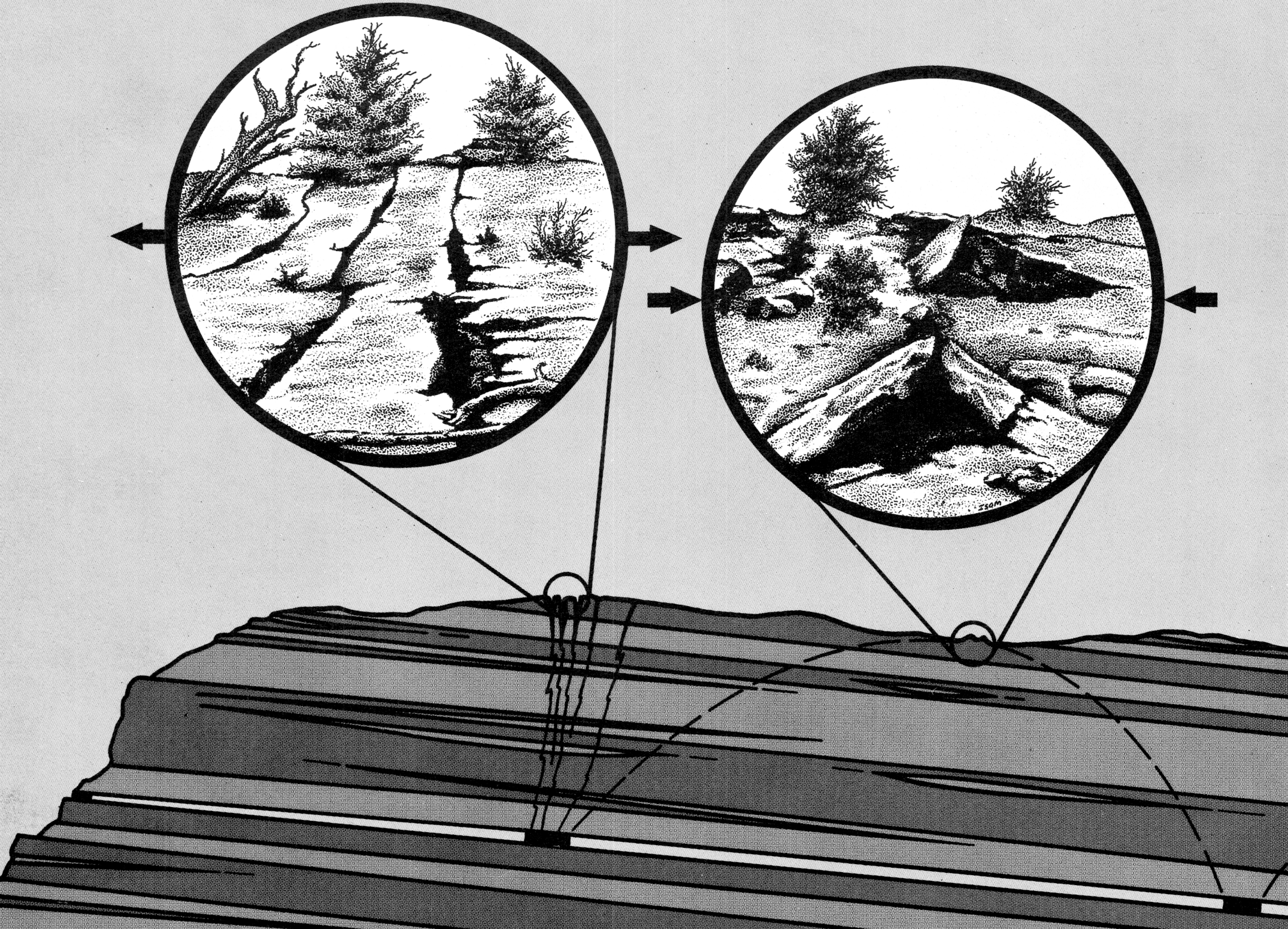
SOME ENGINEERING GEOLOGIC FACTORS CONTROLLING COAL MINE SUBSIDENCE IN UTAH AND COLORADO



GEOLOGICAL SURVEY PROFESSIONAL PAPER 969

FRONTISPIECE.—Northward view across the North Fork Gunnison River showing the geologic and topographic setting in the Somerset coal mining district, Gunnison County, Colo. The rugged topography shown is characteristic of the Somerset mining district. The ridge in the left foreground overlies the mine workings that were selected for one of the subsidence studies. The Mesaverde Formation comprises the area from the light-tan ledges and cliffs in the foreground (Rollins Sandstone) to the ridge crests in the middleground. The coal-bearing portion of the Mesaverde is portrayed by the pinkish-red coloration in the left foreground, caused by the burning of the coal beds, which, in turn, has caused extensive subsidence. The Mancos Shale underlies the Mesaverde Formation. The light-tan ledges and cliffs above the Mesaverde (background) are the rocks of the Ohio Creek Formation. The subdued terrain in the background, with its extensive landslides and green aspen groves (right background), is developed on rocks of the Wasatch Formation, which overlies the Ohio Creek Formation. Some Middle Tertiary intrusives, which form a part of the West Elk Mountains, are on the right skyline.

SOME ENGINEERING GEOLOGIC FACTORS CONTROLLING COAL MINE SUBSIDENCE IN UTAH AND COLORADO

Some Engineering Geologic Factors Controlling Coal Mine Subsidence in Utah and Colorado

By C. RICHARD DUNRUD

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A discussion of the processes of subsidence and their effects on mine safety, coal resource management, and the environment in two geologic settings

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1976

UNITED STATES DEPARTMENT OF THE INTERIOR

THOMAS S. KLEPPE, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

First printing 1976
Second printing 1977

Library of Congress Cataloging in Publication Data
Dunrud, C. Richard
Some engineering geologic factors controlling coal mine subsidence in Utah and Colorado.
(Geological Survey Professional Paper 969)
Bibliography: p.
1. Coal mines and mining–Utah. 2. Coal mines and mining–Colorado. 3. Mine subsidences–Utah. 4. Mine subsidences–Colorado. 5. Engineering geology–Utah. 6. Engineering geology–Colorado.
I. Title. II. Series: United States Geological Survey Professional Paper 969.
TN805.U8D86 622'.33'4 76-7452

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02864-6

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SOME ENGINEERING GEOLOGIC FACTORS CONTROLLING COAL MINE SUBSIDENCE IN UTAH AND COLORADO

By C. RICHARD DUNRUD

ABSTRACT

Subsidence plays a major role in coal mining activities and in the future use of the land surface above the mine workings. Stresses and deformations produced in mine workings, other coal beds, bedrock, and at the ground surface by the processes of subsidence significantly affect mine safety, extraction efficiency, and the surface environment. Basically, the subsidence process comprises two different stress-and-yield conditions in response to the excavation of mine workings.

First, arcuate zones of compressive stress, called compression arches, tend to occur above and below the mine panels and transfer the overburden load in coal-extraction areas to adjacent solid-coal boundaries or barrier pillars. Second, caving and flexure of strata, within the destressed zone encompassed by the arches, into the mine cavities tends to increase the stresses again in the mine workings. Flexure of strata also produces tensile and compressive stresses within lithologic units and shear stresses across lithologic boundaries. With time, and as the mine voids are widened, the compression arches tend to migrate higher in the overburden strata and eventually may reach the surface. This migration continues to transfer overburden stresses back into the extraction area from the mine boundaries or barriers. The rate of migration of compression arches, and, consequently, the rate of stress transfer, depends on thickness and strength of overburden strata, duration and rate of mining, mine geometry, and mining sequence.

The ground surface, other coal beds, ground-water aquifers, methane zones, and economic deposits above and below the mine workings can be damaged by the subsidence processes. Deposits in the mine overburden and the surface are subjected to stresses produced by compression arches and by flexure of strata. As a result of the subsidence processes, deposits are subjected to unloading followed by loading beneath mine openings and, in addition, are subjected to loading followed by unloading beneath remnant coal pillars and near solid-coal mine boundaries.

In an area underlain by several thin beds or by one thick bed, mining sequentially from upper to lower beds, or, in the case of a thick bed, mining separate "benches" or "lifts" from top to bottom commonly is safest and most efficient. However, unless a uniform extraction plan is followed, mining hazards, such as roof falls, bumps, and squeezes caused by stress concentrations, may force premature abandonment of an area of the mine, with resultant loss of reserves. Knowledge of geologic, topographic, and socioeconomic conditions in prospective mining areas is vital to planning safe and efficient mining activities, particularly in areas underlain by thick coal beds or by more than one coal bed.

INTRODUCTION

Subsidence damage resulting from underground coal mining will become a greater problem in the United States as our population increases along with our demand for more energy. The clash between population growth and man's demand for more energy is already very acute in many heavily populated industrial countries, such as Japan (Kaneshige, 1971), but also it is felt in the more heavily populated coal mining areas in the United States. Although lands underlain by coal reserves in the Western United States are still relatively free of industrial and urban development, many areas in the East support industry, housing, or farming.

Many old established urban areas overlying coal mine workings, such as Scranton, Pa., have experienced severe and costly subsidence damage many years after the mines were abandoned. According to recent information (U.S. Bureau of Mines, written commun., Feb. 5 and April 10, 1973), $29 million worth of property, including 2,000 homes, 50 commercial and office buildings, 2 hospitals, and several schools are threatened by subsidence in the Hill section of Scranton—an area in which an estimated 10,000 people live and work. The total cost of surface stabilization of this area by hydraulic mine backfill is estimated to exceed $8 million.

Subsidence damage to the rocks above underground coal mines also can reduce minable coal reserves, decrease mine safety, lower production efficiency, and possibly disrupt the hydrologic regimen. Coal deposits in parts of Wyoming, Colorado, and Utah locally comprise vertical sequences of several minable coal beds interbedded with thick to thin sandstones and mudstones. Deformation caused by mining one coal bed can damage other beds nearby unless the beds are extracted in proper sequence. Ruptures within the rock mass and at the surface may tap and divert ground water or methane pockets associated with the coal beds or may even divert surface-water drainage to underground aquifers or mine workings, which in turn can upset established ground- and surface-water supplies as well as threaten the mine workings.

Coal mine subsidence problems such as these point out that mining plans for new and existing coal mining areas must be based on all existing technology, with the goal of maximizing coal extraction percentages and minimizing the subsidence damage to the overburden and surface. To accomplish this we must know the processes of subsidence that occur both in the overburden and at the surface in various geologic environments and under various methods of mining. This is one of the major goals of coal mine deformation studies underway in the U.S. Geological Survey and is the central theme of this report.

COAL AS AN ENERGY CONTRIBUTOR

Coal is an important part of our current energy supply, particularly for use in generating electric power. The use of coal will no doubt continue to grow rapidly in response to increasing demands on domestic energy resources. In 1970, 17,000 trillion B.t.u.'s from various energy sources were required to produce some 1,260 billion kilowatt hours of electrical energy in the United States (Risser, 1973). Of this total, 1 percent was supplied by nuclear power, 16 percent by hydroelectric power, and 83 percent by the fossil fuels. Coal provided 55 percent of the power contributed by the fossil fuels. Although our total energy requirements are increasing rapidly with time, the demand for electrical energy nearly doubles every 10 years, and, assuming that coal continues to contribute about the same percentage of our electrical energy, the demand for coal will increase accordingly. The projected requirements for coal in the 1970's alone may equal the total amount consumed in the previous seven decades.

Many coal deposits are too high in sulfur, ash, or other constituents to be burned in power plants under existing or proposed clean-air standards. However, various techniques of obtaining synthetic crude oil, natural gas, char residue, sulfur, and fly ash from coal are in advanced stages of study or implementation under the auspices of U.S. Department of the Interior Office of Coal Research (W. A. Bear, oral commun., 1970, 1972). With these processes, the sulfur and ash are recoverable byproducts rather than pollutants. Another pollution-free method of producing electrical energy from coal involves the direct generation of electricity from coal and is called the magnetohydrodynamic (MHD) process; with this process, electrical energy is produced by passing hot gases, derived from coal, through a stationary magnetic field. Should these new techniques eventually prove economical, coal would be an increasingly important source of electrical energy, as well as a source of other forms of energy and material byproducts, for years to come. It will thus be of continuing importance for us to study the effects, including subsidence, of mining needed supplies of coal.

DEFINITION OF SUBSIDENCE

Coal mine subsidence is defined in this report as all deformation within most of the overburden and at the surface that is caused by underground mining. It includes the local upward movement of strata that sometimes occurs above solid-coal mine boundaries or large barrier pillars, which is caused by downwarping of overburden into mine cavities; it also includes the downwarping itself, the associated horizontal tensile and compressive strains produced by strata flexure, and the compressive strain induced by the compression arches.

For the purposes of this report, the term "subsidence" applies to deformation or movement in the overburden two or more mine heights above the immediate mine roof; the term "roof fall" applies to the fall of roof rocks less than two mining heights above the mine roof.

ACKNOWLEDGMENTS

Officials of the U.S. Steel Corp., Bear Coal Co., and Western Slope Carbon, Inc., materially aided the studies undertaken for purposes of this report. They contributed maps of mine workings, offered helpful suggestions and information, and they allowed access to their properties and the use in this report of certain information and pictures taken in their mines. Their help was given in the spirit of making coal mining safer, more efficient, and less damaging to the environment. The author thanks them all for their help and cooperation, particularly Paul E. Watson, general superintendent, western district, U.S. Steel Corp.; J. Boyd McKean, district mining engineer, U.S. Steel Corp.; R. W. Ramey, superintendent, Somerset mine, U.S. Steel Corp.; W. A. Bear, president, Bear Coal Co.; and C. L. Heiner, Western Slope Carbon, Inc.

Two part-time coworkers provided basic data for the preparation of this report. R. Edward McKinley, retired mining engineer, U.S. Steel Corp., made monthly subsidence measurements at Somerset, which were extremely helpful in determining the

processes of subsidence. Robert L. Rasmussen, mine engineer at the Somerset mine, who works part time on the U.S. Geological Survey seismic recording facility at Somerset, provided mine maps and helpful updates on mining operations. Two colleagues, R. L. Parker and R. B. Taylor, provided recent high-resolution aerial photographs of the Somerset district that proved very useful to the mine deformation studies.

PREVIOUS STUDIES

Subsidence studies began in Europe before the turn of the century. Early concepts of subsidence included the so-called law of the normal and law of the vertical (fig. 1). According to the law of the normal (fig. 1*A*), investigators believed that the overburden strata broke and subsided above and parallel to the boundaries of the mined-out areas along fractures perpendicular to the strata. The so-called law of the vertical was developed a few years later. According to this concept the overburden broke and subsided along vertical fractures above the boundaries of the mined-out areas (fig. 1*B*).

During the early 1900's the concepts of limit (or draw) angle and break angle developed following further surface and underground measurements. Measurements in the Ruhr region of Germany and elsewhere in Europe and Russia revealed that subsidence or other deformation affected a surface area larger or smaller than the area mined (fig. 2*A*). The limit angle φ, which is the acute angle defining the limit of subsidence above mine workings, is positive if the surface area affected by subsidence is greater than the mined-out area; it is negative if the deformed surface area is smaller than the mined-out area. The break angle β, which defines the zone of maximum tensile stress caused by flexure of strata (fig. 2*B*), is steeper than the limit angle but may approach the limit angle when it is negative. The limit angle is measured from either the horizontal or from the vertical. The angle relative to the horizontal is chosen in this report because it is consistent with geologic measurement of bedrock attitudes. Limit angles commonly range from 45° to 65° in European coal fields, 55° to 65° in Great Britain, and 45° to 60° in the Ruhr region; they are about 55° in northern France and about 60° in the U.S.S.R.; and they range from 45° to 55° in the Netherlands (where angles are referenced from the horizontal rather than from the vertical) (Zwartendyk, 1971, p. 142–143).

A troughlike subsidence geometry was observed within the limits of the draw in many European coal mining districts. This observation led Lehmann (1919, cited in Zwartendyk, 1971, p. 85–86) to propose his subsidence trough theory. This concept explains tensile and compressive strains in addition to the vertical and horizontal movement and tilting observed above coal mining areas. According to this concept, the rate of change of vertical settlement increases to a maximum from the limits of the draw inward, becomes constant at the point of inflection, and then decreases to zero in the center of the trough, provided the mining area is wide enough to prevent further differential settlement in this area (supercritical mining width) (fig. 2*B*). The mined-out area is said to be of critical extraction width if it is just wide enough to allow maximum subsidence (S_{max}) in the center of

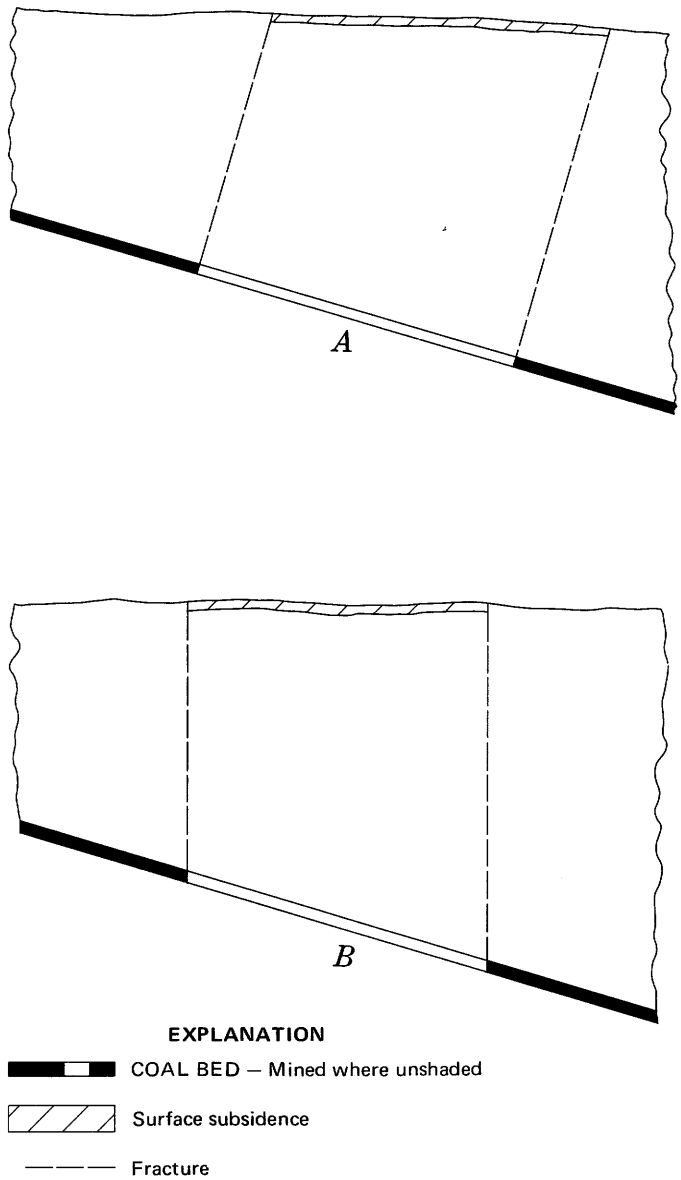


FIGURE 1.—Early concepts of surface and rock mass subsidence processes above mine workings. *A*, Law of the normal; *B*, law of the vertical.

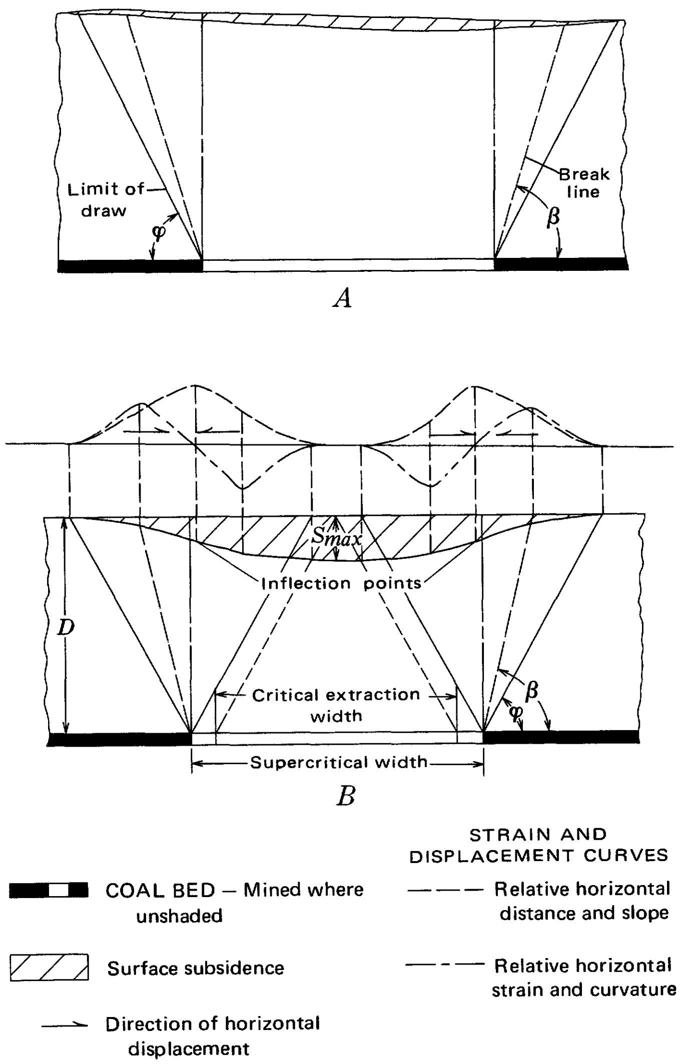


FIGURE 2.—Subsidence trough above a mined coal bed; vertical scale of subsidence trough greatly exaggerated for clarity. *D*, overburden depth. Modified from Zwartendyk (1971, p. 132), Bräuner (1973, p. 4), Mohr (1956, p. 141), and Wardell (1971, p. 206). *A*, Subsidence trough with positive limit (or draw) angle (φ) and positive break angle (β). *B*, Subsidence trough showing critical width of mining that will cause maximum surface subsidence (S_{max}), supercritical width of mining, and the general form of the curves depicting horizontal displacement, slope, strain, and curvature.

the trough (fig. 2*B*). According to Wardell (1971, p. 205), this width varies, but in European coal fields it is between 1.0 and 1.4 times the average overburden depth, depending on the lithology and structure of the overburden and provided the panel length is more than 1.4 times the average overburden depth.

