for room-and-pillar mining at Somerset, Colo. (dashed and solid lines through circled data points), in rugged terrain underlain by moderately strong mudstones and sandstones of the Mesaverde Formation of Late Cretaceous age. The dashed curve shows surface subsidence upon completion of mining; the solid curve through circled data points shows subsidence amounts when the surface appears to have stabilized; difference between the two curves equals residual subsidence. The points enclosed by the square and diamond are for measurements made by Gentry and Abel (1978, p. 204) on a ridge and adjacent draw above a supercritical longwall panel in the York Canyon coal mine, in rugged topography near Raton, N. Mex., where the overburden consists of moderately strong mudstones and sandstones; the subsidence was 25-30 percent less beneath a draw than it was beneath an adjacent ridge (Gentry and Abel, 1978, p. 203-204).

Although complicated by mining and geologic factors, such as adjacent mining areas, mining of vertically superposed coal beds, topography, lithology, and structure, the differential lowering of the overburden strata and the ground surface above subcritical, critical, and supercritical mining areas produces within the overburden and at the surface: (1) vertical displacement, (2) horizontal displacement, (3) tilt, (4) convex (positive) and concave (negative) curvature, and (5) tensile and compressive strain and local rupture (fig. 14*A*, *D*).

As vertical displacements occur within subsidence depressions, tensile stress and attendant strain occur at the margin of the depression due to positive curvature and reach a maximum at the point of maximum curvature (fig. 14*A*, *D*). The tensile strain reaches zero at the point of inflection, where the ground tilt reaches a maximum. The stresses and resulting strains become compressive inward from the point of inflection due to negative curvature and reach a maximum at the point of maximum negative curvature. Above critical or supercritical mining areas, negative curvature and tilt decrease inward and are zero where the curvature is zero. Compressive stresses and strains may be greater above subcritical mining areas than they are above critical or supercritical areas because two zones of compressive stress commonly are superimposed.

Tensile stresses and strains often are greater above coal barriers between two adjacent mine areas where tensile stresses, caused by positive curvature at the margins of the two adjacent depressions, are superimposed (Dunrud, 1976a, p. 4–5; Shadbolt, 1978, p. 727–728). As mining proceeds, the strata and surface are subjected to all these types of deformation until the mining no longer influences the surface. Shear stresses and strains also are generated along major lithologic boundaries by flexure of strata caused by downwarping of the rock mass into mine cavities. Further information on deformations produced by subsidence can be found, for example, in Shadbolt (1978, p. 705–748), in the Subsidence Engineers Handbook of the United Kingdom (National Coal Board, 1966, 1975), Dunrud (1976a), Peng (1978, p. 281–342), Singh (1979, p. 92–112), Salamon (1978, p. 187–208), and Pöttgens (1978, p. 267–282).

Subsidence depressions may not occur, or at least may not be evident without the use of precision surveying instruments, above room-and-pillar mine areas where only a small percentage of the coal is removed (figs. 8, 11, 14*A*, *B*, *C*). In these areas pits may eventually form if the overburden is not thick enough for the cavities to close by bulking of the caved debris. Subsidence pits can occur suddenly and without warning where depressions do not occur. These pits commonly are deeper than the pits within depressions. Pits within subsidence depressions indicate that coal pillars or parts of pillars are present in the mine openings below, but that these pillars are not strong enough to support the weight of the overburden completely (figs. 7, 8, 14*A*). Consequently, the overburden and surface subside, but not as much as if all the coal were removed. Pits form later, sometimes decades later, when the zones of compressive stress above individual mine openings or above the intersections of two mine openings migrate to the surface. The total depth of the depressions and pits may be nearly as deep as or sometimes even deeper than the height of the mine workings, because the collapsed material may spread laterally into adjacent mine openings, particularly where water is present in the mine workings to promote it.

The surface area affected by subsidence commonly is greater than the area mined where all or much of the coal is removed (fig. 14*D*; *A*, right side), and particularly where the overburden is thicker than about 60 m. The draw angle or limit angle ϕ is defined as the angle, referenced to the vertical, made by drawing a line from the margins of the depressions or affected surfaces at the surface down to the margins of the mine area causing the subsidence. Studies in abandoned coal mine areas north of Sheridan, Wyo., indicate that the draw or limit angle is steep to nearly vertical where the overburden is less than about 60 m thick. This angle is nearly 0 above barrier pillars between two adjacent mining panels and ranges from 10° to 25° above solid coal barriers in moderately strong Upper Cretaceous Mesaverde rocks in the Somerset district, Colorado (Dunrud, 1976a, p. 34). However, the limit angle might range from 0° to 35° in many mines of the West, depending on overburden thickness, mining methods, geology, and topography. In the Limburg coal mining area of the Netherlands, the limit angle is approximately 45° (Pöttgens, 1978, p. 267), whereas it averages 35° in British coal fields, but may be less in deeper mines, according to Shadbolt (1978, p. 726). The limit or draw angle probably changes attitude with lithology, structure, strength, and depth of overburden.

The angle of break, or break angle β —which is the angle of inclination of a line connecting points of maximum tensile stress and strain, from the edge of the mine workings to the surface—is less than the angle of draw. The break line—the line connecting points of maximum tensile stress and strain—normally is not straight, but steepens in thick, strong rocks and flattens in thin, weak strata. In the Sheridan, Wyo., area and in the Beulah, N. Dak., area, the break line appears to be nearly vertical to perhaps slightly negative; that is, dipping steeply away from the mine opening (fig. 14*A*). In the Limburg area of the Netherlands, the break angle is about 20° (Pöttgens, 1978, p. 269). Knowledge of limit angle and break angle is important in land-use planning because these angles determine the limits of deformation.

Information regarding the rate and amount of subsidence and attendant surface strain that can be expected for mined-out areas of various widths and heights and for various overburden thicknesses of more than about 60 m can be found, for example, in Zwartendyk (1971); in the Subsidence Engineers' Handbook (National Coal Board, 1966, 1975); in Salamon (1978, p. 187-208); Dunrud (1976a, p. 3-36); Brauner (1973a, b); and Pöttgens (1978, p. 267-282). However, little or no specific information is available on the rupture limits in tension and compression of various types of bedrock or surficial material in any sources known by the authors. Studies to 1978 in the western Powder River Basin show that the rupture limit of bedrock (limit of strain at which rupture occurs)—consisting of weak, soft siltstones, claystones, shales, lenticular sandstones, and coal beds—is significantly lower than that of the soil and colluvium overlying the bedrock. Cracks as wide as 15-20 cm were observed in bedrock but were not observed in overlying colluvium or soil cover except where holes caused by piping failure or the activities of man or animals identified the underlying cracks (fig. 10).

Deformation of the soil and colluvium under tension was observed at the margins of subsidence depressions (figs. 7, 8, 9). Cracks were common in soil and colluvium where differential vertical settlement was more than about 0.8 m within a lateral distance of 3-6 m in overburden 9-25 m thick. Cracks were rare in soil and colluvium at the margins of subsidence depressions where differential vertical settlement was less than about 0.6 m within 3-6 m in horizontal distance. It is not known whether or not the underlying bedrock is cracked beneath the soil and colluvium.

MODERN COAL MINING

Subsidence caused by modern underground coal mining beneath overburden less than about 60 m thick, or less than about 10-15 times the thickness of coal mined, cannot be evaluated in the Powder River Basin and in western North Dakota, because no underground mines are currently operating in these areas. As far as is known by the authors, nearly all current mining in thin overburden is done by surface methods in the United States as well as in the rest of the world, because it is more feasible from an operational and economic standpoint. The recent Subsidence Engineers' Handbook from the NCB (National Coal Board of the United Kingdom, 1975, p. 9), for example, does not predict subsidence amounts where overburden above longwall coal mines is less than about 50 m thick. Subsidence information from NCB also does not apply to pillar and stall (room-and-pillar) mining (1975, p. 40) because coal pillars remaining after mining as well as mine roofs and floors may fail for many years due to stress concentrations and (or) wetting of claystones and shales susceptible to deterioration by water. Information on the effects of modern coal mining by underground methods in overburden less than about 60 m thick appears to be rare or nonexistent.

In compliance with recently enacted Federal Coal Mining Operating Regulations (Federal Register, 1976, 30 C.F.R. 211, May 17, 1976, p. 20261-20273), underground mining of coal on Federal lands may be required in areas where the overburden is of variable thickness because of topography or structure, is locally less than about 60 m thick, but commonly is too thick to mine by surface methods. One primary purpose of the Coal Mining Operating Regulations (Federal Register, 1976, 30 C.F.R. 211.1(b), May 17, 1976, p. 20261) is to:

> ". . . assure the orderly and efficient prospecting, exploration, testing, development, mining, preparation and handling operations, and production practices without avoidable waste or loss of coal or other mineral resources or damage to coal-bearing or other mineral-bearing formations. . . ."

