# Strata Interactions in Multiple-Seam Mining—Two Case Studies in Pennsylvania

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**UNITED STATES DEPARTMENT OF THE INTERIOR**

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| ft | foot | psig | pound per square inch, gauge |
| in | inch | psi/ft | pound per square inch per foot |
| pct | percent | st | short ton |
| psi | pound per square inch | µin/in | microinch per inch |

# STRATA INTERACTIONS IN MULTIPLE-SEAM MINING—
# TWO CASE STUDIES IN PENNSYLVANIA

By Gregory J. Chekan,[1] Rudy J. Matetic,[1] and James A. Galek[2]

ABSTRACT

The Bureau of Mines, in an effort to improve planning and development in coal mining, is investigating strata interactions associated with mining of multiple coalbeds. Two common interactions that occur between adjacent coalbeds are subsidence and pillar load transfer. The study described involves underground observations and measurements conducted at two Pennsylvania mines, each affected by one of these interactions. At the mine affected by subsidence, measurements show that undermining had little effect on upper mine pillar stability, but had a more severe effect on the development and maintenance of entries. Roof-to-floor measurements recorded over four times more convergence in entries developed over gob as compared with entries developed over support pillars in the lower mine. At the mine affected by pillar load transfer, initial in situ measurements have shown the existence of a pressure arch in the lower workings. Prior research has shown that arch interaction between two adjacent openings can create stress concentrations in the innerburden. Underground measurements and results obtained from both mine sites correlate with theoretical and photoelastic multiple-seam models, and eventually these field data will serve to refine model accuracy. Further study of multiple-seam interaction mechanisms will lead to improved mine planning, increased resource conservation, and a safer working environment.

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## INTRODUCTION

The simultaneous mining of adjacent coalbeds or mining over or under a previously mined-out coalbed occurs frequently in the Appalachian Region of the Eastern United States. In West Virginia, Pennsylvania, and Ohio, it is estimated that 57 billion tons of coal exists in a multiple-seam configuration. West Virginia alone has over 50 minable seams (1).[3] In the past, mining sequence was based primarily on availability and economics with little regard to the effects mining would have on coalbeds above and below the one being mined. This has strong implications for resource conservation, especially if these practices continue. Problems that result from strata interactions could render these resources unminable unless methodologies and techniques are developed that minimize interaction affects.

Many researchers have documented the underground problems and strata interactions associated with the mining of multiple coalbeds. Several attempts have been made to define the variables and mechanisms that control these interactions. Stemple (2) conducted the first extensive study of multiple-seam mining in the Appalachian coalfields. He recognized innerburden thickness and physical characteristics as significant factors in the interaction mechanism. His case studies showed that strong competent stratas, such as sandstone in the innerburden, tended to dampen the effects of seam interaction. He also realized the importance of arching principles in the transfer of stress. Dunham (3) attempted to define the principle factors controlling static interactions (4) or stress field induced by old or current workings. He developed a mathematical model using linear regression analysis and convergence data collected from multiple-seam longwall operations in the United Kingdom. His research showed a significant correlation between pillar geometry and ground stability in lower operations. He concluded that the model was a practical approach for predicting interaction effects, but more field data were needed to refine the model. He recommended that similar research be conducted to improve the accuracy of prediction.

Interaction effects have been studied (5-7) using photoelastic models and finite-element analysis. The research led to a better understanding of the interaction mechanisms as well as the variables that influence stress transfer. The investigators classified the variables as either mining or fixed. The fixed variables, in order of importance, include innerburden thickness and physical characteristics, seam depth, seam thickness, stress fields, and coal characteristics. The mining variables, in order of importance, include pillar dimensions and geometries, spatial location of entries, mining method, and mining height. These variables control the interaction mechanism and thus determine the magnitude of stress transfer and its effects on adjacent workings.

Few attempts have been made to verify these interaction mechanisms in situ and their influence on mine ground stability through underground convergence and stress measurement. The Bureau of Mines conducted these studies to develop a better understanding of subsidence and pillar load transfer and its effects on current workings. Eventually, this knowledge will lead to improvements in mine planning and development.

## PILLAR LOAD TRANSFER

Pillar load transfer involves the redistribution of stress between pillars in adjacent workings. This interaction occurs particularly when coalbeds are in close proximity, less than 110 ft (2, 5, 7), and either isolated, remnant pillars (barriers) or many strong, competent pillars are present in the upper workings. This condition may serve to concentrate stresses in the innerburden

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[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

causing ground instability in the upper and the lower workings. The mechanics of load transfer and distribution between adjacent operations have been analyzed extensively by other researchers through the use of mathematical and photoelastic models. Two theories have been developed to explain ground disturbances due to load transfers from adjacent workings-- "pressure bulb" theory and "arching" theory.

Pressure bulb theory (7, 9) assumes that the pillar is the major structural element in the transfer of load. In an analysis developed by Peng and Chandra (8), the pillars are columnized and the weight of the vertical load is uniformly distributed and equally shared by neighboring pillars [tributary area method (9)] as shown in figure 1. The contour lines of pressure resemble bulbs and are present above and below the pillars in both coalbeds. Highest pressure occurs near the bottom and top of the pillar, decreasing vertically to zero influence at a distance approximately four times the pillar width. The vertical pressure experienced at any point in the innerburden is the sum of the two contour lines, but, due to pillar superpositioning, this
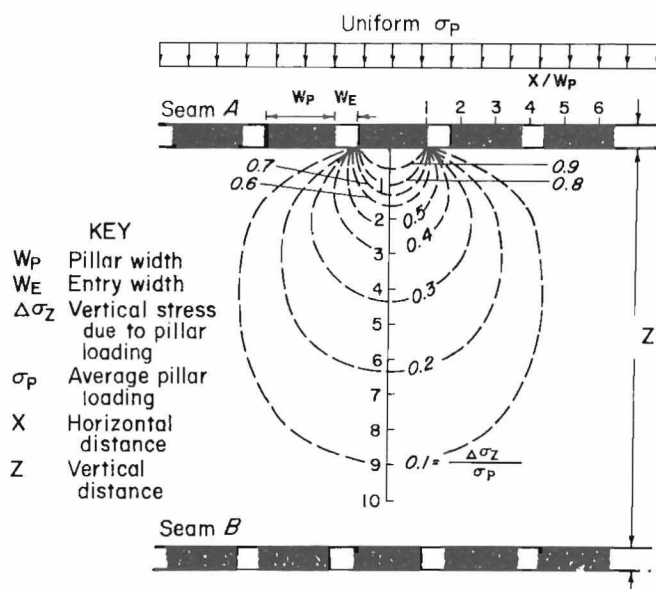
analysis is also extended to include additional pressure from neighboring pillars. The distribution of this vertical uniform loading was analyzed for an isotropic, homogeneous, and perfectly elastic medium.

Haycocks (7-9) further investigated the pressure bulb concept through the use of photoelastic models. The models simulated load transfer and dissipation as a function of three major variables. Pillar geometry and loading, innerburden layering (stratification), and innerburden elastic modulus. Load distribution on model pillars of varied widths ranged from uniformly loaded stressforms to several types of peak-trough loaded stressforms. Innerburden stratigraphy was simulated using layered materials of varied thickness and elastic properties. The following is a summary of the findings:

1. The distribution of load on a pillar affects both the distance and magnitude of the load transfer.

2. Peak-trough loaded stressforms dissipated stress faster and with less influence than did uniformly loaded stressforms.

3. High modulus layering of the innerburden, such as sandstones, tend to inhibit pressure bulb formation while low modulus layering, such as shales, increases vertical and horizontal transfer distances from overlying pillars.