Although most troughs do not precisely fit the model in figure 2*B*, the figure illustrates the reasons for the vertical and horizontal strains that are commonly observed above mined-out areas. The ground surface is convex upward between the limits of the draw and the points of inflection; thus, the tensile strain increases to a maximum at the point of maximum positive curvature and then decreases to zero at the points of inflection, where ground tilt and horizontal extension are at a maximum. Between the points of inflection and the point of maximum subsidence (S_{max}, fig. 2*B*), the ground surface is concave upward, thus causing compressive strain. Between these points, the compressive stresses increase to a maximum and then decrease to zero, provided the mined-out area is of supercritical width.

According to Wardell (1971, p. 209), maximum change in ground slope and length varies in relation to the maximum amount of subsidence (S_{max}) divided by the average overburden depth (*D*), whereas the maximum horizontal curvature varies in relation to the maximum subsidence divided by the square of the average overburden depth (D^2). The area subjected to maximum subsidence has reached a condition of zero strain. However, even this area of maximum subsidence and zero strain was initially subjected to strain during mining. Furthermore, if the mine opening is widened (fig. 2*B*), the surface adjacent to the area affected by subsidence will be subjected to a transient wave of first tensile, then compressive, and finally zero strain as the ground subsides above the enlarging mine opening. Ground-water- and methane-bearing rocks, as well as subsurface water, gas, and sewer mains, and unyielding buildings and foundations, will be subjected to all these strains, and the damage will, in most cases, be cumulative.

Mining of coal adjacent to the mined-out area, as shown in figure 2*B*, leaving a barrier pillar (fig. 3), can cause additional surface strains. Here, two adjacent subsidence troughs superposed over such pillars would interact to produce tensile strain approaching twice the strain produced above a solid-coal boundary.

Both the rate and amount of surface settlement were studied by various foreign investigators (for example, Mohr, 1956, and research cited by Zwartendyk, 1971) in relation to various physical environments. Although much of this information is contradictory and somewhat confusing, they found that, in general, the amount of surface subsidence and deformation, although variable, depended on the strength and thickness of overburden, the width of the mined-out area, and the thickness of the coal bed. A wider mining area or a thicker coal bed increased the rate of surface settlement but, if the extraction was

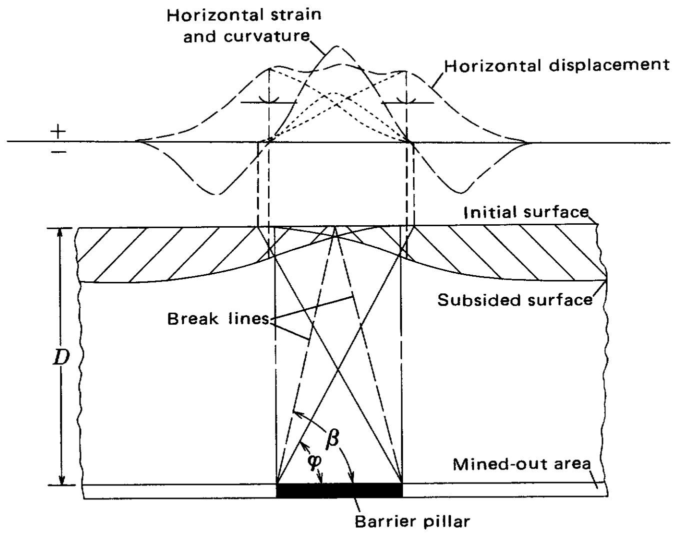


FIGURE 3.—Author's interpretation of how further mining of the coal bed shown in figure 2 would affect deformation of the surface. A barrier pillar now separates two mined-out areas; strain and horizontal displacement curves are shown above cross section. Note that the superposition of subsidence profiles greatly increases the tensile strain above the center of the barrier; also, the horizontal displacement is nearly at a maximum over the entire barrier. Surface damage is most accute above the middle of the barrier pillar; the barrier pillar must be twice as wide as the overburden depth (*D*) multiplied by the cotangent of the limit angle (φ) before surface subsidence is nullified.

uniform or complete and rapid, did not necessarily increase the amount of fracturing. A less complete or less uniform mining method and slower or variable mining speed increased overburden breakage. A thicker and stronger overburden generally decreased the rate of surface settlement for any given mining width and height (Briggs, 1929, p. 181 – 184, cited in Zwartendyk, 1971, p. 91 – 92).

Detailed subsidence studies in the Ruhr coal fields of West Germany shed more light on the behavior of the surface and over burden rocks (Mohr, 1956). The amount and rate of deformation of the surface and rock units were measured from vertical mine access shafts located above either solid-coal or mine barrier pillars (fig. 4). On the basis of these measurements, the positions both of the limits of the draw and of maximum vertical and horizontal strain, as well as the rate of change of these positions with time, were determined. In detail, the limit lines, which define the limits of draw, steepened in strong rocks having large angles of internal friction and flattened in weak rocks having small angles of internal friction. Within the limits of the draw, the shaft linings were sheared and offset many inches (fig. 4*A*) and thrown out of plumb as much as 6 feet (1.8 m) (fig. 4*B*) by flexure of stratified rocks. The linings also were vertically compressed by compaction of rock units—particularly weak rock units—in contact with the shafts.

Maximum lateral shear strain occurred across lithologic boundaries and at points of maximum curvature, which also are the loci of points defining the break line or line of maximum tension. Cumulative deformation in strata above remnant barrier pillars between two mined-out areas suggests that the break lines curve together toward the surface above the barrier pillars owing to the superposition of adjacent subsidence troughs (section, fig. 4). This superposition of the troughs greatly increases the curvature, the tensile strain at the surface, the flexural strain within lithologic units, and the shear strain across lithologic boundaries or bedding planes (fig. 4*A*), compared to the flexural strain and shear strain above solid coal at mine boundaries (fig. 4*B*).

The concepts of break line and break angle are not spelled out by Mohr, but are implicit in his data (1956, p. 141 – 142). According to Grard (1969, p. 46, cited in Zwartendyk, 1971, p. 188), maximum tensile strain exists in bedrock units at the surface when the pillar width is about 0.4 times the overburden depth. As the barrier pillar becomes narrower, an increasing amount of the strata above an interior barrier pillar is affected by superposition of tensile strain (fig. 4). Shear strains were observed in shafts along the limits of the draws above the barrier pillars and along the single limit line above the solid coal boundary (figs. 4*A*, *B*).

Mohr (1956, p. 149 – 150) measured subsidence rates at the surface and within the overburden adjacent to mine access shafts. He observed a timelag between the beginning of mining and the onset of surface subsidence. This suggested that some type of strong, but temporary, support mechanism existed in the overburden. Because all rocks are weaker in tension than in compression, Mohr proposed that arcuate zones of compression, or compression arches, formed above the mined-out areas, and, as mine openings were widened, the arches progressed higher and higher into the overburden until they reached the surface. Beneath these compression arches, subsidence troughs formed in the overburden within the limits of the draws. Wardell (1971, p. 204) postulated that all subsidence ceases within 2 or 3 years after completion of mining. Speed of mining might, therefore, be an important factor governing the severity of deformation at the surface and within the rocks of the overburden. If coal could be extracted

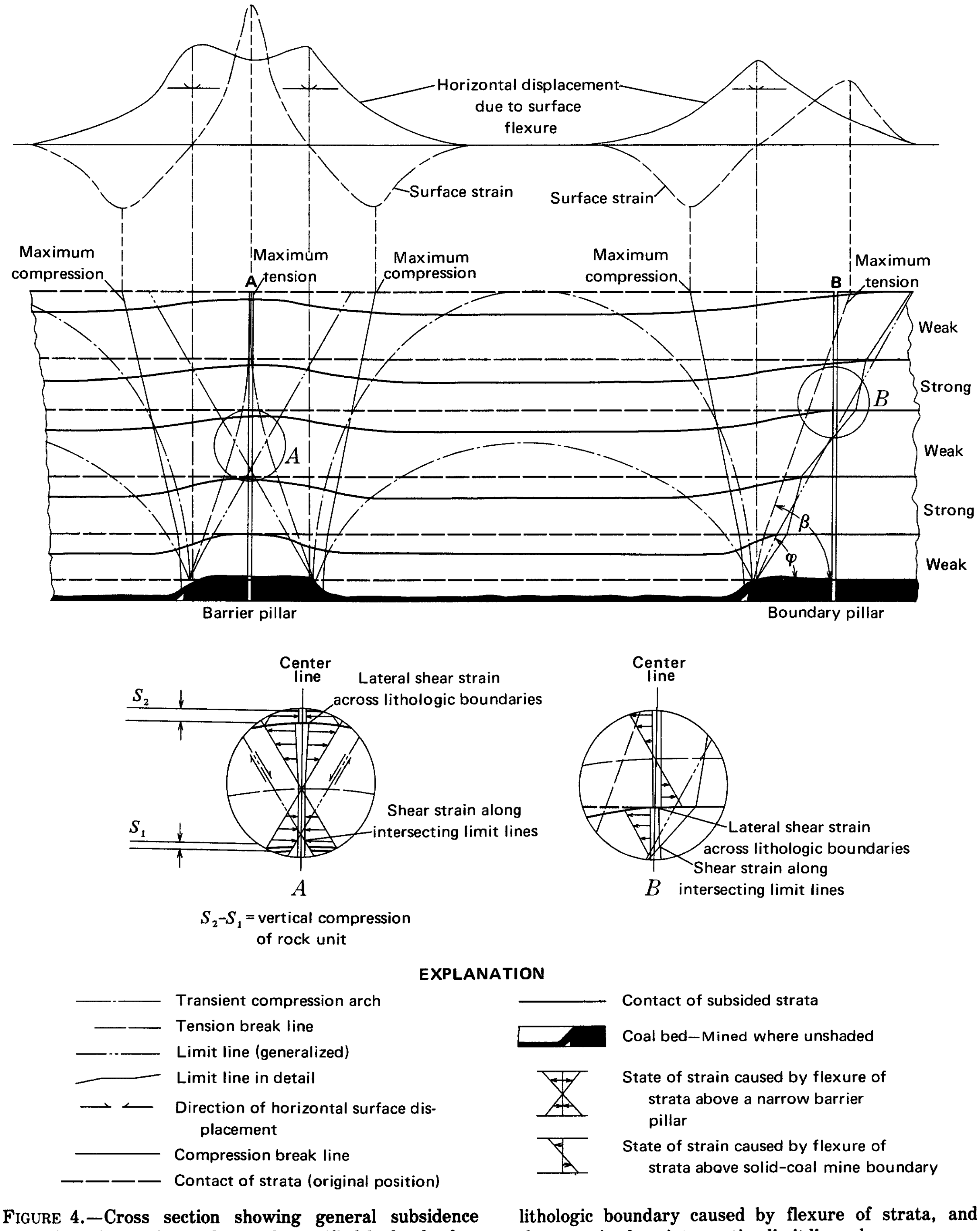


FIGURE 4.—Cross section showing general subsidence yield conditions for surface and stratified bedrock after migration of compression arch to surface. General yield conditions interpreted from measurements made in the Ruhr coal fields by Mohr (1956, p. 146–150); horizontal displacement and strain curves are modified from Zwartendyk (1971, p. 134) and Bräuner (1973, p. 4). *A*, Enlargement ×2 of a segment of shaft A showing vertical settlement (S_2—S_1), lateral shear strain across a lithologic boundary caused by flexure of strata, and shear strain along intersecting limit lines above a narrow barrier pillar. *B*, Enlargement ×2 of part of shaft B and surrounding rock mass showing lateral shear strain across a lithologic boundary caused by flexure of strata and shear strain along the limit line above a solid coal pillar. The lateral shear strain in *A* is greater than the shear strain in *B*.

from an area large enough to minimize strata curvature and flexure before the compression arch migrated to the surface, damage to the surface and to the rocks in the overburden might be minimized.

Wardell (1971, p. 203 – 204), in general, supported the concept of the pressure arch without specifically naming it. On the basis of numerous field measurements, principally within the coal fields of the United Kingdom, he found that ground surfaces above active mining areas did not subside until certain lateral cavity dimensions were exceeded. A delay, therefore, occurs between mining and surface subsidence, but he contended that after surface subsidence begins it will continue at a rate proportional to rate of mining. He also found that these critical lateral cavity dimensions are greater beneath thick overburden than beneath thin overburden, and, for a given overburden thickness, are greater beneath predominantly strong strata, such as sandstones, than beneath predominantly weak strata, such as shales or mudstones.

Another way to minimize surface subsidence damage, if rapid and complete extraction is not possible, is to restrict the width of the mining panel so that compression arches do not migrate to the surface but, instead, stabilize within the overburden. In the coal fields in parts of the United Kingdom, France, Poland, and the U.S.S.R., where overburden thickness ranges from 200 to 3,000 feet (61 – 914 m), investigators found that compression arches normally were stable within the overburden if the widths of the mined-out areas were limited to one-fourth to one-half the height of the overburden, depending on the strength of the overburden strata, and provided that abutments of the arches were supported by barrier pillars strong enough to support the overburden load (Zwartendyk, 1971, p. 187 – 190).

This so-called panel-and-pillar method has been used successfully in the United Kingdom beneath towns, public utilities, and industrial plants. The panels were mined by either longwall or room-and-pillar methods, without backfilling and without causing undue subsidence damage. The validity of this method is supported by Wardell's conclusions (1971, p. 206), which were based on numerous measurements in the United Kingdom. He found subsidence ratios (ratio of maximum surface subsidence (S_{max}) to thickness of the coal bed or mining height (t)) of less than 20 percent of the bed thickness above mining panels that were about one-third the average overburden depth (fig. 5).

In the stratified iron deposits of the Lorraine area in France, "safety" pillars were left unmined in a checkerboard pattern for support, but this pattern

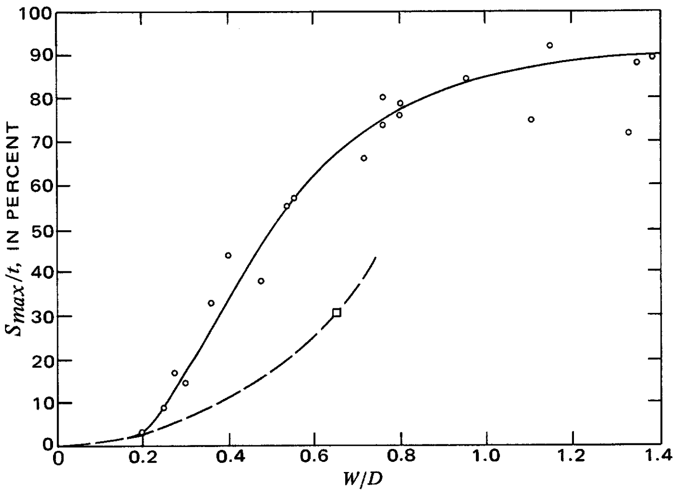


FIGURE 5.—Subsidence ratios (maximum surface subsidence (S_{max}) relative to the thickness (t) of a coal bed) for various ratios of mine panel width (W) to mean overburden depth (D). Measurements are from Wardell (1971, p. 206) for coal fields of the United Kingdom; all coal was extracted by the longwall method in coal beds dipping less than 15° beneath overburden strata with reasonably consistent geologic conditions; all panel lengths were greater than 1.4D. The data point bounded by a square is from maximum subsidence measurement above the 6th Left room-and-pillar mining panel, Somerset mine, Colorado, 3 – 5 months after mining was completed.

was abandoned because of subsidence problems and severe pillar bursts. A method to achieve panel-and-pillar geometry was used in place of this mining procedure with good success (Zwartendyk, 1971, p. 190). Statistics on overburden collapse showed that a panel width of 0.42 times the overburden depth sustained a compression arch within the overburden when panels were separated by sturdy barriers. Many of the panels were nearly 2,000 feet (610 m) long and averaged 280 feet (85 m) wide, while the width of the adjacent barrier pillars averaged 200 feet (61 m). Assuming complete extraction within the panels, the recovery approached 60 percent of the total reserves.

The so-called harmonic method of mining was developed and first implemented by Grond (1947, p. 240 – 291, cited in Zwartendyk, 1971, p. 192) in the Netherlands during 1934. Basically the concept involves mining in such a manner that the final vertical and horizontal surface strains produced by mining in one area are essentially canceled by strains produced by mining in another area. In multiple-bed mining, for example, mine extraction panels might be offset (fig. 6) and mined concurrently by longwall or room-and-pillar methods so as to produce little or no final horizontal strain within the overburden or at the surface perpendicular to the mining panels.

However, transient strains and the presence of

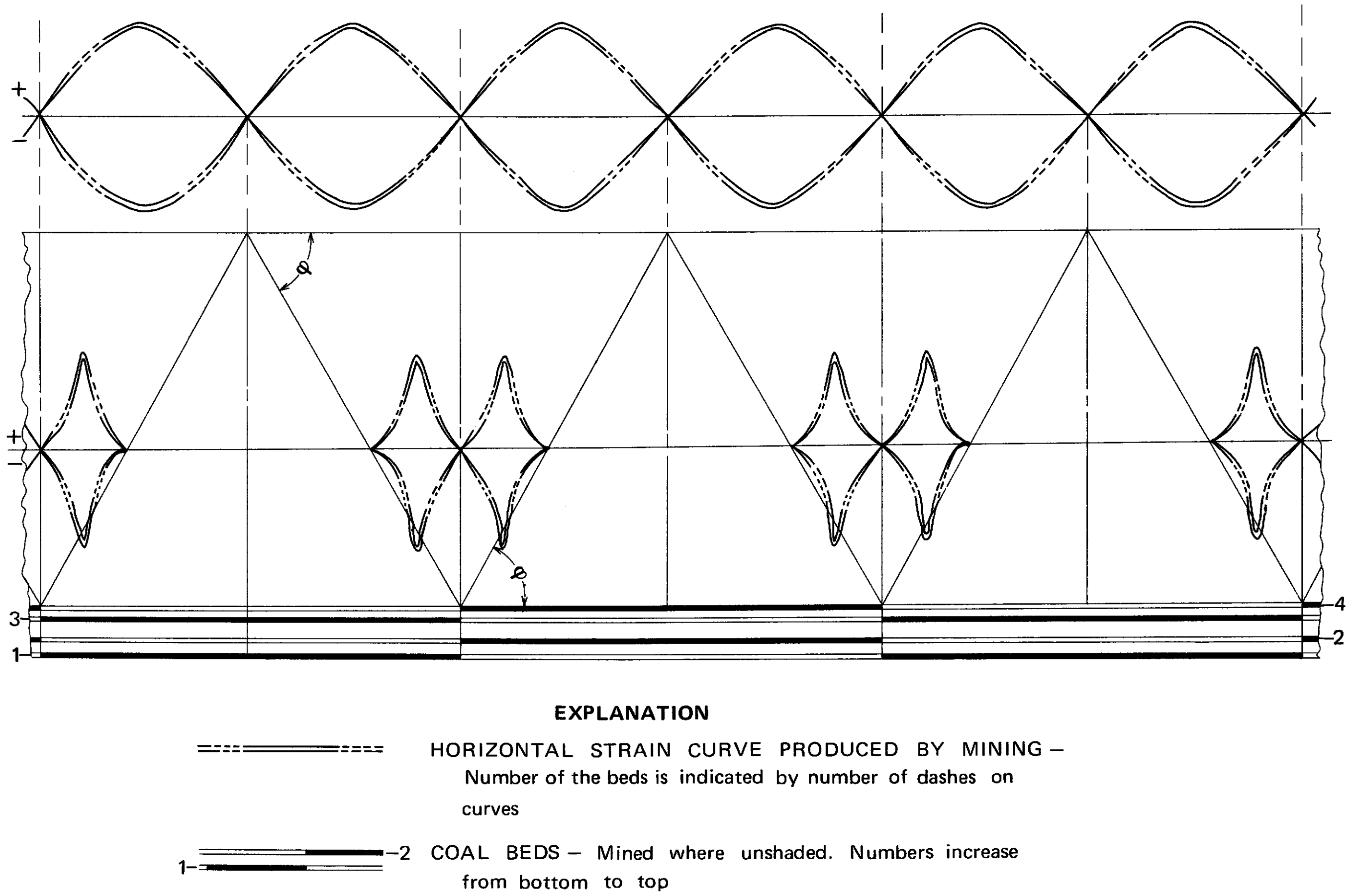


FIGURE 6.—Cross section perpendicular to mine panels, showing concurrent harmonic extraction of four flat-lying coal beds beneath overburden of constant thickness; direction of mining is perpendicular to cross section. Note that final horizontal strains along line of section produced by offset panel mining in any two vertically successive coal beds cancel the effects of each other. Modified from Kaneshige (1971, p. 181).

compression arches within the overburden and at the surface could be damaging. The possible occurrence of tension fractures parallel to a longwall face or, if the room-and-pillar method were used, to a pillar line would be particularly damaging to the harmonic mining procedure. The harmonic method also requires more miners and mining equipment than most mining companies could muster. In addition, the mining operations need to be on a very tight schedule, prohibiting variances such as those caused by miners' vacations, strikes, and coal-haulage interruptions. The procedure might cause high stress concentrations within the strata between coal beds at the mine boundaries, which could cause rock bursts and excessive roof falls at the boundaries. Uneven topography or steeply inclined coal beds would further complicate the design of mine workings to minimize subsidence damage.