The first part of the section on "Underground mining, maximum recovery" (Federal Register, 1976, 30 C.F.R. 211.30, May 17, 1976, p. 20268) stated that:

> "Underground mining operations shall be conducted so as to yield a maximum recovery of the coal deposits consistent with the protection and use of other natural resources, sound economic practice, and the protection of the environment—land, water, and air."

Accordingly, if appropriate from an environmental and resource protection standpoint, mining plans for particular areas may include provisions for mining coal by underground methods beneath overburden less than about 60 m as adjacent coal beneath overburden thicker than about 60 m is mined. In these areas, unless a company planning underground mining operations could negotiate with a surface mining company to mine the coal beneath the thinner overburden or unless the underground company had surface mining equipment, the coal beneath overburden less than about 60 m thick might be mined by underground procedures.

In order to evaluate the overall effects on the environment and on resources caused by underground coal mining beneath thin overburden, future mining sites should be studied to determine such factors as (1) limit or draw angle and break angle, (2) subsidence amount and rate, and (3) local deformation. Studies by the authors (Dunrud and Osterwald, 1978a, b) and others (for example, Gentry and Abel, 1978, p. 202–203; Shadbolt, 1978, p. 729) in areas where the overburden is thicker than about 60 m show that subsidence above modern underground mines commonly equals 60–90 percent of the thickness of coal mined. In the Limburg coal mining area of the Netherlands, maximum subsidence is as much as 96 percent of the extracted coal thickness (Pöttgens, 1978, p. 269). Deformations, in the form of tension cracks, commonly occur at the margins of subsidence depressions, and compression bulges locally occur within the depressions provided that the areas mined are at least as wide and as long as the overburden is thick (critical mining area) and that the maximum amount of coal that can be safely and economically extracted is removed (fig. 15; Dunrud, 1976a, b).

Topography, lithology, structure, and amount of water present in overburden rocks control the rate and amount of subsidence as well as the nature of surface deformation. However, as indicated previously, the mining thickness, areal extent of mining, mine geometry, and overburden thickness commonly are the dominant controlling factors.

Tension cracks commonly are wider, more abundant, and more extensive near cliffs and steep terrain than they are in flat or gently rolling topography (Dunrud, 1976a, p. 12). Results of subsidence measurements above a supercritical longwall mining area in the York Canyon Mine near Raton, N. Mex., where rugged canyon topography is underlain by moderately strong mudstones and sandstones less than about 225 m thick, show that cracks are more extensive and abundant and the horizontal movement was much greater on steep slopes where mining progressed from beneath thicker towards thinner overburden than it was on slopes of similar grade which progressed from beneath thinner towards thicker overburden. In addition, the total amount of subsidence was from 25 to 30 percent greater on ridges than it was in valleys (fig. 15; Gentry and Abel, 1978, p. 203–204). Horizontal surface strain was as much as twice as great as predicted from studies in the United Kingdom.

A similar effect of topography on surface cracking was observed in the fall of 1977 in the Somerset, Colo., area, where moderately strong sandstones, mudstones, and shales 100–200 m thick underlie very rugged topography. Numerous tension cracks, some as much as 50 cm wide, occurred on a steep slope facing in the direction of pillar extraction above a room-and-pillar mining area where coal was mined from beneath a ridge towards a canyon bottom, whereas cracks were rare and only a few centimeters wide on a similar slope facing in a direction opposite to the direction of pillar extraction, where mining progressed from the canyon bottom toward the next ridge.

In overburden consisting of strong rocks, such as well-cemented sandstones, the draw or limit angle steepens and the total amount of subsidence sometimes is less, compared to weaker shales and mudstones (Dunrud, 1976a, p. 5–7). Strong rocks, such as well-cemented sandstones, siltstones, and limestones, may also break into larger fragments than shales or mudstones. Subsidence amounts may be less in strong, massive rocks than in weak rocks because of higher bulking factors in caved zones near the mine workings.

Structural features, such as joints and faults, commonly localize subsidence movements. Open cracks can occur along joints in well-cemented sandstones and other strong rocks, particularly near cliffs (Dunrud, 1976a, p. 8–12). Subsidence can be localized and concentrated along faults, even in thick overburden. Extensive offset subsidence cracks were observed by the authors in Carbon County, Utah, in 1977; they occurred in strong overburden, along fault projections as much as 700 m above the elevation of room-and-pillar mines that were driven in the late 1950's and early 1960's.

Backfilling mine openings with mine tailings or other available material during mining might reduce the amount of subsidence by about 50 percent (fig. 15) and perhaps reduce the rate of subsidence as well, which also commonly would reduce surface damage. This practice, however, is costly, particularly after the mines are abandoned. Abandoned coal mines that have not yet been affected by subsidence cover some 170,000 hectares (418,000 acres) in the 25 coal-producing States. Costs to backfill these mines have been estimated at $12.5 billion by the U.S. Bureau of Mines (Johnson and Miller, 1979, p. 9).

The amount of water present in, or available to, the overburden from the surface also may control the amount and rate of subsidence. In areas where large amounts of ground water are reported to be common in the overburden, such as in the Netherlands (Pöttgens, 1978, p. 267) and the United Kingdom (Piggott and Eynon, 1978, p. 752), subsidence amounting to 90–96 percent of the thickness of coal mined is common in supercritical mining areas, whereas in the Somerset, Colo., and Raton, N. Mex., areas—where small amounts of ground water are present in the overburden—subsidence amounts to about 70 percent of the mining thickness. Rock fragments in caved zones above the mine workings, particularly fragments of weak rocks such as shales and mudstones, may be significantly smaller where submersed in water than in dry or slightly wet zones.

COAL MINE FIRES

Coal mine fires are common in abandoned mine workings in the Sheridan, Wyo., area. The fires threaten both the environment and adjacent unmined coal deposits (fig. 16). According to the U.S. Bureau of Mines (Johnson and Miller, 1979, p. 19), about 250 uncontrolled fires are burning in abandoned underground coal mines in 17 States located primarily in the east and the west, of which about 195 are located in the Western States and approximately 150 in the States of Montana, Colorado, Wyoming, and North Dakota. Studies by the authors show that fires are burning in about a 3-km^2 area in parts of at least five abandoned coal mines 10–20 km north of Sheridan, Wyo. Other areas of various underground mines may be on fire that have not yet been detected.

Most of the fires apparently started in these abandoned mines by spontaneous ignition when oxygen and water were introduced to the mine workings through subsidence cracks and pits and unsealed portals or shafts. Ignition probably occurred initially in piles of coal consisting of fragments of various sizes and fine dust that remained in the abandoned mines where oxygen and water were available in proportions conducive to combustion. Reports published during the past 50 years of laboratory studies on spontaneous heating and ignition of coal (Kim, 1977, p. 2–6) reveal that (1) availability and flow of oxygen, (2) particle size, (3) rank of coal, (4) changes in moisture content, and (5) other factors, such as temperature, pyrite content, geologic structure, and mining practice, are the prime factors causing spontaneous heating and ignition. Coal rank and changes in moisture content appear to be two of the more important factors.

Field studies indicate that, once the coal ignites, the fire can support combustion and spread by drawing fresh air in through open subsidence cracks and pits and exhausting gases via other cracks and pits. Voids created as the coal is burned produce further ground settlement, additional tension cracks, and more pits, which in turn provide more oxygen to the fire. Noxious gases, smoke, and steam produced by the fires are a major source of air pollution in the area.

A reconnaissance sampling of the gases that are exhausted along with smoke and steam through tension cracks and pits was conducted by the authors in the Acme mine area in April 1976 (fig. 4). Analyses by M. E. Hinkle, U.S. Geological Survey, and R. L. Kaplan, MSHA, revealed the presence of carbon disulfide, carbon oxysulfide, and an unknown sulfur compound. Methane in excess of 1 percent by volume was detected in a crack near one of the more intense fire areas. The exhausted gases also commonly contained considerably less oxygen and more helium and carbon dioxide than did the normal atmosphere. Carbon monoxide, ranging from a

FIGURE 16.—Eastward aerial oblique view of the surface effects of an underground coal mine fire above northern part of the Acme mine (November 1975). The firepit, shown in greater detail in figures 17, 18, 19, and 20, is the brown spot in the left center of picture that is exhausting blue smoke and is bounded on the front (west) by plumes of steam. Steam fumaroles can be seen above subsidence pits and cracks throughout the valley. Most of the grass and trees in the foreground were burned when the fire first reached the surface. A coal bed that crops out in the draw about halfway between the road and the firepit (left foreground), will eventually be ignited by the advancing fire unless it is controlled.