Haycocks concluded that pressure bulb theory is useful in analyzing pillar load transfer when a "passive" interaction occurs. This condition can apply when pillars are columnized and lower seam pillars are sufficiently large to prevent from yielding.

Arching theory assumes that the mine opening is the major structural element in the transfer of load. Load transfer is the result of the pressure arch (9-10) that forms around a mine opening upon excavation. The arch is eliptical and exists above and below the mine opening. As shown in figure 2 (11), it consists of "intradosal ground" (tension zone) enveloped by an "extradosal ground" (compression zone). The pillars support the extradosal ground, which is known as the abutment pressure. The magnitude of the



FIGURE 1.—Simplified model of pressure interaction between columnized pillars. Adapted from Peng and Chandra (8).

4

abutment pressure and the shape and height of the arch is dependent upon the depth, the opening width, and the physical nature of the strata. As shown in figure 3, independent arches can form from pillar to pillar provided their strength in situ exceeds that of the abutment pressure. If the pillars yield or fail due to excessive pressure, their load is transferred to neighboring barriers or abutment pillars and a secondary arch may form, as shown in figure 4 (9-10).

Haycocks (5, 7) studied the effect of arching in multiple-seam configurations



FIGURE 2.—Pressure arch around mine opening. Adapted from Dinsdale (11).
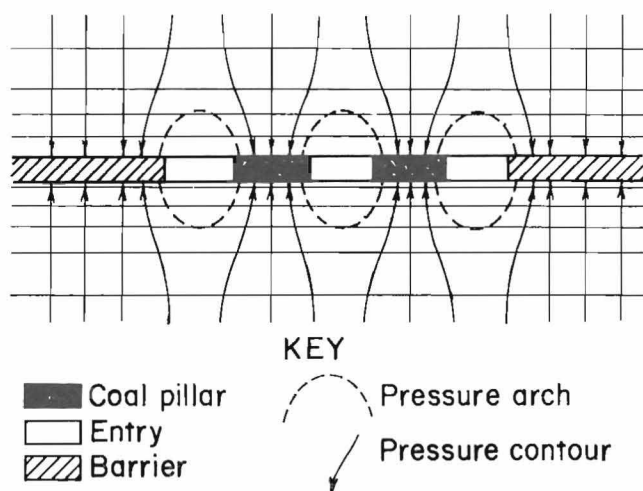


FIGURE 3.—Independent pressure arches forming from pillar to pillar.

using finite-element and stress-vector plots. The models showed that when openings were narrow and in close proximity, the pressure arches interacted, resulting in abnormally high lateral stress and abutment pressures in the innerburden. In addition, for large openings, the pressure arches were less likely to interact, but instead form a destressed zone in the innerburden. In actual mine conditions, this can occur when the panel pillars yield and redistribute their load to larger abutments or barriers. Pillar yielding in the lower workings enables the panel to act as a single, large opening. This creates a destressed zone in the innerburden provided the workings are in close proximity and columnized. Haycocks refers to this change in lower seam loading as a "reactive" interaction, which can be analyzed through the use of arching principles.

CASE STUDY--INDIANA COUNTY, PA

Mine Location and Geology

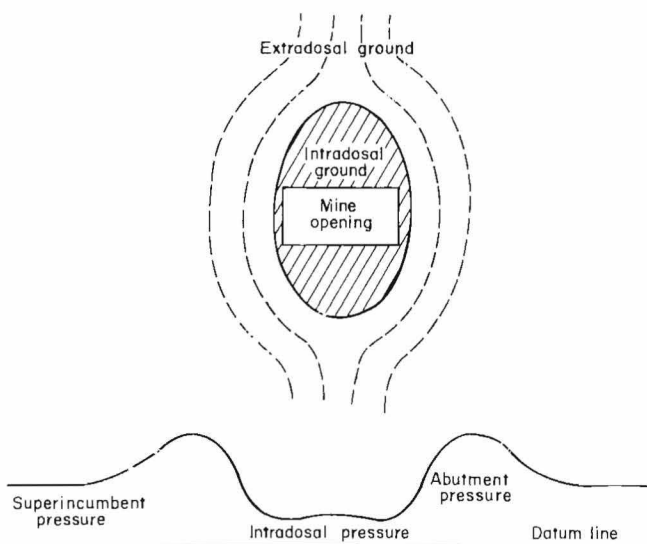The mine studied is located in Indiana County, PA (fig. 5). The study involves
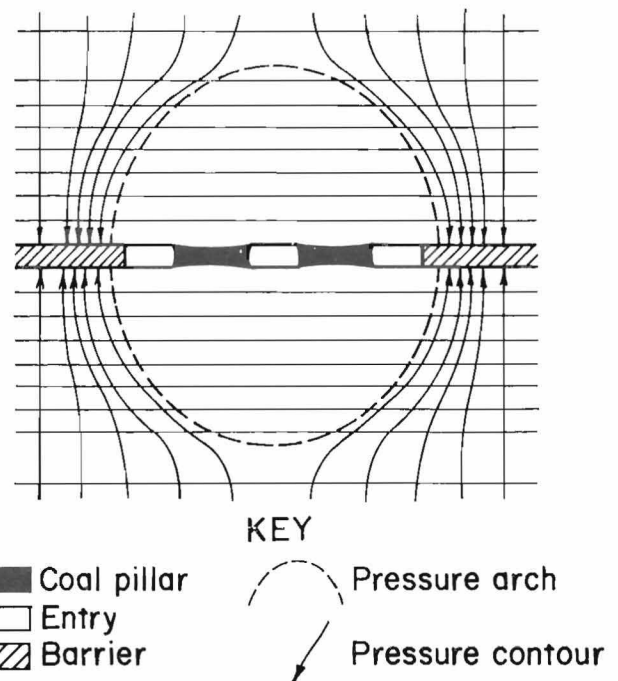


FIGURE 4.—Secondary pressure arch forming on larger barriers after panel pillars have yielded.
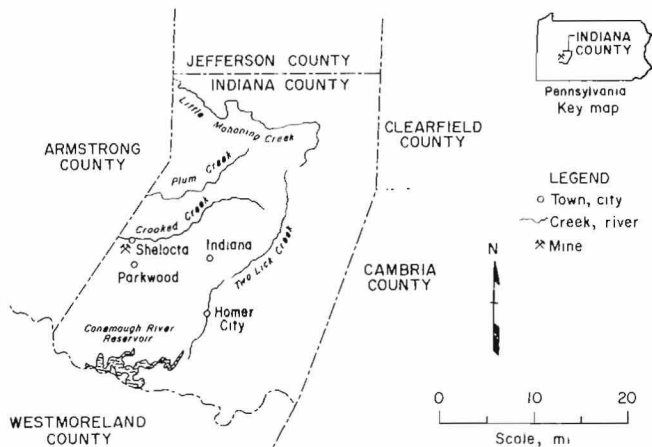
FIGURE 5.—Location of mine in Indiana County, PA.



FIGURE 6.—Generalized stratigraphic column.

the Upper and Lower Freeport Coalbeds, which are mined simultaneously. A generalized stratigraphic column of the study areas (4 East and 1 Left) is shown in figure 6. The overburden above the Upper Freeport Coalbed ranges from 370 to 430 ft and consists predominantly of interbedded shale and sandstone. The innerburden is approximately 65 ft thick and consists of interbedded shale.

The average height of the Upper Freeport Coalbed ("upper mine") is 42 in. The immediate roof is composed of dark-gray shale 10 to 20 ft thick. The immediate floor is composed of 5 to 10 ft of dark-gray fire clay underlain by gray sandy shale. The average height of the Lower Freeport Coalbed ("lower mine") is 52 to 54 in. The immediate roof is composed of 5 to 10 ft of black shale overlain by dark-gray shale. The immediate floor is composed of 5 to 6 ft of light-gray fire clay underlain by gray sandy shale.

