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Relationship Between Horizontal Stresses and Geologic Anomalies in Two Coal Mines in Southern Illinois

By David K. Ingram and Gregory M. Molinda

BUREAU OF MINES



UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft foot

pct percent

in inch

psi pound (force) per square inch

RELATIONSHIP BETWEEN HORIZONTAL STRESSES AND GEOLOGIC ANOMALIES IN TWO COAL MINES IN SOUTHERN ILLINOIS

By David K. Ingram¹ and Gregory M. Molinda¹

ABSTRACT

In situ horizontal stresses were measured to determine the influences of geologic anomalies on the regional horizontal stress field in two coal mines in southern Illinois. Stress measurements were obtained near a normal fault having a 121-ft displacement at the AMAX Wabash Mine and a large coalbed fault at the Kerr-McGee Galatia No. 5 Mine.

Horizontal stress measurements were completed using a Bureau of Mines borehole deformation gauge. The average maximum and minimum horizontal compressional stresses at the Wabash Mine were 1,400 and 800 psi, with the direction of maximum stress ranging from N 78° W to N 83° E. At the Galatia No. 5 Mine, the averages were 1,500 and 500 psi, with the direction of maximum stress ranging from N 85° E to N 75° E. Generally, the geologic anomalies appear to have no dramatic effect of the regional horizontal stresses. However, subtle differences between stress measurements suggest an influence by the fault zone at the Wabash Mine. The larger anisotropic stress conditions at the Galatia No. 5 Mine could be responsible for the increase in kink zones and directional roof failures.

¹Geologist, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

Regional horizontal compressional stress conditions in the Illinois Coal Basin are caused by the Earth's natural dynamic internal forces. The current regional stress field contributes, in most cases, to unexpected roof failures in many underground coal mines throughout southern Illinois (1).² These roof failures are thought to be caused by excessive horizontal stress concentrations creating a downward buckling and collapse of certain roof lithologies in mine openings. In addition, as in most U.S. coal basins, hazardous mine roof conditions are also associated with anomalous geologic structures. These structures contribute to hazardous mine roof by disrupting the continuity of the mine roof strata. The combination of the high regional horizontal compressional stress field and the anomalous geologic structures increases the possibility of unsafe mining conditions.

The objective of this investigation was to determine if there is a measurable influence from either a normal fault

or a thrust zone on the magnitude and orientation of the contemporary regional horizontal compressional stress field. This was accomplished by comparing horizontal in situ stress measurements taken near the geologic anomalies with stress measurements taken away from the geologic anomalies.

An understanding of the nature and magnitude of the influence can assist mine operators in mine design and/or development. For example, conditions could be severe enough to warrant a change in the mining configuration to reduce hazardous stress and/or anomalous geology problems. Depending upon the overall conditions, variations in mining might include supplemental roof support, a reorientation of the crosscuts and entries, cutting slots in the roof and/or floor strata, change in pillar size and design, and induced caving (2).

CHARACTERIZATION OF REGIONAL STRESS FIELD IN SOUTHERN ILLINOIS

Previous investigations have reported that the coal-bearing strata in southern Illinois are currently being subjected to a regional horizontal compressional stress field. This stress field is believed to have a maximum horizontal stress ranging from 1,207 to 3,191 psi, oriented east-northeast to west-southwest. All compressive stresses cited in this report are considered positive. In one investigation, the maximum horizontal stress was determined to be as much as three times the minimum horizontal and vertical stresses. Stress evaluation techniques used in these previous studies included earthquake seismic studies (3-7), underground observations (7-9), and stress measurements (8, 10-14).

Recent earthquake activity in central United States is evidence of a buildup of tectonic stresses, which are periodically relieved by seismic activity. For example, over 700 earthquakes have been documented in the New Madrid (southeastern Missouri) region from 1974 to 1978 (fig. 1) (3). This zone, which is just southwest of Illinois, is the most active tectonic area in the central United States. In addition, research by Herrmann, Sbar and Sykes, and Zoback and Zoback confirms that this tectonic activity is currently creating a horizontal compressional stress field (4-6).

Focal-plane analyses used in these studies have determined that the maximum horizontal compressional stress is oriented east-northeast to west-southwest. Figure 2

shows the locations and focal-plane analyses of four earthquakes in southern Illinois (8). Maximum horizontal compression direction ranges from N 59° E to east-west, compatible with the alignment of the regional stress field throughout central United States.

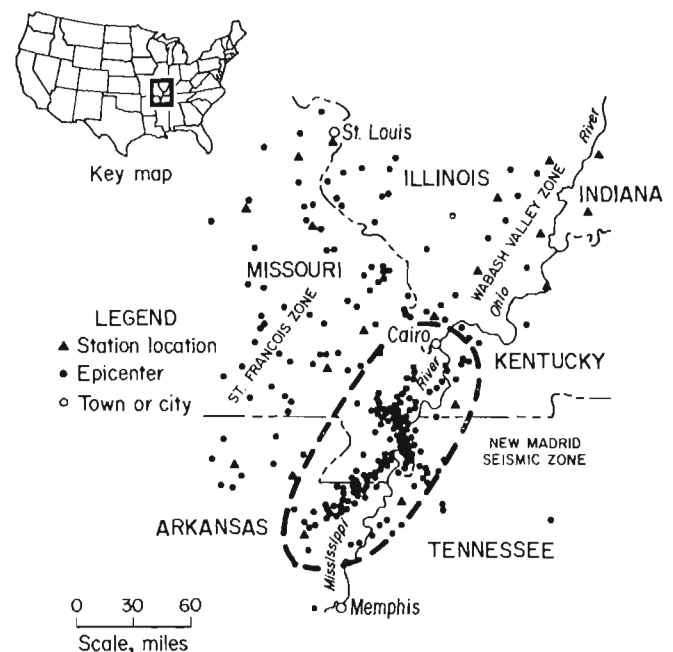


Figure 1.—Location of earthquake epicenters from 1974 to 1978 in New Madrid region (3).

²Italic numbers in parentheses refer to items in the list of references at the end of this report.

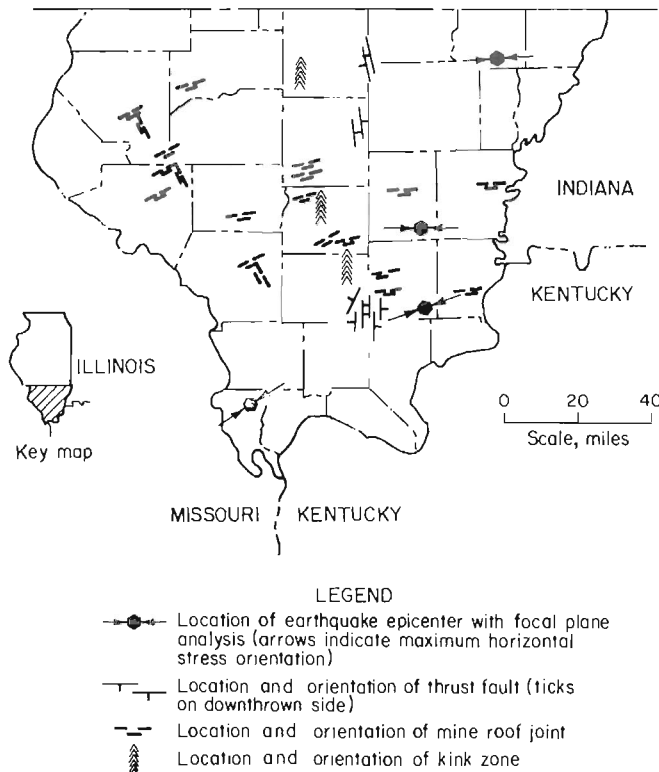


Figure 2.—Locations of earthquake focal-plane analysis, thrust faults, joints, and kink zones; indicators of regional horizontal stress (7-8).

Underground investigations by the Illinois State Geological Survey (ISGS) identify geological features such as thrust faults, joints (rock fractures), kink zones, and directional roof falls as structures currently being formed in response to the regional horizontal compressional stress field. Figure 2 shows the locations and trends of thrust faults in southeastern Illinois. Their strikes range from N 25° W to N 20° E. In general, a thrust fault or reverse fault is a low angled fracture along which the overlying side moves upward, relative to the lower side. They are the result of the current horizontal compressional stress field and are oriented perpendicular to the maximum horizontal compressional stress (8, 15).

Joints trending east-west in southern Illinois are shown in figure 2. Their strikes range from N 50° E to N 70° E in the southwest to N 65° E to N 75° E in south-central Illinois to N 75° E to N 85° E in the southeast (8). These joints are more prevalent in brittle, laminated shale and thin bedded siltstone roof strata than in massive deposits such as sandstone (8). The east-west joints are a type of extension fractures that resulted from the current regional stress field. They are also referred to as release joints (1, 16).

Extension or release joints develop under triaxial stress conditions. Failure that forms along planes perpendicular to the minimum principal stress is always in extension, even when the minimum principal stress is compression. This loss of cohesion in extension occurs along surfaces normal to the minimum principal stress (16). As is the case in southern Illinois, northeast-southwest joint trends are perpendicular to the northwest to southeast axis of the minimum horizontal stress (i.e., parallel to the maximum horizontal stress).