FIGURE 17 (above and facing page).—Northeastward aerial oblique views of the firepit located above the northern part of the Acme mine. *A*, Position of firepit in November 1975. *B*, Position of firepit in April 1978; fire has advanced about 40 m during this period; total length of firepit in 1978 was about 110 m. Note anomalous green grass adjacent to scorched area around firepit. Fire, blue smoke, and steam issue from branching and offset cracks caused by subsidence above the burning coal. Crenulate cracks within and marginal to the pit divert surface runoff and ground water. The firepit area is within a larger subsidence depression that contains numerous old pits and is bounded by tension cracks as much as 3 m wide.

trace to as much as 0.35 percent by volume, also was locally detected.

Fires in the abandoned underground mines locally have breached to the surface or are close enough to the surface to produce ground temperatures that melt snow cover readily during the winter. Bedrock and surficial material weakened by steam and heat generated by fires in coal mines may collapse into underlying cavities without warning, particularly in areas where (1) coal fires have started recently, (2) the overburden is less than about 10–15 times the height of the mine workings, and (or) (3) thermal gradients have not been established and there are no elevated ground surface temperatures.

An underground fire above the northern part of the Acme mine breached to the surface in 1972 and started a large grass fire that also burned a grove of juniper and pinon trees (figs. 4, 17, 18, 19). In the breached area, which is locally called "the firepit," a vertical column of fire and molten rock 1.5–3 m in diameter and an estimated 15 m high supported combustion in the spring of 1976 by burning other coal beds in the section or by burning the combustible products of the coal bed gasified by the fire, or by both processes (fig. 20). Temperatures in flame-filled cracks and chimneys averaged 925°C, as measured with an optical pyrometer. Sulfur deposits are common along smoking cracks with a strong sulfur odor where

the temperature ranged from 90° to 225°C. Near the firepit, temperatures were as much as 150°C in cracks at the margins of scorched and dying grass. Temperatures in steaming cracks in green grass a few meters from the firepit were measured at about 60°C.

Another firepit, which formed above the east-central part of the Acme mine from 1974 to 1977, afforded a good chance to study the processes of firepit formation (figs. 4, 20*A*, *B*). Elevated ground temperatures and fumes had begun to kill the vegetation in November of 1974 when the area was first visited by the authors. During 1975 and early 1976 the ground began to sink into an elongate trench as much as 2.5 m deep, 15 m wide, and 25 m long. Temperatures as high as 150°C were measured in cracks 30 cm down. At the collapse site in April 1976, a strong sulfur odor was detected from tension cracks along the margins of the depression.

The initial collapse occurred in May 1977 near a large tension crack on the east end of the depression. The resulting pit was a jagged hole measuring about 2.5 m long and more than 3 m deep. The pit was encompassed by crenulate, roughly concentric cracks. Collapse is the culmination of successive stoping of overburden rocks above cavities; it operates much like the stoping process above mine cavities that are not burning, except that the process probably is accelerated by the continual enlargement of the underground opening and by effects of high temperatures on the overburden material.

The collapse occurred near a tension crack that had the highest temperatures and produced the most sulfur fumes in the area during 1976. Fire and sulfur fumes were issuing from the jagged hole. The hole may continue to enlarge, now that the initial pit has formed (fig. 20*B*). A coal bed is believed to occur between the abandoned mine workings, which are on fire, and the surface. This bed, if present, also is on fire.

A 1979 subsidence episode and fire in the northwest corner of the New Monarch mine (figs. 4, 21*A*, *B*) yielded considerable detailed eyewitness information about subsidence processes related to mine fires. Subsidence began with a single pit (pit 1, fig. 21*A*) about 2 m wide and 6 m deep that occurred in 1977 (H. F. Alley, oral commun., 1979). About a year after the hole was discovered, a fence was built around the hole as a safety precaution. Steam was first observed in the pit by H. F. Alley in mid-November 1978.

On December 1, 1978, DEQ (Department of Environmental Quality), State of Wyoming, received an air pollution complaint from a local resident concerning large quantities of acrid smoke and steam in the Monarch area (G. L. Mooney, written commun., 1978). Subsequently the fire area was inspected by G. L. Mooney, DEQ, D. L. Donner, USBM (U.S. Bureau of Mines), and L. Hendrickson, OSM (U.S. Office of Surface Mining) on December 19, 1978 (fig. 21*A*, *B*). Steam and smoke were emanating from the initial hole (fig. 21*A*, pit 1) on the site, which had enlarged to about 14 m in maximum diameter and 9 m deep. About half of the fence had collapsed due to enlargement of the pit. In addition, two new subsidence pits were found (fig. 21*A*, pits 2, 3). Pit 3 was located about 7 m north of a high voltage powerline serving the towns of Ranchester and Dayton and adjacent rural areas (T. P. Hammond, Electrical Superintendent, Montana-Dakota Utilities, oral commun., 1979).

FIGURE 18 (above and facing page).—Southward views of the firepit above the northern part of the Acme mine. *A*, Bare ground surrounded by snow 0.25–1 m deep shows that the underground fire is much more extensive than the firepit area (March 1978). *B*, The scorched, cracked, and collapsed ground of the firepit area is in stark contrast with the surrounding lush green grass (May 1978). Other bare spots can be seen in background where either high ground

On January 2, 1979, an explosion shook the P. L. Vine residence located about 600 m south of the subsidence area (P. L. Vine, oral commun., 1979). Black smoke and orange flames were visible above a 30-m-high ridge located between the subsidence area and the Vine residence. The flames appeared to be coming from pit 2. A second explosion was heard and felt by Mr. Vine about 5 hours later. Apparently, either methane present in the mine had suddenly ignited or steam in the mine workings was suddenly released under pressure.

On January 3, another steaming and smoking pit (fig. 21*A*, pit 4) appeared about 30 m west of pit 3 and 3 m north of the powerline (T. P. Hammond, oral commun., 1979). This pit was oblong in plan, measuring about 4 × 8 m and as much as 6 m deep (T. P. Hammond, oral commun., 1979). At this time, fire could be seen at ground level in pit 2. Flames 10–12 m high were observed by T. P. Wollenzien, geologist, Peter Kiewit Sons' Co., the evening of January 3 (fig. 22*A*; T. P. Wollenzien, oral commun., 1979).

G. L. Mooney, DEQ, visited the fire area on the afternoon of January 4 in response to another air pollution complaint from a resident living about 6 km southeast of the fire area. Large quantities of smoke and steam were erupting from pit 2, which now was about 7 m in diameter (G. L. Mooney, written commun., 1979; fig. 22*B*). Only small amounts of smoke and steam were coming from pit 1. Steam and smoke also were emanating from pit 3, where no emissions were noted on December 19. At this time, pit 4 was emitting

temperatures or noxious fumes inhibit growth of vegetation. Blue smoke and fire issue from the firepit and adjacent branching and offset subsidence cracks. Steam is emitted from cracks about 2 m ahead of the fire front in right foreground and also along ridge in background. Craters within the pit are either explosion craters caused by sudden releases of steam and other gases or are local secondary collapse features.

large amounts of steam and smoke, second in volume only to pit 2. Another pit (pit 5) was observed about 15 m north of pit 2. It was estimated that the fire was burning in about three rooms of the abandoned mine (fig. 21*A*).

Fire control attempts began on January 6, when a local contractor began filling pit 4 to protect the powerline from fire damage (T. P. Hammond, oral commun., 1979). During the day, personnel walked across the ground surface between pits 3 and 4. The following morning a steaming pit (pit 6) had formed where persons had walked the previous day (fig. 21*A*, *B*; T. P. Hammond, oral commun., 1979). The snow, which was about 0.5 m deep, had not melted nor was there any other indication of impending collapse (fig. 22*D*). At this time the contractor withdrew his equipment because of the hazard. It was decided to use an emergency fund supplied by OSM to contract for (1) drilling and gamma logging to define the mine workings and solid coal and (2) filling the holes after the mine workings and coal pillars were defined.

The fire area was first visited by Dunrud on January 9, 1979. Large volumes of steam were emanating from pit 5 with lesser amounts from pits 3, 4, and 6 (fig. 21*A*, *B*). A small amount of smoke was present in pit 1; pit 2 was devoid of either smoke or steam. Pit 2 and the north side of pit 4 showed obvious signs of intense heat (fig. 22*C*). Bedrock and surficial materials in the pit were baked and stained red 1-3 cm inward from the surface of pit 2. The surface was blackened with soot a few millimeters thick. Sagebrush around pit 2 was burned or scorched. Interconnecting underground cavities 1-3 m high with arched roofs, located 1-4 m below the ground surface, were observed in pits 2, 4, and 6. Pit 4 had enlarged southward within the past few hours (fig. 22*D*).