CURRENT STUDIES OF SUBSIDENCE PROCESSES

GENEVA MINE AREA, UTAH

Coal mine deformation studies in central Utah and in western Colorado have yielded information on how geology, topography, mine geometry, and method of mining control subsidence. East of the Book Cliffs in the Geneva mining area of the Sunnyside mining district in central Utah, coal is mined from one bed or zone lying beneath overburden strata that vary in thickness from a few feet to more than 3,000 feet (914 m) and dip 6°–15° eastward or northward. The overburden rocks comprise, in ascending order, the Mesaverde Group (Upper Cretaceous), North Horn and Flagstaff Formations undifferentiated (Upper Cretaceous through Eocene), and Colton Formation

(Eocene) (fig. 7). The Mesaverde Group is composed of thick strong sandstones alternating with weak shales and mudstones. The North Horn and Flagstaff Formations comprise claystones, shales, and discontinuous sandstones with thin limestone beds at the top. The Colton Formation consists of thick to thin sandstones which intertongue with, or alternate with, well indurated limy mudstones.

Bedrock units are displaced by faults that trend north-northwest, east, and northwest. The north-northwest-trending faults, which form a linear fault zone, dip steeply to vertically, whereas the east-trending faults dip moderately to steeply and form horst-and-graben structures. The northwest-trending faults, which essentially constitute one fault with local imbrications, exhibit a large left-lateral strike-slip component of movement; the other sets of faults are predominantly dip-slip normal.

Joints are common in the resistant sandstone and siltstone beds. Their attitudes are variable, but two well defined, steeply dipping joint sets that are parallel to the strike and dip of the strata are the most predominant.

While conducting detailed geologic mapping for a study of geologic causes of coal mine bumps, subsidence cracks were mapped and were studied in their relation to mining. A few months after the coal was mined a set of nearly vertical fractures, that trended south-southeast, was observed above a barrier pillar that separated the Book Cliffs and Geneva mines (fig. 8). The coal had been mined too close to the outcrop, particularly in the southern part of the Book Cliffs mine (Dunrud and Barnes, 1972), and the outcrop barrier, which was too thin to support the overburden weight, yielded, creating a cantilever above the mined portion of the Book Cliffs mine. The stresses produced by the cantilever caused the overburden above the property barrier to fail in tension along steeply dipping to vertical joints that parallel the general direction of the barrier pillar. Failure under these circumstances followed as predicted by the law of the normal.

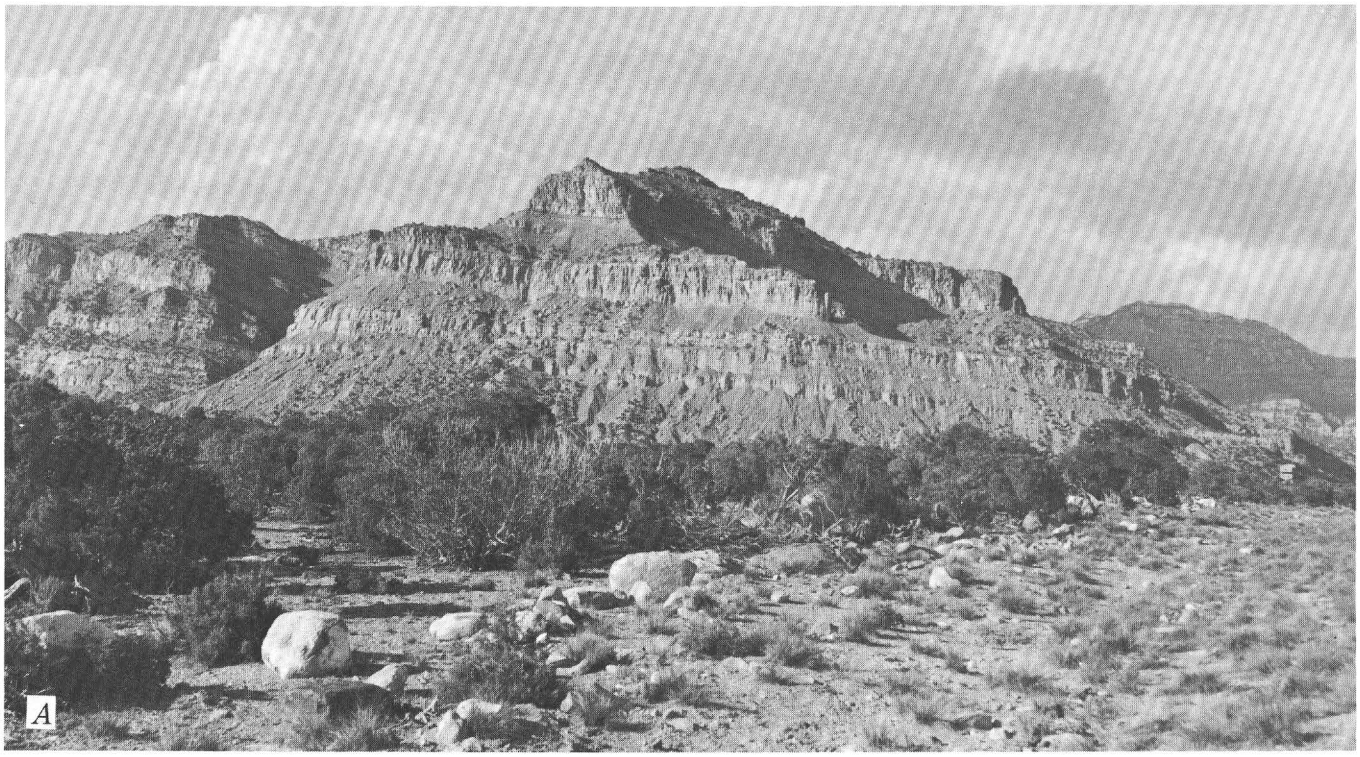
Large tension cracks, some of which are hundreds of feet long and range from about 0.06 inch (1.6 mm) to as much as 3 feet (0.9 m) in width, formed in massive sandstone at the top of the Mesaverde Group about 900 feet (274 m) above the mine area (figs. 9*A*, 9*B*). Maximum cumulative surface extension across this zone of cracks, which was much as 250 feet (76 m) wide, was approximately 5 feet (1.52 m). Manmade structures would, of course, be destroyed by tensile deformation of this magnitude, but, fortunately, the surface in this region is currently inhabited only by an occasional horse, cow, or deer. Some of the wider cracks (figs. 9*A*, 9*B*) emit air from mine workings, indicating their continuity to the mine workings. These cracks divert all surface- and ground-water flow in this area to lower strata or to the mine workings.

Compression features, such as fractured bulges and small anticlines, formed in massive sandstone 900 feet (274 m) above a mined-out area within the Geneva mine about 1½ years after mining was completed (figs. 8, 9*B*, 9*C*). Measurements of the features revealed that the ground surface was shortened locally by as much as 3 feet (0.92 m). The anticlines were alined parallel to the property barrier pillar and roughly perpendicular to retreat-pillar lines in the Geneva mine. This amount of compressive deformation in strong, competent sandstone indicates the presence of very strong horizontal compressive stresses in a direction perpendicular to the barrier pillar dividing the mine properties. The compressive stresses were due either to concave curvature of strata resulting from vertical subsidence or to the presence of a temporary compression arch which had migrated through the overburden to the surface above the mined-out area.

The chronological development of cracks in the area, which was followed through periodic mapping, indicated that a compression arch caused the compressive stresses. However, periodic subsidence measurements would have been necessary to confirm this. The chronological sequence of crack formation was as follows. First, tension cracks were noted above the property barrier (area 1 in fig. 8) in September 1963; no other cracks were noticed at that time. Second, compression bulges and anticlines first mapped in August 1966 (area 2 in fig. 8) appeared, on the basis of freshness of broken surfaces of rock and soil, to be less than 1 year old. Third, very recent tension cracks 0.06 – 4 inches (0.16 – 10 cm) wide were also mapped in August 1966 (area 3 in fig. 8); local fresh breaks in soil indicated that these cracks were only days or weeks old. This sequence of cracking suggests compression-arch failure because the surface apparently subsided to a final profile only after the compression features were produced.

SOMERSET MINING DISTRICT, COLORADO

Although many of the geologic conditions in the Somerset mining district, Delta and Gunnison Counties, Colo., are different from those in the Geneva mine area, the overburden also is similarly



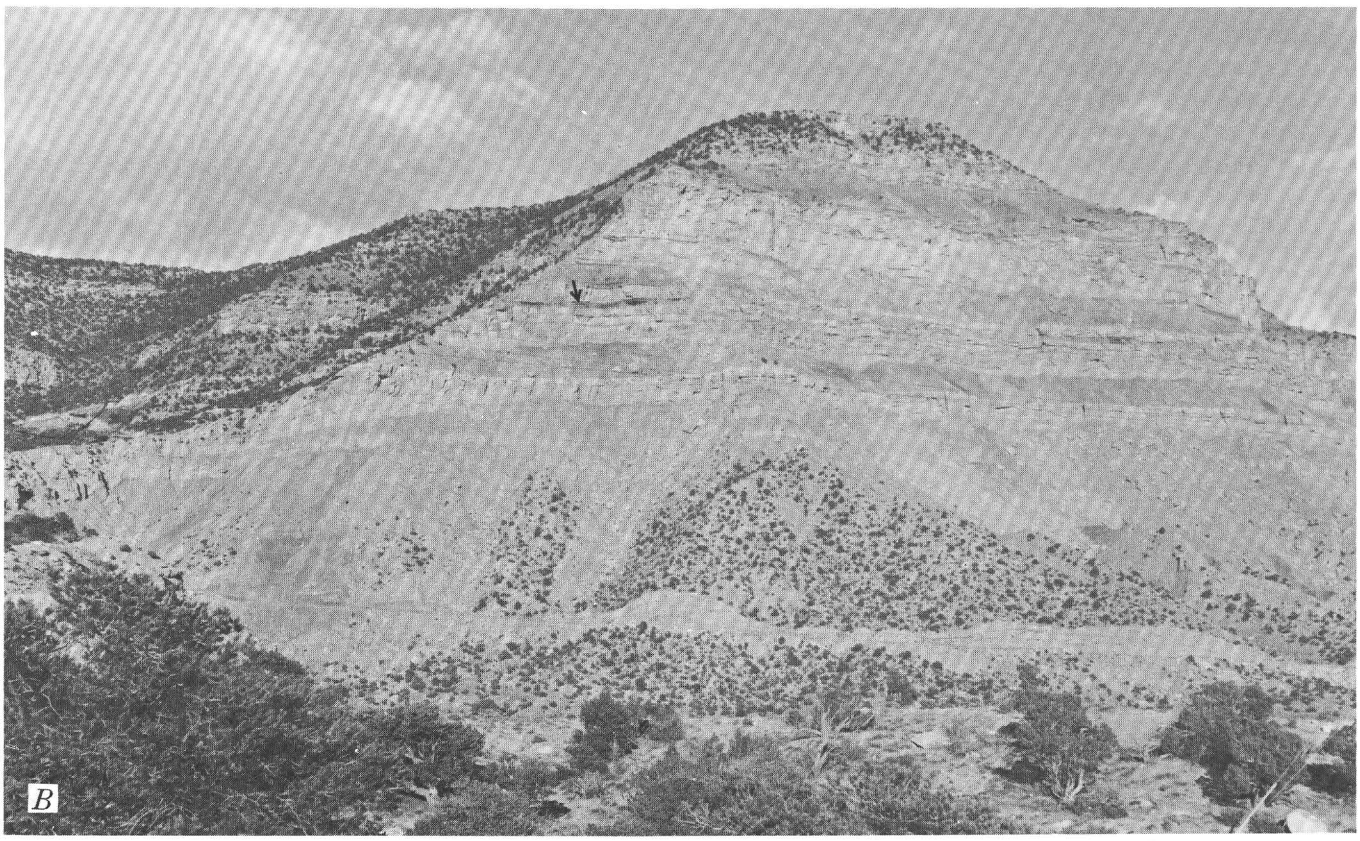


FIGURE 7.—The Upper Cretaceous Mesaverde Group underlying the Book Cliffs near the Geneva mine, Emery County, Utah. *A*, Northeastward view of typical Mesaverde rocks and rugged topography. *B*, Closeup of the lower part of the Mesaverde Group showing the Sunnyside coal bed (arrow), the dark band overlying the second massive sandstone from the bottom and overlain by a thin sandstone. The Mancos Shale underlies the lowermost sandstone.

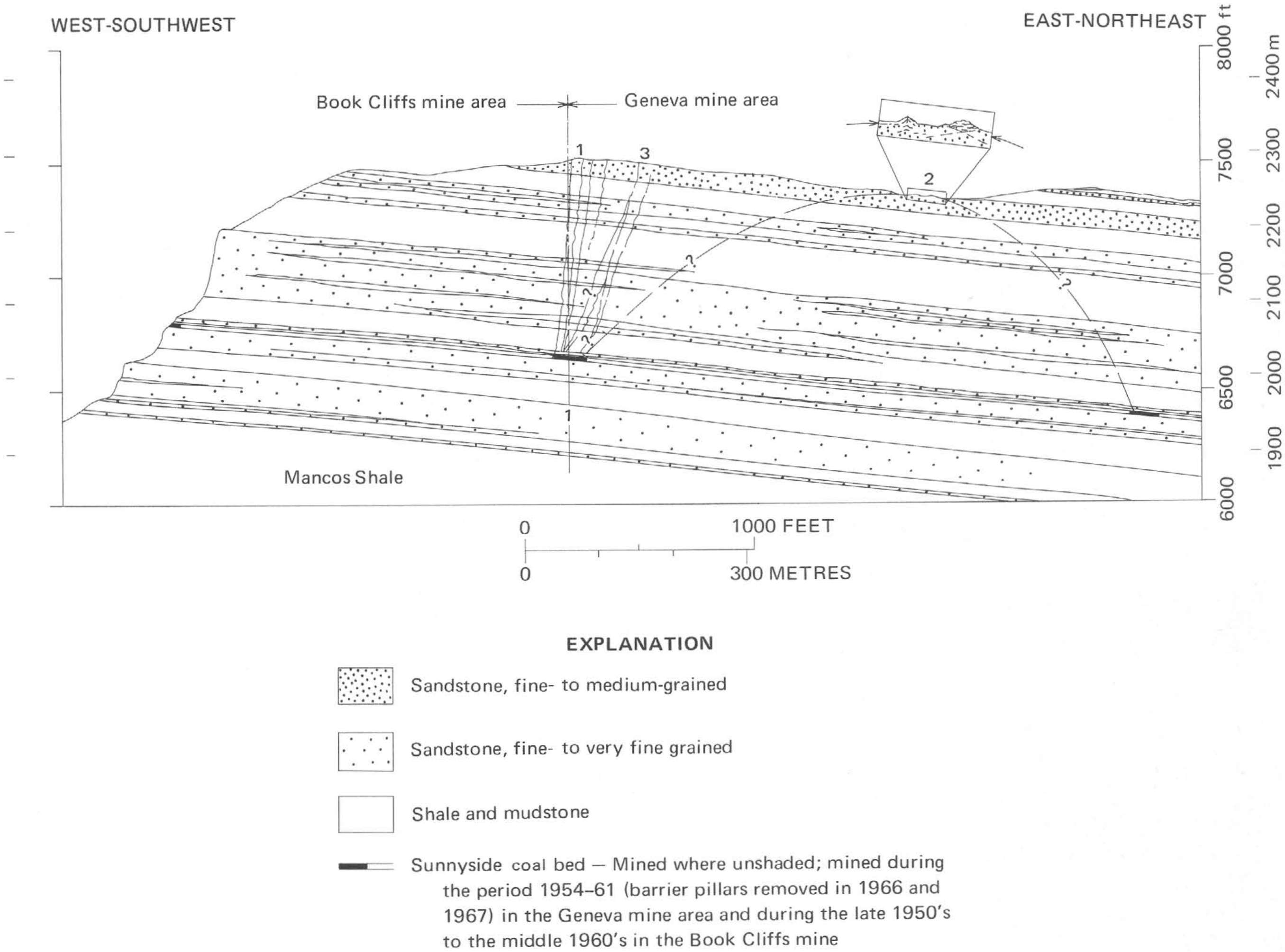


FIGURE 8.—Cross section of the rocks of the Upper Cretaceous Mesaverde Group in the southern parts of the Book Cliffs and Geneva mines, Utah. Major deformational features in rocks above the mined-out areas and adjacent barrier pillars are based on a map by Dunrud and Barnes (1972). (1) First set of tension cracks, (2) compression features probably caused by a compression arch, and (3) a second set of tension cracks.

variable and locally thick because of rugged topography (frontispiece, figs. 10, 11). The overburden ranges in thickness from 0 at the coal outcrop to 2,500 feet (762 m) in short lateral distances beneath ridges. Plutons of Oligocene age (Lipman and others, 1969, p. D37) that constitute part of the West Elk Mountains, intrude coal-bearing strata within a few miles of the mine workings (frontispiece, fig. 10). Another small pluton, perhaps younger than Oligocene, intrudes Mesaverde rocks and much of the overlying Paleocene Ohio Creek Formation only 2 miles (3.2 km) north of current mine workings (fig. 12).

Coal is mined from as many as four coal beds within a stratigraphic interval 500 – 600 feet (152.4 – 182.9 m) thick near the base of the Mesaverde Formation (called formation rather than group in this locality) (figs. 13, 14). In general, the overburden is weaker than the overburden in the Geneva mine area. It comprises thicker mudstones or shales and thinner sandstones than those in the Geneva mine area. Most of the sandstones thicken, thin, and pinch out over short lateral distances, but a thick, persistant, quartzose sandstone, called the Rollins Sandstone Member, underlies the coal beds and forms the base of the Mesaverde Formation. The Mancos Shale underlies the Rollins Sandstone Member.

The bedrock dips northwestward 3° to 6°; locally, the strata steepen or flatten in areas where interstratal warps, which the miners call rolls, are present (fig. 13*B*). Steeply dipping faults, which trend west-northwest, northeast, east-northeast, and north and which offset bedrock units from 5 feet (1.5 m) to more than 20 feet (6.1 m), are present a few miles north of the Somerset mine. A few steeply dipping discontinuous faults with small vertical displacements

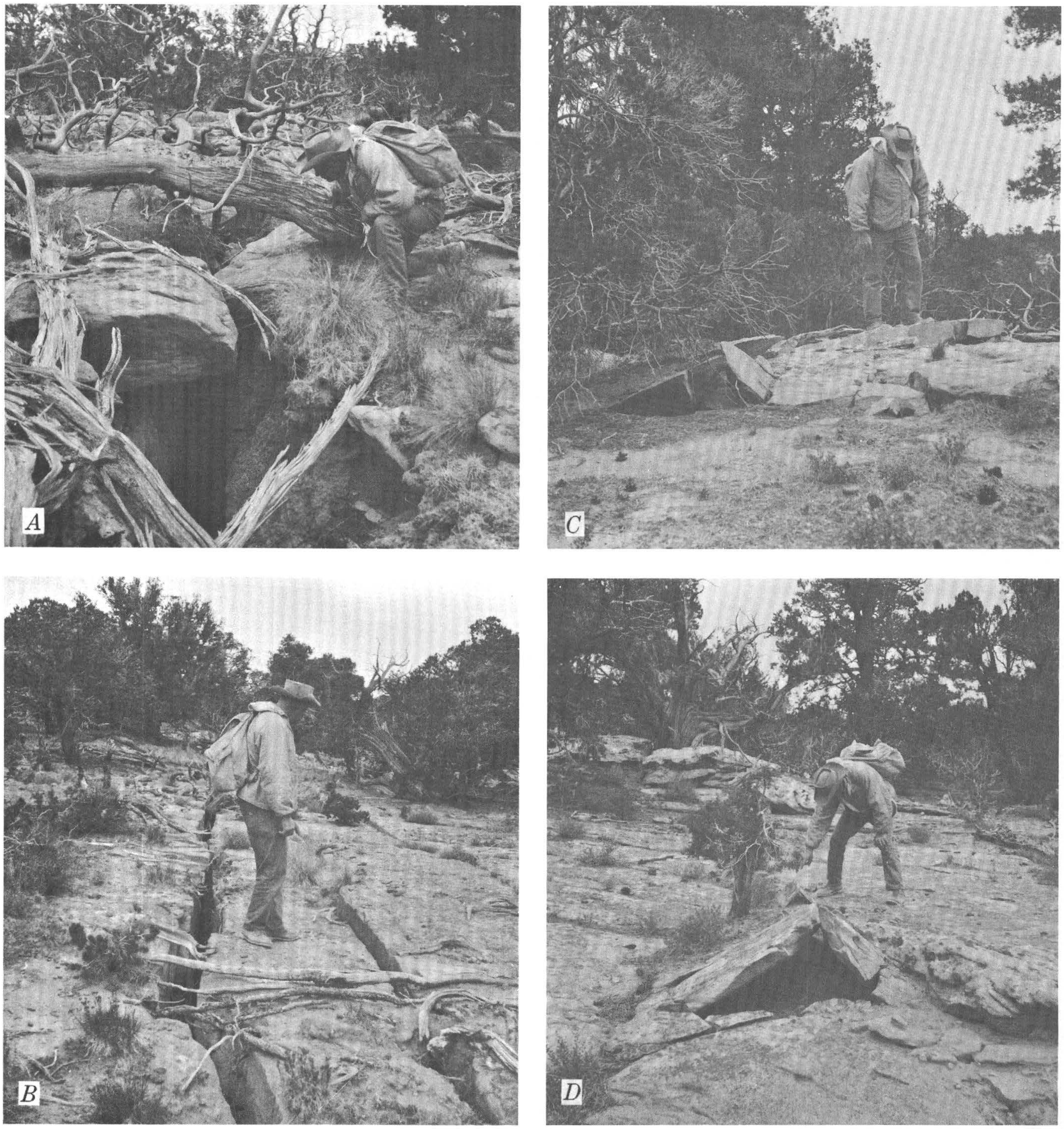


FIGURE 9.—Subsidence damage in a massive sandstone at the top of the Mesaverde Group that resulted from coal extraction about 900 feet (274 m) below. *A* and *B*, Tension fractures as much as 3 feet (0.9 m) wide resulting from cantilever failure above a coal barrier pillar. *C* and *D*, Compression bulges and anticlines probably caused by emergence of a compression arch at the surface above a mined-out area.

and with west-northwest and east-northeast trends are present locally in the Somerset mine.