A kink zone, the term coined by the ISGS, is a type of mine roof failure (1, 8-9). Kink zones occur in many underground coal mines in southern Illinois. The mapping of kink zones has demonstrated that kinks generally trend north-south and usually develop soon after mining (fig. 2) (8). Like joints, kinks occur more frequently in brittle, laminated shale and thinly bedded siltstone roof strata. The characteristics of kinks are similar to those of cutter roof. Kinks occur when the rock layers in the roof buckle downward or collapse along a linear or sinuous trend. The converging, overlapping, and crushing of the buckled rocks along the kink axis is the physical evidence of horizontal compression. The axis of the kink is perpendicular to the direction of the applied maximum horizontal stress. Directional roof falls, oriented north-south, have also been widespread through many coal mines in southern Illinois. They most strongly develop, like kinks, in north-south headings. Their orientation and characteristics imply failure due to the horizontal compressional stress.

Previous studies of stress measurements in underground coal mines and surface boreholes in southern Illinois show a maximum horizontal compressional stress field trending east-west to northeast-southwest. Figure 3 displays the locations of the known stress-measuring studies.

Quantitative stress measurements, obtained by several different stress measuring techniques, have been determined at three study sites in southern Illinois. A study at Inland No. 2 Mine in south-central Illinois utilized the vibrating wire stress meter (10). The researchers reported a maximum horizontal compressive stress of 2,721 psi, oriented N 86.5° E, and a minimum of 862 psi, oriented N 3.5° W, at a depth of 930 ft. These results indicate a 3.2:1 ratio between the maximum and minimum horizontal stresses. Another study, using the Bureau's borehole deformation gauge, was conducted at the Peabody No. 10 Mine in central Illinois (11-12). Results from this study show an average maximum horizontal stress of 1,207 psi at N 73° E and a minimum horizontal stress of 686 psi at N 17° W, under 360 ft of overburden. The ratio between these horizontal stresses is 1.6:1. In a third study, conducted at a mine in south-central Illinois, stresses were measured using strain-relaxation of cored rock from boreholes (8). The study found a maximum horizontal stress of 3,191 psi oriented N 76° E and a

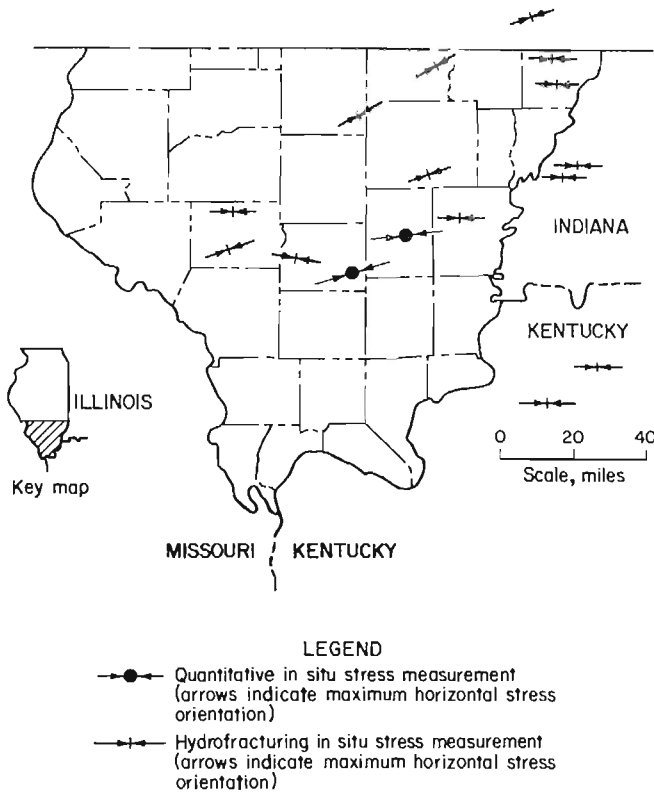


Figure 3.—Location of in situ horizontal stress measurements (8, 11, 13).

minimum of 1,392 psi oriented N 14° W (overburden unknown). The ratio of these horizontal stresses is 2.3:1.

Overall, the range in magnitudes and orientations of these quantitative stress measurements are from 1,207 to 3,191 psi and from N 73° E to N 86.5° E, respectively. The variance between the stress magnitudes may be attributed, at least in part, to the different techniques used, error in measurement, overburden, rock type, or test location with respect to the mine opening.

Other in situ stress measurements are derived from hydrofracturing methods in surface drilled boreholes. Studies referenced in this report only determined the in situ stress orientations, not stress magnitudes. In one

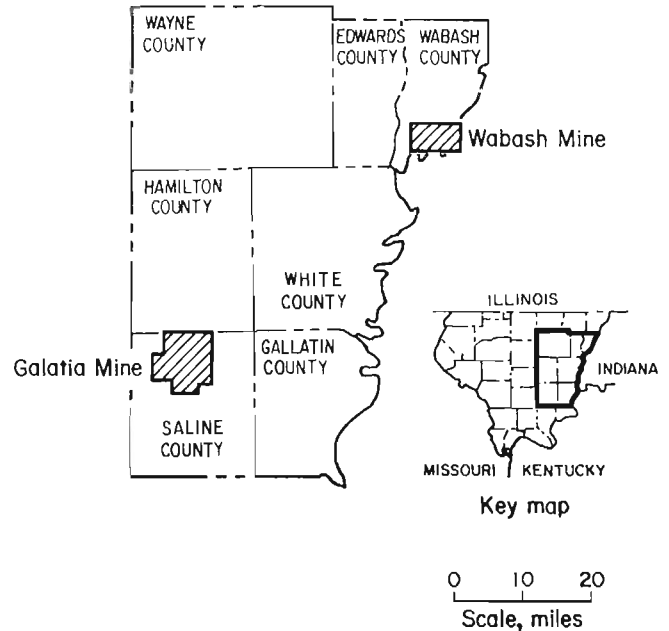


Figure 4.—Location of Wabash Mine and Galatia No. 5 Mine in southern Illinois.

study, the average direction of the maximum horizontal compressive stress was east-west with a range of N 29° E to N 79° W (13). This average orientation is based on 18 stress measurements from 14 boreholes (fig. 3). Another study in southern Illinois used measurements from five boreholes to generate an average maximum compressive stress axis of N 62° E with a range from N 49° E to N 72° E (14). Although these borehole studies do not provide magnitudes of stress, they still support the assumed regional east-northeast to west-southwest compressional stress field. The combination of the quantitative and hydrofracturing studies with the geologic structural evidence, and the current tectonic conditions, supports the conclusion that southern Illinois is currently under the influence of a regional maximum horizontal compressional stress oriented east-northeast to west-southwest.

GEOLOGIC CONDITIONS IN STUDY AREAS

This Bureau study was conducted at the AMAX Wabash Mine and at Kerr-McGee Galatia No. 5 Mine (fig. 4). These mines were selected because they have similar geologic and mining characteristics. Wabash Mine is located in Wabash County, near Keensburg, and Galatia No. 5 Mine is located in Saline County, near Galatia (fig. 4). Both mines are operating in the Springfield (No. 5) coalbed with 860 to 980 ft of cover at Wabash Mine and 525 to 600 ft at Galatia No. 5 Mine. They are mined by

the room-and-pillar method and entries are driven north-south and east-west in the areas selected for testing. The No. 5 coalbed is a member of the Carbondale Formation and ranges in thickness from 4 to 8 ft (fig. 5). The roof strata above the Springfield Coalbed is of a common and fairly uniform lithology in both mines. It is referred to as the Dykersburg Shale and it consists of slightly laminated, medium to dark gray silty mudstone or siltstone (17). This shale, which occurs along the margins of a paleochannel

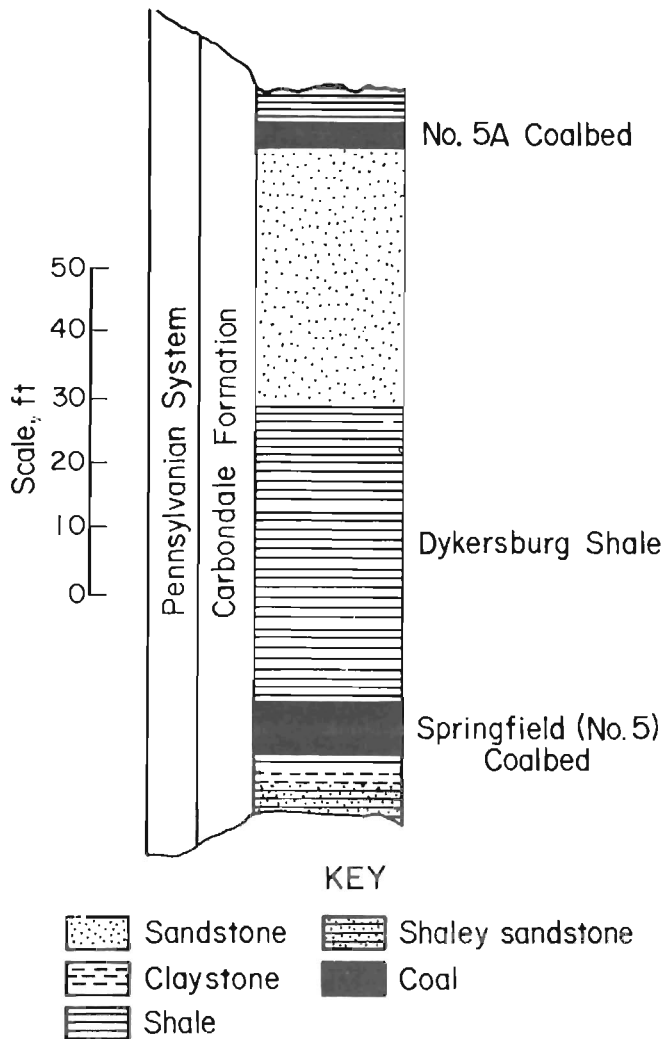


Figure 5.—Generalized stratigraphic column for both study areas.

called the Galatia channel deposit, ranges in thickness from 20 to 45 ft (fig. 6). Both mines are located in the Fairfield Basin of the Illinois Coal Basin, north of the east-west trending Cottage Grove Fault System and Rough Creek-Shawneetown Zone (fig. 7) (8).