A map prepared by D. L. Donner, G. L. Mooney, and C. R. Dunrud, using information from 10 drill holes and a map of the underground mine workings, revealed that the pits and interconnecting cavities occurred above north-trending rooms about 7.5 m wide that are separated by pillars 10-20 m long and 7.5 m wide; crosscuts between pillars are 3-5 m wide (fig. 21*A*). The mine workings, which are 5-6 m high, are in the Monarch coal bed (fig. 21*B*). Results of drilling, gamma-ray logging, and inspection of the pit walls revealed that another 5.5 m of coal, containing five rock partings 50-75 cm thick, occurs above the mine workings; this coal in turn is overlain by 10-22 m of silty claystone with thin local siltstone lenses and a coal bed about 1 m thick located approximately 5 m above the base. Surficial deposits, 1-5 m thick, overlie the bedrock.

Filling of the pits began again on January 10, using a large bulldozer. By midafternoon, pits 4 and 6 were filled. However, a pit suddenly developed beneath the bulldozer during the filling of pit 3, causing it to tip sideways (fig. 23*A*). Inspection of the hole beneath the bulldozer revealed that it was connected northward toward pit 2 by an arched underground passageway 1-2 m high, 2-3 m below the surface. The hole was filled using another bulldozer and backhoe (fig. 23*B*).

New pits continued to develop near the locations of the six original pits after repeated filling. On January 11, steaming pits were observed near, or above, all three pits filled the previous day. On January 12 pits were again observed near the south edge of pit 4 and the north edge of pit 6. Rumbling sounds were heard near pit 4. On January 24 seven new pits, ranging from 1 to 3 m in maximum width and depth, were observed by Mooney and Dunrud near the original pits (fig. 21*A*). Two more steaming and smoking pits were observed north of pits 3 and 5 on March 1, 1979. In addition, cracks 1-20 cm wide were observed around the original pits 1, 3, 4, and 6. By mid-May three additional pits had developed—one circular pit immediately south of pit 2 and two elongate pits east of the original subsidence area (fig. 23*C*).

A subsidence pit and fire also occurred above the south part of the abandoned Acme underground coal mine about 35 m west of a highwall of the Big Horn surface mine on the night of January 22, 1979 (figs. 4, 7*A*, 24). Flames were visible about 10 m above ground level for a few hours. Large volumes of steam and yellowish-gray smoke emanated from a rapidly enlarging pit on January 24 and 25 when Dunrud visited the site (fig. 24*A*). The diameter of the pit enlarged from about 2.5 to 5 m and the volume of steam and smoke tripled or quadrupled in about 20 hours. Acrid steam and smoke filled the

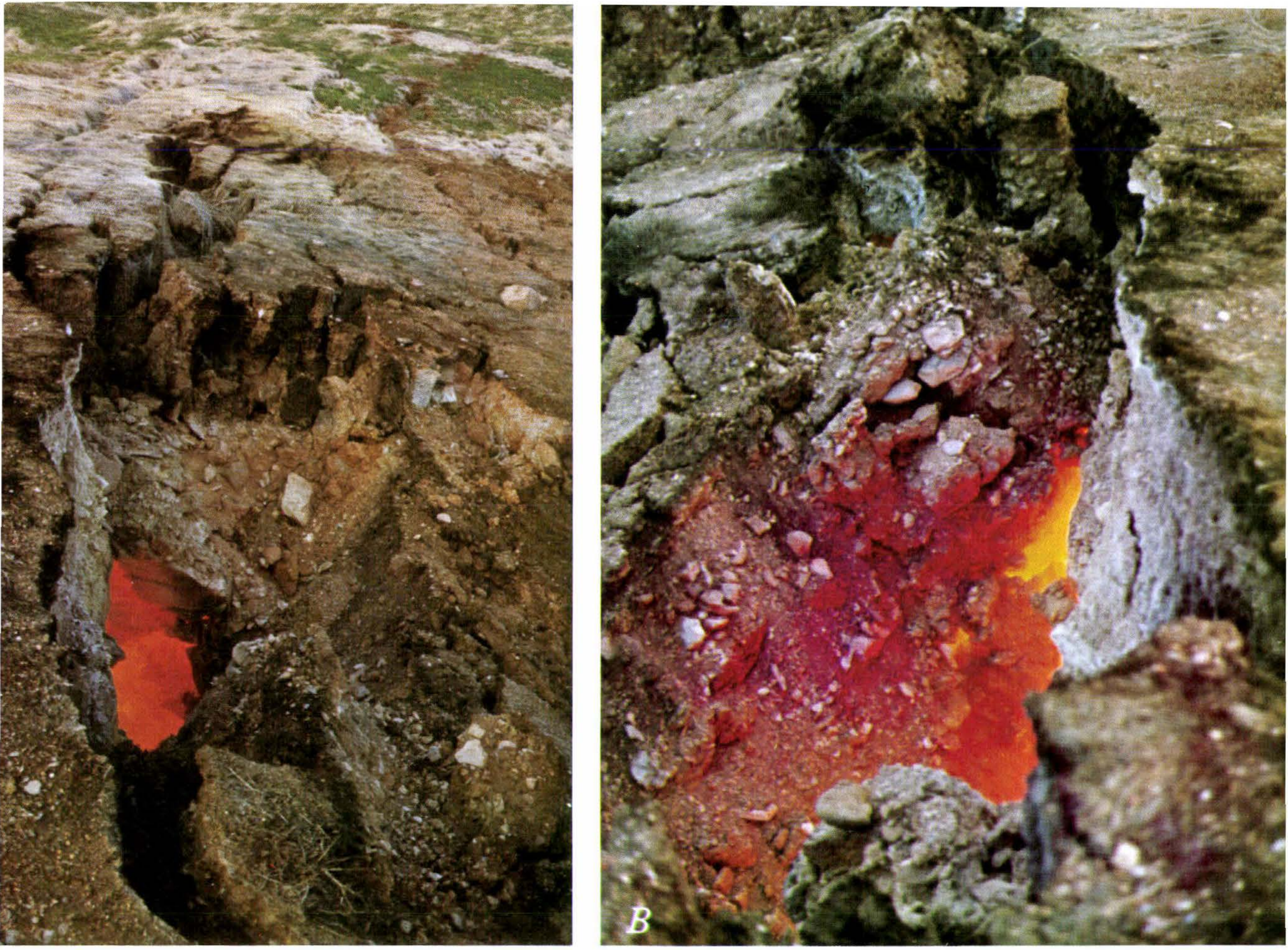
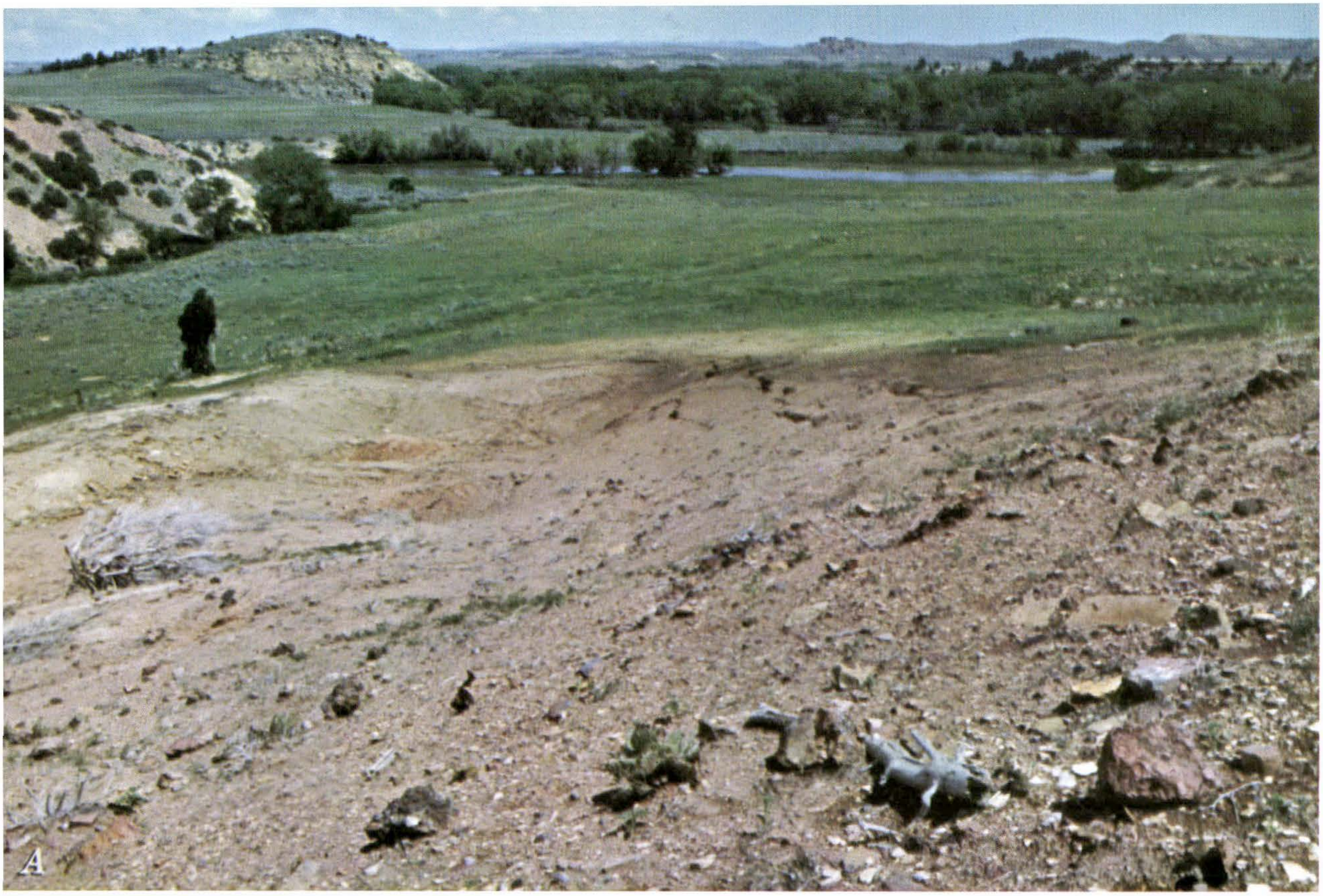