Joints are common in many of the sandstones. They are more variable than those present in the Geneva mine area; however, most dip steeply to vertically and trend north-northeast, north, west-northwest, or east. Most of the streams follow these same directions with a regularity that indicates that they are controlled by the joints. Field studies further indicate that most streams occur along linear zones that are more intensely jointed than the surrounding bedrock. Thus, ridges and valleys, which determine the thickness of mine overburden, are commonly controlled by jointing.

Dikelike intrusive bodies, called rock spars by miners, which comprise very fine to silt-size quartz and feldspar in calcareous to dolomitic cement, are locally common in the mine workings (fig. 15*C*). Although the trend of the spars is less regular than the trend of the faults, they commonly trend west-northwest, east-northeast, east, or north. The spars disrupt the continuity of roof rocks and commonly cause unstable conditions in the mine roof. This in turn can lead to uneven mining practices as miners are forced to abandon workings before normal extraction procedures are completed because of the roof-fall hazard. The presence of rock spars in the mine increases mining costs and difficulty, sometimes to a point where mining is not economic or is unsafe. The Cameo mine, Mesa County, Colo., was abandoned because of increased mining costs resulting from the presence of numerous spars (J. Paul Storrs, U.S. Geol. Survey, oral commun., 1974).

A good general overview of the total bedrock structure in the Somerset mining district is available from Skylab 2 color-infrared imagery (figs. 10, 11). Most lineaments present on the photograph occur along streams, which in turn occur along linear, profusely jointed or faulted zones. Indeed, all but one of the major trends of these lineaments (vector diagram of lineaments in fig. 11) parallel the dominant trends of the faults, joints, and spars in the district.

Current studies in the Somerset district include all the basic elements of coal mine deformation—subsidence, roof falls, and coal mine bumps. As part of the subsidence portion of these studies, an area above the active mining in the "B" bed of the Somerset mine was selected for subsidence measurement (fig. 14). The overburden above current and future mining in this area of the Somerset mine ranges in thickness from 300 feet (92 m) to about 1,600 feet (490 m). The coal beds have been burned back from the outcrop in an irregular fashion for hundreds of feet. Hotspots, probably caused by residual heat from past outcrop fires, are locally present in mine workings near outcrop burn lines. Various shades of red clinker mark the burned beds at the outcrop (frontispiece). The void space created by burning caused the overburden rocks to subside along steeply dipping tension cracks that are similar to the fractures produced by cantilever failure above mine workings near an outcrop (fig. 15*A*). A core from a drill hole that probably intersected one of these fractures revealed ground-up bedrock that looked like fault gouge.

Hot steam and other gases locally vent through tension fractures formed in subsiding bedrock (fig. 15*B*), indicating that the bedrock is locally still very hot and might be a potential source of geothermal energy. Hotspots, which perhaps are related to West Elk Mountain volcanism, also are locally present in mine workings at considerable distances from the outcrop burn lines.

GEOMETRY OF SUBSIDENCE CRACKS

Periodic surface mapping above the 3d South mining area during the last 3 years has revealed a pattern of crack development that is related both to the geometry and the chronology of mining and to joints in bedrock. The first cracks were observed in June 1971 above, and parallel to, the barrier pillar near the eastern mine boundary. The barrier locally widens to as much as 100 feet (30.5 m) and is located between the 8th and 9th Left mining panels, where the 8th Left panel extends about 400 feet (121.9 m) beyond the 7th and 9th Left panels (fig. 14). The cracks, which formed an estimated 2 – 4 months after extraction was completed in the area, are as much as 1 foot (0.3 m) wide. The cracks narrowed westward and were absent where the barrier pillar narrows to a constant 40 feet (12.2 m).

New tension cracks were observed in July 1972, an estimated 3 – 6 months after coal extraction was completed, beneath the ruptured surface area. These cracks occurred in two distinct sets: (1) a linear set that was parallel to the barrier pillar separating the 8th and 9th Left extraction panels and was a continuation of the set mapped a year earlier, and (2) a set of cracks that paralleled and followed the room-and-pillar line as it retreated westward (fig. 14). Both sets are about parallel to the trends of steeply dipping joint sets present in outcropping sandstones in the area.

The linear set of cracks above the barrier gradually narrowed and disappeared at about the 450-foot (137 m) overburden-thickness level. Their position indicated either that the 40-foot (12.2 m) barrier pillar between 8th and 9th Left was yielding enough to prevent tensile rupture of the claystone and shale bedrock and thin soil cover or that a compression arch was present in the strata over 8th Left above the 500-foot (152.4 m) level (figs. 14, 17). Over the 40-foot (12.2 m) barrier pillar, maximum extension beyond the rupture limit in weathered claystone and shale bedrock measured about 2 inches (5 cm). This is only one-sixth the amount of lateral extension beyond

FIGURE 10.—Infrared Skylab 2 photograph of the Somerset mining district, Gunnison County, Colo., and surrounding area. The coal-bearing strata can be seen as a sinuous, light-colored band to the north of the North Fork Gunnison River and west of the Paonia Reservoir. See figure 11 for geographic locations.

rupture that occured above the same barrier at a place where the pillar was 100 feet (30.5 m) wide (instead of the normal 40 feet (12.2 m)) suggesting that the 100-foot- (30.5 m) wide portion of the continuous coal pillar may provide only about one-sixth the vertical yield of the 40-foot (12.2 m) portion. The overburden thickness, however, differs by about 100 feet (30 m) and may account for some difference in crack width.

The other set of tension cracks that parallels the room-and-pillar retreat lines above 8th Left ranged in width from 0.25 inch (0.64 cm) to as much as 1.5 feet (0.46 m) (figs. 14, 15*D*), the widest of any cracks mapped so far. All these cracks revealed horizontal extension in a direction perpendicular to the room-and-pillar retreat line and parallel to the barrier pillars, and one crack also was vertically displaced about 0.5 inch (1.27 cm) down to the east. The crack, which is 1.5 feet (0.46 m) wide (fig. 15*D*) and is located 515 feet (157.3 m) above the mine workings, is at the westward limit of all surface rupture. It defines the

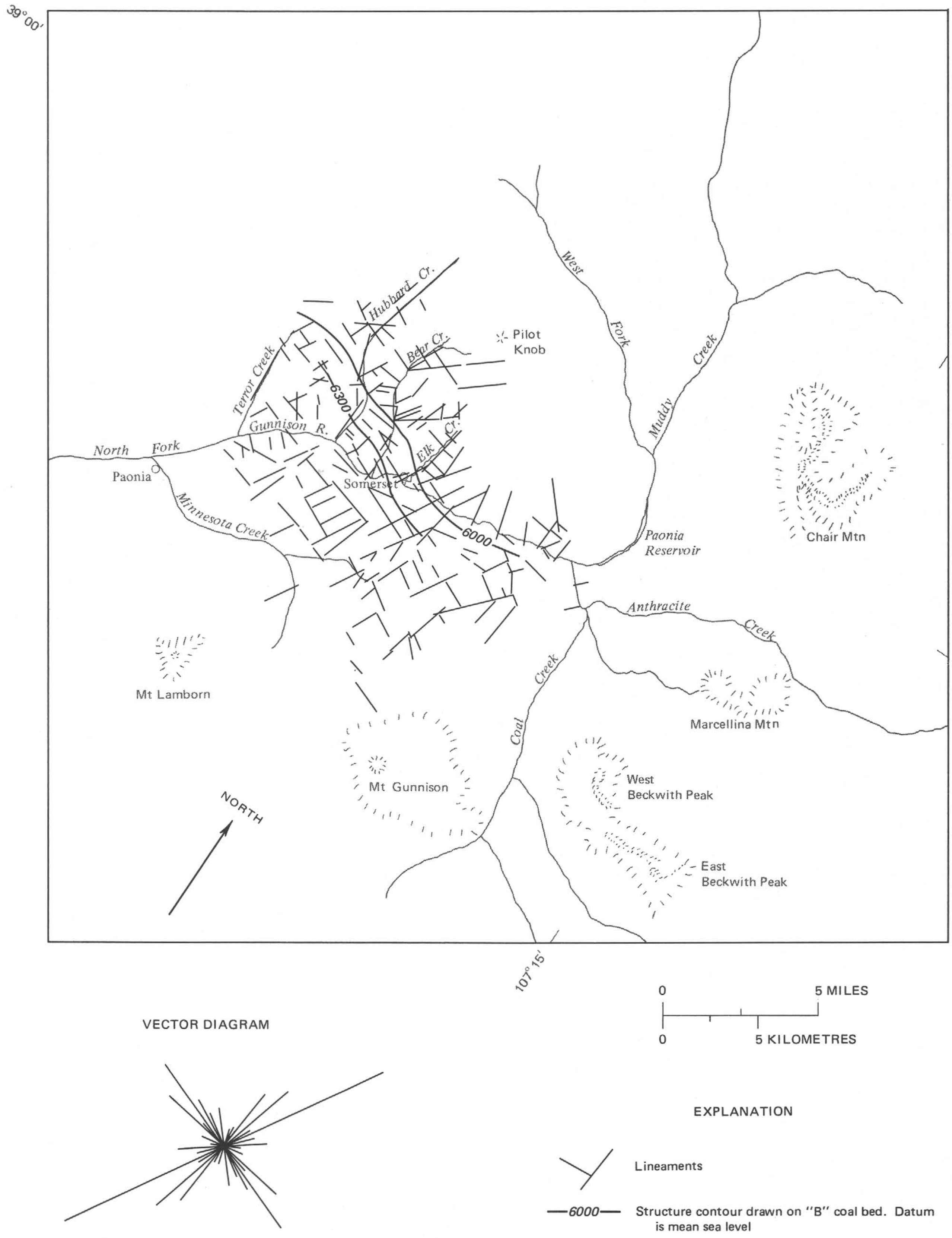


FIGURE 11.—Plot of lineaments derived from the Skylab 2 infrared photograph (fig. 10) of the Somerset mining district. The spatial plot of lineaments covers the area currently under study. Two representative structure contures of the "B" coal bed are shown to indicate bedrock attitude. The Somerset mine is between Elk Creek and Hubbard Creek south of the 6,000-foot structure contour line.

FIGURE 12.—Iron Point, an upper(?) Tertiary pluton that intrudes the Mesaverde Formation and most of the overlying Ohio Creek Formation 2 miles (3.2 km) north of Somerset coal mine, Colorado. View looking westward across Hubbard Creek, sec. 27, T. 12 S., R. 91 W.

limit of extension due to strata flexure and indicates that a compression arch, perhaps about 50 feet (15.2 m) thick at the crest, is present in deeper strata west of this crack (figs. 16, 17).

Subsidence pits were first observed during July 1973 in soil and colluvium averaging 3.5 feet (1.07 m) thick above the 8th mining panel about 1½ years after coal extraction was completed (figs. 14, 15*E*). The pits are roughly circular and 3 – 4 feet (0.9 – 1.2 m) in diameter. A linear tension crack, perhaps 2 – 4 inches (5.08 – 10.16 cm) wide, probably exists at the base of the pit. Apparently the pits are caused by local failure of the soil and colluvium veneer which normally is cohesive enough to bridge a crack of this width without noticeable failure. Pit failure may have been initiated by some heavy animal, such as a cow or horse, stepping through the bridged soil and colluvium veneer. No surface cracks were observed above the coal barriers between 6th and 7th Left panels (fig. 14). This is either because the soil and colluvium or local landslide deposits have successfully bridged existing cracks or because the near-surface bedrock has not yet ruptured. In such situations, cohesive soil, colluvium, or landslide deposits could obscure potentially hazardous cracks and might cause planners to develop potentially untenable land-use plans for the surface area.

In August 1973 another very fresh tension crack was observed and mapped above and parallel to a solid coal barrier between 5th and 6th Left. This crack, which formed in mudstone-sandstone overburden 500 – 600 feet (152.4 – 182.9 m) above the elevation of the mine workings, opened only 4 months after mining in 6th Left was completed. This crack appeared sooner than all other cracks, including those present in even thinner overburden. This is probably because a 300-foot- (91.4 m) wide coal pillar is still present between 5th Left and the mined-out 6th Left panels, thus causing maximum strata flexure into the 6th Left mined-out area; whereas the thin barrier pillars between 6th and 7th panels and 7th and 8th panels yielded to overburden load and therefore reduced lateral flexural stresses.

This situation points out an important factor governing the rate and severity of coal mine subsidence damage: surface damage in overburden of a

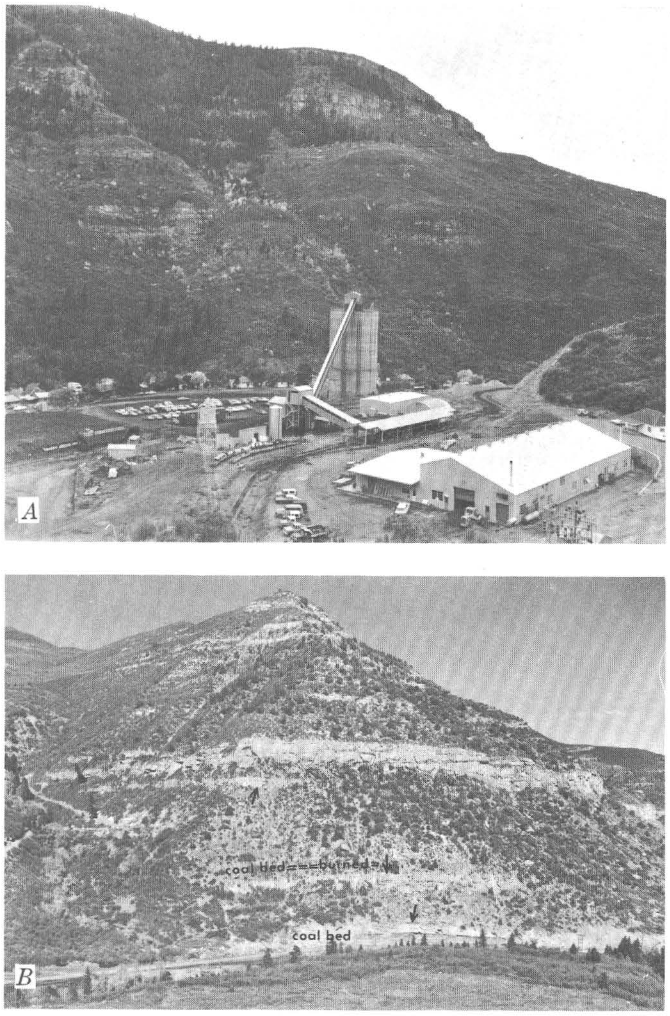


FIGURE 13.—Mesaverde Formation in Somerset mining district, Colorado. *A*, Southward view of the Somerset mine buildings. The basal coal-bearing part of the Mesaverde underlies the brush-covered slope in the background across the North Fork Gunnison River; the barren member forms the higher and steeper tree-covered slope. *B*, Upper part of the coal-bearing portion of the Mesaverde Formation, separated from the overlying barren member by the massive sandstone. Note the lenticular sandstones (arrows). Differential compaction of weak shales and claystone near these strong lenticular sandstones probably produces the undulations (called rolls by miners) noted in certain mining areas. About 2 miles (3.2 km) east of the town of Somerset.

given type and thickness above a mine opening of a given geometry will occur more quickly, and can be more severe, where the mine opening is bounded by massive solid coal pillars than where the mine opening is surrounded by thin coal pillars. This suggests a strict adherence to a mining sequence whereby adjacent mining panels are mined nearly concurrently, as were the 9th, 8th, 7th, and 6th Left panels, rather than completing extraction in one panel before moving to an adjacent one, as occurred in 6th and 5th Left.

Little is known about the surface damage caused by mining the 9th Left panel because it was mined 1½ – 2 years before the study began (fig. 14). Cracks could have been masked by forces of erosion in that length of time. Perhaps some of the cracks above the barrier between 8th and 9th Left panels at the eastern end were caused by mining in 9th Left; however, the chronology of crack development revealed by periodic mapping suggests that most of the cracking was caused by mining in 8th Left. Perhaps the tensile rupture limit was not reached or was not exceeded by flexure of strata into 9th Left until the coal in 8th Left was mined. This is an example of how subsidence in one area can influence subsidence in adjacent areas. (See discussion in section on stress and strain caused by subsidence.)

SUBSIDENCE MEASUREMENTS

Surface measurements made periodically from October 1972 through December 1973 have yielded considerable information on the process of deformation in the overburden strata relative to the position of the room-and-pillar retreat lines and to panel-pillar extraction geometry (table 1; figs. 15, 16, 17). The surface measurements, together with the subsidence-crack geometry, yielded the following subsidence parameters: (1) limit angle relative to solid-coal boundaries, (2) break angle, (3) configurations of compression arches in this particular overburden strata, and (4) ratio of surface subsidence to the thickness of the coal bed or mining height versus the ratio of mining panel width to mean overburden depth (fig. 5). These parameters may change with time as the overburden continues to adjust, so the measurements must continue above mined-out areas in order to determine final limits for these parameters and the post-mining time necessary to achieve surface stability. However, it is important to measure subsidence parameters as mining progresses, as well as the final parameters, because the subsidence processes contribute to the state of stress within the mine workings and within the rocks above and beneath the mine workings.

A complete profile of subsidence related to coal extraction was available for only the area above the 6th Left panel because the bench marks were installed before significant pillar extraction began in that panel. The $A_3 - B_5$ profile in figure 16 shows the relative position of the surface above the 6th Left panel in relation to the position of its pillar retreat line. This profile shows that no surface subsidence occurred until the fourth measurement on June 26, 1973, or

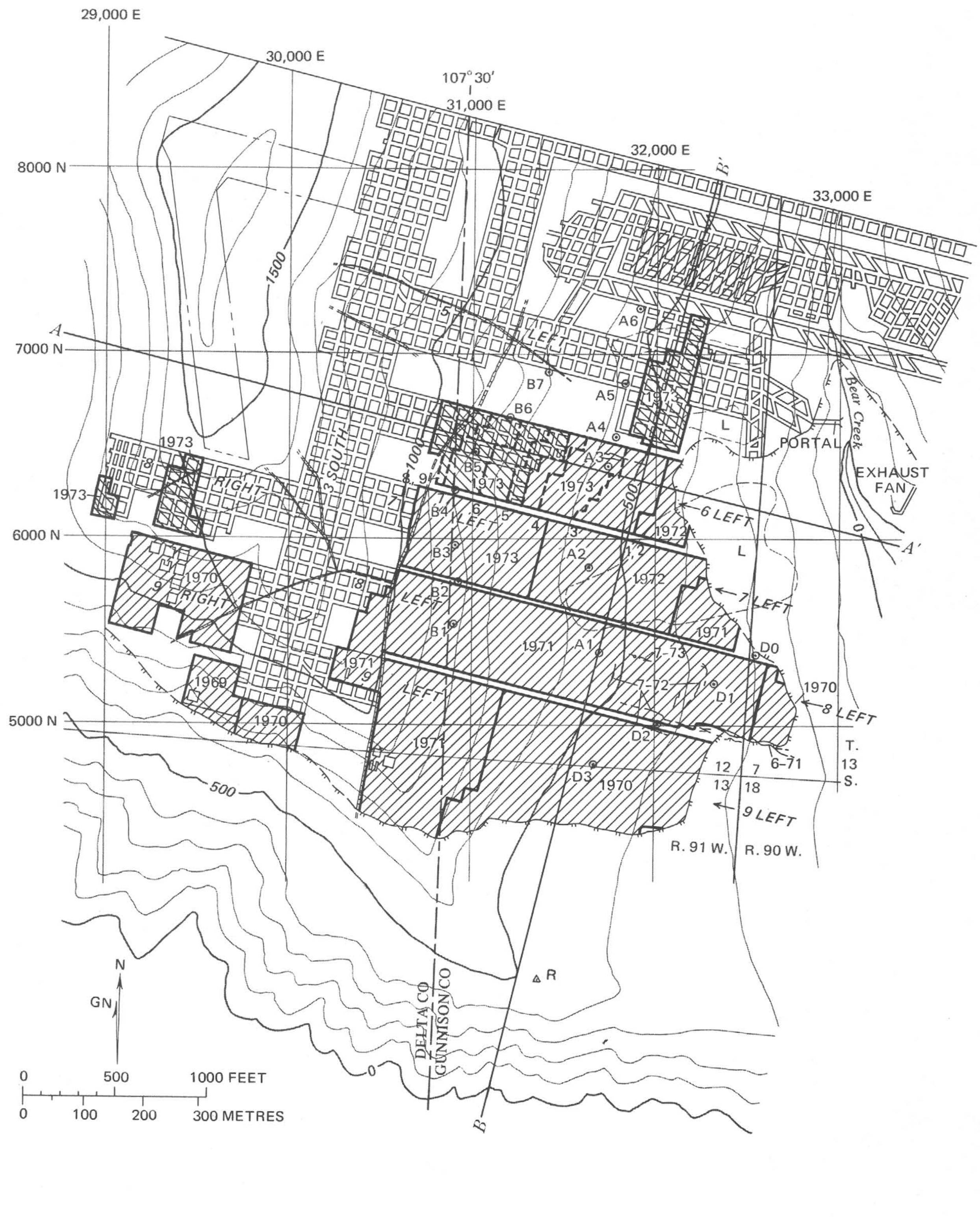


FIGURE 14.—The 3d South area in the Somerset mine, Colorado, showing mine workings, mined-out areas, major rock units near the coal beds, coal beds, and fractures in mine overburden caused by mining the "B" coal bed. Mine base is modified from U.S. Steel Corp. mine map, Somerset mine; overburden contours derived from U.S. Geological Survey Somerset and Bowie 7½-minute topographic quadrangle maps.

