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Effects of Horizontal Stress Related to Stream Valleys on the Stability of Coal Mine Openings

By G. M. Molinda, K. A. Heasley, D. C. Oyler, and J. R. Jones

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	pct	percent
ft	foot	psi	pound per square inch
in	inch	st	short ton
pcf	pound per cubic foot		

EFFECTS OF HORIZONTAL STRESS RELATED TO STREAM VALLEYS ON THE STABILITY OF COAL MINE OPENINGS

By G. M. Molinda,[1] K. A. Heasley,[2] D. C. Oyler,[3] and J. R. Jones[1]

ABSTRACT

The U.S. Bureau of Mines conducted an investigation to determine the nature and frequency of coal mine roof failure beneath valleys. A mechanism for this failure and suggestions for controlling this problem are presented.

Hazardous roof conditions identified in some mines were positively correlated with mining activities beneath stream valleys. Mine maps with overlays of unstable roof and locations of stream valleys show that 52 pct of the instances of all unstable roof in the surveyed mines occurred directly beneath the bottom-most part of the valley. The survey also showed that broad, flat-bottomed valleys were more likely to be sites of hazardous roof than narrow-bottomed valleys. Evidence of valley stress relief was found beneath several valleys in the form of bedding plane faults and low-angle thrust faults. This type of failure, previously believed to be only a shallow phenomena, was found at mining depths as great as 300 ft. In situ, horizontal stress measurements beneath a valley and the adjacent hillsides, confirmed valley stress relief. Numerical analysis of 13 valleys overlying one mine property showed the effect of the valley excavation on horizontal and vertical stress.

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INTRODUCTION

It has long been observed that the coal mine roof appeared to become unstable when mining beneath stream valleys (*1-3*).[4] It has even been suggested that 90 pct of roof falls in the Appalachian coalfields have occurred beneath stream valleys (*4*). The extent of the problem is not clear, but what is clear is that mining without regard to topography is risky. Conversely, the fear of mining beneath stream valleys is so entrenched at some mining operations that unstable roof conditions are assumed to be present under all valleys. Simple study of mine maps and roof falls shows that this is not necessarily true. Rigid adherence to this belief can lead to unnecessary precautions resulting in loss of coal reserves.

Because many of the Appalachian coalfields are located physiographically in a dissected plateau, individual watersheds routinely abut each other. Therefore, most mining will occur under some valley. It then becomes arbitrary and confusing about when to expect poor roof conditions due to changing topography. An understanding of the effects of surface topography on ground control will contribute to the U.S. Bureau of Mines effort toward safe mines. The objectives of this investigation were to (1) document the stability of coal mine roof beneath changing topography, (2) investigate the principal mechanisms of failure to better understand how and when surface topography influences roof stability, (3) investigate the effect of topography on the in situ stress regime, and (4) verify a numerical model which returns the original state of stress in the mine given the depth of cover and valley shape. If this modeling approach can be verified, then the predicted stress state under the valley can be used in the mine planning process.

EVIDENCE OF VALLEY STRESS RELIEF

Coal mine roof failures can result from (1) inherently weak rock and (2) high rock stress. Inherently weak rock can be caused by depositional features such as sandstone channels, rooted clays, stackrock, slump blocks, coalbed splits, transition zones, or clay veins (*5-7*). Stress-related failures are mining induced and represent a return to equilibrium of the roof sequence in the form of cutter roof, snap top, bumps, or other relatively rapid events (*8-9*).

Both of these types of failure can be associated with mining beneath stream valleys. Mechanisms for this strata failure can be suggested by observing how surface drainage is developed. Surface drainage can be structurally controlled by large-scale features such as folds, faults, and joint sets. These structures represent zones of weakness that can channelize water. If structures have surface expressions which influence drainage, often these structures extend to mining depths and influence rock mass quality and roof stability (*5*).

Surface drainage also develops where there is no evidence of crustal failure or other zones of weakness. The dendritic drainage common in the Appalachian Plateau coalfields indicates that there is normally no preferred orientation for surface runoff channels. In addition, geologic mapping shows no consistent jointing at depth under valleys that might indicate structural control of the valley (*10*). Therefore, whereas local structural control of surface drainage may affect roof stability at mining depth, most evidence points to the fact that strata failures beneath valleys occur in the walls and floor of a valley as a result of stress relief. These phenomena are referred to as the "valley effect" (*10*).

It is thought that immature or V-notched valleys tend to concentrate horizontal stresses near their apex, and produce active stress-related failures such as cutter roof, kink roof, and snap top (*11*). Hill verified the existence of high horizontal stress beneath a V-notched valley in West Virginia as predicted by a numerical model (*12*). Instead of concentrating stresses, as in a V-notch confined valley, older more mature valleys appear to be in a stress-relieved state. It is thought that broad, flat-bottomed valleys may be stress relieved because of valley rebound due to unloading as well as the transfer of stress laterally due to loading of the valley walls. Figure 1 shows how relatively less confined valley floor members beneath the broad valley can move when subjected to lateral forces and thereby dissipate those transmitted forces. The figure also shows how

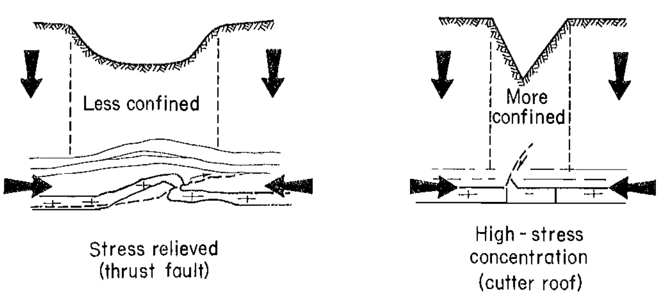

Figure 1.—Theoretical effect of valley shape on horizontal stress and roof control at depth.

[4]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

strata which is more confined beneath a V-notch valley will not move and will concentrate stresses which are then relieved by cutter roof.

Valley wall stress-relief failure is common in the Appalachian Plateau region. Vertical fractures are seen easily in outcrops and road cuts. Sames and Moebs (*13*) have also documented the effect of valley wall fractures and their effect on mining in eastern Kentucky. Stress-relief failures in this region are known as hillseams.

There is abundant surface evidence of strata failures due to buckling of valley floor members. This phenomenon can be seen in excavations for dams and bridge abutments (*14-15*). Violent failures of surface strata in stream valleys and quarries also have been documented (*16-17*). There appears to be no doubt that high horizontal stresses can be sustained at the surface. The structures seen in excavations are usually small thrust faults, with fault gouge or crushed zones due to bed slippage, bedding plane separation, or small folds in weaker members. These features usually occur near the surface (15 to 50 ft deep), but there is also evidence that compressional relief failures can occur much deeper.

Excavation for the Peace River Dam provided evidence of stress relief down to 150 ft below the valley (*14*). Bauer (of the Illinois State Geological Survey) showed that rock strength, as measured in core samples, decreased by an average of 26 pct at a depth of 130 ft below a valley with 160 ft of relief (*2*). An investigation of water transmissivity beneath stream valleys by Wyrich and Borchers notes that stress-relief fractures, which greatly enhance transmissivity, can occur from 100 to 200 ft beneath the valleys (*18*). Matheson and Thompson (*19*) state that valley rebound can also occur in areas of relatively low topographic relief, and that valley flexure is accompanied by bedding slips which give rise to gouge zones. They also note that an increase in the ratio of horizontal stress to vertical stress will cause an increase in the amount of bedding plane slip as predicted by a finite element model.

Many of these same compressional failures observed near the surface are also seen in coal mine roof and contribute to poor rock mass quality and roof falls. Mining at overburden depths of less than 50 ft has always been risky. Much of the problem can be attributed to weathering of broken roof rock by percolating surface water, but mining at greater depths may also be hazardous due to stress-relief fracturing. Surface failures, such as the buckling of quarry floors (pop-ups) and "valley anticlines," may not occur at depth due to increased overburden confinement, but thrust faulting with gouge zones and bedding plane slips are not uncommon and could be the result of valley stress relief. Questions to be answered include "To what degree is coal mine roof stability affected by valley stress relief?," "What are the safe limits of mining around a valley?," and "Which valley geometry parameters most affect roof quality?" These questions were investigated by a program of field observations and are discussed as follows.

MINING EXPERIENCES BENEATH STREAM VALLEYS

Data on mining experience beneath stream valleys were collected to determine if unstable roof could be attributed to surface stream valleys. Operators from seven mines located in Western Pennsylvania and West Virginia were questioned, with mapping conducted at five of the mines to determine the nature of roof quality beneath stream valleys (fig. 2). There appears to be a clear relationship between areas of roof instability in the mines and proximity to stream valleys. This relationship is mentioned by numerous operators, but is rarely quantified or mapped. The following case histories describe the influence of valley topography on roof control in these Appalachian mines.

TANOMA MINE

Figure 3 shows the Tanoma Mine located in Indiana County, PA. Local terrain features gently rolling hills with a dendritic drainage pattern and relief averaging 300 ft. The valley floors range from 350 to 1,250 ft wide, with the widest valley being the flat bottom of Crooked Creek. The Tanoma Mine excavates the Lower Kittanning coal seam (average thickness of 36 in) and mines 650,000 st of coal a year. The coalbed is essentially flat-lying and the depth

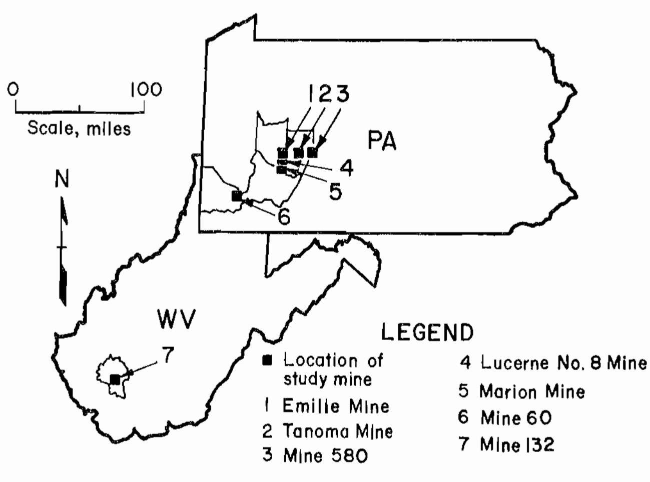

Figure 2.—Location of study mines.

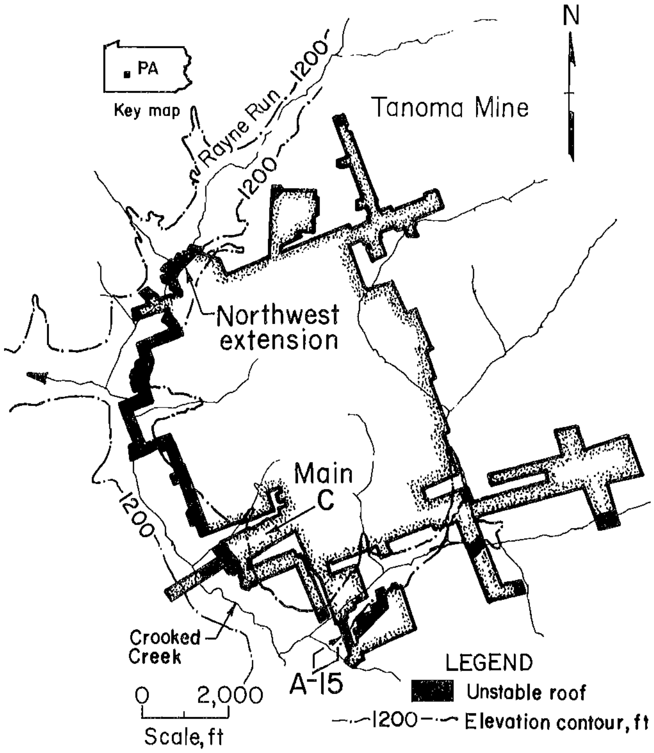

Figure 3.—Tanoma Mine outline and relationship of unstable roof to surface drainage.

of mine ranges between 120 and 475 ft. Figure 3 shows the mine outline with local drainage overlayed. Also, shown are areas of roof instability as reported by the operators. The mine historically has experienced extremely difficult roof control problems when trying to advance its western sections beneath Crooked Creek and Rayne Run. Mining problems under the valley include extreme water leakage, soft bottom, slip planes, and joints associated with roof falls. Heavy supplemental support, including steel legs and crossbar sets, straps, and combination bolts, have been unable to control the roof. Poor roof conditions also exist beneath some of the smaller tributaries overlying other parts of the property. Compression failures, aggravated by channel washouts, water leakage, and soft bottom, characterize roof conditions beneath drainage at Tanoma Mine.

Detailed mapping was conducted in sections Main C and A-15 (fig. 3). Crooked Creek valley over Main C is flat-bottomed and more than 1,200 ft in width. This valley is typical of the more mature drainage patterns in the area. Maximum relief in the area is about 400 ft with about 200 ft of overburden above the section. Extreme instability in the section necessitated tunnel liners under 50 pct of the mined section beneath the stream valley. Two entries advanced completely beneath the valley bottom and exposed a small-erosional channel deposit (30 ft wide) which completely cuts out the coal (fig. 4). The channel was filled with clay and shale, and the immediate roof was of the same lithologic composition.

Evidence of valley stress relief is present in section Main C. Pulverized clay beds and low-angle slip planes indicate horizontal movement near the channel. Bedding plane faults and mud slips occur parallel to the valley and are the result of horizontal compression.

A similar coalbed discontinuity in the northwest extension terminates numerous entries (fig. 3). Other entries remain in coal, but are terminated due to poor roof conditions. Here the coalbed is forced downward due to a channel deposit overhead. Prominent, broad slip planes exit the roof at 45° isolating roof blocks which then drop out. Many of the roof control problems beneath this valley are attributed to this paleochannel and its disturbed margins, but the primary cause of poor roof quality is horizontal stress relief.