FIGURE 19.—Closeup views of the advancing fire front in the firepit (April 1976). *A*, Northward view across the edge of the firepit. The grass is dead near the pit from the effects of heat and noxious gases but is greener than normal in the background where the temperature promotes plant growth. Intense heat from the fire front scorches adjacent grass and shrubs and occasionally causes grass fires. *B*, Southward view across the advancing edge of the firepit. A severe fire hazard exists in late summer and fall. The fire column is hot enough to melt the bedrock.

Tongue River Valley for a few kilometers upstream and downstream from the fire until the pit was filled on January 25.

In contrast to the fire above the New Monarch mine, the fire above the Acme mine produced flames above ground within minutes after the pit formed, perhaps because large quantities of air were available to the mine workings from mine openings exposed on the highwall of the nearby surface mine (fig. 24*B*). Like the fire above the New Monarch mine, large volumes of foul-smelling steam and smoke were emitted from the pit after the fire subsided below ground level. Steam was present in greater proportions at the Acme site than at the Monarch site, perhaps because more water was available. The large quantities of steam probably contributed to the rapid enlargement of the pit.

Fires caused by spontaneous combustion also locally occur on highwalls of abandoned surface mines or on exposed coal in active surface mines (Hertzberg, 1978, p. 47–49) in the Powder River Basin. The coal outcropping at water level in the abandoned Plachek surface mine near the currently active Big Horn mine caught fire, apparently by spontaneous combustion, in the early 1970's (fig. 6). During 1975 and 1976 the fire had spread along the outcrop and was beginning to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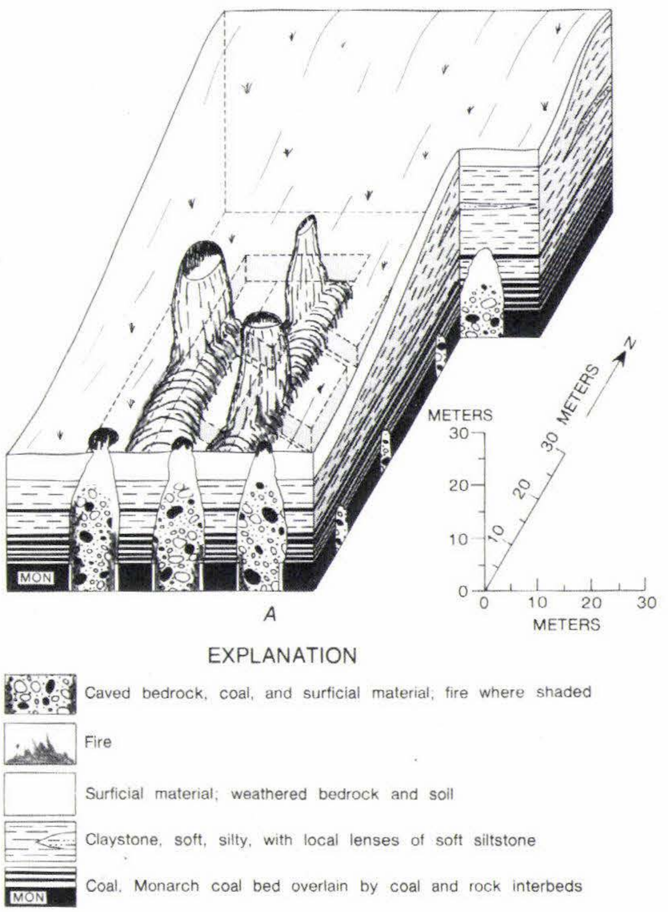

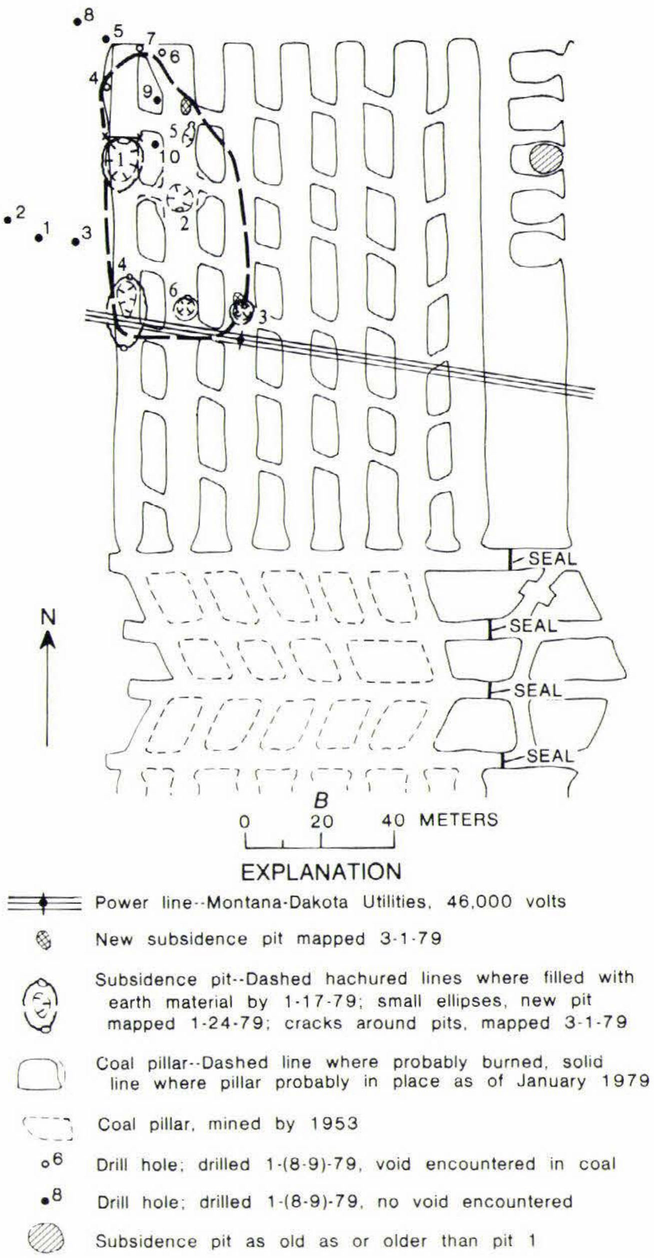

FIGURE 21.—Subsidence and fire above northwest part of New Monarch mine. *A*, Idealized block diagram showing subsidence pits, lithology of overburden, and underground mine workings in the fire area on January 9, 1979. *B*, Map showing relation of room-and-pillar mine workings to subsidence pits, filled pits, new pits, and estimated fire area (outlined by heavy dashed line), January 1979. Compiled by D. L. Donner, USBM, G. L. Mooney, DEQ, and C. R. Dunrud, based on taped traverses, drilling, geophysical logging, and inspection of pits. Voids 0.6 m high were encountered in drill holes 6 and 7; a void 6 m high and fire were encountered in drill hole 4.