WABASH MINE

Geological disturbances found within Wabash Mine include fluvial deposits, faults, joints, and kink zones. It is the faulted area that is of interest to this study. In 1984, six entries were developed in Wabash Mine through a major normal fault to gain access to a substantial coal reserve to the west. These six entries are in rock, inclined 12° to 14° to horizontal, and are approximately 650 ft long. They are supported by steel arches with wood

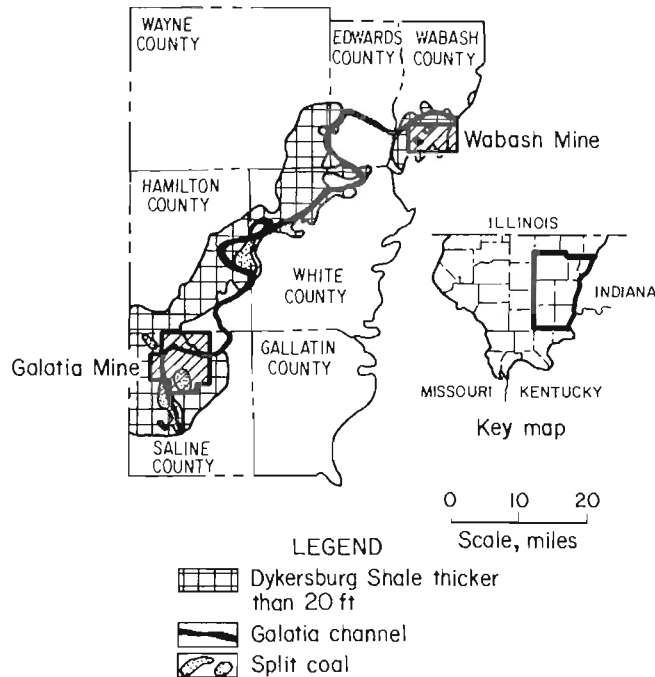


Figure 6.—Location of Galatia channel deposit in southeastern Illinois (17).

timbers and steel lagging. This unique underground excavation provided a good opportunity to investigate the influence of a major fault on the regional horizontal compressional stress field.

Wabash Mine is situated within the Wabash Valley Fault System (fig. 7). This fault system trends north-northeast and consists of numerous high-angle en echelon (overlapping or staggered) normal faults that form horsts grabens (18). The Wabash Valley Fault System is believed to be the result of horizontal extension due to tectonic tensional stresses. These stresses were oriented east-southeast to west-northwest, and most likely were active between post-Pennsylvanian and pre-Pleistocene periods (18).

The New Harmony Fault zone, part of the Wabash Valley Fault System, crosses the western portion of Wabash Mine. In the study area, the largest fault in the New Harmony Fault zone (designated as the major fault) has a maximum displacement of 121 ft. This normal, high-angle (dip 60° to 85°) major fault plane is parallel to sub-parallel to numerous minor faults (all other faults within the study area) (fig. 8). All of these minor faults are high-angle normal faults with displacements ranging from a fraction of an inch to approximately 22 ft. In one case, however, an exposed minor fault appears to be a combined normal-strike slip fault. In every case, these minor faults penetrate the entire coalbed and extend into the visible portion of the immediate mine roof.

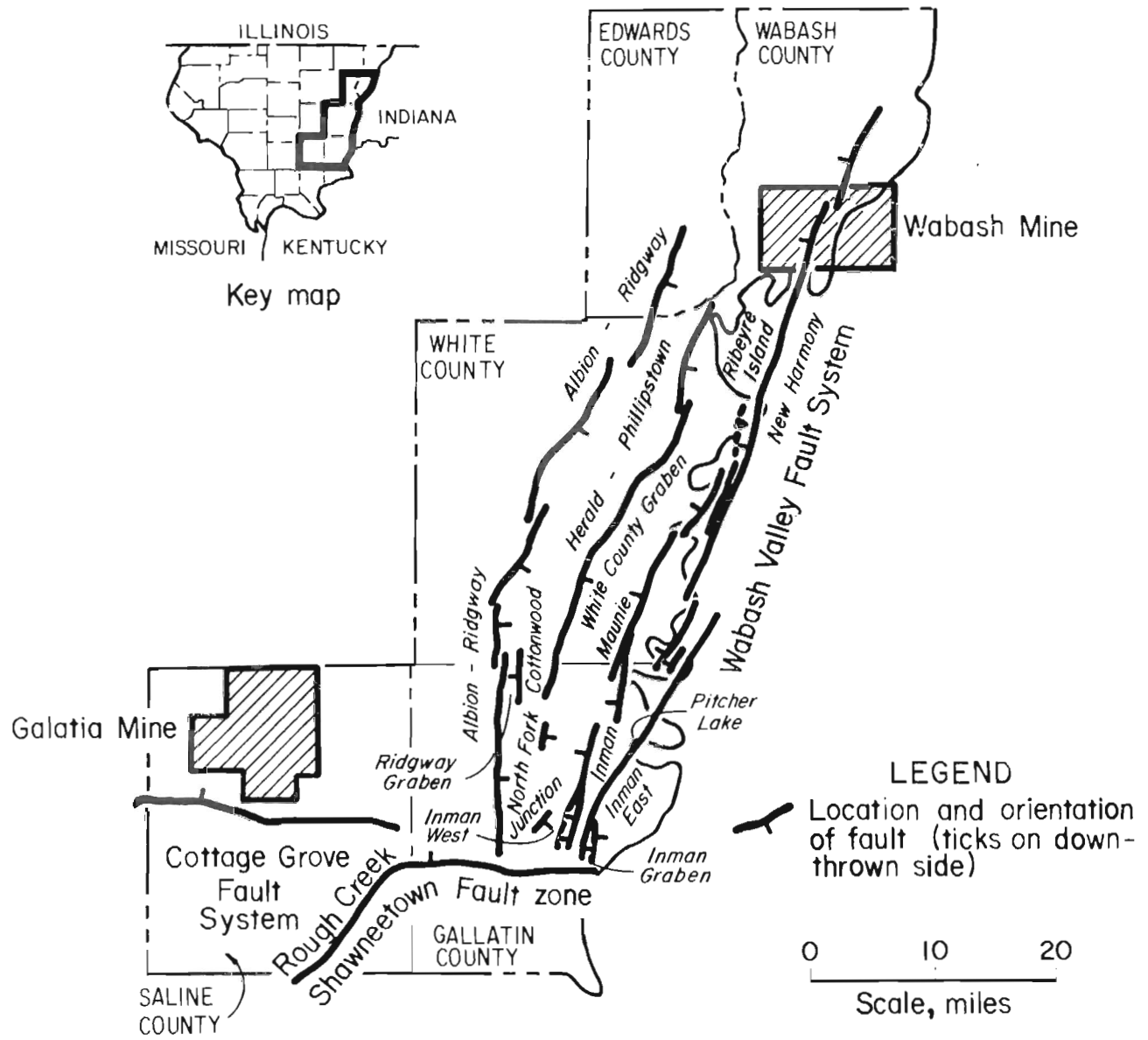


Figure 7.—Location of Wabash Mine within Wabash Valley Fault System (18).