Additional evidence of significant horizontal movement, which resulted in stress-relief failure, is a large open cavity parallel to bedding near the northwest extension. This cavity resulted from significant horizontal movement that caused bedding plane separation and left a void that flowed water freely when encountered by mining.

Mining section A-15 crosses beneath a tributary of Crooked Creek (fig. 3). The development was necked down to three entries because of unstable roof rock and excessive water leakage. In addition, larger pillars were used to stabilize the hazardous zone. The valley bottom at this point is 400 to 500 ft across, with approximately 284 ft of overburden. Again, the roof instability in this section appears to be a result of horizontal compression perpendicular to the trend of the valley. Bedding plane faults parallel to the valley cause the major roof falls. Throughout the zone of unstable roof, the faults curve upward and intersect to isolate blocks of roof which then fall into the mine openings (fig. 5). Faults flatten parallel to the coalbed and rarely offset it. Slippage has occurred on numerous planes in the siltstone roof. Movement is indicated by broad, grooved, slickensided planes and by gouge zones up to several inches thick.

The bedding plane faults, which parallel the stream valley, may be related to valley stress relief. The gouge zones, which occur along the faults, indicate that the horizontal movement which crushed the strata occurred after lithification and was not the result of soft-sediment deformation. Because the roof strata are confined beneath 284 ft of overburden, horizontal compression from valley side-loading may cause only slight dislocation of the strata, but enough to severely disrupt the roof.

The relationship of roof failure to mining beneath valleys at Tanoma Mine is apparent, and the main cause is poor rock mass quality due to horizontal stress failures caused by valley stress relief. The typical weak lithology found along the margins of a paleochannel serve to intensify the roof problems.

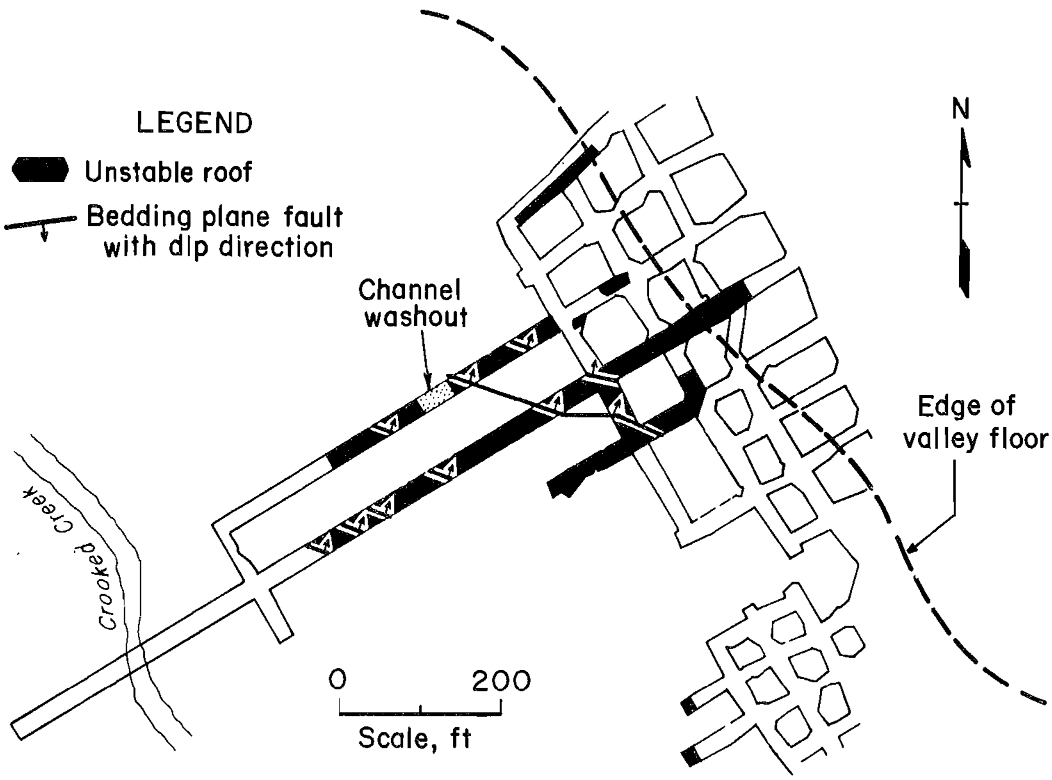

Figure 4.—Main C section of Tanoma Mine with unstable roof occurring in valley bottom.

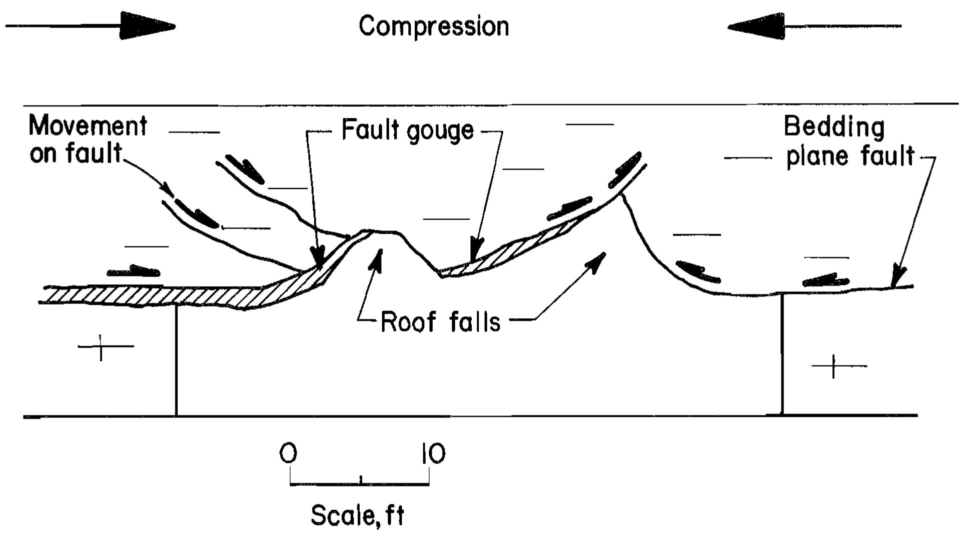

Figure 5.—Horizontal slippage and roof failure in Tanoma Mine caused by compression beneath valley.

MINE 132

Mine 132 is located in Boone County, WV and is working the Powellton Seam (fig. 2). Coal thickness ranges from 4.5 to 8.0 ft. Figure 6 presents the mine outline with local drainage overlain. The West Fork of Pond Creek is the major drainage on the property. The valley is flat and averages 600 ft wide. Terrain in the area is severe, with relief of over 1,000 ft. Mining stops before passing under the West Fork of Pond Creek valley because there is only 20 ft of cover beneath the valley and roof problems were anticipated. A slope is presently being driven to the Eagle seam approximately 200 ft beneath the valley.

Two sets of mains extend beneath Bandy Green Branch Creek, which drains into the West Fork of Pond Creek. Here the coalbed is under about 160 ft of cover. On the surface, the valley is narrow and V-notched and not more than 100 ft wide, with a steep stream gradient of 37 pct. The roof is unstable where the mains cross beneath the stream valley. Workings extending beneath other stream valleys on the mine property have relatively stable roofs. Here roof instability problems occur only beneath Bandy Green Branch.

Figure 7 is a map of roof conditions beneath Bandy Green Branch. The zone of roof instability coincides with the valley bottom. Roof falls more than 100 ft long and more than 20 ft high are common. Once again, bedding plane faults are the cause of roof failure. These horizontal failures are similar to those observed at the Tanoma Mine (section A-15 and Main C). Bedding plane faults also curve into the roof and their linear traces parallel the valley trend. As illustrated in figure 5, horizontal slippage occurs in both directions perpendicular to the fault traces and isolates roof blocks which then fall into the mine

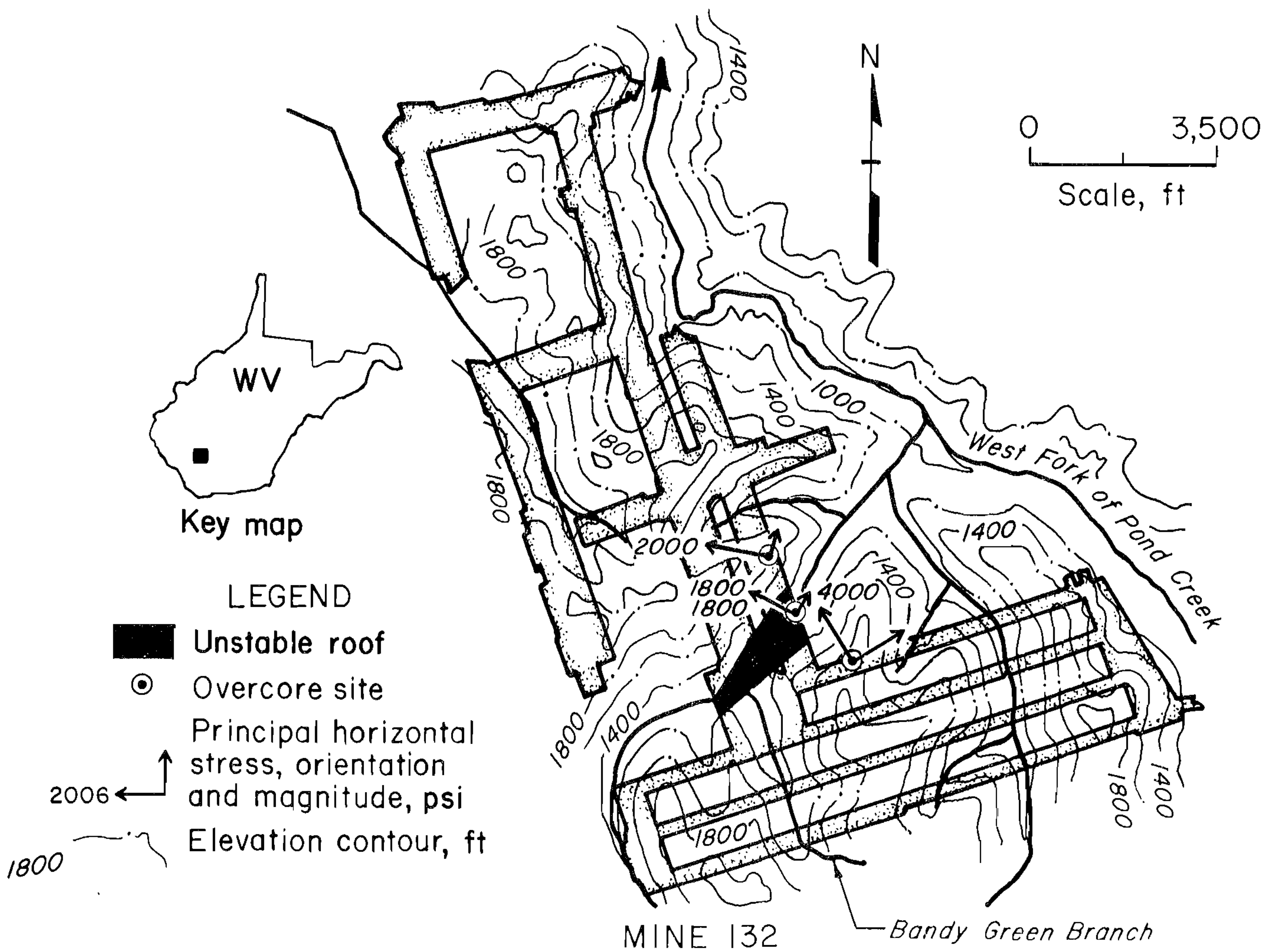

Figure 6.—Mine 132 outline and relationship of unstable roof to surface drainage, and results of horizontal stress measurements.

openings. Fault gouge is several inches thick between beds and contributes to roof instability. Slippage occurs as a result of horizontal compression from valley stress relief. Figure 7 locates in situ stress measurements which confirm stress relief beneath the valley. Data will be presented in following sections.

Compression causes slippage between beds, and when a zone of weakness is reached (i.e., in the valley bottom where there is less confinement from overburden), the fault plane bifurcates and fails into the roof. There is, however, no evidence of active horizontal stress in the form of cutter roof, snap top, or rotated supports.

LUCERNE No. 8 MINE

Lucerne No. 8 Mine is located in Indiana County, PA in the Upper Freeport Seam (fig. 2). The coal thickness is about 50 in. Terrain is gently rolling and valleys are broad, ranging from 100 ft up to 1,200 ft in width. Relief averages between 300 and 400 ft. The depth of the mine ranges from 50 to 700 ft.