◁ FIGURE 20.—Firepit above the east-central part of the Acme mine (May 1977). Broken, cracked, and locally blackened ground and scorched grass provide a stark contrast to the lush green grass surrounding this new firepit. *A*, Eastward view across firepit area. Meadowlands adjacent to the Tongue River are in the background. *B*, Southeastward view showing the jagged pit, which is bounded by crenulate, roughly concentric cracks. The depression (middle) is about 2.5 m deep. The pit, which is more than 3 m deep, contains fire and hot rocks, although they are not visible in picture because of the sunny day. Temperatures in the pit were measured at about 850°C with an optical pyrometer.

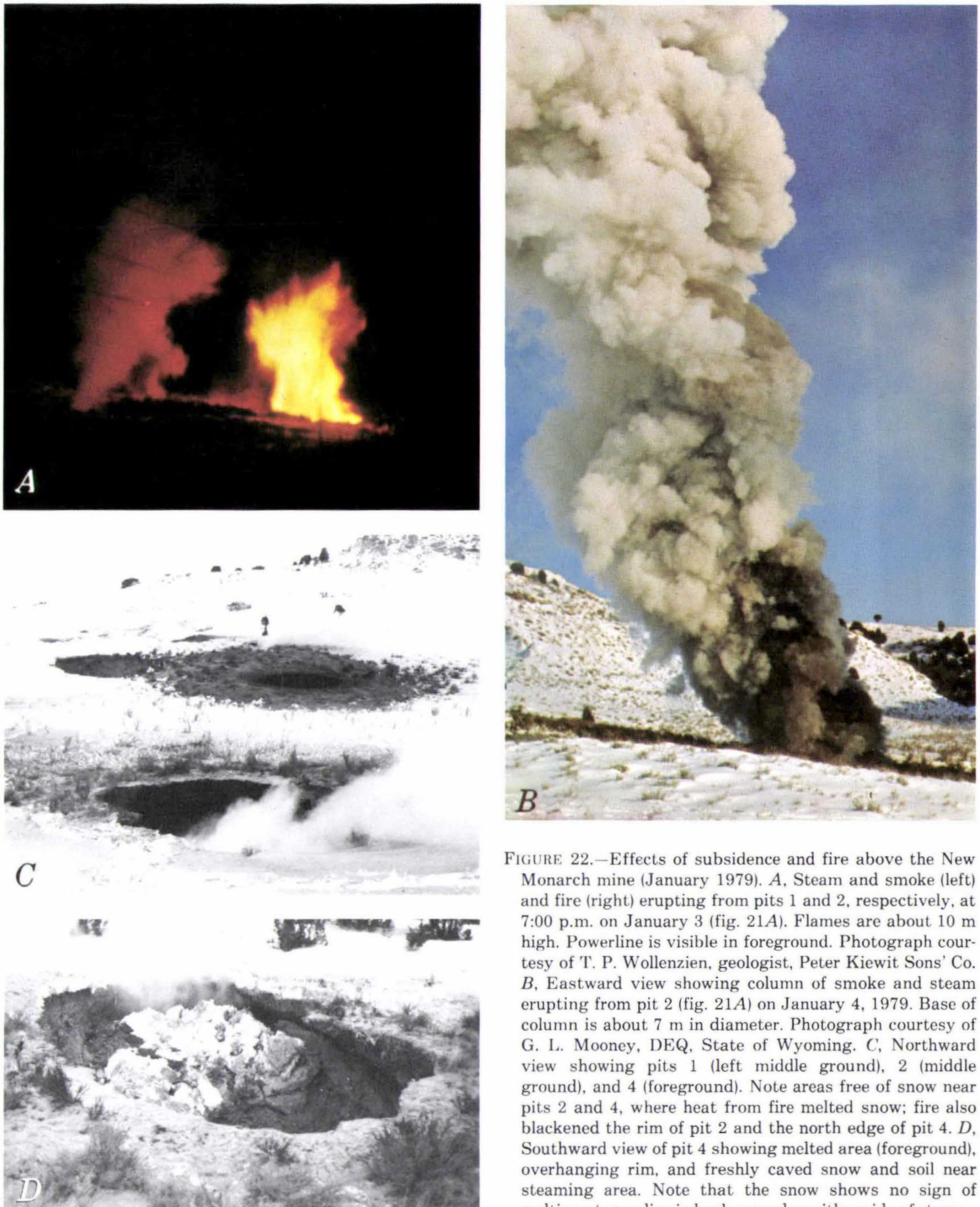

FIGURE 22.—Effects of subsidence and fire above the New Monarch mine (January 1979). *A*, Steam and smoke (left) and fire (right) erupting from pits 1 and 2, respectively, at 7:00 p.m. on January 3 (fig. 21*A*). Flames are about 10 m high. Powerline is visible in foreground. Photograph courtesy of T. P. Wollenzien, geologist, Peter Kiewit Sons' Co. *B*, Eastward view showing column of smoke and steam erupting from pit 2 (fig. 21*A*) on January 4, 1979. Base of column is about 7 m in diameter. Photograph courtesy of G. L. Mooney, DEQ, State of Wyoming. *C*, Northward view showing pits 1 (left middle ground), 2 (middle ground), and 4 (foreground). Note areas free of snow near pits 2 and 4, where heat from fire melted snow; fire also blackened the rim of pit 2 and the north edge of pit 4. *D*, Southward view of pit 4 showing melted area (foreground), overhanging rim, and freshly caved snow and soil near steaming area. Note that the snow shows no sign of melting at cave line in background on either side of steam.

advance underground. Fires such as this can support combustion underground for considerable distances by intaking air and exhausting gases via tension cracks caused by collapse of the overburden into voids left when the coal burned. Steps should be taken to insure that adequate amounts of noncombustible material protects the coal from possible ignition during abandonment and restoration procedures in any future surface mining activities.

Fires also are a serious problem in currently active underground mines. Mine deformation studies in coal mines in Utah and Colorado by the authors (Dunrud and Osterwald, 1978b, p. 58) show that fires are common. The fires apparently start by spontaneous ignition, particularly in areas where stresses are high and heat is produced by resulting deformation of the coal and rock. The areas continue to burn even years after they have been sealed. Steps should therefore be taken to control fires during operation and abandonment of modern underground mines.

SEISMIC ACTIVITY

Small earth tremors commonly are generated by caving and stress readjustments in overburden rocks above underground mine workings and coal fires in the Sheridan, Wyo., area. The authors and other personnel of the U.S. Geological Survey monitored seismic activity above the Acme mine with a temporary seismic network between September 30 and November 4, 1975. The network consisted of 10 vertically oriented seismometers with a natural frequency of 1 Hz, which were connected by wires to a mobile recording laboratory. Ground motion velocity was recorded both on magnetic tape and on visual seismograms. Magnification of the system, with respect to ground-motion velocity, was about 200,000 at 10 Hz. One seismometer was installed within about 185 m of the firepit that breached to the surface in 1972 (figs. 16, 17, 18, 19) during the first half of the recording period and within 30 m of the firepit during the last half of the period.

In addition to earth tremors generated by blasting in the Big Horn and Decker surface mines (figs. 2, 3), 20–90 small earth tremors were recorded per day by the seismometer when it was located about 185 m from the firepit, whereas 550–800 small earth tremors per day were recorded when the seismometer was moved to within about 30 m of the firepit (fig. 25). Later seismic studies, during a 6-week period in the fall of 1976 above the Acme mine, showed a large increase in the seismic activity, which indicated that the fire was accelerating at a rapid rate.

At the site of the firepit, as well as in other areas of the Acme mine, most of the tremors appeared to be caused by breaking and caving of overburden rocks above and adjacent to areas where fires are burning intensely and perhaps have ignited overlying coal deposits. Another source of local seismic activity might be small underground explosions caused by steam suddenly released under high pressure.

A seismic network with audio recording capability and six vertical seismic stations linked to the mobile recording laboratory was installed above the fire area in the New Monarch mine on March 16, 1979. Preliminary results of the audio monitoring reveal thumping, rumbling, and hissing noises that sound like breaking and caving of the overburden and also movement and sudden releases of steam and air within the mine cavities.