Table 1 presents additional site-specific information for the upper and lower mines, where room-and-pillar continuous mining was performed.

Instrumentation and Results

Site 1--4 East

Site 1 was in the 4 East section of the lower mine approximately 150 ft from a large area (1,000 by 1,200 ft) that had been severely affected by the load transfer from overlying pillars, as shown in figure 7. According to the mining plan, the lower seam pillars were developed in advance of the upper seam pillars. Soon after upper pillar development was completed, the panel developments adjacent to the 4 East section in the lower mine

TABLE 1. – Site-specific information for Freeport Coalbeds

|  | Upper mine | Lower mine |
|---|---|---|
| Av. mining height......in.. | 38–42 | 54–60 |
| Pillar centers.........ft.. | 45 ×50 | 45 ×60 |
| Av. entry width.......ft.. | 17–19 | 16–18 |
| Av. extraction........pct.. | 55–60 | 50–55 |
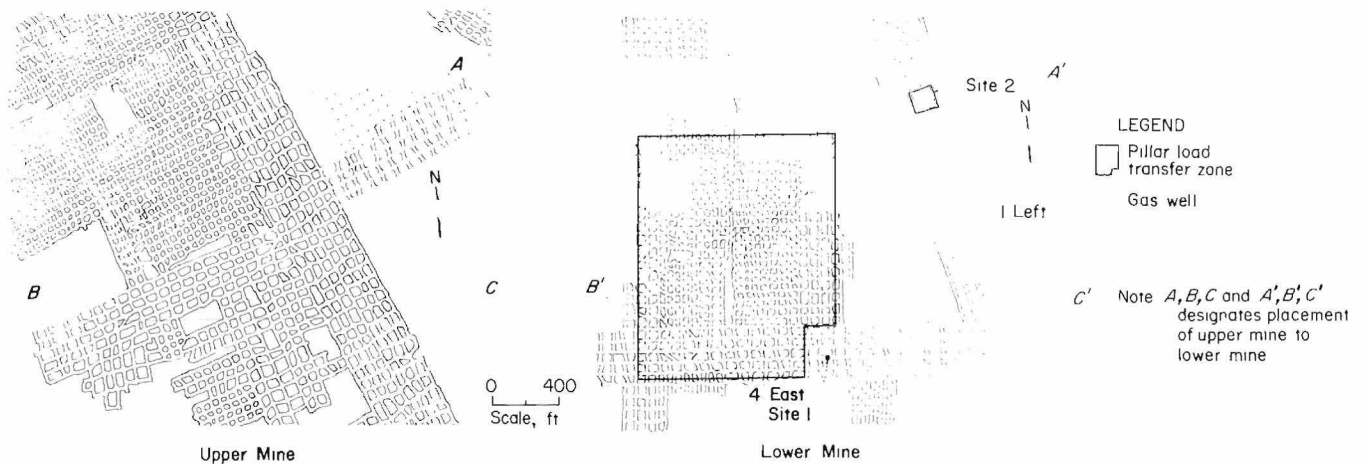
FIGURE 7.—Location of sites 1 and 2 in lower mine and upper mine versus lower mine pillar arrangements.

began to exhibit severe floor heaving and eventual pillar crushing and failure. Within several months, ground movement propagated toward the 4 East section threatening the track-belt entry. Figure 7 shows upper mine pillar versus lower mine pillar arrangement. Pillar geometry was random since superpositioning was not part of the mining plan.

At site 1, located in the lower mine, in situ stress measurements were conducted in the roof strata using a strain gauge cell to determine if a high horizontal stress was present due to pressure arch interaction in the innerburden. The cell is designed primarily to measure the direction and magnitude of the secondary principle stresses. This method involves an overcoring technique of stress relief in which a 3-in-diam corehole is drilled to the point where the in situ stress is to be measured. The cell is then glued to the surface of the corehole and allowed to dry. The cell is then overcored to relieve the stress on the surface to which the cell is attached. The core is then broken off at the end of the hole and the stress relieved strain readings recorded.

Figure 8 shows the type of roof rock encountered during the coring procedure and the depths at which five measurements were performed. Due to support equipment failures, attempts to derive in situ stress values from strain values
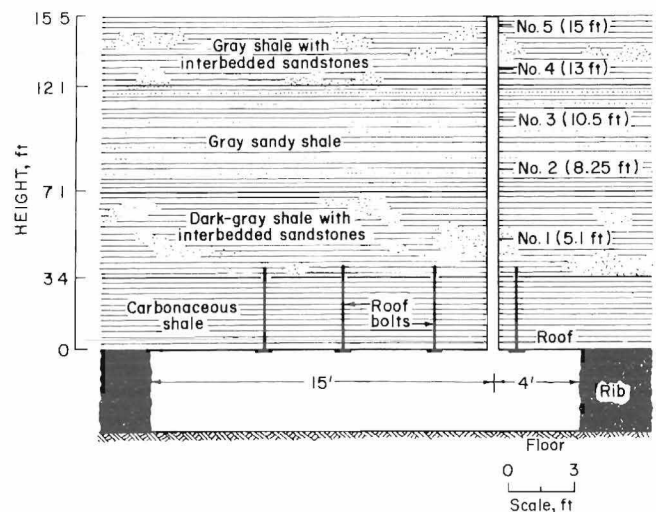


FIGURE 8.—Roof stratigraphy and depths of in situ measurements at site 1 in lower mine.

were unsuccessful. Reduction of data from strain measurements is summarized in table 2 and shows a tensile strain zone (from 5 to 10.5 ft in the roof), followed by a compressive strain zone (13 to 15 ft in the roof). These strain data correlate with intradosal and extradosal zones, which characterize the pressure arch above a mine opening. Although the magnitudes of the associated stress could not be determined, this is evidence of a pressure arch forming from pillar to pillar, as would be the case for strong, competent pillars that do not yield, as shown in figure 3.

TABLE 2. -- Measured strain values

| Measurement | Depth, ft | Measured strain, µin/in | | | Measurement | Depth, ft | Measured strain, µin/in | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $\Delta e_H$ | $\Delta e_V$ | $\Delta e_{45}$ | | | $\Delta e_H$ | $\Delta e_V$ | $\Delta e_{45}$ |
| 1............... | 5.1 | +33 | +121 | +62 | 4............... | 13.0 | -192 | +164 | -208 |
| 2............... | 8.25 | +50 | +270 | 0 | 5............... | 15.0 | -249 | -3 | -152 |
| 3............... | 10.5 | +439 | +230 | +419 | | | | | |

NOTE.--$\Delta e_H$ = change in horizontal strain;
$\Delta e_V$ = change in vertical strain;
$\Delta e_{45}$ = change in strain 45° from horizontal;
+ = denotes tensile strain;
- = denotes compressive strain.

## Site 2--1 Left

Site 2 was located in the 1 Left section of the lower mine (fig. 7). It was anticipated that future pillar development, directly superjacent, in the upper mine would cause problems similar to those experienced in other areas of the mine. Pillars were not superimposed; figure 7 shows upper mine pillar projections versus lower mine pillar arrangements.