Figure 8 shows the mine outline with surface drainage overlayed. Unstable roof rock conditions coincide with several drainage basins, but not all. Thrust faults and bedding plane faults are responsible for roof instability in

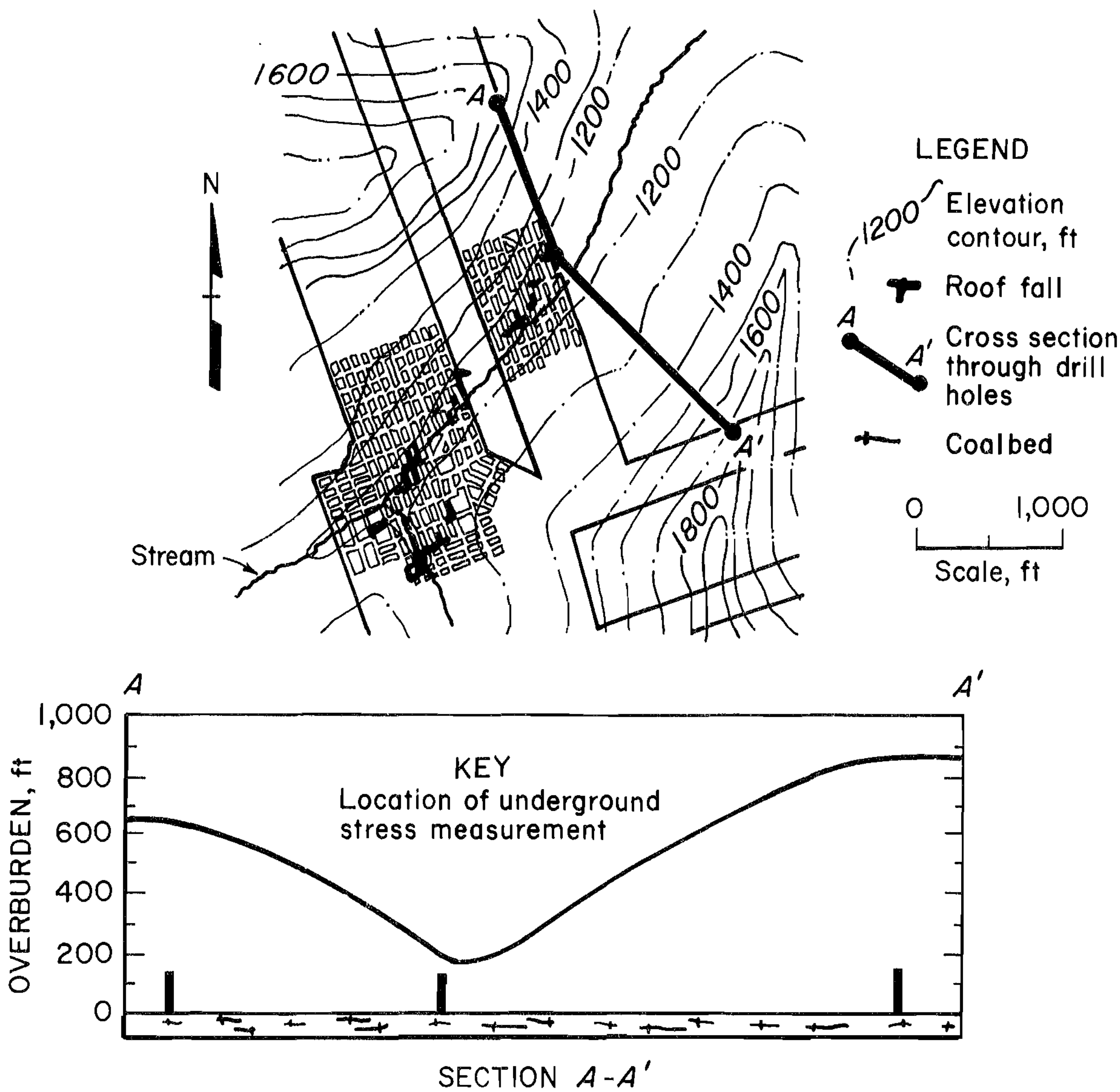

Figure 7.—Map of roof failure beneath Bandy Green Branch and location of overcore holes.

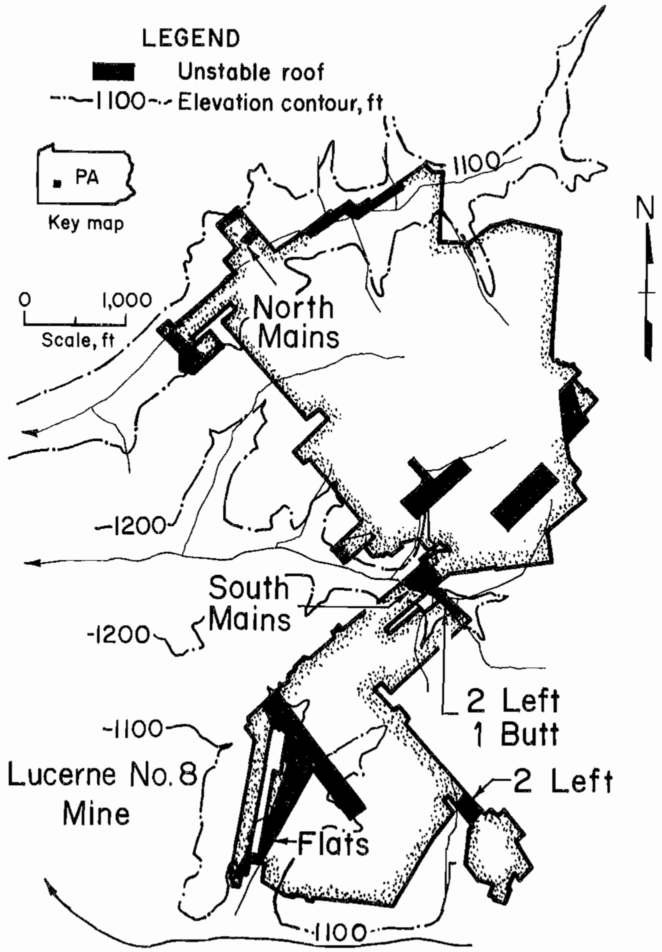

Figure 8.—Lucerne No. 8 Mine outline and relationship of unstable roof to surface drainage.

several of the related areas. The area known as the Flats has particularly unstable roof. The valley above is between 300 and 400 ft wide with approximately 200 ft of relief. The depth of the mine ranges from 50 to 100 ft with poor ground conditions necessitating the use of odd-shaped pillars.

The structural failures in the Flats area are thrust faults. These thrust faults and associated roof falls are closely aligned with the valley trend. Severe disturbance under this valley resulted in the need for abnormally shaped pillars and prohibited pillar removal in the section. Figure 9 shows three exposures of thrust faults in two entries of the Flats area. Relatively large-scale folding and thrust faulting is a result of compression oriented northwest-southeast, or perpendicular to the valley trend. This deformation may be a result of compression due to valley-wall loading which occurred at some time during the valley downcutting. Another possibility is that the sequence is reacting to a regional stress on the area and that the valley provided an unconfined zone for stress relief. The deformation in this section is severe enough to consider a structural origin of these faults. It is possible that they were formed before the valley and that this weak zone controlled consequent surface drainage.

Unstable roof in the area of the South Mains is also due to thrust faulting which parallels the stream valley (fig. 8). Here the coalbed is offset more than 24 in. Falls up to 12 ft high, severely disturbed roof rock, and numerous gouge zones characterize the zone, which is 150 to 200 ft wide. Section 2-left, 1-butt is also disturbed by the same fault zone. These two sections are located directly beneath a stream valley with less than 100 ft of overburden.

The 2-left development to the south crosses beneath a valley at a depth of less than 100 ft. The coalbed is offset more than 18 in by thrusting, with the axis of the fault again paralleling the stream valley. Here, roof problems were controlled by longer pillars.

Thrust faulting in the North Mains section also contributes to roof instability. This section underlies the Hooper Creek Valley. Numerous roof falls have been caused by bedding plane and thrust fault failures which parallel the valley.

EMILIE MINE

The Emilie Mine is located in Armstrong County, PA. Terrain in this area is relatively gentle and typical of this part of the Appalachian Plateau (fig. 2). An east-driving development crosses under Sugar Run (fig. 10). At the crossing, the overburden is about 135 ft and the maximum relief in the area is about 400 ft. The valley bottom is narrow being only 30 to 40 ft wide. There is a zone of unstable roof about 150 ft wide beneath the stream. Roof falls in the area average about 4 to 6 ft high, and supplemental supports (crossbars) are needed at many intersections. Beneath Sugar Run, roof failures are primarily due to isolation of roof blocks by bedding plane faults which curve into the roof. These faults are similar to the other compressional zones previously described. Gouge zones several inches thick characterize the faults. The strike of the faults closely parallels the orientation of the valley (fig. 10). Angled fault planes intersect as they curve into the roof and isolate roof blocks between them, causing roof falls similar to those in figure 5. Thrust faults, with vertical displacements up to 12 in, also affect roof stability. These faults offset the coalbed and do not curve to become bedding plane faults. These compressional structures, because of their characteristics and their alignment

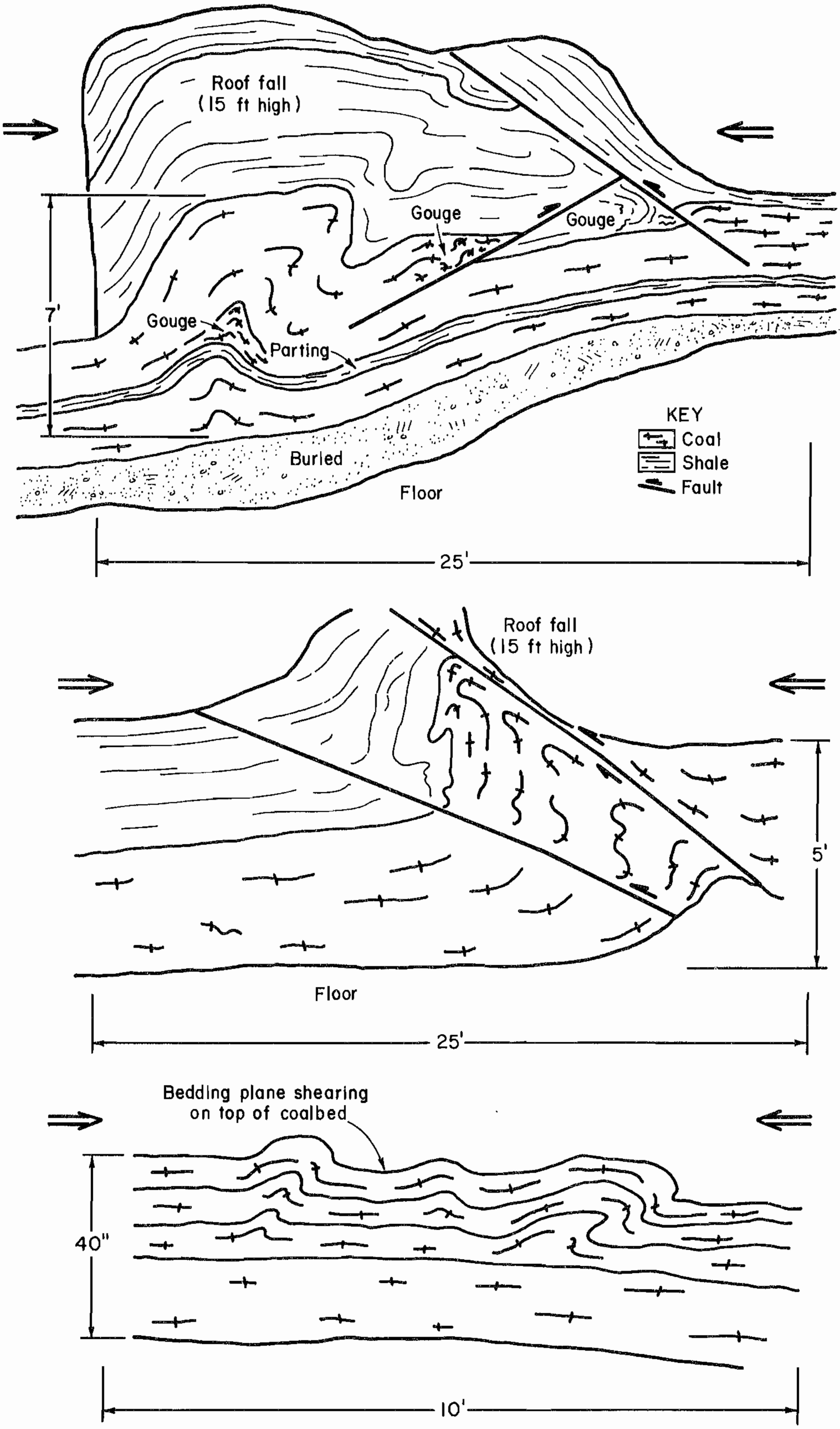

Figure 9.—Thrust faulting and bedding disruption in flats section of Lucerne No. 8 Mine due to horizontal compression.

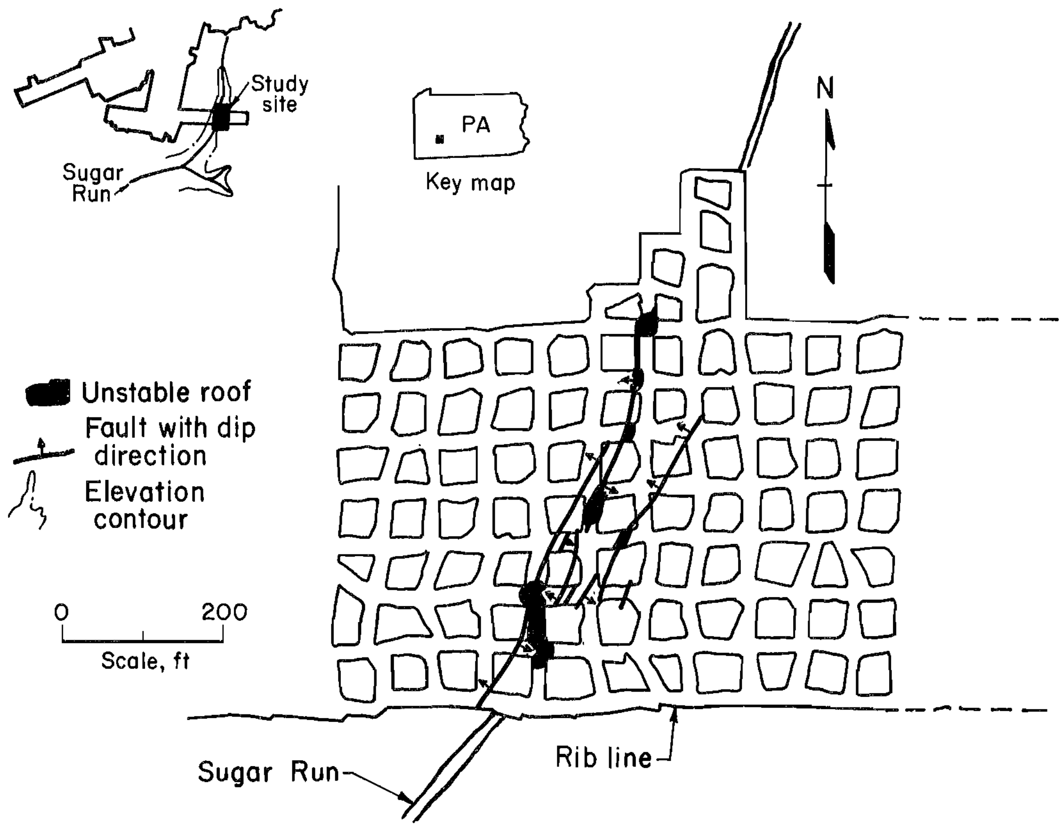

Figure 10.—Map of roof failure beneath Sugar Run at Emilie Mine.

parallel to the stream valley, may be the result of horizontal compression caused by valley-wall loading.