EXPLANATION

"Rocks spars" – Dikelike bodies comprising very fine to silt-sized quartz and feldspar grains in calcareous to dolomitic cement; at elevation of mine workings

Tension cracks at surface – Date indicates when crack was first observed

L — Active landslide – Slow to rapid downslope movement of bedrock and surficial debris; rate of movement governed by degree of saturation

B1 — Surface bench mark – Installed by USGS in October 1972 (row A, 1-3; row B, 1-5; row D, 0-3) and August 1973 (row A, 4-6; row B, 6-7)

R — Surface reference bench mark, on stable ground

—500— Overburden thickness contour – Datum is top of "B" coal bed; contour interval 100 feet (30.5 m)

Retreat line

Room-and-pillar mine workings – Mined out where hachured during period shown: Posted to July 1, 1973 ; Posted to Jan. 1, 1974

5
Retreat line 7/13/73
(see table 1; figs.16,17)

Limit of mine workings (burn line)

30,000 E
5000N — Mine grid – Equals Colorado Grid, Central Region, by adding 400,000 and 1,400,000, respectively, to north and east coordinates

A——A′ Line of section shown in figure 16; section *B-B′* shown in figure 17

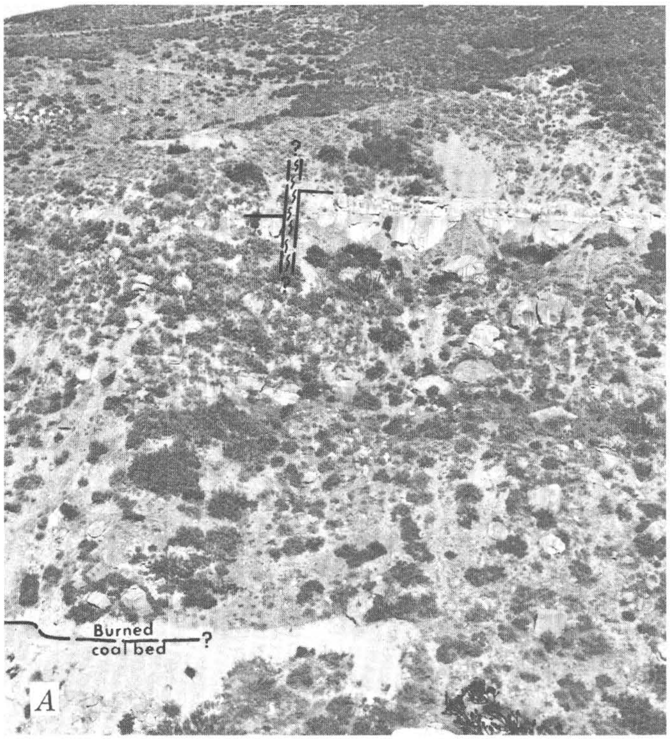
until a mining width approximately equal to the average depth of overburden was excavated. Then, within a 7½-week interval, measurements showed that the surface at bench mark A_3 subsided nearly 2 feet (61 cm) (table 1). Subsidence continued at irregular but shorter intervals through August, was stable from September through November 30, and then the ground surface settled another 0.16 foot (4.8 cm) in December. Bench mark B_5 rose, then went down slightly during measurement period 1 through 4, then settled further during subsequent measurements through December 31, 1973.

Although only two bench marks are located above the 6th Left mining, the periodic measurements yielded rather precise subsidence profiles and limit angles, particularly for profiles 4, 5, and 6 (fig. 16). The limit angle, measured with respect to the horizontal, is 69° – 70° in weak overburden that thickens from 600 to 900 feet (183 – 274 m) over about 400 feet (122 m) of horizontal distance. The limit angle may be less steep for flat-lying surfaces in similar strata. The configuration of profiles 7, 8, 9, and 10 suggests that the limit angle steepens from 75° to perhaps as much as 80° in moderately strong strata beneath steep hillsides which are more than 900 feet (274 m) above the mine workings, although the precision is reduced on these profiles because they are west of the B_5 bench mark.

Profiles parallel to bench marks in rows A and B show how the surface responded to mining at right angles to the orientation of mining panels (fig. 17). Horizontal movement in the north-south direction also was measured each time the vertical angles were measured. The resultant movement of the individual bench marks in rows A and B is plotted at the top of figure 17. The measurements of a diagonal row *D* (table 1, *D* row not shown in fig. 17) indicate that there was little vertical or horizontal movement beneath it after the bench marks were installed, suggesting that in overburden 300 – 470 feet (91.4 – 143.6 m) thick subsidence was virtually complete 1½ years after mining was completed in the eastern part of the 8th and 9th Left panels.

Profiles of the relative vertical and horizontal movement of bench marks comprising rows A and B show that the overburden strata generally formed a trough above the 6th, 7th, and 8th Left mining panels and the barriers between these panels. The horizontal movement was generally toward this trough (fig. 17, table 1), although the bench marks often moved so erratically from measurement to measurement that conventional curves of horizontal displacement, horizontal strain, and curvature, such as those shown in figure 2, would be grossly oversimplified. In addition, as the strata subsided into the mined-out area in 6th Left through November 30, the strata were uplifted above the solid-coal boundary north of 6th Left; then, in December, the surface subsided slightly.

Through November 30, 1973, the limit angle (φ_9 in fig. 17)—measured from the horizontal—varies from 30° to as much as 85° on row A and from 65° to vertical on row B, depending on how it is defined. If limit angle is defined as the acute angle formed by drawing a straight line between the limit of surface movement—whether upward or downward—to the solid-coal boundary and the horizontal, then the limit angle is about 30° in overburden 500 – 600 feet (152.4 – 182.9 m) thick on the row A profiles and is about 62° in overburden 700 – 800 feet (213.3 – 243.8 m) thick on the row B profiles. If it is defined as the acute angle formed by projecting a straight line from the limit of downward surface movement—the edge of the subsidence trough—to the solid-coal boundary and the horizontal, as usually measured, then the limit angle is 82° and 88° for the A and B profiles, respectively. This limit angle was measured only 5 months and 2 months after the room-and-pillar retreat



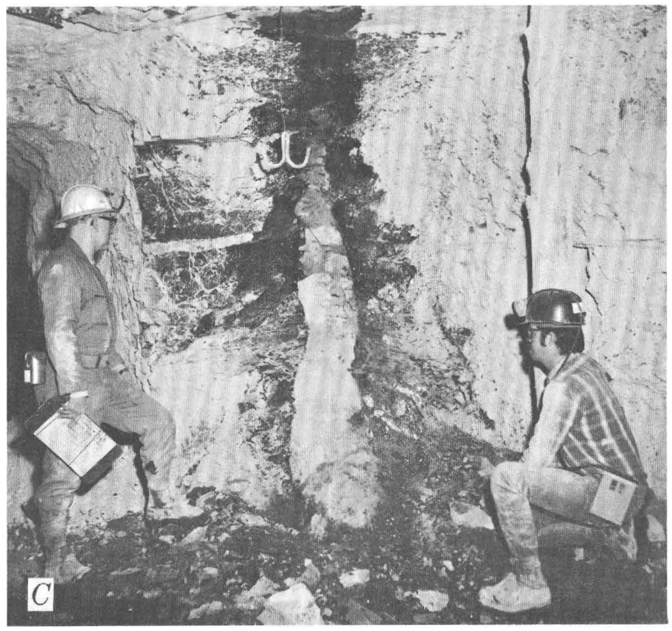


FIGURE 15.—Primary and subsidence fractures. *A*, Offset sandstone produced by subsidence above burned coal beds, Somerset district, Colorado. The sandstone is offset about 12 feet (3.6 m) along a tension fracture that is nearly perpendicular to the dip of the bedrock. Note the broken and weathered appearance of the sandstone to the left of the fracture as compared to the sandstone to the right of the fracture. *B*, Steam vent in a tension rift located in subsiding ground above burned coal beds; some vents might be a source of geothermal energy. *C*, Engineers inspect a rock "spar" that intrudes the "B" coal bed along fractures; contacts in the coal adjacent to the spar are irregular and brecciated but not burned. *D*, Subsidence cracks in weathered bedrock and thin soil which are located parallel to room-and-pillar retreat lines of 8th Left, Somerset mine. *E*, Subsidence pit in soil and colluvium that appears to be underlain by a linear tension crack.

TABLE 1.—*Relative displacement of U.S. Geological Survey subsidence bench marks located above the 3d South area of the Somerset mine, Delta and Gunnison Counties, Colorado*

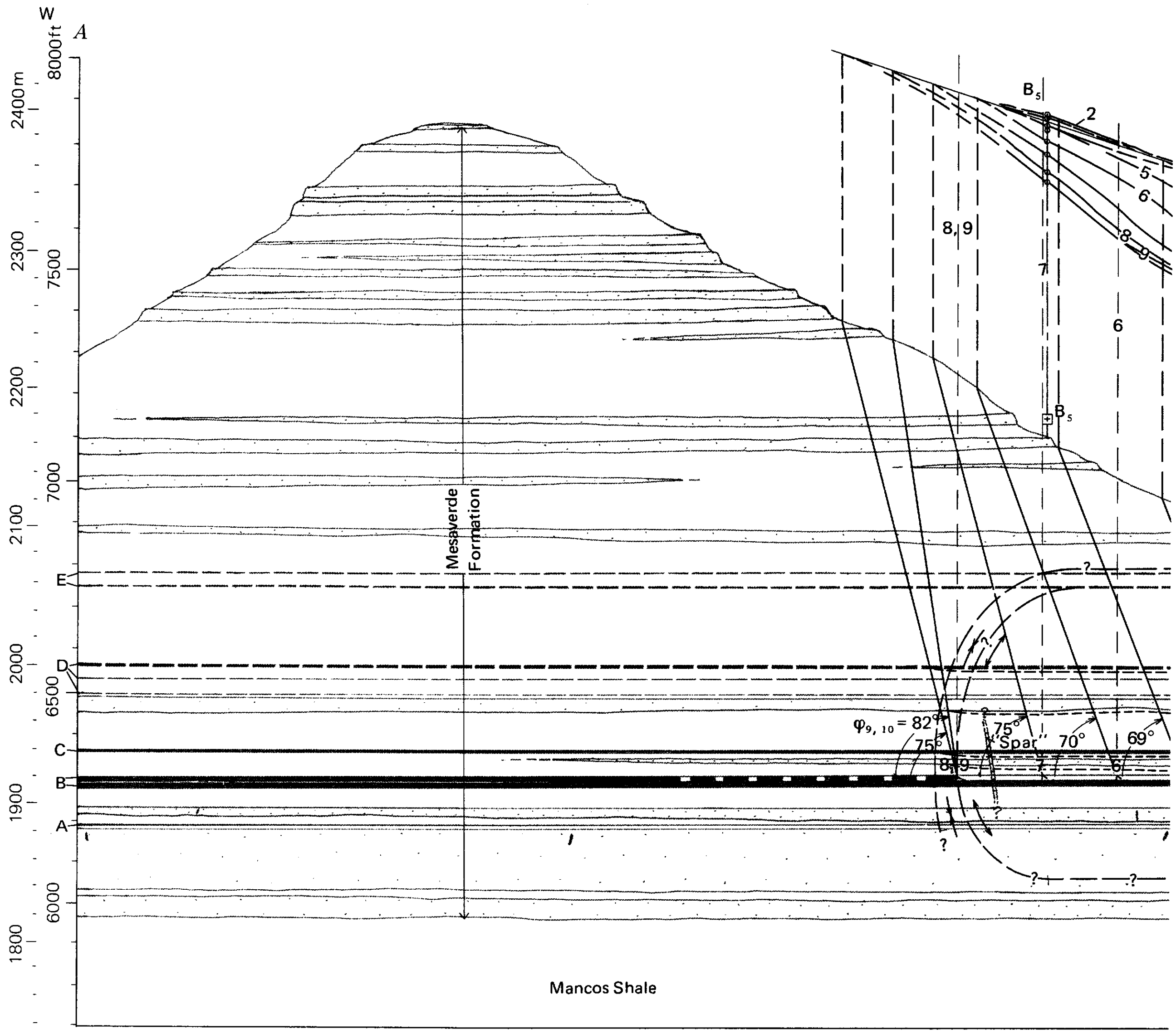
[See figure 14 for bench mark locations; all displacements are in feet (1 ft=30.48 cm); estimated accuracy of measurement, ±0.05 feet (1.52 cm); M, monthly change in position of bench marks horizontally (*H*) to north or south and vertically (*V*); C, cumulative change in position of bench marks horizontally (*H*) to north or south and vertically (*V*); negative sign (–) indicates change horizontally to the south and a decrease in elevation; plus sign (+) indicates change horizontally to the north and an increase in elevation. Leaders indicate no data collected; stations A_4–A_6 and B_6–B_7 were installed in September 1973]

Measuring Period		1		2		3		4		5		6		7		8		9		10	
Date		10–14–72		11–8–72		5–5–73		6–26–73		7–13–73		8–17–73		9–13–73		10–10–73		11–30–73		12–31–73	
Station (shot distance in ft):	Change	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*	*H*	*V*
A_1 (3,330)	M	0.00	0.00	–0.06	–0.06	+0.02	+0.08	+0.08	+0.05	–0.02	+0.03	–0.05	–0.06	+0.18	–0.19	–0.11	+0.18	+0.02	+0.39	–0.23	–0.40
	C	.00	.00	–.06	–.06	–.04	+.02	+.04	+.07	+.02	+.10	–.03	+.04	+.15	–.15	+.04	+.03	+.06	+.42	–.17	+.02
A_2 (3,460)	M	.00	.00	.00	–.47	+.32	–.37	+.25	–.20	–.08	–.15	–.03	–.13	+.27	–.05	–.17	+.25	–.07	–.25	–.15	–.05
	C	.00	.00	.00	–.47	+.32	–.84	+.57	–1.04	+.49	–1.19	+.46	–1.32	+.73	–1.37	+.56	–1.12	+.49	–1.37	+.34	–1.42
A_3 (3,500)	M	.00	.00	+.63	...	–.61	+.05	–.59	–1.98	–.12	–.25	–.24	–.66	+.23	–.15	–.19	+.05	–.02	–.02	–.12	–.17
	C	.00	.00	+.63	...	+.02	+.05	–.57	–1.93	–.69	–2.18	–.93	–2.84	–.70	–2.99	–.89	–2.94	–.91	–2.96	–1.03	–3.13
A_4 (3,520)	M	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.17	–.07	–.03	–.02	–.22	–.19
	C	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.17	–.07	–.20	–.09	–.42	–.28
A_5 (3,600)	M	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.17	+.31	+.14	–.21	–.40	–.21
	C	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.17	+.31	–.03	+.10	–.43	–.11
A_6 (3,740)	M	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.11	+.25	–.04	–.12	–.27	–.33
	C	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.11	+.25	–.15	+.13	–.42	–.20
B_1 (3,970)	M	.00	.00	–.16	–.04	+.40	–.48	+.48	–.16	–.08	–.02	+.08	–.14	+.12	–.14	+.02	–.16	+.24	–.04	+.04	+.02
	C	.00	.00	–.16	–.04	+.24	–.52	+.72	–.68	+.64	–.70	+.72	–.84	+.84	–.98	+.86	–1.14	+1.10	–1.18	+1.14	–1.16
B_2 (4,130)	M	.00	.00	–.10	–.06	+.44	–.80	+.40	–1.28	–.06	–.22	+.14	–.18	–.06	–.06	+.16	.00	+.24	+.22	+.12	–.36
	C	.00	.00	–.10	–.06	+.34	–.86	+.74	–2.14	+.68	–2.36	+.82	–2.54	+.76	–2.60	+.92	–2.60	+1.16	–2.38	+1.28	–2.74
B_3 (4,180)	M	.00	.00	–.08	–.32	–.14	–.73	+.14	–.20	+.02	–.22	+.14	–.34	+.10	–.28	+.16	.00	+.18	–.08	+.06	–.16
	C	.00	.00	–.08	–.32	–.22	–1.05	–.08	–1.25	–.06	–1.47	+.08	–1.81	+.18	–2.09	+.34	–2.09	+.52	–2.17	+.58	–2.33
B_4 (4,240)	M	.00	.00	–.10	–.08	+.53	–.04	–.04	–.18	–.16	+.06	–.02	–.33	.00	–.49	+.04	–.29	+.16	–.12	.00	.00
	C	.00	.00	–.10	–.08	+.43	–.12	+.39	–.30	+.23	–.24	+.21	–.57	+.21	–1.06	+.25	–1.35	+.41	–1.47	+.41	–1.47
B_5 (4,210)	M	.00	.00	.00	+.14	+.49	–.28	–.14	+.26	–.06	–.22	–.04	–.37	–.10	–.31	–.18	–.39	+.04	–.14	+.10	.00
	C	.00	.00	.00	+.14	+.49	–.14	+.35	+.12	+.29	–.10	+.25	–.47	+.15	–.78	–.03	–1.17	+.01	–1.31	+.11	–1.31
B_6 (4,090)	M	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.16	–.24	+.06	+.16	+.06	.00
	C	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.16	–.24	–.22	–.08	–.16	–.08
B_7 (4,010)	M	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.25	+.04	+.17	+.06	+.10	–.08
	C	...	...	...	...	...	...	...	...	...	...	...	...	...	...	–.25	+.04	–.08	+.10	+.02	+.02
D_3 (3,370)	M	.00	.00	–.16	–.16	+.08	+.23	+.06	+.10	–.08	+.05	+.02	–.03	+.16	+.03	–.13	+.08	+.03	+.10	–.02	+.02
	C	.00	.00	–.16	–.16	–.08	+.07	–.02	+.17	–.10	+.22	–.08	+.19	+.08	+.22	–.05	+.30	–.02	+.40	–.04	+.42
D_2 (3,030)	M	.00	.00	–.41	–.16	+.35	–.18	+.06	+.12	–.03	+.03	–.07	–.13	+.15	+.06	–.09	+.07	+.03	.00	–.08	–.06
	C	.00	.00	–.41	–.16	–.06	–.34	.00	–.22	–.03	–.19	–.10	–.32	+.05	–.26	–.04	–.19	–.01	–.19	–.09	–.25
D_1 (2,690)	M	.00	.00	–.17	+.14	–.18	–.08	.00	+.09	+.01	–.10	–.08	+.10	+.13	–.01	–.09	–.20	+.12	+.13	–.12	+.01
	C	.00	.00	–.17	+.14	–.35	+.06	–.35	+.15	–.37	+.05	–.45	+.15	–.32	+.14	–.41	–.06	–.29	+.07	–.41	+.08
D_0 (2,470)	M	.00	.00	–.73	–.02	+.13	.00	+.04	.00	–.04	–.04	–.08	+.04	+.13	+.06	–.06	–.13	+.03	–.04	–.05	+.10
	C	.00	.00	–.73	–.02	–.60	–.02	–.56	.00	–.60	–.06	–.68	–.02	–.55	+.04	–.61	–.09	–.59	–.13	–.64	–.08

lines passed beneath profiles A and B, respectively. In December, 6 months after mining, the surface near bench marks A_5 and A_6, above the solid coal, subsided uniformly below the original surface level, thus eliminating a stable ground point of reference to measure the limit angle and thereby precluding further measurements of limit angle in accordance with either definition.

Limit angles in strata above thin barrier pillars, such as those separating the 6th, 7th, 8th, and 9th Left mining panels, are not measurable because the overburden strata are downwarped on either side of the barrier pillars, creating interacting draws and making it impossible to define the draw attributable to one particular mining area.

The break angle above solid-coal boundaries is considerably different from that above thin barrier pillars, as the subsidence theories previously discussed suggest (figs. 2, 3, 4). Four months after mining was completed beneath the ruptured area, the break angle above a 300-foot (91.4 m) barrier north of 6th Left measured a negative 73°, whereas the break angle in the strata above the thin barriers between 8th and 9th Left panels was nearly vertical. The negative break angle above the solid-coal boundary may be a transient condition that, with time, will become positive. Further periodic mapping for cracks will reveal the final break angle; however, pillar extraction began in 5th Left in November 1973 (fig. 14), and the thick boundary pillar may be mined to a thin one like the others before the final break angle can be determined. Any surface- or ground-water flow or methane pockets will, of course, be intersected by the cracks, and the water or gas might be diverted to lower strata or to the mine workings through cracks in the overburden strata.