To determine if overmining would transfer load to the underlying operations, an instrument array consisting of six borehole platened flatjacks (BPF) (12) and eight convergence stations were installed in selected pillars and entries (fig. 9). BPF's are used to measure pressure changes within the coal pillars. Installation involves drilling a 2-in-diam borehole to the desired depth and inflating a flatjack with a handheld hydraulic pump. BPF's are calibrated in the laboratory and are installed in pillars at a setting pressure equal to the estimated pressure exerted by the overburden using the tributary area method.[4] Setting pressure for each BPF was 900 psig because overburden was approximately 420 ft with a 0.50 extraction ratio. The six BPF's were oriented to measure vertical changes in pillar pressure. Two BPF's were installed per pillar at depths of 25 ft and 10 ft to measure differences in loading between the core of the pillar and its outer perimeter (or skin). Eight convergence stations were installed to measure convergence from the roof to floor surface. Two reference pins were anchored 3 in deep to roof and floor, and subsequent convergence was measured with a removable tube extensometer.

Pillar development in the upper mine was directly superjacent to the instrument array 62 days after installation. Analysis of BPF and convergence data for 329 days indicates that, although some load transfer was detected, overmining had no appreciable affect on ground
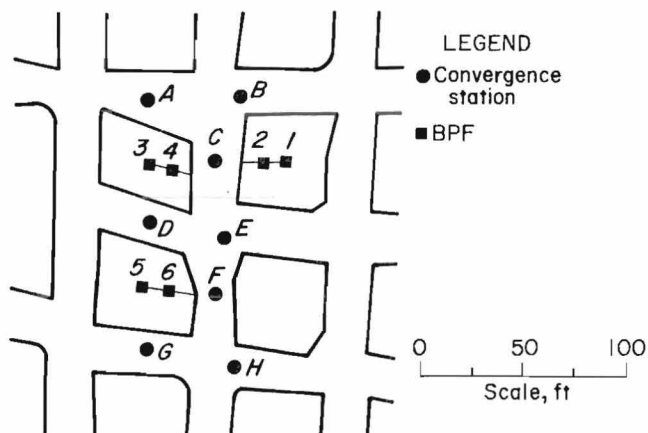


FIGURE 9.—Instrument array showing BPF and convergence stations at site 2 in 1 Left of lower mine.

[4]Estimated pressure, psi = 1.1 psi/ft

(d) $\dfrac{1}{(1-R)}$,

where d = depth, ft;

and R = extraction ratio.

TABLE 3. - Convergence data, inches

| Days | Station | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H |
| 0...... | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 28...... | .085 | .063 | .207 | .016 | .099 | .101 | .235 | .095 |
| 42...... | .145 | .126 | .230 | .077 | .100 | .270 | .318 | .208 |
| 49...... | .145 | .126 | .246 | .093 | .107 | .280 | .360 | .247 |
| 62...... | .145 | .179 | .273 | .096 | .129 | .306 | .425 | .285 |
| 77...... | .145 | .221 | .326 | .145 | .160 | .392 | .490 | .351 |
| 91...... | .145 | .263 | .380 | .165 | .174 | .471 | .574 | .421 |
| 126...... | .261 | .356 | .451 | .253 | .205 | .479 | .693 | .528 |
| 161...... | .295 | .424 | .542 | .318 | .244 | .562 | .820 | .657 |
| 203...... | .343 | .464 | .597 | .325 | .274 | .581 | .882 | .714 |
| 217...... | .351 | .480 | .597 | .340 | .305 | .586 | .897 | .757 |
| 329...... | .421 | .536 | .677 | .368 | .348 | .623 | .929 | .789 |

TABLE 4. - BPF data, pounds per square inch, gauge

| Days | BPF location No. | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 0........ | 900 | 900 | 900 | 900 | 900 | 900 |
| 28........ | 850 | 800 | 800 | 750 | 800 | 800 |
| 42........ | 825 | 800 | 750 | 750 | 800 | 800 |
| 49........ | 825 | 800 | 750 | 800 | 800 | 800 |
| 62........ | 850 | 825 | 800 | 800 | 850 | 825 |
| 77........ | 850 | 850 | 850 | 800 | 850 | 825 |
| 91........ | 900 | 850 | 875 | 825 | 850 | 825 |
| 126........ | 900 | 875 | 875 | 825 | 875 | 825 |
| 161........ | 900 | 875 | 875 | 825 | 875 | 825 |
| 203........ | 925 | 875 | 875 | 825 | 875 | 825 |
| 217........ | 925 | 875 | 900 | 825 | 900 | 850 |
| 329........ | 925 | 900 | 900 | 825 | 900 | 850 |

stability in the lower mine. Convergence and BPF data accumulated during this period are shown in tables 3 and 4, respectively. BPF's 1, 2, and 3, installed at the core, recorded slightly more increase in pressure than did BPF's 2, 4, and 6, installed at the skin. Figure 10, which plots the pressure readings for BPF's 1, 3, and 5, shows that equilibrium pressure was reached approximately 50 days after installation. Moderate increases in core pressure were detected when overmining was superjacent, but this pressure gradually stabilized. Increases in pillar pressure averaged 100 psig for the BPF array during this period. Roof-to-floor convergence ranges from 0.348 in recorded at station E to

0.929 in recorded at station G. Graphs of the four stations recording the most convergence are shown in figure 11. Again, these graphs show increased convergence when overmining was directly superjacent, but afterward convergence
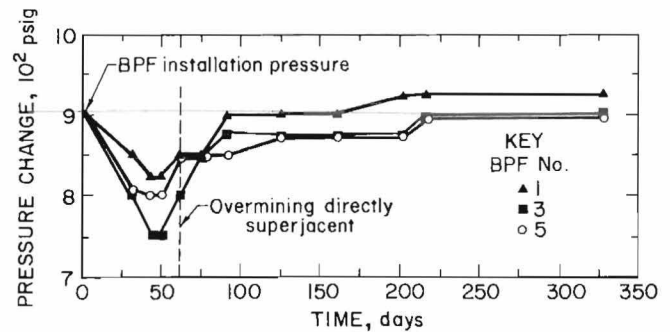


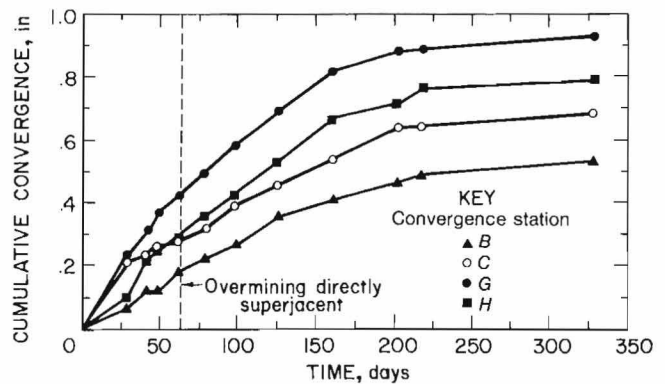FIGURE 10.—Pressure changes recorded for BPF's 1, 3, and 5 for 329 days.



FIGURE 11.—Cumulative convergence at stations B, C, G, and H for 329 days.

gradually stabilizes. Roof-to-floor convergence has averaged 0.586 in for the entire eight-station array during this period.

## CONCLUSIONS ON PILLAR LOAD TRANSFER

The tensile and compressive strain zones measured in the roof strata at site 1 correlate well with pressure arches that are predicted to exist around a mine opening. As discussed earlier, laboratory modeling of multiple openings in close proximity has shown that pressure arch interaction can create zones of excessive stress in the innerburden. This is especially the case for strong, competent pillars that do not yield readily, allowing independent arches to form from pillar to pillar. Results indicate that arch interaction between upper and lower workings is the primary mechanism in the load transfer at this particular study site. When high abutment pressures associated with arch interaction exceed the in situ strength of the rock, ground failure results. In this case, a soft floor strata is the weakest member in the mine structure. Strong competent pillars punching into the floor cause considerable floor heave, as shown in figure 12, which is then followed by eventual pillar failure. When this occurs, their load is transferred to neighboring pillars, forming a secondary arch. This cycle of failure, load transfer and arch formation, continues until sufficient support is encountered to stabilize the load-transfer process such as barriers or abutment pillars.