MINE 60

Mine 60, located in Washington County, PA, works the Pittsburgh Coalbed (fig. 2). Relief averages 300 to 350 ft over the property. Little Chartiers Creek flows north over the western side of the mine. Overburden averages 500 ft beneath Little Chartiers Creek. Figure 11 shows the mine outline and the areas of unstable roof. There is a close relationship between the valley bottom and unstable roof. Roof failure is often related to active stress and begins as cutter roof. Mine operators report that the most severe problems occur in north-south drivage, but they expect difficult mining whenever the mine passes beneath the Little Chartiers Creek valley. In addition, adjacent mines report similar problems beneath this valley. This is an example of unusually high horizontal stress severely affecting roof quality in relatively low relief. There was no evidence of rock mass disturbance before mining, indicating that the premining horizontal stress was never great enough to fracture the roof strata or cause bedding plane failure. When coal is mined (i.e., confinement removed), stress is released and cutters form. Such stress cannot be generated by static overburden loading and must be related to regional stress.

MINE 580

Mine 580 is located in Indiana County, PA and works the Upper Freeport Coalbed (fig. 2). The terrain is gently rolling and relief over the property is up to 250 ft. Figure 12 shows the mine outline and areas of unstable roof. Much of the unstable areas are located beneath the surface drainage. Roof is generally unstable beneath South Branch and especially so beneath Repine Run. The operators feel that roof control will be a problem whenever mining advances beneath Repine Run. Roof control problems include broken and fractured roof, clay veins, slickensides, "rolly shale" (a shale roof member that thins and splits in the roof), soft bottom, and water inflow. The ground control problems at mine 580 are related to poor rock mass quality and not to active stress.

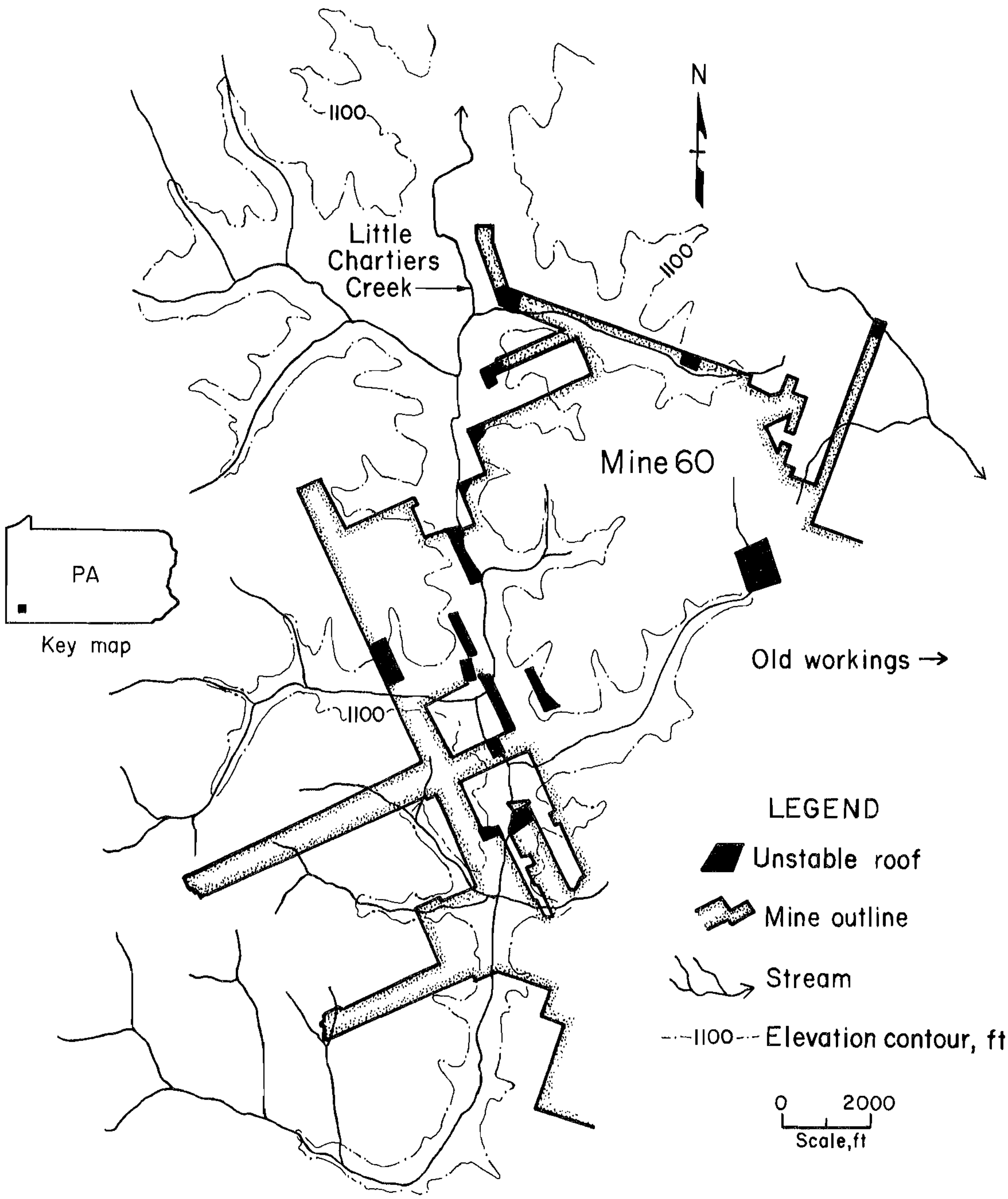

Figure 11.—Mine outline and relationship between unstable roof and surface drainage at mine 60.

MARION MINE

The Marion Mine is located in Westmoreland County, PA and works the Upper Freeport Coalbed. Terrain is gently rolling with relief ranging between 200 and 400 ft over the mine property. The Conemaugh River is the main drainage in the area, and all drainage on the property is tributary to the river. Figure 13 shows the mine outline and areas of unstable roof. Only the bad roof conditions which may be structurally related are considered. Poor quality roof conditions related to inherently weak rock are not included in this figure.

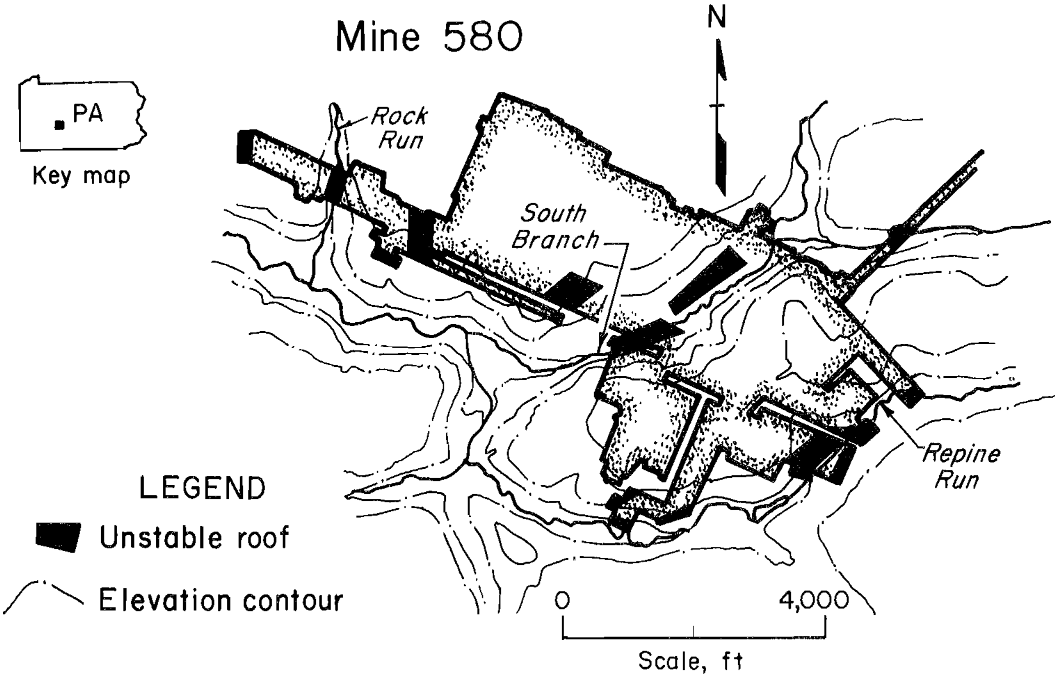

Figure 12.—Mine outline and relationship between unstable roof and surface drainage at mine 580.

Roof instability is closely related to several of the valleys on the surface. Whenever coal is mined beneath the Spruce Creek valley, which marks the eastern boundary of the property, unstable roof is encountered. The valley bottom averages 600 ft in width. Overburden beneath the valley averages 320 ft thick. Roof falls up to 15 ft high are common, and supplementary roof support includes crib sets on top of rails for high falls. A thrust fault zone, averaging 600 ft wide, is coincident with the valley and is responsible for the roof instability.

At location A (fig. 13) there is a low-angle thrust fault with a coalbed offset of 1 ft. Figure 14 is a diagram of two separate exposures of the fault. A 3- to 4-in-thick zone of pulverized fault gouge in the coal and roof rock results in unstable roof (fig. 14*A*). Figure 14*B* shows coalbed deformation caused by compression, but the coalbed is only kinked and has not been sheared.

The origin of the Spruce Creek fault zone is unclear. It could be the result of valley stress relief. Thrust faults, observed at the surface in quarries and foundation excavations and created by stress relief, have more structural disturbance and larger throws. Another possibility is that the fault is a larger structural failure which was present before the valley, which controlled the subsequent drainage. The roof beneath the stream valley at location C (fig. 13) are also unstable, with cutter roof the main cause of failure.

The roof failure beneath Boat Yard Run is a result of unusually high horizontal stress. Cutter roof is common, and long-running falls initiated by cutters are the main cause of failures. The trend of unstable roof closely follows the valley, so it is presumed that there is a relationship. Development beneath the valley has terminated in most cases because of the difficulty in controlling the roof. The valley dimensions are relief averaging 300 ft, a valley bottom width of 500 to 600 ft, and average overburden thickness of 300 ft.

The operators are currently attempting to drive two sections to the north between valleys and are having extreme difficulty (fig. 13, location E). The first development to the east was stopped due to long-running falls (18 ft high) occurring outby the belthead, and the second development is currently experiencing severe roof instability. Cutter roof occurs in north running entries, but not in crosscuts. Cutter roof is observed in sandstone as well as shale roof. This is unusual because sandstone usually has much more resistance to deformation than does shale. Unusually high stresses are causing cutter development immediately after

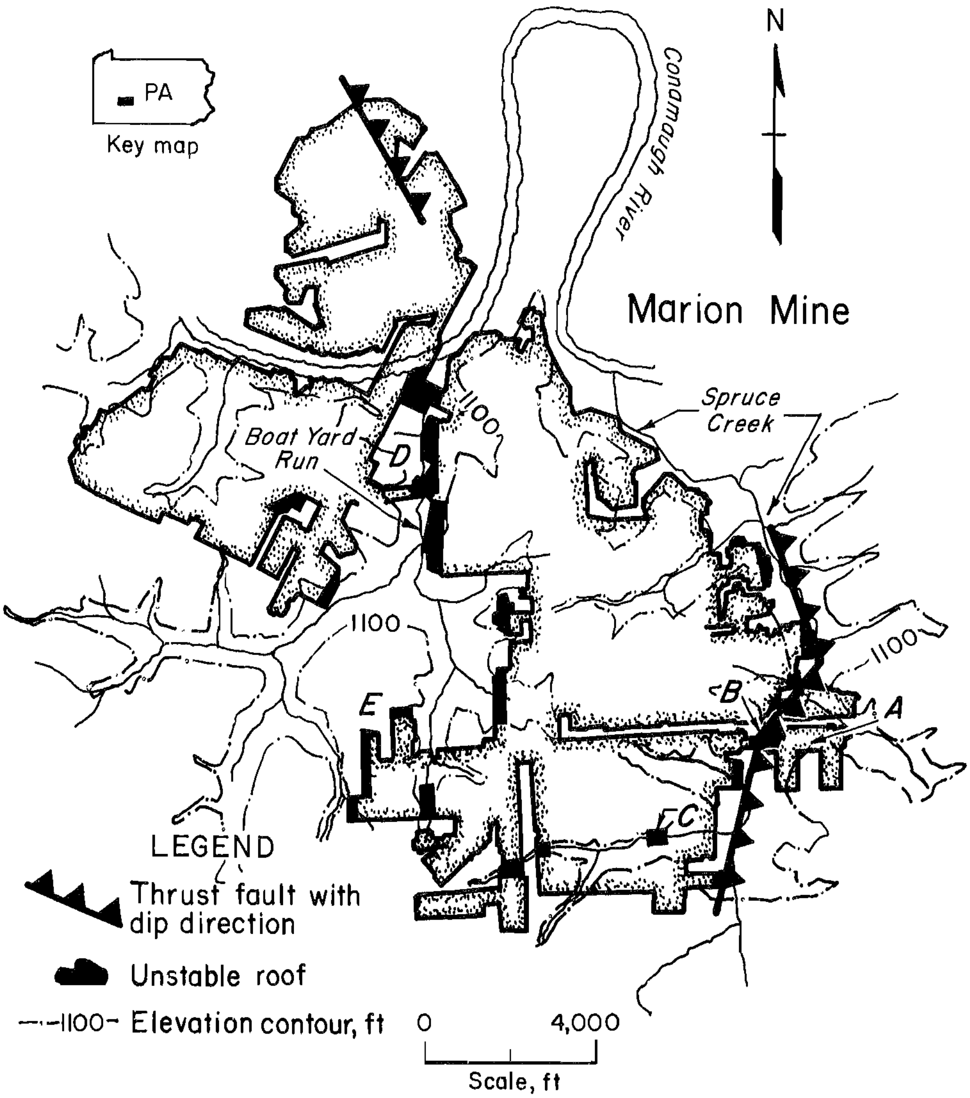

Figure 13.—Mine outline and relationship between unstable roof and surface drainage at Marion Mine.

mining and up to several days after mining. Rails are being used for support and truss bolts are being considered. Angling of entries away from north has had little effect with the cutters just skirting the ribline.