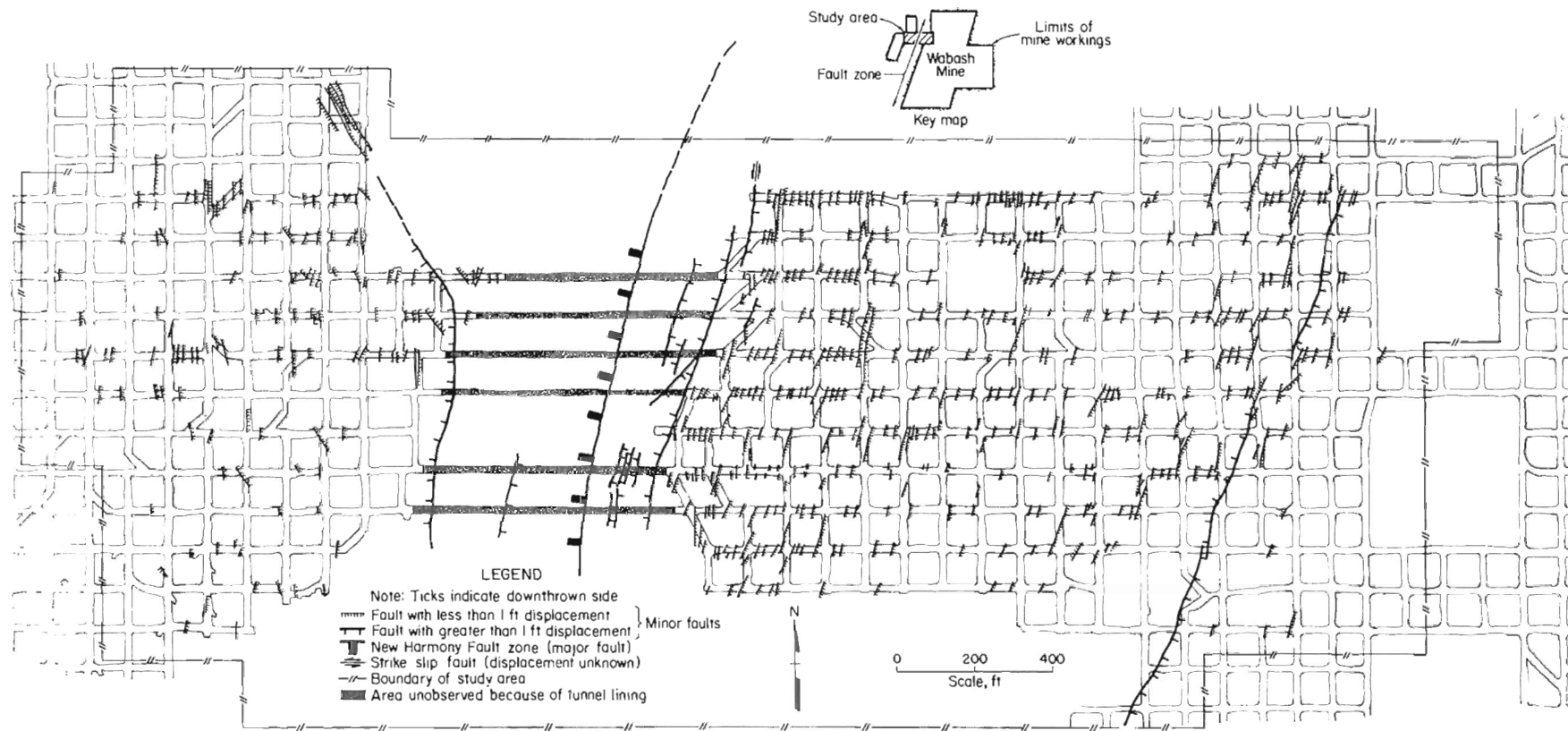


Figure 8.—Distribution and locations of faults in study area at Wabash Mine.

Most of the minor faults with displacements greater than 2 ft were observed to occur within 600 ft of the major fault plane (fig. 8). Some of these minor faults (greater than 2-ft displacements) dip eastward while others dip westward. This random dip direction is characteristic of the larger faults within the Wabash Valley Fault System (18). In contrast, virtually all of the minor faults with less than 2-ft displacements are dipping eastward. This occurs on both sides of the west-dipping major fault plane. Minor faults that dip opposite to a major fault are referred to as antithetic faults (19). This combination of faulting is associated with major grabens (18).

In this study, the western side of the New Harmony Fault zone may be an extension of a graben (White County Graben) within the Wabash Valley Fault System (18). All of the faults mapped during this investigation are believed to have formed along with the Wabash Valley Fault System. This system is not related to the current horizontal compressional stress regime. However, a few small soft sediment or compactional type of minor faults not related to the Wabash Valley Fault System may be present. These soft sediment or compactional faults could have developed during lithification.

Joints striking roughly east-northeast to west-southwest were observed in the mine roof only in the entries east of the major fault. These poorly developed vertical fractures appeared to have a spacing ranging from a few inches to several feet. It is unknown whether these joints are related to the current regional east-northeast to west-southwest compressional stress field. Joints reflect stress activity any time after the rocks are lithified. Therefore, it is difficult to determine if the current stress field is responsible for their formation. These joints may have developed from local variations or short-term reversals of the tectonic tensional stresses responsible for the Wabash Valley Fault System, or these joints may be features of the current regional compressional stress field. They have orientations similar to other jointing patterns in southern Illinois mines known to be related to the contemporary stresses. Also, the absence of joints west of the major fault suggests that the joints developed after faulting. This development could have occurred if the increase in overburden depth increased the confining pressure (i.e., in situ stresses) to a point that prevented the development of the extension joints.

Within the study area, examples of north-south trending kink zones were noted only in the southernmost headings on the west side of the major fault (fig. 9). The severity of the kink zones was considered minor because they only extend for short lateral distances and affect only the first few feet of the immediate mine roof (1). These kink zones were also observed in an area where there was less faulting. One explanation for this condition is that this area may still be under regional compressional stress concentrations that are slightly greater than in the areas where there are numerous faults. Moreover, the existing minor faults in the surrounding area could be partially relieving the current horizontal stress field by microscopic slippage (1).

Another explanation for why these kink zones concentrate in this area is that there may be a subtle change in the roof lithology. The first 6 to 8 in of shale immediately overlying the coalbed appeared to be darker in color than elsewhere. This color could represent a change in the physical properties of the shale. The darker shale may be more brittle and/or thinly laminated and more readily prone to collapse under the influence of the east-northeast to west-southwest compressional stress field.

Wabash Mine does not have a history of major mine roof instability problems related to the current horizontal stress field. Roof failures that occur within the study area are mainly associated with fault planes having displacements greater than 2 ft. Most of these roof falls are minor, with few exceptions. Faults disrupt the lateral continuity of the immediate, and sometimes, the main roof. Depending on the orientation of the fault with respect to the mine entry, the mine roof could be segmented into cantilever beams (20). The directional mine roof spalling that occurs in the kink zones is not detrimental to major roof stability. However, the development of these north-south trending zones does imply some type of compressional stress condition in the east-west trending direction.

GALATIA NO. 5 MINE

Geologic disturbances commonly found within the Galatia No. 5 Mine include compactional faults, local thinning of the coalbed, joints, and kink zones (21). The local thinning of the coalbed (want) is the geologic anomaly that is being studied. Coal production began at the Galatia No. 5 Mine in 1984; main headings were driven to the north and east of the mine shaft. In doing so, a portion of an elongated coalbed want was exposed. Stress determinations were made to identify any influence of this want on the regional horizontal compressive stress field.

The Galatia No. 5 Mine boundary encompasses a portion of an ancient fluvial system (Galatia channel) that disrupts the continuity of the Springfield No. 5 Coalbed throughout southeastern Illinois (fig. 6). This system flowed through the swamp during the peat accumulation. The drainage system developed stream channel, split or parting, and lake or pond deposits within the coalbed. It prevented peat accumulation by depositing mud, silt, and fine sand in the areas that it occupied. The want exposed at Galatia No. 5 Mine is believed to be a remnant of the Galatia channel. This want is approximately 4,300 ft long, 1,300 ft wide, and over 9 ft in viewable thickness (fig. 10). The coalbed gradually thins from 7 ft to 1 ft towards the center of the want. It is overlain by shale and siltstone and lacks evidence of erosion, which is suggestive of a lake deposit. Underground mapping at study areas 1 and 2 revealed several locations where the coalbed was laterally disrupted by a shale parting. This parting may be the remnant of a shallow, low-energy, sluggish, intermittent stream system that connected the ancient lake to the Galatia channel. Future mining could expose a continuous