At site 2, overmining caused no excessive pillar loading or entry deformation in the lower workings. This may be due to large barriers flanking both sides of the 1 Left panel, as shown in figure 7. These barriers may offer immediate support to the load transfer mechanism.

Based on research conducted at this particular site, the following conclusions were reached:



FIGURE 12.—Floor heaving in lower mine near site 1.

1.  Independent arch formation due to pillars that do not yield readily may cause lower mine instability through arch interaction.

2.  As documented by other researchers, a shale innerburden, because of its physical nature, transfers load more readily and may contribute to arch formation.

3.  Barriers or abutment pillars can offer immediate bearing support to pressure arch formation.

4.  Random pillar arrangement may complicate arch interaction and formation and thus contribute to lower mine instability.

## SUBSIDENCE

Strata interactions due to subsidence result when an underlying coalbed is extracted first. Undermining subjects the superjacent strata to a mining-induced stress field (4). The distribution of this stress within the strata is a function of the subsidence process and is most damaging to overlying coalbeds after the critical-to-supercritical subsidence phase has been reached (6-7, 12). Depending upon the uniformity of lower coalbed extraction, there exists a relatively destressed zone toward the middle of the subsidence area. Most ground disturbances in overlying coalbeds occur toward the boundaries of the subsidence trough. Within the trough, strata flexure creates zones of tensile and compressive stress as shown in figure 13 (13). The extent of this zone is defined by the angle of draw, which is dependent upon the geologic and physical characteristics of the strata. As mining develops through this trough, these stresses have a severe affect on entry stability, particularly on the integrity of the roof (2-7, 13-15).
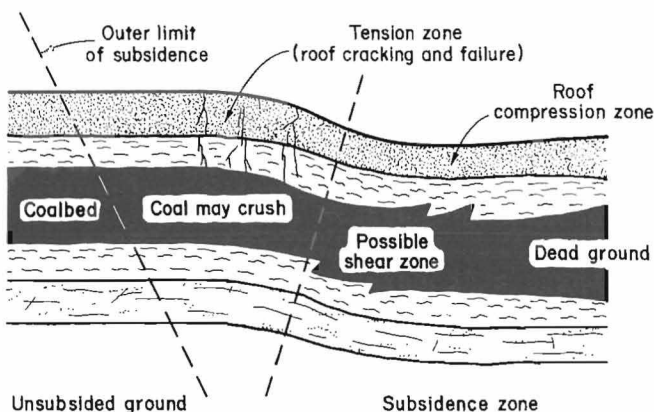
Other types of failure in upper coalbeds that are attributed to undermining include interseam shearing and the effects of arching. In interseam shearing, highly inclined shear or tensile-shear failures develop that result in displacement of the coalbed into lower excavations (6-7, 13). Recent studies (6-7) indicate that the elastic modulus of the superincumbent strata is a major factor influencing this type of failure. Studies have demonstrated that a high-modulus strata such as sandstone is more prone to shear failure. Arching is actually a subcritical phase of subsidence, and its effects on upper coalbeds is dependent upon the opening width to depth ratio and height of the resulting pressure arch. Arching effects can produce a zone of high compressive stress, which may cause pillar and roof-control problems (2, 4, 7-8, 13-15).

### CASE STUDY--GREENE COUNTY, PA

#### Mine Location and Geology

The mine studied is located in Greene County, PA, as shown in figure 14 and is operating in areas of the Sewickley Coalbed (upper mine), which were subsided by undermining of the Pittsburgh Coalbed (lower mine). A generalized stratigraphic column of the study areas (1 Left and 2 East) is shown in figure 15. The overburden above the upper mine ranges from 425 to 580 ft and consists predominantly of interbedded shale with a competent sandstone unit that varies in thickness. The innerburden ranges from 90 to 100 ft and consists of interbedded shale and limestone.

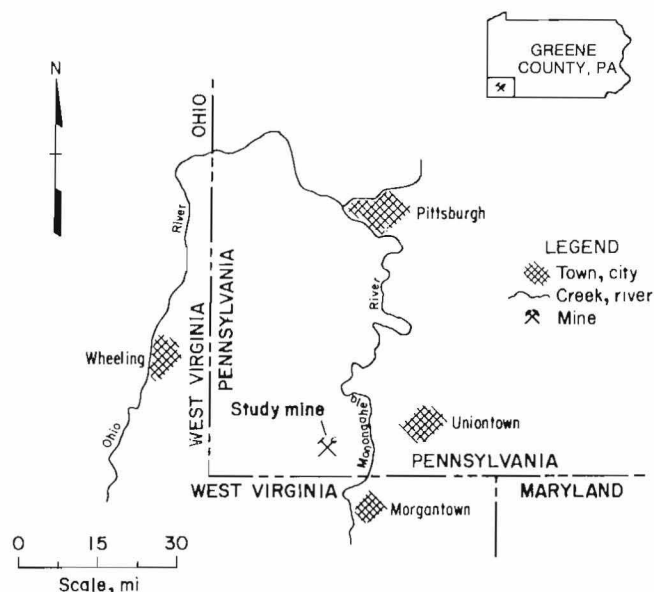The average height of the Sewickley Coalbed (upper mine) is 5 ft. The



FIGURE 13.—Strata flexure in upper coalbed due to subsidence. Adapted from Haycocks, Karmis, and Topuz (13).

FIGURE 14.—Location of study mine in Greene County, PA.



FIGURE 15.—Stratigraphic column of study area.

immediate roof is composed of a highly jointed dark sandy shale that ranges from 10 to 15 ft thick, overlain by a competent limy shale. The immediate floor is composed of a 3-ft-thick dark, limy shale underlain by a competent limestone unit. An underground geologic investigation found no geologic anomalies (clay veins, discontinuities, etc.) in the study areas. Table 5 presents additional site-specific information for the upper and lower mines where room-and-pillar continuous mining were performed.

## Instrumentation and Results

### 1 Left Panel

The 1 Left was a short 400-ft panel that was developed through a subsided

TABLE 5. – Site-specific information for Sewickley and Pittsburgh Coalbeds

|  | Upper mine | Lower mine |
|---|---|---|
| Av. mining height....in.. | 60–64 | 72 |
| Pillar centers.......ft.. | 100×100 | 100×100 |
| Av. entry width......ft.. | 18–20 | 20 |
| Extraction, pct: |  |  |
| Mains.................. |  | 36 |
| Panels................. |  | 100 |

area of the coalbed that was created by pillar retreat activities in the lower mine. The boundary of this retreat mining in the Pittsburgh Coalbed is shown as the gob line in figure 16. The 1 Left panel started in subsided ground (over gob) and developed across the gob line and onto support pillars located in the lower mine. It was developed and retreated in less than 50 days. Several years earlier, the 1 East panel crossed the gob line (from over support pillars and onto gob in the lower mine) and experienced two roof falls (as shown in figure 16) but had encountered no displacements in the coalbed. These ground conditions indicated that the strata, directly superjacent to the gob line, were flexed due to subsidence, and mine personnel were anticipating these same conditions in the 1 Left panel. Predicting