ENVIRONMENTAL CONSEQUENCES OF COAL MINING

Adverse effects on the environment caused by underground mining or surface mining, in addition to potential hazards to life and property and effects on population growth, commonly comprise (1) disruption of the Earth's surface, bedrock, or other mineral deposits; (2) diversion or pollution of surface or underground water; and (3) spontaneous ignition of underground fires with the attendant land disturbance, water and air pollution, and surface fires. Past mining by both procedures has produced all of these effects in the Powder River Basin. However, in all cases known to the authors, the surface mining activities have produced less severe and shorter term problems than past underground mining. This is primarily because fire hazards are reduced by the extraction of most of the coal in the surface mining areas (compared to only a small percentage of the coal in the underground mining areas), and because problems such as damage to the surface,


A
B

FIGURE 23 (facing page and above).—Some pitfalls of filling subsidence pits. *A*, Track of large bulldozer (D-9 Caterpillar) fell into pit, which suddenly developed above an underground cavity (January 1979). *B*, Cavity beneath bulldozer initially was as much as 4 m deep. Backfilling operations beneath track took about an hour (January 1979). *C*, Southward aerial view of the subsidence and fire area (May 1979). Cracks and pits occur near the pits that were filled in January. Also new elongate pits occur to the east.

water diversion, and pollution are open to view and can be examined, assessed, and corrected. In the underground mines, however, these problems may be hidden for many years or even many decades after mining is completed (figs. 2*A*, 7–11, 16–24).

Modern surface mining activities in the Powder River Basin include well-planned sequential removal of topsoil, bedrock, and coal followed by replacement of spoil, topsoil, and revegetation (figs. 2, 3). Thus the land can be restored and put back into use in a few years or decades. Unstable conditions, locally common at the sites of older surface mines (fig. 6), and possible unstable conditions in restored spoil can be minimized by grading and compaction in accordance with design specifications based on detailed, on-site geologic and geotechnical investigations of the bedrock and of broken and mixed rock in mine spoil. The fire hazard can be minimized by assuring that all coal outcrops and other remaining piles of coal are adequately blanketed by noncombustible material. Surface mine operators, therefore, can have good control of restoration procedures and can minimize long-range environmental damage if mining activities are properly planned and implemented from the initial cut to the final restoration of the highwall.

Many of these provisions and others are part of the Coal Mining Operating Regulations (Federal

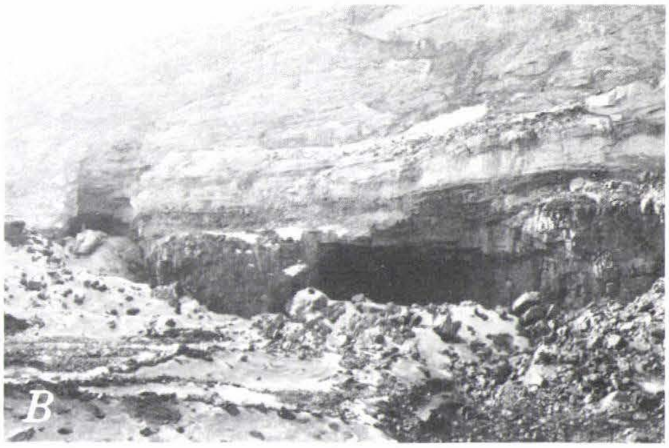

FIGURE 24.—Fire in the southern part of the Acme mine (January 1979). *A*, Southward view of the fire area showing emission of a large column of steam and yellowish-gray smoke from a newly formed pit. Maximum height of spoil pile (background) is about 15 m. *B*, Westward view of highwall in Big Horn mine, located about 35 m east of steaming pit. Height of highwall is about 15 m. Two entries of the Acme mine (fig. 4) are exposed; the roof of the smaller one on the left (fig. 14*C*) has begun to collapse, whereas the wider one on the right still is intact.

Register, 1976, 30 C.F.R. 211.1 to 211.4, May 17, 1976, p. 20261-20264), in the National Environmental Policy Act of 1969 (Public Law 91-190, 42 U.S.C. 4321-4347, Jan. 1, 1970), as amended (Public Law 94-83, Aug. 9, 1975), and the Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87) as implemented by the Surface Mining Reclamation and Enforcement Provisions (Federal Register, 1977, Part II, 30 C.F.R. 700-725, December 13, 1977, p. 62639-62712).

Changes, diversion, and pollution of water are under study by other governmental agencies, but it appears to the authors that these effects can be minimized by proper planning based on on-site studies of geologic and hydrologic conditions. In any case, these effects are, in the opinion of the authors, less damaging than those often caused by modern underground mining of thick beds beneath thin overburden, wherein surface and ground-water flows may be changed and (or) diverted by surface depressions, tension cracks, and subsidence pits or troughs, and they may be locally contaminated by garbage and other refuse being placed in subsidence pits or troughs. Depressions resulting from extraction of thick coal beds by surface methods in the Powder River Basin can perhaps be eliminated or minimized, in areas where topographic conditions and ownership or lease areas are amenable, by borrowing material from adjacent hills to compensate for the volume of coal removed, as is currently planned by Big Horn Coal Co. (figs. 2, 7, 8).

Environmental hazards caused by past underground mining in the Sheridan, Wyo., area include subsidence of the ground surface, diversion of surface and ground water, coal mine fires and attendant surface subsidence, and pollution of the air and water (frontispiece *A*, *B*; figs. 7, 8, 16-20). Grasses and plants commonly die or are stunted near subsidence cracks, bulges, and along the margins of subsidence pits where the root systems are dewatered. Subsided lands are of limited use, and commonly are not useful for livestock grazing because stock can fall into pits and cracks (fig. 4). Also the noxious fumes emanating from cracks above burning coal mines have killed trapped cattle, in some cases, after exposure of less than an hour (Dan Scott, Padlock Ranch, Dayton, Wyo., oral commun., 1976).

Grass fires and forest fires also have been started when underground coal fires reached the surface. In 1972, a grass fire was ignited when a firepit in the northern part of the Acme mine first breached to the surface (figs. 16–20). The fire burned about 1.5 km^2 of winter range grass and trees before it was brought under control.

All these environmental hazards limit the value of the land above these abandoned mine workings for agricultural, residential, or industrial development. Damage is compounded when the value of the lost coal is added to the damage done to the surface and to any overlying coal beds that often catch fire.

Periodic geologic and seismic studies of the Acme and New Monarch mine areas show that the fires are increasing in size and are spreading into unmined coal. It is estimated that at least five different fires are burning over a 3-km^2 area (fig. 4). Other fires, such as reported in the Black Diamond mine in 1911 (Kuzara, 1977, p. 215–216), may still be burning although there presently is no surface evidence of a fire. Unmined coal beds of economic value locally overlie mine areas that are on fire, and they are threatened by the spreading fires below (figs. 4, 16–24). Seismic studies in the Acme and New Monarch mine areas also indicate that collapse and possibly underground explosions are increasing rapidly in these areas. Fires of this magnitude, in the opinion of the writers, may best be controlled by constructing a strip mine firebreak, isolation barrier, or isolation trench (Johnson and Miller, 1979, p. 18–21) around the burning area in order to cut off the supply of coal available to the fire. Carefully planned strip mining of the coal around fire areas, using mining procedures that protect personnel from subsidence and fire hazards, may be the best method to control fires in underground mines less than about 60 m, or about 10–15 times the coal thickness, below the surface and also might be economic in areas where large amounts of coal remain in place. Many local ranchers, coal operators, and others also favor timely strip mining around and within fire areas as the most effective control measure (figs. 16–24).

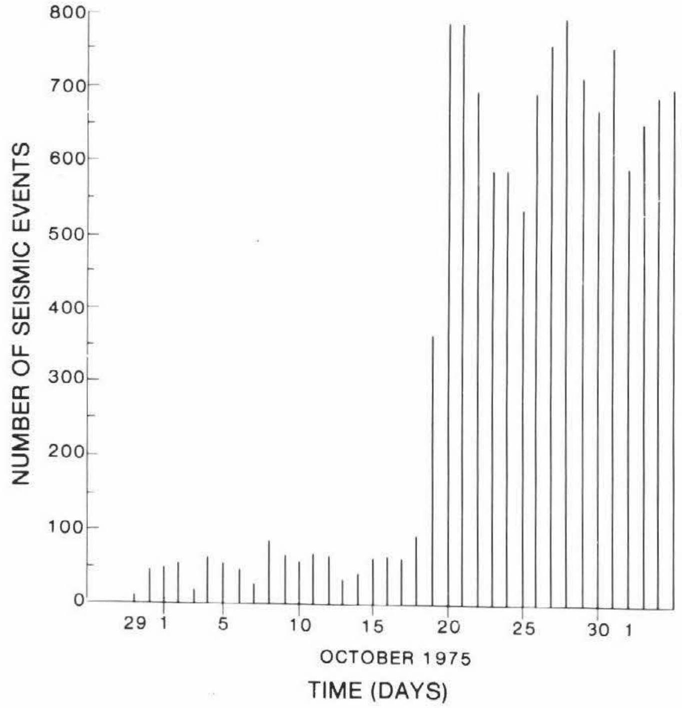

FIGURE 25.—Graph showing the daily number of small earth tremors at a seismometer station located near the firepit in the northern part of the Acme mine. The station was located about 185 m from the firepit from September 29 to October 19, 1975, then was moved to within about 30 m of the firepit. Note the approximate tenfold increase in number of events when the station was moved closer to the firepit. The earth tremors apparently are caused by the breaking and collapse of overburden material and perhaps by small underground explosions.