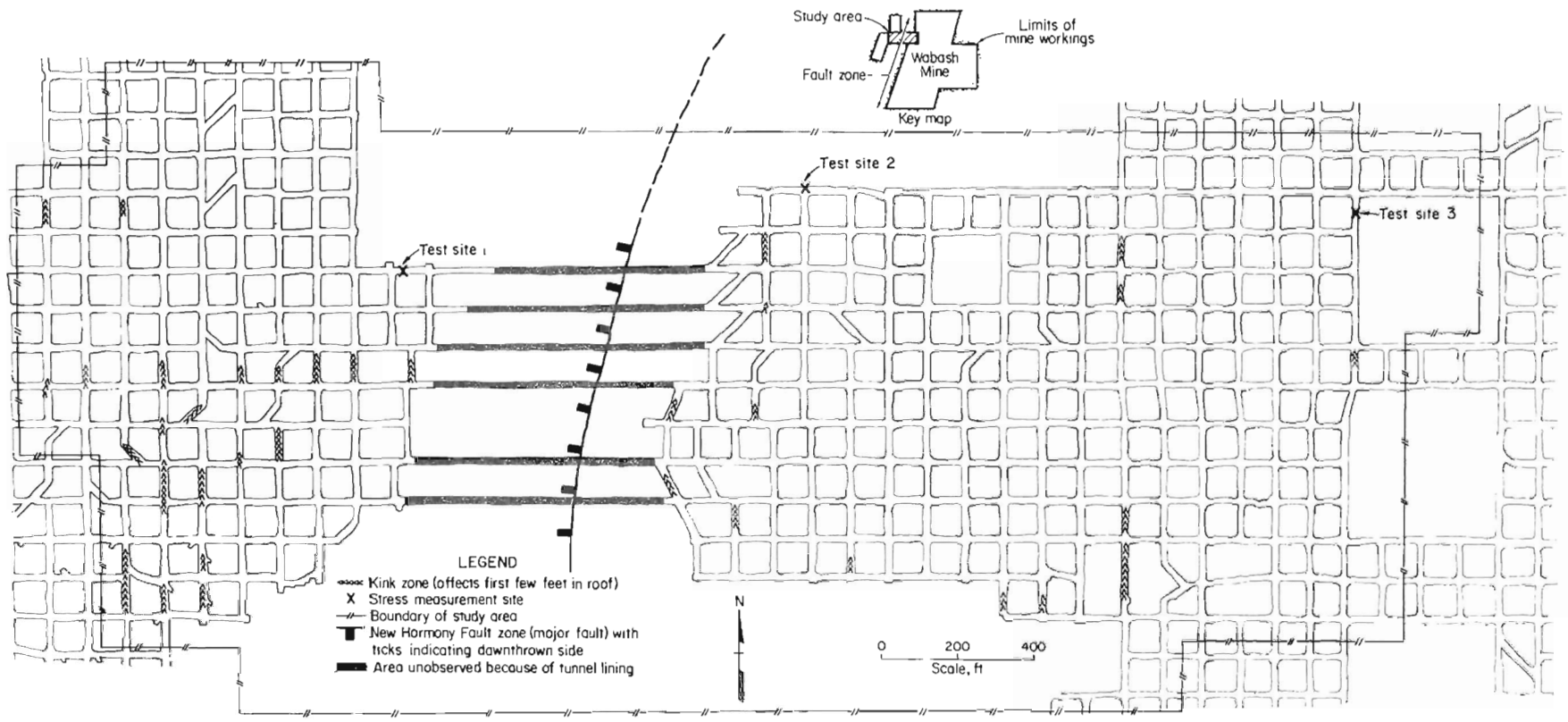


Figure 9.—Kink zones in study area at Wabash Mine.

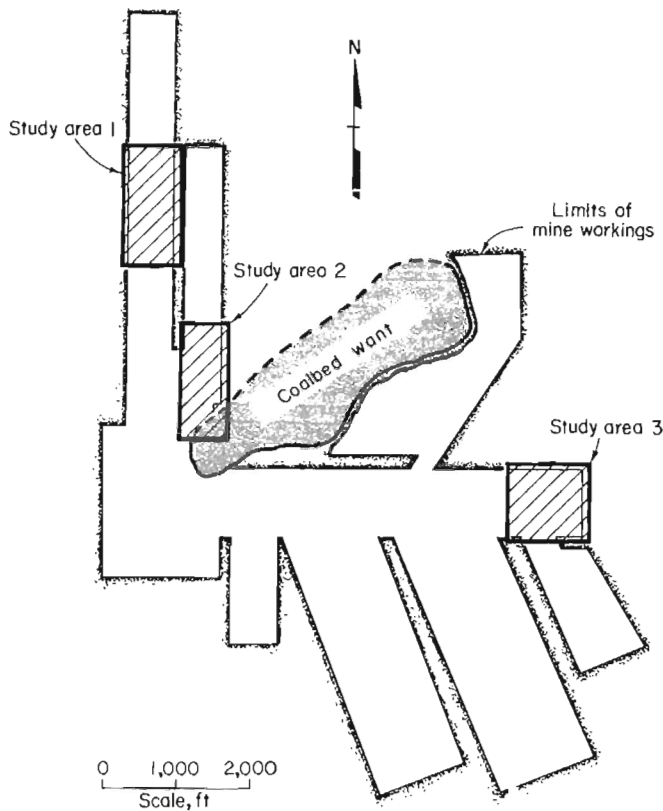


Figure 10.—Location of coalbed want (ancient lake deposit) at Galatia No. 5 Mine.

coalbed parting between the lake deposit and Galatia channel.

An underground geologic study done in 1985 by a Kerr-McGee geologist (21) identified east-northeast to west-southwest trending joints occurring in the Galatia No. 5 Mine (fig. 11). The orientation of these vertical joints ranged from N 55° E to east-west, with the majority striking N 80° E. They were observed in tight parallel sets with spacing from 0.5 in to several feet. The Bureau's underground geologic investigation found similar jointing patterns at two of the three study areas (fig. 12). These joints were also vertical and appeared to occur in parallel sets with a spacing from a couple of inches to several feet. Their orientations ranged from N 38° E to N 88° E, with the majority striking N 75° E. They were observed to be more prevalent in the roof strata at the intersections (rooms). Most of the joints terminated several feet into the coalbed, while some penetrated through and into the floor. Geologic mapping in the third study area, showed few joints (fig. 12).

Joints at Galatia are believed to be directly related to the current east-northeast to west-southwest horizontal compressive stress field (21). Like joints of the Wabash

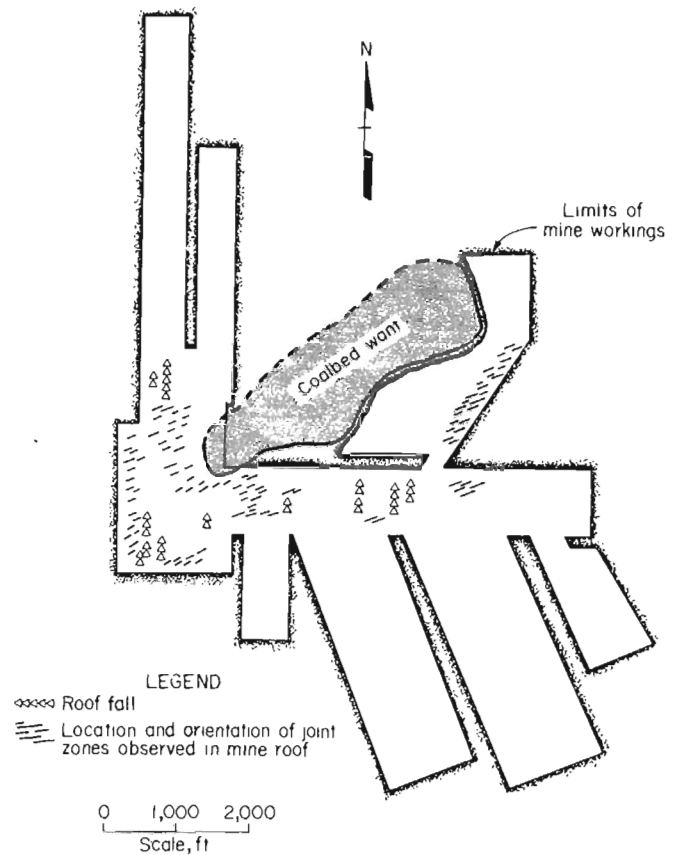


Figure 11.—Location of joints and roof falls at Galatia No. 5 Mine (21).

Mine, they have orientations similar to other jointing patterns inferred to be caused by the regional horizontal compressive stress field (8). It is possible that they may be related to major geologic structures such as the lake and Galatia channel deposits. However, their density, preferred orientation, and occurrence suggest that they are not. The absence of joints in the eastern part of the mine may be attributed to a compositional difference between the roof lithology at study areas 1 and 2, and that at area 3. The average unconfined compressive strength of the roof rock at area 3 is approximately 41 pct greater than at area 1 (table 1). In general, an increase in compressive strength is accompanied by an increase in tensile strength. This increase in rock strength at area 3 could be sufficient enough to prevent the development of fractures.

Numerous kink zones were mapped in the entries of all three study areas (fig. 12). Practically all the kink zones are trending north-south in north-south oriented entries and/or crosscuts. Kink zones in the Galatia No. 5 Mine are thought to be the results of the horizontal compressional stress field. There is no apparent evidence of any geologic features influencing the development of these kinks.