While it is possible that valley stress relief formed the Spruce Creek Fault zone, it appears that active horizontal stress is present beneath Boatyard Run and most likely is present over the entire property. This is presently the most serious problem for roof control at Marion Mine. The fact that unusually high horizontal stresses occur over much of the property indicates that the stress is regional in nature and not generated or related to the valley geometry. The correlation of stream valleys with unstable roof may be explained by considering that an applied horizontal regional stress has been relieved in areas of low confinement such as beneath a stream valley. The Marion Mine is an example of a mine where both poor rock mass quality, due to ancient valley stress relief, and active contemporary stress are adversely affecting the roof conditions.

Table 1 is a summary of the occurrence of valleys and unstable roof found in each of the mines discussed.

Table 1.—Summary of occurrence of unstable roof related to valleys at each study mine

Mine	Unstable roof beneath valleys	Valley stress relief	Active horizontal stress	Primary stress failures
Tanoma Mine	X	X	NAp	Bedding plane slips.
Mine 132	X	X	NAp	Do.
Lucerne No. 8 Mine	X	X	X	Thrust faults, cutter roof.
Emilie Mine	X	X	NAp	Thrust faults.
Mine 580	X	X	NAp	Bedding plane slips.
Marion Mine	X	X	X	Cutter roof.
Mine 60	X	NAp	X	Do.

NAp Not applicable.

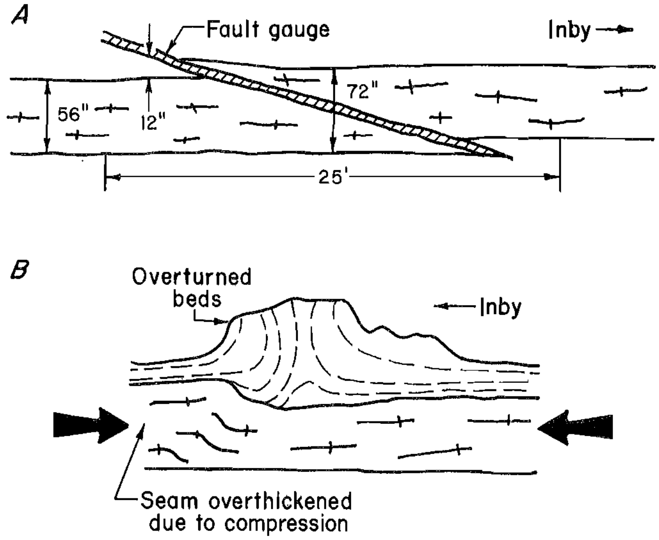

Figure 14.—Thrust faulting and roof disturbance in Spruce Creek fault zone at Marion Mine.

RELATIONSHIP OF VALLEY GEOMETRY TO FREQUENCY OF ROOF FAILURES

Data from five of the mines previously described was collected and analyzed to determine the frequency and nature of occurrences of roof failure beneath stream valleys. Complete information from Emilie Mine and mine 132 was unavailable.

In addition, the influence of valley geometry on roof failures was examined. The mines used for this portion of the study are all located in western Pennsylvania. Operators were questioned and asked to identify the areas of unstable roof on base maps. All areas of bad top were included, except those which were related to unconsolidated or inherently weak strata. The large zones of poor quality roof were categorized into discrete regions by fitting to a grid of approximately 1,000-ft squares. The surface terrain above each area of unstable roof was characterized by several variables including thickness of cover, amount of relief of associated valley, width of the associated valley floor, valley shape factor (height of relief/width of valley floor ratio), and proximity of the bad top occurrence to the valley floor (fig. 15). The distribution and frequency of unstable roof was then determined with respect to these variables.

Thickness of cover at the five mines ranged from 20 to 715 ft. It was found that unstable roof was normally distributed with respect to thickness of overburden. With the present data, which include 169 examples of unstable roof, there appears to be no clustering of occurrences towards thin or thicker cover. This is also true when considering only those examples of unstable roof that occur directly beneath the valley floor (0 to 20 pct valley location, fig. 15). This indicates that the amount of overburden alone does not influence roof instability in the test group. The location of unstable roof relative to the valley floor was the most significant relationship observed, with 52 pct of unstable roof occurring beneath the portion of the valley with 20 pct of the maximum relief.

Only 10 pct of the unstable roof was found beneath the valley portion with 80 to 100 pct of the maximum relief (figs. 15-16). There are several possible explanations for this observation. First, valleys may be located preferentially in zones of structural weakness caused by faulting, and this structural disturbance weakens rock strata beneath the valley bottom. This structural alignment, while common to the Allegheny Front is, however, not common in the gently folded Appalachian Plateau region. Second, strata immediately below valley bottoms may be weathered and weakened. Weathering commonly occurs no deeper than 50 ft below surface (*20*). Because unstable roof occurrences are not skewed toward depths that shallow, weathered rock does not appear to be a factor. Third, unusually high stress can develop beneath valley bottoms, causing cutter roof and snap top. These examples of active horizontal stress were not, however, observed beneath many stream valleys in the mines studied. Fourth, poor rock mass quality may result from valley wall loading and lateral stress transfer. These types of failures due to poor rock mass quality have been described previously and are common to the Appalachian region.

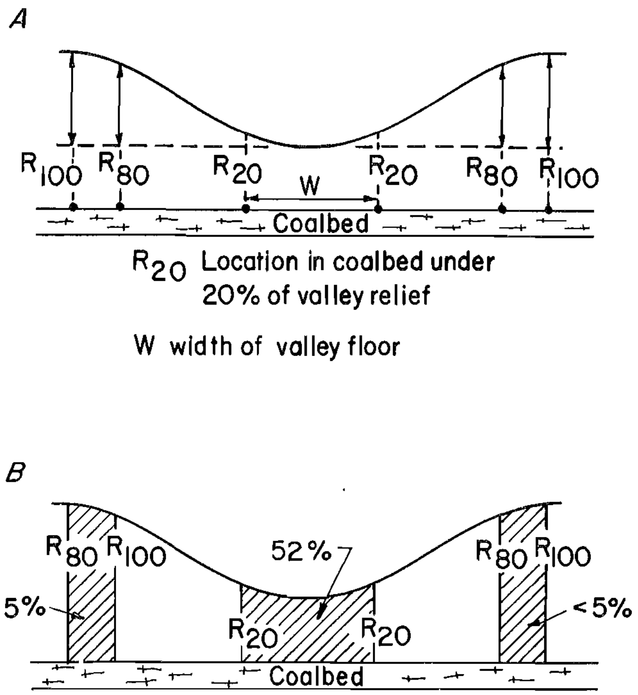

Figure 15.—*A*, Valley cross section. Geometric variables used in parametric study; *B*, location of most instances of unstable roof (52 pct) and location of least instances of unstable roof (10 pct).

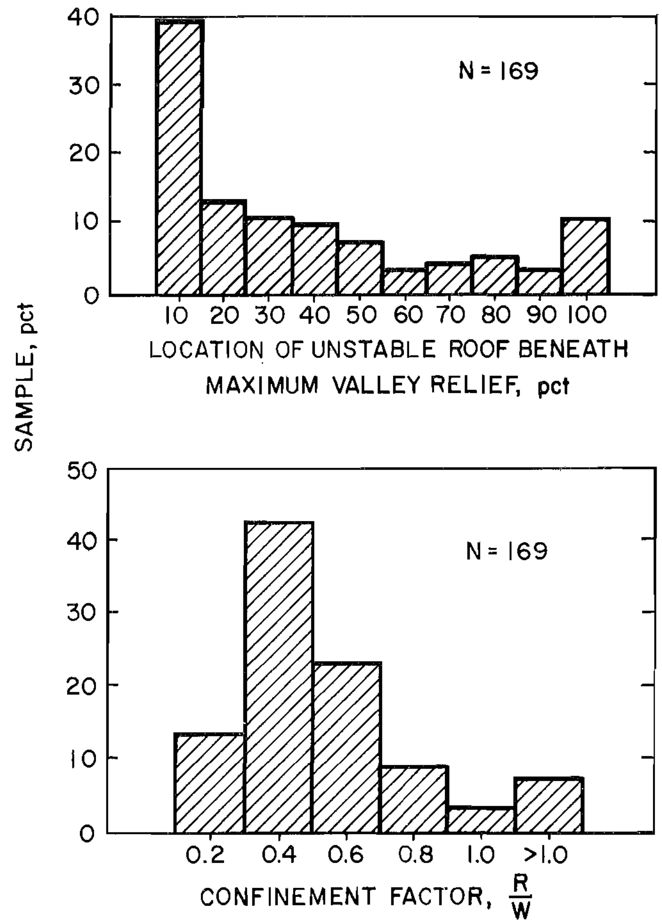

Figure 16.—Distribution of unstable roof with respect to location beneath valley and valley shape.

The relationship between the shape of the valley and all occurrences of unstable roof was also significant. The variable used is the ratio of the height of relief of the associated valley to the width of the valley floor. This ratio also defines the confinement of the valley floor. Sixty-six percent of unstable roof instances occurred beneath valleys with confinement factors between 0.4 and 0.6 (fig. 16). This indicates that unstable roof is more likely to occur beneath broad valleys rather than it is under narrow-floored valleys.

In summary, the data suggest that the most likely site of unstable roof relative to topography occurs when mining advances beneath a valley floor which is broad and flat-bottomed and, thus less confined. The least likely location of unstable roof is beneath the top of the adjacent valley wall.

FIELD STUDY OF VARIATION OF HORIZONTAL STRESS BENEATH VALLEY

BethEnergy Mine 132 was selected as the test mine to determine the effect of a valley on in situ horizontal stress. The study site, previously described, is located beneath Bandy Green Branch valley, which is a steep-walled (37 pct slope gradient), V-shaped valley. Severe roof failures occur in numerous places beneath this valley, and these failures closely follow the valley trend.

It is thought that V-shaped valleys in steep terrain would concentrate stresses immediately beneath the valley apex, contributing to cutter roof and ground control problems. It is also thought that broad, flat-bottomed valleys would transmit stresses horizontally and experience buckling and thrust-faulting in the unconfined valley floor strata. The terrain overlying the mine has high relief, up to 1,000 ft (fig. 6).

Four core holes were drilled into the roof to measure the horizontal components of stress (fig. 6). Two holes were located beneath the valley floor and one hole was located under each adjacent hillside. These locations were chosen to test the effect of the valley on the horizontal stress field. The Bureau borehole deformation gauge (BDG) and the overcoring method were used. Figure 17 shows the arrangement of boreholes and stress measurements. A total of 16 stress measurements were successful, with the highest measurement taken at 24.3 ft into the roof in hole 4. Several tests were unsuccessful because of core breakage, which contributed to instrument failure. All four holes were drilled within 5 ft of a coal barrier to minimize the effect of the mine opening. The final successful test at hole 1 was at 15.7 ft into the roof. Because this height is still within one opening width of the mine roof, the measurement may be affected by the mine opening. The other three holes were drilled more than 17 ft into the mine roof and these measurements are thought to represent premining horizontal stress.

These are the first coal measure horizontal stress measurements available for the area. Previous measurements of stress in the Beckley area, 50 miles to the southeast, indicate an average regional principal stress of 3,300 psi oriented N64E (*21*). The trend of the principal stress in all four test holes at BethEnergy is northwest, ranging between N32W and N87W. Stresses trending northwest at BethEnergy may reflect the regional stress in Boone County, WV, or may be a local phenomena related to topography. A northwest orientation is perpendicular to the direction of the stream valley, and explains the horizontal roof failures documented beneath the valley (fig. 7). These compressional failures, along the trend of the valley, were caused by stresses which were parallel to bedding and oriented northwest-southeast.

As the area was stressed regionally, Bandy Green Branch was concurrently downcutting its valley. The removal of confinement (overburden) created a site for the relief of stress beneath the valley and this effect is preserved in the roof rock. The ratio of horizontal-vertical stress beneath holes 2 and 4 (beneath the valley) is 10.2 and 10.4, and between holes 1 and 3 (beneath the hillsides) are 2.8 and 4.1, respectively (table 2). This increased ratio beneath the valley reflects its reduced confinement and the increased potential for valley stress relief failures.