**FIGURE 16.—Location of study areas 1 Left and 2 East showing gob line in lower mine and roof-fall activity in upper mine.**
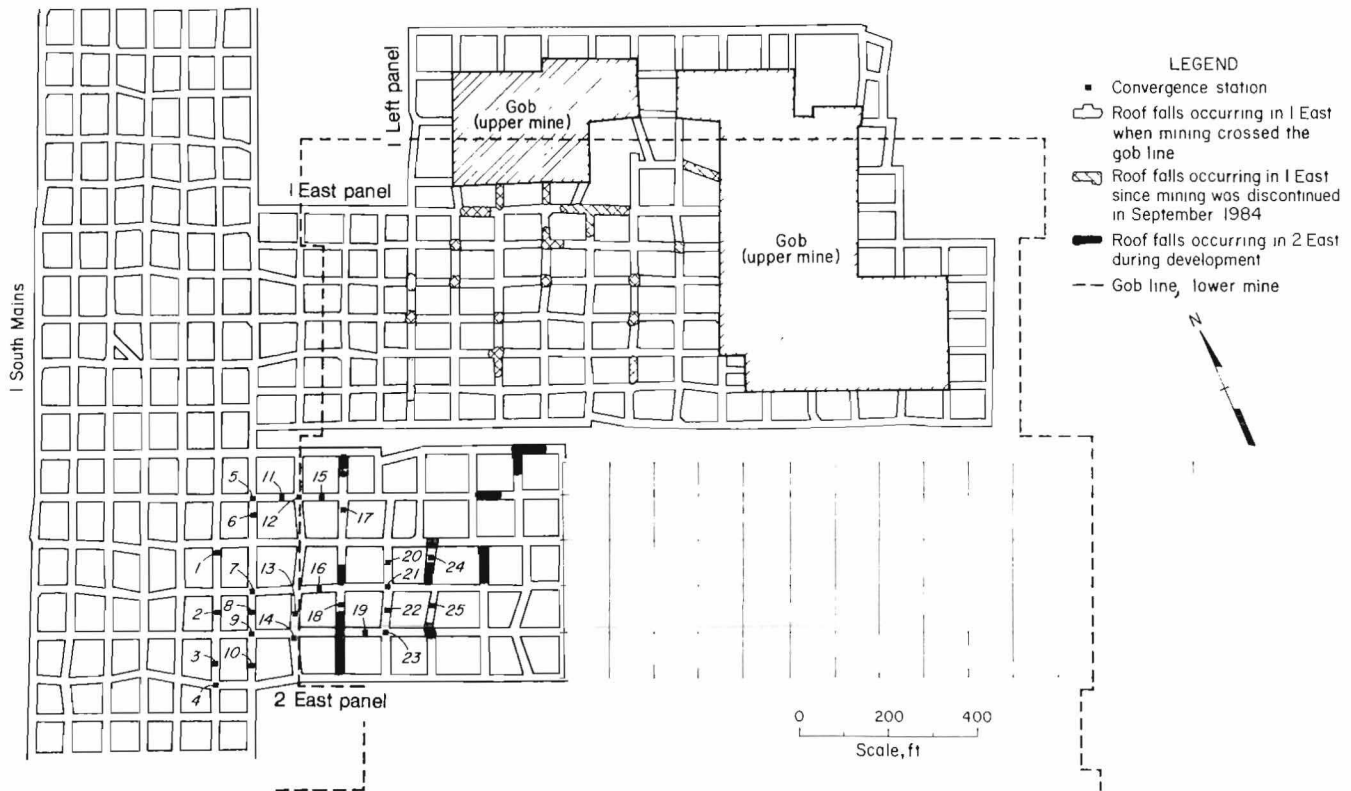
the location of the subsidence trough within the coalbed is difficult. Al- though current theories and models are based on surface subsidence, their appli- cation for predicting in-mine subsidence could prove useful. Based on a model re- cently developed by the Bureau (16-17), the edges of the subsidence trough at the Sewickley Coalbed level were calculated to be approximately 102 ft inby to 300 ft outby the gob line of the lower mine for this case. The edges of the predicted trough and pillar arrangements in 1 Left before retreat mining are shown in figure 17.

To determine if the trough affected pillar loading and stability, four BPF's were installed during development to mea- sure vertical changes in pillar pres- sure. Setting pressure[5] was approximate- ly 1,000 psig for each BPF as overburden was 580 ft with an extraction ratio of 0.36.

Figure 17 shows BPF location in se- lected pillars. The instruments recorded no increases in pillar pressure during development. The major ground problem encountered within the trough during de- velopment was the occurrence of a large roof fall, 10 to 12 ft high, over gob (fig. 17). This fall started in a cross- cut at the face and eventually propagated into the belt entry causing considerable production delays.

BPF pressure increased, as antici- pated, when retreat mining approached the instrumented pillars. The graph in figure 18 shows the pressure changes re- corded for the four BPF's during devel- opment and retreat mining. Pressure in- creases ranged from 400 to 700 psig but were not considered significant because they did not render a pillar or adjacent pillar unminable during retreat. Obser- vations of roof behavior at the face showed the roof strata to fall tight against the pillar line, causing no ex- cessive loading in adjacent pillars from
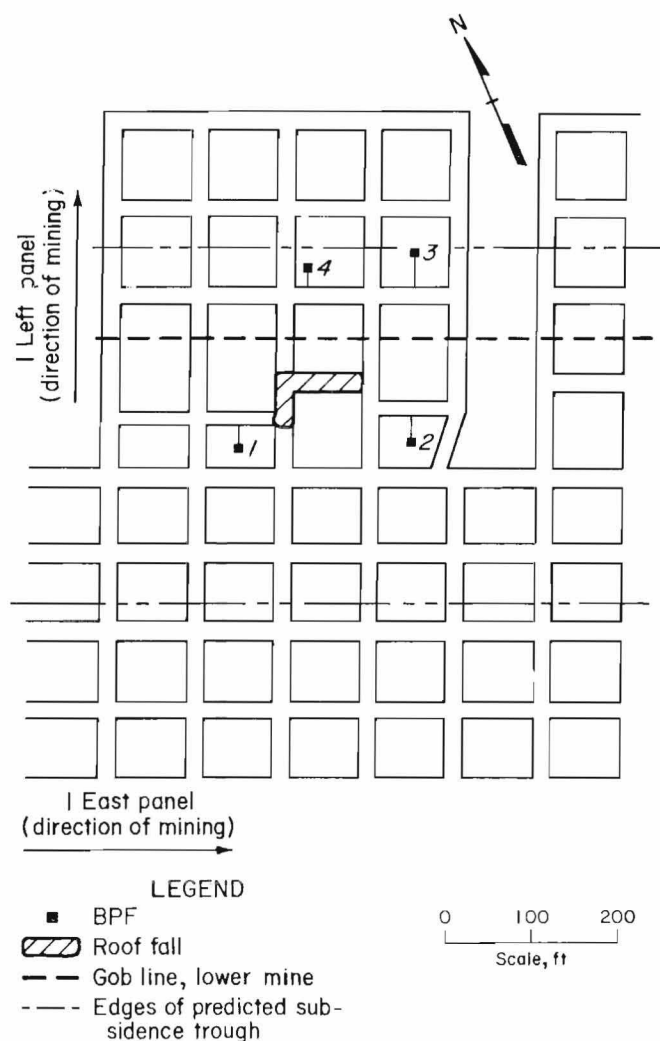
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[5]See footnote 4.

FIGURE 17.—Pillar arrangements and BPF locations in 1 Left before retreat mining.



FIGURE 18.—Pressure changes recorded for BPF's in 1 Left during development and retreat mining.

roof cantilevering. The 1 Left panel was completely retreated, but ground water inflow and accumulation slowed retreat operations in the 1 East panel. Eventually, retreat mining was discontinued in the 1 East panel due to this condition.