EXPLANATION

Coal bed in lower coal-bearing part of Mesaverde Formation — Mined where unpatterned; A, B, C, D, and E denote nomenclature of coal bed in general use within the area. Bed position projected from existing drill-hole and outcrop information

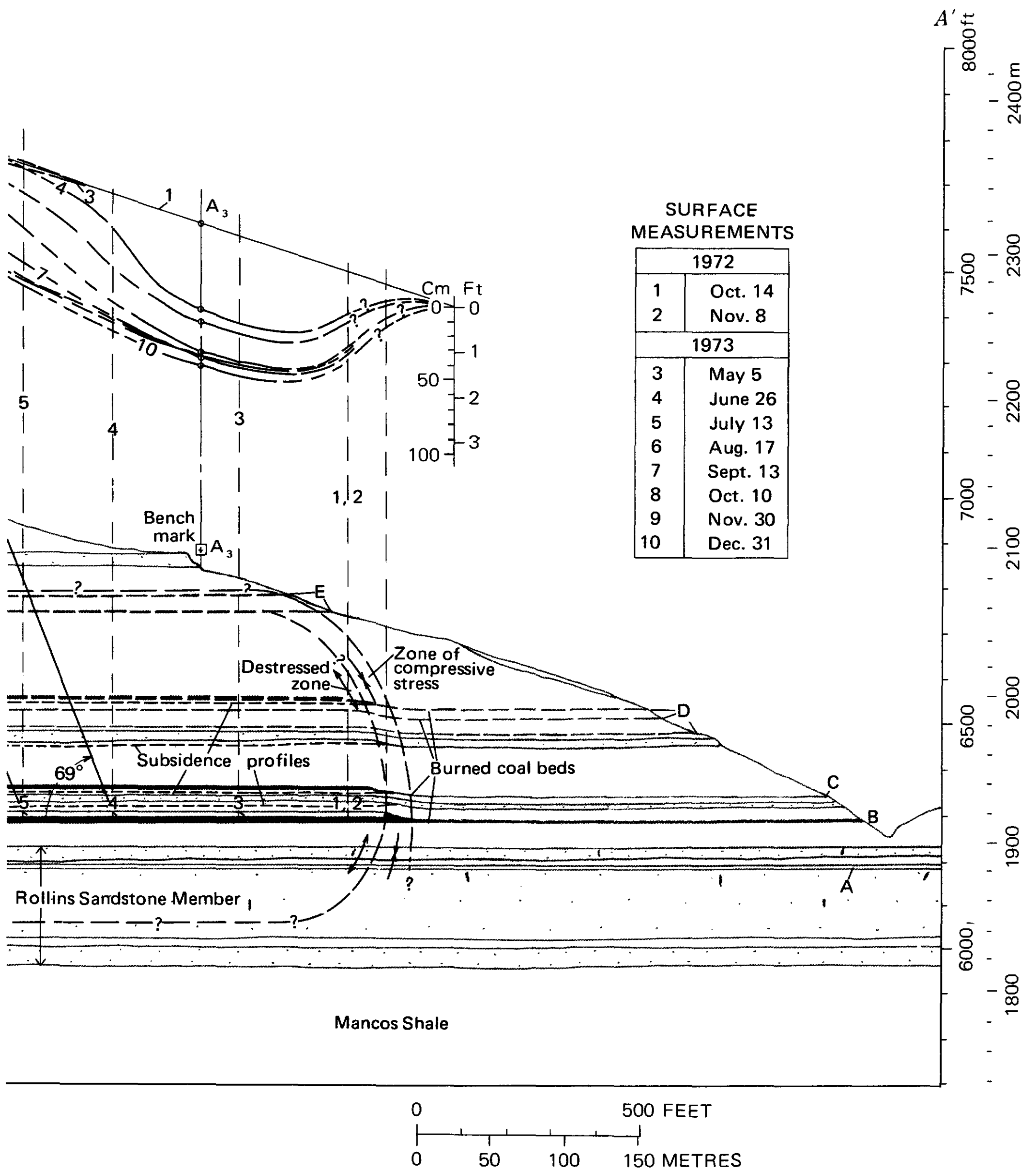
Sandstone of Mesaverde Formation — Fine- to medium-grained, feldspathic

Rollins Sandstone Member at base of Mesaverde Formation — Fine- to very fine grained, quartzose; elongate elliptical iron concretions 0.5-2.5 ft (0.15-0.76 m) in long dimension locally common

Shale and mudstone — Upper Cretaceous Mancos Shale below the Rollins Sandstone Member; all others in Mesaverde Formation

FIGURE 16.—Cross section $A-A'$ through the 3d South area, Somerset mine, Colorado, enlarged to show stratigraphic, mining, and subsidence details. (See fig. 14 for cross section location.) Vertical exaggeration of subsidence profiles is ×100; dates of surface measurements are keyed to subsidence profiles and the positions of room-and-pillar retreat lines by the use of surface-measurement date numbers (1–10); mining as of Jan. 1, 1974.

The subsidence profiles, particularly for the *B* row of bench marks, show that maximum subsidence through December 1973 occurred above the barrier between 7th and 8th Left rather than above the mined-out panels, as one would expect. This indicates that compression arches are bridging the overburden



load to the barriers above the 6th, 7th, and 8th Left mining panels. Compression arches, and an inner destressed zone, also probably extend beneath the mine openings; however, the force of gravity probably reduces the crest depth of the arches considerably as compared to their crest height above the mine workings (figs. 16, 17). Shrinkage stoping, a process wherein fractured and buckled strata occupy a larger volume than originally, could not, in the opinion of the author, account for the geometry of the subsidence profiles for bench marks A and B (particularly B) nearly as adequately as the presence of compression arches.

The barriers, in turn, apparently yielded to this increased load, which produced a general troughlike depression over the mined-out panel-pillar complex, or "super panel," compared to the amount of yield in the massive, solid-coal pillar north of 6th Left. On the basis of subsidence-crack data and surface measurements (figs. 14, 16, 17), the arch above 8th Left appears to be about 500 feet (152 m) high and spans a panel about 450 feet (137 m) wide. Surface-crack

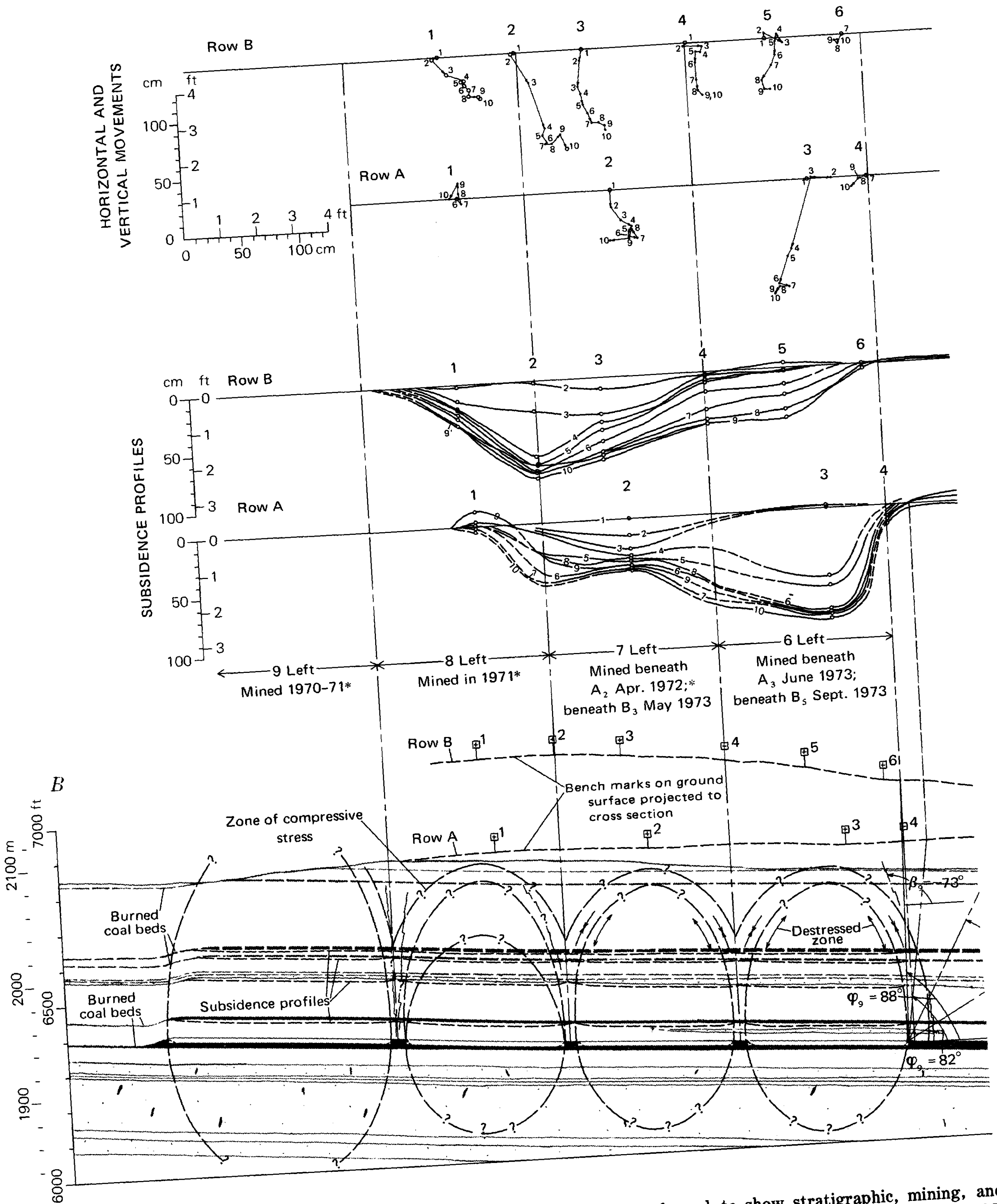
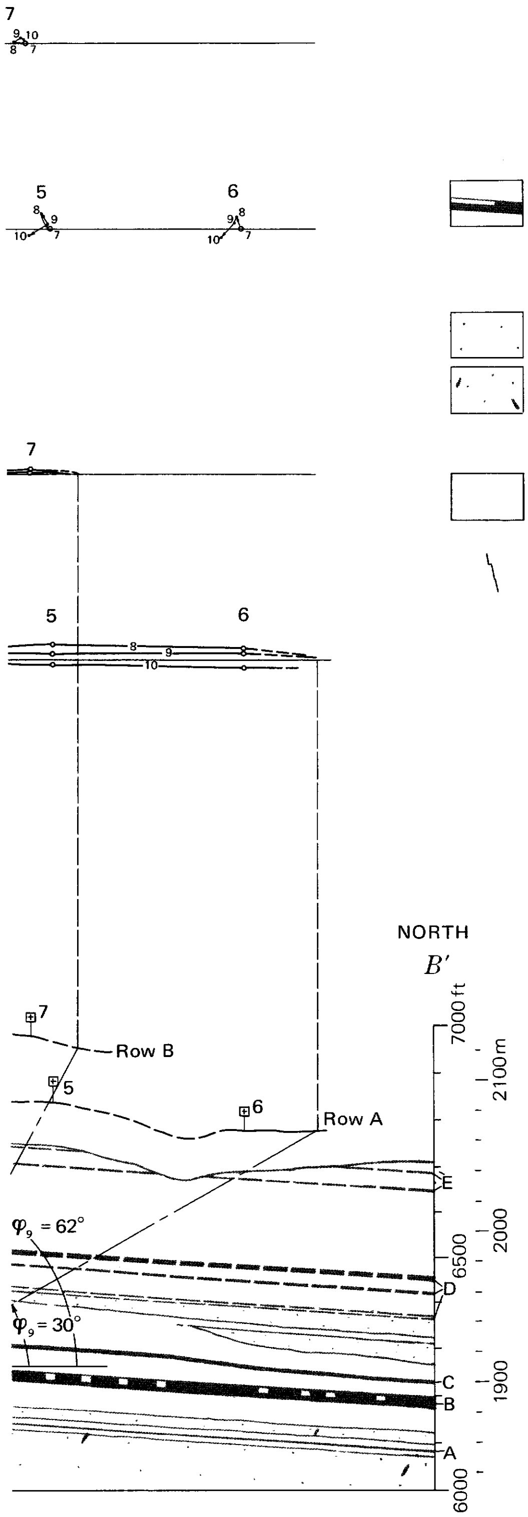


FIGURE 17.—Cross section B-B' through the 3d South area, Somerset mine, Colorado, enlarged to show stratigraphic, mining, and B is ×100; horizontal and vertical exaggeration of north-south and vertical movement of individual bench marks of rows A and B movement by use of surface-measurement date numbers (1 – 10); mining as of July 1, 1973.



EXPLANATION

Coal bed in lower coal-bearing part of Mesaverde Formation — Mined where unpatterned; A, B, C, D, and E denote nomenclature of coal bed in general use within the area. Bed position projected from existing drill-hole and outcrop information

Sandstone of Mesaverde Formation — Fine- to medium-grained, feldspathic

Rollins Sandstone Member at base of Mesaverde Formation — Fine- to very fine-grained, quartzose; elongate elliptical iron concretions 0.5-2.5 ft (0.15-0.76 m) in long dimension locally common

Shale and mudstone — Upper Cretaceous Mancos Shale below the Rollins Sandstone Member; all others in Mesaverde Formation

Fracture in mine overburden — Projected from surface crack toward nearest barrier pillar underground

SURFACE MEASUREMENTS**

1972	
1	Oct. 14
2	Nov. 8
1973	
3	May 5
4	June 26
5	July 13
6	Aug. 17
7	Sept. 13
8	Oct. 10
9	Nov. 30
10	Dec. 31

*Mined before bench marks were installed

**Subsidence bench marks installed Oct. 1972, except A_4, A_5, A_6, B_6, and B_7, which were installed Aug. 1973

subsidence details. (See fig. 14 for cross section location.) Vertical exaggeration of subsidence profiles of rows A and (upper two rows) is X100; dates of surface measurements are keyed to the subsidence profiles and individual bench-mark geometry indicates that the compression arch apparently migrated upward in the strata from a height of 300 feet (91 m) to 500 feet (152 m) in a year's time. Subsidence measurements indicate that similar arches probably are present above the 6th and 7th Left panels, at least at the level of row B, although surface cracks were not observed above these panels and benchmark control is not adequate to verify the true position of the arches at the level of row A. Surface cracks are absent above the 6th and 7th Left panel barriers either because the tensile rupture limit was not exceeded in the surficial veneer or, if the cracks occurred in the bedrock, because they are masked by the colluvium or landslide deposits that are prevalent in the area.

If it is assumed that the compression arch above the 8th Left mining panel approximates half of an ellipse with its major axis oriented perpendicular to the coal bed, then the ratio of major to minor axis would be approximately 450:225, or 2.0, for panel-pillar mining in 3d South. Mohr (1956, p. 150) suggested that the configuration of the upper half of the stress ellipse is related to Poisson's ratio for the overburden strata by the formula:

$$\frac{a}{b} = m\text{-}1,$$

where

a = the major axis of the ellipse,

b = the minor axis of the ellipse, and

m = the reciprocal of Poisson's ration (μ).

For overburden strata comprising mudstones, shales, coal beds, and lenticular sandstones in the Somerset mine area

$$m = 1+\frac{a}{b} = 1+2 = 3, \text{ and}$$

$$\mu = \frac{1}{m} = \frac{1}{3} = 0.33.$$

Shoemaker (1948, p. 7), in his review of Fenner's analyses of stresses around mine workings, showed that a uniform elliptical zone of compressive stress occurs around a single mine entry when the axial ratios of the ellipse are $a{:}b = (m\text{-}1){:}1$, the same ratios as presented by Mohr.

STRESS AND DEFORMATION CAUSED BY SUBSIDENCE

Previous and current mine deformation studies have revealed that the vertical and horizontal components of stress caused by overburden load and by any tectonic stresses present cannot be transmitted through mine openings but must be redistributed around them. The redistribution is accompanied by deformation, or yield, that continues until equilibrium is once again attained. This can produce large changes in the natural state of stress. The strata above and below the mine openings, for example, are subjected to increased high- to low-angle compressive stresses in the elliptical zones of compressive stress. These zones encompass the strata above and below the mine openings and transfer part or all the overburden stresses to mine boundaries or barriers of the mining panels (fig. 17). The upright and inverted arches also encompass inner zones of much lower stress relative to the concentrations of compressive stress within the arches.

As the mine workings become more extensive, the arches migrate upward and downward, and the strata transected by them are subjected to increased compression, followed by decompression and continued migration of the arches. Within the destressed zones, Mohr's measurements (1956, p. 146 – 149) and mine studies by the author show that the strata buckle downward and upward (bottom heave) into the mine cavities and produce tensile and compressive stresses within major lithologic boundaries and shear stresses across lithologic boundaries due to flexure of strata, as shown in figures *4A* and *4B*. This buckling or downwarping also transfers some of the original overburden stresses from mine boundaries or barrier pillars back into the mine workings or mined-out areas. As the arches migrate farther upward and downward, an increasingly greater part of the overburden stresses is transferred back into the mine workings.

In addition, as mining progresses, the strata above coal pillars, particularly the weaker strata above strong barriers between mining panels, are compressed vertically because the overburden load is concentrated above them by arching and strata flexure (S_2-S_1 in fig. *4B*). A similar compressing effect, although reduced by the force of gravity, occurs in the strata beneath large strong pillars.

In the upper part of lithologic units, flexure produces both tensile stresses and compressive stresses that are oriented parallel to the bedrock attitude. The tensile stresses occur in zones where the strata are positively curved (above coal pillars), whereas the compressive stresses occur in zones where the strata are negatively curved (above mining cavities and near coal pillars or mine boundaries) (fig. 4). Owing to flexural slip, lateral shear stresses and accompanying strains are present along major lithologic boundaries. The lateral flexural and shear stresses are greater above narrow barrier pillars (figs. *4A*, 17) than above solid-coal boundaries (figs. *4B*, 17), provided that the narrow pillars are strong enough to support the concentrated overburden stresses. Within the strata above a barrier pillar, as in figure *4A*, a above the barriers separating 6th, 7th, 8th, and 9th Left panels, two diagonal shear stresses should occur along the crossing limit lines; whereas a single diagonal shear stress should develop along the limit line above solid-coal mine boundaries, such as north of 6th Left (fig. 17). As the 5th Left panel is mined, the single shear stress along the limit line should be transected by another limit line and accompanying shear stress, and the flexural and shear stresses should increase unless the barrier pillar is narrow enough to yield significantly.

Unmined coal beds in the strata within the influence of migrating compression arches will be subjected to stress changes, including: (1) low- to high-angle compressive and tensile stress concentrations in the arch and the destressed zone, respectively; (2) horizontal tensile and compressive stresses within lithologic units and shear stresses along lithologic boundaries caused by flexure of strata; (3) possible high- to moderate-angle shear stresses at the limits of the draw; (4) local increased vertical compression above and below coal pillars, caused by concentration of overburden stresses; and (5) reduced vertical compression above and beneath mine voids. Coal beds subjected to these stresses probably will be much more hazardous to mine if recovery factors equaling those attainable in undisturbed beds (figs. 18, 19*A*, 19*B*, 19*C*) are sought.

In addition, should the compression arches surrounding destressed zones stabilize within portions of strata containing coal beds, subsequent mining in these beds could encounter any combination of these stresses, which could perhaps cause compressive roof failure and the possible loss of valuable coal reserves. The "E" coal beds, for example see figure 16, probably are within the zone of the compression arch above and parallel to the mined-out panels. The height of the compression zone in a profile parallel to mined-out panels (fig. 16) is controlled by the height of the arches spanning the mining panels (fig. 17), which in turn is controlled by the width of the panels. Ropski and Lama (1973, p. 118) found, from measurements in holes driven above the coal bed being mined by the longwall method, that the strata higher than 3 to 3.5 times the thickness of the coal bed being mined were relatively undamaged by longwall mining because the strata flexed into the mine cavities without fracturing. However, their study revealed only the aspects of subsidence damage resulting from mining above the longwall face; they did not investigate the nature and extent of subsidence effects above remnant-pillar boundaries of the longwall panels.

The stresses encountered in mining coal beds above the "B" coal bed in the 3d South area (fig. 17) probably will vary greatly depending on whether the coal is extracted from above the mined-out areas or from above the barriers in the "B" coal bed. Mining in a multiple-bed mining area commonly is safer and extraction ratios are higher if the beds are mined from top to bottom, provided that uniform extraction procedures are followed. If barriers or isolated pillars are left in the extraction process, however, the underlying coal beds may be affected, particularly if the stratigraphic interval between beds is small and the overburden is thick (figs. 19*D*, 19*E*, 19*F*). Stemple (1956, p. 39) found that the damage to a subjacent bed can be of two types if water or gas is abundant in the area: (1) sudden intrusion of water or methane from overlying mine workings through subsidence cracks, and (2) weight manifestations (stress concentrations), due to increased loading, beneath isolated pillars or solid-coal mine boundaries.

An example of stress concentrations caused by uneven extraction was seen by the author in a mine of the Somerset district where the "C" bed was mined prior to mining in the "B" bed. The stratigraphic interval between the two beds is about 50 feet (15 m). Mine pillars 60 feet by 60 feet (18.3 x 18.3 m) that were left in the "C" bed caused serious local bump and roof-fall hazards when the underlying "B" bed was mined beneath them (figs. 19*D*, 19*E*). However, beneath areas of nearly complete extraction in the "C" bed (fig. 19*F*), overburden stresses in the "B" bed were relieved, and recovery was excellent, with no hazard to miners.

Recent mining in the "C" coal bed in parts of the Somerset mine 50 – 60 feet (15.2 – 18.3 m) above old mine workings that were driven in the "B" bed during the early to middle 1930's encountered unstable roof conditions and stress concentrations that were related to this prior mining. Although most of the rock strata above the "C" bed are unstable owing to the presence of numerous slickensided fractures, certain areas of the roof are particularly unstable (figs. 19*B*, 19*C*). These areas commonly occur above, and aline with, old mine entries in the "B" bed. Bumps and sudden roof falls were a constant hazard to men and equipment when workings were driven above coal barriers in the "B" bed. These conditions indicate that stresses are still concentrated above the barrier 40 or more years after "B" bed mining.