The total horizontal stress field is considered to be the sum of the stress due to overburden and gravitational loading, the stresses being transferred horizontally to the valley bottom due to the "valley effect," and the regional stress. The total horizontal stress is considered to be at least as great as the magnitude of the largest measured stress at each hole. If the Poisson effect of gravity loading (table 2, calculated horizontal stress) is subtracted from the largest horizontal stress at each hole, there is excess stress present at each site. Excess stress is calculated to be 1,762 psi at hole 1, 1,719 psi at hole 2, 1,719 at hole 4 and 3,683 psi at hole 3 (table 2). This excess stress is the sum of the stress contributed by the "valley effect" and the

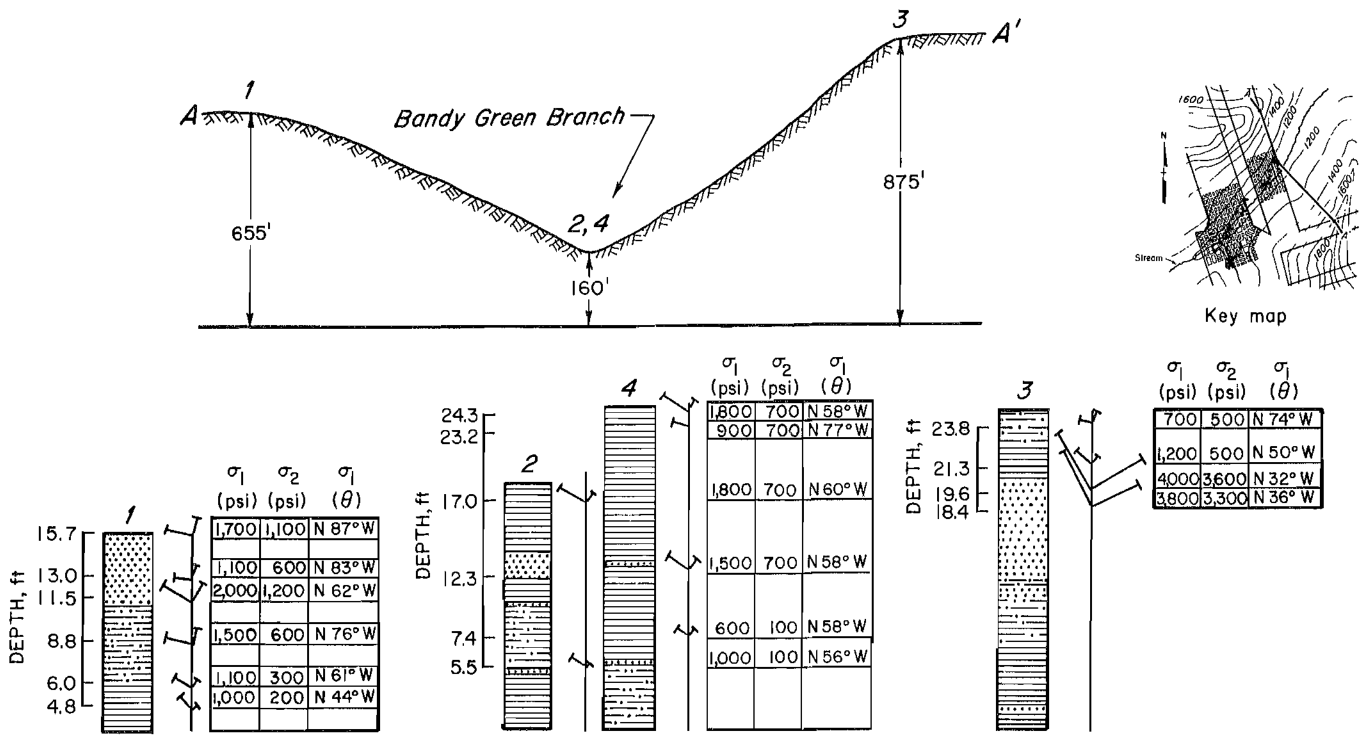

Figure 17.—Horizontal stress measurements in roof strata around Bandy Green Branch Valley.

regional stress. The horizontal stress contributed by the "valley effect" is calculated to be 297 psi by a numerical model (table 3, Valley 9). By removing this stress from the measured value (1,800 psi) the remaining regional stress beneath the valley is 1,503 psi. The difference between calculated regional stress beneath the adjacent hill (3,683 psi) and the calculated regional stress beneath the valley (1,503 psi) is 2,180 psi. This represents the amount of stress relief beneath the valley due to bedding plane faulting.

Table 2.—Relationship between measured stress and calculated stress at mine 132

Hole	Over-burden, ft	Calc. vert. stress, psi	Measured horiz. stress, psi	Calc. horiz. stress, psi	Excess horiz. stress, psi	Horiz. stress / vert. stress
1 . .	655	720	2,000	238	1,762	2.8
2 . .	160	176	1,800	91	1,719	10.2
3 . .	875	962	4,000	317	3,683	4.1
4 . .	160	176	1,800	81	1,719	10.2

Table 3.—Comparison of modeled stress and calculated stress for 13 valleys above mine 132

Valley	Depth of seam, ft	Normal vert. stress, psi	Model vert. stress, psi	Normal horiz. stress, psi	Model horiz. stress, psi	Vert. stress conc.	Horiz. stress conc.
1 . . .	415	445	631	191	352	1.4	1.8
2 . . .	300	322	449	138	297	1.4	2.2
3 . . .	415	445	592	191	316	1.3	1.7
4 . . .	380	407	565	175	305	1.4	1.7
5 . . .	290	311	450	133	287	1.4	2.2
6 . . .	395	423	611	182	336	1.4	1.8
7 . . .	430	461	721	198	418	1.6	2.1
8 . . .	160	171	289	74	239	1.7	3.2
9 . . .	150	161	267	69	297	1.7	4.3
10 . .	200	214	344	92	288	1.6	3.1
11 . .	60	64	71	28	106	1.1	3.8
12 . .	60	64	69	28	140	1.1	5.0
13 . .	214	229	365	98	266	1.6	2.7

In some West Virginia mines, entries adjacent to roof falls experience stable roof due to stress relief (*15*). In fact, a "caving entry" was successfully used at Kitt Mine to distress outside entries in a longwall development section. Movement along bedding planes as roof strata moved toward the cave is believed to be the mechanism of stress relief. This type of roof failure is exactly the type of movement which has occurred beneath the Bandy Green Branch at mine 132. Therefore, it is considered that the bedding plane faults which disrupt the roof integrity have partially relieved the excess stress beneath the valley.

The effect of this excess horizontal stress under the valley may be similar to that which causes cutter roof. Cutters tend to buckle the strata perpendicular to the direction of applied stress because this is the path of least resistance. The path of least resistance is parallel to the valley trend when a horizontal stress is applied perpendicular to the valley trend. This implies that valleys oriented perpendicular to the principal stress would be more likely to experience stress-relief failure. This was confirmed by the modeling study performed on valleys above mine 132 and discussed later in the report.

Two stress measurements at the bottom of hole 2 indicate that the stress field is strongly biaxial. With little confinement to the northeast, failure would be likely to occur parallel to the valley trend. Similar conditions exist at the bottom of hole 1, but may not result in poor rock mass quality due to higher confinement (i.e., greater overburden).

To summarize, the stress measurements at mine 132 indicate that stress relief has occurred beneath the valley bottom. It is estimated that over 2,000 psi of stress relief has occurred through bedding plane slippage. Additionally, the measured northwest orientation of the principal horizontal stress is consistent with the trend of the bedding plane failures in the mine roof beneath the valley. This means that these failures could well have been caused by a northwest horizontal stress.

NUMERICAL ANALYSIS OF STRESS REGIME AT MINING DEPTH AT MINE 132

The variety of ridge heights, hillside slopes, bottom widths, seam depths, and orientations of the valleys over the minesite (132) make a simple, intuitive estimate of the coalbed stress very difficult. However, a good estimate of the stress field under a given valley can be critical to the optimum mine design in this area. Therefore, to better define the effect of the valley topography and the regional stress on the geologic stress field at the mine level, a numerical analysis of 13 horizontal stress fields below valleys at mine 132 was conducted. This helped explain some of the geologic features and ground control problems actually found below these valleys.

The numerical method used in the topographic analysis was the explicit finite-difference technique as implemented in the program FLAC.[5] This particular modeling technique can provide accurate solutions for two-dimensional,

[5]Reference to specific product does not imply endorsement by the U.S. Bureau of Mines.

elastic problems as in the case of a valley cross-section. In this analysis of topographic stress effects, 13 different models simulating the 13 different valley cross-sections in figure 18 were run and analyzed. In these models, the finite-difference grids contained an average of 30 elements in the horizontal (X) direction and 22 elements in the vertical (Y) direction. These models were gravity loaded with symmetry boundary conditions on both ends and vertical displacements fixed along the bottom of the grid. The geologic material in the model was assumed to be linear elastic, isotropic, and homogeneous with an elastic modulus of 3,120,000 psi, a Poisson's ratio of 0.30, and a density of 154 pcf. The final results of the 13 model analyses are presented in table 3.

This table contains several columns which may need some explanation. First, the depth of seam refers to the amount of overburden between the coalbed and the center of the valley. The columns labeled "normal vertical stress" and "normal horizontal stress" list the stresses that would be present at the given depth on the assumption that the surface is level, with overburden everywhere equal to that beneath the valley center. This is stress due solely to the weight of the overlying rock. These normal stresses are equal to 1.07 times the depth for the vertical stress and 0.46 times the depth for the horizontal stress. (The previous multiplication factors correspond to a gravity loaded material with a density of 154 pcf and a Poisson's ratio of 0.30.) The columns labeled "model vertical stress and model horizontal stress" show the stresses as calculated by the FLAC models. These calculated stresses include the effects of topography and are considerably different from the normal stresses. The final two columns on the table show the stress concentrations due to the topography and are calculated as the ratio of modeled stress to normal stress.

An increase in topography has increased the stress under the valley, as calculated by the FLAC model algorithm. The magnitude and diversity of these stress increases can clearly be seen in figure 19, which present a comparison of the normal and modeled stresses. In some cases, depending on the depth and valley shape, the stress increase is as low as 10 pct; however, in other situations (in particular

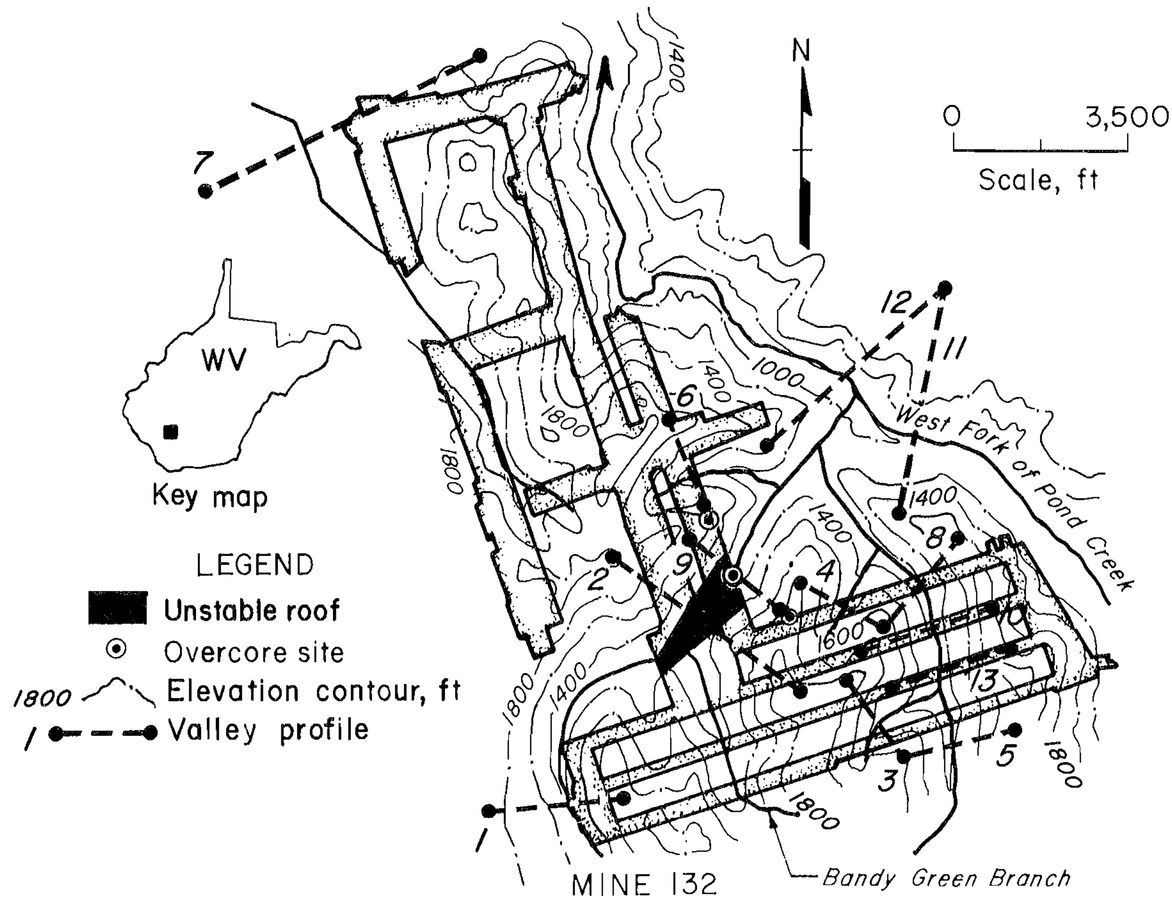

Figure 18.—Valley profiles over mine 132 used in numerical analysis.

the horizontal stress at shallow depths), the stress increase has been as large as 500 pct. These figures illustrate the stress increases caused by the valley topography. It is apparent that knowledge of the magnitude of this stress increase could be critical to mine design under these valleys.

A closer examination of the stresses calculated by the finite-difference models can provide some insight into the effect of the depth and the valley geometry on the topographically induced stress field at mine 132. Figure 20 shows the actual cross sections of Valleys No. 9 and No. 12 with three coal seams simulated at depths of 50, 150, and 300 ft below the valley floor. Figure 21 shows the horizontal (sxx) and vertical (syy) stresses along the three different seams under Valley No. 9 as calculated by the FLAC model. Examination of the horizontal stress curves reveals that they do not decrease as the overburden decreases under the valley, as would be expected. Rather, the horizontal stress is actually concentrated under the valley at the two greater depths.