## 2 East Panel

2 East was a long 2,200-ft panel developed off the 1 South Mains. It started from over support pillars located in the lower mine and developed across the gob line into subsided ground as shown in figure 16. To better understand immediate ground movement as entries were developed through the subsidence trough, roof-to-floor convergence measurements
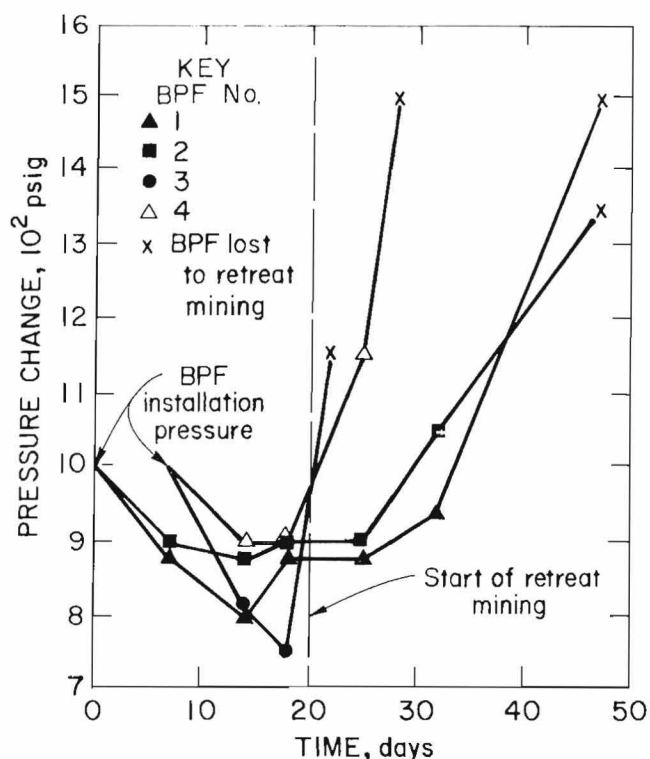
were used in the 2 East panel. A total of 25 convergence stations were installed within the trough area, 14 in entries developed over support pillars and 11 in entries developed over the gob of the lower mine. As shown in figure 16, large roof falls 10 to 12 ft high occurred over gob during pillar development, but with greater frequency than in other gob line crossings. Convergence measurements taken over 143 days showed that the average total convergence measured in entries developed over the gob was over four times the amount measured in entries developed over support pillars. Figure 19 shows cumulative convergence for stations 2, 8, and 13 installed in entries developed over support pillars and stations 18, 22, and 25 installed in entries developed over gob. This graph shows that a nearly uniform rate of convergence is occurring on both sides of the gob line, but the rate increases dramatically once the gob line is crossed. Table 6 lists cumulative convergence measured over 143 days for all stations.

TABLE 6. - Cumulative convergence measured for 143 days

| Station | Cumulative convergence, in |
|---|---|
| Entries developed over support pillars: | |
| 1...................... | 0.11 |
| 2...................... | .15 |
| 3...................... | .16 |
| 4...................... | .13 |
| 5...................... | .19 |
| 6...................... | .12 |
| 7...................... | .15 |
| 8...................... | .24 |
| 9...................... | 1.39 |
| 10..................... | .27 |
| 11..................... | .16 |
| 12..................... | .17 |
| 13..................... | .31 |
| 14..................... | .95 |
| Entries developed over gob: | |
| 15..................... | .33 |
| 16..................... | .96 |
| 17..................... | 1.11 |
| 18..................... | 1.56 |
| 19..................... | 1.50 |
| 20..................... | 2.71 |
| 21..................... | 1.46 |
| 22..................... | 1.38 |
| 23..................... | 1.38 |
| 24..................... | .73 |
| 25..................... | 1.33 |



FIGURE 19.—Cumulative convergence for stations 2, 8, 13, 18, 22, and 25 for 143 days.

## CONCLUSIONS ON SUBSIDENCE

Throughout the subsidence area, the coalbed showed no vertical displacements that would indicate an interseam shearing. Although no stress measurements were conducted to verify zones of tension and compression, it could be assumed that the recorded movements and recurring problems were a result of strata flexure. The following observations support this:

First, as mining development crossed the gob line in the 2 East panel, roof-to-floor convergence increased, as did the incidence of roof falls. Figure 20 plots ground movement and depth in relation to distance from the gob line.
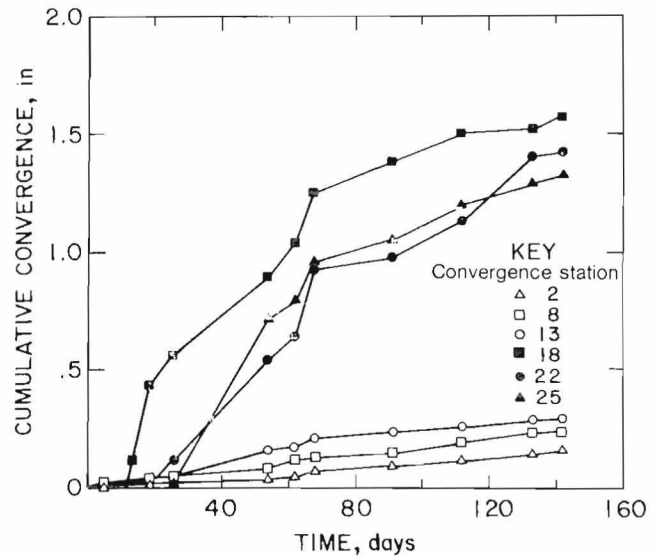
Graph A deals with overburden; graph B depicts the cumulative length of roof falls; graph C shows cumulative convergence measured over a period of 143 days for selected stations and their locations; and graph D is the predicted subsidence profile (16-17). Graph D shows that the subsidence trough begins 102 ft outby the gob line, and that subsidence reaches a maximum at 300 ft inby the gob line. Graphs B and C, which depict ground movements, correlate well with graph D because roof-to-floor convergence and frequency of roof falls increase dramatically as the gob line was crossed. Graph A shows there were no dramatic fluctuations in overburden above the panel.

Second, all roof falls in the study area occurred in entries developed over gob; no roof falls occurred in entries developed over support pillars. In addition, the roof-fall activity continued in the 1 East panel well after retreat mining operations were discontinued in September 1984, as shown in figure 16.

Finally, most roof falls displayed a similar type of roof failure, usually along a natural roof joint. As shown in figure 21, these joint surfaces were smooth, having no cohesive properties. This natural jointing system was present throughout the study area, yet as
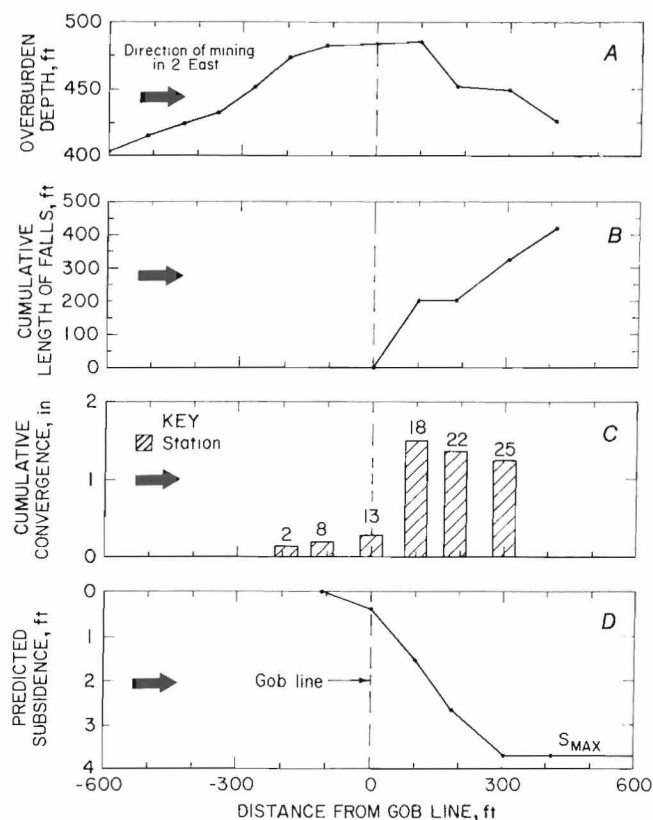
FIGURE 20.—Ground movement and depth in relation to gob line.