Elevated stresses on mine workings and resulting bumps and roof falls in the "C" Slope and 1 Right mine workings commonly were reflected in increased local seismic activity, which was recorded by a seismic station located about 1,000 feet (305 m) north of the area (fig. 18). Peaks of seismic activity in mid-January, early February, late February, and

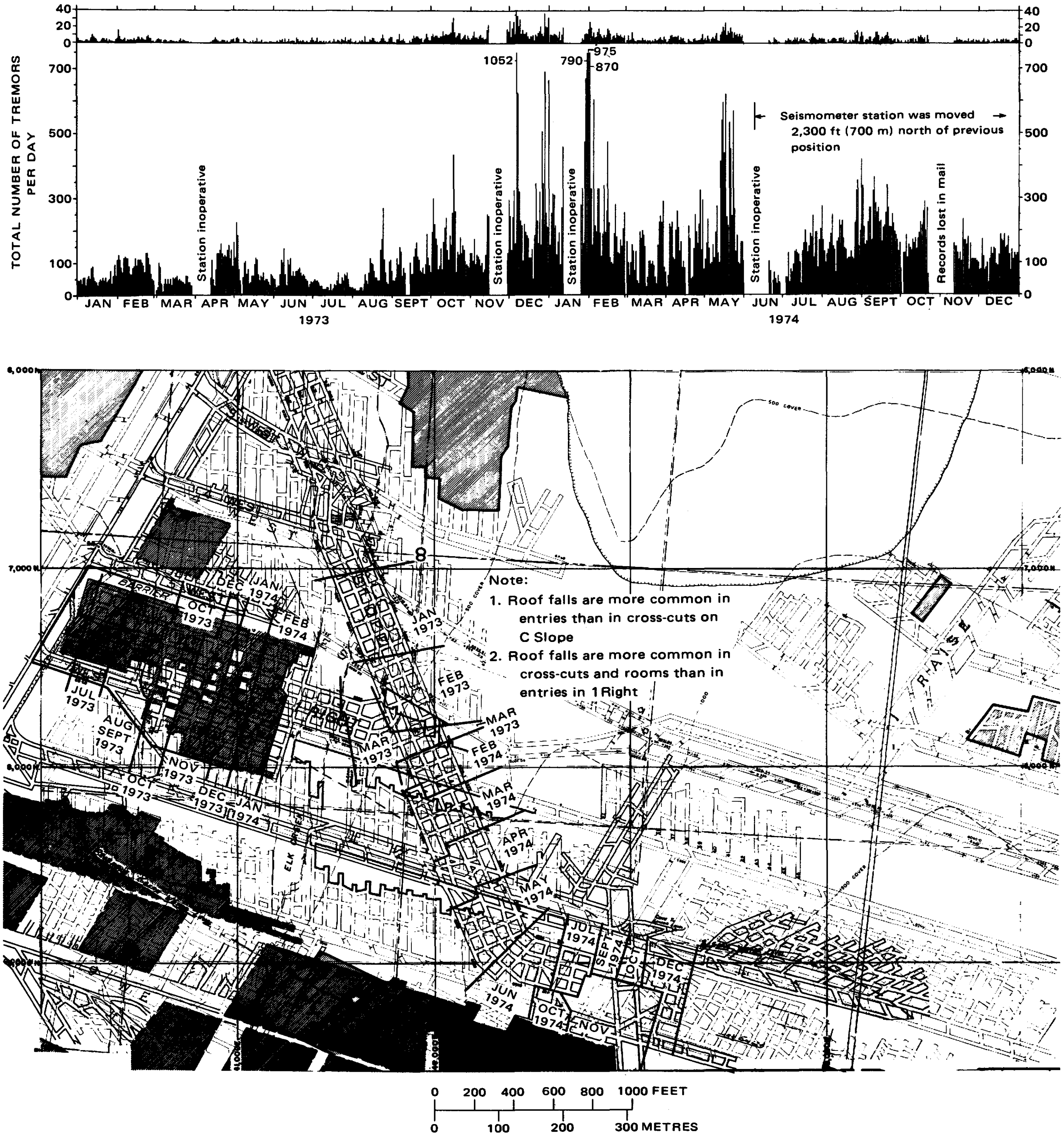


FIGURE 18.—Composite map of part of the Somerset mine workings and histograms of the daily seismic activity during 1973 and 1974 in the Somerset mining district, Colorado. The mine workings in gray are in the "B" coal bed, which was mined in the early to middle 1930's; the workings in black are in the "C" coal bed, 50 – 60 feet (15.2 – 18.3 m) above the "B" bed, which was mined in 1973 and 1974. Mining progress in the "C" coal bed is shown by lines bracketing the month and locations in which mining took place. The lower histogram is the total daily seismic activity recorded; the upper histogram is the seismic activity between an estimated 1 and 2 on the Richter scale. Note that the seismic activity commonly increased when the mine workings in the "C" coal bed were driven above large coal pillars left in the "B" coal bed.

early March 1973 coincide with mining in the "C" Slope above barrier pillars or isolated blocks of coal in the "B" bed north of 4 West and 5 West. Peaks in early May and late August 1973 correspond with periods of severe roof-fall hazard in crosscuts of 1 Right. The first peak above 400 tremors per day in 1973, which occurred in mid-October, coincided with mining in 1 Right above a remnant barrier pillar in the "B" bed.

The very large peaks of seismic activity in early and late December 1973 and late January 1974 correspond with periods of unstable roof conditions during development and extraction in areas of 1 Right above old mine workings in the "B" bed. Miners were unable to remove all pillars because of severe roof-fall dangers and, as a result, stresses increased and bumps were common on the unmined pillars. The next high peak in mid-May 1974 coincides with a period when the "C" Slope entries were driven above a barrier pillar in the "B" bed. As the slope entries were driven northward during the period from late February to early May 1974, the overburden thickness increased from 500 to 1,000 feet (152 – 305 m) (fig. 18). Although records show a reduction in overall seismic activity because the station was moved 2,300 feet (700 m) farther north of the mine, the peaks of seismic activity during late July and August, mid-September, and mid-October 1974 again coincided with periods of mining above and around a large block of coal in the "B" bed when bumps and roof falls were very intense. In fact, the hazard was so severe that mining was stopped for most of the month of August, and mining was permanently terminated in two entries above the large block of coal (fig. 18).

An inverse stress effect—the transmission of stresses from the "C" to the old "B" mine workings—was noted recently in one of the old mine entries in the "B" bed that is used for air ventilation in the "B" mine. Numerous roof falls occurred beneath a coal barrier adjacent to the "C" workings and threatened mine ventilation in the "B" bed. Abutment stresses in this barrier, caused by recent mining in the "C" bed, are apparently being transmitted to the underlying "B" mine workings where they are causing roof falls. This interaction of stresses between mine levels suggests that beds separated by a thin (perhaps 50 feet (15.2 m) or less) stratigraphic interval perhaps should be mined simultaneously by uniform procedures, having retreat lines in the upper bed slightly ahead of those in the lower bed and making sure that all pillars in one bed are vertically alined with pillars in the other bed.

High concentrations of compressive stress, such as those present beneath coal barriers, could be transmitted downward, perhaps 100 feet (30.5 m) or more, even if the coal beds were mined in sequence from top to bottom. Ideally, therefore, the barriers between panels, if necessary for reasons of mine safety, should be thin enough—perhaps 20 – 25 feet (6.1 – 7.6 m) or less—to yield, and thereby reduce the stress concentration and ensuing subjacent or superjacent transmission of stresses to a safe level. The other alternative is to design for uniform partial recovery and thereby diffuse rather than concentrate overburden stresses. Stemple (1956, p. 45 – 50), in his review of multiple-bed coal mining in Virginia, West Virginia, and neighboring States, found that roof falls (fig. 19*B*), bumps, and squeezes (fig. 22) often forced abandonment of coal reserves when mine planners attempted greater recovery than could be achieved under a uniform partial-extraction plan.

Bumps in the Kenilworth and Castle Gate mines in central Utah were eliminated when a uniform mining pattern was substituted for pillar extraction, resulting in greater coal recovery with greater mining safety according to J. Paul Storrs (oral commun., 1974).

Many problems faced in multiple-bed coal mining, therefore, are related to the processes of subsidence. The best remedy for these problems is to design for uniform extraction. If geologic conditions or thick and variable overburden preclude complete coal extraction, sequential partial uniform extraction from top to bottom, with columnized support pillars, might yield the maximum of a given coal reserve with a maximum safety factor. However, Stemple (1956, p. 51) reported that, according to mining men he interviewed, in areas where two coal beds are separated by a very thin stratigraphic interval (generally 25 – 50 feet (7.6 – 15.2 m), depending on strength of strata), concurrent partial uniform extraction was thought to be most successful.

Processes of subsidence can be affected both directly and indirectly by the presence of active natural stresses. The geometry of compression arches might be altered by natural stresses if they add to or subtract from the stress field of the arches. For example, an eastward-trending stress field, disclosed by mine-deformation and seismic studies, is locally active in the Geneva mine area. This stress field has the effect of prestressing the strata in that direction and could reduce the height-to-width ratio of the eastward-trending compression arch shown in figure 8. The height-to-width ratio seems small compared to that measured in the Somerset area. The greater strength of the strata in the Geneva mine area would, of course, account for some of the difference in geometry.

Subsidence can be indirectly influenced by active natural stresses if the stresses cause numerous roof falls and bumps. These stresses could force abandonment of mine areas before mining is completed in a uniform manner, which in turn could produce greater subsidence damage because of uneven mine geometry. Preliminary studies indicate that stresses are still active in the Somerset district near channel sandstones that are locally common. The stresses and attendant fractures apparently are caused by flexure of strata above and below the channel sandstones as a result of differential compaction. The roof-fall hazard normally is greater near these channel deposits and can lead to premature abandonment of a mine area before mining is completed, resulting in uneven mine geometry and high concentration of stresses produced by subsidence processes.

The processes of subsidence, roof falls, and bumps are thus interlocked in an often irreversible set of causes and effects. If roof falls or bumps are prevalent in certain areas of a mine because of physical conditions or poor mining practices, uneven extraction procedures often follow. This produces greater subsidence damage in the nearby strata, which, in turn, can create anomalous stress problems in other coal beds or can produce stress problems in adjacent mine areas, causing premature abandonment of an area that otherwise might have been uniformly and efficiently mined with minimal hazard to life and property. A thorough knowledge of geologic conditions during the mine-planning stage, derived from detailed drilling studies, surface mapping, and perhaps selected test mine entries, will help identify problem areas before mining starts so that these areas can be mined more safely and efficiently and with minimal adverse effects on the environment, on nearby coal beds or other deposits, or on the bed to be mined.

CASE STUDY OF THE RELATIONSHIP BETWEEN A MINE AND THE PHYSICAL ENVIRONMENT

Subsidence often sets in motion a chain of events that can significantly affect the mining activity as well as the physical environment. Not only can coal production and mine safety be threatened, but also adjudicated surface and underground water rights can be affected. Of course, these problems are multiplied and are magnified if the surface area above the coal mines supports dense housing or heavy industry.

An example of how underground coal mining can disrupt the surface and subsurface environment is recorded in the history of the Oliver No. 2 mine, which is located in the "D" coal beds south of the North Fork Gunnison River, about 2 miles (3.2 km) east of the Somerset mine (fig. 20). The mine comprises a system both of raises on a 5- to 7-percent grade that roughly parallels the direction of the dip of the coal bed and of entries that parallel the strike of the coal bed. The mine portals are located at the outcrop of a "D" coal bed overlooking the North Fork Gunnison River. The surface area near the mine is sparsely settled and supports summer grazing for cattle and horses.

The Oliver No. 2 mine, which was begun in the 1930's and provided coal for the Oliver power plant, was closed in October 1953 after methane gas and water were encountered in quantities that were too costly to control. A four-entry raise was driven southward beneath overburden which increased in thickness from a few tens of feet near the outcrop to 1,250 feet (381 m) beneath a high ridge and then

FIGURE 19. (facing page)—Stress effects from multiple-bed coal ▷ mining, Somerset district, Colorado. In *A* through *C*, the lower bed of coal was mined first; and in *D* through *F*, the upper bed was mined first.

A, Damage to roof and rib in the "E" coal bed caused by mining "D" coal bed, 150 feet (45.8 m) below "E" bed, 25 years prior to mining "E" bed. Roof bolts and landing mats provided adequate support until the limit of mining in underlying "D" coal bed was traversed; timbering (background) was then required to prevent roof falls and possible coal bumps.

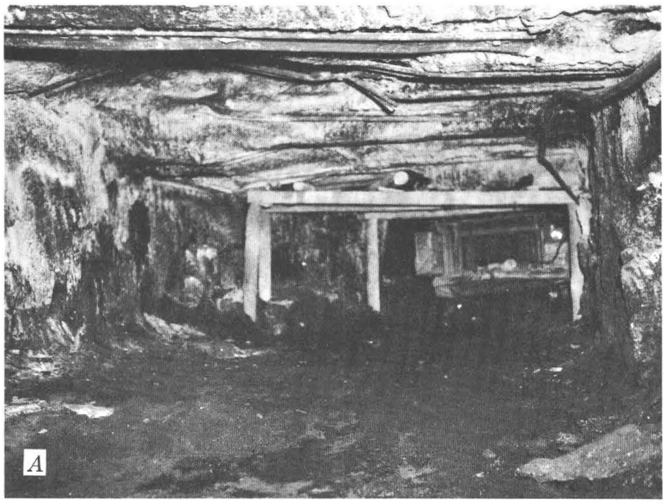
B, Sites of roof falls and generally unstable roof conditions in a crosscut in the "C" bed that is located 45 feet (13.7 m) above workings in the "B" bed that were mined about 40 years before mining the "C" bed.

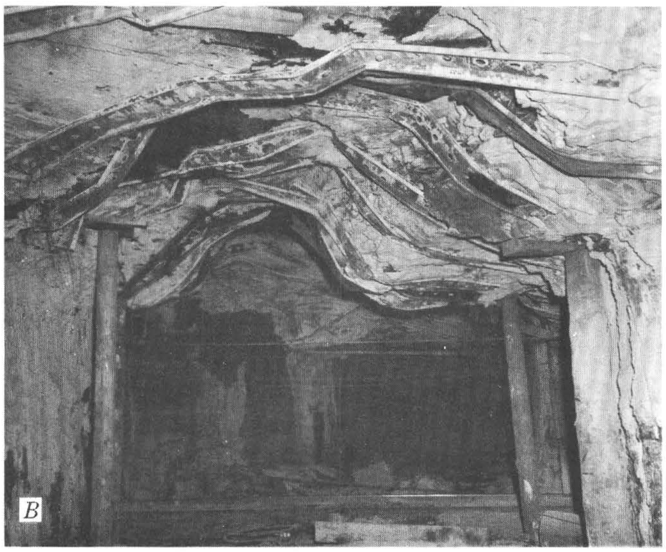
C, Unstable roof conditions in the "C" bed along a slope haulageway above workings in the "B" bed that were mined about 40 years before mining the "C" bed.

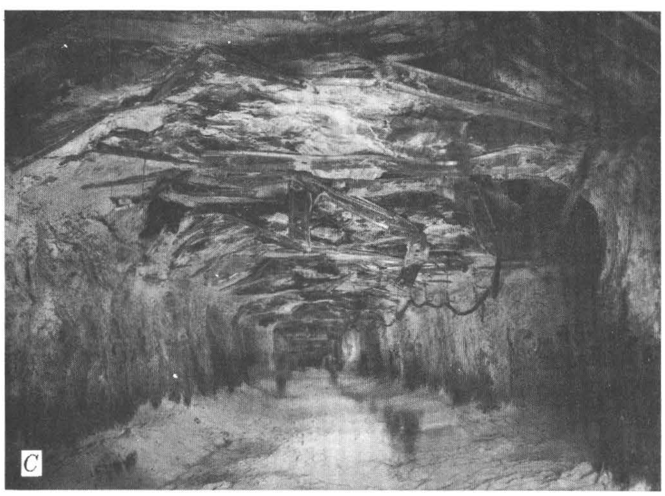
D, Damage to right rib and roof in the "B" coal bed beneath about 1,200 feet (366 m) of overburden caused by local stresses beneath an isolated pillar 60 feet by 60 feet (18.3X18.3 m) left in the "C" coal bed about 50 feet (15 m) above and collimated with the pillars in the "B" bed. Note the dramatic difference between the rib and roof conditions on the right side of the mine opening beneath the isolated pillar in the "C" bed and those of the left rib where the coal was mined out in the "C" bed before "B" bed was mined.

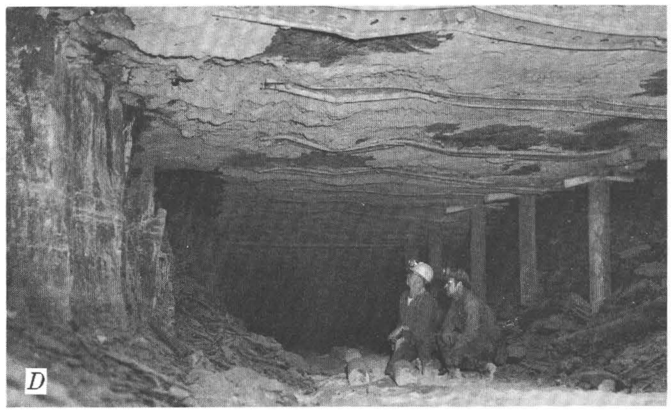
E, High stress concentrations in an isolated pillar 60 feet by 60 feet (18.3X18.3 m) in the "B" coal bed beneath about 1,300 feet (397 m) of overburden. The pillar ribs in the left and right foreground show no signs of stress because the coal was completely mined out in "C" bed before "B" bed was mined, whereas the isolated pillar is yielding to stresses from an isolated pillar in "C" bed directly above the yielding pillar in "B" bed, even with massive props surrounding it. The author monitored about 100 coal bumps during a 3-hour period, as the yielding pillar was split by a mining machine.

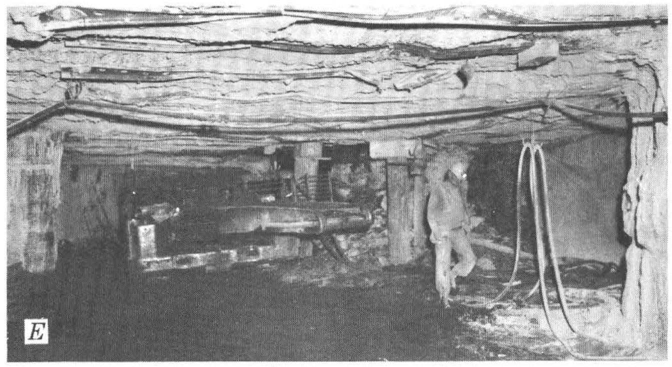
F, View of ideal rib and roof conditions in the "B" coal bed beneath about 1,300 feet (397 m) of overburden where the coal was mined out in the overlying "C" bed before "B" bed was mined. The overburden stress was reduced to essentially the 50 feet (15 m) of strata separating the two coal beds.

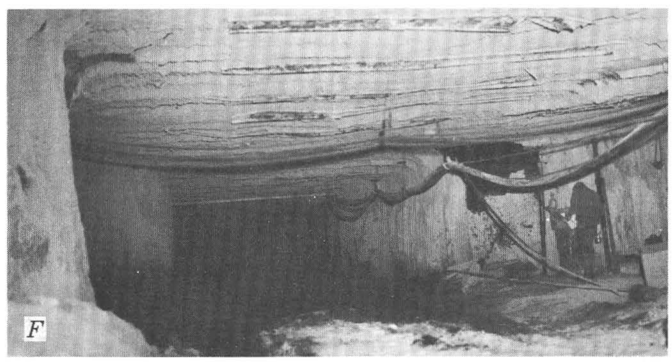












decreased within a distance of about 1,500 feet (457 m) to 325 feet (99 m) beneath an east-trending, joint-controlled side canyon of Sylvester Gulch (fig. 20). At this point a four-entry system was driven eastward (7 East) directly beneath, and parallel to, the east side canyon. The 7 East panel was driven about 300 feet (91.4 m), then work began on driving 6 East. Suddenly large volumes of water and methane began to gush from the floor of the top entry of 6 East, forcing the evacuation and closure of the mine.

The mine was sealed and has remained closed. The Oliver electric power plant also was subsequently closed, although other sources of coal supplied it for a

FIGURE 20.—Composite aerial photograph and underground map of the Oliver No. 2 mine area, Colorado. This mine was closed in October 1953 because of a sudden intrusion of water and methane gas. The scrub oak and other woody plants that originally grew in the bare spot above the exhaust portal were killed when the methane leaked through fractures to the surface after the portals were sealed. The beaver pond apparently dried up when subsidence fractures above 7 East tapped the ponds and the nearby spring source and diverted the water underground. Photograph by R. B. Taylor, U.S. Geological Survey, 1973.

few years. After the mine was sealed, the methane leaked out of the mine to the surface through fractures in the overburden in sufficient quantity to be detected with a miner's lamp (C. L. Heiner, oral commun., 1974). The methane killed the scrub oak and all other woody plants in the area (fig. 21), leaving only the grasses unaffected. According to Garner (1974), the presence of methane in soil provides an environment in which certain bacteria utilize the methane and produce hydrogen sulfide and nitrous oxide in their life processes; the presence of the hydrogen sulfide and perhaps nitrous oxide disrupts root transpiration of woody plants and ultimately may kill the plants.