This stress concentration is actually a result of the two ridges pushing toward the valley center. The lack of horizontal stress increase at the 50-ft level is a result of this area being on the border of a horizontal stress-relief zone generated under the valley bottom. A look at the vertical stresses in figure 21 also reveals some interesting observations. The vertical stress does indeed decrease as the overburden decreases towards the center of the valley; however, the magnitude of this decrease is diminished at the greater depths. This lack of stress reduction is the result of the weight of the ridges being spread over a larger area as the depth increases. Theoretically, at some depth, the effect of topography on vertical stress becomes zero.

The final observation from figure 21 is that at the two shallower depths, 50 and 150 ft, the horizontal stress is greater than the vertical stress calculated beneath Valley No. 9. Through geologic time, this higher horizontal stress would be expected to cause compressional features such as bedding plane slips or small thrust displacements. This model provides a mechanism for the compressional roof failures observed beneath Bandy Green Branch at the 160 ft depth. Horizontal compression exceeded confining pressure from overburden and overcame cohesion along bedding planes. Possibly, at 300 ft beneath this valley vertical pressure would be sufficient to confine compression and prevent horizontal slippage. Table 3 shows several

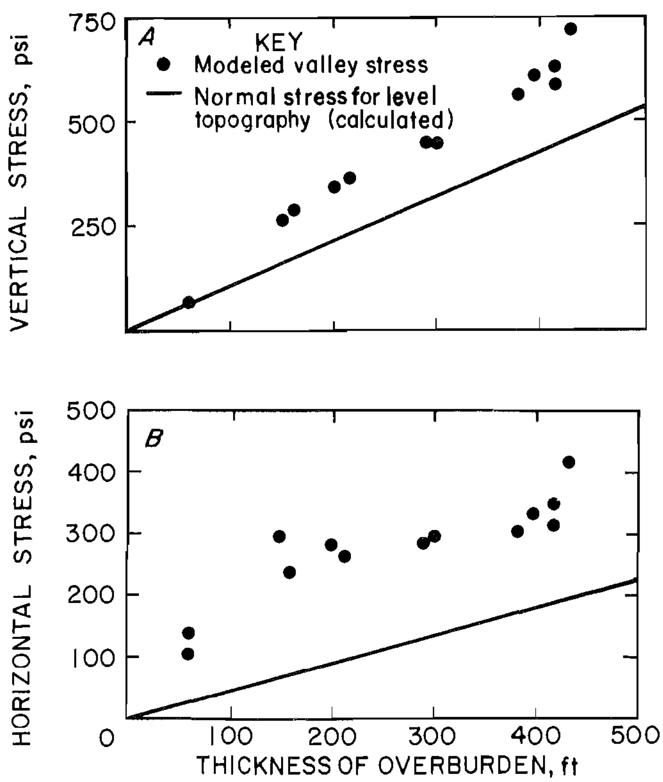

Figure 19.—Comparison between modeled stress at mine level under valleys at mine 132 and theoretical stress for level topography. *A*, Vertical; *B*, horizontal.

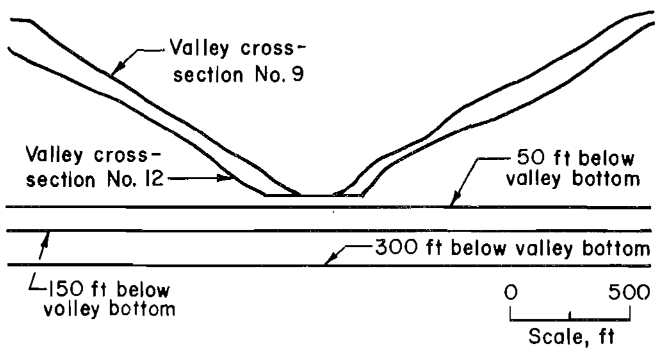

Figure 20.—Cross section of Valleys No. 9 and No. 12 with simulated coalbed horizons at mine 132.

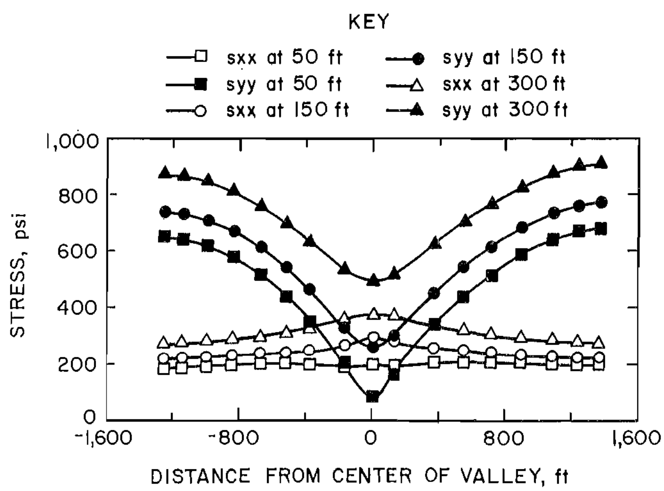

Figure 21.—Horizontal (sxx) and vertical (syy) stresses at various horizons below apex of Valley No. 9 at mine 132.

other valleys with horizontal stress concentrations above 3.0. None of these valleys have yet been undermined, making it impossible to confirm expected roof problems.

To investigate the effect of the valley shape on the stress field, figures 22 and 23 present comparisons of the horizontal and vertical stresses at identical depths under Valleys No. 9 and No. 12 (fig. 18). All the valleys investigated in this study had similar slopes and relief; therefore, the only factor which is truly different between Valleys No. 9 and No. 12 is the width of the valley floor (100 ft for Valley No. 9 and 350 ft for Valley No. 12). This difference in valley floor width distinctly influences the horizontal stresses (sxx) at the 50-ft level where the stresses show a decided drop under Valley No. 12 (fig. 22). This drop in horizontal stress at the center of Valley No. 12 is a result of the wider valley bottom which generates a larger stress-relief zone that encompasses the 50-ft level under Valley No. 12, whereas the stress-relief zone under Valley No. 9 did not encompass the 50-ft level.

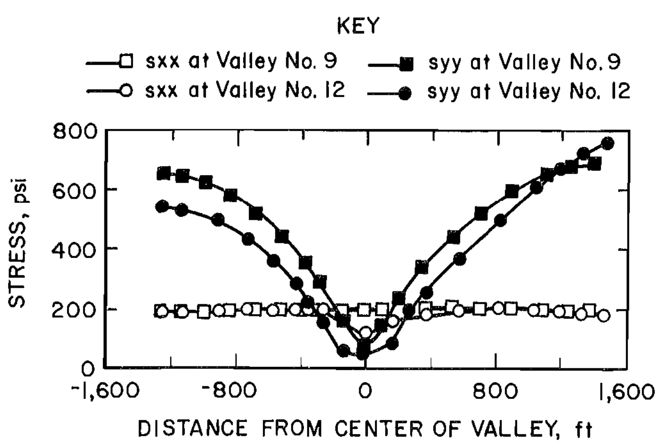

Figure 22.—Comparison of stress between Valleys No. 9 and No. 12 at mine 132 at 50 ft deep.

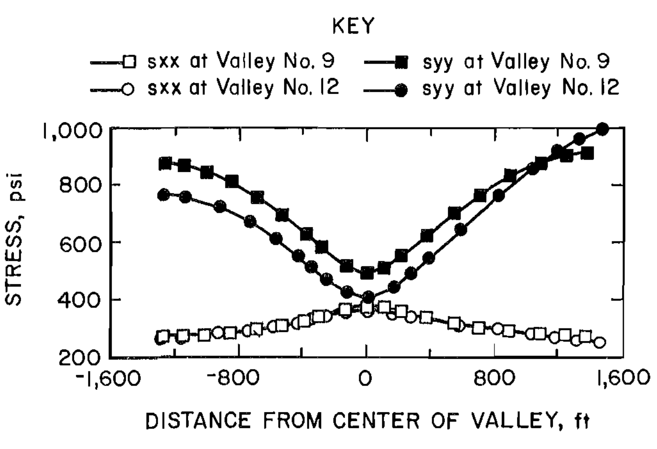

Figure 23.—Comparison of stress between Valleys No. 9 and No. 12 at mine 132 at 300 ft deep.

Examination of the horizontal stresses in figure 23 shows that the effect of the horizontal stress-relief zone at 300 ft below the two valleys is negligible and therefore, the curves are practically superimposed. At this depth, the difference in the shape of the two valleys makes no difference in their effect on horizontal stress, although there is still a "valley effect" horizontal stress concentration due to overburden removal. Figure 24 is the same comparison of stress beneath Valleys No. 9 and No. 12 with stresses modeled at 500 ft. The stress concentration beneath the valley floor remains, but appears to be diminishing.

The vertical stress curves between the two valleys are also similar. The only two major differences are (1) the flatness of the center of the 50-ft curve over Valley No. 12, which is due to the greater width of the valley floor, and (2) the overall lower values of vertical stress for Valley No. 12, which is due to the general difference in overburden between the two valleys (see figure 20).

The next major step in examining the stress field under the valleys was to vectorially add the regional horizontal stresses to the topographic stresses. This summation theoretically gives the total geologic stress field at the mine level, and should provide considerable insight into the geologic features and ground-control problems actually found in these valleys (table 4). The exact values of the regional-local stresses used for these calculations were 1,400 psi for the maximum regional horizontal compressive stress and 500 psi compression for the minimum horizontal stress, with the maximum stress being oriented at N70W. These values for the regional stress were approximated from the overcoring data presented earlier in this report.

Table 4.—Comparison of total geologic stress fields of all valleys at mine 132

Valley	Valley bearing	Offset from regional stress, deg	Maximum horizontal stress, psi	Minimum horizontal stress, psi	Vertical stress, psi
1 . . .	S. 14 E.	56	1,735	812	631
2 . . .	S. 17 E.	53	1,674	752	451
3 . . .	S. 56 W.	54	1,704	790	600
4 . . .	S. 40 W.	70	1,700	766	565
5 . . .	S. 15 E.	55	1,666	742	450
6 . . .	S. 72 W.	38	1,706	817	621
7 . . .	S. 27 E.	43	1,779	881	726
8 . . .	S. 41 E.	29	1,579	719	290
9 . . .	S. 29 W.	81	1,694	672	267
10 . .	S. 20 E.	50	1,646	725	344
11 . .	S. 82 E.	12	1,456	604	73
12 . .	S. 45 E.	25	1,527	576	69
13 . .	S. 20 E.	50	1,636	720	367

The initial results from adding the regional stresses to the topographic stresses are shown in table 4. This table also gives the valley orientation (reference to the south),

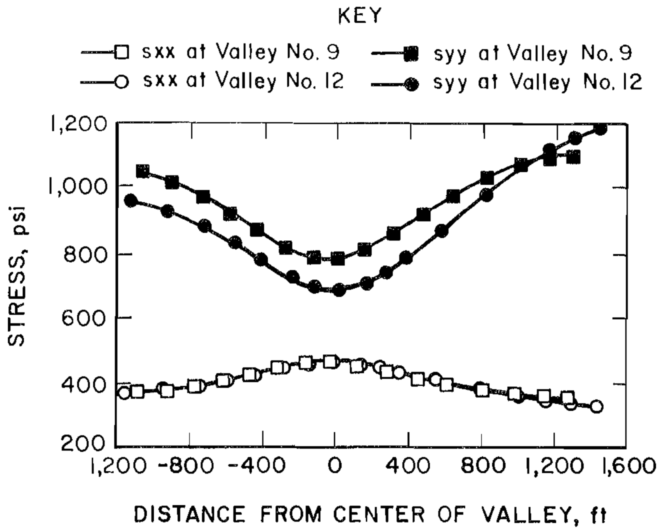

Figure 24.—Comparison of stress between Valleys No. 9 and No. 12 at mine 132 at 500 ft deep.

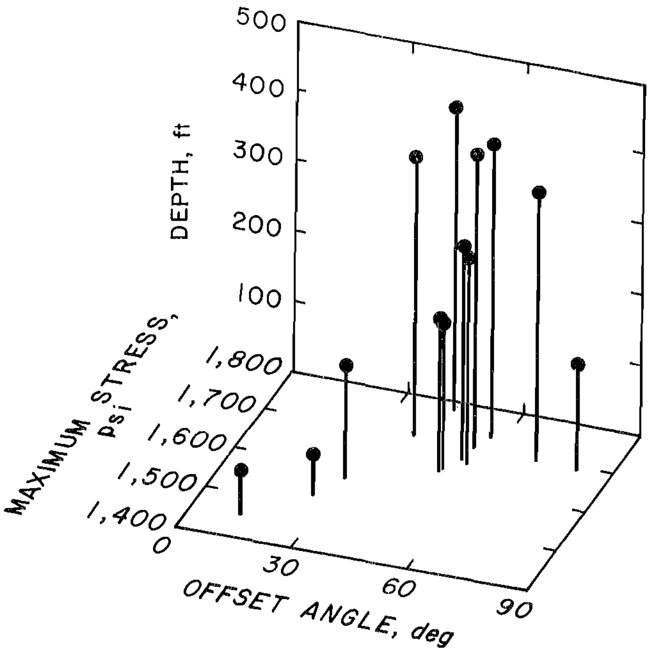

Figure 25.—Three-dimensional graph showing increase in maximum horizontal stress with offset angle and depth of valleys above mine 132.

and the offset of the valley from the regional stress, which is the number of degrees the strike of the valley is offset from the orientation of the maximum regional stress. The table also shows the maximum and minimum horizontal stresses and the vertical stress as calculated by FLAC. When the offset angle is 90°, the valley cross section will exactly parallel the maximum regional stress and therefore, the concentrated horizontal compressive stress at the valley center due to the topography will vectorially add to a maximum with the regional stress. The closer the offset angle is to 90° the higher the maximum horizontal stress will be. The exact effect of the offset angle on the value of the resultant maximum horizontal stress is not readily apparent in table 4 because the depth of the point where the stress field is being calculated also has a pronounced effect on the resultant horizontal stresses, and the valley calculation points are at various depths.