FIGURE 21.—Failure along roof joint.

mentioned earlier, all roof falls occurred in entries developed over gob. Presuming that the roof is in flexure, these joint surfaces would provide natural planes for tension failure. A major set of roof joints was oriented approximately N 55° W, subparallel to the direction of mining. This could further explain the phenomenon of high frequency of roof falls in intersections and entries parallel with the face.

The increase incidence of roof falls within the subsidence trough required the installation of additional roof support. Roof stability in entries developed over support pillars was readily maintained with 6-ft conventional bolts on 4-ft centers. Cribs and posts were installed as dictated by the general roof-support plan. Entries developed over the gob required more comprehensive roof support, consisting of 5-in by 7-in by 16-ft timbers bolted on 2-ft centers. In addition, many intersections along the track
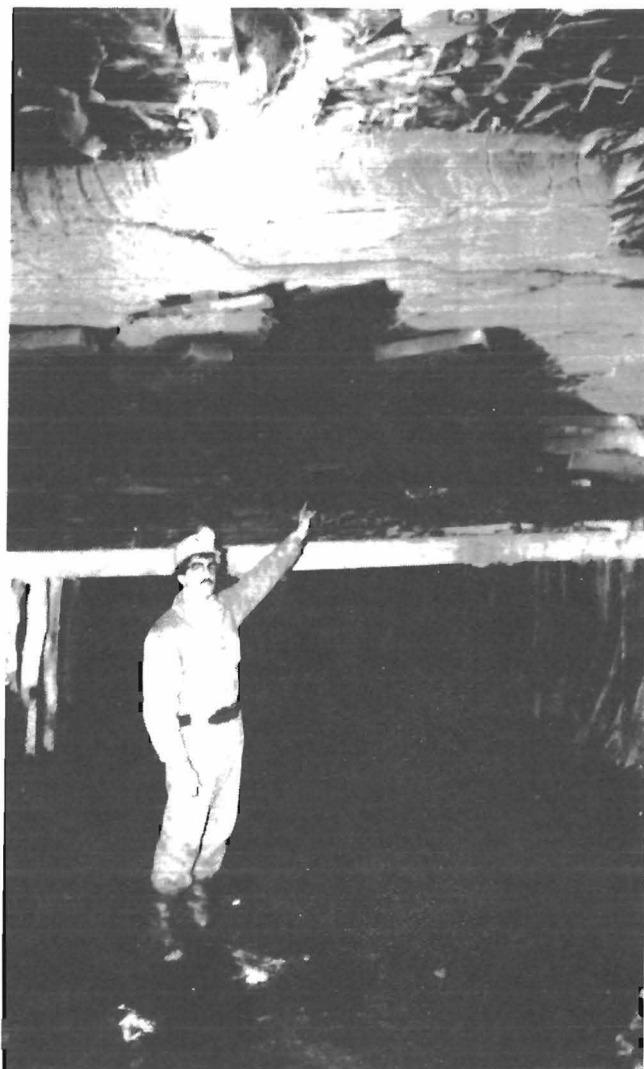
and belt entries were supported with 6-in steel I-beams set on posts or cribbing. These support requirements, combined with downtime to clean and resupport fall areas, lowered production considerably. The graph in figure 22 shows the average tonnage per shift as the 2 East panel mined through this subsidence trough versus a similar panel, 2 North, located in the same mine but not affected by subsidence. It is interesting to note that high production values for the 2 East panel are less than the low values for the 2 North panel. As mining progressed further into the subsided zone, roof conditions improved slightly and production increased, but the supplemental support was still required.
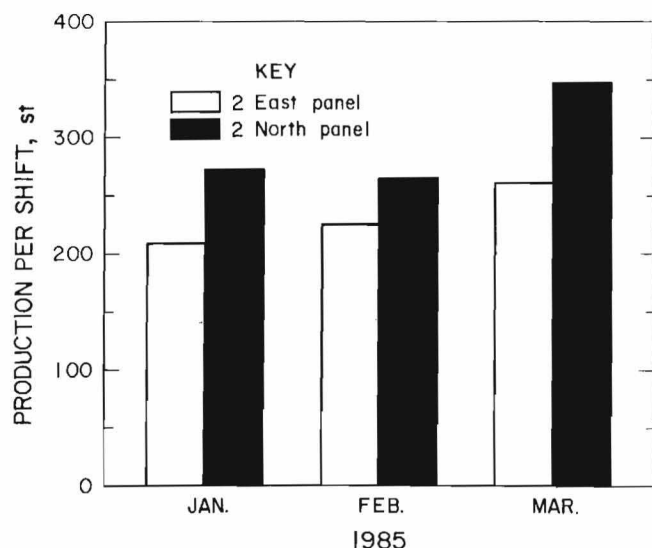
FIGURE 22.—Production figures for 2 East and 2 North.

Based on information collected at this study site, the following conclusions were reached:

1. Subsidence in the Sewickley Coalbed, caused by undermining of the Pittsburgh Coalbed, resulted in lower production and increased roof support costs during development and retreat mining.

2. Entry convergence and roof-fall activity increased dramatically as development crossed the gob line and proceeded into subsided ground. Falls occur predominantly in highly jointed zones in the roof strata. The direction of mining in relation to the direction of roof joints may contribute to roof-fall activity.

3. Strata flexure has little effect on pillar stability when percent extraction is kept low, leaving sufficient coal in place. In this case, pillars were 80 by 80 ft with 36 pct extraction.

4. The location of the subsidence trough, as predicted by the model (16-17), correlated well with recorded ground movements and observed ground behavior. The application of this model for predicting in-mine subsidence will be studied further at this and other sites.

## DISCUSSION

Interactions between adjacent workings that are a result of pillar load transfer are difficult to predict because the complex nature of the mechanism is not yet fully understood. Once the mechanism responsible for this interaction is better defined through further laboratory and field research, problem areas may be anticipated and possibly eliminated. Initial research indicates that the pressure arch theory is a feasible concept in understanding the interaction mechanism, but it requires further study. Literature reports in many cases that pillar superpositioning and a mining sequence of upper coalbed first can increase the stability of lower workings, but this is not always entirely effective. Barriers and abutment pillars are also beneficial in limiting interaction effects by providing immediate support to load transfer.

Problems associated with subsidence of an overlying coalbed can be reasonably predicted through careful premine planning and analysis, including accurate mapping of lower mine workings, a geologic evaluation of innerburden and overburden, and the mapping of roof joints and geologic features. This information together with other site specifics (such as age of workings, uniformity or pillar extraction, mining height, etc.) should be used collectively to anticipate areas within the coalbed where problems may result or be magnified by undermining. Continued research into the development and application of subsidence models will improve the accuracy of prediction.

Minimizing problems may require changing the normal mining or roof control plan. Changes in the mining plan may include reducing percent extraction, decreasing roof span width, staggered pillar arrangements, or changing the heading of entries. The roof control plan may also necessitate modifications to contend with changing roof conditions; e.g., different roof bolt types and lengths as well as additional supplemental supports.

Due to economics, ownership, and availability, a mine operator may have little control over coalbed mining sequence. Consequently, in cases where underlying coalbeds are extracted first, subsidence in upper beds may result in lower production and increased roof support costs. Cooperative planning within the mining community can avoid this and lead to substantial improvements in resource conservation.

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