Shortly after the mine was closed, the water in the

FIGURE 21.—Southward view of the rugged topography above the Oliver No. 2 mine, Colorado. The exhaust portal (P, in left foreground) was sealed inthe late 1950's. The scrub oak and other woody plants that originally grew in bare spot above exhaust portal apparently were killed when methane gas leaked through fractures from the mine to the surface.

east-side canyon, which was fed by springs above the 7 East mine workings, ceased to flow (W. A. Bear, oral commun., 1972). This water, to which the Bear family had the rights, has not flowed with any regularity since the mine was closed. Investigation by the author revealed the presence of large dry beaver ponds, with dams as much as 6 feet (1.8 m) high, above the 7 East entries (fig. 20). These dams indicate that a perennial water supply was once available from springs nearby but that the springs have been dry or only flowed intermittently for many years. Although no surface cracks were positively identified in 1972, they could have been covered by erosion-deposition, mass wasting, and revegetation in only a few years. Local scarps in soil and colluvium noted in the area might be erosional remnants of subsidence scarps.

Field evidence indicates that, after the mine was closed, subsidence fractures formed in the strata above the 7 East entries and faces of the raise and eventually migrated to the surface and drained the beaver ponds in the east-side canyon (fig. 20). Although coal pillars were not extracted in most of the Oliver No. 2 mine, the vertical and downdip component of stress produced by the weight of the high ridge above the mine workings, together with the reduction of frictional resistance at the top of the coal bed owing to mine development, apparently was sufficient to produce tension fractures along local joints in the thin overburden beneath, and parallel to, the side canyon. The fractures tapped the beaver ponds and nearby springs and diverted the surface flow underground. The mining reports indicate that the water- and methane-filled fracture encountered in 6 East might be a tension fracture produced by decollement-type movement of the strata above a "D" coal bed prior to mining.

The "B" and "C" coal beds are present beneath these mine workings, and at least one "E" bed of minable thickness occurs above the mine workings. Subsidence may have significantly reduced the minable reserves represented by these beds because mines in the "B" and "C" beds may be threatened by intrusion of methane and water from the old "D" workings through subsidence cracks and the "E" bed(s) may be locally transected by subsidence fractures and stress concentrations above solid-coal boundaries. In summary, then, not only were wildlife, vegetation, and surface-water rights affected by surface-water diversion and methane leakage via subsidence fractures, but potential production from subjacent and superjacent coal reserves probably also was reduced considerably.

SUMMARY

Subsidence studies in Utah and Colorado show that the mode of subsidence depends upon: (1) the geometry of mine workings, (2) the lithology, structure, and thickness of the overburden, (3) direction of dip of the coal bed relative to its outcrop, and (4) proximity of mine workings to coal outcrop, unless an adequate coal barrier is left to support the overburden strata. In multiple-bed coal mining, the mining activities in one bed can cause stress problems in another bed during current or subsequent mining. Subsidence parameters, such as break line, limit angle, configuration of compression arch, and ratio of surface subsidence to coal extraction thickness, and how they are controlled by mine geometry and geology in two areas of Colorado and Utah are described in the following list:

1. A nearly vertical break line is caused by cantilever failure in strong overburden above a wide property barrier in the Geneva mine area and illustrates operation of the law of the normal or the law of the vertical in gently dipping strata that underlie overburden comprising strong, thick, jointed sandstones and interbedded mudstones (fig. 8).
2. Nearly vertical break lines also occurred in weak strata above a thin coal barrier between the 8th and 9th Left mining panels in 3d South, Somerset mine and likewise illustrate the law of the normal for tensile failure produced by positive flexure of strata above thin barriers separating adjacent mine cavities (figs. 3, 4, 17).
3. A break line, with a negative angle of 78° ($\beta =$ -78°), was observed in weak overburden above the solid-coal barrier north of 6th Left, Somerset mine only 4 months after mining was completed beneath the ruptured area. Strength of overburden appears to govern the rate of fracturing—a -73° ($\beta = -73°$) break line was inferred in strong overburden above the Geneva mine workings 6 - 12 years after mining was completed (figs. 8, 17); in this case, however, pillars were not completely removed.
4. The limit angle in weak to moderately strong overburden strata, which is 650 - 900 feet (198 - 274 m) thick (fig. 16), measured 69° - 70° relative to the position of the room-and-pillar retreat line in the 6th Left mining panel in the Somerset mine. The limit angle appears to steepen to 75° or more in moderately strong overburden 900 - 1,000 feet (274 - 305 m) thick, although bench mark control is not good beyond the 900-foot (274 m) overburden level (fig. 16).
5. The overburden above a 300-foot- (91.4 m) wide coal barrier north of 6th Left in the Someset mine was uplifted slightly through November 30, 1973, probably in response to overburden subsidence into the 6th Left mine void (fig. 17). If the uplifted area is included as part of the surface area affected by subsidence, the limit angle ranges from 35° to 65° in weak overburden 550 - 700 feet (168 - 214 m) thick; if the limit angle is measured relative to the subsiding zone, it ranges from 82° to 88°. A slight uniform subsidence occurred above the barrier in December,

thus precluding further determination of limit angle and suggesting that the limit angle is only a transient parameter above pillars between two mining panels.

6. Maximum subsidence to date (Jan. 1, 1974) in the B row of subsidence benchmarks above the 3d South area was measured above the barrier between 7th and 8th Left rather than above a mined-out area (fig. 17). This, in addition to subsidence-crack data, indicates that compression arches, perhaps about 50 feet (15 m) thick at the crest, are bridging the strata to the barriers and that the subsidence measured above roughly the 500-foot (152.4 m) overburden-thickness level actually results from yield or collapse of barriers pillars rather than from subsidence of strata into mine voids. The depth of the inverted arches that are believed to occur beneath the mine voids is not known but should be considerably less than that of the arches above the voids. The height-to-width ratio for the arches in the overburden appears to be about 1:1. The height of the arch parallel to the long direction of mining panels (fig. 16) is controlled by the position of the arch spanning the barrier pillars oriented perpendicular to the long direction of the panels (fig. 17). This produces abutment stresses on the pillar retreat line as well as on the barriers. A squeeze, such as the one shown in figure 22, can occur if rooms are developed too far ahead of extraction.

7. Stresses produced by flexure of strata within the destressed zone of the compression arches are oriented perpendicular and parallel to the long direction of the mining panels, as are the compression arches above and below the mine workings. Both flexure and caving of strata into mine workings or mined-out areas tend to transfer an increasing amount of the overburden stresses from solid coal boundaries and barrier pillars back into the mine workings or mined-out areas as the arches migrate higher into the overburden. This may explain why miners commonly encounter reduced stress levels on mining faces and along pillar lines after caving occurs in mined-out areas behind the pillar lines.

8. In multiple-bed coal mining, individual coal beds normally can be extracted more safely and completely if the beds are mined from top to bottom, provided the coal is uniformly extracted so that stresses cannot concentrate on isolated pillars and be thereby transmitted to underlying coal beds. However, it may be best to mine two beds concurrently using uniform methods if the beds are separated by only a thin (generally 25 – 50 ft (7.6 – 15.2 m)) stratigraphic interval. It might also be best to reverse the sequence and mine coal beds uniformly from bottom to top in areas where the methane or water is abundant in nearby strata. If overburden rocks, for example, contained methane and water, large quantities of methane or water could accumulate in mined-out areas; if these accumulations were above current mine workings, they might be tapped by subsidence fractures and perhaps pose a greater threat to mine safety and coal reserves than would reversal of the recommended mining sequence.

9. The direction of dip of a coal bed relative to its location of outcrop can have a significant effect on mining safety and efficiency. If a coal bed is mined updip from where it crops out, even if the bedrock dips only a few degrees, a downdip decollement-type movement of the mine overburden is possible because the downdip component of gravitational force is unrestrained at the outcrop and the frictional resistance at the top of the coal bed is reduced due to mining. This could produce a severe hazard to life, coal reserves, and surface environment. For example, if the bedrock dipped westward instead of eastward at the same angle in the Geneva mine area (fig. 8), the entire block of overburden strata west of the fractures above the property barrier would be laterally unrestrained, and it could slide above mine workings, crushing pillars, men, and equipment beneath it. Needless to say, the effects on hydrologic regimen and on the surface environment also would be drastic.

10. The subsidence ratio for the ground surface above the 6th Left mining panel (table 1, figs. 14, 16) is

$$S_{max}/t = 3.1 \text{ ft}/10 \text{ ft} = 0.31,$$

where

S_{max} = maximum surface subsidence, and
t = mining height.

Comparing subsidence ratio to the ratio of panel width (W) and average overburden depth (D) above the mined-out area (fig. 16) produces the following result:

$$W/D = 450 \text{ ft}/\frac{950 \text{ ft} + 410 \text{ ft}}{2},$$
$$= 450 \text{ ft}/680 \text{ ft} = 0.66.$$

The subsidence ratio is considerably lower than that determined by Wardell (1971, p. 206; fig. 5) for the same W/D ratio in many longwall mines of the United Kingdom. This could be because longwall mining induces greater surface subsidence, because a compression arch is bridging the 6th Left mining panel, or because the overburden strata are stronger at Somerset than in the United Kingdom. Complete room-and-pillar extraction should induce at least as much subsidence as complete longwall extraction under similar conditions. Weak overburden strata and interbedded coal in the Somerset district probably is as weak as those of the United Kingdom. Therefore, the low subsidence ratio further indicates that compression arches bridge the overburden strata across mining panels. Should the compression arches fail with time, the subsidence ratio may approach Wardell's (1971) curve.

SUGGESTIONS TO MINE PLANNERS

Previous and current subsidence studies indicate that a distinction must be made between subsidence and subsidence damage because most subsidence damage to the overburden and surface results from horizontal strain produced by differential vertical settlement of the mine overburden. Under geologic and mining conditions, such as those in the Geneva and Somerset mining areas, subsidence fractures can propagate through many hundreds of feet of strata. In order to estimate the probable effects of subsidence in areas of underground coal mining, mine planners should take into account such factors as (1) overburden thickness, lithology, and structure in the strata above and below the mine workings; (2) the geometry of mine workings; (3) the coal bed thickness; (4) the number of minable coal beds present; (5) the rate of mining; and (6) the natural and manmade environment at the surface. The first four factors vary with locality, and the last two factors often vary with time. The present and future conditions of an area, together with present and anticipated energy needs, determine the proper blend of extraction efficiency and preservation of the surface environment.

Uniform coal extraction tends to cause the overburden to settle uniformly and, therefore minimizes subsidence damage. If, in addition, the coal bed could be completely extracted, this method would produce maximum yields. However, if complete extraction is planned by room-and-pillar methods, it may be impossible to mine uniformly during the development and extraction phases if the overburden is deep and stresses are high. Under these conditions, retreat lines must be close to solid coal or else a squeeze may develop (fig. 22), which would cause

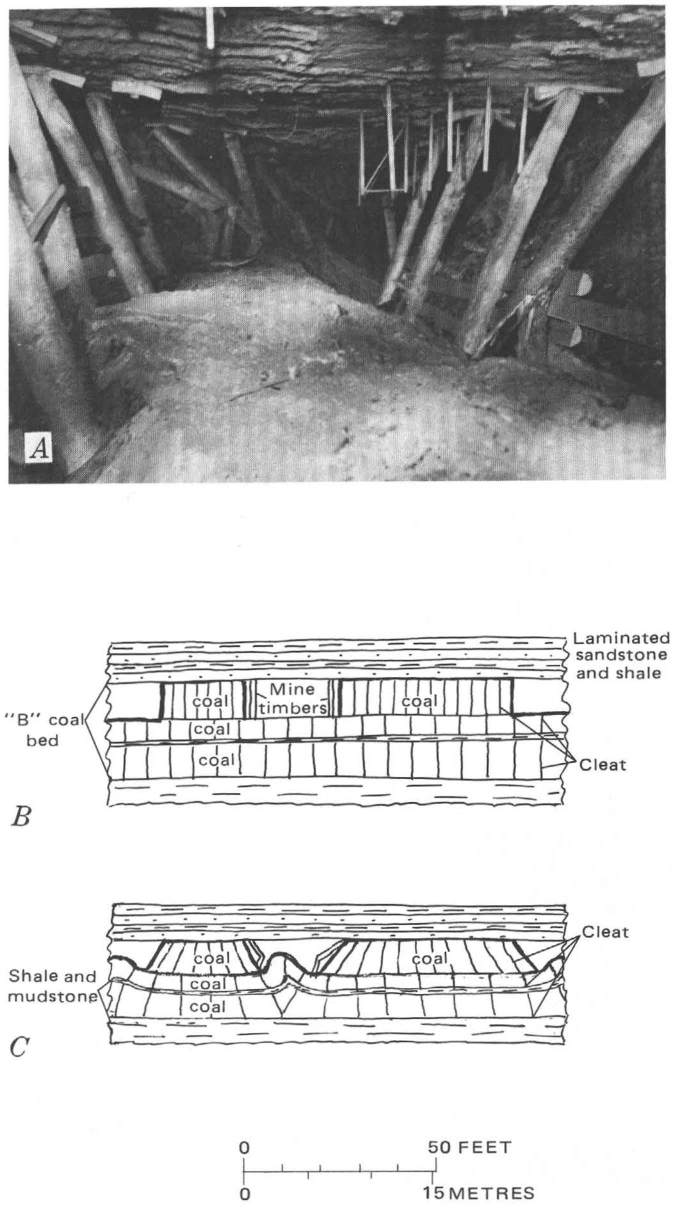


FIGURE 22.—Coal mine squeeze in "B" coal bed, Somerset district, Colorado. *A*, A mine opening that was closed by coal flowage in response to abutment stresses ahead of a pillar extraction area. The squeeze was caused by driving too many workings ahead of the area of pillar extraction. *B*, Cross section of mine workings and adjacent pillars before squeeze shown in photograph. *C*, Cross section of same area after squeeze.

extensive loss of coal reserves. Therefore, in many instances uniform geometry can be attained only after mining is completed, provided that necessary coal barriers are thin enough to crush out so that stresses are relieved. The other alternative is to design for a uniform partial extraction procedure near solid coal, so that mining stresses are diffused and the possibility of a squeeze is minimized. The mine geometry, therefore, is a very important factor to consider when planning a new mining operation.

In shallow overburden, where stresses are low, certain compromises might be made in designing mine geometry that would preserve the integrity of the overburden and surface without increasing the stress problems underground, whereas such compromises might prove hazardous and nonproductive where overburden ranges in thickness from 500 to more than 1,000 feet (152 – 305 m).

For example, room-and-pillar mine workings might be developed in a single coal bed beneath shallow overburden; then the pillar ribs could be uniformly sheared off in a multistage extraction sequence until a large percentage of the coal is extracted without damage to the overburden or surface. This is done locally in Japan, in areas where living space and energy are in an equally short supply. More than 90 percent of a coal bed was extracted by this method. The harmonic method of extraction also is used locally in multiple-bed mining (Kaneshige, 1971; fig. 6).

Beneath deep overburden, however, the bump and roof-fall problems could be very severe if more than two or three rooms were developed ahead of extraction or if harmonic mining procedures deviated from a rigid time and tonnage schedule; consequently, uneven mining procedures locally may be inevitable during the extraction phase unless partial extraction is planned.

A uniform partial extraction procedure with a secondary recovery procedure was recently successfully implemented in the Bear mine, Somerset district, according to W. A. Bear, Bear Coal Co. (oral commun., 1974). Mining officials of the U.S. Geological Survey initially proposed that rooms and crosscuts be driven 16 feet (4.9 m) wide on 50-foot (15.2 m) and 60-foot (18.3 m) centers, respectively, in a block of coal in the "C" coal bed in order to minimize stress effects to the underlying "B" coal bed, which was controlled by another company. Scientific counsel for the company controlling the "B" bed proposed an alternative procedure wherein rooms 16 feet (4.9 m) wide would be developed on 84-foot (25.6 m) centers to prohibit the possibility of a squeeze. Then a 10-foot (3.05 m) slab of coal would be cut off two adjacent sides of each mine pillar on the retreat, thereby widening all mine openings to 26 feet (7.93 m) and, at the same time, reducing all pillars to 58 by 58 feet (17.7 x 17.7 m) (C. T. Holland, oral commun., 1971). This procedure, which was subsequently approved by mining officials of the U.S. Geological Survey, leaves uniform support pillars that diffuse overburden stresses and minimize stress effects to another coal bed, while at the same time yielding a reasonably high percentage (50 percent) for multiple-bed coal mining.

A new modified longwall mining procedure is under development by Eastern Associated Coal Corp. (R. W. Thomas, vice president in charge of mine planning, oral commun., 1973) in one of their mines where changing geologic conditions make conventional longwall mining unsuitable. Basically, the procedure involves using a continuous miner to cut a longwall face 150 – 300 feet (45.7 - 91.5 m) long beneath self-advancing, cantilevered, hydraulic roof-support machines. This method takes advantage of both the safety, economy, and productivity of the longwall method and the ability of the continuous mining machine to adapt to varying coal thicknesses and other changing geologic conditions. Using this procedure, the chain pillars probably can be mined in sequence with the longwall face advance, making it possible to produce a uniform final mine geometry. Of course, a decision must be made as to whether complete extraction is feasible and is in accordance with applicable mining laws in a particular mining area before this procedure is implemented.

Subsidence rupture can be damaging to mining operations as well as to the overburden and surface environment. In some cases, particularly in sparsely settled areas, coal mines may be threatened more than the surface environment by subsidence rupture because of the threat of the sudden intrusion of methane gas or large volumes of water. This is particularly true in geologic environments where water and methane are abundant. Mining companies should, therefore, balance production with ongoing research on subsidence and other types of mine deformation for their own benefit as well as in the interests of conserving coal and protecting the environment. Accurate structural and lithologic maps with overlays showing mine workings and overburden configuration relative to the coal bed or beds will prove very useful in planning new mines or expanding existing ones. Periodic subsidence measurements designed to determine subsidence parameters, such as limit angle, break angle, and transient and stable compression-arch configurations, can yield subsidence parameters, which in turn can help identify areas of potential stress concentrations and attendant deformations that might occur near or within the mine workings. This information, in turn, could produce tangible returns in extraction efficiency and mine safety.

It is evident that mine safety and efficiency and the effects of mining on the physical environment are interlocked with subsidence and other facets of mine deformation, such as roof falls, bumps, and squeezes. It also follows that mine design should be based not only on expected subsidence damage above a retreating room-and-pillar line or longwall face, as Ropski and Lama (1973, p. 109 – 118) recognized, but also on subsidence effects above barriers, solid-coal mine boundaries, and any other uneven geometry called for in the mining plans. In the case of multiple-bed coal mining, the overall success, in terms of mine safety, coal extraction ratios, and environmental protection, must be measured by the overall success of the multiple-bed mining operation, rather than by the overall successes of mining one bed. It also is evident that knowledge of overburden thickness, geology, and the environment are particularly critical to planning a multiple-bed mining operation that will produce a maximum amount of coal with a minimum risk to life and property.

The sequence of mining coal beds also is very important because of the possibility of causing stress concentrations. Stresses produced in the strata by mining a coal bed will affect any coal beds present in overburden and, to a lesser but important extent, in the subjacent strata. A sequence of mining beds from top to bottom normally is safer and more efficient, paricularly if the final geometry is uniform so that stresses are not concentrated in isolated pillars and barriers and manifested downward to underlying coal beds; however, if the stratigraphic interval between two coal beds is generally 25 – 50 feet (7.62 – 15.24 m) thick, concurrent, partial, uniform extraction of both beds may be the safest and most efficient method. Also, a sequence of mining from bottom to top might be less hazardous and more productive in certain areas where water or methane is abundant because mine voids in upper beds may store large amounts of water or methane that could later be a hazard to life and property if tapped by subsidence fractures induced by mining in lower beds. In short, the safest and most efficient method and sequence of mining depends on all the geologic and environmental factors present in the area.

CONCLUSIONS

Analysis of subsidence processes and their effects upon underground coal mining lends a new perspective to the effects of mining on safety, conservation of coal resources, and protection of the ground surface above mine workings. The studies show that the mine workings, the strata above and beneath the mine workings, and the ground surface form a delicately balanced system of often irreversible causes and effects that can be seriously affected by subsidence. The excavation of underground mine workings can set in motion an interrelated chain of environmental and mining problems that can not only affect the manmade and natural elements of the environment but also threaten the mining operation. The studies clearly reveal that the geology of the coal beds and overburden strata in a proposed mining area should be accurately known in advance of mine planning so that the mine can be designed in harmony with the physical surroundings. Such an approach is highly desirable in planning mines in one coal bed, but it is vital in multiple-bed mine planning if hazards to life, property, and the environment are to be reduced to a minimum.

One of the key aspects of mine planning is to weigh the various mining, geologic, and environmental factors in order to insure that the balance between coal recovery and subsidence effects is responsive to current and future needs for both coal resources and protection of the environment in the area. It should be recognized that a timelag of months or even years probably will occur between the following events: (1) recognizing the need for subsidence research, (2) implementing and performing subsidence research, and (3) applying the results of research studies to subsidence control and formulating subsidence-control legislation. Subsidence-control regulations should be flexible enough to change as national needs change.

Historically, mining legislation has been inflexible to changing demands for coal production and environmental protection. For example, if the land surfaces were more valuable than underlying coal deposits at the time subsidence control legislation was enacted, the requirements for preservation of the land surface normally would be more stringent than requirements for protecting underlying coal resources. It is clear, from recent energy shortages, that provisions for flexibility should be written into future mining regulations so that we can maintain a judicious blend of coal-extraction efficiency, mine safety, and environmental protection, as the changing times require.

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☆ U.S. Government Printing Office: 1977-779-591