Figure 25, a three-dimensional plot of maximum horizontal stress plotted against offset angle and depth, aids in the visualization of the interactive effect of both the offset angle and the depth. From this figure, the maximum horizontal stress does indeed increase with both the offset angle and depth as presumed. Therefore, when the regional stress is considered, not only does the shape of the valley influence the stress field, but so does the orientation of the valley with respect to the direction of the principal regional stress.

Because some shear-type failures had been observed underground, it seemed reasonable to investigate the maximum shear stress developed in the various valleys. Therefore, a calculation of the maximum shear stress in the three-dimensional stress field and the normal force on the maximum shear plane was performed. The exact orientation of this shear plane was not specifically determined because both the orientation of the entries and the lithology under the valleys are variable and will have a predominant influence on the orientation of any failures observed underground. The results of the maximum shear stress calculation are presented in table 5. Clearly, some of the shear stresses in this table are fairly high, especially considering the minimal values of the normal stresses providing the shearing restraint.

Table 5.—Shear stresses expected in Powellton Coalbed in mine 132

Valley	Depth of coalbed, ft	Maximum shear stress, psi	Normal stress on shear plane, psi	Ratio shear stress-normal stress
1 ...	415	552	1,183	0.47
2 ...	300	611	1,060	.58
3 ...	415	554	1,148	.48
4 ...	380	567	1,132	.50
5 ...	290	608	1,058	.57
6 ...	395	547	1,157	.47
7 ...	430	529	1,250	.42
8 ...	160	644	934	.69
9 ...	150	714	981	.73
10 ..	200	651	995	.65
11 ..	60	692	765	.90
12 ..	60	729	798	.91
13 ..	214	635	1,000	.64

To further investigate the relative probability of shear failure in the stress fields under the modeled valleys, a ratio of the maximum shear stress to the normal stress on the shear plane was developed. This ratio is also presented in table 5. A higher ratio is more likely to produce a shear-type failure in that particular valley. This shear stress to normal stress ratio agglomerates the effects of depth, valley topography, the regional stress, and the relative orientation of the valley into one number which quantifies the probability of shear failure in that valley. Examination of table 5 shows that the two valleys where the coal seam is the shallowest, No. 11 and No. 12, have the greatest possibility of shear failure. This is a direct result of the high horizontal regional stress and the lack of overburden to provide confinement and is not substantially influenced by the valley shape or orientation. The next four valleys in terms of probability of shear failure, 9, 8, 10, and 13, do show the effect of the valley topography and orientation on the probability of shear failure, although seam depth still has a significant influence.

Figure 26 is an interpretation of the modeled horizontal stress, and the observed and inferred roof effects for valleys No. 9 and No. 12 at mine 132. These two valley profiles represent end members of valley shape progressing from V-notched to flat-bottomed. The sequence (*A*, *B*, *C*) in figure 26 represents the evolution of a valley from youthful (Valley No. 9) through mature (Valley No. 12) to rejuvenated (Valley No. 12 is projected into the future). There are two coal seams depicted beneath each valley. The Powellton seam (being mined) and the deeper Eagle seam (recently opened to mining). Horizontal stress is concentrated beneath the youthful V-notch (Valley No. 9) and this stress increases with depth (fig. 26*A*). If horizontal stress exceeds vertical confinement and the shear strength of the bedding, then compressional failures, slips, and thrust faults occur (fig. 26*A*). At this point, some of the valley stress is relieved and the in situ stresses are moved towards equilibria. If the coalbed is deeply buried or the bedding of the roof strata is particularly strong, then no premining failures occur and stresses are not relieved. In this case, cutter roof may occur as the built up stresses are relieved by mining. The Powellton seam shows evidence of valley stress relief (figs. 6-7). It remains unknown whether the underlying Eagle seam has failed in a similar fashion.

Valley No. 12 (West Fork of Pond Creek) can be considered to have once been as youthful as Valley No. 9 (fig. 26*B*). As the drainage matured and the valley deepened and broadened, the compression failures which presumably occurred at the youthful stage were gradually subjected to changing stresses. The valley floor approached the Powellton seam, and horizontal stress immediately below the valley was reduced as the valley floor broadened and separated the adjacent ridges and their ability to transfer load (fig. 26). However, the shear stress on the coal seam was increased because overburden confinement was reduced at a faster rate than horizontal compression (table 5). The result is that strata beneath valleys which have not experienced previous stress relief shearing were most likely to now fail in this mode. Valleys which have already failed have continued slippage along sheared surfaces which result in additional poor rock mass quality and difficulty with roof control. At a depth of 300 ft, stresses are again concentrated beneath Valley No. 12, because of the relative depth beneath the stress-relieved zone. At greater depths, horizontal stress contours will flatten out and the effect of the topography will disappear.

The third pair of valleys in figure 26*C* represents Valley No. 12 in the process of rejuvenation at some future point. If uplift were to occur, and the West Fork of Pond Creek began to downcut through the Powellton seam, the new valley notch would represent a youthful disruption of the in situ stress and result in a stress state similar to that beneath Valley No. 9. The result would be a concentration of stresses and the stresses would be redistributed as the valley evolved.

The valleys forming the watershed above mine 132 are in various stages of evolution, with the West Fork of Pond Creek being the most mature. The state of stress at the coal seam level beneath them depends on the shape of the valley, the depth of cover, and the orientation of the valley with respect to the principal regional stress. The relative risk of compressional failure based on shear stress is given in table 5. Finally, perhaps the most important factor in whether failure will occur, given the necessary stresses, is the shear strength of the roof sequence. This important factor is difficult to measure or estimate because of the infinite variety and character of the many bedding planes and interfaces which makeup coal measure rocks.

Modeling stress changes on mine openings has provided important insight into the effect of valley geometry on those stresses. Relative changes in stress over a property can be obtained based solely on topography, but a reasonable estimate of regional stress is necessary to provide real numbers to be used to prescribe support.

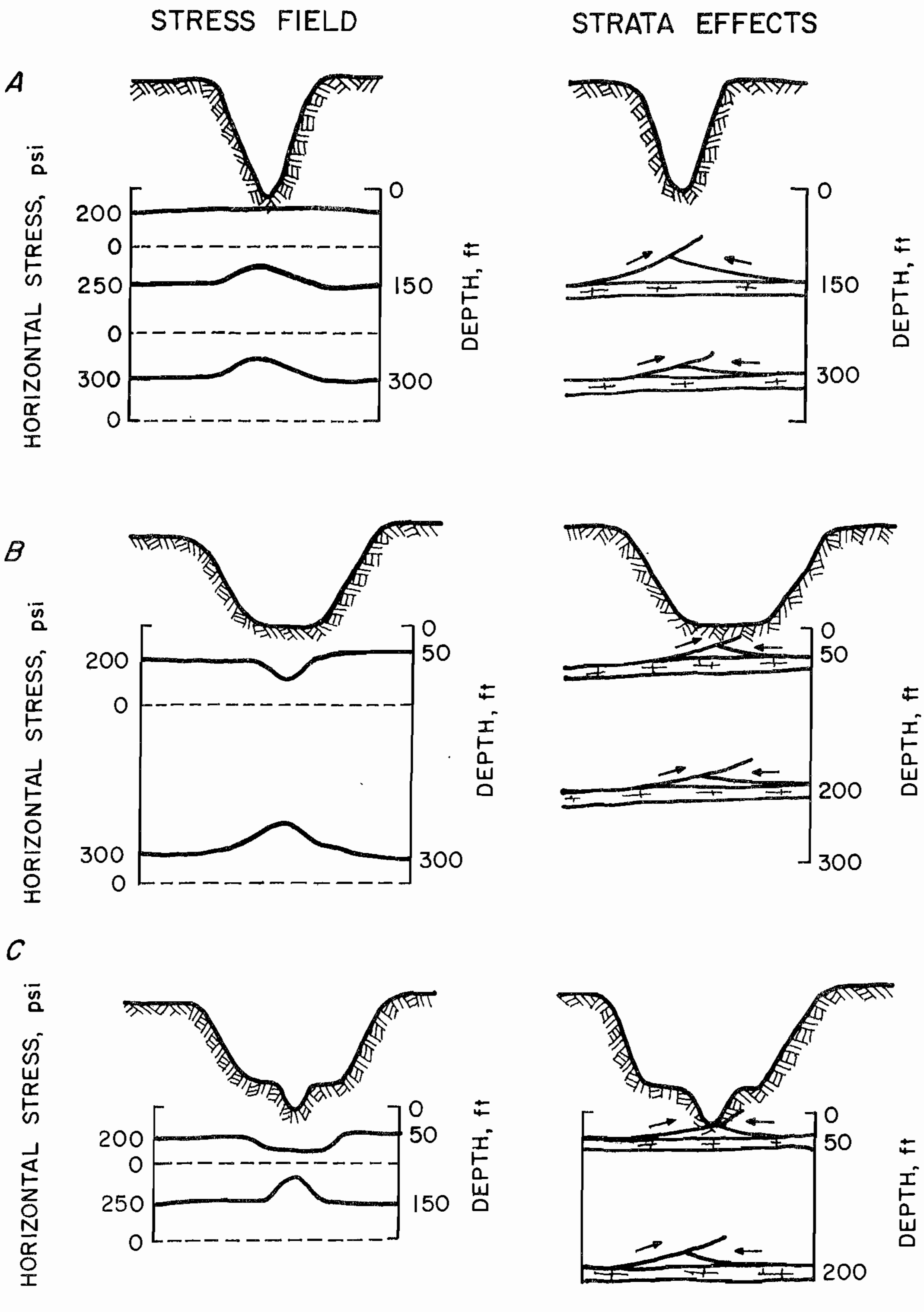

Figure 26.—Representation of modeled stress field and roof effects beneath Valleys No. 9 and No. 12. *A*, Valley No. 9; *B*, Valley No. 12; *C*, rejuvenated Valley No. 12.

CONCLUSIONS

A detailed study of the distribution of unstable roof in 7 mines in West Virginia and Pennsylvania showed a strong correlation between roof failure and specific locations beneath stream valleys. Fifty-two percent of individual unstable roof occurrences were located beneath the area of the valley with less than or equal to 20 pct of the maximum overburden. Only 10 pct of unstable roof occurred beneath the valley with 80 to 100 pct of the maximum overburden. Poor roof conditions tended to occur beneath the broader, flat-bottomed valleys more often than beneath the more confined narrow-bottomed valleys (66 pct). The mechanism of failure varied significantly between mine properties, but the most likely mode of failure was by horizontal compression of roof members. This type of failure has been interpreted in many cases as the result of valley stress relief. Previously thought to occur only near surface, evidence of compressional failure of roof strata has been observed to depths of 300 ft. As a result of this study, it is believed that, in many cases, poor rock mass quality beneath valleys is caused by broken cohesion of bedding and buckling of bedded strata. The shear strength of the immediate roof sequence plays a role in whether stress will be relieved by strata failure prior to mining or whether stresses will remain concentrated and be relieved by cutter roof failure during mining.

In situ horizontal stress measurements obtained by overcoring may indicate the regional horizontal stress in Boone County, WV is oriented approximately N70W and reach almost 4,000 psi at a depth of 875 ft. A stress measurement beneath the adjacent valley of 1,837 psi, as well as compressional strata failure, indicate that stress relief has occurred beneath a relatively steep-walled valley.

Numerical modeling of 13 valleys overlying a mine in West Virginia indicate that the valley excavation tends to concentrate horizontal stresses beneath the valley apex. A model of a broad-bottom valley shows that there is a stress-relief zone developed down to 50 ft beneath it. Whereas horizontal stresses are diminished in this broad valley, large shear stresses can form because of the reduced confinement, making this type of valley one of the most subject to shear failure. With greater depth, stresses are again concentrated beneath the apex. When horizontal stresses are concentrated beneath the apex and they exceed the confinement ability of vertical load, large shear stresses can form and lead to compressional failure. Additionally, valleys oriented at large angles to the direction of maximum regional stress are at greatest risk to high shear stresses. Valleys that have existing stress relief failures and are still subjected to horizontal compression will also experience the most significant compressional roof failure. Thickness of cover, shape of the valley, and the magnitude and orientation of the regional stress all influence the stress field at the mine level.

It is important in the mine planning process to be aware of the effect of surface topography on the stability of coal mine openings. The shape of the valley, the depth of the coalbed, the magnitude and orientation of the regional horizontal stress, and the orientation of the valley relative to the regional stress all play a role in determining the stability of entry.

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APPENDIX.—GLOSSARY OF TERMS

Bad Top - Refers to hazardous roof conditions in a coal mine.

Bedding Plane Faults - Horizontal slip planes parallel to bedding along which there has been movement.

Cutter Roof - Failure in mine roof rock which begins as a fracture plane in the roof rock parallel to and, located at, the roof-rib intersection. The fracture propagates upward into the roof over the mine opening at an angle usually steeper than 60° from the horizontal.

Fault Gouge - Weathered clay-like or crushed rock which occupies the interface between two fault surfaces and is the result of fault movement.

Hillseams - Vertical extension joints in rock which are the result of valley walls moving towards the valley as a result of unloading. Hillseams are most prominent near outcrop.

Kink Roof - Buckling of roof strata in the middle of the entry due to horizontal compression.

Outby - Refers to locations away from the working face.

Valley Anticlines - Structures which form as a result of the buckling of floor strata of a stream bed as a result of stream downcutting.

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