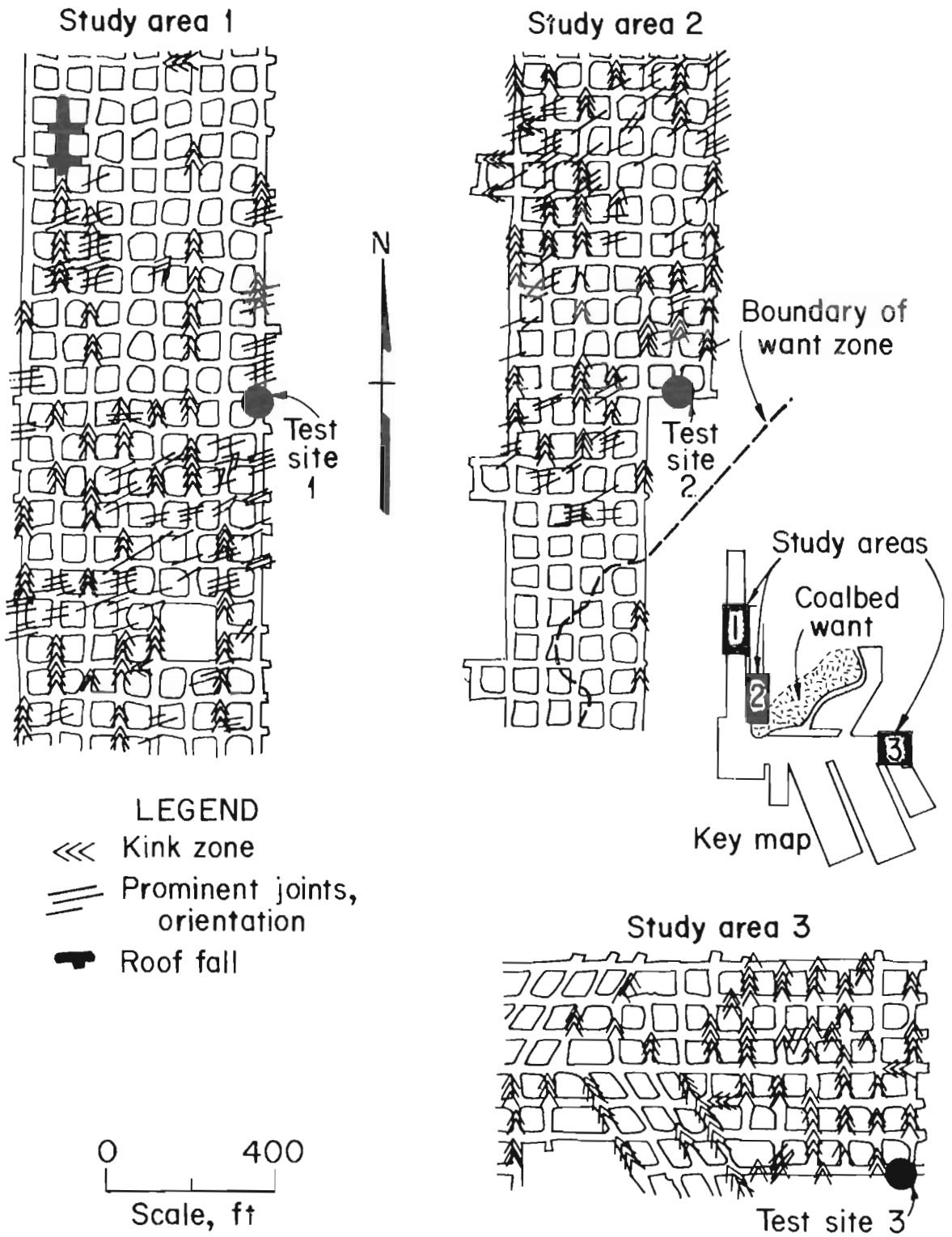


Figure 12.—Geology of three test areas at Galatia No. 5 Mine.

TABLE 1. - Unconfined uniaxial compressive strength of Dykersburg Shale from Wabash Mine and Galatia No. 5 Mine

Test site	Height of sample in borehole, in	Compressive strength, psi	Test site	Height of sample in borehole, in	Compressive strength, psi
WABASH			GALATIA		
WA-1	96	6,241	KM-1	115	8,111
	99	5,597		121	5,637
	108	6,229		124	7,206
	108	6,373		127	6,769
Average	ND	6,106		133	7,015
Std dev	ND	357		151	7,795
WA-2	85	7,037		163	7,694
	120	4,263	Average	ND	7,175
	121	7,338	Std dev	ND	825
	132	6,672	KM-2	68	6,824
Average	ND	6,328		134	9,114
Std dev	ND	1,403	Average	ND	7,969
WA-3	160	6,280	Std dev	ND	1,619
	156	6,902	KM-3	46	11,532
	156	6,666		64	10,790
	180	5,684		68	10,358
	184	4,766		74	10,942
	184	5,399		151	13,787
	184	5,590		155	10,132
	188	5,220	Average	ND	11,267
Average	ND	5,813	Std dev	ND	1,332
Std dev	ND	737	Total avg	ND	8,914
Total avg	ND	6,016	Total std	ND	2,259
Total std	ND	850			

ND Not determined.

Roof failures at the Galatia No. 5 Mine appear to be related to the current horizontal stress field and/or normal geologic conditions (21). As of 1986, there had been 25 major roof failures. Nineteen roof falls were oriented north-south in north-south headings. This north-south orientation implies a strong influence of the regional east-northeast to west-southwest stress field. The wide distribution of these roof falls suggests that they are not all related to any one particular geologic feature. A few of the failures are believed to be caused by the presence of a slip or fault plane, while others are related to weak bedding planes. Mine roof conditions in the entries surrounding the three study areas are, for the most part, stable. Irregular mine roof spalling does occur along the joints and kink zones. Spalling associated with the joints is caused by the combined vertical separation of the joints and horizontal separation of the roof strata bedding planes. This was observed in the fallen thin narrow slabs

of roof rock. Spalling within the kinks disturbs a zone in the immediate roof approximately 2 ft wide, 6 to 8 in deep, and between 10 and 170 ft in length.

In summary the Wabash Mine and Galatia No. 5 Mine have characteristics that make them ideal sites to study the horizontal stresses in southern Illinois and the possible effects of large geologic anomalies. Both mines are located in southeastern Illinois, they operate in the same coalbed with similar roof strata, use the room-and-pillar method of mining, and have entries oriented north-south, east-west. A major normal fault that displaces the coalbed 121 ft is exposed in Wabash Mine; in the Galatia No. 5 Mine entries have been developed around a portion of a coalbed want (ancient lake deposit). Both mines have physical evidence of the current regional east-northeast to west-southwest compressional stress field. They both have joints trending east-northeast to west-southwest, kink zones and/or directional roof falls oriented generally north-south.

IN SITU HORIZONTAL STRESS MEASUREMENTS

All horizontal stress measurements were obtained from vertical boreholes in the roof strata using the Bureau's borehole deformation gauge (22-24) (fig. 13). The deformation gauge measures three diametral strain deformations, 60° apart, as stresses are released by overcoring. Strain deformations are measured by the gauge in a 1.5-in-diam borehole as it is overcored by a 6-in-diam borehole. Strain deformation measurements are combined with the overburden vertical stress and physical property values of the overcored rock to compute stress magnitude and orientation. Theoretical overburden stresses were determined using the following equation (25):

$$T = 1.1 D,$$

where T = vertical stress, psi,

and D = overburden depth, ft.

Physical property values of the lithology are measured from rock core samples obtained during overcoring. These rock property parameters include axial and diametral Young's modulus values, axial Poisson's ratio, and unconfined compressive strength. The combined data are used to compute the magnitude and direction of the two principal stresses in the plane perpendicular to the axis of

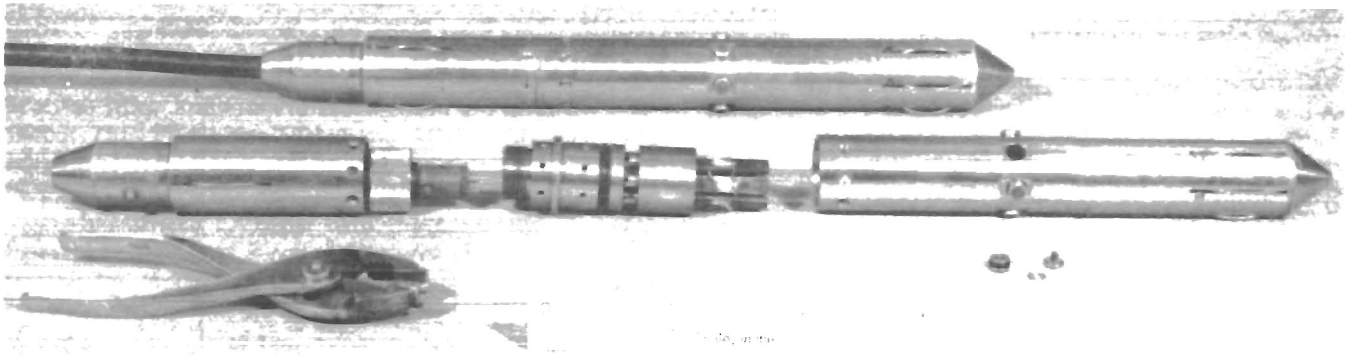


Figure 13.—Bureau of Mines borehole deformation gauge used to measure in situ stresses released during overcoring.

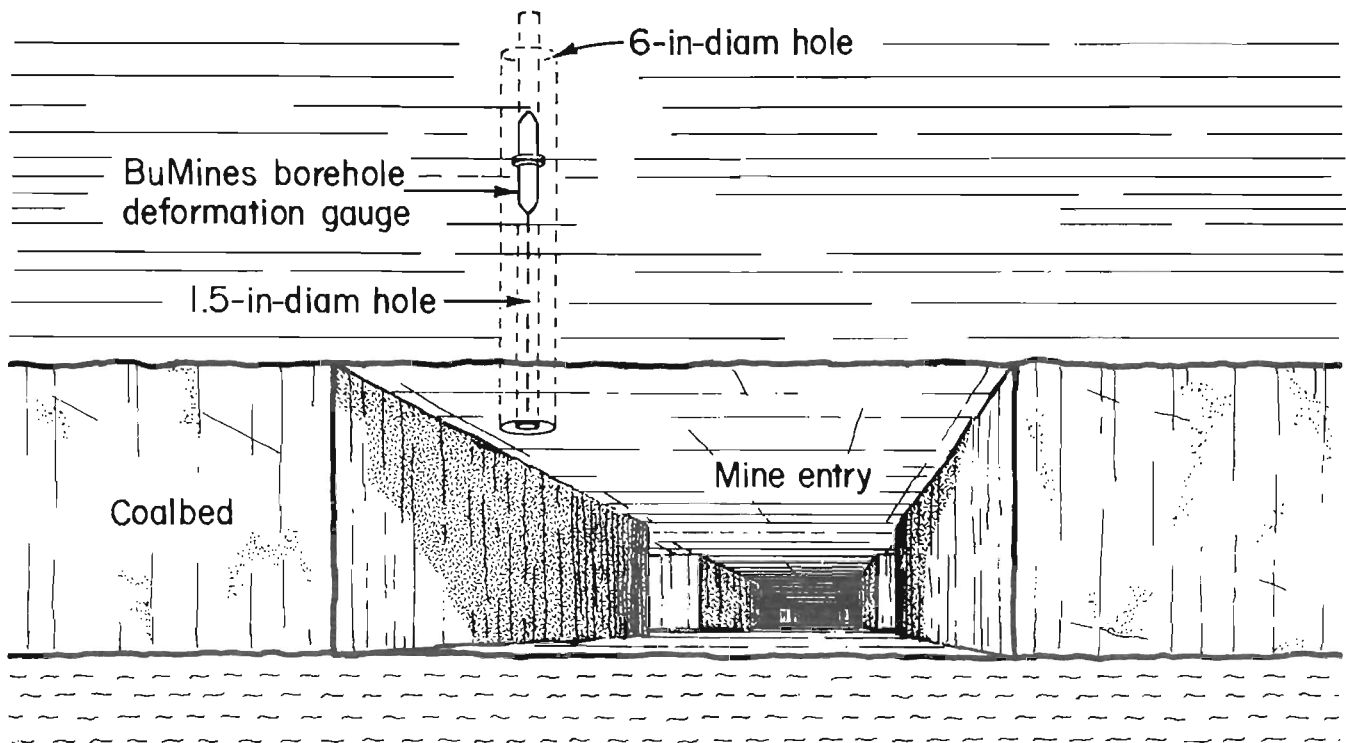


Figure 14.—Instrumentation plan for test sites.