Water introduced from the surface seems only to increase the intensity of fires in this subbituminous coal. Other methods of control, such as hydraulically backfilling a slurry of retardant material through drill holes to the fire areas or operations to seal the fire, as done by the U.S. Bureau of Mines in several areas (for example, Whaite and Allen, 1975, appendix by Carlson), probably would not be cost effective on a fire the size of the Acme mine fire. Moreover, it would not recover any remaining coal.

Studies of coal mine fires suggest that the potential fire hazard also should be considered in planning in-place coal gasification or oil shale retorting activities. It would seem that advancing fire fronts can only be controlled as long as the supply of oxygen and withdrawal of gases are under controlled conditions. The presence of underground voids could create subsidence and cracks in the overburden that might allow the fire to intake air and exhaust gases independently from the designed system which, in turn, could result in out-of-control fires. The key factor is to control subsidence by either backfilling or designing the gasification or retorting operation such that the cavities are small enough and the overburden is deep enough to provide a stable overburden above stable rubble-filled cavities (fig. 14*A*). (See Shoemaker and others, 1979, p. 140–153, for examples of coal gasification model studies.)

HAZARDS IN RELATION TO LAND USE

The hazards to people, animals, and structures caused by coal mining activities can significantly affect future uses of the land because the severity of subsidence hazards may govern how mined lands are developed. Two of the basic hazards caused by coal mining—subsidence and landslides—also are identified as geologic hazards in "Warning and preparedness for geologic-related hazards, April 12, 1977" (Federal Register, 1977a, Proposed procedures, p. 19292–19296). A geologic hazard is defined in this document as:

> ". . . a geologic condition, process, or potential event that poses a threat to the health, safety, or welfare of a group of citizens or to the functions or economy of a community or larger governmental entity . . ." (p. 19292).

Coal mine subsidence hazards to people include the sudden collapse of the ground surface above mine openings (figs. 7, 8, 11, 12, 13), above tension cracks bridged by soil (figs. 9, 10), or collapse above cavities created by underground coal fires (figs. 16–20). Subsidence also can occur in spoil of surface mines, particularly in areas where increased surface loading and (or) rising water tables cause a reduction of porosity (Charles and others, 1978, p. 229–251). The greatest hazard to life and property in the Sheridan, Wyo., area is the sudden collapse of the ground surface into underground fires. In addition to ground collapse, the effects of tension, compression, and tilt due to the formation of depressions can damage structures beyond repair. Larger structures with small tolerances for deformation—such as multistory apartment buildings (Thorburn and Reid, 1978, p. 87–99), schools (Stephenson and Aughenbaugh, 1978, p. 100–118), factories, and powerplants—commonly will sustain the greatest damage unless they are designed to withstand the stresses and deformations caused by subsidence.

Landslides, which include rockfalls, slides, slumps, and earthflows on surface mine highwalls or reclaimed spoil material, can be a hazard to people and equipment during mining operations and also to people and structures after restoration, abandonment, and subsequent development of the mined land, unless proper grading, compaction, and vegetation procedures are followed. Small landslides on subsidence pits and cracks could damage adjacent structures or perhaps be a hazard to people and animals in the area. Landslides also may be triggered by subsidence on unstable slopes or, conversely, the increased surface loading from landslides above unstable mine openings may cause further subsidence.

Subsidence pits and cracks caused by underground mining and underground fires currently are a hazard to only a few persons traveling in the area and to animals. However, should lands underlain by underground mines be developed for either residential or industrial use, a hazard to many people and structures could exist in much of the area above abandoned underground mines (fig. 4). Abandoned coal mines with surface subsidence features are located in other areas in the western Powder River Basin that are not included in figure 4. Maps showing such aspects as present subsidence areas, fire areas, areas underlain by coal mines, thickness of overburden, and thickness of coal mined are needed to more precisely delineate current and potential hazard areas. (See also Ivey, 1978, p. 163–174.) Structures for residential or industrial use should not be sited above abandoned mines unless existing underground voids are located by systematically compiling appropriate subsidence and land-use maps and by conducting on-site engineering geologic studies, by drilling and geophysical studies where needed (Ivey, 1978, p. 163–174), or by other methods, and stabilized by such procedures as backfilling or grouting. Surface structures also might be designed to withstand the effects of subsidence in lieu of stabilization procedures. (For examples see National Coal Board, 1975, p. 64–95; Bell, 1978, p. 562–578; Johnson and

Miller, 1979; Geddes, 1978a, b; Shadbolt, 1978, p. 739–744; and Wood and others. 1978.

SUMMARY AND CONCLUSIONS

Subsidence studies in the western Powder River Basin and in western North Dakota indicate that, in overburden less than about 60 m thick or less than about 10–15 times the thickness of coal mined, the land surface can be reclaimed and returned to its original use, or to some other use, more quickly, easily, and cheaply if thick coal beds are mined by surface methods than if they are mined by underground methods, provided that proper restoration procedures are followed. Subsidence above room-and-pillar workings driven 25–80 years ago is still hazardous to man, animals, and the environment, and may continue to be a hazard for many years or many decades to come. Studies of subsidence above current underground coal mines indicate that subsidence effects—such as depressions, cracks, and bulges—would be caused by modern underground mining procedures, where the amounts of coal reserves extracted are acceptable in terms of economics, conservation, and hazard reduction. Depressions and cracks also disrupt the normal flow of surface and ground water.

Some subsidence pits, particularly in areas where the most dramatic and potentially hazardous collapses occur, may be deeper than the original height of the mine openings, because (1) the material spreads or is transported laterally into adjacent mine openings as it collapses, particularly in water-filled mine openings, (2) it compacts more than the state of the original material due to wetting and drying, or (3) it is subjected to both of these processes.

Coal recovery from thick coal beds in the weak rocks of the Tongue River Member of the Fort Union Formation is much greater, and long-range environmental problems are smaller, when modern surface mining procedures are employed rather than underground room-and-pillar mining, where the overburden is less than about 60 m thick, or where the overburden thickness is less than about 10–15 times the mining thickness. In view of current coal mining technology and the subsidence effects from modern underground coal mining, surface mining may be the best way to produce coal in any area where coal thickness and overburden conditions make the operation economical, provided that proper restoration procedures are followed.

Coal mine fires, which often start by spontaneous ignition in the subbituminous and lignitic coal fields of Montana, Wyoming, and North Dakota, increase the damage to the environment manyfold compared to normal subsidence damage. The fires also consume large amounts of valuable energy resources as they create unsightly and hazardous steaming and smoking cracks and firepits, and pollute the air and water. Strip mine firebreaks appear to be the most effective way to control large underground fires beneath thin overburden, such as the large fires in the Acme and New Monarch mines. Most of the fires start spontaneously with the entry of oxygen and water through subsidence cracks. Once started, the fire spreads by creating larger cavities, increased subsidence, and additional cracks to intake oxygen. Careful consideration should therefore be given to subsidence and possible cracking in planned in-place gasification or retorting of combustible hydrocarbons such as oil shale.

Results of this report reveal a paradox. The land devoid of subsidence features, and therefore the most desirable for development, may be the most hazardous to develop if the area (1) is underlain by room-and-pillar mine workings, (2) the overburden depth is less than about 60 m thick or about 10–15 times the original height of the mine workings, and (3) sufficient coal remains underground adjacent to unstable mine openings to support, or partially support, the overburden. In these areas the land surface may be unaffected by subsidence for many years, or even hundreds of years, depending on the strength of the rock and the hydrologic conditions in the overburden. However, when and if surface collapse occurs as a result of successive collapse above the mine openings, the resulting pits can be much more of a threat to people, animals, and structures than the normal subsidence depressions and boundary cracks that commonly occur above mine workings where all, or nearly all, the coal was removed.

In the opinion of the writers and others (for example, Ivey, 1978, p. 174), guidelines are needed to assure that all available mining and mine subsidence information is systematically assembled, evaluated, and made available to land-use planners before mined lands are developed for residential or industrial use or other uses involving the public welfare.

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