a borehole, for each overcore (26). Figure 14 illustrates the typical instrumentation configuration for all of the test sites. In both mines, the dimensions of the entries where the stress measurements were taken averaged 18 ft wide by 7 ft high. Overcoring for stress measurements began at approximately 5 ft above the roof bolts and continued up for approximately 10 ft.

A total of 31 in situ horizontal stress measurements were completed during this investigation. Fifteen measurements were obtained at Wabash Mine and the rest at Galatia. Results are presented in table 2. Averaged

values for each borehole were determined by taking each set of stress values obtained within a borehole and resolving these values to a common, arbitrary coordinate system (x,y) using standard stress analysis techniques. After the stress values (S_x,S_y,S_{xy}) are determined in the arbitrary coordinate system, they are averaged to calculate the magnitudes and orientations of the maximum and minimum horizontal stresses for each borehole. Because of the accuracy of the stress determination, averaged stress values discussed in this report are rounded off to the nearest 100 psi.

TABLE 2. - Stress determinations from Wabash Mine and Galatia No. 5 Mine

Test site and number	Measurement point		Stress, psi		Bearing (P)	Ratio (P to Q)
	Height, ¹ in	Overburden depth, ft	P	Q		
WABASH						
WA-1:						
A	73	973	1,421	1,105	N 78° E	1.3
B	95	971	1,134	965	N 44° E	1.2
C	109	969	1,313	867	N 79° W	1.5
D	168	965	1,362	1,030	N 89° E	1.3
E	181	963	1,274	888	N 88° W	1.4
Average	ND	ND	² 1,300	² 1,000	N 88° E	1.3
WA-2:						
B	121	849	1,533	949	N 89° E	1.6
C	144	847	1,606	981	N 81° E	1.6
D	157	845	1,423	768	N 76° E	1.9
F	192	843	1,263	735	N 84° E	1.7
Average	ND	ND	² 1,500	² 900	N 82° E	1.7
WA-3:						
B	84	861	1,451	670	N 82° W	2.2
C	96	860	1,599	572	N 89° W	2.8
D	109	858	1,405	589	N 72° W	2.4
E	156	855	1,493	559	N 69° W	2.7
F	168	854	1,356	540	N 77° W	2.5
G	181	852	1,606	643	N 81° W	2.5
Average	ND	ND	² 1,500	² 600	N 79° W	2.5
Total avg	ND	ND	² 1,400	² 800	ND	1.8
GALATIA						
KM-1:						
B	72	572	1,448	388	N 78° E	3.7
C	121	568	1,980	586	N 72° E	3.4
D	139	566	1,674	467	N 77° E	3.5
E	157	564	1,654	533	N 71° E	3.1
Average	ND	ND	² 1,700	² 500	N 74° E	3.4
KM-2:						
A	44	601	1,363	523	N 84° E	2.6
B	62	599	1,334	502	N 72° E	2.7
C	75	598	1,338	497	N 76° E	2.7
D	122	595	1,296	709	N 71° E	1.8
E	134	593	1,462	507	N 70° E	2.9
G	170	591	1,249	496	N 68° E	2.5
Average	ND	ND	² 1,300	² 500	N 74° E	2.5
KM-3:						
A	52	521	1,530	551	N 89° E	2.8
B	70	519	1,505	537	N 89° E	2.8
C	103	516	1,359	570	N 80° E	2.4
D	121	514	1,341	569	N 82° E	2.3
E	140	513	1,404	545	N 82° E	2.6
F	157	511	1,565	568	N 88° E	2.8
Average	ND	ND	² 1,500	² 500	N 85° E	2.6
Total avg	ND	ND	1,500	500	ND	2.8

ND Not determined. ¹Distance from top of coalbed. ²Rounded to nearest 100.

To maintain consistency, all stress measurements were conducted under similar conditions. Therefore, all overcoring was done in the Dykersburg Shale. Table 1 shows the unconfined compressive strengths of the shale for all six test sites. Overcoring boreholes were positioned in an outside entry, near the roof and rib line, adjacent to some form of barrier pillar. Theoretically, barrier pillars help distribute mining induced stresses which could affect the in situ stress measurements.

Figure 9 shows the locations of the three test sites at Wabash Mine. Sites 1 and 2 were positioned about 500 ft

on either side of the major fault plane. Site 3 was located approximately 1,800 ft east of the fault plane. The locations of the three test sites at the Galatia No. 5 Mine are shown on figure 12. Site 2 was situated about 200 ft north of the ancient lake deposit, while sites 1 and 3 were located about 3,000 ft north and 5,000 ft east of site 2. These sites were situated so that measurements near the fault plane and lake deposit would be made under comparable conditions and could be compared with measurements made away from these anomalies.

DISCUSSION

Measured horizontal compressional stresses at the Wabash Mine and Galatia No. 5 Mine are mutually consistent (fig. 15). Table 2 shows all of the measured horizontal stress magnitudes and orientations for both mines. The average maximum horizontal stress (P) at Wabash Mine is 1,400 psi with the orientation ranging from N 78° W to N 88° E. At the Galatia No. 5 Mine the average maximum horizontal stress is 1,500 psi, with the orientation ranging from N 85° E to N 75° E. The average magnitude of the minimum horizontal stress (Q) at Wabash Mine is 800 psi and is 500 psi at Galatia. The difference in the minimum horizontal stresses (Q) between the two mines accounts for the difference in the ratios of P to Q. The Galatia No. 5 Mine average P to Q ratio of 2.8 is greater than that of the Wabash Mine, 1.8. Horizontal stress measurements obtained in this study are compatible with other stress magnitude and orientation values determined from previous studies throughout southern Illinois.

The measured horizontal stress is composed of two components. These are the horizontal component and the excess horizontal component. This horizontal component (due to Poisson's effect), which is caused by overburden and Poisson's ratio of the strata, is calculated to estimate the excess horizontal component (i.e., excess stresses) (27). The horizontal component by Poisson's effect (S_h) is approximated by the following equation:

$$S_h = \frac{\nu}{1-\nu} \sigma_z,$$

where ν = Poisson's ratio,

and σ_z = vertical stress.

The value, S_h , obtained by this equation is then subtracted from the measured maximum and minimum horizontal compressional stresses to determine the excess

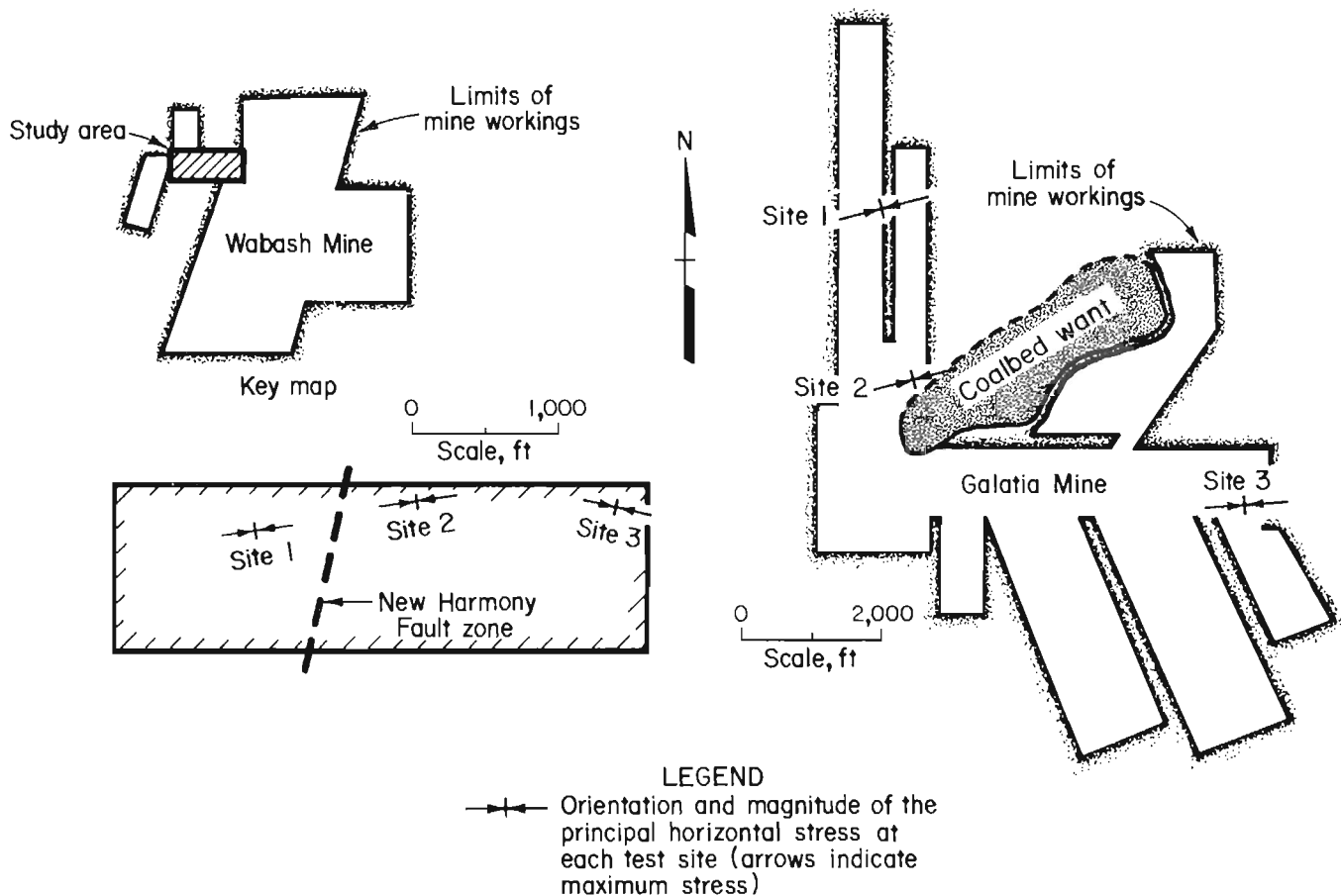


Figure 15.—Stress orientations and magnitudes for Wabash and Galatia Mines.

horizontal stress. Subtracting the Poisson's effect from the measured averaged maximum horizontal stresses at both mines indicates an excess maximum horizontal stress of 1,000 psi at the Wabash Mine and 1,400 psi at Galatia No. 5 Mine. The 1,000-psi excess maximum horizontal stress at the Wabash Mine approximates the average theoretical vertical stress of 1,000 psi. At the Galatia No. 5 Mine, however, the excess maximum horizontal stress of 1,400 psi is approximately two times greater than the average theoretical vertical stress of 600 psi. The larger stress ratio at the Galatia No. 5 Mine could be the reason it has more kink zones and/or directional roof falls than the Wabash Mine. Furthermore, eliminating the Poisson's effect from the average horizontal stresses from both mines indicates that the excess horizontal stress decreases as the overburden increases.

A closer observation of the average horizontal stress values from each test site at both mines shows some variance that should be noted. The most noticeable variations in the stress measurements are from sites 1, 2, and 3 at the Wabash Mine and site 1 at the Galatia No. 5 Mine. Stress determinations from Wabash sites 1 and 2 indicate a stress approximately 300- to 400-psi greater minimum horizontal stress (Q) than measured at other Wabash sites and the Galatia No. 5 Mine. This greater compressive minimum horizontal stress causes a corresponding decrease of the ratio between P and Q to about one half that of other test sites. These larger minimum horizontal stresses, at Wabash sites 1 and 2, only occurred near the major fault plane. It is possible that this 300- to 400-psi increase in the minimum horizontal stresses is an indication of an influence by the New Harmony Fault zone.

At Wabash site 3, the orientations of the maximum and minimum horizontal stresses are about 20° to 25° different from those at the other five test sites. One explanation for this difference is the possibility that the measured orientations at site 3 represent the normal orientations of the maximum and minimum horizontal stresses at the Wabash Mine. This assumes that the stress orientations at Wabash sites 1 and 2 are influenced by the fault zone. This influence on sites 1 and 2 would be seen as an approximately 20° northeast rotation of the horizontal

stress axes. If this were the case, the magnitudes of the regional maximum and minimum horizontal stresses at both mines would be similar but there would be a slight difference of about 24° in the regional orientation of the horizontal stresses between the two mines. On the other hand, the orientation of the stress field measured at site 3 may be due to other factors such as an actual but local rotation of the horizontal stress field, an influence from the mine geometry, the influence of some undetected geologic feature, or an inaccuracy in orienting the gauge during the stress measurements.

At the Galatia No. 5 Mine, site 1 indicates an approximately 300-psi greater magnitude in the maximum horizontal stress (P) than what was measured at the other five test sites. This larger maximum stress also increases the P to Q ratio to 1.3 to 2.3 times the ratios at all the other test sites. This larger maximum horizontal stress at Galatia site 1, could be an actual local increase in the regional stress field or an influence of the multiple seam mining, mine geometry, and/or an undetected geologic feature.

Overall, measured horizontal stresses at the Wabash Mine and Galatia No. 5 Mine appear to represent the regional trend of the horizontal compressional stress field in southern Illinois. Consistency of the stress magnitudes and orientations imply no dramatic influence from either the fault plane or want zone. The anisotropic stress conditions between the excess horizontal stresses and the theoretical vertical stress are the most likely cause for the more numerous kink zones and/or directional roof falls at the Galatia No. 5 Mine than at the Wabash Mine. There are slightly larger minimum horizontal stresses near the New Harmony Fault zone in the Wabash Mine. There is also a 20° difference in the orientation of the measured horizontal stress field between the sites near the fault plane and a site away from the fault plane. These differences in the stress magnitudes and orientations suggest a possible influence of the New Harmony Fault zone. The larger maximum horizontal stresses at Galatia site 1 may be the result of a local increase in the horizontal stress-field, or an effect from mining or some unseen geologic condition.

SUMMARY

1. Previous investigations have documented a regional east-northeast to west-southwest horizontal compressional stress field in southern Illinois. Evidence of this stress field includes earthquakes, geologic structures, and in situ stress measurements. Over 700 earthquakes were documented between 1974 to 1978 in the New Madrid region just southwest of Illinois. Underground observations have concluded that thrust faults, joints, kink zones, and directional roof falls are currently being formed in response to this regional horizontal stress. The average in situ stress measurements from three studies show a

maximum horizontal stress of 2,373 psi in a orientation ranging from N 86° E to N 73° E (8, 10-14).

2. The Wabash Mine and Galatia No. 5 Mine have similar mining characteristics, major geologic anomalies, and evidence of horizontal stress conditions. Both mines are located in southeastern Illinois, operating in the Springfield No. 5 Coalbed with similar roof lithology, using a room-and-pillar design, and have entries oriented north-south and east-west. The Wabash Mine exposes a major normal fault that displaces the coalbed approximately 121 ft. The Galatia No. 5 Mine exposes a coalbed want

(ancient lake deposit) that occupies a large portion of the coalbed zone. Both mines have east-west trending joints, and north-south trending kink zones and/or directional roof falls that are physical evidence of the current regional horizontal compressional stress field.

3. In situ horizontal stress measurements were obtained in vertical boreholes in the roof strata using the Bureau's borehole deformation gauge. All overcoring boreholes were positioned in an outside entry, near the roof and rib line, adjacent to some form of barrier pillar. At the Wabash Mine, two sites were positioned on either side of the New Harmony Fault zone. A third site was located away from the fault zone. At the Galatia No. 5 Mine, one site was situated near the want while two other sites were located north and east away from the want. All the sites were situated such that measurements near the fault plane and coalbed want would be made under comparable conditions and could be compared with the other measurements away from the possible influence of these anomalies.

4. A total of 31 in situ horizontal stress measurements were completed during this investigation. Fifteen measurements were obtained at the Wabash Mine; 16 were obtained at the Galatia No. 5 Mine. The average magnitude and orientation of the maximum horizontal stresses (P) are 1,400 psi with the orientation ranging from N 78° W to N 88° E at the Wabash Mine; at the Galatia No. 5 Mine the average maximum horizontal stress is 1,500 psi with the orientation ranging from N 85° E to N 75° E. The average magnitude of the minimum horizontal stress (Q) is 800 psi at the Wabash Mine and 500 psi at Galatia No. 5 Mine. The 1,000-psi excess Wabash maximum horizontal stress (P) is generally equal to the averaged theoretical vertical stress of 1,000 psi. The 1,400-psi Galatia excess horizontal stress is approximately two times the 600-psi theoretical vertical stress.

CONCLUSIONS

Horizontal stress measurements and certain geologic structures at the Wabash Mine and Galatia No. 5 Mine correspond with other previous studies done in southern Illinois. These studies conclude that southern Illinois is currently under the influences of a regional horizontal compressional stress field with the major stress field direction at east-northeast to west-southwest. The consistency of the stress measurements indicate no dramatic change in the regional horizontal stress field near the geologic anomalies within the study areas. The slight

differences in the horizontal stresses that do occur are near the New Harmony Fault zone in the Wabash Mine. These differences could suggest a slight increase in the minimum horizontal stress and a slight rotation of about 20° in the orientation of the maximum and minimum horizontal stresses near the fault zone. The larger biaxial stress conditions between the vertical and horizontal planes are most likely the cause for the more numerous kink zones and joints at the Galatia No. 5 Mine than at the Wabash Mine.

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